Green Steel Economics

Comparing Economics of Green H_2-DRI and Traditional Steelmaking Around the World

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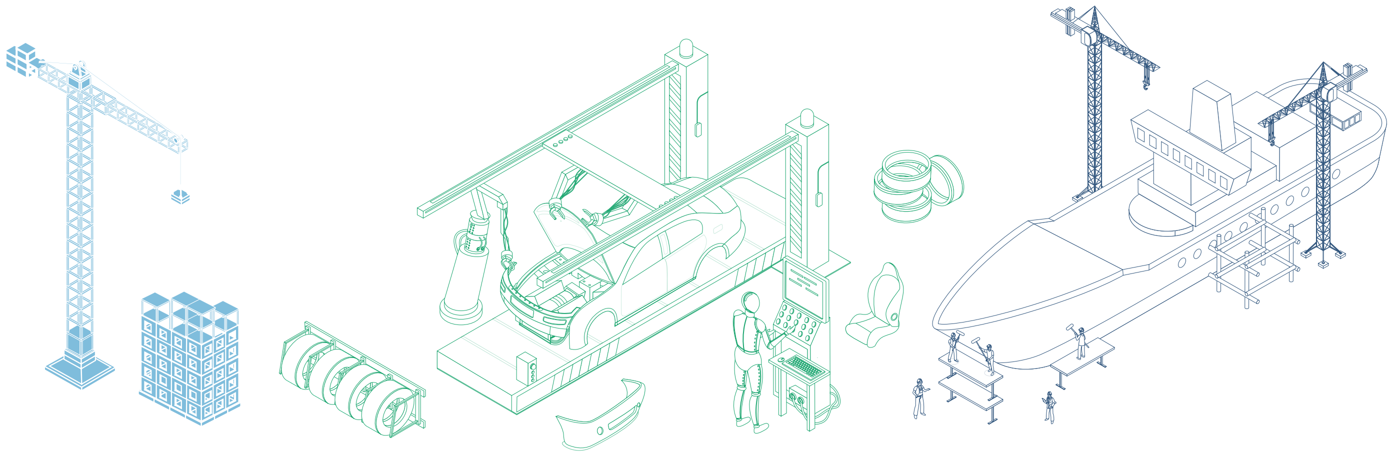

Executive Summary

The global steel industry accounted for over 7% of global greenhouse gas (GHG) emissions and over 11% of global CO_2 emissions. The urgency to align with the Paris Climate Agreement's targets necessitates substantial CO_2 reductions in this sector by 2050, with considerable near-term actions. The Hydrogen Direct Reduced Iron (H_2-DRI) process utilizing green hydrogen made with renewable/no-carbon electricity promises significant emission reductions and a transition to greener steel production in the sector.

The adoption of green H_2-DRI-EAF steelmaking involves financial considerations varying by country, influenced by hydrogen costs and carbon pricing mechanisms. The study assesses the costs of green H_2-DRI-EAF steelmaking compared to traditional Blast Furnace-Basic Oxygen Furnace (BF-BOF) and Natural Gas Direct Reduced Iron-Electric Arc Furnace (NG-DRI-EAF) routes across seven major steel-producing countries, including the U.S., EU, China, Japan, South Korea, Brazil, and Australia. It utilizes a detailed financial model to calculate the levelized cost of steel (LCOS) using expenses such as capital investments, raw materials, labor, and energy costs, adjusting for varying levels of hydrogen use. The key questions answered by this report are: 1) How much is the green steel premium per ton of steel in each country? 2) How much is the green steel premium per unit of final product (car, building, ship) in each country? 3) How different H_2 prices and carbon pricing can influence the green steel premium in each country?

Green Steel Premium Results

This shift to green H_2-DRI is initially more costly and results in a so-called "green premium". Figure ES1 illustrates the green steel premium comparison across various countries, showing the cost of steel production using both traditional and green H_2-DRI-EAF steelmaking routes at different H_2 price points. For example, with H_2 priced at $1.0/kg, the LCOS for the green H_2-DRI-EAF route is lower than that of conventional steelmaking routes, providing a compelling economic case for its adoption without relying on subsidies or carbon pricing strategies.

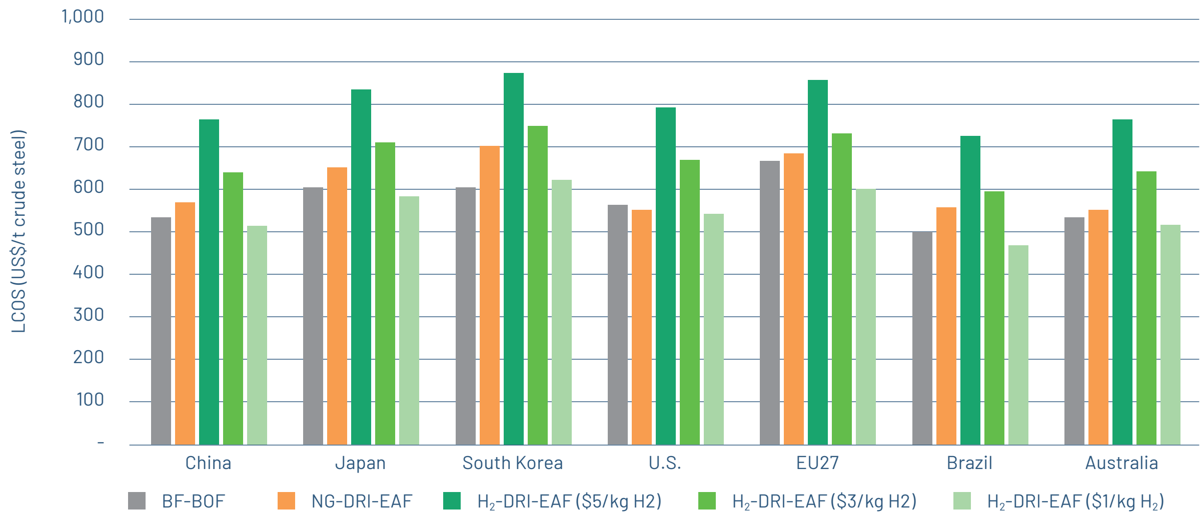

Figure ES1: Levelized Cost of Steel ($/t crude steel) for BF-BOF, NG-DRI-EAF and green H_2-DRI-EAF in countries studied (Source: this study)

Notes: Assumed 5% steel scrap is used in both BF-BOF and DRI route. No carbon price is considered.

The cost of producing green H_2 is currently higher than natural gas but is expected to significantly decrease as early as 2030. The levelized cost of H_2 (LCOH) in 2030 is forecasted to be in a range that makes green H_2-DRI-EAF be cost-competitive with NG-DRI-EAF in many countries at H_2 prices below $2/kg H_2. At these H_2 prices, the green H_2-DRI-EAF nears parity with greenfield BF-BOF steelmaking cost.

Figure ES2 shows the green steel premium in China across varying H_2 prices and carbon pricing scenarios. At \$0 CO_2 price, the cost for green H_2-DRI-EAF steelmaking is highest, requiring H_2 prices to drop to about \$2/kg to be competitive with NG-DRI-EAF methods. Introducing a carbon price shifts this dynamic significantly. With a \$15/ton CO_2 price, green H_2-DRI-EAF at \$1.5/kg H_2 undercuts the BF-BOF cost (\$539/ton). As the carbon price rises to \$30 and \$50 per ton, green H_2-DRI-EAF becomes increasingly competitive, achieving cost parity with BF-BOF at higher H_2 prices. The graph shows that at a CO_2 price of \$30, the LCOS aligns with BF-BOF when H_2 is priced below \$2.2/kg, and it becomes even more competitive at higher carbon prices of \$50, reaching cost parity at H_2 prices just over \$2.8/kg. This trend indicates a strong influence of carbon pricing on the economic feasibility of adopting green H_2-DRI-EAF steel production. Similar results were observed regarding the impact of carbon pricing in other countries.

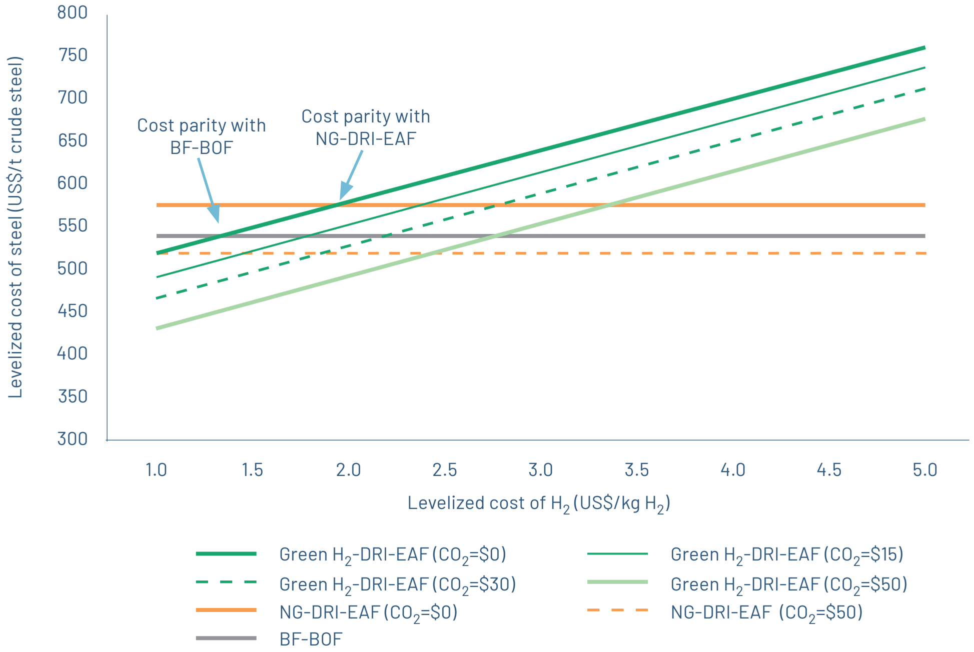

*Figure ES2. Levelized Cost of Steel (\$/t crude steel) with varied levelized costs of H_2 at different carbon prices in **China** (Source: this study)*

Notes: Assumed 5% steel scrap is assumed to be used in both BF-BOF and DRI route. For this analysis, it is assumed that carbon pricing will be applied in the form of credits or allowances for green H_2-DRI-EAF plants. Eligible plants would receive carbon credits based on the reduction of their carbon intensity relative to the benchmark set by BF-BOF operations, which can then be traded on the carbon market.

Impacts on the End-use Sectors

As green steel incurs a cost premium, this directly affects the material costs of downstream use sectors. This report has analyzed the potential cost increases related to three notable downstream sectors; automobile, construction and shipping, using steel produced via the H_2-DRI-EAF method compared to conventional methods for those sectors.

The green steel premium is negligible for the automotive and building construction sectors.

The global automotive industry accounts for 12% of global steel demand. The impact of the green steel premium on car prices demonstrates a minimal overall effect. For example, in Japan, when the price of H_2 is \$5/kg, the additional cost per ton of steel using the green H_2-DRI-EAF method is about \$231, leading to an extra \$208 per passenger car, which represents less than a 1% increase on the average passenger car price of \$28,000 in Japan. Projections indicate that with potential reductions in H_2 costs to \$1.3/kg, the green premium could vanish, making green H_2-DRI-EAF prices comparable to traditional BF-BOF steel costs in

Japan. Moreover, the introduction of a carbon pricing mechanism could further decrease this green premium, enhancing the affordability and market viability of using green H_2-DRI-EAF steel in automotive manufacturing. Similar results in terms of impact of H_2 price and carbon pricing on green steel premium in auto manufacturing were observed in other countries studied as shown later in this report.

Similarly, the economic impact of using green H_2-DRI-EAF steel in building construction is quite minor compared to traditional BF-BOF steelmaking. For example, in China, at a hydrogen cost of \$5/kg, the green premium for steel is about \$225 per ton. This translates into an additional cost of roughly \$563 for a 50 m^2 new residential unit (assuming 50 kg of steel per m^2), which is a small portion of the overall cost of purchasing such a residential unit. Future reductions in hydrogen costs or the implementation of carbon pricing could also reduce or eliminate this green premium, potentially making green H_2-DRI-EAF steel a cost-effective alternative for construction in China and other countries. The construction industry (building and infrastructure) accounts for 52% of global steel demand.

Incorporating green H_2-DRI-EAF steel into shipbuilding shows only a modest increase in costs. With hydrogen priced at \$5/kg, the green premium per ton of steel in China is \$225. For a 40,000 DWT (Deadweight tonnage) bulk ship, which typically uses about 13,200 tons of steel, this translates to an additional \$3 million per ship. Given the typical price of a 40,000 DWT (Deadweight tonnage) bulk ship is over \$30 million, the green premium represents around 10% cost increase. The reason for this relatively higher green steel premium as a share of total cost for shipbuilding compared to cars and buildings is higher share of steel cost in the shipbuilding cost. Over 95% of a ship consists of steel. However, it should be noted that the top three shipbuilding nations, China, South Korea, and Japan, account for over 90% of global shipbuilding. Therefore, the green premium discussion for shipbuilding mostly matters in these three countries. In addition, shipbuilding accounts for a small share (around 3%) of global steel demand and does not have to be a market leader in green H_2-DRI-EAF steelmaking. As the price of H_2 drops and green steel premium decreases substantially the use of green H_2-DRI-EAF steel in the shipbuilding sector can be considered.

Although the green steel premium analysis varies by plant, our results provide a good initial investment guide across countries. Showing costs for various hydrogen and carbon prices aids decision-making by the government and steel industry. Despite significant green premiums per ton of steel, the premium per unit of final product (cars or buildings) is negligible, making the overall conclusions relevant for any specific site.

Financing and Recommendations

The financing of H_2-DRI projects is crucial for the transition, utilizing both public and private funding to mitigate financial risks associated with green H_2-DRI technology. Notable instances include H_2 Green Steel (H_2GS) in Sweden, securing €1.5 billion in equity financing in 2023, followed by over €4 billion in debt financing, supported further by a €250 million grant from the EU Innovation Fund. In Germany, Salzgitter AG's SALCOS program received approximately €1 billion in subsidies for a new H_2-DRI plant. Similarly, ArcelorMittal's German project received €1.3 billion from the European Commission's Recovery and Resilience Facility to support new electric arc furnaces and a H_2-DRI plant. Sweden's HYBRIT initiative, involving SSAB, LKAB, and Vattenfall, was notably backed by a SEK 3.1 billion grant from the Swedish Energy Agency. In the U.S., the Department of Energy recently announced \$1 billion to support two H_2-DRI projects in the U.S.

Finally, we recommend strategies for different stakeholders to support the adoption and expansion of green H_2-DRI-EAF steelmaking around the world and how to address the initial green premium. Governments are urged to enact supportive policies like tax rebates and other incentives for green H_2 production, alongside investments in R&D and infrastructure to lessen green hydrogen costs. Power market reforms are needed in some countries to help increase the renewable electricity generation for green H_2 production at lower cost. Public procurement policies can boost market demand and mitigate financial risks for green H_2-DRI steel producers by prioritizing the use of green steel in publicly funded projects.

Steel companies are encouraged to transition from traditional BF-BOF routes to green H_2-DRI by forming partnerships for a reliable green hydrogen supply and by engaging in industrial-scale pilot projects. They should also secure market demand through long-term supply agreements with major end-use sectors, which could involve sharing the costs of the green premium.

Automotive and construction companies can integrate green steel into their procurement strategies to stimulate demand and help cover the green premium. Automotive companies in particular can also enhance their market positioning by promoting the climate, environmental, and health benefits associated with a transition to green steel and reduction of coal-based steelmaking in their supply chains, while construction firms can engage in green private procurement to cater to climate-conscious clients.

Major shipbuilding and shipping companies are recommended to utilize both public and private procurement strategies to boost adoption of green steel, thus reducing the green premium through government policies and commercial agreements. Establishing robust supply chains with green H_2-DRI steel manufacturers is essential to ensure a steady demand for green steel, promoting its broader adoption in the industry.

Content

1. Introduction

The global steel industry emitted over 3.6 billion tons of carbon dioxide (CO_2) in 2019. This accounted for over 7% of global greenhouse gas (GHG) emissions and over 11% of global CO_2 emissions (Hasanbeigi 2022). To align with the Paris Climate Agreement's goal of limiting global warming to "well below" 2°C, the global steel industry must significantly reduce its CO_2 emissions by 2050 with meaningful reduction in the near-term as well.

Iron and steelmaking primarily consist of primary and secondary production routes. Primary steelmaking predominantly utilizes the Blast Furnace-Basic Oxygen Furnace (BF-BOF) route, where iron ore is transformed into molten iron and subsequently refined into steel and has a substantial energy use and CO_2 emissions. In contrast, secondary steelmaking generally employs the Electric Arc Furnace (EAF) process, recycling scrap steel with low CO_2 emissions. Another prominent method is the Direct Reduced Iron (DRI) route, which mainly uses natural gas-derived syngas to reduce iron ore into DRI for steel production via EAF. Meanwhile, the Hydrogen Direct Reduced Iron (H_2-DRI) route, particularly when utilizing H_2 produced from renewable energy (green H_2), offers a promising decarbonization solution for primary steelmaking. Known as green H_2-DRI, this method significantly reduces CO_2 emissions and provides a cleaner alternative to conventional steelmaking methods, aiming to drastically cut the global carbon footprint of primary steel production. Several commercial-scale projects in Europe and Asia have begun or announced to use H_2-DRI steelmaking.

As shown in this report, transitioning to green H_2-DRI-EAF steelmaking initially results in a higher production cost compared to the traditional BF-BOF route leading to what is commonly referred to as the "green premium." The green premium represents the additional expense incurred when adopting this cleaner, more climate-friendly steel production method. The higher costs are primarily due to the current price of green hydrogen and the investments required for this new technology and infrastructure. However, this report suggests that these green premiums are not as high as commonly believed particularly when captured at the total cost of final products. Having a good estimate of green steel premiums will help with proper policy making and decision making by the end-use sectors who could help to pay a portion of this premium through green public or private procurement of steel (Hasanbeigi et al. 2023a).

This report examines the financial aspects of green H_2-DRI-EAF steelmaking compared to traditional steelmaking techniques in different countries. The report assesses various steelmaking routes, their CO_2 emissions, and the economic impact of transitioning to green H_2-DRI-EAF route, focusing on seven countries including China, Japan, South Korea, the United States, the European Union, Brazil, and Australia. It also evaluates the green steel premium in these countries under different hydrogen prices and carbon pricing scenarios. Additionally, the report covers the potential impact of green steel premium on the costs of final products like cars, buildings, and ships. The global automotive industry accounts for 12%, construction (building and infrastructure) accounts for 52% and shipbuilding accounts for around 3% of global steel demand (Worldsteel 2023). The automotive and building sectors were selected because of their importance in global steel demand. Also, the automotive sector has relatively fewer actors (car companies) that could be pioneer the use to green steel in their products, which, as shown in this study, results in a minimal price increase. The shipbuilding sector is important in several major steel producing countries, i.e. China, Japan, and South Korea that together account for over 90% of global shipbuilding.

The key questions answered by this report are: 1) How much is the green steel premium per ton of steel in each country? 2) How much is the green steel premium per unit of final product (car, building, ship) in each country? 3) How different H_2 prices and carbon pricing can influence the green steel premium in each country?

2. Global Iron and Steel Industry

Global steel production more than doubled between 2000 and 2022. The growth was dominated by steel production in China driven by China's economic growth and industrialization in the past two decade. However, with the slowdown in China's economy and construction industry in the past few years, China's steel production drops slightly in the past few years, which has caused a plateau in the global steel production trend (Figure 1).

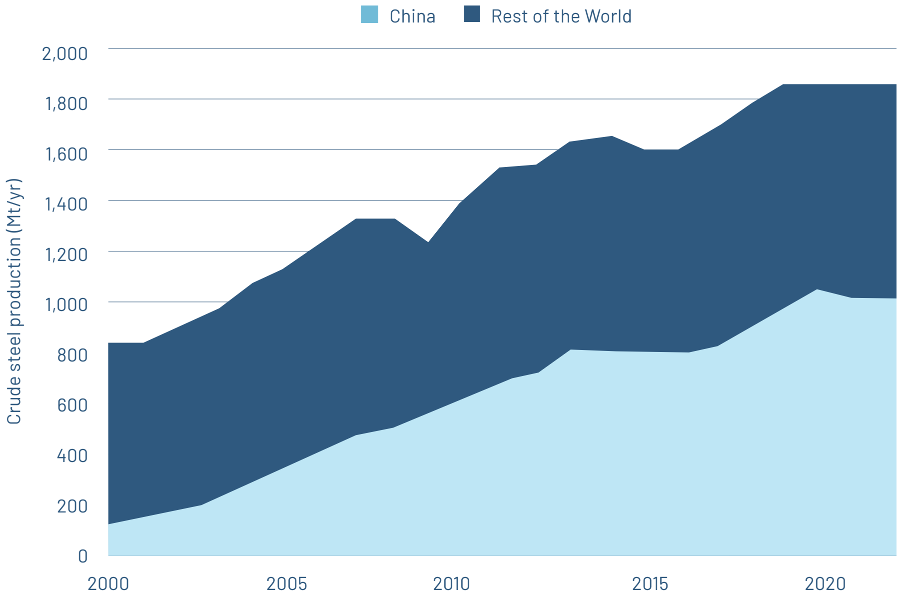

Figure 1. Crude steel production in China and rest of the world, 2000–2022 (worldsteel, various years)

In 2022, global steel production totaled approximately 1,885 million tonnes, dominated by China, which produced 54% of the total, amounting to 1,018 million tonnes. India was the second largest producer with 125 million tonnes, accounting for 7% of global output, followed by Japan and the U.S., producing 89 and 80.5 million tonnes, respectively. Other significant contributors include Russia, South Korea, Germany, Türkiye, Brazil, and Iran, each contributing between 2% and 4% of the world total (Figure 2). The rest of the world combined produced 294 million tonnes, representing 16% of global steel production. This distribution highlights the vast disparity in steel production among countries, with China's output dominating the global steel production by far.

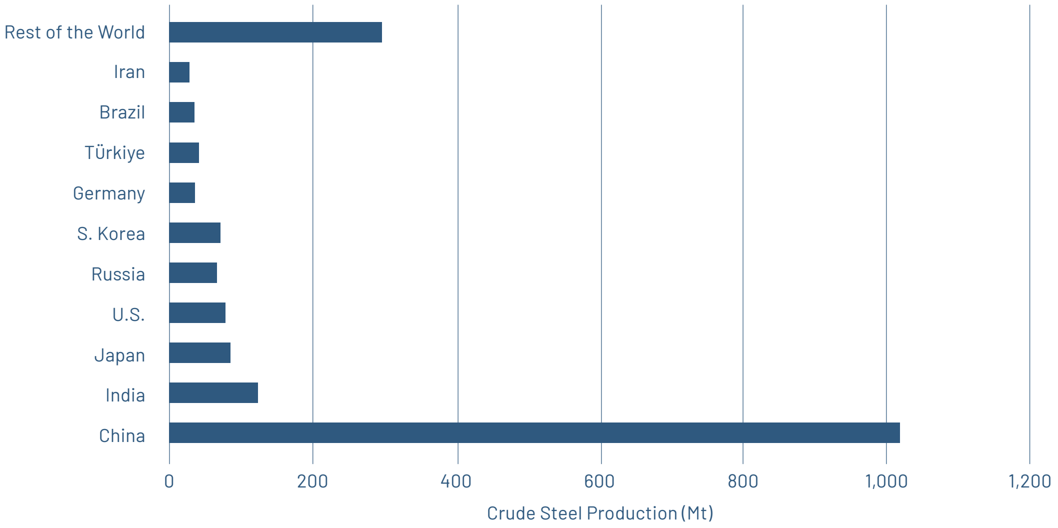

Figure 2. Top 10 steel producing countries in 2022 (worldsteel, 2023)

The global steel industry emitted over 3.6 gigatons of CO_2 ($GtCO_2$) in 2019. Global BF-BOF steel production emitted around 3.1 $GtCO_2$, and global EAF steel production emitted around 0.5 $GtCO_2$ in 2019 (Hasanbeigi 2022). Based on these, the global steel industry accounted for over 7% of total global GHG emissions and over 11% of total global CO_2 emissions in 2019. Figure 3 shows the results of this analysis, with China standing out as responsible for 54% of the global steel industry's CO_2 emissions in 2019 (Hasanbeigi 2022).

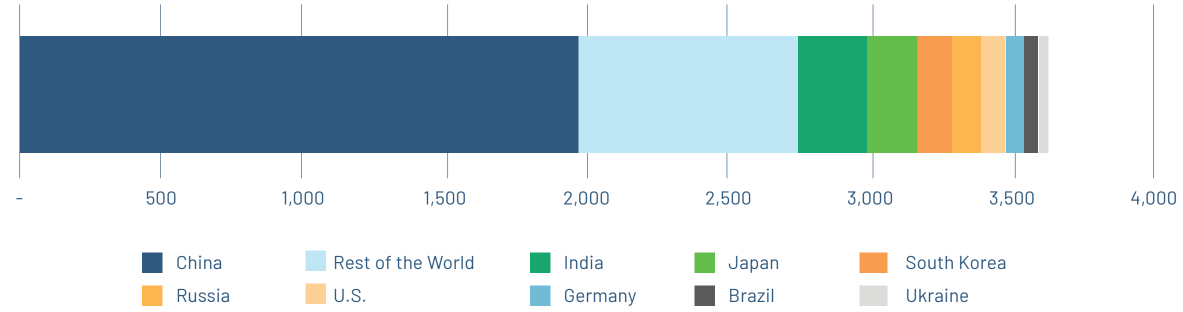

Figure 3. Total CO_2 emissions ($MtCO_2$) from steel production in major producing countries 2019 (in $MtCO_2$) (Hasanbeigi 2022)

The top 20 exporting countries account for over 90% of total world steel exports. According to worldsteel (2023), China, Japan, EU27, South Korea, and Germany were top five exporters and EU27, U.S., Germany, Italy, and Türkiye were top five importers of steel in 2022. The significant global trade of such a carbon-intensive commodity has substantial implications for the embodied carbon in traded steel as shown in our recent study (Hasanbeigi et al. 2022). This embodied carbon in traded steel often is not accounted for in national and international carbon accounting and climate policies.

Table 1. Top 20 exporters and importers of steel in 2022 (worldsteel 2023)

Rank	Total exports	Mt
1	China	68.1
2	Japan	31.7
3	European Union (27)[1]	26.0
4	South Korea	25.5
5	Germany[2]	22.3
6	Türkiye	18.0
7	Russia	17.9
8	Italy[2]	16.0
9	Belgium[2]	14.7
10	Brazil	12.1
11	India	12.1
12	France[2]	11.5
13	Taiwan, China	9.9
14	Netherlands[2]	9.4
15	Indonesia	9.2
16	Spain[2]	8.4
17	United States	8.3
18	Viet Nam	7.4
19	Malaysia	7.1
20	Austria[2]	6.8

Rank	Total imports	Mt
1	European Union (27)[1]	48.1
2	United States	28.9
3	Germany[2]	21.0
4	Italy[2]	20.2
5	Türkiye	17.4
6	China	17.1
7	South Korea	13.7
8	Thailand	13.4
9	Belgium[2]	12.5
10	Poland[2]	12.0
11	France[2]	12.0
12	Viet Nam	11.5
13	Indonesia	11.2
14	Mexico	10.9
15	Netherland[2]	10.3
16	Spain[2]	9.8
17	Canada	9.4
18	Philippines	7.6
19	Taiwan, China	7.1
20	Czechia[2]	7.0

1 Excluding intra-regional trade

2 Data for individual European Union (27) countries include intra-European trade

3. Primary Iron and Steelmaking Routes

Primary iron processing and steelmaking is essential to meet the global demand for steel, which cannot be fully satisfied by scrap-based secondary steelmaking alone. The availability of high-quality scrap is limited, and as economies grow, especially in developing regions, the demand for new steel outpaces the availability of steel scrap. Primary steelmaking processes, such as the Blast Furnace-Basic Oxygen Furnace (BF-BOF) route and its alternatives aimed at reducing CO_2 emissions: the Natural Gas-based Direct Reduced Iron-Electric Arc Furnace (NG-DRI-EAF) and the innovative H_2-based Direct Reduced Iron-Electric Arc Furnace (H_2-DRI-EAF), are crucial for producing the volumes of new steel required for infrastructure, construction, and manufacturing. This chapter briefly explains these three primary iron and steelmaking routes. Figure 4 shows the simplified production process for BF-BOF, natural gas DRI-EAF, and H_2-DRI-EAF.

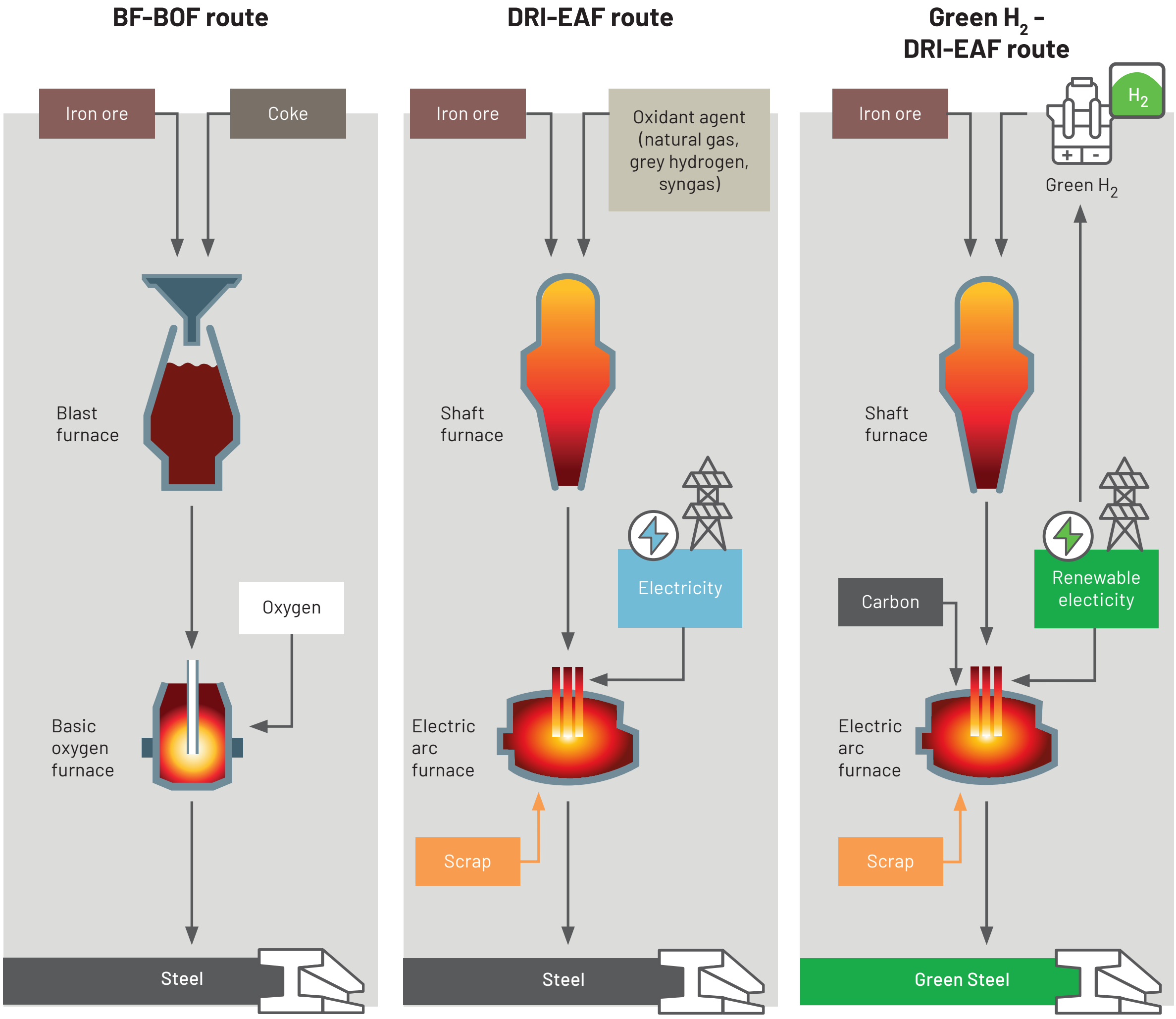

Figure 4. The production process for BF-BOF, natural gas DRI-EAF, and H_2-DRI-EAF (IRENA, 2022)

Blast Furnace-Basic Oxygen Furnace (BF-BOF) Steelmaking

The Blast Furnace-Basic Oxygen Furnace (BF-BOF) route for steelmaking is a two-stage process primarily involving the conversion of iron ore into pig iron, followed by the transformation of pig iron into steel. Initially, iron ore is mixed with coke and limestone in a blast furnace. The coke serves as both a fuel and a reducing agent, helping to separate the iron from its oxides, while limestone acts as a flux to remove impurities. Hot air is injected into the bottom of the furnace, causing the coke to burn and generate temperatures upwards of 1,600°C. This results in molten iron, or pig iron, which is then tapped from the bottom of the furnace.

In the second stage, the molten pig iron is transferred to a basic oxygen furnace (BOF), where it is converted into steel. In the BOF, pure oxygen is blown through the molten iron to burn off excess carbon and other impurities. Scrap steel is often added to the mix to control the temperature and the chemical composition of the steel being produced. The process is highly exothermic, meaning it generates its own heat. Once the desired steel chemistry and temperature are achieved, the molten steel is cast into various forms, such as slabs, billets, or blooms for further processing. This traditional method is highly energy- and carbon-intensive and accounts for over 71% of steel production globally, especially in regions heavily reliant on integrated steel plants.

Natural Gas-based Direct Reduced Iron-Electric Arc Furnace (NG-DRI-EAF) Steelmaking

The Natural Gas-based Direct Reduced Iron (NG-DRI) and Electric Arc Furnace (EAF) steelmaking process is a key method for producing steel with a lower carbon footprint compared to traditional blast furnace methods. The process begins with the production of direct reduced iron (DRI) using natural gas as both a fuel and a reductant in a shaft furnace. In this stage, iron ore pellets or lumps are fed into the DRI plant where they are heated and chemically reduced by a mixture of H_2 and carbon monoxide derived from natural gas. This reduction occurs at high temperatures and does not fully melt the iron, thus producing a solid sponge iron (DRI).

Following the DRI production, the sponge iron is then fed into an Electric Arc Furnace (EAF), where it is melted down to produce steel. The EAF operates by passing high-voltage electric arcs between charged electrodes, generating intense heat that melts the DRI, along with supplementary steel scrap, to refine the composition of the steel. Fluxes such as lime are added to combine with impurities and form a slag layer that is easily separable from the molten steel. The EAF is highly efficient and the process is faster than traditional steelmaking, typically taking less than an hour per batch. The EAF method not only utilizes recycled materials effectively but also offers flexibility in operation and significant reductions in GHG emissions when compared to conventional blast furnace methods, making it a sustainable choice for modern steel production.

H_2-based Direct Reduced Iron-Electric Arc Furnace (H_2-DRI-EAF) Steelmaking

The H_2-based Direct Reduced Iron (H_2-DRI) process represents a significant advance in the decarbonization of steel production. In this process, H_2 is used as the reducing agent instead of carbon-heavy alternatives like coke or natural gas, leading to a substantial reduction in CO_2 emissions. When H_2 is produced from electrolysis using renewable energy sources, the result is what's termed as "green H_2" or green H_2-DRI, which has minimal to zero CO_2 emissions. This method produces direct reduced iron (DRI) that is subsequently melted in an Electric Arc Furnace (EAF), providing a much cleaner alternative to the conventional blast furnace-basic oxygen furnace (BF-BOF) route (see the next chapter for CO_2 intensity of different primary steelmaking routes).

The appeal of H_2-DRI-EAF lies in its potential to drastically lower the carbon footprint of primary steel production on a global scale. The process begins with the generation of green H_2, which then reacts with iron ore in a reduction reactor, producing iron with significantly lower emissions compared to traditional methods. This iron is not melted but rather transported to an EAF where it is melted down to produce steel. The DRI produced could also be melted in BOF to produce steel.

The steel industry worldwide is increasingly embracing H_2-based direct reduced iron (H_2-DRI) technology as a pivotal strategy for achieving low-carbon steel production. Numerous projects are being initiated or are already in progress, particularly within Europe and Asia, as reflected in various reports. Nations and steel corporations are setting aggressive carbon reduction goals, and the adoption of H_2-DRI technology is accelerating due to its ability to significantly diminish CO_2 emissions. In Europe, the momentum is strong as numerous H_2-DRI initiatives advance, supported by substantial investments in both research and infrastructure to support this green transition.

Technological advancements are enhancing the viability of green H_2-DRI, driven by more efficient electrolyzers and the declining costs of renewable electricity generation. These innovations are reducing green H_2 production costs, making green H_2-DRI a more competitive alternative to traditional steelmaking.

Market dynamics in the steel industry are shifting due to growing demand for low-carbon products. Stakeholders such as consumers, investors, and regulators are increasingly demanding transparency and decarbonization of supply chains, including steel. This demand from major steel users like automotive manufacturers, construction companies, and shipbuilders, who are setting ambitious carbon reduction targets, is significantly driving the market for steel produced via low-carbon technologies like H_2-DRI. This market pull is a critical factor propelling the adoption of green H_2-DRI technology. Similarly, other factors such as carbon prices and the introduction of carbon borders such as the EU Carbon Border Adjustment Mechanism (CBAM) hold the potential to reduce the competitiveness of carbon intensive steel processes.

4. CO_2 Intensity of Different Primary Steelmaking Routes

A comparison of CO_2 emissions across different steelmaking technologies highlights the significant CO_2 benefits of adopting green H_2-DRI-EAF methods. Figure 5 shows CO_2 intensity of different new primary steel production plants in China. The results might be slightly different for other countries depending on the fuel mix and electricity emissions factor. A new BF-BOF plant in China results in approximately 1.9 tons of CO_2 per ton of steel, not accounting for rolling and finishing. A new NG-DRI-EAF plant in China powered by conventional grid electricity can cut emissions to 1.0 ton of CO_2 per ton of steel—a 46% reduction. Utilizing 100% renewable electricity in the NG-DRI-EAF process further reduces emissions to 0.66 tons CO_2 per ton, achieving a 64% decrease compared to BF-BOF. The most drastic reduction occurs with the green H_2-DRI-EAF route, using entirely green H_2, which slashes CO_2 emissions to just 0.06 tons per ton of steel, offering a dramatic 94% and 97% reduction compared to the grid-powered NG-DRI-EAF and traditional BF-BOF processes, respectively. These CO_2 intensities might slightly vary for other countries depending on the fuel mix and electric grid emissions factor in each country.

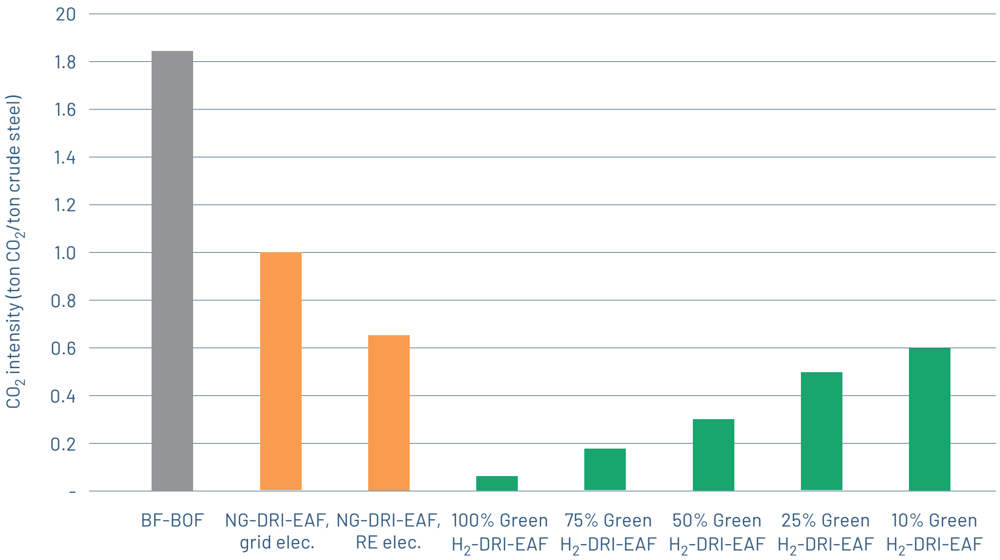

Figure 5. The CO_2 intensity of different new primary steel production plants in China (Source: this study)

Notes: This is for crude steel production and does not including rolling and finishing. The CO_2 intensities might vary slightly for other countries depending on the fuel mix and electric grid emissions factor in each country.

The increase in green H_2 usage within the H_2-DRI-EAF steelmaking process demonstrates a clear pathway for reducing carbon emissions, moving from 10% to 75% replacement of conventional reductants. This shift results in CO_2 emissions dropping from 0.60 to 0.18 tons per ton of crude steel, effectively decreasing the carbon footprint with each step towards higher green H_2 utilization. This strategy provides tangible evidence that even partial implementation of green H_2 can significantly diminish CO_2 emissions, offering a practical method for steel manufacturers to gradually transition away from the more carbon-intensive BF-BOF process.

For a green H_2-DRI-EAF steel plant in China producing 1 million tons annually, fully utilizing 100% green H_2 could result in cutting up to 1.84 million metric tons of CO_2 emissions each year compared to the traditional BF-BOF process. Even incorporating a 10% share of green H_2 in the H_2-DRI process could achieve substantial reductions, eliminating approximately 1.28 million metric tons of CO_2 annually.

5. Green Steel Premium for H_2-DRI-EAF Steelmaking

5.1 Analysis Method

This study covers seven major steel producing countries/region: China, Japan, South Korea, U.S., EU, Brazil, and Australia. While Australia only produced 5.7 Mt of steel in 2022 and ranks 29th globally, it is the number one global exporter of iron ore and given its rich iron ore and renewable energy resources, it was therefore included in the study due to its potential to play a key role in the future green H_2-DRI iron production and trade.

The study includes a techno-economic assessment that compares the costs of producing steel using a green H_2-DRI-EAF process to traditional BF-BOF and NG-DRI-EAF methods for a plant with an annual output of one million tons. A detailed financial model considers a range of expenses including capital investments, raw materials like iron ore and H_2, fuel, labor, and operational and maintenance costs, along with the costs of electricity from various sources. This model is designed to adjust for varying levels of H_2 substitution in the DRI production process.

The economic evaluation method applied in the study spreads the initial capital expenditures over the expected lifespan of the facility, utilizing net present value (NPV) calculations to assess costs over time, bringing future costs to present value terms. It also projects annual operational costs throughout the plant's operational duration, factoring in different inflation rates for various inputs. The overall production costs are then aggregated annually over a 20-year period. This approach provides a foundation to analyze the cost premium associated with low-carbon steel production, aiming to establish both the economic viability and the climate advantages of switching to an H_2-DRI-EAF process that relies on H_2 instead of fossil fuels.

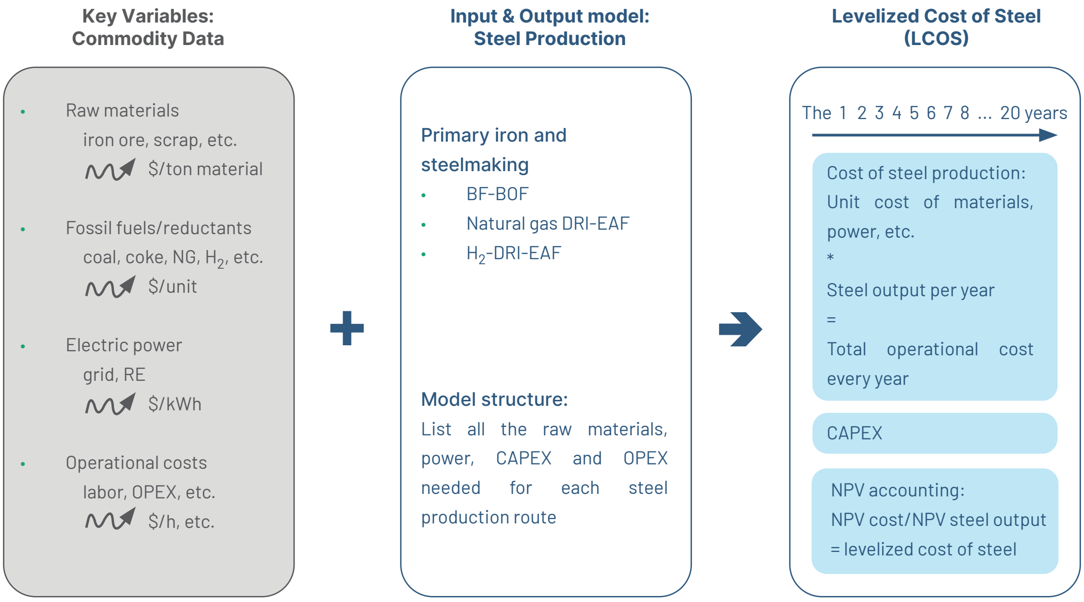

Figure 6. Analysis framework for calculation of levelized cost of steel (LCOS) production

5.2 Cost of H_2 and its projections

The cost of green H_2 production is the most critical factor in determining the economic feasibility of the green H_2-DRI steelmaking process (Figure 7). While the current cost of green H_2 is generally higher than natural gas for use in the DRI process, projections indicate a substantial reduction in these costs, as early as 2030, enhancing the competitiveness of green H_2-DRI. The levelized cost of H_2 used in this study assumes the full cost of H_2 delivered to steel plants including transport and storage.

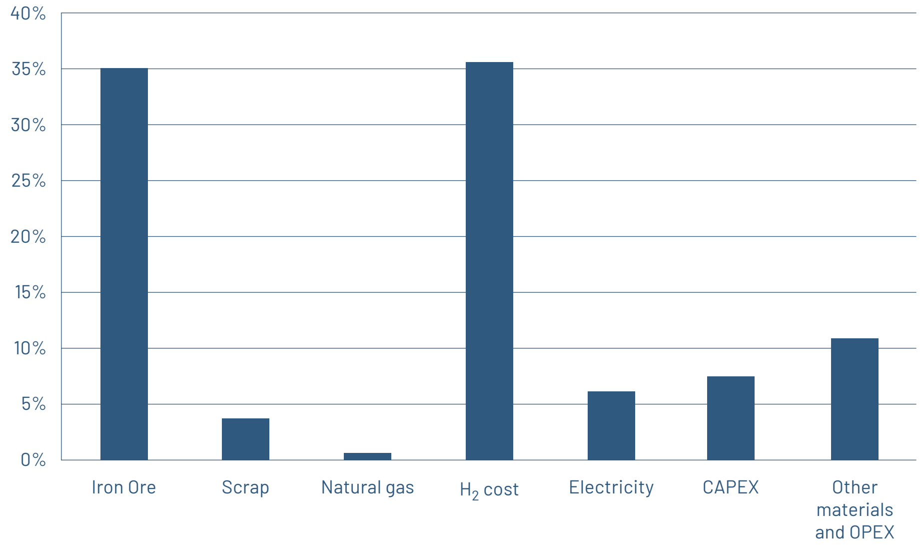

Figure 7. Share of each component from the LCOS of a new green H_2-DRI-EAF plant in China (This is for 100% green H_2 at \$4/kg H_2) (Source: This study)

The forecast suggests a significant price drop by 2030, positioning green H_2 competitively against existing gray H_2 plants in markets like Brazil, China, Sweden, Spain, and India. Figure 8 shows the levelized cost of H_2 (LCOH) in 28 markets in 2030 (BloombergNEF 2023). The LCOH in many markets in 2030 will be in a range that makes green H_2-DRI-EAF become cost-competitive with NG-DRI-EAF in many markets at H_2 prices below \$2/kg H_2. To get to this level of H_2 prices, it may require electrolyzer price below \$400/kW and electricity price below <\$0.02/kWh (Bataille, et al. 2021).

This price competitiveness is expected to spread across most markets by 2035, making green H_2 less costly. The decline in green H_2 costs is driven by economies of scale, substantial decline in electrolyzers systems costs (Figure 9), and supportive government policies. For instance, the Inflation Reduction Act in the U.S. and the European Union's Hydrogen Bank both aim to subsidize and promote the growth of green H_2 through commercial-scale projects. These initiatives are expected to help reduce the cost of green H_2 to between \$1 and \$2 per kilogram in 2030s, making it competitive with fossil fuel-based H_2. At H_2 prices below \$1.5 kg H_2, green H_2-DRI-EAF steelmaking become cost-competitive with BF-BOF steelmaking in many markets without any price on carbon.

Cost projections up to 2050 suggest that with continuous technological improvements and increased deployment of renewable energy sources, the levelized cost of green H_2 could decline even further. This trend is crucial for countries examined in this study to justify accelerated investment in green H_2-DRI steelmaking in China, Japan, South Korea, the U.S., the EU, Brazil, and Australia. Each of these countries is expected to see varying rates of cost reduction based on local energy policies, the availability of renewable resources, and technological advancements.

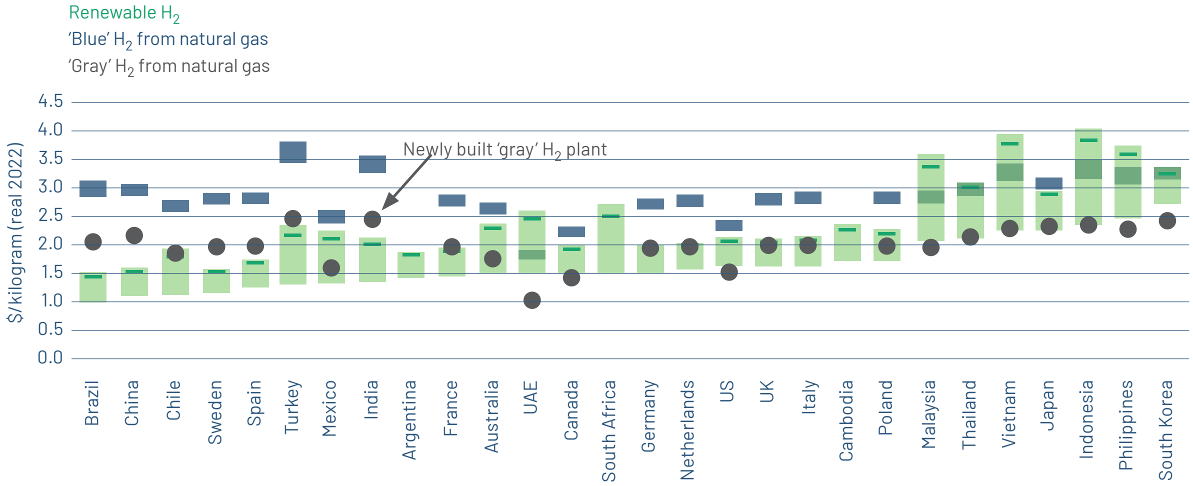

Figure 8. Levelized cost of H_2 in 28 markets in 2030 (BloombergNEF 2023)

Notes: Based on project financing year. Assumes our optimistic electrolyzer cost scenario. Renewable $LCOH_2$ range reflects a diversity of electrolyzer type, Chinese alkaline (low) to PEM (high). The electrolyzer's electricity is sourced from the cheaper renewable resource. Capital and operational costs for blue H_2 are sourced from the National Energy Technology Laboratory. Gas prices derived from BNEF's 2023 LCOE Update. Grid electricity prices assumed at $75 (real 2022) for all modeled markets.

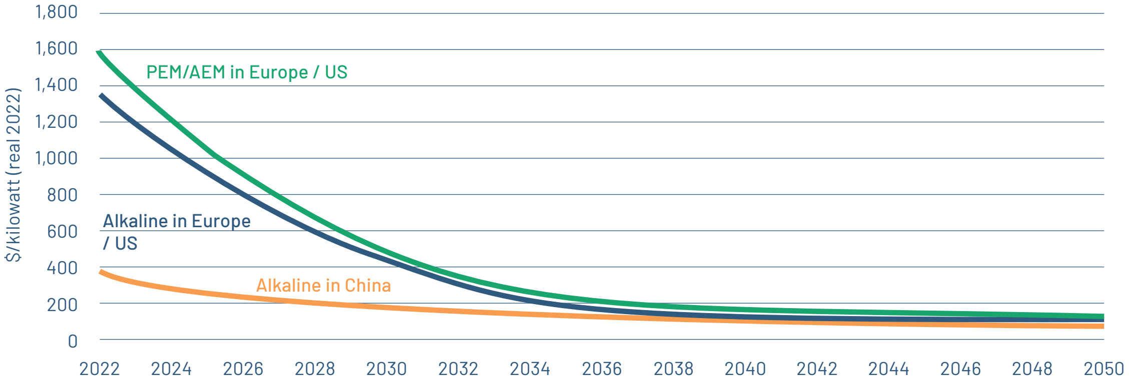

Figure 9. Benchmark electrolysis system cost, 2022–2050 (BloombergNEF 2023)

Note: Engineering, procurement and construction (EPC) costs are included. Assumes a single sale in 2022 of several tens of megawatts and several hundreds of megawatts in 2025. PEM stands for proton exchange membrane. AEM stands for anion exchange membrane.

5.3 Green Steel Premium Comparison across Countries

Our analysis reveals that utilizing green H_2 (H_2) in the steelmaking process offers notable cost advantages at lower H_2 prices, particularly when compared to traditional blast furnace-basic oxygen furnace (BF-BOF) and natural gas direct reduced iron-electric arc furnace (NG-DRI-EAF) methods. Specifically, with H_2 priced at $1.0/kg, the levelized cost of steel (LCOS) for the green H_2-DRI-EAF route is significantly competitive, providing a compelling economic case for its adoption without relying on subsidies or carbon pricing strategies (Figure 10).

The comparative analysis of steel production costs across different countries highlights a notable variation in LCOS for both traditional and green H_2-based processes. For instance, Brazil, China, and Australia show a lower LCOS for the green H_2-DRI-EAF method.

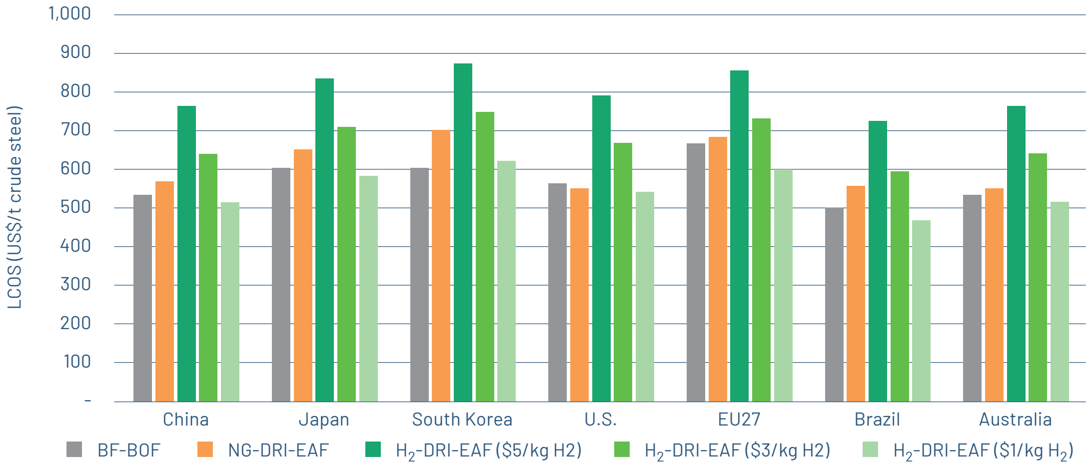

Figure 10. Levelized Cost of Steel ($/t crude steel) for BF-BOF, NG-DRI-EAF and green H_2-DRI-EAF in countries studied (Source: this study)

Notes: Assumed 5% steel scrap is assumed to be used in both BF-BOF and DRI route. No carbon price is considered.

In contrast, Japan, South Korea, and EU experience higher LCOS for green H_2-DRI-EAF technology. This suggests that while the potential for cost competitiveness of green H_2-DRI-EAF exists globally, the extent to which this technology becomes economically viable depends significantly on the local cost of H_2 and the existing cost of steel production with traditional routes.

The following sections show how the cost of H_2 significantly impacts the financial feasibility of the green H_2-DRI-EAF method for steel production in different countries. It calls for policies aimed at reducing H_2 production costs to ensure that this less carbon-intensive steelmaking alternative remains competitive with traditional methods.

It is evident that the implementation of a carbon pricing mechanism will affect the economic viability of the green H_2-DRI-EAF process in comparison to the traditional BF-BOF route. This research highlights that carbon pricing or allowances can serve as a financial incentive for driving green H_2-DRI-EAF adoption in steel production, at both increased speed and scale. For this analysis, it is assumed that carbon pricing will be applied in the form of credits or allowances for green H_2-DRI-EAF plants. Eligible plants would receive carbon credits based on the reduction of their carbon intensity relative to the benchmark set by BF-BOF operations, which can then be traded on the carbon market, valued according to the current carbon price per ton of CO_2.

5.4 Green Steel Premium across H_2 Prices and the Impact of Carbon Prices in China

At zero carbon pricing, green H_2-DRI-EAF steelmaking in China is costlier than both BF-BOF and NG-DRI-EAF methods, requiring a H_2 price of about $2/kg to match the costs of NG-DRI-EAF and around $1.4/kg to reach cost-parity with BF-BOF. However, when a carbon price of $15 per ton of CO_2 is introduced, the cost-parity point changes. At this carbon price, producing steel via green H_2-DRI-EAF at $1.0/kg H_2 costs $491 per ton, undercutting the BF-BOF method's $539 per ton, illustrating a substantial economic incentive for adopting greener steel production methods. This cost benefit becomes more pronounced at a carbon price of $30 per ton, where the LCOS for green H_2-DRI-EAF matches the BF-BOF cost at a H_2 price of $2.2/kg. As the carbon price increases to $50 per ton, green H_2-DRI-EAF becomes even more competitive, aligning its costs with the BF-BOF process at H_2 prices over $2.8/kg. This analysis underscores the significant role of carbon pricing in enhancing the financial viability of green steel technologies by rewarding lower carbon intensity, thereby supporting broader adoption of green H_2-DRI-EAF steelmaking (Figure 11).

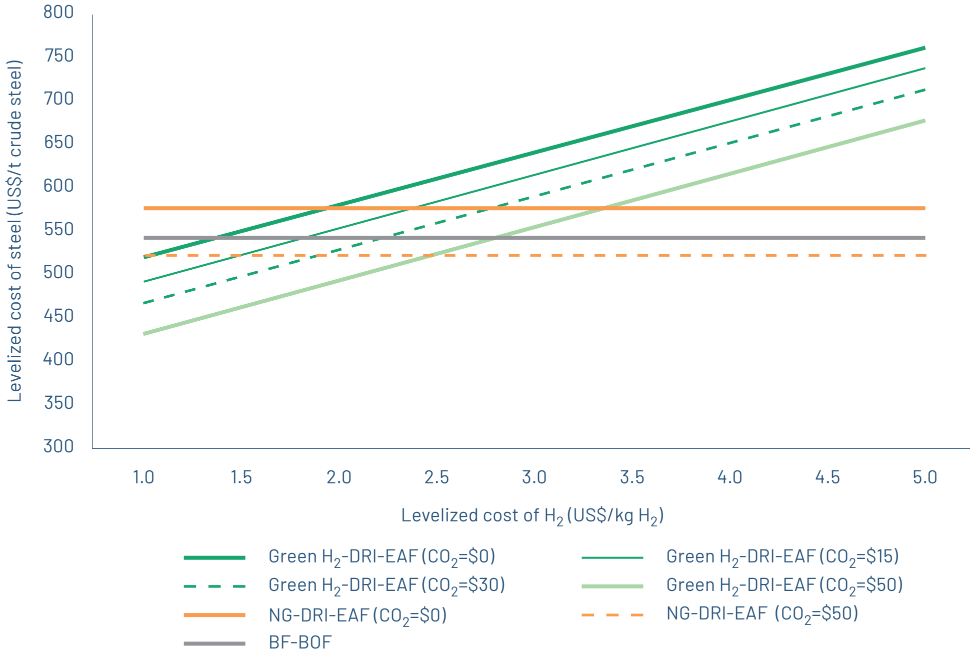

Figure 11. Levelized Cost of Steel ($/t crude steel) with varied levelized costs of H_2 at different carbon prices in ***China*** *(Source: this study)*

Notes: Assumed 5% steel scrap is assumed to be used in both BF-BOF and DRI route. For this analysis, it is assumed that carbon pricing will be applied in the form of credits or allowances for green H_2-DRI-EAF and NG-DRI-EAF plants. Eligible plants would receive carbon credits based on the reduction of their carbon intensity relative to the benchmark set by BF-BOF operations, which can then be traded on the carbon market.

The potential income from selling carbon credits generated by a given green H_2-DRI-EAF plant could help mitigate the initially higher costs linked to green H_2 production. This financial relief can facilitate quicker adoption of this technology. Carbon pricing serves as an effective economic equalizer for emerging low-carbon technologies, including green H_2-DRI-EAF. By offering a financial advantage for producing steel with lower carbon intensity, carbon pricing can spur investments and encourage wider adoption of H_2-DRI-EAF steelmaking.

In China's green H_2-DRI-EAF steel production, the cost breakdown is distinctly different from the traditional BF-BOF route. At a H_2 price of $4/kg H_2, iron ore remains a significant expense, accounting for 35% of the total LCOS, while green H_2 emerges as another major cost component, also at 35%. The costs of other materials and operational expenses (OPEX) remain at around 12%, with capital expenditures (CAPEX) making up only 8% of the total LCOS. This highlights a fundamental shift in the cost drivers from traditional energy sources like coke or coal in BF-BOF routes to H_2 in green H_2-DRI-EAF.

China is rapidly advancing its green H_2 production capabilities, setting a target of 80 GW of installed electrolyzer capacity by 2030 under its Green H_2 Energy Plan. This expansion leverages advancements in both alkaline and PEM electrolyzer technologies. Historically dominant in alkaline technology, China is now expanding into PEM to meet global efficiency demands. These efforts are complemented by falling renewable energy costs and scaling economies, aiming to make green H_2 cost-competitive with fossil-fuel-derived H_2. The national policy supports substantial investment in renewable infrastructure and green H_2 projects, in line with China's goal for carbon neutrality by 2060. Although not explicitly related to steel production, this policy includes detailed plans for H_2 infrastructure development, spanning production, storage, and transportation, and integrating H_2 across various sectors by 2035, and positioning China as a leader in the global green H_2 market.

5.5 Green Steel Premium across H_2 Prices and the Impact of Carbon Prices in Japan

In Japan, without carbon pricing, green H_2-DRI-EAF steelmaking initially shows a higher cost than both the BF-BOF and NG-DRI-EAF methods. To match the cost of NG-DRI-EAF, the H_2 price must be around \$2/kg, and to achieve cost parity with BF-BOF, it drops to roughly \$1.3/kg. Introducing a carbon price of \$15 per ton of CO_2 shifts these dynamics. At this carbon price, producing steel with H_2 at \$1.7/kg in the green H_2-DRI-EAF process has the same LCOS as the BF-BOF. The green steel economics improves with a carbon price of \$30 per ton, aligning the costs of green H_2-DRI-EAF with BF-BOF at a H_2 price of \$2.0/kg. As the carbon price increases to \$50 per ton, the cost competitiveness of green H_2-DRI-EAF further improves, matching BF-BOF costs at even higher H_2 prices (Figure 12).

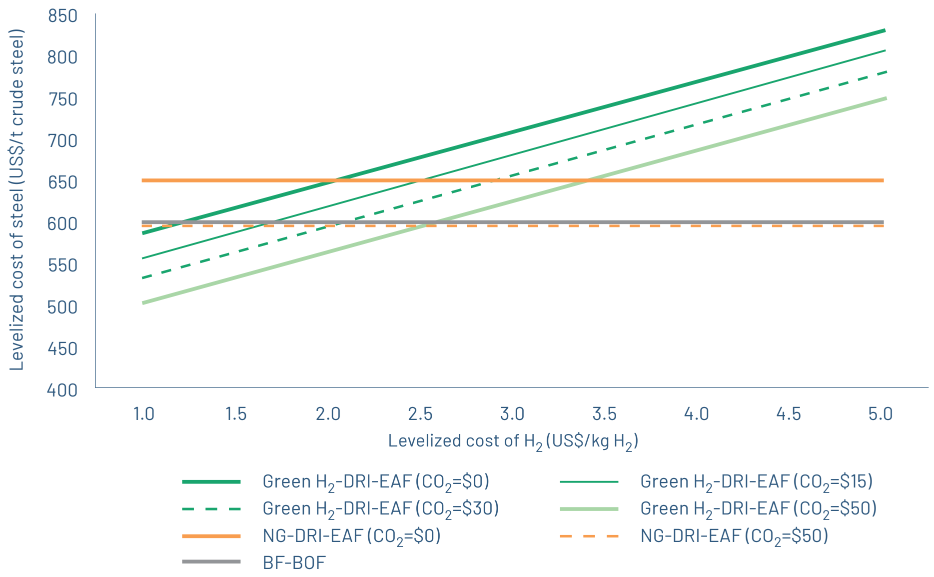

*Figure 12. Levelized Cost of Steel (\$/t crude steel) with varied levelized costs of H_2 at different carbon prices in **Japan** (Source: this study)*

Notes: 5% steel scrap is assumed to be used in both BF-BOF and DRI route.

Japan is aiming to capture a 10% share of the global electrolyzer market by 2030, driven by advancements in its domestic electrolyzer production capabilities. The country plans to establish 15 GW of H_2 electrolyzer capacity, involving local firms both in Japan and worldwide, with an ambitious focus on expanding green H_2 production. To enhance this sector, Japan is investing in advancing various electrolyzer technologies including alkaline, PEM, and SOEC, while targeting a 75% cost reduction for these systems. The national strategy is underpinned by several policy frameworks such as the Basic H_2 Strategy, the Green Growth Strategy, and the 6th Strategic Energy Plan, all aiming to establish an "H_2 society." This initiative is backed by significant funding, notably from the Green Innovation Fund, which supports substantial investments in green H_2 projects like the Fukushima H_2 Energy Research Field (FH_2R)—once the world's largest green H_2 production facility. Despite limited domestic renewable resources, Japan is securing green H_2 through international collaborations, focusing on technological standardization and cost reductions to boost the competitiveness of its H_2 technologies on the global stage.

5.6 Green Steel Premium across H_2 Prices and the Impact of Carbon Prices in South Korea

In South Korea, our analysis for steel production costs reveals varying costs across different carbon pricing scenarios and H_2 prices. With no carbon price, the green H_2-DRI-EAF method starts at $621 per ton of steel at $1/kg H_2, slightly above the BF-BOF cost of $605. South Korea is the only country among the seven countries studied where even at $1/kg H_2, the LCOS for green H_2-DRI-EAF remains above that of the BF-BOF route. This is partly because of high price of renewable electricity in South Korea. However, as carbon pricing is introduced, the competitiveness of green H_2-DRI-EAF increases. At a carbon price of $15 per ton of CO_2, the cost for green H_2-DRI-EAF drops to $596 per ton at $1/kg H_2, already offering savings over BF-BOF. This trend strengthens with higher carbon prices: at $30 and $50 per ton of CO_2, the costs for green H_2-DRI-EAF reduce further to $571 and $537 per ton at $1/kg H_2 price, underscoring substantial cost reduction compared to the BF-BOF process. With carbon prices at $50 per ton of CO_2, green H_2-DRI-EAF reaches cost-parity with BF-BOF at slightly above $2/kg H_2.

South Korea's largest steel company, POSCO, is developing its own green H_2-DRI steelmaking process, branded as HyREX. Instead of a shaft furnace used in conventional DRI technology, HyREX utilizes a fluidized reduction method, where high-temperature reduction gases are evenly dispersed through a distributor plate at the bottom of the reactor, causing powdered iron ore to float and mix, facilitating the reduction reaction. The HyREX technology allows the use of BF-grade iron ore without the need for prior processing into higher-grade pellets, which is a common requirement in H_2-DRI technology using a shaft furnace. Additionally, the system is being designed to optimize heat supply, essential for maintaining the reduction reaction, by allowing temperature control across multiple reactors, enhancing the efficiency of the process. POSCO plans for industrial scale construction of a HyREX plant in 2030s (POSCO, 2024).

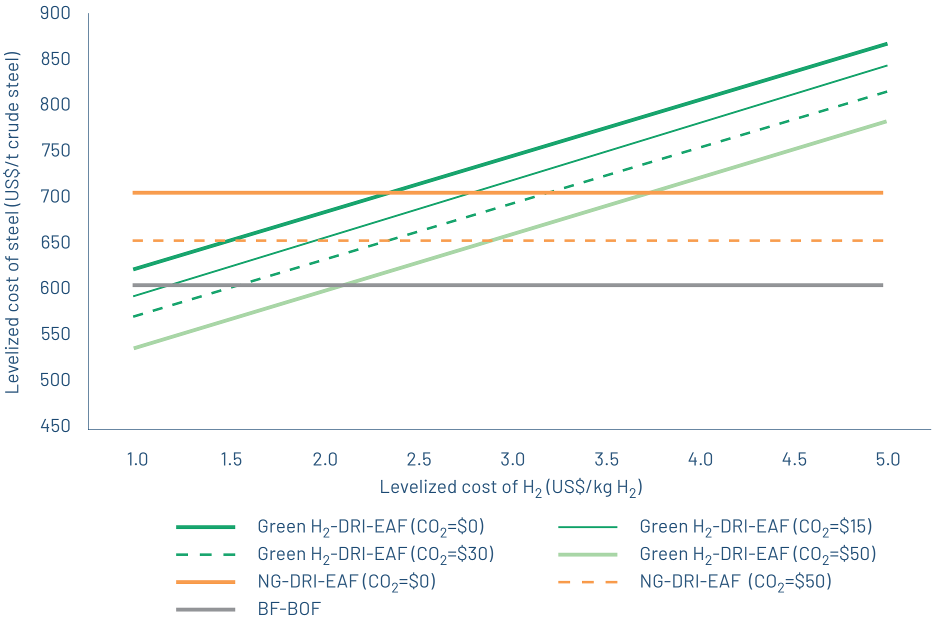

Figure 13. Levelized Cost of Steel ($/t crude steel) with varied levelized costs of H_2 at different carbon prices in ***South Korea*** *(Source: this study)*

Notes: Assumed 5% steel scrap is assumed to be used in both BF-BOF and DRI route.

Like its East Asian neighbors, China and Japan, South Korea is pursuing advancements in H_2 electrolyzer technologies, setting ambitious targets to position itself as a leader in the H_2 sector. The country's strategy includes developing 100 MW-class H_2 electrolyzer technology and investing significantly in various types of electrolyzers such as high-efficiency alkaline, PEM, and SOEC. There's a strong emphasis on bolstering the domestic supply chain for these technologies. South Korea's H_2 economy roadmap outlines major financial investments in research and development, as well as the launch of pilot projects to scale green H_2 technologies. This strategy aims to increase green H_2 production and also focuses on international cooperation and policy development to support the H_2 industry.

5.7 Green Steel Premium across H_2 Prices and the Impact of Carbon Prices in the U.S.

In the U.S., at zero carbon price, green H_2-DRI-EAF with H_2 priced at $1.0/kg stands at $544 per ton—marginally less expensive than NG-DRI-EAF at $550 per ton, but slightly more costly than BF-BOF at $565 per ton. The cost-parity for green H_2-DRI-EAF and BF-BOF happens at $1.4/kg H_2. With a carbon price of $15 per ton of CO_2, the cost-parity for green H_2-DRI-EAF and BF-BOF happens at $1.8/kg H_2. The most dramatic shift occurs at a carbon price of $50 per ton, where green H_2-DRI-EAF reaches cost parity with BF-BOF at $2.7/kg H_2.

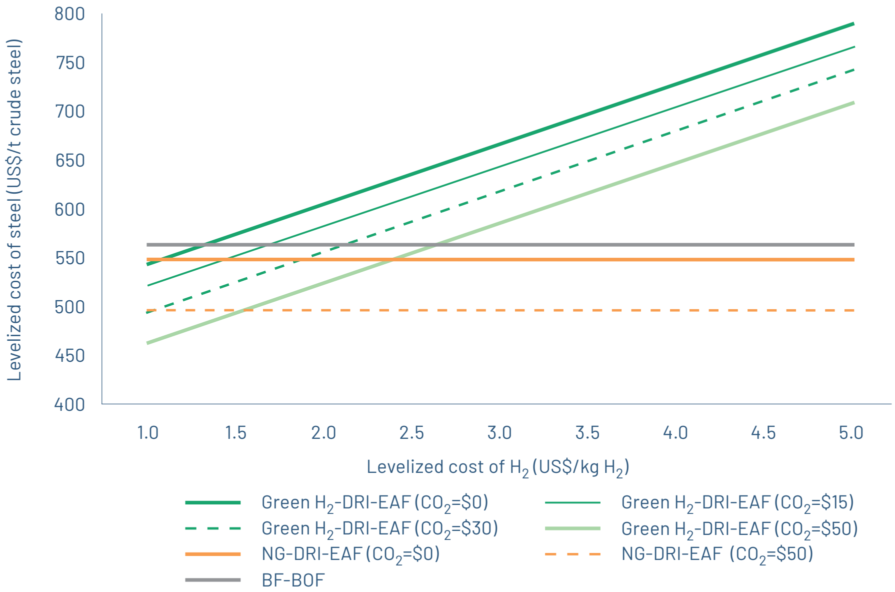

*Figure 14. Levelized Cost of Steel ($/t crude steel) with varied levelized costs of H_2 at different carbon prices in **the U.S.** (Source: this study)*

Notes: 5% steel scrap is assumed to be used in both BF-BOF and DRI route.

The United States is advancing its position in the green H_2 sector, backed by robust government policies and incentives. A pivotal element of this strategy is the tax incentive under Section 45V of the Inflation Reduction Act, which provides substantial credits for green H_2 production, aiming to reduce costs and stimulate market growth. This is part of a broader initiative that includes significant federal funding and investments in research and development to enhance electrolyzer technologies. These efforts are designed to increase efficiency, decrease production costs, and make green H_2 a viable competitor against traditional energy sources. Additionally, the U.S. government is focusing on expanding the necessary infrastructure for H_2 production, storage, and distribution across various sectors including the industry sector.

5.8 Green Steel Premium across H_2 prices and the iImpact of Carbon Prices in the EU

The EU has one of the highest LCOS across all steelmaking routes. In the EU, the cost dynamics of green H_2-DRI-EAF steelmaking showcase a compelling transition away from traditional methods under different carbon pricing scenarios. Without any carbon tax, green H_2-DRI-EAF reaches cost-parity with BF-BOF route at a H_2 price of \$2.0/kg H_2. This is the highest H_2 price at which green H_2-DRI-EAF becomes cost-competitive with BF-BOF among the seven countries studied. At a carbon price of \$50 per ton of CO_2, the LCOS for green H_2-DRI-EAF drops further at cost-parity with BF-BOF is achieved at a much higher H_2 price of \$3.3/kg H_2. The carbon price in the EU ETS market in early May 2024 was over \$75 per ton of CO_2. At this carbon price, the cost parity point can be achieved at H_2 price of \$4/kg H_2. In June 2024, the carbon price in EU ETS market was above \$75 per ton of CO_2.

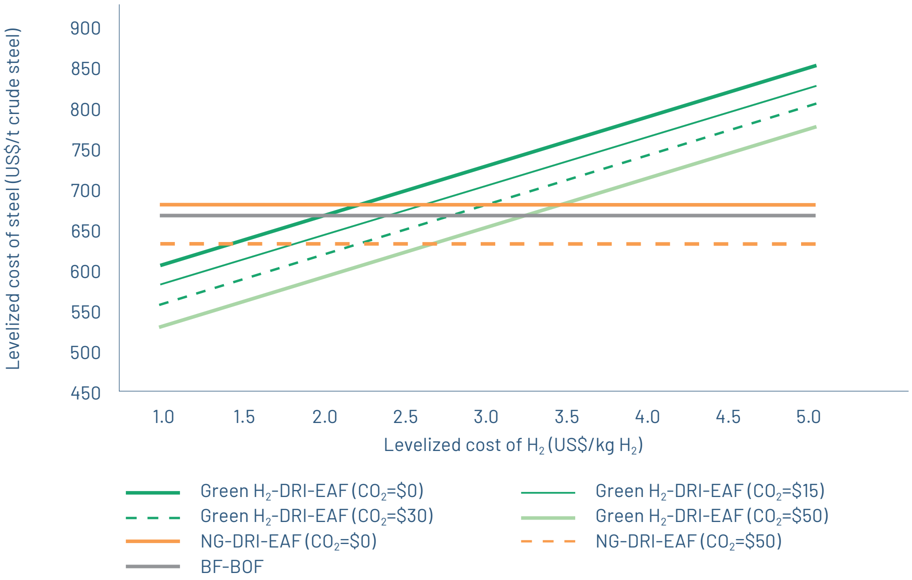

*Figure 15. Levelized Cost of Steel (\$/t crude steel) with varied levelized costs of H_2 at different carbon prices in **the EU** (Source: this study)*

Notes: 5% steel scrap is assumed to be used in both BF-BOF and DRI route. In June 2024, the carbon price in EU ETS market was above \$75 per ton of CO_2.

The European Union (EU) is one of the frontrunners in driving the development of a robust green H_2 market. Its ambitious strategy, outlined in the 2020 EU H_2 Strategy, focuses on five key areas: investment support, stimulating production and demand, creating a H_2 market and infrastructure, research and cooperation, and international collaboration. A critical piece of this strategy is the establishment of the European Clean H_2 Alliance, which supports collaboration between public and private stakeholders to develop an investment agenda and project pipeline. Financially, the EU leverages instruments like the Innovation Fund and the European H_2 Bank to support large-scale renewable H_2 projects, aiming to bridge the cost gap with conventional methods. Additionally, the recently adopted delegated acts under the Renewable Energy Directive define clear criteria for "renewable H_2" and establish methodologies for calculating life-cycle emissions. In April 2024, the first European H_2 Bank auction awarded €720 million to seven green H_2 projects from Finland, Spain, Portugal and Norway. The second auction is expected to be published in the third quarter of 2024.

5.9 Green Steel Premium across H_2 Prices and the Impact of Carbon Prices in Brazil

In Brazil, without carbon pricing, the LCOS of green H_2-DRI-EAF steelmaking is competitive at \$476 per ton with H_2 priced at \$1.0/kg, undercutting both the traditional BF-BOF method at \$504 and NG-DRI-EAF at \$557. As carbon pricing is implemented, green H_2-DRI-EAF becomes more cost-effective. At a carbon price of \$15 per ton of CO_2, the cost-parity with BF-BOF is achieved at \$1.9/kg H_2. This economic benefit is further amplified at higher carbon prices. For example, at \$30 and \$50 per ton of CO_2, the cost-parity point is at H_2 prices of \$2.2/kg H_2 and \$2.7/kg H_2, respectively.

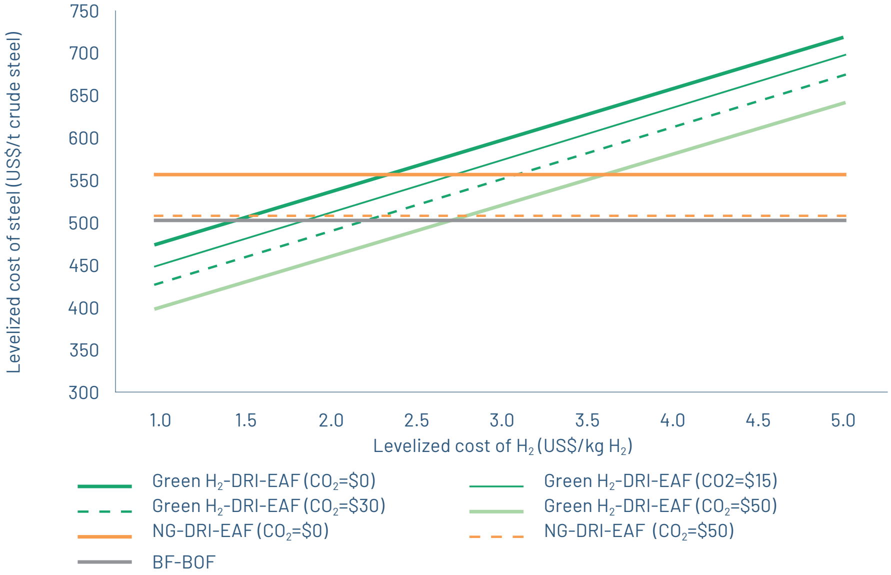

Figure 16. Levelized Cost of Steel ($/t crude steel) with varied levelized costs of H_2 at different carbon prices in ***Brazil*** *(Source: this study)*

Notes: 5% steel scrap is assumed to be used in both BF-BOF and DRI route.

Brazil is rapidly emerging as a major player in the green H_2 sector, with a framework outlined in its National H_2 Program (PNH_2) launched in 2021. The PNH_2 prioritizes six key areas, including research and development (R&D). A significant development is the recently approved Green H_2 Bill, which establishes a legal framework for low-carbon H_2 production. This framework includes the creation of the Low-Carbon H_2 Development Program (PHBC) that will offer economic incentives for producers through competitive bidding processes. Recognizing the potential for domestic applications, the bill also encourages the use of green H_2 in various sectors, particularly as an energy source and for agricultural fertilizer production. To further stimulate innovation, Brazil promotes "regulatory sandboxes" for the development of green H_2 production facilities and services.

5.10 Green Steel Premium across H_2 Prices and the Impact of Carbon Prices in Australia

In Australia, without carbon pricing, green H_2-DRI-EAF steelmaking costs start lower than traditional methods at $516 per ton for H_2 at $1/kg, compared to $536 for BF-BOF. The cost-competitiveness of green H_2-DRI-EAF diminishes as the H_2 price increases with the cost parity with BF-BOF happening at $1.3/kg H_2. The implementation of a $15 carbon price significantly enhances the economic viability of green steel. At a H_2 price of $2/kg, and at $30 per ton of CO_2, the LCOS for green H_2-DRI-EAF further drops to $527 per ton, and at a $50 carbon price, it decreases to $493 per ton, which are lower than LCOS of $536 for BF-BOF in Australia.

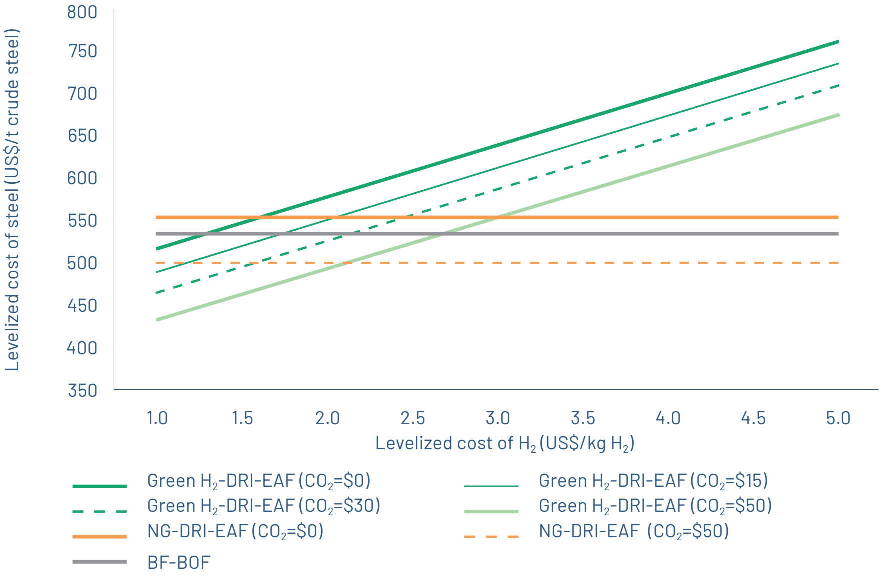

Figure 17. Levelized Cost of Steel ($/t crude steel) with varied levelized costs of H_2 at different carbon prices in ***Australia*** *(Source: this study)*

Notes: 5% steel scrap is assumed to be used in both BF-BOF and DRI route.

The Australian Government is seeking to boost the development of a competitive green H_2 industry through its National H_2 Strategy, most recently updated in 2023. This strategy prioritizes both domestic production and the potential for future exports. A cornerstone initiative is the $2 billion H_2 Headstart program, which directly allocates funding to large-scale green H_2 projects, aiming to drive down production costs. Beyond financial support, the strategy emphasizes technological innovation by supporting domestic capabilities. Recognizing its vast renewable energy resources and suitable land, Australia is also strategically investing in regional H_2 hubs through a dedicated $500 million program.

6. Impact of Green Steel Premium on Final Products Cost

While there are different challenges for transitioning to green H_2-DRI-EAF steelmaking as outlined in Hasanbeigi et al. (2024), a higher LCOS as shown above, known as the "green premium," when compared to the traditional BF-BOF route is one the most important challenges that steel producers and policymakers need to navigate. However, this green premium is not as high as commonly believed or communicated by steel intensive companies. Having a good estimate of the green steel premium will help with proper policymaking and decision-making by the end-use sectors who could help to pay a portion of this premium through green public or private procurement of steel. In the subsections below, we demonstrate and discuss the impact of green steel premium on car prices, construction costs, and shipbuilding costs in the countries studied.

6.1 Impact of Green Steel Premium on Car Prices

The automotive industry accounts for 12% of global steel demand (worldsteel 2023). The additional cost attributed to using green H_2-DRI-EAF steel in passenger vehicles—known as the green premium—is aligned with studies that estimated automotive sector as a likely first mover for green steel procurement and demonstrates minimal impact on overall vehicle pricing. For example, in China, when the price of H_2 reaches $5/kg, the green premium for steel produced via Green H_2-DRI-EAF, compared to the traditional BF-BOF methods, stands at approximately $225 per ton steel. Assuming on average 0.9 ton of steel used in a passenger car, this translates to an additional cost of about $203 per passenger car, which represents a less than 1% price increase on an average price of passenger car in China ($22,000), maintaining affordability and market stability. Future projections suggest that with H_2 costs potentially reducing to $1.4/kg, the green premium could effectively disappear, making green H_2-DRI-EAF steel economically comparable to conventionally produced steel. With the introduction of carbon price/credit, the green premium for H_2-DRI-EAF steel can substantially drop even further (Figure 18). Similar conclusions can be drawn based on the analysis of green steel premium on car prices in other countries studied (Figure 19). It should be noted that the average price of a passenger car in the U.S. is over $40,000 while in the EU and Australia is around $30,000.

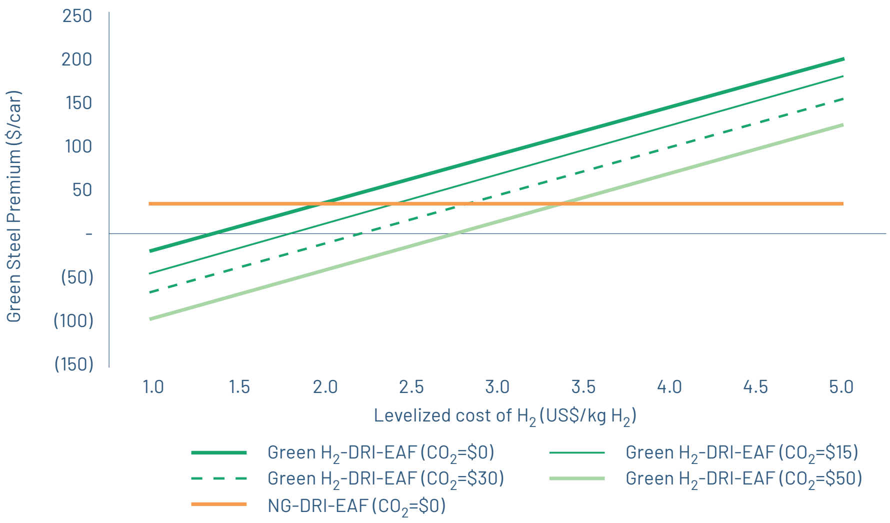

*Figure 18. Impact of green steel premium on car prices in **China** under different H_2 and carbon prices*

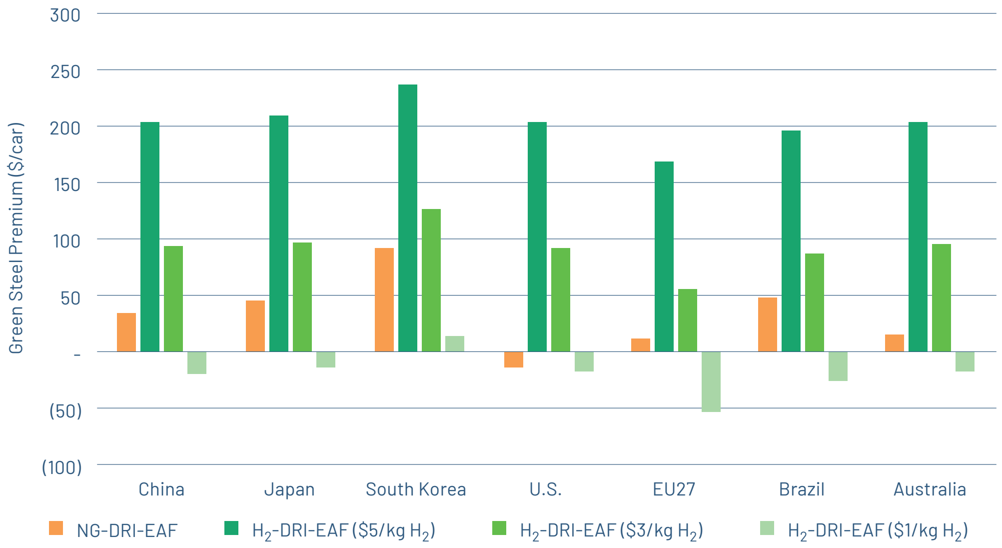

Figure 19. Impact of green steel premium on car prices in countries studied under different H_2 with no carbon prices.

6.2 Impact of Green Steel Premium on Building Construction Cost

The construction industry (building and infrastructure) accounts for 52% of global steel demand (worldsteel 2023). In the context of building construction in China, the economic effect of adopting green steel produced by H_2-DRI-EAF route can be considered minimal when compared to conventional BF-BOF steelmaking route. Using the green H_2-DRI-EAF route, the additional cost of steel at a H_2 price of $5/kg is approximately $225 per ton of steel, translating into an added expense of about $563 for a 50 m^2 residential building unit (assuming 50 kg steel per m^2 used for low to mid-rise residential building). This represents a small fraction of the total cost of a residential building. In addition, with future reductions in H_2 cost or the introduction of carbon pricing, the green premium could diminish or even disappear, making green H_2-DRI-EAF an economically viable alternative for building construction in China (Figure 20). Similar conclusion can be drawn based on the analysis of green steel premium on building construction cost in other countries studied (Figure 21).

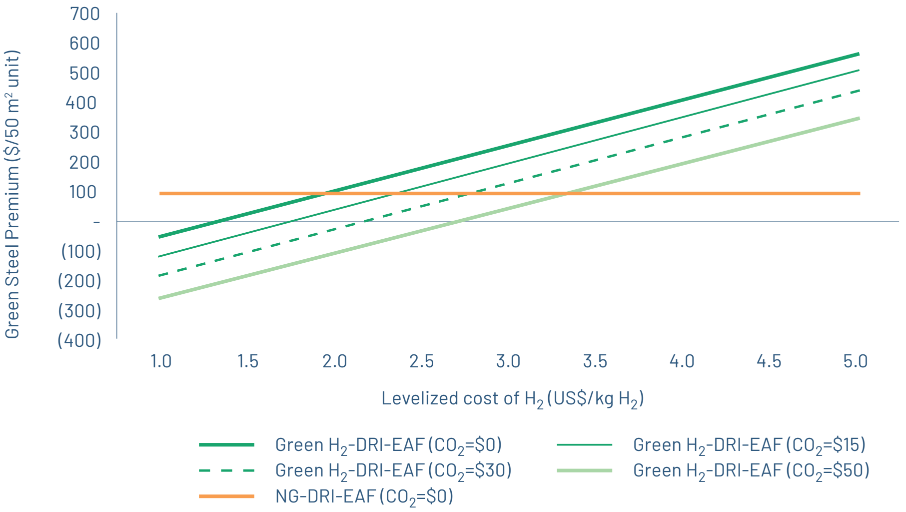

*Figure 20. Impact of green steel premium on building construction cost in **China** under different H_2 and carbon prices.*

Note: This is for a 50 m^2 residential building unit assuming 50 kg steel per m^2 used for low to mid-rise residential building.

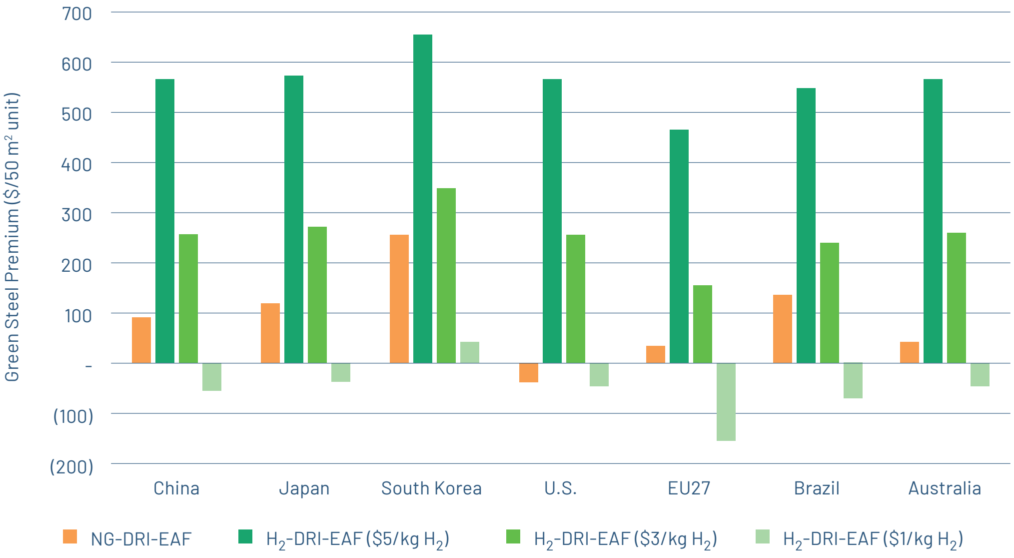

Figure 21. Impact of green steel premium on building construction cost in countries studied under different H_2 with no carbon prices

Note: This is for a 50 m² residential building unit assuming 50 kg steel per m² used for low to mid-rise residential building.

6.3 Impact of Green Steel Premium on Shipbuilding Cost

The top three shipbuilding nations, China, South Korea, and Japan, account for over 90% of global shipbuilding. Incorporating green H_2-DRI-EAF steel into shipbuilding shows a small cost increase for ship building. In the case of China, which is the world's largest steelmaker and the largest shipbuilder a H_2 cost of $5/kg entails the green premium for steel reaching around $225 per ton of steel. In the case of South Korea, the green premium is $263 per ton of steel at $5/kg H_2.

While there are many types of ships in the global market. This analysis focused on a bulk carrier ships which are built in large numbers every year around the world. For example, to build an average 40,000 DWT (Deadweight tonnage) bulk ship, approximately 13,200 tons of steel are needed. If green H_2-DRI-EAF at $5/kg H_2 is used in China to build this ship, the additional cost would be about US$ 3 million per ship in China. In the case of South Korea, the additional cost would be US$ 3.5 million per ship. Considering the average cost of a new 40,000 DWT bulk ship is over $30 million, this represents less than 10% increase in the overall ship's price for China and 11.6% in South Korea, adding a new green competitive dynamic between the two shipbuilding giants.

The reason for this relatively higher green steel premium as a share of total cost for shipbuilding compared to cars and buildings is higher share of steel cost in the shipbuilding cost. Over 95% of a ship consists of steel.

Anticipated reductions in H_2 costs in the future could nullify this green premium, aligning the costs of green H_2-DRI-EAF steel with those of traditional BF-BOF steelmaking. Moreover, the introduction of carbon pricing could further reduce the green premium costs, enhancing the financial attractiveness of adopting green H_2-DRI-EAF steel in the maritime sector (Figure 22). Similar conclusion can be drawn based on the analysis of green steel premium on ship building cost in other countries studied (Figure 23).

Since shipbuilding accounts for a small share of global steel demand and does not have to be a market leader in green H_2-DRI-EAF steelmaking. As the price of H_2 drops and green steel premium decreases substantially the use of green H_2-DRI-EAF steel in the shipbuilding sector can be considered.

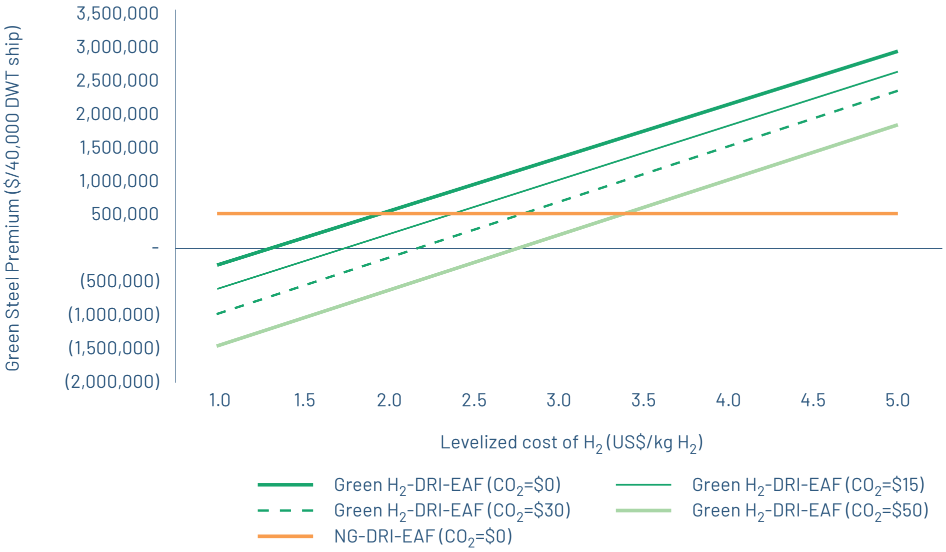

Figure 22. Impact of green steel premium on shipbuilding cost in ***China*** *under different H_2 and carbon prices*

Note: This is for an average 40,000 DWT (Deadweight tonnage) bulk ship.

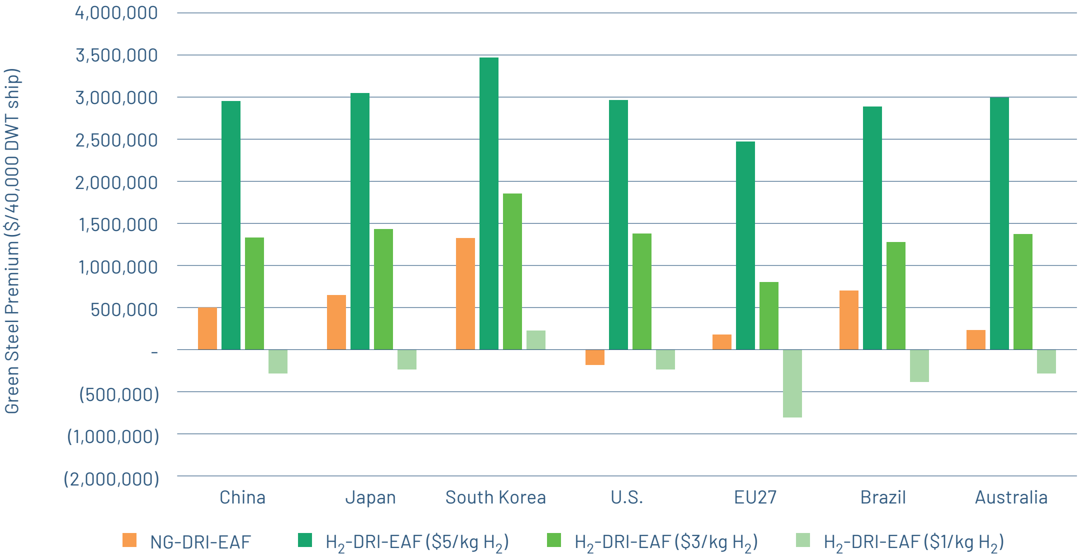

Figure 23. Impact of green steel premium on shipbuilding cost in countries studied under different H_2 with no carbon prices

Note: This is for an average 40,000 DWT (Deadweight tonnage) bulk ship.

7. Gradual Substitution of Natural Gas with Green H_2 in the DRI Route

The gradual integration of green H_2 into the H_2-DRI-EAF steelmaking process presents a strategic approach to reducing carbon emissions with manageable economic impacts and smoother transition. The analysis indicates that at a H_2 cost of $4/kg, the initial 10% replacement of natural gas with green H_2 in the direct reduction (DR) process increases the LCOS only slightly over the natural gas DRI-EAF route in all countries studied. As the proportion of green H_2 is scaled up to 25%, 50%, 75%, and ultimately 100%, the LCOS relative to NG-DRI-EAF sees a progressive increase (Figure 24).

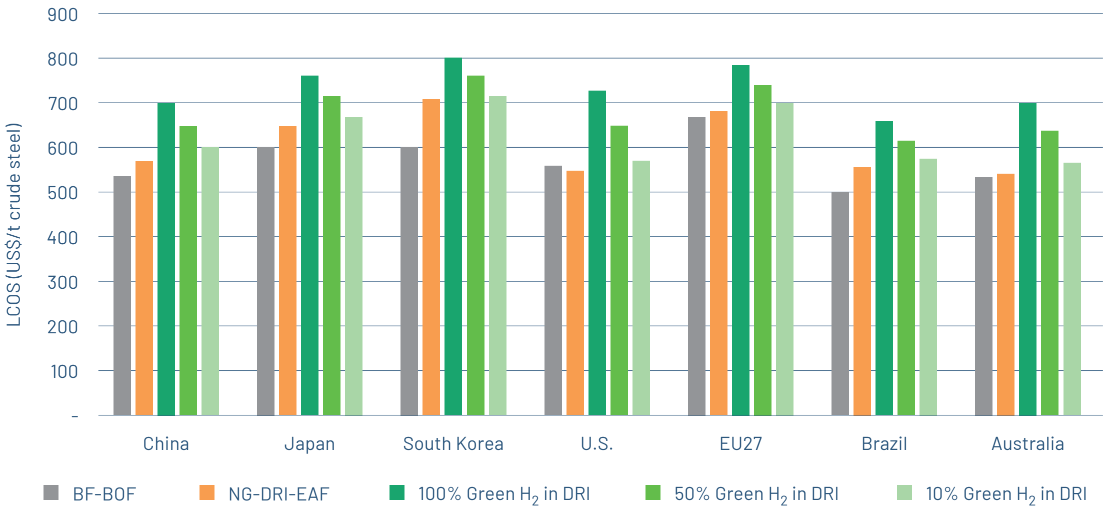

Figure 24. Levelized cost of steel (LCOS) for BF-BOF, NG-DRI-EAF, and H_2-DRI-EAF at ***H_2 price of $4/kg H_2*** *for different levels of H_2 ramp up in DRI, ranging from 10% to 100% green H_2, compared to natural gas (Source: this study)*

Notes: 5% steel scrap is assumed to be used in both BF-BOF and DRI route. No carbon price is considered.

At a H_2 price of $2/kg H_2, the dynamic changes significantly. Using 100% green H_2 in the H_2-DRI-EAF process results in the LCOS being slightly higher than the conventional BF-BOF route, yet offers a small cost reduction compared to the NG-DRI-EAF route in all countries studied except in the U.S. and Australia where natural gas prices are relatively low. This favors green H_2 over natural gas as the reductant in DRI process when the H_2 cost is at $2/kg H_2. At this price, in most countries studied using natural gas in the DR process will cost more than using green H_2.

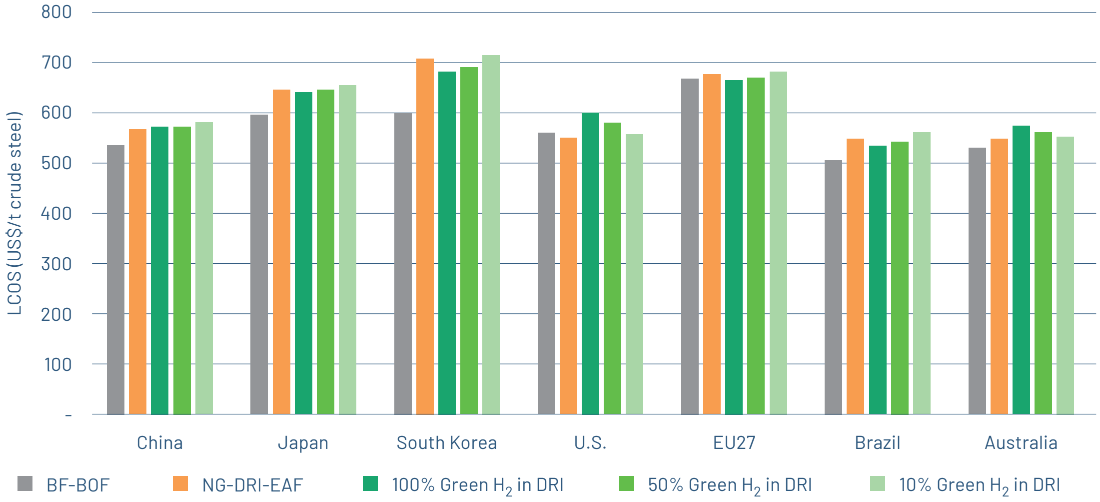

Figure 25. Levelized cost of steel (LCOS) for BF-BOF, NG-DRI-EAF, and H_2-DRI-EAF at ***H_2 price of \$2/kg H_2*** *for different levels of H_2 ramp up in DRI, ranging from 10% to 100% green H_2, compared to natural gas (Source: this study)*

Notes: Assumed 5% steel scrap is assumed to be used in both BF-BOF and DRI route. No carbon price is considered.

The gradual integration of green H_2 into the H_2-DRI-EAF process allows plants to optimize existing infrastructure and adapt to new H_2-DRI route while managing the economic implications of transitioning to green H_2. By initially incorporating lower percentages of green H_2, facilities can address the challenges posed by the currently high cost of green H_2, the early development stages of H_2 infrastructure, and the ongoing refinement of regulatory frameworks and incentives for H_2 use. As H_2 production costs decrease and supportive policies become established, H_2-DRI steel plants can increase their use of green H_2 significantly, reducing their CO_2 intensity while preserving competitive pricing in the market.

It should be noted that among the countries studied, only the U.S. and Australia are net exporters of natural gas. Other countries studied, and in fact, most other major steel-producing countries, do not have sufficient domestic natural gas resources and are net importers of natural gas. This makes the steelmakers in those countries vulnerable to natural gas price fluctuations, geopolitical tensions, and energy security risks.

Both major DRI technology providers, Midrex and Tenova, are proving H_2-ready DRI technology that can start working with natural gas and gradually phase in H_2 up to 100% at a small to no additional cost (Midrex 2023, Tenova 2024). Meanwhile, POSCO plans to commercialize HyREX by 2030, which is a DRI steelmaking process with fluidized reduction using 100% H_2 based on FINEX technology.

However, it should be noted that natural gas is still a fossil fuel that produces GHG emissions from production, transport, and end use. Very importantly, methane leaks from natural gas drilling, transport, and processing can be large. Addressing these methane emissions is crucial for the climate advantages of natural gas to be realized. In addition, natural gas supply is a challenge for many countries that rely on imports and its subject to price volatility. For these natural gas importing countries, it may not make financial sense to build natural gas import and supply infrastructure for their steel industry where local renewable energy resources are available that could produce green H_2 at prices low enough to make green H_2-DRI-EAF more economical than NG-DRI-EAF.

Therefore, once the LCOS for green H_2-DRI-EAF gets close or below NG-DRI-EAF, it simply makes more sense to use 100% green H_2 in the DRI process than using natural gas. The use of natural gas in the next few years (by 2030) could be justified in certain countries where the supply of green H_2 at a reasonable price is currently limited. Any new NG-DRI-EAF plant should be built Hydrogen-ready, so it can seamlessly switch to 100% green H_2 in the near future.

8. Renewable Energy, Green H_2 Production, and Electrolyzer Capacity

To produce one ton of steel using the H_2-DRI route, about 60 kg of H_2 are necessary. For a plant designed to produce one million tons of steel annually, this equates to a yearly H_2 requirement of 60,000 tons. Generating this H_2 through water electrolysis, assuming 56 kWh needed per kg of H_2 produced with the electrolyzer efficiency of 70% will lead to an annual electricity demand of approximately 3,377 GWh for a 1-Mt/year plant.

Central to this H_2 production is electrolyzer technology, particularly most commonly used Proton Exchange Membrane (PEM) and Alkaline electrolyzers, which operate at 60% to 80% efficiency. The operational capacity factor of these electrolyzers, which measures the actual running time against the maximum possible, is crucial. This factor is largely influenced by the variability of renewable energy sources. A higher capacity factor means the electrolyzers operate more consistently, allowing for the use of smaller, more cost-effective systems. On the other hand, a lower capacity factor would require larger systems to compensate for the intermittence of renewable energy availability.

The capacity requirements for electrolyzers needed for H_2 production for a green H_2-DRI plant producing one million tons of steel annually can vary significantly based on the capacity factor. For example, with a 30% capacity factor, the plant would need about 1,285 MW of electrolyzer capacity. However, if the capacity factor could be increased to 80%, the required capacity drops to just 482MW. This highlights the critical need to align renewable energy production with electrolyzer capacity to optimize both efficiency and economic feasibility (Figure 26).

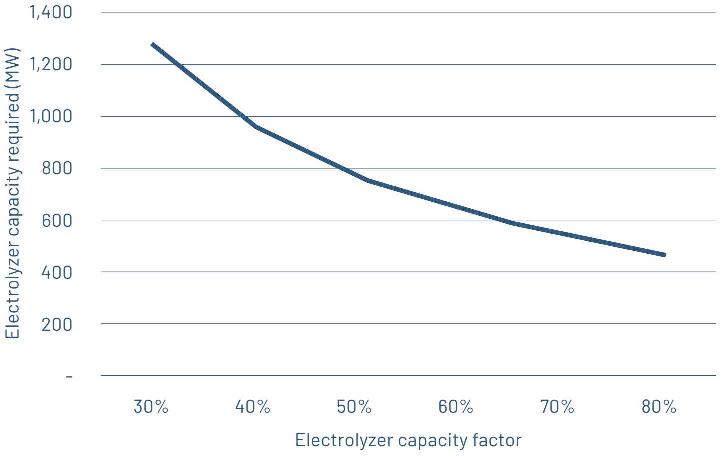

Figure 26. Electrolyzer capacity required to produce H_2 for 1 Mt/year steel produced with green H_2-DRI-EAF process

Note: We assumed 60 kg H_2 is needed per ton of steel produced by the green H_2-DRI route, and 56 kWh is needed to produce one kg of green H_2 with electrolyzer efficiency of 70%.

At a 50% electrolyzer operational capacity factor, a one million tons per year green H_2-DRI-EAF steel plant requires 771 MW electrolyzers capacity installed. Assuming an average cost of H_2 electrolyzers priced at \$1,000 per kW, the total capital expenditure would be approximately \$771 million. However, with anticipated reductions in electrolyzer prices, these costs could significantly decrease. By 2030, a 25% reduction in costs would lower the expense to \$578 million, and a 50% decrease would bring it down to \$386 million. It should be noted that the cost of electrolyzers manufactured in China is estimated to be about a third of the cost for those produced in the U.S. and the EU.

It should be noted that the levelized cost of H_2 used in our economic analysis to calculate LCOS already includes the capital cost needed for H_2 electrolyzers.

Based on the variable output of renewable energy sources, steel companies can implement an electrolyzer setup designed to produce an excess of green H_2 during peak energy production times. This surplus H_2 can be stored and utilized during periods when renewable energy generation is low, ensuring a continuous H_2 supply for uninterrupted steel production. Aligning the operation of electrolyzers with the availability of renewable energy and implementing robust H_2 storage solutions, such as high-pressure gas tanks, are crucial for maintaining stable operations in a green H_2-DRI plant.

China, Japan, South Korea, the United States, the European Union, Brazil, and Australia are actively enhancing their green H_2 sectors through a variety of supportive measures aimed at growing this emerging industry. These measures are designed to facilitate the production and adoption of green H_2, including its use in new applications like green H_2-DRI steelmaking. The strategies generally involve financial incentives, technological advancements, and infrastructural developments, which collectively contribute to lowering production costs and increasing the competitiveness of green H_2 in each country. Table 2 shows a brief summary of green H_2 strategies, policies and initiatives in the countries studied.

Table 2. Green H_2 policy snapshot in countries studied

Country	Policy Framework	Financial & Strategic Initiatives
China	Green H_2 Energy Plan	• Target of 80 GW electrolyzer capacity by 2030. • Expanding from alkaline to PEM electrolyzer technologies. • Reduction in renewable energy costs to make green H_2 competitive. • Comprehensive investment in green H_2 infrastructure. • Integration of H_2 in various sectors by 2035.
Japan	Basic H_2 Strategy	• Aims for 10% of the global electrolyzer market by 2030. • Plans to establish 15 GW of H_2 electrolyzer capacity. • Investment in various electrolyzer technologies. • Significant funding from the Green Innovation Fund. • International collaborations to secure green H_2.
South Korea	H_2 Economy Roadmap	• Developing 10MW scale H_2 electrolyzer technology by 2030. • Aims to enhance electrolyzer efficiency. • Strong emphasis on domestic supply chain for electrolyzer technologies. • Major financial investments in R&D. • Launch of pilot projects to scale green H_2 technologies at 0.25M tons capacity by 2030. • International cooperation and policy development support.
U.S.	National Clean H_2 Strategy	• Tax incentive under Section 45V of the Inflation Reduction Act. • Significant federal funding and R&D investments. • Expanding infrastructure for H_2 production, storage, and distribution. • Focus on efficiency and reducing production costs.
E.U.	EU H_2 Strategy	• Establishment of the European Clean H_2 Alliance. • Innovation Fund and European H_2 Bank funding. • Clear criteria for "renewable H_2" under Renewable Energy Directive. • First auction awarded €720 million to seven green H_2 projects in April 2024.
Brazil	National H_2 Program	• Green H_2 Bill creating a legal framework for production. • Development of the Low-Carbon H_2 Development Program. • Promotes use of green H_2 in various sectors. • "Regulatory sandboxes" for innovation in H_2 production.
Australia	National H_2 Strategy	• $2 billion H_2 Headstart program for large-scale projects. • Emphasis on technological innovation and domestic capabilities. • Investment in regional H_2 hubs through a $500 million program.

9. International Experiences with Financing H_2-DRI Projects

Financing H_2-DRI technology is vital for the steel industry's shift towards a less carbon-intensive production route. This transition relies heavily on a blend of innovative financing models that include public and private funding streams. Governments support H_2-DRI technology through significant grants and tax benefits, helping to reduce the financial risks of this new technology in both Europe and the U.S.

The private sector plays a critical role through direct investments and securing long-term supply contracts for low-carbon steel. These contracts provide stable revenue, enhancing the financial feasibility of such projects. For example, H_2 Green Steel has formed enduring partnerships with leading automotive manufacturers, ensuring a reliable demand for its green steel products. This blend of public incentives and private sector engagement is essential for supporting the development and adoption of H_2-DRI steelmaking. Below we briefly discuss how different H_2-DRI projects in Europe and the U.S. are being financed. Table 3 shows a summary of financing details for various international H_2-DRI projects.

H_2 Green Steel (H_2GS) is setting a precedent in the green steel sector with its substantial funding achievements for its H_2-DRI plant. In 2023, H_2GS secured €1.5 billion through equity financing to lay the groundwork for what is slated to be the world's first major green steel plant located in Sweden. The following year, they added over €4 billion in debt financing. Additionally, the EU Innovation Fund contributed a €250 million grant, further bolstering H_2GS's financial base. Strategic partnerships with major automotive firms like Volvo and Scania, alongside a supply agreement with Rio Tinto for high-grade iron ore, ensure a robust demand and supply chain for H_2GS low-emission steel products (H_2 Green Steel, 2024).

Sweden's SSAB, in collaboration with LKAB and Vattenfall, has developed the HYBRIT initiative, which is significantly supported by the Swedish Energy Agency through the Industrial Leap program with a grant of SEK 3.1 billion (approximately US$ 282 million). This project is distinctive for its extensive backing from private investments by the owner companies, which account for around 75% of the funding for this pioneering technology (Hybrit, 2023).

In Germany, Salzgitter AG is advancing its SALCOS program, focusing on low CO_2 steelmaking through the integration of "Energiron ZR® Direct Reduction" technology in a newly planned H_2-DRI plant. This initiative is supported by approximately €1 billion in subsidies from both the Federal Republic of Germany and the State of Lower Saxony, complemented by a similar amount from Salzgitter AG's own financial reserves (Salzgitter AG, 2023).

ArcelorMittal's German project is being supported with a significant €1.3 billion from the European Commission's Recovery and Resilience Facility, aligning with the EU's strategies to minimize fossil fuel use and enhance sustainability in heavy industries. This support will facilitate the establishment of a H_2-DRI plant and three new electric arc furnaces in Bremen and Eisenhüttenstadt to replace traditional steel production methods and potentially reduce annual CO_2 emissions by producing 3.8 million tonnes of green steel (European Comission, 2024). Concurrently, Thyssenkrupp is investing €2 billion to shift from traditional steelmaking to greener methods in Germany, with expectations for additional funding (thyssenkrupp, 2022). In the U.S., the Department of Energy is advancing the adoption this technology by allocating two $500 million ($1 billion in total) to support two H_2-DRI projects in Mississippi and Ohio (US DOE, 2024). In South Korea, the H_2-DRI project financing scale is much smaller which is at $20.4 million from 2023 to 2025 compared to its ambition. Currently, POSCO, the Korean government and Korean steel companies are aiming to commercialize HyREX technology (H_2-DRI with fluidized bed reduction reactor) by 2030 based on POSCO's FINEX technology.

Table 3. A summary of financing details for various international H_2-DRI projects

Project	Location	Equity Funding	Debt Financing	Subsidies	Total Funding
H_2 Green Steel (H_2GS)	Europe	€1.5 billion raised in equity for setting up operations.	Secured over €4 billion in debt in January 2024 to support construction and operations.	Awarded a €250 million grant from the EU Innovation Fund to aid in the development of green steelmaking facilities.	>€5.75 billion
Salzgitter AG - SALCOS®	Germany	Financing primarily through more than €1 billion of company's own funds.	None specified.	Received around €1 billion in subsidies from the Federal Republic of Germany and the State of Lower Saxony, specifically allocated for this pioneering green steelmaking technology.	>€2 billion
SSAB H_2 DRI - HYBRIT	Sweden	Predominantly funded by the owner companies—SSAB, LKAB, and Vattenfall.	None specified.	Granted SEK 3.1 billion (approximately US$ 282 million) by the Swedish Energy Agency's Industrial Leap program to support the establishment of a new H_2-DRI facility.	Significant proportion covered by owner companies
ArcelorMittal's H_2-DRI	Germany	No specific equity funding detailed.	None specified.	Benefited from a €1.3 billion state aid measure approved by the European Commission under the German Recovery and Resilience Facility (RRF), aligning with the EU's H_2 Strategy.	€1.3 billion
Thyssenkrupp's H_2-DRI Plant	Germany	Part of a broader €2 billion investment in decarbonization strategies by Thyssenkrupp.	Additional public and private funding expected to be raised to support the project.	None specified.	€2 billion+ expected
U.S. Department of Energy Project in Mississippi	USA	None specified.	None specified.	Swedish steelmaker SSAB plans to establish its commercial-scale HYBRIT facility with a green H_2 DRI in Perry County, Mississippi.	$500 million
U.S. Department of Energy Project in Ohio	USA	None specified.	None specified.	Cleveland-Cliffs' Middletown Works facility in Ohio is transitioning from coal-based ironmaking to hydrogen-ready DRI technology.	$500 million
POSCO's HyREX	South Korea	None specified.	None specified.	Technology development of HyREX, a fluidized bed reduction steelmaking with 100% hydrogen.	KRW 26.9 billion (USD 20.4 million) [2023~2025]

Source: (H_2 Green Steel, 2024; Salzgitter AG, 2023; Hybrit, 2023; European Commission, 2024; Thyssenkrupp, 2022; US DOE, 2024).

10. Conclusions and Recommendations

In this study, we have conducted an in-depth financial analysis comparing economics of green H_2-DRI and traditional steelmaking in seven key countries using the levelized cost of steel (LCOS). We highlight the varying costs of green steel production that can be substantially influenced by hydrogen prices and carbon pricing mechanisms. While the traditional BF-BOF steelmaking process currently has lower LCOS, green H_2-DRI-EAF could be competitive or even cheaper in regions with supportive policies, lower green hydrogen costs, or carbon pricing mechanism.

The impact of the green steel premium on end products such as cars, buildings, and ships is analyzed to understand the broader economic implications of adopting green H_2-DRI-EAF steel. For the automotive industry, the additional cost of using green steel is minimal, affecting the overall vehicle price by less than 1%. This minimal impact suggests that the transition to green steel could be economically feasible for manufacturers without significantly affecting consumer prices. Similarly, in the construction sector, the green steel premium accounts for a very small (less than 1%) of the cost of a building. In the shipbuilding sector, the green steel premium accounts for a larger share of the product price but still around 10% of a ship price for a typical bulk carrier studied. However, shipbuilding accounts for only around 3% of the global steel demand. These green premiums can be managed through effective policy interventions and advancements in green steel production technologies. These sectors are crucial for widespread adoption as they represent significant steel consumption and have substantial potential for driving the demand for green H_2-DRI-EAF steel.

When constructing compelling arguments to boost demand for green steel, in addition to what is highlighted in this study on how negligible is the green premium per unit of final products for cars and buildings, several other factors should be considered. These include the ease of passing the cost premium to end consumers, the direct procurement of steel by buyers (which is typically not the case in sectors like construction or energy), and the simplicity of the supply chain, allowing buyers to easily influence suppliers. Additionally, it's important to consider how long buyers would need to pay the premium. These factors significantly impact investment decisions for H_2-DRI steelmaking and should be addressed.

Below we outline some of the key actions that governments, steel companies, automotive companies, building construction companies, and ship building companies can take to help address the initial green premium of H_2-DRI-EAF steel and help with wider adoption of H_2-DRI-EAF technology in different countries.

Actions for Governments

Governments can play a pivotal role in accelerating the adoption of green H_2-DRI steelmaking technologies by implementing a range of supportive and financial incentives aimed at reducing the costs associated with green hydrogen production and supporting the investments in green H_2-DRI steel plants. Such incentives could include tax rebates, grants, and subsidies that make it financially viable for steel manufacturers to invest in green H_2-DRI technology. Additionally, offering incentives for renewable energy used in hydrogen production can lower the operational costs of green hydrogen. These could be in the form of corporate PPA mechanisms that provide steel companies with reliable, cost efficient and green electricity needed for large scale hydrogen production. Governments can also provide funding for research and development to advance electrolyzer technologies, thereby reducing the cost of hydrogen production over time. Proper infrastructure investments, such as building or subsidizing the construction of hydrogen pipelines, can further lower logistics costs, making the operation of green H_2-DRI plants more feasible. These combined efforts can significantly diminish the green premium associated with green H_2-DRI steel production, making it a more attractive option for industries and promoting broader adoption.

Whilst government financial support and incentives will be integral to the transition towards green steel production, the use of meaningful targets can help facilitate pointed government and corporate policies to increase the production of green steel. Setting top-down targets for green H_2-DRI production can help ensure the steel sector can decarbonize their operations, a much need action given no meaningful decarbonization progress has been made in the sector to date and the sector is noted as "off-track" to be net-zero by 2050 by the IEA. Such targets should align national decarbonization targets with the steel sector ensuring policies are directed towards green H_2-DRI technology.

On the demand side, governments can use green public procurement policies as a powerful tool to support the early adoption of green H_2-DRI steel. By leveraging their substantial purchasing power, governments can create initial market demand for green steel by specifying it as a preferred material in publicly funded construction projects, vehicle fleets, and naval procurements (Hasanbeigi et al. 2024, 2023b, 2022). This not only provides a market for green H_2-DRI steel but also helps to cover the initial green premium, thus reducing financial risk for steel producers. Such public procurement policies would send strong signals to the broader market and industry, incentivizing further investments in green H_2-DRI technologies and establishing a robust supply chain.

Actions for Steel Companies

Steel companies need to drive the transition away from traditional BF-BOF steelmaking route to green H_2-DRI steelmaking technologies. To successfully make this shift, steel producers can engage in joint ventures or partnerships with technology providers and renewable energy companies to ensure a reliable and cost-effective supply of green hydrogen. Establishing industrial scale pilot projects can help these companies refine the processes and demonstrate their commercial viability. Financial strategies such as accessing green bonds, climate/sustainability-linked loans, or government-backed financing can provide the necessary capital for these large-scale transformations. By progressively increasing the share of green H_2-DRI in their production portfolio, steel companies can gradually phase out older, carbon-intensive BF-BOF processes, thereby reducing their carbon footprint while aligning with Paris Agreement targets.

To secure market demand for green H_2-DRI steel and address the financial challenges posed by the initial green premium, steel companies can collaborate with key stakeholders including governments, automotive manufacturers, construction companies, and shipbuilders. By entering into long-term supply agreements with these entities, steel companies can ensure a steady demand for their green steel products. Such partnerships could be further supported by contractual agreements where the additional costs associated with the green premium are shared or offset by the end users, which could be facilitated through green procurement policies from these sectors. This is what H_2 Green Steel company has been doing to partially finance the construction of H_2-DRI plant in Sweden.

Actions for Automotive Companies

Automotive companies, which are significant consumers of steel, have a key role to play in promoting the transition to green H_2-DRI steel through their procurement policies and collaboration with steel manufacturers. By integrating green steel requirements into their supply chain, car manufacturers can drive demand and incentivize steel companies to invest in H_2-DRI production technologies. As shown earlier in this report, the green steel premium will have a negligible impact on the final cost of a car (less than 1% increase). For instance, companies like Volvo Cars and Polestar, which have committed to using low-emission steel, can leverage their purchasing power to negotiate agreements that include clauses for the adoption of H_2-DRI steel. These agreements could include sharing or fully covering the green premium associated with green steel production, thus alleviating the financial burden on steel manufacturers and accelerating the industry's shift towards green H_2-DRI steelmaking. Additionally, automotive companies can work closely with their customers by promoting the environmental and climate benefits of vehicles made with green steel, potentially commanding a premium price that reflects the higher manufacturing costs but also aligns with increasing consumer demand for low-carbon products.

Moreover, automotive companies can play a key role in shaping market expectations and standards by forming alliances and participating in global initiatives like SteelZero. Through these platforms, they can collaborate with other industries and stakeholders to establish common standards and commitments for green steel usage, thereby creating a larger, consolidated demand that can further drive down costs through economies of scale. Such collaborative efforts can be supported by public policies like the Carbon Border Adjustment Mechanism (CBAM) in the EU, which encourages the adoption of low-emission production methods by imposing higher costs on imported high-emission steels.

Actions for Construction Companies

Through collaborations with governments, construction companies can influence the establishment and enforcement of green public procurement policies that mandate or highly favor the use of green steel, which can support H_2-DRI steelmaking. These policies could involve financial mechanisms like tax incentives or preferential bidding to lessen the cost burden associated with the green premium of H_2-DRI steel. For privately funded projects, construction firms can leverage the growing demand from eco-conscious clients who prioritize sustainability. By implementing green private procurement initiatives, these companies can market the use of green steel as a premium feature of their projects, potentially fetching slightly higher market rates and enhancing the overall appeal of their constructions to the climate-conscious customer. As shown earlier in this report, green steel premium has a very small impact on the total constriction cost (less than 1%).

Moreover, the larger construction companies can strengthen their market position by combining their purchasing power and advocating for and adopting green steel through partnerships and long-term contracts with steel producers. This ensures a steady demand for green steel, providing steel manufacturers with the economic assurance needed to invest in and expand H_2-DRI production capacities.

Actions for Ship Building Companies

To address the initial green premium associated with green H_2-DRI steel in shipbuilding, shipbuilding companies and shipping enterprises like Maersk can harness both public and private procurement programs effectively. Governmental bodies can play a pivotal role through green public procurement policies that prioritize or mandate the use of green steel in publicly funded naval and service vessels. Such policies can reduce the cost burden by covering a portion of the green premium, making it financially feasible for shipbuilders to transition towards green H_2-DRI steel. On the private sector front, leading shipping companies can implement green private procurement policies that demand low-embodied carbon steel for constructing new ships and retrofitting old ones. By signaling a strong market demand for green steel, these companies encourage steel producers to scale up green H_2-DRI production processes, thereby gradually reducing the green premium.

Furthermore, shipping companies can strengthen their collaboration with steel manufacturers to create a robust supply chain for green H_2-DRI steel. By entering long-term purchase agreements or joint ventures, they can secure a steady demand for green steel, providing steel manufacturers the confidence to invest in and expand green H_2-DRI steel production facilities.

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About Transition Asia

Founded in 2021, Transition Asia is a non-profit think tank that focuses on driving 1.5°C-aligned corporate climate action in East Asia through in-depth sectoral and policy analysis, investor insights, and strategic engagement. Transition Asia works with corporate, finance, and policy stakeholders across the globe to achieve transformative change for a net-zero, resilient future. Visit transitionasia.org to learn more.

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Global Efficiency Intelligence is a U.S.-based research and consulting firm specializing in industrial decarbonization. The firm offers market-based solutions alongside comprehensive analyses of technology, systems, industry practices, business strategies, and policies relevant to the industrial sector. Utilizing systems thinking, integrative modeling, and data analytics, GEI transforms data into actionable insights and delivers science-based engineering solutions for global industrial decarbonization.

About Solutions for Our Climate

Solutions for Our Climate (SFOC) is an independent nonprofit organization that aims to accelerate effective climate action and energy transition in Asia. SFOC is led by legal, economic, financial and environmental experts and works closely with domestic and international players. We focus on research, litigation, community organizing, and strategic communications to deliver practical climate solutions in the region and build movements for change.