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Green H_2-DRI Steelmaking:

15 Challenges and Solutions

Authors: Ali Hasanbeigi, Cecilia Springer, Hannah Irish

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Executive Summary

Iron and steel manufacturing is one of the most energy and carbon-intensive industries worldwide. 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. Decarbonization in the steel industry will be pivotal in reaching global climate targets. A transition from conventional, coal-based steelmaking to utilizing green hydrogen in direct reduced iron production (H_2-DRI) represents a great opportunity for producing low-carbon steel. Several commercial-scale projects in Europe and Asia have begun or announced to use H_2-DRI as an input for steelmaking. Still, there are some technological, economic, and other barriers to cost-effectively scaling up this technology to a level needed to meet a substantial portion of global steel demand as well as climate goals.

This report analyzes these different challenges and proposes possible solutions. **The challenges and solutions are discussed under the following five categories:**

- Cost, Economic Viability and Market Dynamics of Green H_2-DRI
- Metallurgical Complexities and Technical Challenges in H_2-DRI Steelmaking
- Clean Energy Requirement and Infrastructure for H_2-DRI Processes
- Regulatory Framework and Standardization for H_2-DRI
- Stakeholder Engagement and Skill Development in H_2-DRI Transition

One of the primary hurdles is the technology's cost and economic viability. Major economic barriers are the high cost of hydrogen production and the relative price of renewable electricity compared to fossil fuels in most regions of the world. Solutions include leveraging advancements in production economies, achieving economies of scale, and exploring financial support mechanisms and policies to make H_2-DRI technology more economically attractive. It should be noted that the impact of so-called green premium for H_2-DRI is minimal on the price of final products (e.g. cars, buildings, ships, etc.).

From a metallurgical perspective, H_2-DRI introduces complexities in steelmaking processes, such as chemical composition and embrittlement variances. Without an inherent carbon source, there are challenges to ensuring the H_2-DRI will behave chemically as is necessary for high-quality steel production with carbon addition, though the carbon footprint is lower. It will be necessary to carefully control the conditions of an H_2-DRI plant to ensure a consistent and high-quality final steel product, particularly with the current global shortage in the supply chain of high-grade iron ore. These issues may necessitate equipment modifications, even in plants that already utilize an electric arc furnace (EAF) in their steelmaking. With these modifications, rigorous quality control measures and the implementation of advanced control systems are needed to ensure product quality and process efficiency.

Green hydrogen production is highly energy-intensive, and hydrogen is not as strong a reducing agent as its fossil fuel predecessors. As a result, the energy demand from switching to green H_2-DRI steelmaking will require large-scale renewable electricity production. However, the intermittent nature of renewables and their need to be sited close to resource-abundant areas pose an infrastructure challenge that varies by region and can drive up the costs of H_2-DRI steelmaking. Proper renewable energy, green hydrogen generation, and distribution planning are needed to address this challenge. This can vary for each country/region.

Furthermore, the report highlights the lack of a consistent policy and regulatory framework as a significant impediment. There is also an absence of clear global regulations and standards for hydrogen production, handling, and storage, which require policy intervention. Additionally, there will need to be training to create a shift in the workforce to accommodate this new technology.

Recommendations include implementing carbon pricing mechanisms, providing financial incentives for adopting green H_2-DRI technology and for building more renewable electricity and green H_2 infrastructure, green public and private procurement of steel made with green H_2-DRI to support early adopters, establishing clear regulations and standards for green hydrogen production and steelmaking processes to ensure quality and safety.

The social perspective, particularly resistance to change among stakeholders and policymakers, and a general lack of awareness about H_2-DRI technology are also identified as challenges. There is a need for more education programs and public-private partnerships to build support for green H_2-DRI technology and facilitate its adoption.

Transitioning to green H_2-DRI steelmaking pathways has major potential for decarbonizing the steel industry, contributing to over 7% of annual global GHG emissions. Though scaling up the technology comes with challenges, there are opportunities to lessen these challenges with technological innovations, regulatory support, and stakeholder collaboration. These challenges represent hurdles to overcome, not walls that halt the industry's progress towards net-zero emissions.

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What's H_2-DRI?

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). Iron and steelmaking technologies primarily revolve around two key processes: primary and secondary steelmaking. The Blast Furnace-Basic Oxygen Furnace (BF-BOF) route is the predominant method for primary steelmaking. In this process, iron ore is converted into molten iron in a blast furnace (BF) and refined into steel in a basic oxygen furnace (BOF).

This traditional method is known for its high production capacity and high energy- and carbon intensity. On the other hand, the Electric Arc Furnace (EAF) process, primarily used in secondary steelmaking, predominantly recycles scrap steel. EAF melts scrap steel using high-power electric arcs, making it a more flexible and less carbon-intensive than BF-BOF. Natural gas-based Direct Reduced Iron (DRI) is another significant method, where natural gas is used to produce a syngas of H_2 and CO that is used as a reductant to convert iron ore into DRI, which is then fed into an EAF for steelmaking.

The Hydrogen Direct Reduced Iron (H_2-DRI) process emerges as a promising decarbonization solution for primary steelmaking. In H_2-DRI, hydrogen replaces carbon-intensive reductants like coke or natural gas, significantly reducing CO_2 emissions.

When hydrogen is produced via electrolysis using renewable energy (green H_2), the process is called Green H_2-DRI and has no/very low CO_2 emissions.

Green H_2-DRI produces direct reduced iron using green hydrogen, which can then be melted in an EAF, offering a cleaner alternative to the traditional BF-BOF route. This holds great potential to drastically cut down the carbon footprint of primary steel production globally. Figure 1 shows the simplified production process for BF-BOF, natural gas DRI-EAF, and H_2-DRI-EAF.

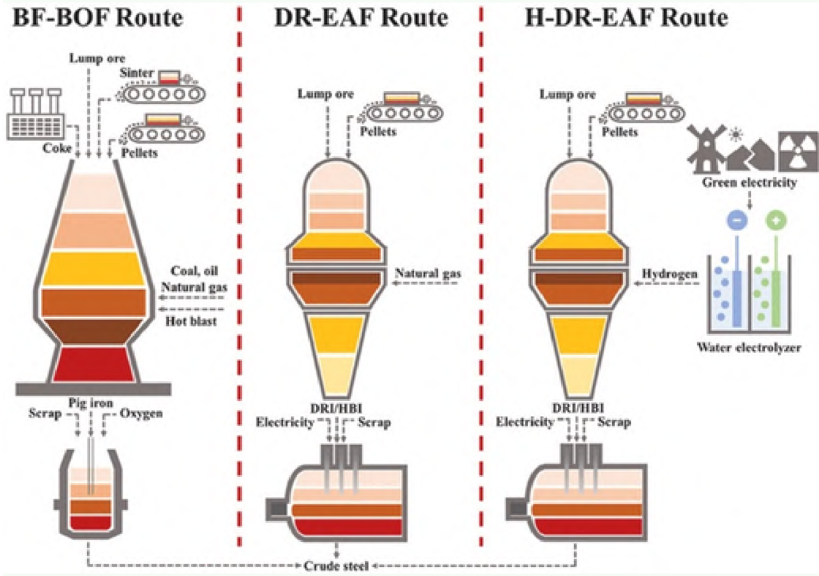


Figure 1. The production process for BF-BOF, natural gas DRI-EAF, and H_2-DRI-EAF (Wang et al. 2021)

Globally, there is a growing trend towards adopting H_2-DRI processes, with several projects announced or underway, particularly in Europe and Asia (Table 1).

Table 1. Some of the announced or under-construction H_2-DRI plants globally (as of February 2024)

Steel Company	Location	Status
SSAB, LKAB, Vattenfall (Hybrit project)	Sweden	Under construction
H_2 Green Steel	Sweden	Under construction
Salzgitter AG	Germany	Announced
Thyssenkrupp Steel Europe	Germany	Announced
ArcelorMittal	Germany	Announced
POSCO	South Korea	Announced
Baosteel	Saudi Arabia	Announced
Kobe Steel & Mitsui	Oman	Announced

In the following chapters, we look into the challenges and potential solutions associated with implementing Green H_2-DRI in the global steel industry. These are categorized into five critical areas:

- **Cost, Economic Viability and Market Dynamics of Green H_2-DRI:** This chapter explores the financial aspects, market readiness, and economic challenges of implementing Green H_2-DRI technology in the steel industry.

- **Metallurgical Complexities and Technical Challenges in H_2-DRI Steelmaking:** This chapter focuses on the metallurgical complexities, production techniques, operational challenges, and technological adaptations necessary for successful H_2-DRI steelmaking.

- **Clean Energy Requirement and Infrastructure for H_2-DRI Processes:** This chapter looks into the energy requirements, utility considerations, and infrastructural demands, including renewable energy integration, essential for Green H_2-DRI steelmaking.

- **Regulatory Framework and Standardization for H_2-DRI:** This chapter discusses the need for clear regulations, standards, and metrics for hydrogen production, handling, and H_2-DRI steelmaking processes.

- **Stakeholder Engagement and Skill Development in H_2-DRI Transition:** This final chapter addresses the social aspects, including stakeholder resistance, public awareness, and the development of a skilled workforce to support the transition to H_2-DRI in the steel industry.

1. Cost, Economic Viability, and Market Dynamics

Challenges

The high cost of hydrogen production represents an economic barrier to the ability of H_2-DRI steelmaking to become a viable technology at scale. **Hydrogen is currently more are still expensive than natural gas or coal/coke, the primary fuels and reductants used in conventional steelmaking.** This is due, in part, to the relatively high costs of renewable electricity as an input to green hydrogen. Though on a decline in recent years, renewable electricity costs are still higher than fossil fuel-generated electricity in some regions (IRENA, 2021).

While there is an expectation for renewable electricity prices to fall and normalize in the future, the timeline and the equilibrium to which they will settle remain uncertain. The current energy market conditions, exacerbated by post-COVID economic recovery, insufficient natural gas storage reserves, and geopolitical tensions, further complicate the assessment of hydrogen production costs. Fluctuating energy prices have created an uncertain landscape, making assessing the long-term profitability of traditional steelmaking methods such as the BF-BOF pathway challenging. It is unclear to what extent and at what pace renewable electricity prices and, therefore, green H_2 production costs will drop in different regions of the world.

Our analysis shows that at a hydrogen price of \$5/kg H_2, around 40%-50% of H_2-DRI production cost is the H_2 cost. Renewable electricity costs account for around 70% of green H_2 production costs. Therefore, the price of renewable electricity substantially impacts the H_2-DRI production cost.

Global Efficiency Intelligence and its collaborators are conducting a detailed study to compare the steel production cost of green H_2-DRI, natural gas DRI, and BF-BOF in several major steel-producing countries under various conductions and H_2 processes. The result of that study will be published in May 2024.

Solutions

Despite the current high costs, projections for the future remain optimistic. Anticipated advancements in production technology and the growing demand for green hydrogen in the shift toward decarbonization are expected to reduce H_2 production costs. The advancements and increased demand will support economies of scale and technological progress that should drive down the per-kilogram cost of hydrogen production and make green H_2-DRI more economical.

As the demand for green hydrogen increases, **economies of scale and the declining cost of renewables could decrease hydrogen production cost by over 30% by 2030** (World Steel Association, 2022). Renewable energy production costs have fallen significantly in recent years. This trend is expected to continue despite the current energy market instability, especially as solar PV technology becomes less expensive.

Additionally, hydrogen electrolyzer CAPEX should be reduced with the growing economy of scale and increased automation of the hydrogen manufacturing process. Electrolyzer CAPEX alone is expected to decrease by up to 50% compared to current levels, which could help to reach a cost of around 2 USD/kg of H_2 by 2030 (Figure 2). If the green hydrogen production costs fall as predicted, then by 2030, it could be a competitive reductant source for DRI-EAF steel production. In the meantime, financial support will be needed to decrease the premium for low-carbon to make H_2-DRI a more attractive choice for steel production.

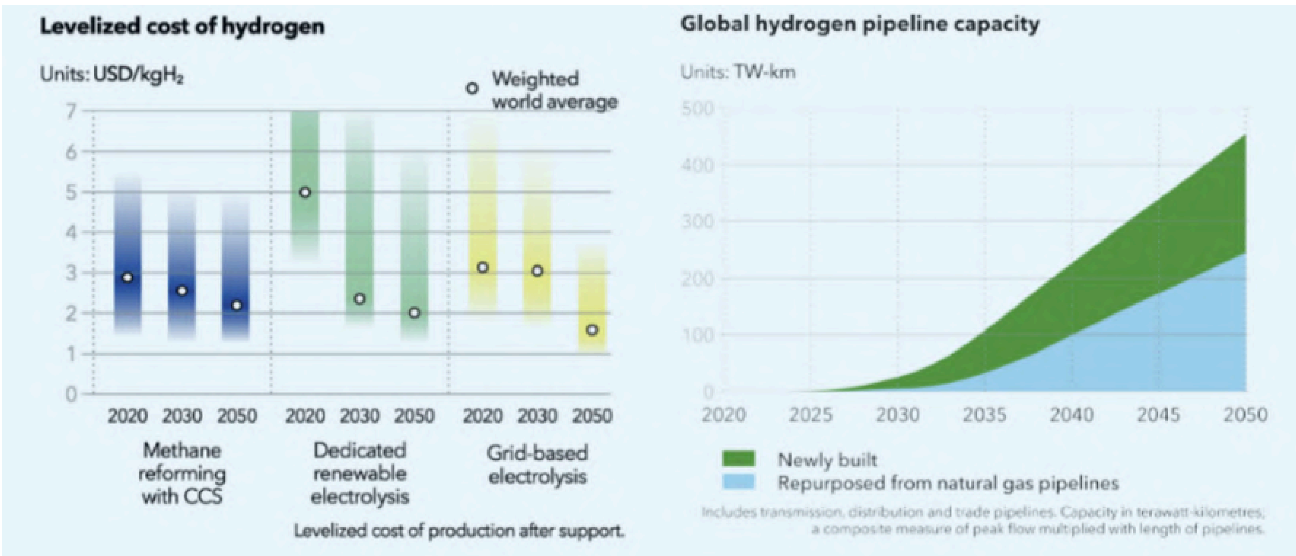


Figure 2. Projected levelized cost of hydrogen up to 2050 (DNV 2022)

Even if the cost of steel increases by $200 per ton due to the adoption of green H_2-DRI technology compared to the conventional BF-BOF steelmaking, the overall impact on the final product, such as cars, buildings, ships, and machinery, remains negligible. For instance, considering the steel consumption of a passenger car, which typically utilizes around 900 kg of steel per vehicle in the U.S., a $200 per ton increase in steel cost would only translate to approximately a $180 increase in the price of a car. In the context of automotive manufacturing, where the cost of a vehicle can amount to tens of thousands of dollars, this incremental cost rise is relatively minor and unlikely to significantly affect consumer affordability or market dynamics. Thus, despite the initial increase in steel price associated with the transition to H_2-DRI, the overall impact on the affordability and accessibility of end products remains minimal.

2. Metallurgical Complexities and Technical Challenges

This Chapter looks into the technicalities and innovative solutions pivotal to successfully implementing H_2-DRI in steel production. This chapter explores the metallurgical complexities inherent in the H_2-DRI process, including the nuances of production techniques and the operational challenges of transitioning from traditional steelmaking methods to H_2-DRI. It also examines the technological adaptations and advancements required to maintain and enhance steel quality, efficiency, and environmental compliance in the H_2-DRI process. Each section within this chapter addresses specific technical hurdles, ranging from equipment modifications to process optimization, and presents forward-thinking solutions and strategies to overcome these challenges.

2.1 Impact on downstream steelmaking processes

Challenges

Though switching to H_2-DRI is beneficial in reducing the carbon footprint of manufacturing steel, enabling this fuel switch while preserving product quality may face some challenges. **Using 100% hydrogen to produce DRI can result in variances in chemical composition that may require retrofits to existing downstream processes** or the development and addition of new processes as outlined below (Pattison & Mirgaux, 2020; Devlin et al., 2023):

Equipment Modifications: Differences in H_2-DRI as a feedstock for steel production could require retrofits to an EAF or BOF or use different alloying elements to produce the desired steel grades. The critical modification for EAFs to effectively use a substantial amount of DRI, whether H_2-based or natural gas-based DRI, involves transitioning to continuous DRI feeding through a conveyor system. While this adaptation is straightforward for new or greenfield projects, typically designed with continuous feeding capabilities, retrofitting older facilities presents a challenge. These legacy plants, originally configured for bucket charging, can only accommodate up to 20% DRI in their charge without risking material clumping, necessitating structural overhauls to support continuous DRI integration.

Storing, Handling, and Workforce Training: Storing and handling DRI and hydrogen safely can be more challenging than with conventional iron ore and coke, leading to a need for specialized facilities and increased safety measures. Changes in these methods may also require specialized training to ensure employees have the necessary skills for safe and efficient operations.

Variations in Quality: Achieving proper heat balancing in downstream processes can also be more challenging with hydrogen steelmaking than conventional materials. As the direct reduction of iron in the H_2-DRI process requires a higher heat (850-900 C), the furnace bed will be cooled down, affecting the reaction's speed, which may reduce the production volume. Thus, screening of the pellet size and its high quality is essential for this process.

Emissions regulations and compliance: Meeting emission standards may necessitate additional investments in emission control technologies, aligning with the drive to reduce GHG emissions.

Solutions

Steel manufacturers must carefully plan their shift to H_2-DRI processes on a phased approach to mitigate risks and ensure a smoother transition. This includes conducting feasibility studies, investing in R&D, and collaborating with hydrogen technology, materials science, and engineering experts.

Several solutions to optimize the H_2-DRI processes include ensuring a consistent supply of high-quality iron ore and other raw materials, minimizing variations in raw material processes, and maintaining high hydrogen purity. Suppose the raw material challenge cannot be met by supply. In that case, downstream processes must become more flexible, such as using BF-grade iron ore pellets in the DRI shaft furnace or DRI-grade iron ore fines in DRI with fluidized bed reactor.

However, both approaches require additional processes to prevent impurities or avoid the "sticking' phenomenon (Devlin et al., 2023). Implementing effective and advanced control and automation systems for real-time monitoring and adjustments in the H_2-DRI process becomes crucial to maintaining product quality and process efficiency. The application of screening systems will help the upstream of the H_2-DRI process to produce high-quality pellets.

Retrofits or replacements of existing steelmaking furnaces will ensure they can accommodate H_2-DRI as a feedstock. This may include modifications to the furnace design and burners. Integrating the H_2-DRI with other downstream steelmaking equipment can also help reduce the challenges of material transfer and increase process synchronization, minimizing energy losses and enhancing overall efficiency. Developing efficient material handling and storage systems will reduce the risk of contamination. Further improvements on refractory material need to be considered.

Finally, steelmakers should foster a culture of continuous improvement and innovation to identify opportunities for enhancing efficiency in both the H_2-DRI process and downstream steelmaking.

2.2 Productivity, DRI quality, and impact on operating conditions of refractory systems

Challenges

Many variables in the H_2-DRI steelmaking process must be very carefully assessed and regulated to produce high steel grades. However, it is challenging to assess productivity metrics for H_2-DRI steelmaking, and a current lack of standard metrics for this technology yields different productivity-measuring methods from different companies, making it difficult to compare H_2-DRI steelmaking plants (Hoffmann et al., 2020). Plant-level differences in DRI quality and steel composition, along with operational and equipment variation, can contribute to the challenge of developing accurate productivity metrics (Bhaskar et al., 2022).

DRI with a higher iron content will generally lead to higher productivity, so lower iron content and higher impurity levels can reduce the productivity of a DRI plant. Lower quality DRI can make producing steel in the EAF more difficult, leading to increased defect rates. **H_2-DRI plants need to use the high quality (DR grade) iron ore, containing 67% iron on average, currently accounting only for 4% of global iron ore shipments** (IEEFA, 2022). The overall quality of iron ore has reportedly declined in recent years in parts of the world, so it is challenging to quickly increase the production of DR-grade iron ore globally. The steel composition being produced at the plant can also affect performance. For example, steels with higher alloying element content generally have low productivity.

Differences in plant operating conditions will also affect productivity. H_2-DRI may increase wear and tear on refractory materials, crucibles, and other equipment. Particularly, wear is likely to increase without carbon in the EAF unless refractory systems are redesigned or carbon is added in pre-melter before DRI or in the EAF feed (Hornby, 2021).

Solutions

Though plant-level variations in operations, steel composition, and DRI quality make it complicated to standardize productivity metrics for H_2-DRI steelmaking, there are several ways to make metrics generalizable, such as measuring productivity as the amount of steel produced per unit of DRI consumed or as the amount of steel produced per unit of energy consumed (Wang et al., 2021). Developing these standardized metrics is an important step in the commercialization of the technology. It will allow companies to compare productivity between different plants, track productivity over time, and help companies identify areas where productivity can be improved (Hoffmann et al., 2020).

Some technical solutions for the assessment of H_2-DRI productivity metrics include (Rosnera et al., 2023; Devlin et al., 2023):

- **Process modeling and simulation:** Computer models can be used to simulate the performance of plants, develop metrics that consider the specific operating conditions of each plant, and even predict the plant's productivity. Additional benefits could include using the models to simulate different operating conditions to help optimize plant design.

- **Data analytics:** Data analytics can analyze historical data from DRI steelmaking plans and identify key performance indicators (KPIs) that correlate with productivity, such as the amount of DRI produced per hour. Once the KPIs have been identified, they can be tracked and monitored to assess productivity over time.

- **Sensors and instrumentation:** Real-time data from plants can be collected via sensors and instrumentation, which can monitor performance and identify bottlenecks or inefficiencies potentially impacting productivity. For example, sensors could be used to monitor the temperature and pressure of H_2 gas in the reduction process.

- **Applying computerized simulation and modeling** with various operational control parameters could be a suitable solution to this challenge.

Recent innovations in refractory materials designed to withstand higher temperatures and corrosive environments typical in H_2-DRI processes can also help. H_2-DRI steelmaking is still a relatively new technology, with less experience producing high steel grades. More research and development are needed to optimize the process and ensure that it can consistently produce high-quality steel (ING, 2023). Fortunately, researchers are working to develop productivity methods with the abovementioned approaches. For example, developing a metric that considers the quality of the DRI used, the composition of the steel being produced, and the plant's operating conditions for a granular look at productivity (Chang et al., 2023).

2.3 Slag volume and bath mixing

Challenges

Another technical challenge associated with H_2-DRI steelmaking arises from bath mixing and slag foaming issues.

Bath mixing is important in EAF steelmaking to ensure homogenous bath temperature and melting behavior of the metallic charge. Poor mixing can lead to stratification of the bath's temperature profile, skull formation, icebergs, localized superheating, and taphole freezes during tapping. H_2-DRI presents a specific challenge owing to its poor melting behavior compared with conventional DRI. This is compounded by the fact that conventional stirring in an EAF is provided by oxygen injection, which is less feasible when melting DRI without the carbon level to facilitate this practice.

Slag foaming in the EAF has been one of the key technological advances in traditional EAF steelmaking for the past 30 years. By generating CO gas through the oxidation of carbon, the volume of the slag is increased such that the electric arcs are completely submerged and stabilized. As a result, extremely high power can be used, dramatically increasing heat transmission efficiency to the bath and reducing overall power consumption by around 15% (Stewart, 2023).

Natural gas DRI generates significant CO volumes during melting due to the reaction between intrinsic carbon in the material and unreduced FeO.

This gas generation within the slag generates a foamy condition wherein gas bubbles inflate the slag and substantially expand its volume. This expanded slag volume can sufficiently immerse the electric arcs completely within an EAF and dramatically increase stability and heating efficiency (Figure 3).

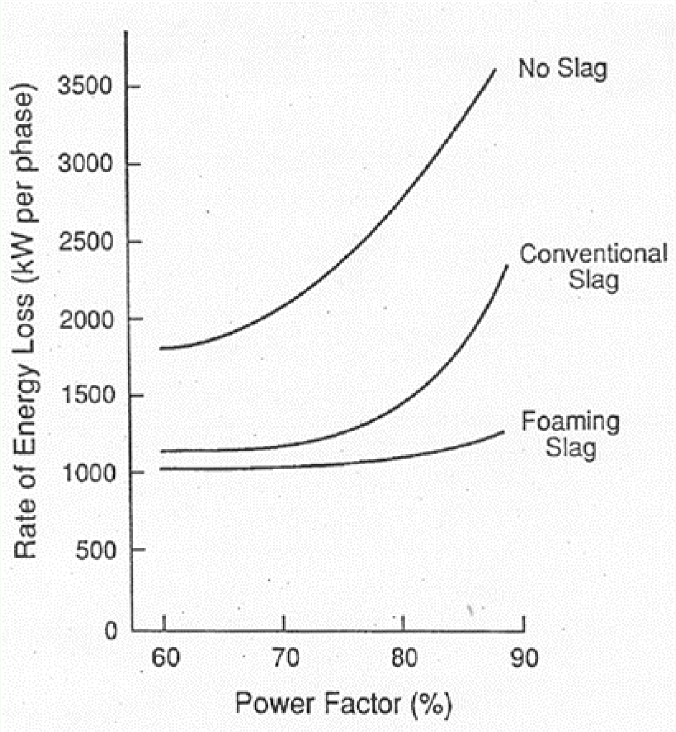


Figure 3. Impact of slag foaming on EAF efficiency (Adapted from Pretorius, 2022).

However, in the case of H_2-DRI, there is no carbon presence in the EAF; therefore, energy saving such as the one seen with CO foam is not achievable when H_2-DRI is used in EAF. In the With Direct Reduction Iron, coke/anthracite is often injected to improve foaming behavior, and biomass can be a good, cleaner candidate for replacement with H_2-DRI.

However, this will require a substantial amount of biomass since, if oxygen rates are maintained during the transition to H_2-DRI to maintain productivity, demand for biocarbon will potentially increase to 20-25 kg per ton of liquid steel.

The demand for U.S. EAFs alone would be around 0.5-1 million metric tonnes (Mt) per year. This is a challenge because the biomass supply chain to support this demand must be further developed (Stewart, 2023).

To analyze the energy balance of the EAF process, both electrical and chemical energy must be considered within the control volume. Higher carbon content in the charge material results in a greater supply of chemical energy to the furnace, as energy is released during the decarburization process. This results in a concomitant decrease in electrical energy requirement. In NG-DRI EAF processes, roughly 30% of the overall energy supplied to the furnace results from the combustion of carbon. In the case of H_2-DRI, no energy is supplied by decarburization, and thus, significantly more electrical energy must be utilized.

Poor slag foaming practices can have negative consequences, including reduced heat transfer from the arc to the molten steel bath, increased refractory wear, increased noise levels, and increased risk of slag spills (Luz et al., 2018).

To address bath mixing and slag foaming issues in H_2-DRI steelmaking, accurate and reliable measurement techniques and modeling applications must be developed and tested to improve the processes (Midrex, 2021).

Solutions

Despite the challenges, a growing body of research on bath-mixing and slag-foaming issues in H_2-DRI steelmaking is essential for developing new technologies and practices to improve performance and efficiency. However, one key solution is the addition of biocarbon or other sources of carbon either during the pre-melting of iron ore before DRI or to the feed at EAF. Adding small but sufficient carbon to the process will remove the bath-mixing and slag-foaming issues.

In addition, the following approaches can help decrease inappropriate H_2 slag foaming and promote mixing (Kirschen et al., 2021; Cavaliere et al., 2022):

- Use of a top lance to inject oxygen and other gasses into the bath
- The use of a bottom stirring system can promote mixing.
- The use of slag modifiers can change and improve the properties of the slag and improve foaming performance
- Effective use of a slag door and hot heel can retain sufficient slag within the EAF to shield the arcs during arcing to a flat bath as in DRI melting

2.4 Control of impurities and production of high-grade steel

Challenges

Producing high-quality steel grades in EAF demands ore-based metallics such as NG-DRI or H_2-DRI to dilute residual elements such as copper and tin in scrap. However, DRI may introduce additional gangue material into the steelmaking process if high-quality iron ore pellets are not used. Specifically for H_2-DRI, the management of nitrogen in steel becomes an issue in steelmaking. Higher impurity levels of lower-grade iron ore can also increase the volume of slag produced. As EAFs are particularly sensitive to ore quality, at high slag volumes, the amount of iron lost to oxidation of impurities will be significant (Figure 4) (Stewart, 2023).

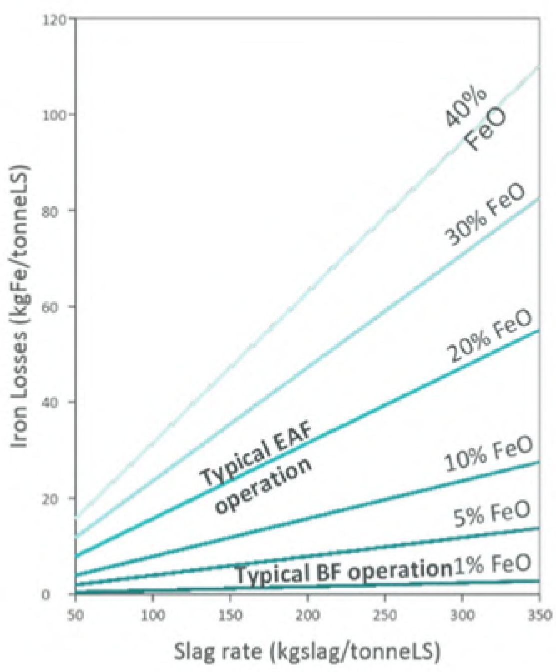


Figure 4: Increased iron losses as a result of a higher slag volume (Stewart, 2023)

Increased slag can also increase slag disposal costs in some cases, particularly in a changing regulatory landscape (Nicholas & Basirat, 2022). In the United States, scrutiny is expected to increase for managing its harmful components. As EAF slag is often sold or given away to be used in landscaping material, as ballast, or as infill for local consumers, losing this disposal avenue with increased slag content may pose an extra challenge (Stewart, 2023).

Using high-quality iron ore reduces these complications; however, limited DR-grade iron ore availability may challenge the global expansion of H_2-DRI steelmaking. **Currently, only about 4% of the global iron supply is DR-grade.** Several initiatives are underway to increase the supply of DR-grade iron ore, access to which is crucial for controlling the complex processes in H_2-DRI steelmaking to ensure a high-quality final steel product (Nicholas & Basirat, 2022).

Solutions

Identification of iron ore grade is important in controlling for impurities. Iron ore can be tested in a laboratory or in a pilot plant. Laboratory ore testing typically involves measuring the content of iron and gangue minerals and the ore's reducibility. Pilot plant testing can determine the performance of ore grades in an H_2-DRI reactor, providing more realistic data on the reduction efficiency and product quality of different grades. Finally, mathematical modeling can simulate the H_2-DRI process and predict the performance of different ore grades. This can be useful for screening different ore grades and identifying the most promising candidates for further physical testing in a lab or pilot plant.

One solution is to analyze the composition of the input and output material both quantitatively and qualitatively in every step of the process from time to time. The quality of iron ore pellets should be carefully controlled at the iron ore mines where palletization is done.

Inputs to H_2-DRI with lower-grade ores can also be modified or upgraded. Beneficiation and blending are methods that allow the production of higher-quality iron ore for inputs to H_2-DRI from lower-grade ores. Beneficiation is the process of upgrading the quality of iron ore by removing the impurities and gangue minerals. There are a variety of methods for beneficiation, including floatation, gravity separation, and magnetic separation. Blending, on the other hand, does not upgrade the low-grade iron ore itself but does combine lower-grade ore with higher-grade, enabling a smaller quantity of potentially costly high-grade ore to be used while still meeting the quality requirements for H_2-DRI steelmaking.

Process modifications and the development of new processes can enable lower-grade iron ore to be suitable for the H_2-DRI steelmaking process without modification to the ore input itself. The DRI and EAF processes can be modified, such as operating the DRI plant at a lower temperature to reduce the amount of impurities produced. Other new processes that use low-grade iron ores more efficiently are being developed. For example, processes are in development that use higher temperatures and/or pressures to improve reduction efficiency in the DRI process (Devlin et al., 2023).

Impurities from the hydrogen itself can also be controlled through the use of high-purity hydrogen, use of advanced process control, and use of advanced melting and finishing technologies such as vacuum degassing, electro-slag remelting, and powder metallurgy (Hoffmann et al., 2020).

2.5 Implications of reduced carbon content on energy use, electrode consumption, and overall EAF operation

Challenges

Carbon utilization in DRI plays a vital role in supplying energy and facilitating essential chemical reactions in steelmaking processes. Traditionally, carbon is instrumental in providing chemical energy, reducing iron oxide in both DRI and slag and inducing slag foaming during EAF operations.

Carbon in DRI is efficient or energetically favorable for a few reasons:

- It releases additional thermal energy upon contact with steel due to its exothermic decomposition as Fe3C. It supplies around 3 kWh/ton of liquid steel additional thermal energy.
- Its presence in dense DRI enables efficient delivery of carbon to the steel-slag interface.
- Combustion of carbon exhibits high efficiency, with approximately 97% of the energy being delivered to the steel bath.

These efficiencies are significant, as the chemical energy package to the EAF can account for over 50% of the total energy delivered to the furnace for DRI-fed EAFs (Stewart, 2023).

Switching to H_2-DRI reduces carbon content (Table 2), leading to an 11% increase in energy demand per ton and an 11% decrease in asset productivity based on chemical energy considerations. In-situ carbon in the iron product is significantly more efficient than externally added carbon, although efficiency levels may vary across different steel plants (Hornby, 2021).

Table 2. MIDREX Natural gas-DRI and H_2-DRI with varying H_2 mixes (Midrex, 2021)

Feed Gas		100% Natural Gas	Natural Gas replacement by Hydrogen			100% Hydrogen
			20%	50%	70%	
Reducing Gas	H_2	55%	62%	72%	77%	100%
	CO	35%	28%	18%	13%	0%
	Others	10% (mostly CO_2, H_2O, CH_4, N_2)				
	H_2/CO	1.6	2.2	4.0	5.9	n/a
Carbon in DRI		2.5% 4% w/ ACT	~1.5%	~1.0%	~0.5%	0%
CO_2 emissions (kg_{CO2} / t_{DRI}) *		500 < 250 w/CCUS **	400	250	150	From heater (if fuled by hydrocarbons)

* only includes CO_2 emissions from flue gas (largest source)
** CCUS = carbon capture for Utilization and Storage

Note: The above table is for the MIDREX technology. The technology from other companies such as ENERGIRON may have different parameters.

Solutions

Given the substantial contribution of chemical energy to EAF operations, maintaining a certain level of carbon in the iron product remains crucial. Following the reduction of iron oxide by carbon in DRI, the subsequent combustion of carbon with injected oxygen or oxygen from FeO in the slag provides additional energy, enhancing overall system efficiency.

Augmenting the carbon content in DRI partially offsets the increased energy demand associated with its melting, improves slag characteristics, and prolongs refractory lifespan. The formation of foam slag via carbon combustion enhances slag quality, reduces electrode degradation, and improves heat transfer efficiency.

Employing off-gas analysis aids in identifying optimization opportunities within the steelmaking process, allowing for adjustments in carbon and oxygen levels. This optimization ensures efficient and cost-effective steel production while maintaining desired quality standards. The evaluation of increasing carbon content in DRI should be conducted on a site-specific basis to maximize benefits in DRI-EAF plants (Hornby, 2021).

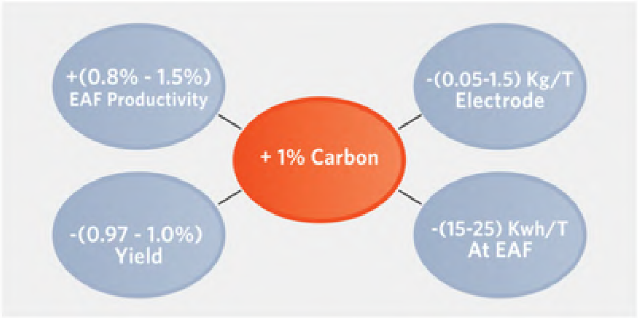


Figure 5: Effect of 1% carbon in DRI on EAF Operations (Sanjal, 2015)

2.6 Melting behavior: higher melt temperatures, slower feeding rates, and potential for icebergs

Challenges

DRI habitually clusters and forms "icebergs" or "ferrobergs" if it is not fed continuously to an EAF. The energy balance and melting behavior determine the maximum feed rate of DRI, as DRI melting is a quasi-steady-state process. The target is to keep the bath temperature roughly steady while allowing DRI to consistently melt without iceberg (Stewart, 2023). Typical DRI feed rates are 30 -40 kg DRI/min/MW or 3-5 tons per minute for a 120 MW furnace. However, the **low carbon content of H_2-DRI impedes smooth melting and can decrease the maximum achievable feed rate**. This decreasing productivity can severely impact energy efficiency, as cooling and off-gas losses to an EAF are 40 MW (Stewart, 2023).

H_2-DRI may also necessitate slower feeding rates of raw materials into the EAF to achieve the necessary temperatures needed for melting. The carbon in NG DRI lowers the melting temperature of the iron. This is not present in H_2-DRI and thus presents the challenge.

Solutions

Due to these challenges, precise control and optimization are critical to reduce icebergs from impurities or incomplete reduction of iron ore and prevent material flow obstruction and disruption to the operation (Hoffmann et al., 2020).

Ensuring a consistent feedstock is a challenging but imperative requirement to meeting emissions regulations while maintaining energy efficiency. Effective control systems and real-time monitoring will be essential for stable operations.

To ensure control and optimization, manufacturers should invest in research and development, optimize processes, implement advanced control systems, and innovate materials (Midrex, 2021).

Key strategies to overcome challenges include:

- Investment in advanced furnace designs optimized for H_2-DRI or preheating raw materials before they enter the furnace. Advanced furnace designs include better insulation, refractory materials, and innovative heating.
- Development and use of high-temperature-resistant refractory materials that can withstand elevated temperatures to extend the lifespan of furnace linings and reduce maintenance costs.
- Investment in efficient material handling systems that can accommodate slower feeding rates without causing bottlenecks or interruptions, such as improved conveyors or feedstock conditioning.
- Implementation of rigorous control measures and real-time monitoring systems to ensure the quality of iron ore and detect for and respond to variations in the process. This may include training operators and staff to effectively manage and troubleshoot the entire process to ensure stable and efficient operation.
- Addition of sufficient biocarbon or other carbon sources to the process.

Collaboration with experts in metallurgy and hydrogen technology is crucial for implementing effective solutions. Continuous adaptation to evolving technologies and regulations is also essential for the success of H_2-DRI in steel manufacturing (Midrex, 2021).

Researchers at Missouri Tech found that the increased turbulence in the bath from C/FeO interaction in pellets greatly improves thermal transfer and thus melting behavior in the bath (Stewart, 2023).

3. Clean Energy Requirement and Infrastructure

This Chapter focuses on the critical aspects of energy requirements and infrastructure development essential for effectively implementing Green H_2-DRI in the steel industry. This chapter discusses the energy-intensive nature of hydrogen production, the challenges of integrating renewable energy sources, and the infrastructural demands for a successful transition to Green H_2-DRI steelmaking. The chapter also explores the logistical considerations for hydrogen storage and transportation, addressing the complexities of ensuring a consistent and reliable supply.

3.1 Energy efficiency of H_2-DRI processes

Challenges

Conventional blast furnace-based ironmaking is more energy-efficient than H_2-DRI because coal and natural gas are better at reducing iron ore than the much lighter hydrogen gas, which requires more energy and heat for the same ore reduction. Energy efficiency improvements will be required, but they often come at a cost, and it can be challenging to balance the need for energy efficiency with economic viability, especially in an already competitive market such as the steel industry (Kurrer, 2020).

It is also less efficient to produce green hydrogen than fossil fuel-based hydrogen production methods. Most hydrogen today is produced through steam methane reforming (SMR), which requires natural gas and releases CO_2. Electrolysis produced from water and renewable energy sources can be much less efficient than SMR, as it involves energy losses of a high enough magnitude to affect the overall efficiency of the green H_2-DRI in steelmaking (U.S. Energy Information Administration, 2023). Hydrogen is also a low-density gas that requires energy-intensive processes, such as compression and liquefaction, to be eligible for transport. It is, therefore, important to minimize energy losses during transport (Hren et al., 2023).

Finally, beyond issues of the hydrogen itself, the DRI process also requires the energy-intensive production of oxygen through methods such as cryogenic air separation. However, it will be challenging to find more energy-efficient ways to generate oxygen.

Solutions

There are several solutions for enhancing the energy efficiency of green H_2-DRI production process, including (Kurrer, 2020; World Steel Association, 2022):

- Utilizing heat and gas recovery systems to capture and reuse heat generated during the DRI process for steam generation, preheating raw materials, or heating other processes.
- Using high-efficiency burners that allow for precise control of the combustion process, reducing energy waste and emissions. This can be coupled with combustion air preheating to further improve efficiency.
- Optimizing the thermal integration of various process stages within the H_2-DRI facility
- Investing in advanced furnace designs that are well-insulated and equipped with efficient heating mechanisms to reduce energy consumption during melting and reduction phases.
- Developing efficient and safe hydrogen storage solutions to ensure a continuous hydrogen supply without energy-intensive fluctuations.
- Utilizing advanced process control systems and real-time monitoring to optimize the H_2-DRI process, adapt to changing conditions, and minimize energy waste.

Implementing these solutions and continually seeking opportunities for improvement is essential for achieving higher energy efficiency in H_2-DRI processes and enhancing the competitiveness of this process.

3.2 Renewable energy options, locations, and transmission infrastructure requirements

Challenges

Green hydrogen production requires substantial electricity, as it takes around 56 kWh of electricity to produce one kg of green hydrogen. Also, it takes around 60 kg of hydrogen to produce one ton of steel with a green H_2-DRI process. Therefore, we would need around 60,000 tonnes of hydrogen for a green H_2-DRI plant that produces 1 Mt of green steel per year. The annual electricity demand to produce this amount of H_2 is around 3,377 GWh/ year, assuming 56 kWh needed per kg of H_2 produced with the electrolyzer efficiency of 70%.

Developing suitable electrolyzers and sufficient amounts of renewable energy is important to the commercial viability of H_2-DRI steelmaking. However, the location and intermittency of renewables and the cost of hydrogen storage solutions present a challenge to economically procuring the electricity and hydrogen needed in green H_2-DRI plants (World Steel Association, 2022).

Generating electricity from prevailing renewable energy technologies such as solar PV or onshore/offshore wind varies across time of day and seasons due to the nature of wind patterns and solar irradiation. As a result, a significant amount of operational storage is needed to use green hydrogen effectively to ensure continuous steel production.

Sufficient hydrogen storage at usage sites will be necessary to provide adequate hydrogen feedstock for the production of DRI. Still, storage systems have capital requirements, increasing the cost of green hydrogen delivered.

Additionally, renewable electricity is often generated in remote locations, far from steelmaking plants, indicating a need for increased electricity transmission and distribution infrastructure to connect these renewable energy sources to steel plants (Strielkowski et al., 2021).

Solutions

The overall expansion of renewable energy production and infrastructure worldwide will make this a more attractive solution for generating sufficient overall renewable energy.

It is ideal for co-locating green hydrogen production facilities with renewable electricity generation near the steel plant. Still, if the RE-H_2 generation site is not close to the steel plant where H_2 will be used, there will be a need for H_2 transport infrastructure.

Implementing hybrid renewable energy systems that combine multiple sources, such as solar, wind, and hydroelectric power, can provide a more consistent and reliable energy supply for green hydrogen production and result in a higher capacity factor. This approach leverages the strengths of different renewable sources, compensating for the intermittency of individual energy types. This hybrid system can be integrated with energy storage solutions like batteries or pumped hydro storage to further enhance reliability and ensure a continuous H_2 supply for the H_2-DRI process.

Upgrading the existing electrical grid with advanced management systems and smart grid technologies can significantly improve the efficiency of renewable energy distribution for green hydrogen production. Smart grids, with real-time monitoring and adaptive response capabilities, can efficiently manage and distribute renewable energy based on demand and supply fluctuations. This includes the ability to reroute power from surplus areas to those with higher demand, optimizing the use of renewable energy for H_2-DRI processes. Additionally, integrating artificial intelligence (AI) and machine learning algorithms can predict energy demand patterns and optimize energy distribution, reducing wastage and improving overall system efficiency.

Underground salt caverns can offer cost-effective storage solutions for hydrogen, but these salt formations are not uniformly available across different regions, and multiple salt caverns may be needed for a single steel plant. Green hydrogen imports will likely be inevitable for some countries with poor renewable energy resources. Still, the higher cost will keep the steel sector a challenging imported hydrogen market (Cho, 2021).

The Swedish HYBRIT project, a joint venture between SSAB, LKAB, and Vattenfall, is an example of an active H_2-DRI steelmaking pilot that uses hydrogen storage to ensure an adequate supply for DRI. The project uses renewable electricity from wind and hydropower to produce hydrogen, then transported to the pilot plant in Luleå, Sweden, for storage and DRI production (HYBRIT, 2023).

3.3 Production of green H_2 and electrolyzer capacity requirements

Challenges

Electrolyzers are still an expensive technology, and the lack of substantial hydrogen supply from the difficulties of scaling up renewables for electrolysis coupled with the substantial energy requirement from DRI poses a challenge for the consistent powering of EAFs. To produce one million tonne of steel annually via green H_2-DRI steel production, around 480-1,280 MW of electrolyzer is needed, depending on the total operational hours of the electrolyzer and the capacity factors of the renewable electricity generation (Figure 6). This poses significant challenges regarding grid capacity constraints and necessitates upgrades to accommodate the required power.

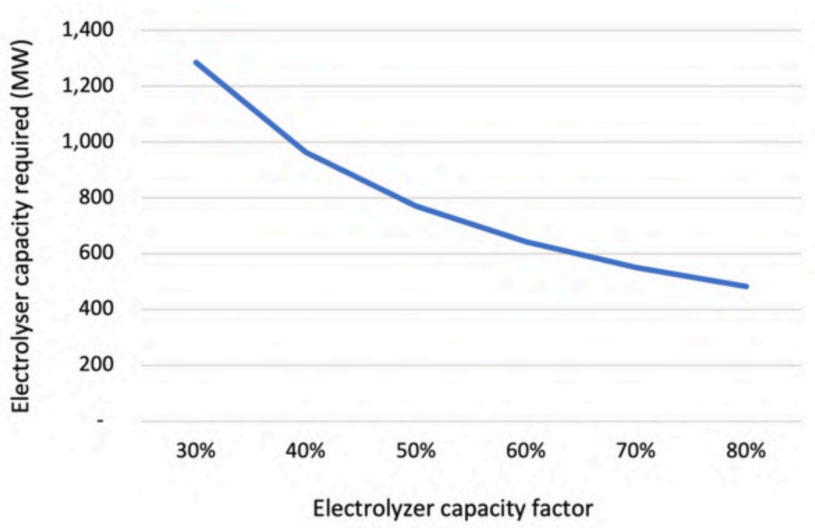


Figure 6: Electrolyzer capacity required to produce H_2 for 1 Mt/year steel with green H_2-DRI process

Note: We assumed 60 kg H_2 is needed per tonne of steel produced 3% we 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%.

Global hydrogen use reached 95 Mt in 2022. Less than 0.1% of global dedicated hydrogen today comes from electrolysis, with 76% and 23% coming from natural gas and coal, respectively. If all current dedicated hydrogen production were produced through electrolysis, there would be an annual electricity demand of 3,600 TWh — more than the electricity generation of the entire EU. By the year 2030, there will be a surge in hydrogen demand, growing by over 1.5 times to surpass 150 million metric tons, of which almost 30% will be attributed to new applications (IEA 2023). Therefore, transitioning the global hydrogen production to green hydrogen represents a significant decarbonization challenge in itself.

Solutions

To address the challenge of expensive electrolyzers, increased investment in research and development is essential. This investment should focus on improving electrolyzer efficiency, reducing manufacturing costs, and enhancing scalability. With successful RD&D, electrolyzer CAPEX is expected to decrease by up to 50% by 2030.

Scaling up renewable energy infrastructure is critical to meet the substantial energy demands of green hydrogen production. Governments and private sector entities should prioritize investments in renewable energy projects, such as solar and wind farms, to ensure an adequate supply of renewable electricity for electrolysis. Additionally, incentives and policies to encourage renewable energy deployment can accelerate this expansion.

Grid capacity constraints pose a significant challenge to electrolyzer deployment. Upgrading grid infrastructure to accommodate the increased power demand from electrolyzers is necessary. This includes investments in grid modernization, grid storage solutions, and smart grid technologies to optimize energy distribution and ensure reliable power supply to electrolysis facilities.

Governments worldwide especially in major steel producing countries should implement supportive policies and regulatory frameworks to incentivize the transition to green hydrogen production. This may include subsidies, tax incentives, carbon pricing mechanisms, and renewable energy mandates to stimulate investment in electrolyzer capacity and renewable energy deployment. Clear and stable policies can provide certainty to investors and drive the growth of green hydrogen markets. In recent years, policies to support green hydrogen has been emerging is some countries such as 45V tax credit in the U.S., India's National Green Hydrogen Mission, EU Hydrogen strategy, China's Green Hydrogen Energy Plan among others.

Clean hydrogen could be produced through other pathways than electrolysis. "Blue" hydrogen from natural gas using steam methane reforming (SMR) or autothermal reforming (ATR) coupled with Carbon Capture and Storage (CCS) are potential alternatives, as they promise around a 95% emissions reduction (Bataille et al. 2021). A similar effect could be achieved using zero-emission nuclear power to supply the electrolyzers. It is unlikely that an H_2-DRI-EAF plant based on renewable hydrogen could operate without some reliance on grid-mix electricity. However, a combination of measures such as small local buffer H_2 storage or battery electric storage of renewable overcapacity can help minimize grid reliance *(Green Hydrogen Market, 2023)*.

3.4 Water demand for electrolysis

Challenges

As electrolysis involves splitting water (H_2O) into hydrogen (H_2) and oxygen (O_2), the process consumes a substantial amount of water in addition to renewable electricity. This is an issue for alkaline electrolysis and proton exchange membrane (PEM) electrolysis, both of which can be water-intensive. Additionally, the quality of water used in electrolysis is essential, as high-purity water is typically required to avoid contamination and degradation of equipment. About 9-11 liters of deionized or demineralized water is required to produce 1kg of hydrogen using electrolysis (Saulnier et al., 2020). This is a challenge for commercial hydrogen production as excessive freshwater consumption can strain local water resources, potentially leading to environmental concerns, particularly in water-scarce regions.

Solutions

Balancing the need for hydrogen production with water conservation is crucial for the sustainability of the H_2-DRI process. Manufacturers must prioritize responsible water management practices while maintaining operation efficiency and viability. The following are areas where solutions could be employed to reduce water consumption (Devlin et al., 2023; KPMG India Services, 2022):

Electrolysis Efficiency

- **Advanced electrolysis technologies:** Water-efficient electrolysis technologies can reduce water used. For example, solid oxide electrolysis cells (SOECs) can operate at high temperatures, potentially reducing water consumption.
- **Improved Electrolysis Inputs:** Improved catalysts and materials in the electrolysis process can reduce the amount of water required to produce hydrogen.
- **Optimized Cooling Systems:** Cooling can also be water-intensive, so using efficient cooling technologies such as air-cooled systems can reduce the electrolysis water footprint.
- **R&D:** Investing in research and development can also be economical to explore new innovative technologies and materials that can further enhance electrolytic water efficiency.

Water Recirculation and Reuse

- Implementing systems for water reuse and recirculation within the electrolysis process can reduce the overall water demand and can be particularly effective in closed-loop systems. This will include purification and treatment systems to ensure re-used water is of high purity.
- If H_2 production is located next to the H_2-DRI plant, the water could be captured and reused after it leaves the DRI furnace shaft (Trollip et al. 2022).

Plant Siting

- **Optimal Plant Locations:** Choosing plant locations in regions with abundant water resources can minimize the impact on local water availability.
- **Regulatory Compliance:** Obtaining permits and approvals for water-intensive operations will ensure compliance with local and national regulations related to water usage and environmental impact, making for more responsible and less burdensome water use for electrolysis.

A detailed feasibility study on specific water consumption and potential water sources for green hydrogen production within the steel sector must be carefully analyzed before transitioning to green hydrogen. This must be carried out during the project feasibility and approval stages, and regional freshwater availability must be considered to assess the impacts of excess water usage by the proposed plants. New steel plants should be approved to become water-neutral by recharging more groundwater than used. Existing plants will need to focus more on water recycling and treatment facilities and invest in systems to store water for future use.

3.5 Storage, transportation, and pipeline for hydrogen

Challenges

As hydrogen is a very light gas, it can be difficult and expensive to transport and store in large quantities. Therefore, it is better to transmit the renewable electricity and produce the green H_2 close to steel plants where it would be used in green H_2-DRI. If H_2 must be transported, the following challenges and solutions may apply.

Currently, bulk hydrogen storage utilizes pressurized tubes at 100 bar, which can be bundled together to meet specific storage volumes. Unlike natural gas, hydrogen storage in pressure vessels demands materials resistant to hydrogen embrittlement and fatigue. As interest in hydrogen supply chains grows, several vendors offer pressure vessel bulk hydrogen storage in pipe bundles for commercial use. Meanwhile, large-scale hydrogen storage is also being implemented in geological formations, with five facilities worldwide using salt caverns and other hard rock formations to store thousands of tonnes of hydrogen at pressures of around 100-200 bar (Mallapragada et al. 2020).

The Hydrogen Europe Backbone report notes challenges for developing pipeline transport, as current operational gas pipeline sizes in Europe vary, ranging from 20-inch to 48-inch diameters or even larger. Energy is transported as a function of the pipe size and applied pressure. For natural gas, a 36-inch diameter pipeline has a transport capacity of around 7GW, whereas a 48-inch diameter pipeline has a transport capacity of 13GW. For hydrogen, this could be optimized to 17GW with higher flow rates of the lighter gas, though increasing flow rates could increase compressor costs (Guidehouse, 2020).

However, it can be difficult to contain hydrogen due to its small molecular size, and specialized infrastructure may need to be developed to enable large-scale distribution. Approximately 5,000 km of hydrogen pipelines are available worldwide, compared to 3 million km for natural gas. Existing high-pressure natural gas transmission pipes could be converted to deliver pure hydrogen in the future if they are decommissioned for natural gas transport, but suitability will vary and need to be assessed on a case-by-case basis, depending on the steel used and the purity of the hydrogen being transported. Transporting hydrogen will also require three times the volume as natural gas, so additional transmission and storage capacity may still be required across the network, even with the repurposing of natural gas pipelines (World Steel Association, 2022).

Solutions

To mitigate challenges associated with hydrogen transportation and storage, establishing green hydrogen production facilities near steel plants should be prioritized. By producing hydrogen close to the point of use, transportation costs and complexities are minimized, promoting cost-effectiveness and logistical efficiency.

However, if H_2 needs to be transported, it will be important to develop logistical solutions to support the distribution and storage of hydrogen, as the hydrogen market is still growing.

Investing in innovative bulk hydrogen storage technologies, such as pressure vessel bundles and geological formations like salt caverns, can address the need for large-scale hydrogen storage (Mallapragada et al. 2020).

There are four appealing options available for hydrogen transport, three of which involve shipping: ammonia, liquid hydrogen, and liquid organic hydrogen carriers (LOHC). The fourth option entails transporting compressed hydrogen via pipelines, either by laying new ones or upgrading existing gas pipelines. Each of these forms have advantages and disadvantages that should be carefully considered (Blanco 2022; IRENA 2022)

Developing hydrogen pipelines optimized for efficient transport is crucial for establishing hydrogen supply chains. While challenges exist in adapting existing gas pipelines, optimizing pipeline sizes and pressures for hydrogen transport can maximize energy transmission capacities while minimizing infrastructure costs, facilitating the widespread distribution of hydrogen.

Exploring the potential repurposing of decommissioned natural gas pipelines for hydrogen transport offers a cost-effective solution. By repurposing existing infrastructure, such as high-pressure transmission pipes, the hydrogen distribution network can be expanded, leveraging existing assets while minimizing the need for extensive new infrastructure development. However, careful consideration must be given to the compatibility of pipeline materials with hydrogen, as hydrogen's small molecular size can cause embrittlement in certain metals.

Figure 10 shows the levelized costs of delivering hydrogen by ship in the form of liquified H_2, ammonia, and LOHC.

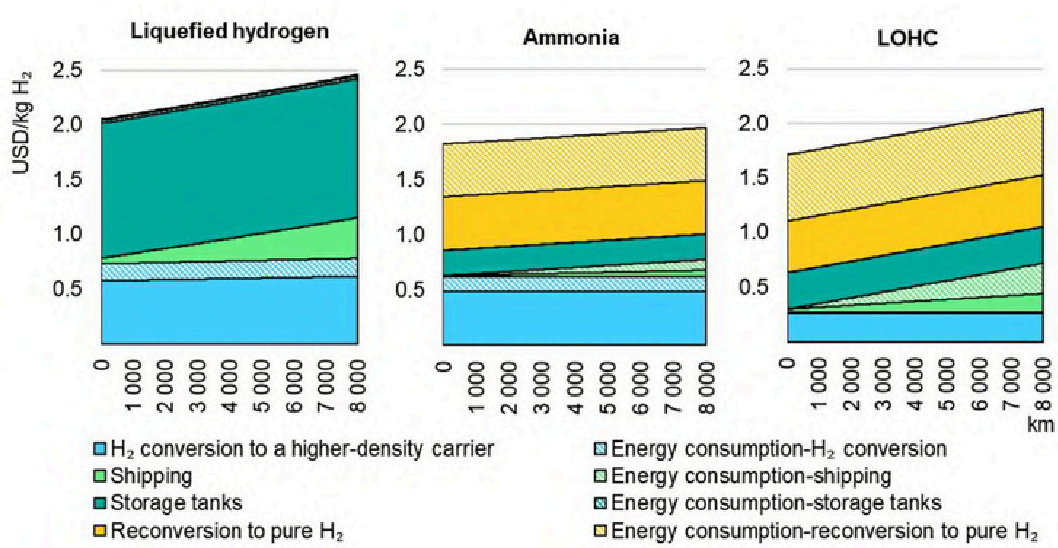


Figure 8. Levelized costs of delivering hydrogen by ship, according to distance (IEA 2023b)

3.6 Storage and transportation of DRI and hot briquette iron (HBI)

Challenges

Iron ore and DRI are heavy and bulky materials, so they can be expensive to transport. Hot briquette iron (HBI) is preferred for long-distance and marine transportation due to its increased stability to oxidation and breakage. DRI is highly reactive, so it is susceptible to oxidation, which can degrade its quality and make it less suitable for steelmaking. Hot briquetting is done to prevent oxidation, and HBI must be stored and transported in a sealed environment with an inert atmosphere. However, the specialized equipment and facilities required to carefully control the conditions to prevent it from oxidizing are not yet widely available for storage and transport (Kinch, 2022). HBI is also sensitive to moisture, which can cause it to rust. To prevent condensation, it must be kept dry during storage and transportation in carefully controlled elevated temperature conditions. However, maintaining the desired temperature requires specialized transportation equipment.

Maintaining these specialized conditions, particularly for heavy and dense material such as HBI, can make transporting difficult and expensive, especially in regions with already limited transportation infrastructure.

Solutions

Some companies are developing new technologies and management strategies for addressing the storage and transportation challenges associated with HBI. These include (Hoffmann et al., 2020 & Kinch, 2022):

- **Packaging:** Some companies are developing new types of packaging for HBI, which can help prevent oxidation and moisture absorption.
- **New Transportation Methods:** Developing new transportation methods such as specialized railcars and ships can overcome HBI transport obstacles.
- **Co-Location of HBI Production and Steelmaking:** Producing HBI closer to the EAFs where it will be used can minimize storage and transportation hurdles by eliminating the need to store and transport HBI.
- **New Storage Methods:** A potential storage solution is to store HBI in sealed silos under an inert atmosphere, such as argon, to prevent exposure to oxygen and moisture. However, this will require a significant investment in new storage facilities.

Such projects are currently in development. The EU-funded H_2Future project is developing a new type of HBI storage silo as well as a new type of HBI railcar that is designed to minimize the risk of damage during transportation, and the Hybrit pilot-scale H_2-DRI plant provides valuable insights into the challenges and opportunities for storing and transporting HBI (HYBRIT, 2023)

4. Regulatory Framework and Standardization

Challenges

As H_2-DRI steelmaking is a new and emerging technology, regulatory and normative challenges need to be addressed before it can be widely adopted. There is a lack of clear and consistent regulations for hydrogen production, use, and safety management, as well as standards and codes for H_2-DRI steelmaking.

In many countries, the regulatory landscape for hydrogen is still evolving, and there is no clear guidance on how hydrogen produced from different sources (e.g., green H_2, blue H_2, grey H_2, etc.) should be regulated. Additionally, many countries offer subsidies for renewable energy projects, but these subsidies are often not yet available for hydrogen production. This can make it difficult for steelmakers to invest in H_2-DRI production, as there is uncertainty in the future regulatory environment and available incentives.

Hydrogen production and use in H_2-DRI steelmaking also present safety challenges that need regulation. Hydrogen has the highest National Fire Protection Association (NFPA) flammability scale rating of 4, meaning it combusts and is flammable even with small amounts of air and at low hydrogen-to-air ratios of 4%. Storage and transportation present special concerns (KPMG India Services, 2022).

Finally, there is a lack of clear and consistent regulations on the use of hydrogen in steelmaking. Many existing steelmaking regulations are based on the traditional BF-BOF and EAF processes, and these regulations may not be suitable for H_2-DRI production, which can increase the risk and safety concerns.

Solutions

Governments worldwide are considering policies and reforms to support the transition to H_2-DRI steelmaking, such as implementing carbon pricing mechanisms, providing financial incentives for green H_2 production and for adopting H_2-DRI-EAF steelmaking, and establishing clear regulations and standards for hydrogen production and steelmaking processes.

- **Carbon Pricing Mechanisms:** Taxation or cap-and-trade programs to make traditional BF-BOF steelmaking more expensive, encouraging the adoption of H_2-DRI steelmaking.
- **Financial Incentives:** Offering tax breaks, grants, or other forms of financial support can reduce the costs of H_2-DRI steelmaking and make it a more attractive alternative to conventional steelmaking. One example would be tax credits for green H_2 production and tax incentives to steel producers investing in green H_2-DRI technology.
- **Renewable Energy Support:** Beyond direct support for H_2-DRI steelmaking, governments can support the development of renewable energy projects to provide a clean and reliable electricity supply. This could include tax credits, feed-in tariffs, and renewable portfolio standards.

- **Regulatory and Normative Solutions:** Developing clear regulations and safety standards for H_2-DRI steel production will help ensure quality, safety, and consistency. In addition, establishing carbon reduction targets for the steel industry or creating green public procurement policies that favor low-carbon steel will provide a clear demand signal to the steel industry for low-carbon steel. For safety standards, this includes regulations on the storage, handling, and transportation of hydrogen.
- **Infrastructure Updates:** Updating safety protocols, risk assessments, and training for handling hydrogen-based systems will help to prevent leaks and ensure safety.

When developing policy reforms, it is important to consider many practical factors, including the availability and cost of hydrogen, grid capacity, and social and economic impacts on workers and communities in the steel industry. By taking a comprehensive approach that addresses all these factors, governments, and industry stakeholders can create a policy environment that effectively utilizes the biggest-impact policy mechanisms to support the adoption of H_2-DRI technology.

5. Stakeholder Engagement and Skill Development

Challenges

Though H_2-DRI steelmaking presents a major opportunity to decarbonize the steel industry and reduce global CO_2 emissions, there is a lack of awareness and understanding of the technology among policymakers and other stakeholders. The steel industry is also very traditional, and so there is resistance to change among some stakeholders. The lack of awareness and resistance can make it difficult to get support for policies promoting this technology.

The adoption of a commercialized H_2-DRI route would require sufficient H_2-DRI technology providers and Original Equipment Manufacturers (OEMs) to facilitate widespread adoption. Currently, only a few OEMs offer H_2-DRI technologies for pilot-scale projects, and the lack of significant technologies and capacities might pose a barrier to widespread adoption of this technology

Additionally, skilling for H_2-DRI operation can be a challenge and an opportunity for the steel industry. A steel sector without current hydrogen consumption has no skill pool to facilitate green hydrogen supply or use within industrial configurations. Therefore, specific training or re-educational programs will be needed for the adoption of H_2-DRI technology, and for the initial development and installation of green hydrogen systems.

However, this allows the creation of new jobs within hydrogen R&D, systems construction, operations, maintenance, transportation, and storage.

Finally, there is a limited push from steel consumers towards decarbonizing the steel sector. The construction, infrastructure, and automobile sectors are the biggest consumers of steel, and they are highly fragmented, representing a low overall push for decarbonization of steel as there is currently limited to no incentive the use of low-carbon steel within these end-use sectors.

Solutions

There is a need for awareness campaigns and educational initiatives targeted at policymakers, stakeholders, and the general public to disseminate knowledge about H_2-DRI technology and its potential benefits for decarbonizing the steel industry. These efforts can help overcome resistance to change and garner support for policies promoting the adoption of this technology.

The investment in the research and development of H_2-DRI technologies should be increased by governments, private companies, and international organizations to accelerate the scalability of this technology. This can involve providing grants, subsidies, or tax incentives to technology providers and Original Equipment Manufacturers (OEMs) to spur innovation and overcome barriers to widespread adoption. Major steel producing countries such as China and India need to develop their domestic capacity for H_2-DRI technology.

Implementing specialized training and skill development programs tailored to the needs of the steel industry is critical. This is to equip workers with the necessary knowledge and expertise for operating H_2-DRI facilities and handling green hydrogen systems. These programs can range from vocational training for technicians to academic courses for engineers and researchers, helping a skilled workforce to support the transition to H_2-DRI steelmaking.

On the steel demand side, collaboration and engagement with major steel-consuming sectors such as construction, infrastructure, and automotive industries is needed to incentivize the use of low-carbon steel and create market demand for H_2-DRI steel products. This can involve partnerships, joint initiatives, and supply chain agreements to integrate sustainability criteria into procurement practices and encourage the adoption of H_2-DRI steel by end-users. For example, H_2 Green Steel, which is building a green H_2-DRI plant in Sweden, signed a 7-year binding agreement for 1.5 billion euros with ZF, a lage supplier to the automotive industry globally. The company has several other such agreements with other companies using steel in their products (H_2 Green Steel 2024).

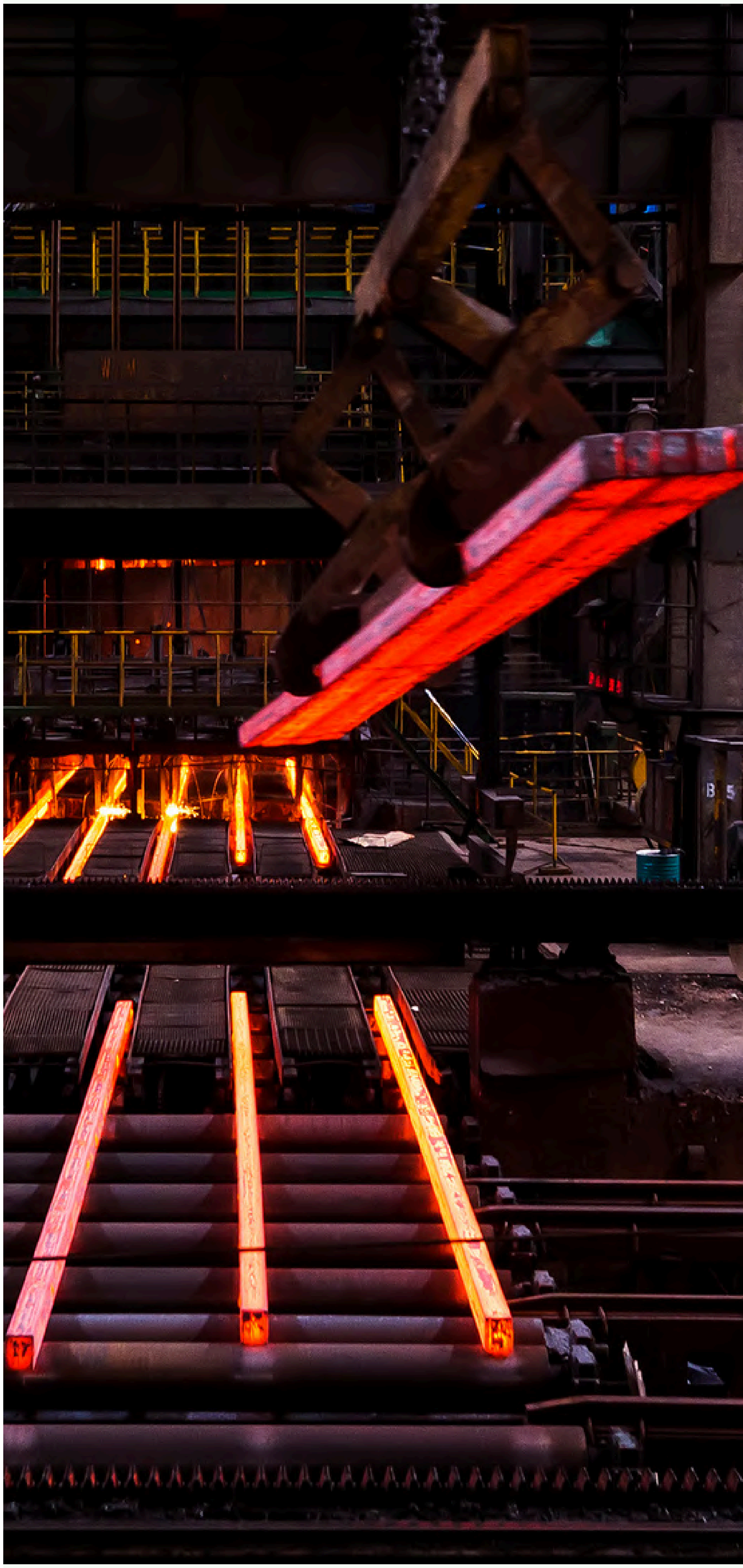
In addition to the private sector, green public procurement policy should be promoted to leverage government's lage purchasing power to increase demand for low-carbon steel and therefore incentivise the adoption of technologies such as H_2-DRI (Hasanbeigi et al 2023, 2022).

Conclusions

This analysis of the transition to green H_2-DRI in steel manufacturing reveals a complex interplay of technical, economic, and regulatory challenges despite the significant climate and environmental benefits. Economically, the high costs associated with hydrogen production and the relative price of renewable electricity compared to fossil fuels emerge as substantial barriers. Technologically, the shift to H_2-DRI introduces complexities in steelmaking processes, including variances in chemical composition and the need for advanced control systems to maintain product quality. The energy-intensive nature of hydrogen production, coupled with the infrastructural demands for renewable energy integration, poses additional challenges.

From a regulatory perspective, the absence of a consistent global framework for hydrogen production, handling, and storage necessitates urgent policy intervention. This is compounded by the lack of sufficient supportive regulatory and policy framework for H_2-DRI and the need for a skilled workforce adept in new technologies.

However, there are solutions to each of these challenges. The transition to H_2-DRI presents an unparalleled opportunity for the steel industry to align with global climate targets. The successful implementation of H_2-DRI technology hinges on addressing these multifaceted challenges through coordinated efforts across various sectors.



Role of Governments: Governments play a crucial role in facilitating the transition to green H_2-DRI steel production. They should prioritize establishing a robust regulatory framework that incentivizes the adoption of H_2-DRI technology. This includes implementing policies such as carbon pricing or other financial mechanisms (e.g., tax incentives and rebates) to make green H_2-DRI steel production economically viable and providing subsidies or tax incentives for renewable energy sources. Investment in infrastructure, particularly for renewable energy generation and hydrogen distribution, is crucial. Governments should also foster international cooperation to standardize regulations and share best practices, ensuring a cohesive global approach to green H2-DRI steel production.

Role of the Steel Industry: The steel industry must proactively embrace innovation and invest in research and development to overcome the technical challenges associated with H_2-DRI. This includes refining the DRI-EAF steelmaking process to accommodate hydrogen as a reducing agent and investing in this technology. The industry should engage in collaborative projects and partnerships to leverage collective expertise and resources. Pilot projects are essential for testing and demonstrating the feasibility of H_2-DRI on a commercial scale. Several such large-scale H_2-DRI projects are already under construction, and more are announced. The industry must also actively participate in policy discussions to ensure that regulatory frameworks are aligned with practical realities and technological capabilities.

Role of Other Stakeholders: Educational institutions should develop specialized training programs to prepare a workforce skilled in H_2-DRI technology. Non-governmental organizations, industry associations, and the media play a critical role in raising awareness about the benefits of green H_2 DRI steelmaking, thereby generating demand for low-carbon steel. Financial institutions and investors can support the transition by funding green H_2-DRI steel plants. End-users and consumers should be encouraged to prefer products made with low-carbon steel, creating a market-driven push for green steel produced by the H_2-DRI technology.

References

- 100%RE Map. (2023). Green Hydrogen Market: Potentials and Challenges. https://100re-map.net/green-hydrogen-market-potentials-and-challenges/
- Bararzadeh Ledari, M., et al. (2023). Greening steel industry by hydrogen: Lessons learned for the developing world. International Journal of Hydrogen Energy. https://www.sciencedirect.com/science/article/pii/S0360319923029178?via%3Dihub
- Bataille, C.; Neff, J.; Shaffer, B. (2021). "The Role of Hydrogen in Canada's Transition to Net-Zero Emissions." The School of Public Policy Publications, Volume 14:30, November 2021.
- Bhaskar, A., et al. (2021). Decarbonization of the Iron and Steel Industry with Direct Reduction of Iron Ore with Green Hydrogen. Energies, 13(3), 758. https://www.mdpi.com/1996-1073/13/3/758
- Bhaskar, A., et al. (2022). Decarbonizing primary steel production: Techno-economic assessment of a hydrogen-based green steel production plant in Norway. Journal of Cleaner Production, Volume 350, 131339. https://www.sciencedirect.com/science/article/pii/S0959652622009659?via%3Dihub
- Blanco, Herib (2022). "What's Best for Hydrogen Transport: Ammonia, Liquid Hydrogen, LOHC or Pipelines?" May 5, 2022.
- Cavaliere, P., et al. (2022). Integration of Open Slag Bath Furnace with Direct Reduction Reactors for New-Generation Steelmaking. Metals, 12(2), 203. https://www.mdpi.com/2075-4701/12/2/203
- Chang, Y., et al. (2023). Influence of hydrogen production on the CO2 emissions reduction of hydrogen metallurgy transformation in iron and steel industry. Energy Reports, Volume 9, December 2023, Pages 3057-3071. https://www.sciencedirect.com/science/article/pii/S2352484723000914?via%3Dihub
- CHO, R. (2021). Why We Need Green Hydrogen. https://news.climate.columbia.edu/2021/01/07/need-green-hydrogen/
- Denholm, P., et al. (2022). Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035. Golden, CO: National Renewable Energy Laboratory. NREL/TP 6A40-81644. https://www.nrel.gov/docs/fy22osti/81644.pdf
- Devlin, A., et al., (2023). Global green hydrogen-based steel opportunities surrounding high-quality renewable energy and iron ore deposits. https://www.nature.com/articles/s41467-023-38123-2
- Direct from Midrex (2021). 1st quarter. https://www.midrex.com/
- DNV, 2022. Hydrogen forecast to 2050. https://www.dnv.com/focus-areas/hydrogen/forecast-to-2050.html
- Ghosh, A.M., Vasudevan, N., & Kumar, S. (2021). Compendium: Energy-efficient Technology Options for Direct Reduction of Iron Process (Sponge Iron Plants). New Delhi: The Energy and Resources Institute. https://www.teriin.org/sites/default/files/2021-08/Direct%20Reduction%20of%20Iron%20Process.pdf

- Green Steel for Europe Consortium. (2021). Technology Assessment and Road Mapping (Deliverable 1.2).
- Guidehouse. (2020). European Hydrogen Backbone: How a dedicated hydrogen infrastructure can be created. Utrecht: Gas for the climate.
- H2 Green Steel (2024). Latest News. https://www.h2greensteel.com/latestnews
- Hasanbeigi, A. (2022). Steel Climate Impact - An International Benchmarking of Energy and CO2 Intensities. Global Efficiency Intelligence. Florida, United States.
- Hasanbeigi, Ali; Bhadbhade, Navdeep (2023). Green Public Procurement of Steel in India, Japan, and South Korea. Global Efficiency Intelligence, LLC.
- Hasanbeigi, Ali; Shi, Dinah; Bhadbhade, Navdeep (2022). Advancing Buy Clean Policy in Canada. Global Efficiency Intelligence, LLC.
- Hoffmann, C., et al. (2020). Decarbonization challenge for steel. McKinsey & Company. https://www.mckinsey.com/industries/metals-and-mining/our-insights/decarbonization-challenge-for-steel
- Hornby, S. (2021). Hydrogen-Based DRI EAF Steelmaking - Fact or Fiction. https://imis.aist.org/store/detail.aspx?id=PR-382-024
- Hren, R., et al. (2023). Hydrogen production, storage and transport for renewable energy and chemicals: An environmental footprint assessment. Renewable and Sustainable Energy Reviews, Volume 173, 113113. https://www.sciencedirect.com/science/article/pii/S1364032122009947?via%3Dihub
- HYBRIT Development. (Year). HYBRIT - Zero carbon steel. https://www.hybritdevelopment.se/en/
- Hydrogen explained. (2023). U.S. Energy Information Administration. https://www.eia.gov/energyexplained/hydrogen/production-of-hydrogen.php
- IEA, (2023). Hydrogen. Available at https://www.iea.org/energy-system/low-emission-fuels/hydrogen
- IEA. (2019). The Future of Hydrogen. https://www.iea.org/reports/the-future-of-hydrogen
- IEA. (2020). Iron and Steel Technology Roadmap. https://www.iea.org/reports/iron-and-steel-technology-roadmap
- IEA. (2023a). Hydrogen. https://www.iea.org/energy-system/low-emission-fuels/hydrogen
- IEA. (Year). Electrolysers. https://www.iea.org/energy-system/low-emission-fuels/electrolysers
- IEA (2023b). Energy Technology Perspectives 2023.
- IEEFA. (2022). Iron Ore Quality a Potential Headwind to Green Steelmaking. https://ieefa.org/resources/iron-ore-quality-potential-headwind-green-steelmaking-technology-and-mining-options-are
- ING. (2023). Hydrogen sparks change for the future of green steel production. https://www.ing.com/Newsroom/News/Hydrogen-sparks-change-for-the-future-of-green-steel-production.htm

- IRENA (2022). Global Hydrogen Trade to Meet the 1.5°C Climate Goal Part II: Technology Review of Hydrogen Carriers.
- IRENA. (2016). Global Hydrogen Trade to Meet the 1.5°C Climate Goal: Technology Review of Hydrogen Carriers.
- IRENA. (2020). Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5⁰C Climate Goal. International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pdf
- IRENA. (2021). Making the breakthrough: Green hydrogen policies and technology costs. International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/-//-/media/Files/IRENA/Agency/Publication/2020/Nov/IRENA_Green_Hydrogen_breakthrough_2021.pdf?la=en&hash=40FA5B8AD7AB1666EECBDE30EF458C45EE5A0AA6
- Ito, A., Langefeld, B., & Götz, N. (2020). The future of steelmaking – How the European steel industry can achieve carbon neutrality. Roland Berger GmbH, Munich.
- Kinch, D. (2022). Direct-reduced iron becomes steel decarbonization winner. https://www.spglobal.com/commodityinsights/en/market-insights/blogs/metals/062222-dri-steel-decarbonization-direct-reduced-iron
- Kirschen, M., et al. (2021). Process Improvements for Direct Reduced Iron Melting in the Electric Arc Furnace with Emphasis on Slag Operation. Processes, 9(2), 402. https://www.mdpi.com/2227-9717/9/2/402
- KPMG India Services. (2022). Green Hydrogen Opportunities and Roadmap for India, White Paper –Steel sector.
- Kurrer, C. (2020). The potential of hydrogen for decarbonising steel production. European Parliamentary Research Service, Scientific Foresight Unit (STOA). https://www.europarl.europa.eu/RegData/etudes/BRIE/2020/641552/EPRS_BRI(2020)641552_EN.pdf
- Luz, A. P., et al. (2018). Slag foaming practice in the steelmaking process. Ceramics International, Volume 44, Issue 8, Pages 8727-8741. https://www.sciencedirect.com/science/article/pii/S0272884218305005?via%3Dihub
- Mallapragada, D. S., Gençer, E., Insinger, P., Keith, D. W., & O'Sullivan, F. M. (2020). Can Industrial-Scale Solar Hydrogen Supplied from Commodity Technologies Be Cost Competitive by 2030? Cell Reports Physical Science, 1(9), 100174. https://doi.org/10.1016/j.xcrp.2020.100174
- Müller, N., et al. (2021). Assessment of fossil-free steelmaking based on direct reduction applying high-temperature electrolysis. Cleaner Engineering and Technology, Volume 4, October 2021, 100158. https://www.sciencedirect.com/science/article/pii/S266679082100118X?via%3Dihub

- Nicholas, S., & Basirat, S. (2022). Iron ore quality a potential headwind to green steelmaking – Technology and mining options are available to hit net-zero steel targets. Institute for energy economics and financial analysis. https://ieefa.org/resources/iron-ore-quality-potential-headwind-green-steelmaking-technology-and-mining-options-are
- Patisson, F., & Mirgaux, O. (2020). Hydrogen Ironmaking: How It Works. Metals, 10(7), 922. https://www.mdpi.com/2075-4701/10/7/922
- Pawelec, G., & Fonseca, J. (2022). Steel from Solar Energy - A Techno-Economic Assessment of Green Steel Manufacturing. Available at Hydrogen Europe
- Perpiñán, J., et al. (2023). Technical and economic assessment of iron and steelmaking decarbonization via power to gas and amine scrubbing. Energy, Volume 276, 127616. https://www.sciencedirect.com/science/article/pii/S0360544223010101?via%3Dihub
- Pretorius, E. 2022. Electric Steelmaking Fundamentals. Association for Iron & Steel Technology (AIST).
- Pye, S., et al. (2022). Regional uptake of direct reduction iron production using hydrogen under climate policy. Energy and Climate Change, Volume 3, 100087. https://linkinghub.elsevier.com/retrieve/pii/S2666278722000174
- Rechberger, K., et al., (2020). Green Hydrogen-Based Direct Reduction for Low-Carbon Steelmaking. https://onlinelibrary.wiley.com/doi/10.1002/srin.202000110
- Rosnera, F., et al. (2023). Green steel: design and cost analysis of hydrogen-based direct iron reduction
- ROLAND BERGER GMBH. (2020). The future of steelmaking – How the European steel industry can achieve carbon neutrality.
- Samadi, S., et al. (2023). The renewables pull effect: How regional differences in renewable energy costs could influence where industrial production is located in the future. Energy Research & Social Science, Volume 104, 103257. https://www.sciencedirect.com/science/article/pii/S2214629623003171
- Sanjal, S. (2015). The Value of DRI – Using the Product for Optimum Steelmaking. https://www.midrex.com/tech-article/the-value-of-dri-using-the-product-for-optimum-steelmaking/
- Saulnier, R.; Minnich, K.; Sturgess, P. K. (2020). "Water for the Hydrogen Economy." WaterSMART Solutions Ltd., November 2020.
- SSAB. (Year). HYBRIT – A new revolutionary steelmaking technology. https://www.ssab.com/en/fossil-free-steel/insights/hybrit-a-new-revolutionary-steelmaking-technology
- Stewart, D. J. C. (Year). H2DRI-EAF – Technical Challenges and Roadblocks.
- Strielkowski, W., et al. (2021). Renewable Energy in the Sustainable Development of Electrical Power Sector: A Review. Energies, 14(24), 8240. https://www.mdpi.com/1996-1073/14/24/8240

- Trollip, H., McCall, B., & Bataille, C. (2022). How green primary iron production in South Africa could help global decarbonization. Climate Policy, 22(2), 236–247. https://doi.org/10.1080/14693062.2021.2024123
- US DOE. (2023). Hydrogen Production: Electrolysis. Office of Energy Efficiency & Renewable Energy. https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis
- Vogl, V., et al. (2021). Phasing out the blast furnace to meet global climate targets. Joule, 5, 2646–2662. https://www.cell.com/joule/fulltext/S2542-4351(21)00435-9?_returnURL=https%3A%2F%2Flinkinghub.elsevier.com%2Fretrieve%2Fpii%2FS2542435121004359%3Fshowall%3Dtrue
- Wang, R. R., Zhao, Y. Q., Babich, A., Senk, D., & Fan, X. Y. (2021). Hydrogen direct reduction (H-DR) in steel industry—An overview of challenges and opportunities. Journal of Cleaner Production, Volume 329. https://www.sciencedirect.com/science/article/pii/S095965262103972X?via%3Dihub
- World Steel Association. (2022). Fact sheet, Hydrogen (H2)-based ironmaking.
- Yadav, D., Guhan, A., & Biswas, T. (2021). Greening Steel: Moving to Clean Steelmaking Using Hydrogen and Renewable Energy. New Delhi: Council on Energy, Environment and Water.
- Yongjuan, T. (2018). Water consumption and wastewater discharge in China's steel industry. https://www.researchgate.net/figure/Iron-and-steel-production-and-its-water-flow-processes_fig2_328951354
- Zhou, Y., et al. (2021). Application of submerged gas-powder injection technology to steelmaking and ladle refining processes. Powder Technology, Volume 389, Pages 21-31. https://www.sciencedirect.com/science/article/pii/S0032591021003946?via%3Dihub

List of Acronyms

- **AE:** Alkaline Electrolyzer
- **BF:** Blast Furnace
- **BF-BOF:** Blast Furnace-Basic Oxygen Furnace
- **CAPEX:** Capital Expenditure
- **CCS:** Carbon Capture and Storage
- **CO:** Carbon Monoxide
- **CO2:** Carbon Dioxide
- **DR:** Direct Reduction
- **DRI:** Direct Reduced Iron
- **EAF:** Electric Arc Furnace
- **EU:** European Union
- **FS:** Foamy Slag
- **H2:** Hydrogen
- **H2-DRI:** Hydrogen Direct Reduced Iron
- **HBI:** Hot Briquetted Iron
- **KPI:** Key Performance Indicator
- **LOHCs:** Liquid Organic Hydrogen Carriers
- **MW:** Megawatt
- **NG:** Natural Gas
- **NFPA:** National Fire Protection Association
- **OEMs:** Original Equipment Manufacturers
- **OG:** Oxygen Converter Gas Recovery System
- **OGA:** Off-Gas Analysis
- **PEM:** Proton Exchange Membrane
- **PEMFC:** Proton Exchange Membrane Fuel Cell
- **PI:** Partially Reduced Iron
- **POT:** Power on Time
- **PV:** Photovoltaic
- **R&D:** Research and Development
- **RED II/III:** Renewable Energy Directive II/III
- **SMR:** Steam Methane Reforming
- **SOECs:** Solid Oxide Electrolysis Cells
- **TTT:** Tap to Tap
- **VIU:** Value-in-Use