WORKSHOP ON HYDROGEN UTILIZATION IN IRON- AND STEELMAKING AT THE 2024 AIST EUROPEAN STEEL FORUM

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Background

On 7 November 2024, international leaders in efficient iron- and steelmaking convened in Essen, Germany, to participate in a workshop on hydrogen utilization. The event was connected to the 2024 European Steel Forum. The Association for Iron & Steel Technology (AIST) Roadmap for Iron and Steel Manufacturing: Revolutionizing U.S. Global Leadership for a Sustainable Industrial Supply Chain provided the framework to create a successful workshop focusing on impactful areas of the iron and steel industry. The AIST Roadmap addresses high-priority challenges in steel manufacturing that are broadly deployable to a diverse set of manufacturing sectors. It focuses on four technology themes: (1) material and energy optimization, (2) electrification of iron and steel processes, (3) alternative low-carbon reductants and energy sources, and (4) carbon capture, utilization and storage. The Clean Hydrogen for Clean Steel Workshop focused on the third technology theme within the AIST Roadmap. The National Renewable Energy Laboratory (NREL) and the U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office (HFTO) cohosted the workshop, providing expertise on hydrogen generation, storage and utilization.

The event was motivated by the many challenges facing the iron and steel industry today, including declining iron ore quality, contamination of steel scrap with detrimental nonmetallic and nonferrous metals, supply chain disruptions, operational and capital expenditure requirements, and regional decarbonization policies. Although no single solution will address all challenges, a broad portfolio of emerging technologies may help support continued growth of the sector. Among these emerging technologies are several hydrogen-based approaches. These approaches could facilitate utilization of regional energy resources, resulting in globally competitive material processing.

The objectives of this workshop were to:

- Assess the state of the art for iron reduction using hydrogen.
- Discuss operational requirements and lessons learned from demonstrations.
- Understand current technology gaps and identify collaborative research and development (R&D) opportunities.
- Facilitate collaboration and cooperation in the development and demonstration of related technologies.
- Accelerate commercialization through technology demonstration in real-world operating conditions.

Participants of the workshop were asked to provide input on the following high-level questions:

- What are key R&D questions that must be solved to deploy hydrogen-based technologies?
- How can a working group/stakeholders move the needle for the industry?
- Are there technology gaps or technologies that have not yet been demonstrated that are needed to reduce risk of commercialization of hydrogen-based technologies?

Workshop Introduction

The workshop started with three introductory presentations, including:

- "Welcome and Introduction," by Rebecca Erwin and Tomas Green, HFTO.
- "AIST Perspective," by Ron Ashburn, AIST.
- "Hydrogen Solutions for the Steel Industry," by Mike Grant, Air Liquide.

In the welcome and introduction, the role of hydrogen as a key element for achieving steel sector goals, job growth, energy security and resilience was highlighted. A pathway for hydrogen utilization in 10–20% of steelmaking by 2050 was discussed. This percentage would translate to about 1–3 million metric tons (MMT)/year of hydrogen demand.[1] The portfolio of iron- and steel-related projects supported by the U.S. Department of Energy was discussed, including projects funded by

[1]The lower end of this estimate assumes production of 120 million metric tons (MMT) of steel per year in 2050, consistent with the U.S. Department of Energy's Industrial Decarbonization Roadmap (2022; https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf). The higher end assumes production of 130 MMT steel per year to enable exports of 8% of U.S. steel production, consistent with current practice (International Trade Administration, "Global Steel Trade Monitor – Steel Exports Report: United States," Washington, D.C., May 2020. https://legacy.trade.gov/steel/countries/pdfs/exports-us.pdf).

the Industrial Technologies Office and the Advanced Research Projects Agency-Energy (ARPA-e).

Ron Ashburn, AIST's executive director, provided an overview of the global steel landscape, discussing future challenges and opportunities for efficient manufacturing. He opened with current and projected global steel demand. In 2023, 1,892 MMT of steel was produced globally, where the input materials comprised of 14.7% scrap, 26.1% metallurgical coal and 59.2% iron ore. Steel production is projected to increase to 2,459.6 MMT by 2050.

Ashburn also reviewed the current steel process routes, global energy consumption and global electricity demand. He identified a significant gap in renewable electricity generation versus current energy demand. Future targets for electrolytic hydrogen production are ambitious, and there is some concern of impairing competitive industries and creating new dependencies. Further work is needed to understand how to calibrate market incentives for renewable hydrogen and prioritize scarce funding and determine on which parts of the value chain to focus.

Ashburn highlighted energy infrastructure and the automotive sector as expanding market opportunities for steel. Specifically, he focused on the need to produce lightweight vehicle bodies, battery support and protection, electric motors, and charging infrastructure. He pointed out that energy production and transport are steel-intensive — 65 tons of steel is needed per mile of power line. These markets have the potential to play a critical role by signing offtake agreements for steelmakers adopting new hydrogen-based technologies.

He also highlighted that production is declining in many regions, such as the European Union and United States. Steel production in these regions has not returned to pre-Great Recession levels, and imports continue to increase market share. Ashburn indicated that these regions would need a path to protect their industrial base, and hydrogen-based steel production could be an answer. It would allow increased competitiveness with Asian markets and further utilization of regional resources.

In the workshop plenary, Mike Grant, global technology director of steel production at Air Liquide, reviewed hydrogen integration strategies for steel. He highlighted 1,850 km of existing hydrogen pipelines, emphasizing that the expertise to transport hydrogen exists but needs to be expanded further. Grant then detailed the opportunities and challenges associated with using hydrogen as a reductant. He showed that direct reduction of iron based on 100% electrolytic hydrogen is an option for DRI production; however, the resulting hydrogen direct reduced iron (DRI) must be treated differently in downstream processing. The presence of carbon in iron is essential for processing in electric arc furnaces (EAFs). Hydrogen-based direct reduction must be accompanied by a high-efficiency carbon injection system to carburize the steel bath to provide chemical energy to the EAF process. Grant highlighted the development of a high-efficiency carbon injection system as a key part of the equation for ensuring the success of hydrogen-based steelmaking routes.

Breakout Sessions and Discussions

Following the presentations, the workshop involved four roundtable discussions as described in Table 1.

Direct Reduced Iron and Balance of Plant

Although the reducing gas used in direct reduction is generally derived from natural gas, the reducing syngas itself includes carbon monoxide and, critically, hydrogen. Shifting the composition of this gas toward hydrogen, or replacing it with 100% hydrogen is possible, and would produce water as a byproduct after reduction.

In the workshop discussion, a consensus was reached that the primary open technical challenges for hydrogen DRI include thermal management and carburization. Although the traditional natural-gas-based direct reduction process is exothermic, the reaction of iron ore with

Table 1. Breakout Session Structure

Session name	Topics discussed
Direct Reduced Iron and Balance of Plant	Hydrogen direct reduction of iron (DRI) and CO foaming in the electric arc furnace; iron ore quality and iron content; alternate hydrogen reduction technologies to hydrogen DRI; customer willingness to pay a premium for hydrogen-based technology
Smelting Furnaces	Electric smelting furnace (ESF) demonstration and economy of scale; integrating fluidized bed reactors with ESFs; evaluating the impacts of hydrogen DRI in ESFs; required carbon content of ESFs; carburization of hydrogen DRI inside the furnace
Hydrogen Integration	Hydrogen availability and storage; safety risks associated with hydrogen; hydrogen embrittlement and cracking in steel pipes and vessels; reforming the direct reduction process from natural gas to hydrogen
Ore Quality	Quality of ore from various bodies, including metallurgical end uses; beneficiation processes, including both chemical and physical methods; gangue content and handling

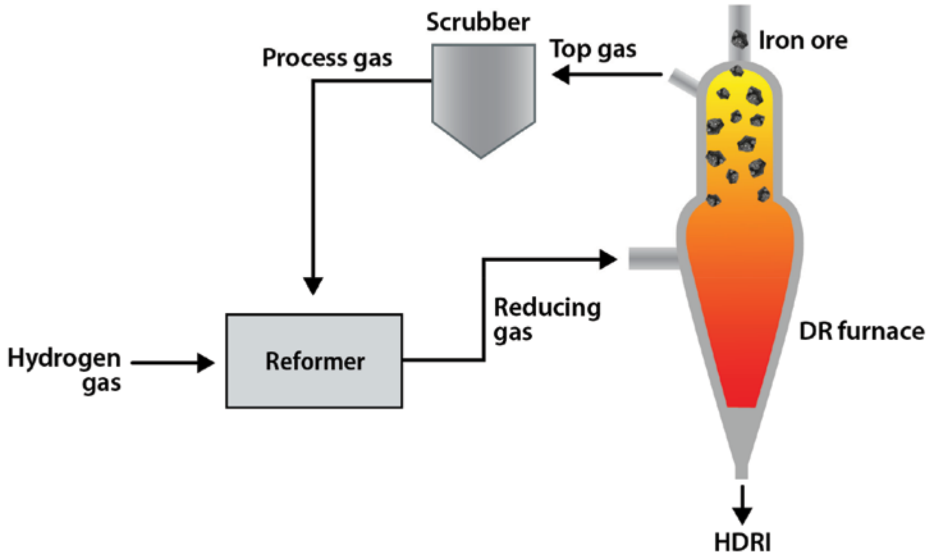

Figure 1. Schematic of integration of hydrogen into direct reduction processes. The reducing gas already contains hydrogen; therefore, introducing more hydrogen is feasible but raises challenges, including those related to thermal management. Image from National Renewable Energy Laboratory.

hydrogen is endothermic. Therefore, thermal management strategies must be developed specific to hydrogen direct reduction of iron (H_2DRI). The product of H_2DRI is not carburized (does not contain carbon). Therefore, the energy requirement of melting H_2DRI is higher than natural-gas-based DRI products, but consequences arise in subsequent processing steps. The iron produced by the direct reduction process is often fed into EAFs. The low carbon content of H_2DRI affects melting properties as it melts at a higher temperature. It also affects the energy balance of EAF operation as a significant percentage of energy is supplied by carbon combustion and slag foaming to protect the refractory and electrodes and ensure correct composition of the melt.

It was noted that the absence of carbon in H_2DRI can suppress CO foaming in the EAF, making it difficult to effectively stir the melt and remove contaminants like nitrogen. Although it was agreed that carburization is important, the best method for carburization of H_2DRI was identified as an open question. Discussion focused on supplemental carburization in the H_2DR furnace now versus later in the EAF. Although carburization makes sense in the direct reduction process that includes natural gas, adding natural gas to H_2DR that uses pure hydrogen for reduction may not be desirable. However, adding carbon to the EAF may not alleviate problems associated with H_2DRI melting, and could interfere with the balance of charge carbon and carbon injection necessary to ensure efficient EAF operation. The lack of one clear pathway confirms that a single solution may not be necessary, and that different methods may be preferable in different scenarios. Depending on the intended downstream processes and the grade of iron ore, carburization could be accomplished using a variety of methods.

Iron ore quality and content were identified as potential key challenges. The supply chain for direct reduction pellets is becoming increasingly constrained. However, it may be possible to use blast furnace (BF)-grade pellets rather than direct reduction pellets for H_2DR. To date, insufficient evidence exists to determine conclusively that

BF-grade pellets are adequate for H_2DRI. Specifically, there was debate whether and how gangue affects metallization, especially as the increased slag formation will limit diffusion of hydrogen during the reducing process. The group identified this as an area for further study. Open questions exist regarding the use cases and quality of the final product, as it may be difficult to achieve low nitrogen and low carbon content using H_2DRI, and adaptation in metallurgy is needed.

Different hydrogen reduction reactor configurations were also discussed. Fluidized bed reactors have technical challenges, including the tendency to form sticking and agglomeration of particles and maintaining the fluidized bed due to recirculation. With hydrogen, there is an opportunity to operate under lower temperatures in fluidized bed direct reduction reactors, as the ideal reaction temperatures are different. Vertical shaft furnaces also have challenges including sticking and thermal management. Plasma technology, which is a lower technology readiness level than production of H_2DR, overcomes many of the thermal challenges of H_2DR. There are research studies that indicate this technology can achieve a higher metallization rate than H_2DR, as plasma recombines to gas and creates heat. However, challenges in scaling plasma technologies remain. The identified challenges with plasma recirculation involve how to both maintain temperature and separate water vapor from the process.

Process integration and utilization of hydrogen throughout the plant was evaluated as an opportunity. It was generally agreed that hydrogen should be prioritized for reduction, not as fuel for heating. Purposefully making hydrogen for burning was not regarded as ideal, but it was noted that it may be worthwhile in the case that excess hydrogen is available. If an alternative fuel is sought, biogas was considered a better option than hydrogen for heating purposes. This fuel could also be used elsewhere in the steel value chain (e.g., for mining fleets and warehouses). Induction melting is also a viable alternative to combustion in some cases, and prioritization of electrification within reason, accounting for stress on the grid, was generally viewed favorably. However, refractory technology needs to further be adapted to induction melting practices.

The use of oxygen from electrolytic hydrogen production was identified as an opportunity. Oxygen could not only help offset the costs of hydrogen production but also be integrated with existing steelmaking processes, such as coke plants. Thermal integration with a solid oxide electrolyzer is another promising technology. A key challenge is top gas cleaning with various methods, including removing impurities like sulfur, CO and water from the hydrogen gas.

Finally, the group discussed the customer perspective and willingness to pay a premium for hydrogen-based technology. There was no consensus on customer willingness to pay for products made with hydrogen. Those who did not see a premium price as likely identified too many steps in the value chain to accommodate a premium. The group also identified consumer distrust in alternative steel production technologies: mass balances do not always alleviate the end user's concerns about new processes, and it was emphasized that a direct relationship with the end user is important for transparency.

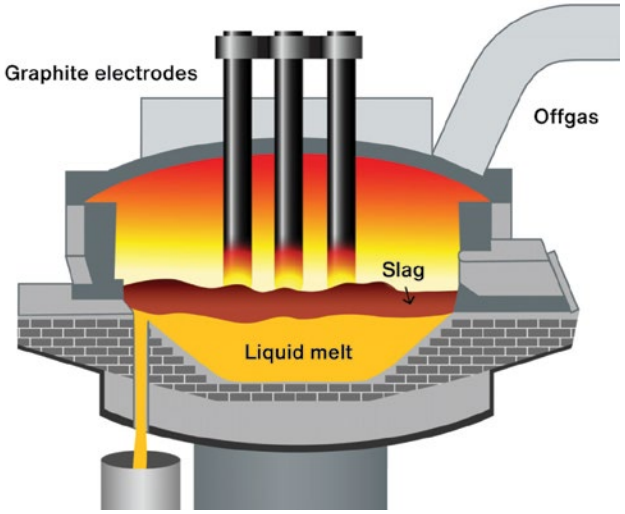

Figure 2. Electrified furnaces may play a significant role in processing iron reduced using hydrogen. Image from National Renewable Energy Laboratory.

Smelting Furnaces

EAFs can melt different charge mixes of scrap and DRI/hot briquetted iron for steelmaking but was not specifically designed for 100% DRI/hot briquetted iron charge. Many impurities present in the iron ore pellets remain through the DRI process, resulting in potentially higher gangue content in the EAF. One possible side effect of the H_2DRI–EAF route is the need to manage higher gangue in the charge, which may result in larger slag volume, higher energy consumption, and a reduction in process yield.

The ESF was identified as a key technology of interest by participants. ESFs have proven the ability to process a variety of feed materials and can be designed and configured to fit different operating modes. However, it is difficult to

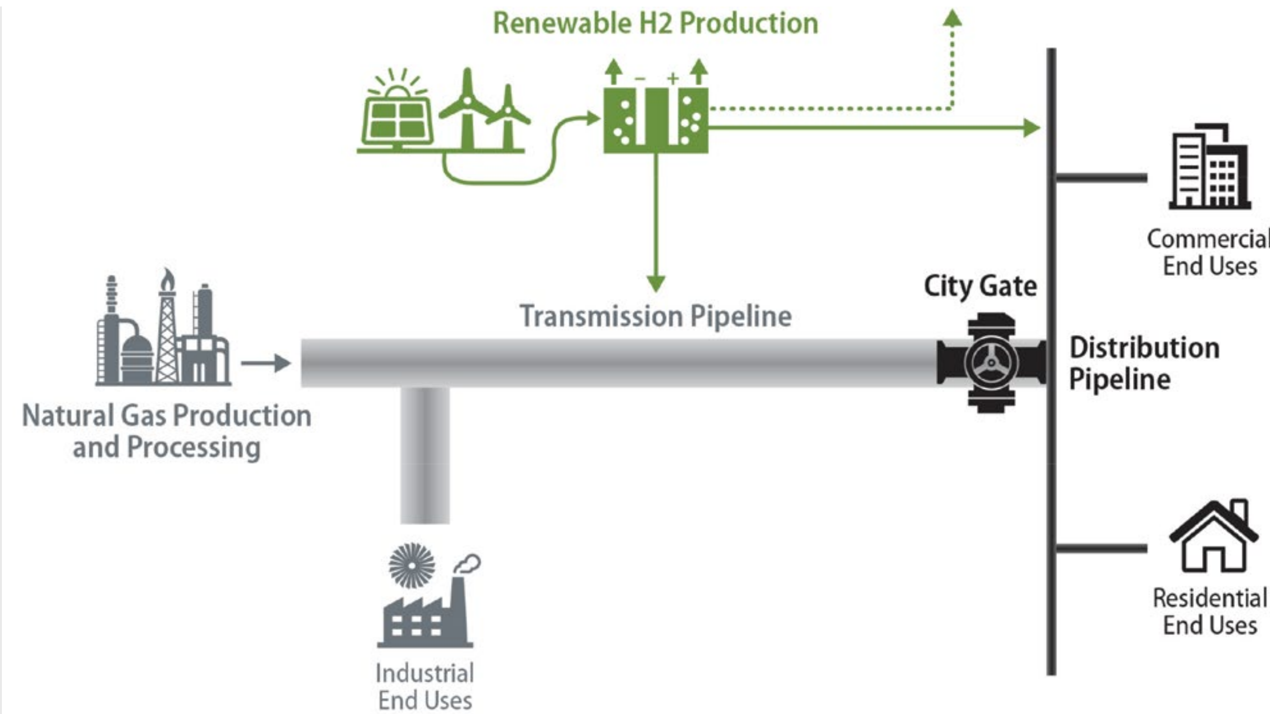

Figure 3. The iron and steel industry could potentially be just one industrial end user in a complex hydrogen distribution system. This scenario was considered, as was tightly coupled hydrogen production and utilization on-site at steelmaking facilities. Image from National Renewable Energy Laboratory.

design a "universal" ESF that can effectively and flexibly process different feedstocks. ESFs can use natural gas and/or hydrogen as reductants, and have been proven to effectively handle dust, byproducts and very high gangue feed — but the key is in knowing this upfront and designing for it. ESFs may also be used without investing in a converter — either in producing pig iron/hot metal for EAF steelmaking, or for use in the continuous reduced iron steelmaking process, which has been demonstrated at pilot scale.

ESF demonstration and economy of scale were identified as the key challenges for commercialization. The technology is proven for ferroalloy production and ironmaking for niche ores, but iron smelting requires a much higher heat load that needs to be demonstrated. Slag tapping rate is well-demonstrated and poses little risk, but productivity of the metal tapping rate needs to be proven. Additionally, process control requires demonstration before widespread adoption by industry.

Integrating fluidized bed reactors with ESFs was identified as an area of interest. These reactors produce fine DRI that cannot be used effectively in EAF steelmaking. This fine DRI material could potentially be processed in an ESF, but the tolerance limit for fines is unknown.

When evaluating the impacts of H_2DRI in an ESF, participants argued there is little effect on refinement of impurity elements but additional carbon input must be considered. The required carbon content of ESF and ability to carburize H_2DRI inside the furnace needs further exploration through R&D. Specifically, it is unclear if carbon is required for smelting H_2DRI, and if so, where it should be added in the flowsheet. Carbon utilization is low in most operations, so it may be suitable to add it in the ESF. Additionally, H_2DRI poses the risk of lower metallization; therefore, feeding lower metallized DRI could be an option for smelting.

Hydrogen Integration

A strong consensus was reached that economic and reliable hydrogen availability is key to achieving successful integration of hydrogen steel manufacturing. Optimizing cost and reliability, local resources, power generation system sizing, and hydrogen storage are important factors. This process may include a large network of users in addition to steelmakers as illustrated in Fig. 3 or may be tightly coupled with steelmaking processes.

Availability of affordable energy is critical to the value proposition of hydrogen integration, which leads to constraints in site location. Hydrogen storage also plays a major role, providing reliability and often decreasing the sizing of the energy generation system. However, hydrogen storage technologies are lacking. Geologic storage solutions, such as salt caverns, limit siting. Further development of lined rock caverns or engineered hydrogen storage could be critical to the success of H_2DRI projects. Alternatively, development of hydrogen pipelines could supply a reliable feedstock and mitigate geographic siting locations. Although significant hydrogen pipeline assets exist in Europe today, including pipes owned by Airgas that have been operational for many years, they are not near the scale that would be necessary to substantively impact industry. It is possible that over time, the growth of hydrogen supply and demand may spur further development of current regional networks and distribution infrastructure that connects regions of low-cost hydrogen production with large-scale demand.

Safety risks associated with hydrogen are also a concern. Similar to the use of other energy carriers, hydrogen poses certain safety risks when used on a large scale. As a light gas of small molecules, hydrogen requires special equipment and procedures to handle it. Although this technology exists today, as evidenced by Airgas' hydrogen pipelines, it would require significant investments to deploy at scale. Because of safety concerns, leak detection and appropriate gas handling are critical.

Additionally, hydrogen can lead to embrittlement and cracking in steel pipes and vessels. Austenitic stainless steels are more resistant toward hydrogen embrittlement. New infrastructure for hydrogen storage and transportation cannot be constructed with the most economical materials. As a result, significant and costly retrofits to existing natural gas infrastructure will be required. Reforming the direct reduction process from natural gas to hydrogen may not be as significant from an infrastructure and safety perspective, as the natural-gas-based direct reduction process already produces a significant amount of hydrogen.

The point was made that it is cheaper to transport hydrogen than transmit electricity. Specifically, it was stated that the capital cost of hydrogen transportation systems was found to be 10 times lower than the cost of electrical grid integration in a study interconnecting the United Kingdom with Europe. The cost of land is the driver and this calculation is site-specific.

It was also noted that capital costs can be lowered by increasing storage capacity. Less energy generation equipment is needed when storage exists, as it can accommodate variability in energy production. Ultimately, optimizing production versus storing hydrogen is a site-specific optimization problem. An alternative to on-site production and storage of hydrogen is hydrogen delivery, which will require network innovation. However, it was observed that the technology to transport hydrogen has existed for more than 60 years. Also, existing natural gas pipeline infrastructure may be viable for hydrogen transport, but more research is needed. Finally, it was noted that long-haul pipeline challenges are well understood, but "short haul" is a challenge.

Additionally, it was noted that energy storage in the form of thermal storage may be efficient. There was particular interest in the possibility of storing thermal energy in H_2DRI itself, which could be used for preheating the reducing gas.

In addition to optimizing production, storage and transport of hydrogen, additional flexibility may be possible on the demand side. The steel industry currently does not consider storage and flexibility when assessing or optimizing costs. This may be unwise. Although current processes tend to be steady state, even 10% flexibility in load reduces storage demand, and capital costs for storage are expensive. Load flexibility could be achieved either by ramping processes up and down or by using multiple reducing gases (i.e., natural gas and hydrogen). It was asserted that the cost associated with storage orders of magnitude are more expensive than the cost of creating a dynamic process. This discrepancy suggests further exploration of the potential to ramp operations up and down. Furthermore, the product itself can be viewed as energy storage. Excess production of steel when feedstock prices are low may be the most economical way to utilize energy resources. Despite a consensus that dynamic processes may be valuable, there was discussion on the timescale of dynamic processes, and whether those processes should be dynamic seasonally or daily (e.g., Argentina ramps down when natural gas is in high demand for winter heating).

With respect to safety, there was a consensus that hydrogen safety is well understood and manageable from an internal perspective, but that public perception of hydrogen safety continues to pose a challenge. Risk assessments and associated controls will need to be updated to incorporate risks associated with hydrogen use. Steelmakers are already developing and deploying process safety management systems to manage the risk associated with hazardous toxic or flammable materials.

Ore Management – Beneficiation

Large-scale implementation of various steelmaking innovations, deployed alone or in combination, will require attention to the availability of suitable iron ore. The preferred feedstock for H_2DR is direct reduction pellets with an iron content of 67% or greater. By comparison, BF-grade pellets have an iron content of about 65%. However, it may be possible to use lower-grade pellets for hydrogen-based technologies. This possibility was identified as an area for future R&D. Methods for utilizing lower-grade iron ore could include producing direct-reduction-grade pellets or developing DRI and smelting technologies that can accommodate more gangue. Although global iron ore production remains strong, the content of iron in ore deposits is a concern when considering growing demand for direct reduction pellets as the industry seeks to reduce its emissions. Direct-reduction-grade iron ore currently comprises only about 4% of global iron ore supply.

The quality requirements of pellets, such as physical, chemical and metallurgical specifications, depend on each ironmaking furnace, and those requirements influence the operation of the iron ore pelletizing plant. The final use of iron ore pellets in ironmaking reactors requires high mechanical properties. Required properties may change when more hydrogen is utilized.

Significant discussion centered around beneficiation processes. Although crushing and grinding require significant energy inputs, melting is also very energy-intensive, creating trade-offs in gangue removal at the beneficiation stage versus slag management later in the process. Therefore, optimizing steel product quality must be balanced with yield losses in the production processes. There is not a current consensus regarding best practice, which may in part result from the geologic diversity of iron ore deposits. Generally, it was observed that downstream management of impurity elements is more expensive.

Rather than a universal preference for beneficiation or smelting, there was consensus that the best route for refining ore depended on the ore body. Different technologies are required by different geologies/mineralogies of the ore body. Beneficiation is physical, whereas smelting is chemical. For example, when nonferrous species are in the crystalline structure of the ore, it is not possible to remove them through grinding and crushing. Therefore, pyrometallurgical (smelting) processes are required for gangue rejection when physical processes are unavailable. Where beneficiation is possible, it is generally less expensive; however, it also results in iron losses and tailing waste. Where beneficiation is possible, it is generally ore-body-specific while smelting tends to be more similar across different ore bodies. Even if optimization of the ore refining process solutions are clear-cut, it was noted that miners are reluctant to spend money on beneficiation, preferring to shift the problem downstream.

Management of specific ore bodies based on quality was also discussed, with frustration expressed that the highest-grade iron ore deposits are currently being utilized for low-grade products such as rebar, which was viewed as a waste of optimal product. Currently, industry is often balancing cost for low- versus high-grade ores and blend as much low-grade ore into their products as they can. They are, in essence, wasting high-grade ore by diluting it with low-grade ore. This topic led to further discussion of the need to establish price-setting mechanisms.

It was noted that there may be a limit for beneficiation innovation. It is a challenge to improve iron content without losing iron in the process. Furthermore, site-specific challenges, like the lack of water in the Australian outback, are often encountered.

Finally, potential future sources of iron were considered, including red mud, copper tailings, mill scale, legacy or new steelmaking slag, and iron-rich mine waste. However, some opposition to these sources was voiced, as these feedstocks are not economical under current market conditions.

Conclusion

The discussions at the workshop provided valuable insights into stakeholders' perspectives surrounding hydrogen for the iron and steel sector, including the current challenges and opportunities to enable large-scale deployment of H_2DRI. The main outcomes of the workshop include the following:

- The open technical challenges for H_2DR include thermal management and carburization. The low carbon content of H_2DRI affects melting properties, the energy balance in the furnace, and slag foaming to protect the refractory and electrodes and ensure correct composition of the melt. Depending on the intended downstream processes and the grade of iron ore, carburization could be accomplished using various methods for different operations.

- The ESF was identified as a key technology of interest to handle the increase of gangue volume and for its proven ability to process a variety of feed materials. There are a few key differences to keep in mind. First, there is low slag basicity in the ESF, resulting in higher capacity for MgO, thus influencing refractory design. In comparison to the EAF, the ESF employs a higher hearth power density and a thin freezer lining to protect the refractory, so lining/refractory wear is not as big of a concern. ESF demonstration and economy of scale were identified as the key challenges for commercialization. The technology is proven for ferroalloy production and ironmaking for niche ores, but iron smelting requires a much higher heat load that needs demonstrated. The required carbon content of the ESF and ability to carburize H_2DRI inside the furnace needs exploration through R&D.
- A strong consensus was reached that economic and reliable hydrogen availability is key to successful integration of hydrogen steel manufacturing. Optimizing cost and reliability, local resources, power generation system sizing, and hydrogen storage are important factors. It was claimed that the capital cost of hydrogen transportation systems was found to be 10 times lower than the cost of electrical grid integration in a study interconnecting the United Kingdom with Europe. The cost of land is the driver and this calculation is site-specific.
- Regarding iron ore quality and iron content, rather than a universal preference for beneficiation or smelting, there was consensus that the best route for iron ore refining depended on the ore body. However, an open question was identified on whether direct-reduction-grade pellets are needed for hydrogen-based technologies, and further R&D was called for.
- Alternate hydrogen reduction technologies that were discussed included fluidized bed reactors, vertical shaft furnaces, plasma technology and hydrogen injection in blast furnaces.

According to AIST's Roadmap for Iron and Steel Manufacturing: Revolutionizing U.S. Global Leadership for a Sustainable Industrial Supply Chain, the most considered alternative for carbon-based (e.g., coke or natural gas) reduction of iron ore and overall energy generation is hydrogen because of its potential to be produced at scale. As these technologies mature and the hydrogen economy continues to develop, hydrogen for steel applications can become more cost-effective and prevalent. Although challenges remain, hydrogen as an energy source and reductant for steelmaking has the potential to revolutionize the iron and steel industry in the future. ✦