Roadmap for Iron and Steel Manufacturing:
REVOLUTIONIZING U.S. GLOBAL LEADERSHIP FOR A SUSTAINABLE INDUSTRIAL SUPPLY CHAIN

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Principal Investigator: Ronald E. Ashburn
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Roadmap for Iron and Steel Manufacturing: Revolutionizing U.S. Global Leadership for a Sustainable Industrial Supply Chain

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01. Executive Summary

In May 2022, AIST received a multiyear grant from the U.S. Department of Commerce and its National Institute of Standards and Technology to compile a decarbonization roadmap on behalf of the U.S. steel industry. The objective was to identify and prioritize research areas to address the technologies, infrastructure and workforce needs that will decarbonize the iron and steel industry and advance steel manufacturing competitiveness across the steel industry value chain.

As a highly engineered material, steel is a critical industry of the future. In addition to its foundational role for the economic and defensive security of our nation, steel provides solutions for the growth of modern society as the cost-efficient, sustainable material of choice for manufacturing, construction, infrastructure, transportation, power generation, energy transport, aerospace, storage, and many other applications.

In 2023, the U.S. steel industry produced approximately 80.7 million metric tons of steel, supported approximately 82,800 direct jobs, and reached revenues of over US$110 billion (USGS Mineral Commodity, Iron and Steel, 2024). Advancements in steel manufacturing technologies over the last decade have enabled continuous improvements in steel property performance, energy efficiency and environmental stewardship.

The domestic industry's comparative advantage, in terms of economics and greenhouse gas emissions, is derived from the fact that 68.3% of all steel produced in the U.S. in 2023 was via the recycled scrap–intensive electric arc furnace (EAF) process. This fact contrasts significantly with the rest of the world, whereby 71.1% of all steel produced globally in 2023 was from the iron ore-intensive blast furnace – basic oxygen furnace (BF–BOF). In comparison, the BF–BOF process has higher capital expenditure (CAPEX) requirements and process CO_2 emissions per ton of steel produced.

The industry is now positioning for pivotal growth to meet the anticipated demand for American-based steel production to support expected national infrastructure investments such as roads, bridges and buildings, in addition to green energy generation, storage and transport. American prosperity will indeed depend on a sustainable industrial supply chain for steel.

Despite these advantages, there are mounting global pressures that undermine the economic vitality of the U.S. steel industry. As the world moves to adopt the EAF process route, the global demand for high-quality metallic feedstock, in the face of mounting global environmental constraints, may catapult scrap to precious metal status. Just as concerning is global steel overcapacity, approaching 40% today, which leads to market-distorting behaviors from bad actors that have injurious impacts on free markets such as the U.S.

The challenges are not solely foreign in nature. The misconception that steel is not advanced manufacturing must be overcome if we are to attract and develop the diverse workforce demanded by today's steel industry. The notion that Amazon®, Uber® or a mobile phone app is high-tech in comparison to steel manufacturing mandates that we adopt a completely different paradigm for educating the public about manufacturing's role for economic vitality and quality of life for our citizens. Just as important, new training requirements for the workforce need to be introduced as we aggressively adopt more digitalization and decarbonization technologies.

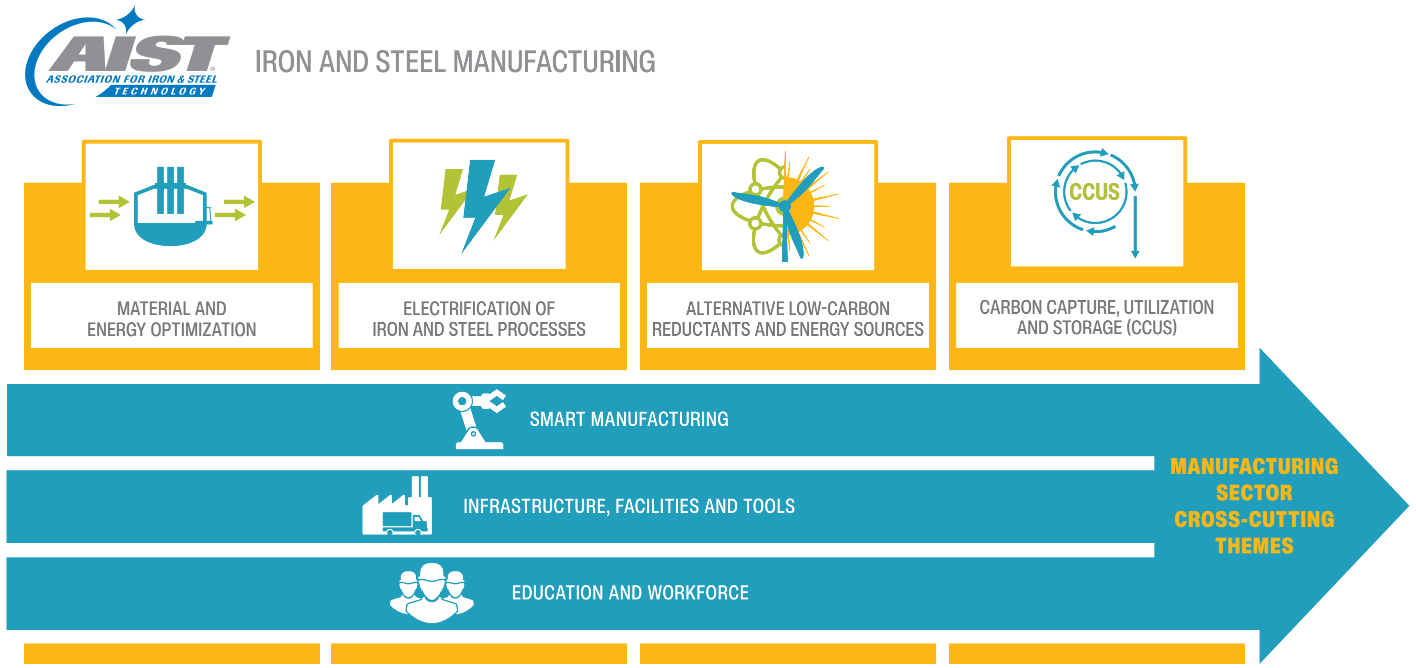

Figure 1. The four technology themes and three cross-cutting themes for the Association for Iron & Steel Technology Roadmap.

To overcome these challenges and to bolster the U.S. steel industry's role as an innovation leader in manufacturing, the Association for Iron & Steel Technology (AIST), headquartered near Pittsburgh, Pa., has led a large-scale, industrially driven and consortia-based effort for developing the *Roadmap for Iron and Steel Manufacturing: Revolutionizing U.S. Global Leadership for a Sustainable Industrial Supply Chain.* The objective of the AIST Roadmap is to address high-priority challenges in steel manufacturing that are broadly deployable to a diverse set of manufacturing sectors.

Today, the 4th Industrial Revolution (or Industry 4.0) is driving "smart" steel production, leveraging critical new technologies such as advanced sensorization, industrial drones and robots, artificial intelligence (AI), and machine learning. However, the challenges with modern steelmaking, caused by raw material constraints, increasing restrictions on emissions, and renewable power and grid parity, are pushing the frontiers of innovation. We must identify the pathways to merge smart solutions with advanced processes that enable raw material and energy flexibility, low-emission metallization, recycling and waste stream valorization, near-net-shape manufacturing, and lighter-weight, higher-performance steel products.

An equally important component to the technical challenges facing the steel industry is the need for a skilled workforce that is trained and enthusiastic about engaging with these new technologies. The next generation of a diverse and inclusive workforce is needed across all stages of production, including engineers, operators, maintenance and supply chain management.

This AIST Roadmap outlines the pathways for achieving the U.S. manufacturing vision in the steel industry by identifying the industry's grand challenges and priorities. To focus these grand challenges for iron and steel manufacturing, the AIST Roadmap utilizes a matrix consisting of four Technology Themes and three Cross-Cutting Themes (see Fig. 1). To facilitate crossover applications into other manufacturing sectors, the Technology Themes align with the Department of Energy's "Industrial Decarbonization Roadmap" published in 2022.

Four Technology Themes:

1. Material and Energy Optimization
2. Electrification of Iron and Steel Processes
3. Alternative Low-Carbon Reductants and Energy Sources
4. Carbon Capture, Utilization and Storage (CCUS)

Three Cross-Cutting Themes:

1. Smart Manufacturing
2. Infrastructure, Facilities and Tools
3. Education and Workforce

The AIST Roadmap has engaged stakeholders including raw material suppliers, steelmakers, equipment manufacturers, end users, government, academia and investors to identify strategic goals intended to produce significant impacts for the U.S. steel industry and manufacturing supply chain. Given the economywide predominance today for mitigating carbon intensity, the AIST Roadmap focuses heavily on decarbonization strategies associated with technology and workforce.

The Strategic Goals of the AIST Roadmap:

- Define a current baseline for the U.S. steel sector to decarbonize the iron and steel industry.
- Address high-priority technical research challenges to growing the U.S. manufacturing sector.
- Enhance innovation capacity and improve industrial competitiveness.
- Identify economically viable technical pathways to achieve a net-zero-emission iron and steel industry by 2050.
- Develop a plan through partnerships with community colleges, trade schools and universities for workforce development.

With this perspective, the AIST Roadmap comprises three main chapters to address the strategic goals associated with the steel industry:

- Technology Baseline
- Technology Process Adaptation
- Workforce Development

Technology Baseline

The Technology Baseline chapter describes the iron- and steelmaking processes and their carbon intensities, and provides a review of other roadmaps for the iron and steel industry in the United States. The chapter describes the status of current technologies and innovations, their challenges, and obstacles and examples of ongoing domestic and international decarbonization projects.

With its preponderance of metallic scrap-based electric steelmaking, the U.S. steel industry currently maintains a global leadership position for the production of clean, low-emissions steel. Despite this leadership position, the U.S. steel industry remains committed to and invested in a more sustainable future based on technological innovation, which represents a key strategy to enhance global competitiveness and to insulate against unfair trade distortions.

To better understand the impact on carbon emission reduction and the timeline for commercial implementation associated with technological innovation, AIST surveyed its global membership to gather data on the current status of numerous evolving technologies as identified within the Technology Baseline.

Technology Process Adaptation

The Technology Process Adaptation chapter presents the results from the broad industry survey with impact on carbon emissions reduction and the associated timeline to commercial implementation for the decarbonization strategies, irrespective of potential scalability limitations. This chapter also provides an action plan with short-, medium- and long-term outcomes; challenges; and strategies to address these challenges with recommendations for scale-up and commercialization.

From the survey and as depicted in Fig. 2, more than 30 unique strategies were revealed, each of which can and will have an impact on reducing or eliminating carbon emissions. While the impact for each varies, the mitigating technologies to decarbonize the iron and steel industry with the largest potential impact were identified as:

- Molten oxide electrolysis (Timeline 16.9 years from 2024, carbon emission reduction 1,195 kg CO_2/metric ton of crude steel produced).
- Hydrogen-based DRI (Timeline 10.7 years from 2024, carbon emission reduction 1,181 kg CO_2/metric ton of crude steel produced).
- Hydrogen production and storage (Timeline 11.6 years from 2024, carbon emission reduction 1,073 kg CO_2/metric ton of crude steel produced).
- Electric smelting furnaces (Timeline 9.1 years from 2024, carbon emission reduction 974 kg CO_2/metric ton of crude steel produced).
- Replacement of coke with net-zero carbon syngas (Timeline 15.9 years from 2024, carbon emission reduction 967 kg CO_2/metric ton of crude steel produced).
- CCUS storage and utilization (Timeline 14.9 years from 2024, carbon emission reduction 947 kg CO_2/metric ton of crude steel produced).
- Green electricity EAF process (Timeline 10.2 years from 2024, carbon emission reduction 928 kg CO_2/metric ton of crude steel produced).

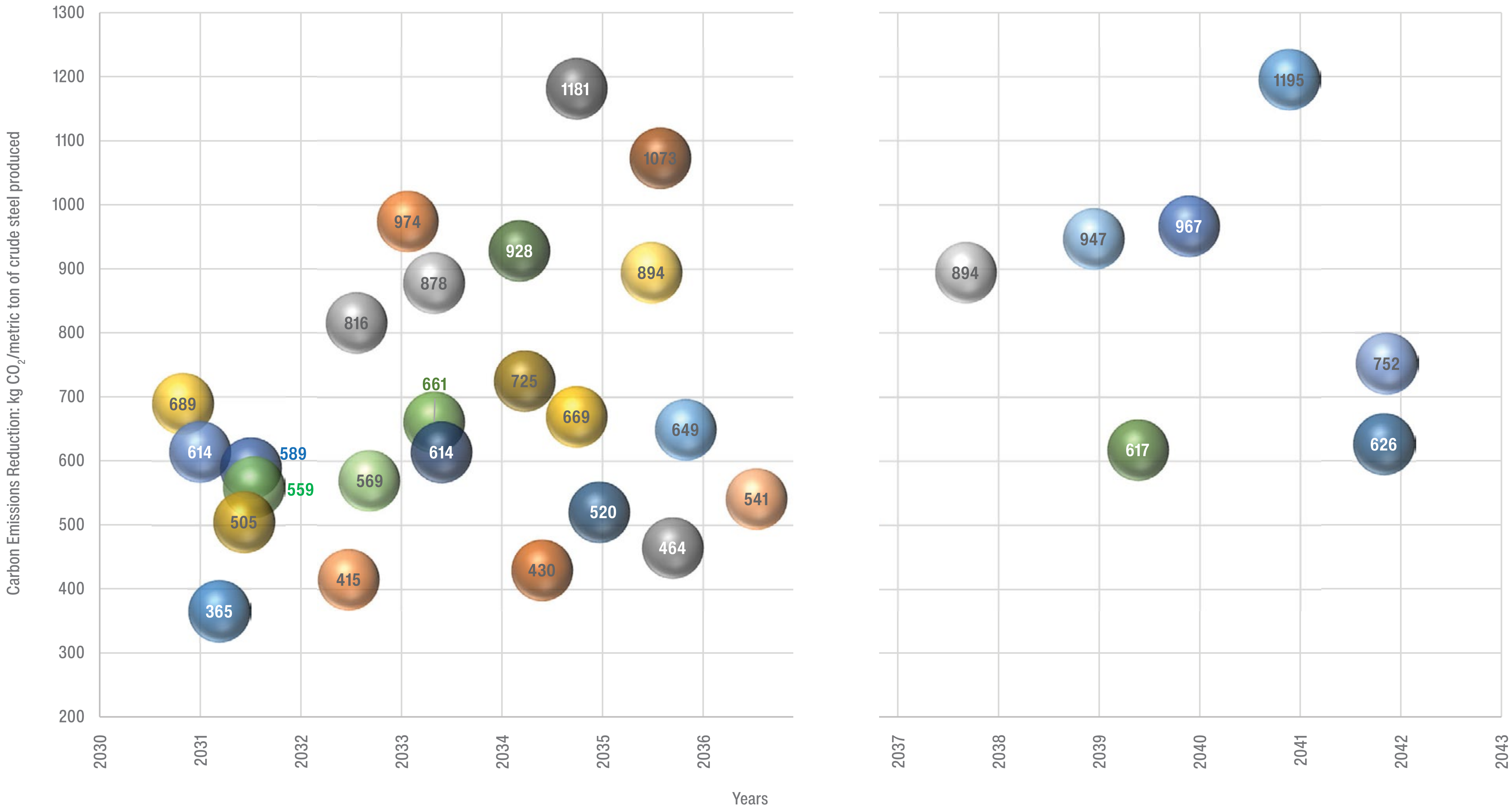

Figure 2. Iron and Steel Decarbonization Strategies: Impact on carbon emissions reduction and timeline to commercial implementation in the U.S. (respondent data outside the U.S. reflects different results; descriptions of the Decarbonization Technologies are in Appendix B).

- Molten oxide electrolysis - 1195
- Hydrogen-based DRI - 1181
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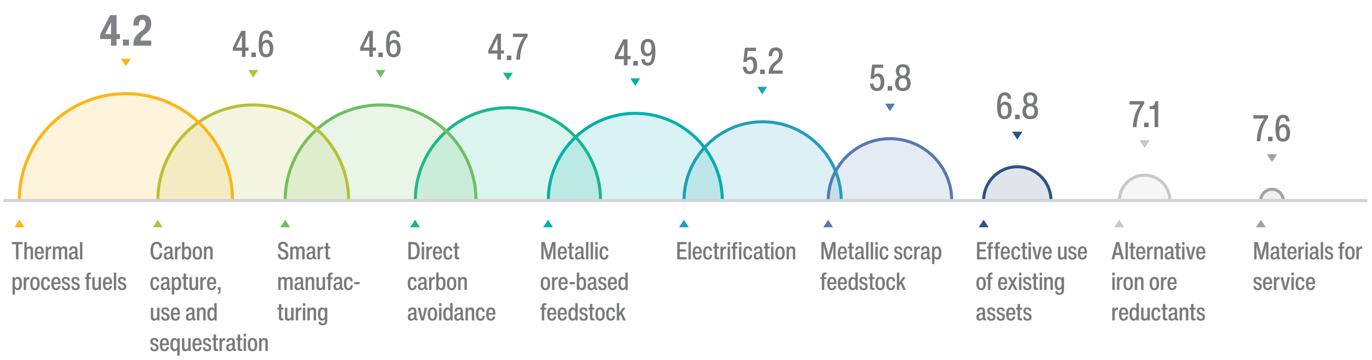

Figure 3. Industry Priority for Iron and Steel Decarbonization Technologies (Rank 1–10).

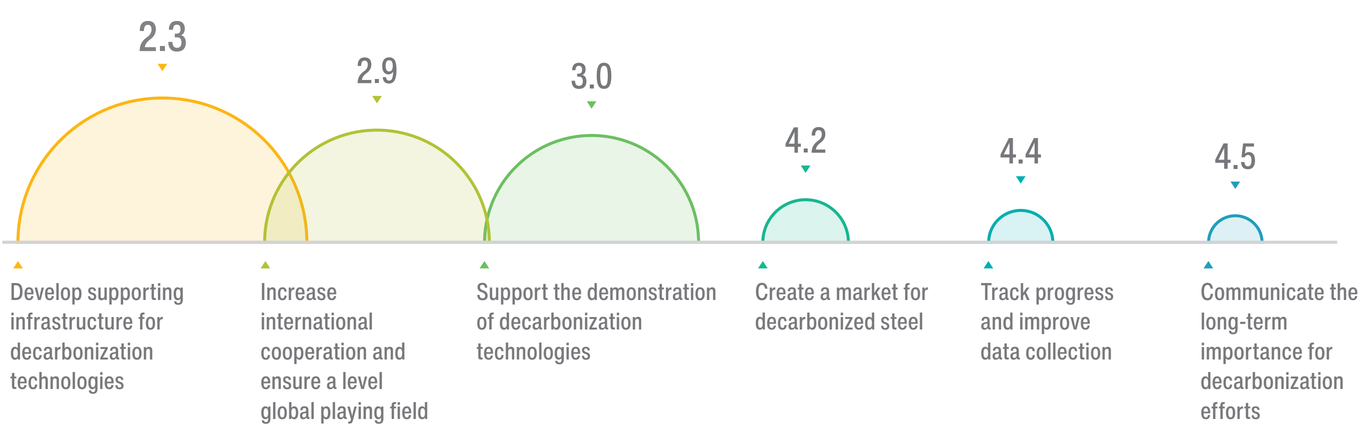

Figure 4. Industry Priority for Related Government Initiatives (Rank 1–6).

The survey results emphasized the strategic importance of investing in innovative decarbonization technologies along the entire iron- and steelmaking value chain, from raw material selection to finished products. The survey results also provide a tool for the steel industry to evaluate evolving technologies to facilitate strategic decisions on the best path toward decarbonizing specific processes on an immediate, short-, medium- and long-term basis.

In a related AIST survey of major U.S. steel producers, each company ranked their overall priority for 10 broad categories related to iron and steel decarbonization technologies (Fig. 3).

While thermal process fuels (e.g., hydrogen, natural gas, oxygen, biofuels) received the highest rank (i.e., lowest value), the survey results were diverse and revealed multiple priorities industrywide, which again emphasizes the strategic importance of investing along the entire value chain.

Within this same survey, the respondents were asked to rank their priority for how the U.S. government should address six issues related to iron and steel decarbonization (Fig. 4).

The development of supporting infrastructure for de-risking decarbonization technologies (e.g., public/private partnerships) received the highest rank, followed by increasing international cooperation to ensure a global level playing field. The role of public/private partnerships and international diplomacy will be essential to achieving the strategic goals of the AIST Roadmap.

Workforce Development

The Workforce Development chapter provides an action plan for workforce availability and an infrastructure for education and development to meet industry needs for a skilled, diverse and inclusive workforce by 2044. The chapter provides immediate, short-term, medium-term and long-term actions; challenges; strategies to address the challenges; and a list of suggested tactics to enhance workforce development programs.

A key finding from within the workforce challenges is the imperative to improve society's impression about and understanding of the steel industry. Since 2021, the industry has seen a multigenerational investment cycle, one that has brought about approximately US$26 billion in private investment by steel producers in North America. The industry is proactively investing in new technologies that will allow it to do more with less, and to do it better. In the meantime, domestic policy has thus far encouraged the development of a green energy grid which will drive new steel demand over the long term.

Despite the optimism, steel struggles in the court of public opinion, which has impeded workforce development efforts. If you ask the average person about steel, you may hear that steel is obsolete and uses outdated technology; that it's bad for the environment and an unsafe work environment. What society does not realize, or perhaps takes for granted, is that steel is: strong, durable, easily formed and machined; you can weld it and attach things to it; it's magnetic; it's cost-effective; and it is the most recycled material on the planet.

What the public also doesn't see is that steel is an evolving engineered material that can improve the quality of life here on Earth and perhaps beyond. Steel has an unbeatable value proposition, and the public paradigm needs to shift from an industry perceived to be unsafe, dirty and old to one that is safe, green, smart and essential.

While there has been significant CAPEX investment in recent years, there is no such investment in a collaborative market outreach to educate the public about the vision for steel. The last concerted effort was the "Steel Alliance" which disbanded 20 years ago amidst myriad industry bankruptcies. In this regard, two fundamental facts exist:

- A green energy economy will be steel-intensive. Wind towers, solar farms, electric vehicles, hydrogen power plants and all forms of power transmission are steel-intensive and cannot be constructed without steel.
- Steel is and will continue to be energy-intensive to produce. As an example, the steel industry in Ohio uses more energy than all other users in the state combined. If the steel industry is going to rely on green energy, it will need lots of it and it must be competitively available.

The vision is clear: a green energy economy will require a sustainable steel industry. Simply put, green energy needs steel and steel needs green energy. The industry must educate the public about this interdependence. Such outreach will undoubtedly enhance all workforce development efforts.

This motivation includes expectations from society, customers and investors to demonstrate meaningful advancement for Environment, Social and Governance (ESG) initiatives. The building of a green energy infrastructure will also underpin long-term domestic steel demand, which is both opportunistic for industry and beneficial for society.

Final Thoughts

Technological advancements and the corresponding efforts for workforce development related to evolving steel manufacturing processes will eventually reduce carbon emissions from the industry in the long term, ultimately leading to direct carbon avoidance. In many respects, a technological renaissance is already underway within the global steel industry which will reinforce the critical role for steel within the global economy and for improving the quality of life for all.

Many of the evolving solutions will also be applicable to the entire materials manufacturing sector. However, the effort will require sufficient time for research and development to de-risk the significant investments necessary to convert the existing steel manufacturing infrastructure. A transition era will be essential to sustaining the economic viability of the many companies leading this multigenerational transformation.

During this pivotal time, governmental engagement, policy and diplomacy will be essential to encourage innovation and to avoid current global steel overcapacity from undermining these investments.

Public/private partnerships with the steel industry, such as the establishment of a manufacturing institute, would facilitate the commercial transition of innovative decarbonization technologies into scalable, cost-effective and high-performing manufacturing solutions. An institute would also create and implement workforce development programs to ensure the future viability of the industry. While the U.S. steel industry will evolve these technologies and programs over time, an institute would accelerate the effort to ensure global leadership is preserved.

The capability to engage industry at all levels will be critical for the long-term success of this grand effort to decarbonize industry. In this respect, the U.S. steel industry has the vigor of scale, impact and accountability for coordinating stakeholders to hasten the path toward net-zero carbon emissions for the entire manufacturing supply chain.

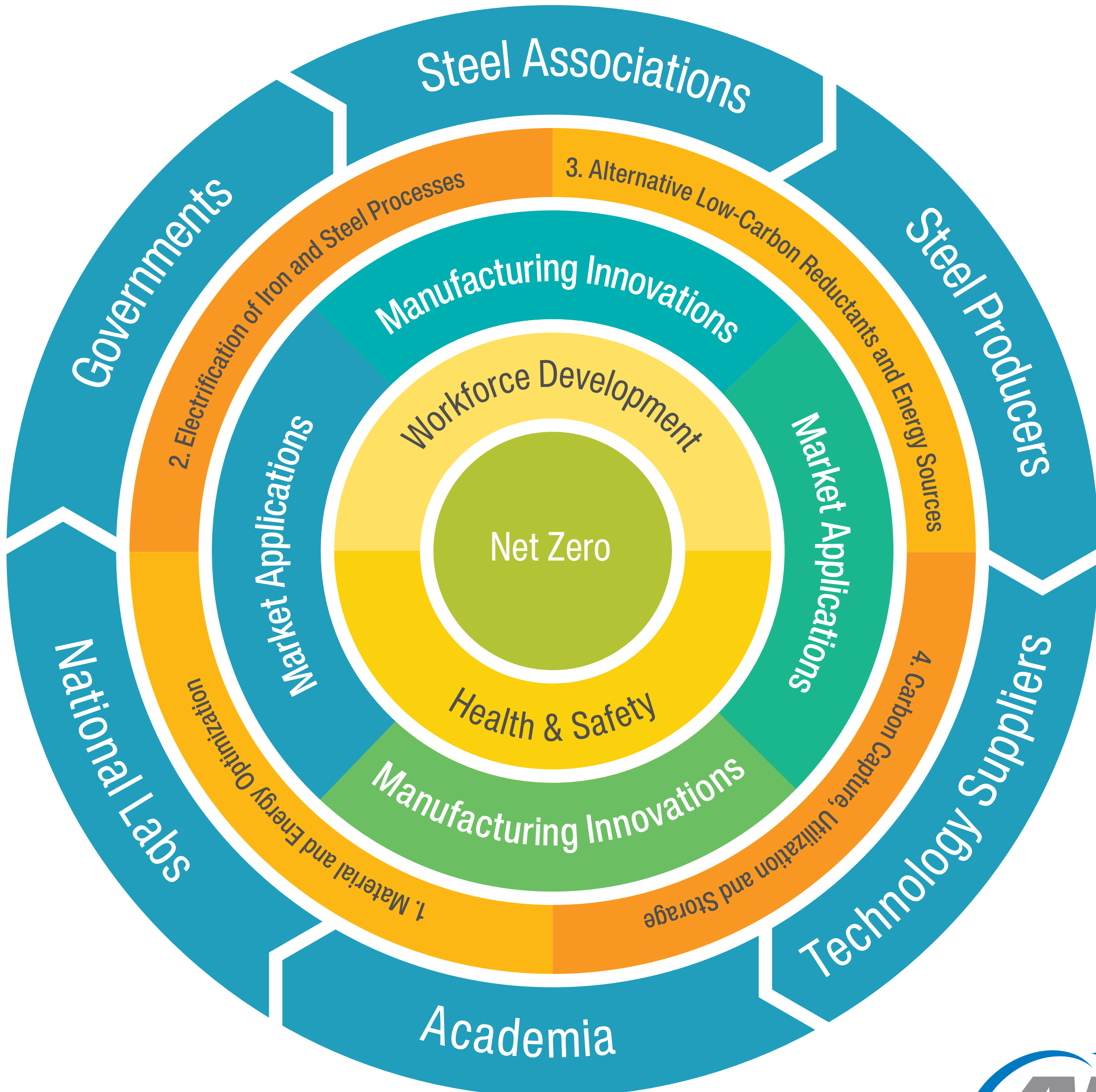

Figure 5. The engagement cycle leading to net-zero emissions for the U.S. steel industry.

The Roadmap for Iron and Steel Manufacturing: Revolutionizing U.S. Global Leadership for a Sustainable Industrial Supply Chain aims to transform the U.S. manufacturing sector by advancing research challenges in the iron and steel sector. This collaborative effort is depicted in the engagement cycle leading to net-zero emissions in Fig. 5. It is, and will continue to be, a work in progress with constant evolution and transformation.

This roadmap is focused on technologies and solutions to enhance innovation capacity and improve industrial competitiveness for the U.S. iron and steel industry. When viewed from a global perspective, the results will vary dependent on geographical location, availability of raw materials and energy sources, regional politics and environmental regulation, and national or corporate sustainability goals.

02. History and Evolution of the U.S. Iron and Steel Industry

For the last half-century, steel has been produced commercially via the blast furnace–basic oxygen furnace (BF–BOF) route and the electric arc furnace (EAF) route. The BF–BOF process uses mainly natural resources of iron ore as input material, and these facilities are generally referred to as integrated steel mills. The EAF process commonly uses recycled steel scrap as input material, and these facilities are generally referred to as mini-mills.

Blast furnaces historically used only charcoal as an energy source up until about 1840, when coke derived from the baking of coal started replacing charcoal as the preferred fuel and reducing agent.[1,2] In 1884, charcoal was still used to make 10% of iron and steel in the United States, and it continued to be used on a small scale up until 1945.

Coke has a higher crushing strength than charcoal, which allowed blast furnaces to become taller and larger and increase productivity. The replacement of charcoal with coke revolutionized the industry and tied mills to coal-mining areas to reduce the transportation cost. Mills consumed more coal than iron ore at that time and it was more economical to locate closer to the coal mines. Pittsburgh, PA, which is surrounded by large coal deposits and is located at the junction of three rivers, was an ideal location for steelmaking. Similarly, modern steel mills today may choose to locate near renewable energy sources rather than coal-mining areas, which will change the geographical distribution of future steelmaking facilities in the United States.

The United States reached its peak world crude steel production share of 72% during World War II. Production in the United States peaked in 1973, when the crude steel annual output reached 137 million metric tons. During this period, global steel production had grown even faster, and in the 1950s the U.S. crude steel production share in the world began to decline. During the economic recession of the early 1980s, U.S. iron and steel production drastically reduced as some steel companies declared bankruptcy and many mills permanently closed. At this time, the U.S. crude steel production fell to 107 million metric tons, more than 20% below its peak only a decade earlier. The alleged causes of the closures were dumping of imports below cost, high labor costs, poor management, lack of asset investment, unfavorable tax policies and costs of environmental controls.[1,2] In the Pittsburgh region, mill closures led to a regional unemployment rate that peaked at 17.1% in January 1983, with local unemployment rates as high as 27.1% in Beaver County. Between 1970 and 1990, the region lost 30% of its population.[3,4]

However, it should be noted that during the period of production decline, the U.S. steel industry underwent a transition toward a less capital-intensive, scrap-based steel production process through the EAF, in the so-called mini-mills.

This evolution was motivated by market forces that discouraged the traditional integrated mills from maintaining production of lower-value long products needed by the domestic fabrication and construction sectors. One of the earliest such mills to be built in the U.S. was Nucor Corp.'s plant in Darlington, SC, under the leadership of Ken Iverson in 1969. Mini-mills, which gained momentum in the U.S. in the 1970s and 1980s, have significantly lower capital and operating costs, which has ultimately contributed to their competitiveness and overall sustainability. Key technologies adopted by mini-mills include: (1) EAFs for scrap melting, which are largely electrically powered; (2) ladle metallurgy practices to adjust and control chemistries prior to casting; (3) continuous casting, including near-net-shape casting methods that reduce the need for extensive thermomechanical processing and thus energy; (4) optimized scrap processing and handling; (5) advanced sensors, automation and control; and (6) various energy recovery systems.

Prominent domestic mini-mill operators include Nucor Corp., CMC and Steel Dynamics Inc., among others. Since mini-mills generally do not rely on carbothermic reduction, the average energy consumption and carbon emissions footprint of the U.S. steel industry rivals the lowest in the world. To produce a ton of steel in an EAF requires approximately 2.1–2.4 GJ/ton liquid steel, while producing a ton of steel in a BF–BOF requires approximately 10.5–11.5 GJ/ton liquid steel.[5,6]

The domestic industry's comparative advantage, in terms of economics and greenhouse gas emissions, is derived from the fact that 68.3% of all steel produced in the U.S. in 2023 was via the recycled scrap–intensive electric arc furnace (EAF) process. This fact contrasts significantly with the rest of the world, whereby 71.1% of all steel produced globally in 2023 was from the iron ore–intensive BF–BOF process (World Steel in Figures 2024). In comparison, the BF–BOF process has higher capital expenditure (CAPEX) requirements and process CO_2 emissions per ton of steel produced.

In 2023, the U.S. steel industry produced approximately 80.7 million metric tons of steel, representing 4.4% of global share. Raw steel was produced by mini-mills at 37 companies with a combined total of 97 plant locations in the United States. The integrated steel mills comprised two companies at 12 locations: Cleveland-Cliffs Inc. and United States Steel Corporation. The transition from integrated steel mills to mini-mills has been feasible mainly due to the availability of steel scrap, a robust electrical power grid and the cost-effectiveness of the EAF process. Although EAF production is dominant in the U.S., integrated production, while highly energy-intensive, remains essential to the creation of advanced high-strength steels (AHSS) and other value-added steel grades. The quality gap between mini-mill and integrated production continues to narrow.

Today, the U.S. steel industry is facing global challenges related to steel overcapacity by approximately 40%, which has led to market distortion caused by the dumping of steel into the U.S. market. The overcapacity is mainly attributed to industrializing countries, most notably China, installing new integrated steel mills due to the lack of steel scrap availability and an electrical power grid in those countries. These facilities produce steel with higher CO_2 emissions than facilities in the United States.[7]

03. Background of the Association for Iron & Steel Technology

The Association for Iron & Steel Technology (AIST), headquartered near Pittsburgh, PA, is a 501(c)(3) non-profit organization with 18,600 members in 2024 from more than 70 countries. With 29 Technology Committees representing all facets of the iron and steel manufacturing process and 22 local Member Chapters spread across six continents, AIST provides the global steel industry with an incomparable network of steel knowledge and expertise.

AIST's mission is to advance the technical development, production, processing and application of iron and steel. Its vision is to be a global leader in networking, education and sustainability programs for advancing iron and steel technology. As AIST works to promote a diversified industry workforce to retain and grow its membership, it is cognizant of the need to remove barriers to entry for many prospective AIST members from around the world, which can transcend the Association and have a positive impact on the industry.

In support of this effort, the AIST Foundation has evolved programs to promote the steel industry as a viable and rewarding career choice in fulfillment of the Foundation's mission to ensure the steel industry of tomorrow will have a sufficient number of qualified professionals.

Over the last decade, AIST has worked to better understand the needs and preferences of steel professionals living in non-high-income countries, steel professionals under the age of 30, and female steel professionals. AIST and the AIST Foundation are supportive of all individuals joining the association and welcomes diversified participation in its programs.

04. Information Gathering

The Roadmap comprises three main chapters to address the strategic goals associated with the steel industry:

- Technology Baseline.
- Technology Process Adaptation.
- Workforce Development.

The information and data within this report were gathered by literature review, interviews, surveys, and input from events and workshops organized within the project. The different sources of data and information were used to develop a consolidated list of decarbonization technologies with their main challenges/barriers to decarbonization and energy efficiency.

The industry-led workshop and event-based approach enabled AIST to gather knowledge and experience from its membership, which encompasses steel manufacturers, raw material suppliers, equipment manufacturers, logistics organizations and universities all aligned with the steel manufacturing industry, to drive the development of a comprehensive roadmap. Team members in this process represent a diverse steel manufacturing value and supply chain, including executives, technical experts, operators, etc., who are actively engaged in deploying and developing technologies for the industry. The team members also provided information on the refinement of the themes and needs of discussion items at the workshops. The Roadmap was developed through the discovery stage, development stage, and review and validation stage of the project. The information-gathering and roadmapping process is illustrated in Fig. 6.

05. Roadmapping Process

The AIST consortium consisted of the Steering Committee, Business Boards I and II, Industry Partners (all in Appendix A) and AIST's members. The working groups brainstormed different project options and utilized the value creation methodology to evaluate the most technically feasible pathways for decarbonization.

During the initial discovery stage, AIST worked with its stakeholders to establish project teams and a baseline understanding of the steel industry's status about collecting industry technology challenges of infrastructure, workforce needs and culture change requirements. The outcome of the discovery stage was a review of available decarbonization technologies and their main challenges. This review also covers the U.S. technology areas at the forefront of decarbonization and technology areas where international competitors are outpacing or have the potential to outpace the domestic steel industry.

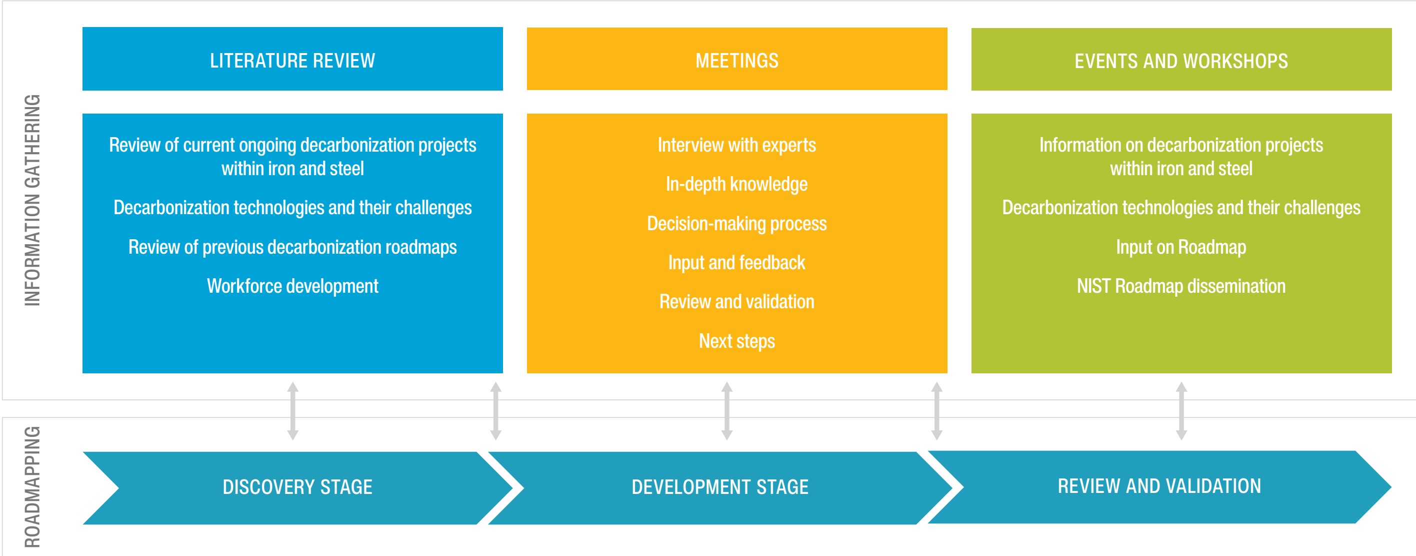

Figure 6. The information-gathering and roadmapping process.

During the formative development stage, AIST evaluated the impact of all challenges more broadly across the industry, with a focus on enhancing innovation capacity and improving industrial competitiveness. The evaluation focused on the innovations and education required, while maintaining economic competitiveness and designing a pathway that is inclusive to all. The outcome of this stage was the formation of chapters for Technology Process Adaptation and Workforce Development.

During the review and validation stage, meetings and discussions were held to ensure the Roadmap articulated its strategic goals including the identification of potential pathways to reach these goals through technology, innovation, job creation and education. The outcome of the review and validation stage was the final Roadmap.

06. Acknowledgments

The AIST Roadmap was sponsored by the National Institute of Standards and Technology (NIST), an agency of the U.S. Department of Commerce.

Thanks are extended to all members of the AIST Consortium. We sincerely appreciate the extensive contributions of the working groups, Business Boards I and II, the steel industry partners, and many individual AIST members for their contributions (Appendix A); this report would not be possible without their valuable insights.

07. Disclaimer

This report was prepared by the Association for Iron & Steel Technology as an account of work sponsored by NIST. The views and opinions expressed herein do not necessarily state or reflect those of NIST or any other institution, organization or company.

08. Technology Baseline

Background on Iron- and Steelmaking Processes and Carbon Intensities

According to the Biden Administration, the United States needs to achieve carbon-free electricity by 2035 and net-zero greenhouse gas (GHG) emissions by 2050.[8] Reaching a carbon-neutral steel industry will provide benefits in terms of public health, economic growth and reduced impact of climate-related disasters. Steel and metals manufacturing are reliant on fossil fuels, primarily due to the use of carbon for the reduction of iron ore.

The CO_2 intensities and the EAF ratio for the major steel-producing countries are shown in Fig. 7.[7] The figure shows the countries that rely heavily on EAF steel production generally emit the least CO_2, in comparison to those countries that produce steel via the integrated BF-BOF route.

Relative to most countries, the percentage of EAF-based production in the U.S. is high (approximately 68.3% in 2023), and the overall recycling rate of steel in the U.S. has been between 80% and 90% during the past decade.[9]

Results show that when looking at national steel production, Italy and the U.S. have the lowest CO_2 emissions intensities among the countries, at less than 1,000 kg CO_2/t crude steel.

The weighted average CO_2 emissions intensity (weighted by their share of production from total production) of the steel industry in the countries studied in 2016 was 1,971 kg CO_2/t crude steel.[7] According to Worldsteel Association's Sustainability Indicators, the global average CO_2 emissions intensity has been rising and was 1,920 kg CO_2/t crude steel in 2023.[10]

According to the IEA, total global CO_2 emissions in 2023 reached a record high of approximately 37.4 billion metric tons. Based on global steel production of 1.89 billion metric tons in 2023, the global steel industry emitted approx. 3.63 billion metric tons CO_2 in this same year, representing 9.7% of all global emissions.

The key factors influencing CO_2 emissions intensity in the steel industry are:

- Share of EAF steel in total steel production.
- Fuel shares (e.g., Canada uses much more natural gas than Türkiye).
- Electricity grid CO_2 emissions factor.
- Age of steel facilities.
- Capacity utilization.
- Environmental regulations.
- Cost of energy and raw materials.
- Type of feedstocks in BF–BOF and EAF (e.g., sinter versus pellet versus scrap).
- Level of penetration of energy-efficient technologies.
- Steel product mix in each country.

The EAF process uses steel scrap as its main raw material and emits on average 600 kg CO_2/ton crude steel depending on raw material selection, while the BF–BOF process uses iron ore as its main resource and emits on average 1,800 kg CO_2/ton crude steel.[7] EAF capacity is restricted primarily due to the availability of recycled steel scrap and affordable electricity. To substitute for steel scrap, EAFs consume iron units from ore-based metallics such as direct reduced iron (DRI), hot briquetted iron (HBI) and pig iron.

Use of pig iron in the EAF is common worldwide but yields higher CO_2 intensity than EAF-based steels made with 100% scrap. DRI and HBI production require high-quality iron ore with an Fe content of 67% or above but have a much lower CO_2 burden than the BF process (see Table 1). Worldwide, there is a limited supply of high-quality iron ore pellets to allow for large-scale replacement of BF iron with DRI or HBI units. One option being pursued in the U.S. and the EU is the use of BF-grade pellets in DRI processing units followed by a smelting step with the resultant hot metal fed to BOF converters. The steelmaking production routes are shown in Fig. 8 and average CO_2 emissions per steelmaking process step are shown in Table 1.

The EAF process route, which uses recycled steel scrap, eliminates about 80% of the CO_2 emissions in comparison to the carbon found in BF crude steel (see Table 1). The EAF process sometimes requires the addition of pig iron or DRI to dilute undesired elements, such as Cu, Ni, S, P and Sn in scrap. These elements cannot easily be removed during liquid steel processing, resulting in deleterious effects downstream in high-value thin-gauge products such as automotive sheet causing surface cracking (hot shortness) during secondary cooling or thermomechanical treatment.[11] Opportunities to produce high-value products, such as automotive sheet from steel scrap, would decrease the need for ore-based metallics and decrease CO_2 emissions. Potential routes to achieving this are: (1) improved sorting of steel scrap and separation of copper,[12] (2) removal of copper during liquid steelmaking, and/or (3) mitigating process conditions during casting and thermomechanical processing to ameliorate the effects of copper.[13]

As shown in Table 1, the blast furnace process is the most energy-intensive part of the iron- and steelmaking route, with significant consumption of solid and gaseous fuels and a high carbon intensity. Based on a 2000 study by Fruehan and Paxton,[6] around 4 GJ/metric ton steel can be saved in the BF and roughly 0.6 GJ/metric ton steel can be saved in the EAF process. The steel industry has since achieved some of these targets.

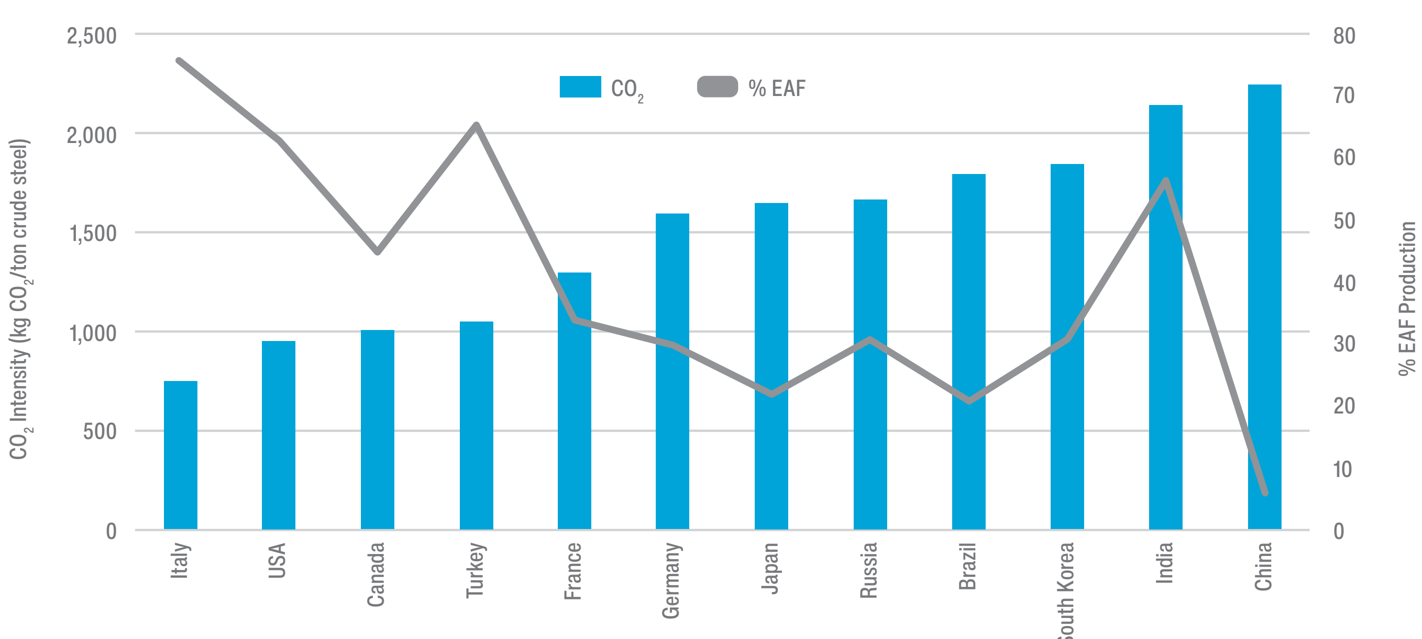

Figure 7. CO_2 emissions intensity (Scope 1 and 2) and electric arc furnace (EAF) ratio for different countries.[7]

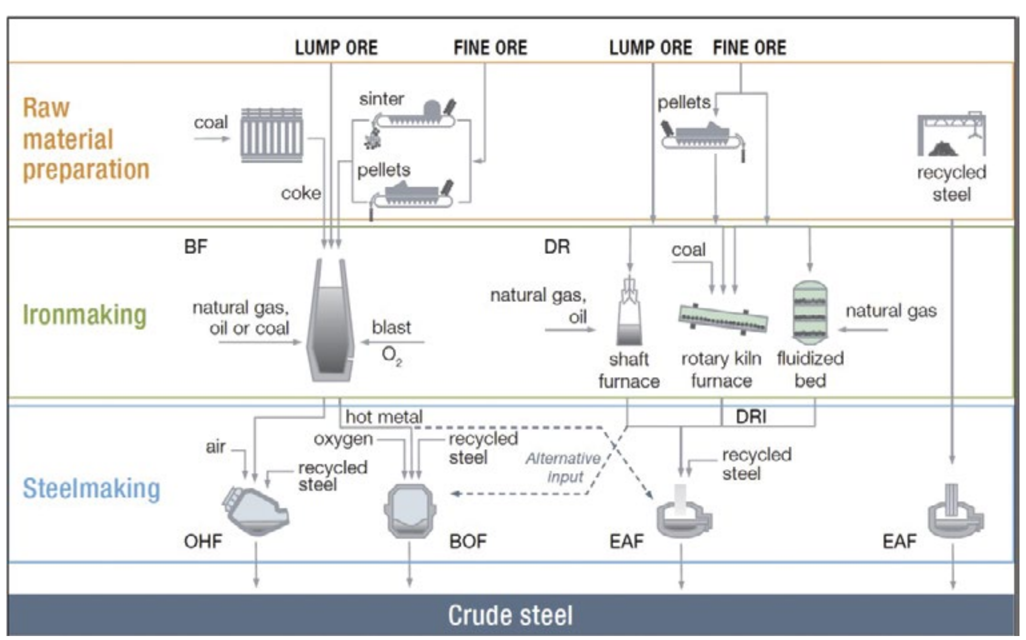

Figure 8. Steelmaking production routes (worldsteel 2019b).[9] Table 1 shows various studies of CO_2 emission intensities.

Table 1. Compilation of Reported Total CO_2 Emission Studies of Different Steelmaking Production Routes.[14]

Source	Total emissions (kg CO_2/t steel)			
	BF (with coke, sinter)	BOF	EAF–DRI	EAF–Scrap
Ameling, Endemann, Igelbüscher[15]	1,950		1,316	
Barati[16]	1,922		1,310–1,452	
Becerra, Duarte[17]	1,695		984–1,147	
Birat, Hanrot, Danloy[18]	1,750		870	360
Duarte, Tanavo, Zendejas[19]	1,850		1,090	
Fruehan, Fortini, Paxton, Brindle[6]	1,447–1559	189–207		364–416
Scholz, Pluschkell, Spitzer, Steffen[23]	1,091a–1,158b			225a–277b
Hornby-Anderson, Metius, McClelland[20]			632–1,880	441
Hornby-Anderson, Trotter, Varcoe, Reeves[21]	1,922–1,959		912–1,259	441
Kopfle, Metius[22]	1,959		713–1,140	466
Scholz, Pluschkell, Spitzer, Steffen[23]	1,371a–1,518b			
Zuliani, Scipolo, Duarte, Born[24]	1,696	148		

Note: a = theoretical minimum value excluding electricity; b = practical minimum value excluding electricity.

The industry has started addressing several areas within the steel manufacturing value chain to achieve cost and efficiency improvements and reductions in emissions. However, many of these efforts are still not commercially deployable and will require further insights for de-risking that can only come through enhanced innovation, research and development. To obtain a carbon-neutral steel industry, there is need for extensive research to lower the emissions in existing EAF and BF–BOF routes as well as in new innovative and alternative iron- and steelmaking technologies. The main technologies to decarbonize the U.S. steel industry and their status on application in the steel industry have been identified within the Steel Industry Baseline chapter.

Review of Other Roadmaps for the Iron and Steel Industry in the United States

The U.S. Department of Energy (DOE) published "Bandwidth Study on Energy Use and Roadmaps Potential Energy Saving Opportunities in U.S. Advanced High-Strength Steels Manufacturing" in 2017.[25] The study presented current opportunities and R&D opportunities for energy savings considering AHSS production. The current opportunity for energy savings that could be obtained if state-of-the-art technologies and practices are deployed was estimated to be 7.4 TBtu per year. In addition, the energy savings that could be obtained in the future if applied R&D technologies under development worldwide are deployed was estimated to be 3.2 TBtu per year.

The current greatest energy-saving opportunities for AHSS production were identified as follows:

- Cold rolling — 3.3 TBtu (or 43% of the current opportunity).
- Hot rolling — 2.1 TBtu (or 29% of the current opportunity).
- BOF steelmaking — 0.9 TBtu (or 13% of the current opportunity).

The greatest R&D energy-saving opportunities for future AHSS production were identified as follows:

- Blast furnace ironmaking — 2.0 TBtu (or 63% of the R&D opportunity).
- Cokemaking — 0.4 TBtu (or 13% of the R&D opportunity).
- Cold rolling — 0.3 TBtu (or 11% of the R&D opportunity).

The DOE published its "Industrial Decarbonization Roadmap" in 2022 which identified four key pathways to reduce industrial emissions through innovation in American manufacturing: (1) Energy Efficiency; (2) Industrial Electrification; (3) Low-Carbon Fuels, Feedstocks and Energy Sources; and (4) Carbon Capture, Utilization and Storage.[26],[27] These decarbonization pillars were applicable across all industrial subsectors and have the capability to deliver near-term and future reductions of greenhouse gas emissions. The Industrial Decarbonization Roadmap identified five of the highest CO_2-emitting industries where industrial decarbonization technologies can have the greatest impact across the nation. These five industrial sectors represent approximately 51% of energy-related CO_2 emissions in the U.S. and were identified as petroleum refining, chemicals, iron and steel, cement, and food and beverage. These industries represent 15% of U.S. economywide total CO_2 emissions.

Key recommendations from the Industrial Decarbonization Roadmap were: (1) Advance early-stage RD&D and invest in multiple process strategies; (2) demonstrate testbeds to accelerate and de-risk deployment; (3) utilize industrial emissions and process heating; (4) system integration and impact of carbon reduction technologies on the supply chain; and (5) conduct modeling and systems analyses to expand use of technologies.

The DOE published the "Pathways to Commercial Liftoff: Industrial Decarbonization" report in 2023.[28] The report provides pathways to decarbonize eight industrial sectors including iron and steel and compared the operating costs and carbon emission intensities for the following steel production routes: BF–BOF and carbon capture and storage (CCS); scrap-based EAF; natural gas DRI/HBI followed by EAF; and hydrogen DRI/HBI followed by EAF. The report showed that the retrofitted EAF routes (scrap-based EAF, natural gas DRI/HBI followed by EAF, and hydrogen DRI/HBI followed by EAF) will likely have lower emissions intensities than the BF–BOF and CCS route. The U.S. iron and steel decarbonization "Pathway to Liftoff" could require US$25–40 billion in capital investment through 2050 to scale decarbonization technologies. This includes implementing currently deployable decarbonization technologies such as energy efficiency, industrial electrification, and transitioning to EAF production route, as well as implementing technologies currently at R&D stage, such as hydrogen DRI/HBI, CCUS, and alternative iron and steel production processes (e.g., molten oxide electrolysis, DRI-electric smelting furnace (ESF), HIsmelt, HYBRIT).[29]

The DOE reports show that there are great opportunities to reduce carbon emissions along the whole iron and steel value chain. The AIST Roadmap further builds on the decarbonization pillars identified within the DOE's Industrial Decarbonization Roadmap and identifies current decarbonization technologies and projects applicable for the iron and steel industry, their status, main challenges and obstacles, and a proposed pathway to fully decarbonize the iron and steel industry by 2050.

Four Technology Themes

The four technology themes in this roadmap are based on the DOE's "Industrial Decarbonization Roadmap" pillars and are identified as **(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 (CCUS).** The main decarbonization technologies applicable in the iron and steel industry within each technology theme were identified and are presented in this chapter.

The main challenge with adopting these decarbonization technologies is maintaining economic viability for the companies producing iron and steel through the transition era. A strategy to de-risk the technological innovation associated with the transition era is required.

I. Material and Energy Optimization

The steel industry is continuously investigating and implementing solutions to improve material and energy yield at their facilities. Examples can be implementing automation and smart manufacturing such as artificial intelligence (AI) and robotics across an array of applications, developing new alloys including next-generation advanced high-strength steels that require less material per application, optimizing recycling for raw material inputs such as metallic scrap, and reuse of coproducts from the overall production process such as power generation from offgas heat. This chapter describes available

Table 2. Estimated Specific Energy Consumption and Specific CO_2 Emissions Per Metric Ton of Product of the Current Pathways For Iron And Steel Production In Europe In 2009.[148]

	Primary energy (GJ/t)	Direct energy (GJ/t)	Total CO_2 emission (tCO_2/t)	Direct CO_2 emission (tCO_2/t)
Coke plant	6.827	6.539	0.824	0.794
Sinter plant	1.730	1.549	0.211	0.200
Pellet plant	1.204	0.901	0.075	0.057
Blast furnace	12.989	12.309	1.279	1.219
BOS plant	-0.253	-0.853	0.202	0.181
Electric arc furnace	6.181	2.505	0.240	0.240
Boom, slab and billet mill	2.501	1.783	0.125	0.088
Hot strip mill	2.411	1.700	0.120	0.082
Plate mill	2.642	1.905	0.133	0.098
Section mill	2.544	1.828	0.127	0.084
Pickling line	0.338	0.222	0.016	0.004
Cold mill	1.727	0.743	0.075	0.008
Annealing	1.356	1.086	0.070	0.049
Hot-dip metal coating	2.108	1.491	0.104	0.059
Electrolytic metal coating	4.469	2.619	0.208	0.046
Organic coating	1.594	0.758	0.074	0.003
Power Plant	12.173	12.173	1.989	1.989

technologies and solutions to improve material and energy optimizations in iron- and steelmaking.

Iron- and steelmaking are energy-intensive processes. Roughly 400 kg of CO_2 is emitted per ton steel in the EAF. A modern EAF typically consumes 300–400 kWh of electricity per liquid ton of steel. The processing stage of liquid steelmaking and refining serves as the gatekeeper for adjusting the steel chemistry and ensuring quality by removing unwanted impurities. Chemical energy provides an additional 300–400 kWh of energy to the process through bath reactions involving oxygen, carbon and oxy-fuel burner inputs. Energy losses include those through the EAF shell and those to water-cooled components. The theoretical minimum energy

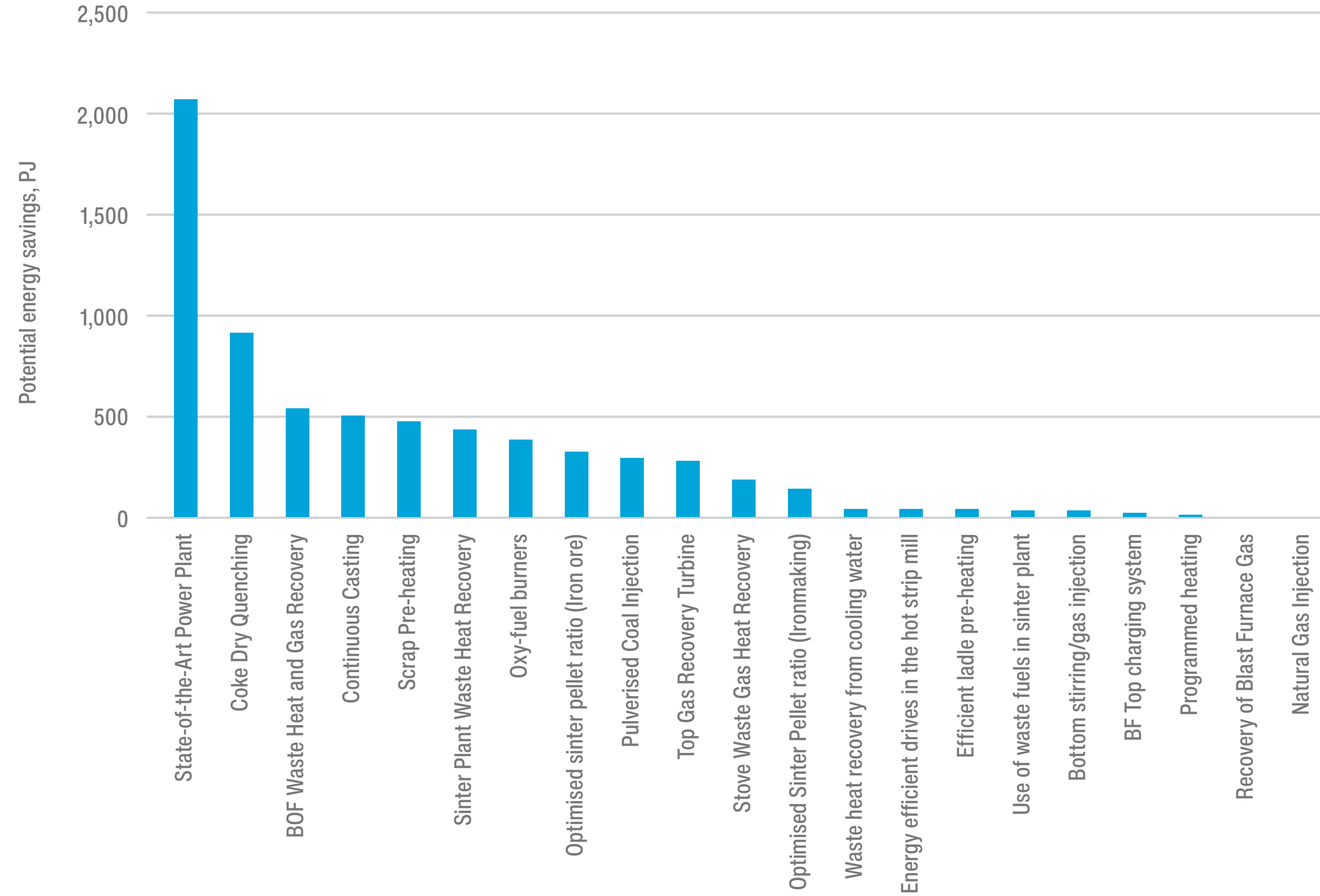

Figure 9. Ranking of the potential energy savings for best available technologies in the EU iron and steel industry in 2009.[149]

required for melting steel and raising it to casting temperature is approximately 370 kWh/liquid ton of steel. Thus, depending on material recoveries and effective energy transfer, the EAF can be 20–30% more energy efficient than the current state of the art.[29,30,31]

The report "Prospective Scenarios on Energy Efficiency and CO_2 Emissions in the EU Iron & Steel Industry" compared the energy and CO_2 requirements for various stages of ironmaking and steelmaking, considering embedded chemical energy, process heat, required mechanical work, etc., and the results are shown in Table 2. Primary energy refers to the actual energy content (lower heating value) together with the upstream energy used to produce a material (e.g. energy to produce electricity). Direct energy refers to the energy use of a specific installation only. Total CO_2 emission refers to the direct CO_2 emission to air due to use of material together with the upstream emissions (emitted by suppliers) of a limited list of materials. Direct CO_2 emission refers to only CO_2 emission to air of a specific installation. In the integrated route, ironmaking in the BF, which currently involves reducing iron oxides with carbon, is the largest contributor of the processing steps. In the integrated route, there is additional CO_2 associated with cokemaking and agglomeration.[32]

The same study also evaluated the best available technologies on energy saving potential in the European iron and steel industry, see Fig. 9. This potential is a measure of the total energy savings when a specific technology is installed at all possible facilities in the EU. The crude steel production in EU-27 in 2009 was 138.8 million metric tons and the capacity share was BOF 55.9%, EAF 43.6% and OHF 0.5% (World steel in Figures 2010). This report points to the significant potential for a reduction of CO_2 through advancements in available technologies today.

Within the category material and energy optimization we offer the following technologies to enhance industry competitiveness.

Optimizing the DRI–EAF Process Route of Steelmaking

DRI is a key raw material for reducing carbon emissions in steelmaking. The DRI-EAF process route will enable CO_2 emission reduction of approximately 45% compared to the BF-BOF route. DRI-EAF emits about 1.2 tons of CO_2 per ton of steel, while BF-BOF emits about 2.2 tons. Other benefits are that the DRI-EAF process route can use recycled steel scrap and green hydrogen as energy input. This will further reduce the carbon emission reduction significantly compared to conventional steelmaking.

DRI production is limited due to the availability of high-quality iron ore, which needs to have 67% or higher iron content and low level of impurities. There is not enough high-quality iron ore to meet global steel demand. DR-grade iron ore is rare, making up about 4% of the world's iron ore supply. To overcome this issue, one option being pursued is the use of BF-grade pellets in DRI processing units followed by a submerged arc furnace (SAF) melting stage with the resultant hot metal fed to BOF converters. Another process route, developed by Tenova, is a new technology combination to produce direct reduced iron using lower-quality BF-grade pellets in an open slag bath furnace (OSBF). Various companies are also developing fluidized bed reduction processes using hydrogen to reduce iron ore. This process would also enable the usage of iron ore fines as input material.[33]

Maximizing Steel Scrap for Steelmaking

Utilizing recycled steel scrap for steelmaking through the EAF process will eliminate roughly 1,500 kg CO_2 per ton steel in comparison to the blast furnace process.[7] More than 68.3% of steel in the U.S. is already produced through the scrap-based EAF process. The primary challenge for EAF scrap charging and recycling is the presence of undesired elements, such as Cu, Ni, S, P or Sn, in scrap. These elements cannot easily be removed during liquid steel processing, resulting in deleterious effects downstream, such as hot shortness or cracking during thermomechanical processing (TMP) and hot deformation at elevated temperatures. While all steel can be recycled, the limitation is that the products that can be remade are limited to those that are not thin-gauged, which often means lower value. Examples are Cu and Sn in steel scrap which originates from tinplate, wires and motors in cars; these can cause surface cracking (hot shortness) during secondary cooling or thermomechanical treatment. The cracking phenomenon occurs at 0.1 wt. % Cu content or greater. Shredded car scrap and obsolete heavy scrap have an upper tolerance level of Cu contents of 0.23 wt. %, which is a significantly higher level than what causes surface hot shortness. This problem will become more significant over time, as Cu and other undesired element levels are anticipated to rise further in scrap with the push for automotive electrification. Inevitable feedstock changes made in ironmaking or recycling will result in adjustments needed in this stage to ensure quality and process control downstream. To overcome these issues, end-of-life processing of steel scrap including product design for circularity will be strategically important across the broader economy. Sorting of steel scrap at the scrap yard involves physical separation, magnetic separation, shredding and sensor-based sorting. Sensor-based sorting technology of steel scrap at the scrap yard is under development and involves camera-based optical recognition, laser-induced breakdown spectroscopy (LIBS), x-ray transmission and fluorescence (XRT and XRF), and prompt gamma neutron activation analysis (PGNAA) in combination with machine learning algorithms.[12] Impurity elements can also be refined to a certain degree at the steel mill. In an experimental study by Xiaojun Hu et al., it was demonstrated that Cu removal from a steel melt by using $FeO\text{-}SiO_2\text{-}CaCl_2$ slag at 1,873 K was possible. The study showed that 40% of the Cu in the steel melt was removed within 10 minutes by volatilization of CuCl into a gas phase.[34] The ratio of metal to slag used was 100 g to 15 g. Global material flows of steel scrap trade will also be of importance to securing raw material assets of steel scrap for steelmaking.

Ongoing industrial projects related to steel scrap represent steel scrap sorting and processing, automated analysis on the alloy content in steel scrap, scrap bucket charging, etc. Currently the most common method to reduce Cu content in scrap heats is to dilute with pig iron, which contains low Cu contents but has a high embedded carbon footprint during manufacturing, when considering the embedded energy in carbon currently spent (and CO_2 emitted). The steel industry has successfully managed to increase the tolerable Cu content through process control and deploying machine learning in scrap sorting.[12]

Optimized Blast Furnace Process

The blast furnace is currently the most economical pathway for producing large volumes of high-quality metallic iron. However, the BF also produces more CO_2 than it does metallic iron. The BF is a complex, multiphase heat and mass exchange reactor where the process consists of many steps in different temperature zones. The BF is a steady-state continuous process in which coke is burned in front of the tuyeres and produces CO, CO_2 and heat. To better understand and optimize the process, extensive 3D modeling can be done to simulate the raceway, active coke zone, cohesive zone and stack zone. Optimizing the BF can be done by increasing the material yield and energy efficiency in the process route. Research needs to be done on optimizing the charge and smelting process and to obtain the lowest cost while mitigating carbon emissions.

Energy Optimization in the EAF Process

Depending on material recoveries and effective energy transfer, the EAF can theoretically be 20–30% more energy efficient than the current state of the art.[29,30,31] This gain can be achieved by setting the best control profiles for the EAF, such as regulating transformer power, balancing oxygen, carbon, natural gas, etc., and optimizing the raw material mix and tapping temperature. It is also important to keep the refractory in good conditions to avoid heat dispersion, avoid contact between electrodes and scrap, and have enough slag/foam on top of the melt to reduce radiation and convection from the top of bath and keep the molten metal hotter. Machine learning methods and optimized power purchasing can help to reduce energy consumption and cost, as well as to improve average tap-to-tap time. EAF operations with postcombustion CO can further improve energy recovery.

Material and Energy Recovery From Slag

Steel slag is the main coproduct produced at steel mills. Recovery of thermal heat from liquid slags and extraction of valuable metals are of great importance. Heat exchangers extract thermal energy from the slag and transfer it to water or oil. The captured energy can be used for various processes, such as gas preheating or generation of steam. Metals from slag can be extracted by magnetic separation and recycled. The near-zero-waste concept aims to reduce, reuse, and recycle waste at its source, and minimize all waste where landfill and incineration without energy are applied. This minimizes any possible negative effects of waste discharged to the environment.

Opportunities to Design or Produce Alloys That Are Less Carbon-Intensive

Higher-strength steels for auto bodies have provided benefits in vehicle weight reduction and fuel efficiency. With a lower weight per application, the carbon footprint of steel can be reduced in the manufacturing process and during its in-use stage by consuming less fuel. Development of higher-strength structural steels for construction is essential for affordable and sustainable housing. High-silicon electrical steels for motor laminations and transformer cores are important, and there are innumerable opportunities throughout the economy such as durable bearings for wind turbines; corrosion-resistant coatings or alloys for extreme environments; and wear-resistant and fatigue-resistant steels for life extension and enhanced performance and/or efficiency. New hydrogen-cracking-resistant steels are also needed to store or transport hydrogen in support of the evolving "hydrogen economy." All these examples represent critical areas of manufacturing competitiveness for the U.S. industry.

Use of Oxy-Fuel and/or Air-Oxy-Fuel Burner Technology

Oxy-fuel and air-oxy-fuel combustion are established technologies that are used in diverse high-temperature melting processes including in the iron and steel industry. The use of oxy-fuel or air-oxy-fuel technology helps to improve the thermal efficiency of any high-temperature heating process. The major reasons for the improved thermal efficiency performance are the absence or reduction of nitrogen diluent in the oxidizer stream which reduces the energy carried away with nitrogen in the exhaust flue, and the effective heat transfer rate from furnace gases to the melt or material increases.[35] This improved thermal efficiency assists in reducing fuel usage per pound of material processed.

Oxy-fuel burner technologies are utilized in both integrated steel mills and mini-mills. Applications of oxy-fuel and air-oxy-fuel burner technologies include ladle preheating,[36] steel reheating furnaces,[37,38,39] electric arc furnaces[40] and annealing furnaces.[41] The amount of fuel savings from air-oxy-fuel or oxy-fuel burners depends on several factors, including but not limited to the type of furnace, furnace air leakage, how the oxy-fuel technology is implemented, and the type of oxy-fuel burner used. A major portion of the energy for combustion derives from hydrocarbon fuels, and the conversion of the carbon in the fuel to CO_2 is a major source of greenhouse gas emissions from combustion processes. Therefore, the fuel savings as much as 15–40% by use of oxy-fuel or air-oxy-fuel burners assist in the reduction of the carbon footprint from furnace operations. Additionally, reduced fuel consumption using oxy-fuel or air-oxy-fuel technology is an added advantage as energy-intensive industries move toward the use of low-carbon-intensity fuels such as hydrogen and ammonia. These low-carbon-intensity fuels are currently expensive compared to fuels like natural gas, and therefore, use of oxy-fuel or air-oxy-fuel burner technology can help to reduce fuel costs and provide economic benefits to iron and steel producers.

Smart Manufacturing

Smart manufacturing will transform the steel industry in the way we source raw materials and manufacture and market our products through horizontal and vertical supply chain integration. Smart manufacturing involves digitalized technologies and smart sensors, flexible mills, and near-net-shape products. Digital technological pathways along with materials and engineering advancements can be utilized to reduce environmental emissions. Integrating digital transformation technologies into an industrial operation requires a holistic shift in how the business operates and affects all aspects of an organization, from its business model to its culture, and may require a significant change in management mindset. One of the most important challenges in digital transformation is the resistance to change within

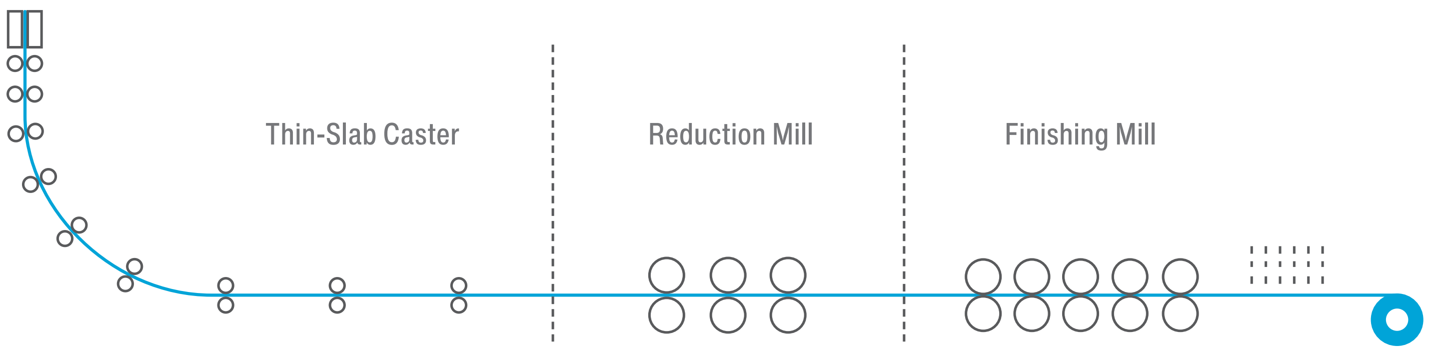

Figure 10. Schematic layout of in-line casting/rolling steel for steel sheet production.[150]

organizational culture. Employees and leadership must be aligned with the digital vision to foster a mindset that embraces innovation and continuous learning.

Data analytics of process data must continue to evolve to optimize production conditions to account for variations in feedstock which will be necessary to show improvements in economy and quality.[11] Digitalization offers manufacturers opportunities to improve operational efficiencies, optimize heat and power, improve design and materials, and optimize logistics and transport, which benefits their business and environmental impact. One specific area of development includes research for deploying advanced sensors that are capable of tolerating the harsh environment of a steel plant with respect to temperature, force and humidity. These sensors, including fiber-optic applications, will be essential for data collection and pattern recognition. Digitalization can also be used to optimize power grid integration for variable renewable energy sources, creating an interconnected grid with multidirectional power flow. In this regard, digitalization will allow integration of the production cycle with electrical energy usage and will further increase the usage of green power and reduce Scope 2 emission by steel producers. Overall, the application of smart manufacturing technologies can optimize energy and resource usage and improve supply chain management.

Further, steel mills need to evolve flexible production lines where they can easily change production routes to adapt to their customers' needs. A flexible manufacturing system involves production lines that can rapidly alter the type of product being produced, which allows facilities to respond to market changes quickly. It requires a fully computerized system that allows adjustments in either production volume or the types of manufactured items. While challenging for steel production, the EAF has revealed enhanced efficiency with respect to power utilization and "start-stop" cycles in comparison to the BF, which performs best in constant steady-state operation.

Near-Net-Shape Cast Products

The near-net-shape casting of products occurs where the initial solidification of the custom component is as near as possible in size and shape of the final product. This process minimizes the need for additional production processes such as rolling, surface finishing and machining, thereby reducing scrap generation, waste material, costs and carbon emissions. Examples of near-net-shape production technologies across manufacturing sectors are additive manufacturing, linear and rotary friction welding, die casting, sand casting, investment casting, and injection molding. For metals, near-net-shape casting processes have eliminated the need for reheating and the degree of required hot rolling.

For long steel products, near-net-shape production has been well known since the 1970s, including the so-called "dogbone" continuous casting for beam production used throughout the construction industry. More recently in the 2010s, the so-called "micro-mill" technology has evolved the production of reinforcing bar and merchant bar steels. This single-strand process utilizes in-line casting and contiguous rolling for enhanced energy and production efficiency. Within the U.S., this micro-mill technology from Danieli (Italy) has been deployed by CMC and Nucor at multiple plants and is under evaluation (2024) by others, including Pacific Steel Group. Competing technologies from SMS (Germany) are currently under installation by Hybar LLC.

By far, the most significant impact from near-net-shape cast products has evolved since the 1980s for flat steel products. Initially trialed in 1988 by Nucor, the compact strip mill technology from SMS has revolutionized the production of steel strip and sheet across the world. While there are now numerous competitors including Danieli, the process generally includes the casting of a "thin" slab ranging from 50 to 150 mm in thickness fed in-line to a hot mill. Hot-rolled coils are delivered from liquid steel in a connected casting and rolling facility in an uninterrupted and continuous manufacturing process. These casting-rolling plants are considerably more compact than conventional slab casting and rolling mills. Within the U.S., this compact strip mill technology from SMS has been pioneered and deployed by Nucor as well as Steel Dynamics. A competing technology from Primetals Technologies (Austria) called Arvedi ESP claims 45% lower energy consumption and associated costs compared to conventional mills with separate casting and rolling processes. Accordingly, endless casting-rolling plants also have substantially lower CO_2 emissions.[42] This technology is currently under installation by U. S. Steel.

The near-net-shape production processes can affect scale formation and the ability to control product quality, surface quality, mechanical properties, and recyclability. New methods of microstructure control will be required for near-net-shape casting processes, which combine casting with thermomechanical processing, as the production processes become more widely deployed. As the content of residual elements in scrap accumulate, mitigating surface cracking through microstructure control will be crucial. In addition, new advanced high-strength steels, combining strength and low-density with allowable downstream processing, i.e. forming, coating and joining, will continue to be needed. In cases like those discussed above, materials science informatics may be used as a tool to find new alloy chemistries and processing pathways. Machine learning tools coupled with extensive databases can be used to explore wider compositional spaces to optimize alloy chemistries[43,44] or to optimize processes.[12] Scrap blends will need to be optimized to lower costs while avoiding issues with hot shortness.

Co-Location of Iron and Steel Production Facilities

Co-locating DRI production facilities with EAF melting facilities allows for an opportunity for significant energy savings by enabling the hot transfer of DRI to the EAF. Hot DRI transfer is reported to save approximately 26 kWh/ton liquid steel for every 100°C increase in hot-charge DRI temperature in the EAF.[45] This could be an important enabling technology for improving the efficiency of melting carbon-free, high-melting-point, hydrogen-produced DRI.

Other synergies have also been envisioned through the combination of manufacturing processes, such as combining carbon black production with DRI production using methane. Here, the hydrogen byproduct of the carbon black production process could be utilized for DRI feedstock production with a low CO_2 footprint. Most integrated steelmaking mills co-locate coke plants with blast furnace facilities, which enables bridging technologies for improved utilization of offgas streams between processes and allows for the centralization of sequestration and heat recovery facilities. Co-location of DRI and BF facilities could also provide similar benefits.

De-Coupling of Iron and Steel Production Facilities

Although steelmakers, particularly those in Europe, are pursuing decarbonization strategies that integrate direct reduction ironmaking with EAF steelmaking, we should note a potential, alternative strategy, one in which iron production is decoupled from steel production. In this scenario, ironmaking facilities could be centered in places with access to iron ore and clean energy, and steelmaking facilities being centered in the markets the final product is intended to serve.

For example, Vale is exploring the feasibility of building a number of so-called iron ore mega hubs in the Middle East, having signed memorandums of understanding and cooperation agreements with the Kingdom of Saudi Arabia, the United Arab Emirates and the Sultanate of Oman in 2022. These hubs would leverage the region's abundant natural gas and solar energy, extensive DRI infrastructure, and know-how to produce a briquetted direct reduced iron. As Vale envisions, it would build and operate concentration and briquetting plants within the hubs, and investors or customers would construct and operate the direct reduction plants and be the off-takers of HBI for either the export or domestic markets.

In a similar vein, Vale in 2023 signed a memorandum of understanding with the Port of Açu, Brazil's largest, privately owned deepwater port, to study the development of a mega hub. The hub would include a gas-fired DRI plant that potentially could be switched over to green hydrogen.

In the United States, Vale is negotiating a project in 2024 with the Department of Energy to build a plant utilizing its cold iron ore agglomeration technology. The plant, to be built on the Gulf Coast, would have a capacity of 1.5 million tons annually and would be co-located with a direct reduction plant. The project aims to be in commercial operation by 2029.

Challenges and Knowledge Gaps With Replacing BFs With DRI–EAF

Challenges with replacing the BF with DRI–EAF production routes at integrated steel mills include the physical and logistical integration of a DRI production module as well as the EAF–ladle furnace units in an existing BF iron plant and BOF steel plant. Ideally, the location of the EAF should be close to the DRI production to take advantage of the energy efficiency benefits of hot DRI transfer to the EAF. Physical space may be a limiting constraint, which may create difficulties with the logistics of material handling. Producing steel grades with lower levels of impurities (e.g., Ni, Cu, Mo, Cr, S, N, P) with an EAF may also be challenging when using 100% steel scrap. EAFs typically have a smaller batch size than the BOF, which may require more heating and refining time

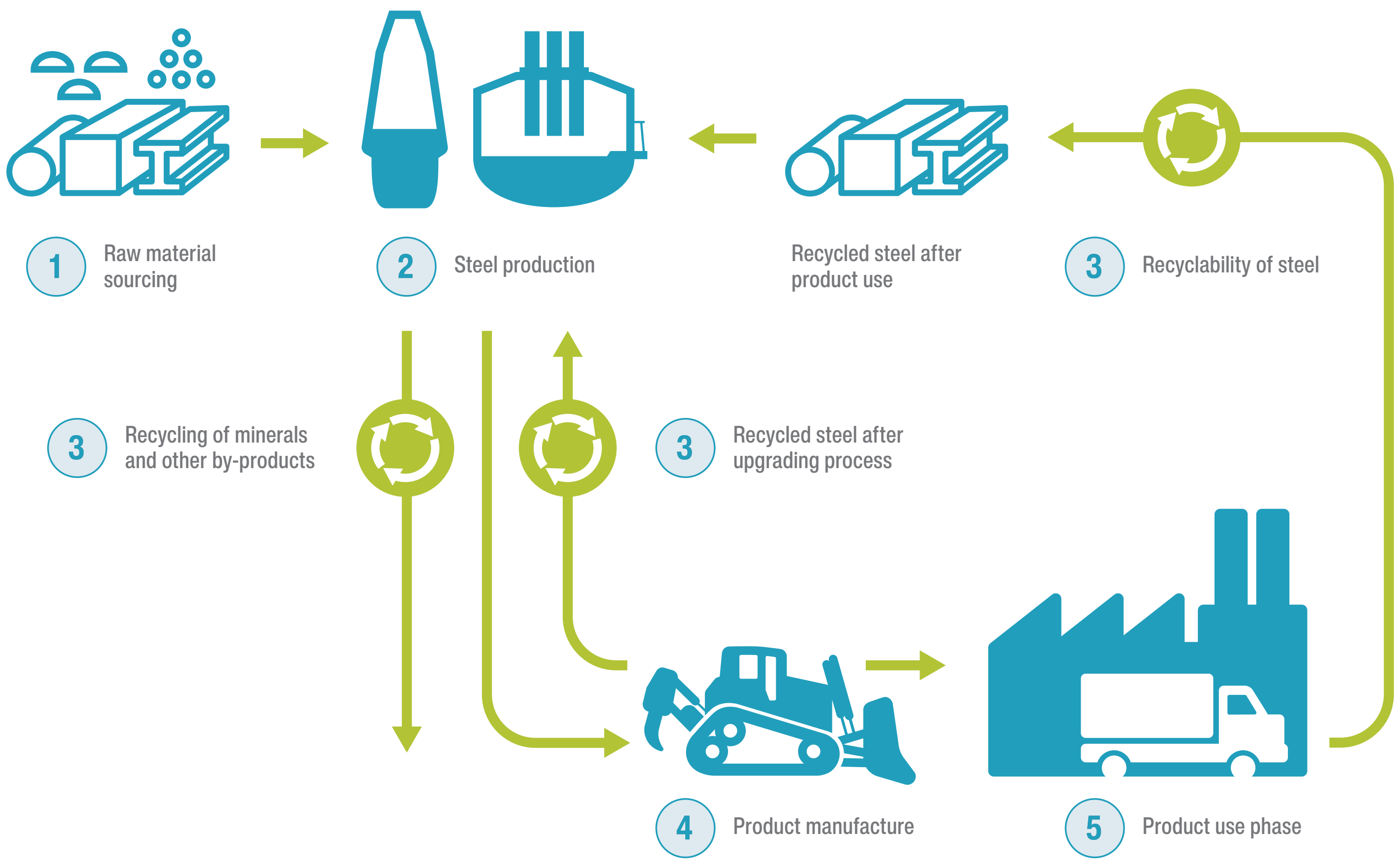

Figure 11. The life cycle of steel and recyclability of steel products.

in secondary metallurgy due to the absence of a hot metal pretreatment step. The EAF tap weight also affects the pacing of the continuous casting process. A smaller EAF tap weight may require shorter tap-to-tap times and high-powered EAFs. The tap-to-tap time will further affect the pacing of ladle metallurgy furnace processing and the continuous casting speed, which depends on the geometry and size of the cast. There may also be more chemical analysis and temperature analysis needed for the same reason. To replace one BF, approximately three DRI shaft furnaces and four EAFs are needed. This estimation is based on the assumption that an average DRI shaft furnace produces 2 million tons/year, an EAF 1.5 million tons/year and a BF 5.65 million tons/year.[46]

Challenges and Knowledge Gaps in Recycling Steel Scrap

Challenges in the recycling of steel scrap (see Fig. 11) include determining the potential for deploying sorting and separation technologies to separate residuals from scrap, and for removing residuals in the liquid state. Technological breakthroughs are needed for handling variations in scrap impurities (Cu, S, P, N, etc.) to enable scrap and other feedstock flexibility, including technologies for mitigating residual induced cracks during casting and thermomechanical processing. Also required is further understanding of what product lines can be sustained through a nonlinear scrap-based feedstock supply chain, when considering the uncertainties in chemistry.

There have been significant advancements in scrap metal sorting techniques, mainly due to the growing demand for recycled metals. Using effective sorting techniques has become essential to maximize resource recovery and reduce waste. The ferrous and nonferrous metals are separated using shredders in combination with massive magnetic sensors. Sometimes the metal streams are further detected and sorted using metal analysis equipment. Traditional scrap sorting technologies include hand sorting, eddy current separation, flotation sorting and gravity-based separation. More modern sorting technologies include near-infrared spectroscopy, x-ray fluorescence spectroscopy, LIBS, hyperspectral imaging, optical-based sorting, robotics and artificial intelligence, and integrated sorting techniques. These technologies also allow for alloy analysis and optimization of scrap sorting based on scrap composition.

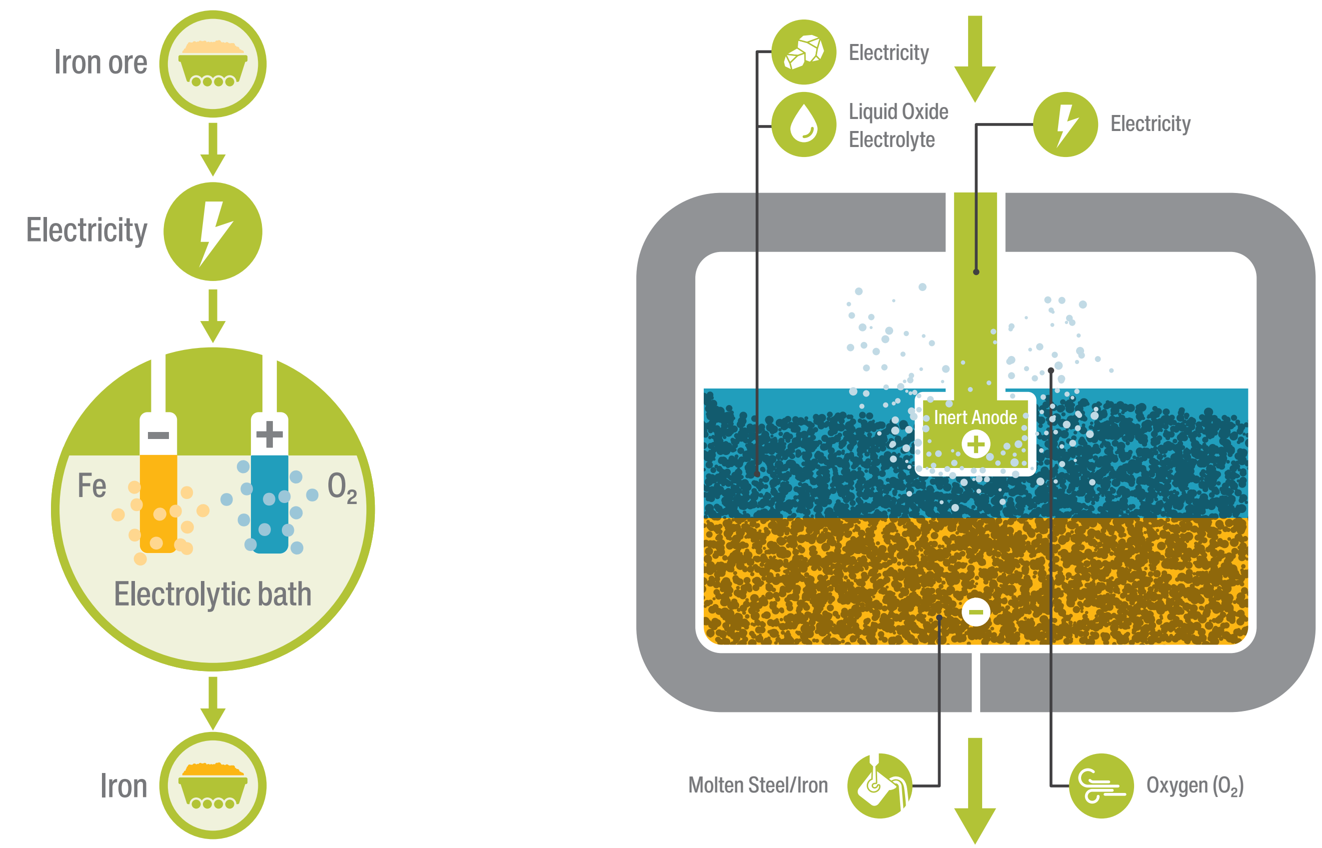

Figure 12. The ArcelorMittal SIDERWIN process (left) and Boston Metals process (right).

II. Electrification of Iron and Steel Processes

Electrification to Replace Fossil-Fuel-Driven Equipment With Electric Power From Renewable Sources

The challenge with intermittent renewable power (solar/wind) is the lack of sufficient energy storage and ability to achieve fossil-free operation during downtimes. A steelmaking plant generally should operate continuously with greater than 85% utilization to generate sufficient output to return its cost of capital, i.e., to pay back the capital investment. Co-locating near continuous renewable power sources (e.g., hydroelectric, geothermal stations or nuclear power) is a viable option, but the location requires steel market access and must consider that competition from other sectors needing the same green power may make it too expensive (e.g., grid parity with natural gas). Several domestic EAF facilities have announced plans to collaborate with local utility companies to take advantage of the benefits of their geographic location to integrate locally generated green electricity into the local grid that supplies their facilities. Examples of this are EVRAZ North America's collaboration with Xcel Energy and Lightsource BP in Colorado; Nucor Steel Sedalia LLC's collaboration with local wind power company Evergy in Missouri; and Steel Dynamics Inc.'s collaboration with wind power company Nextera Energy Resources for its facility in Sinton, TX.[47]

The application areas for electrification to decarbonize the steel industry is broad. Electrification may offer opportunities for product innovation/improvement in addition to carbon reduction. The metals and steel industry require higher temperatures around 1,600–1,800°C, which can be difficult to achieve through electrification. The following iron and steel industry processes have been identified to have the potential to replace fossil fuels with renewable electricity.

Electrolysis Reactor for Iron Production

The use of an electrolysis reactor rather than the traditional blast furnace offers an attractive route to replace carbon with electrons to produce iron electrolytically. This could be achieved through both low- and high-temperature electrolysis reactors, which have been demonstrated in the laboratory and at the pilot scale. One type of electrolysis reactor is aqueous electrolysis electrowinning of iron oxide ore in aqueous alkaline solutions. The process involves iron ore suspended in concentrated aqueous sodium hydroxide (NaOH) solutions with a cathode (e.g., graphite electrode) and an anode (e.g., nickel) to extract iron metals by applying a constant current. At laboratory scale, efficiencies of above 90% with respect to iron deposition have been obtained. However, scaling these systems to the production levels required for industrial steel production remains a significant challenge to its viability.

Current industrial efforts in electrolysis reactors for steelmaking focused on replacing the traditional blast furnace with an electrolysis reactor is one of the long-term options being explored by ArcelorMittal and others to achieve steel production that has the potential to drastically decarbonize ironmaking while also creating a more energy-efficient process. The low-temperature SIDERWIN process (see Fig. 12), developed in Maizières, France, by ArcelorMittal[48] can offer a lower-capital-cost option for replacing carbon. The project was funded through the EU Horizon 2020 program at just under US$8 million and was finalized in September 2022. This process is anticipated to reduce the company's carbon intensity by about 30% while also increasing energy efficiency by approximately 30% compared to a traditional blast furnace. In 2023, ArcelorMittal and John Cockerill announced plans to develop the Volteron™ plant, which is based on the same principle as the SIDERWIN process. The Volteron plant is targeted to start production in 2027.[49]

Boston Metals[50] has demonstrated a high-temperature electrolysis process using molten oxides, which has the potential for higher kinetics. Boston Metals is a U.S. startup out of the Massachusetts Institute of Technology that just recently closed a series C funding round of US$262 million. Boston Metals is working to deploy a demonstration plant in 2024–2025. Electra has constructed a pilot plant facility at its Boulder, CO, headquarters to produce metallic iron from high-impurity ores. Electra is an electrochemical process that operates at 140°F. The product is high-purity, low-carbon iron in approximately 1-meter-square plates, which can be melted together with steel scrap in the EAF.[51,52]

Electric Smelting Furnaces

The electric smelting furnace (ESF) technology is a long-established reduction process used in the nonferrous metals industry. The iron- and steelmaking route involves a DRI unit combined with an ESF and followed by the BOF process. The conventional BF is eliminated. There are two distinct designs for the ESF unit: the spherical shell design and the rectangular six-in-line-furnace design. Both designs are widely used for smelting and processing ferroalloys such as FeNi, $FeTiO_3$, platinum group metals, Ni and Cu. A rectangular smelter's dimensions are usually 40 m x 15 m x 9 m, while the round units can have diameters up to 20 m and heights up to 6 m. When converting the ESF into a steelmaking process, there are technical restrictions on the furnace's size that must be met to guarantee consistent thermal expansion of the refractory material. Due to the high presence of gangue oxides and varying levels of carbon in DRI/HBI, additional amounts of lime, dolomitic lime and doloma are required in the ESF. These divergences in raw material input will further affect the metallurgical conditions, electrical energy demand, chemical energy and the size of the hot heel in the furnace. The gangue present in the DRI/HBI charge reduces the metal yield and lowers the basicity of the slag unless compensated with additional acidic flux. The increase in the quantity of process slags in comparison to standard operation using steel scrap affects the lifetime of the refractory lining and increases the electric demand due to the higher incoming slag volume. Due to these process conditions using DRI/HBI, both the melting time and the tapping time of the heat can be considerably longer than that of standard operation using steel scrap.[53]

The DRI–ESF technology is predicted to be able to reduce CO_2 emissions by more than 80% in comparison to the conventional BF steel route. Compared to the BF, the ESF technology can process a larger range of iron ore grades, including medium-grade ores with low yield losses. Low-grade ores are difficult to process in EAFs using the H_2DRI or DRI process pathways; as a result, new electric smelting technologies must be created and implemented. In March 2023, BHP and Hatch signed a contract to build a small-scale ESF pilot plant in Australia.[54] In September 2022, Hatch also signed a contract with Tata Steel to provide the engineering for the reducing electric furnace to make green steel at the IJmuiden plant in the Netherlands.[55] In March 2023, thyssenkrupp in Duisburg placed an order to construct a hydrogen direct reduction plant and two melters. The plant is scheduled to be completed by the end of 2026 and will have a hydrogen DRI capacity of 2.5 million metric tons per year.[56] In 2024, Cleveland-Cliffs Middletown Works received a DOE grant to replace its blast furnace with a 2.5 Mt hydrogen DRI plant and two 120 MW electric melting furnaces.[57]

Scaling Up of Electric Induction Furnaces to Lower Emissions

An electric induction furnace heats metal by electromagnetic induction. Induction heating equipment can be a heating furnace, melting furnace, vacuum induction furnace, metal quenching and tempering induction heating furnace, etc. The advantages of induction furnaces are rapid heating, nonoxidizing atmospheres which minimize scale formation and losses, compact installations, and flexible heating and cooling configurations. Induction furnaces can reduce emissions like carbon dioxide, nitrogen oxides and sulfur dioxide by at least 50% in comparison to the traditional EAF.[58] Induction furnaces don't produce direct emissions (Scope 1) since they don't burn fossil fuels like traditional furnaces. On the other hand, induction furnaces don't have refining capabilities. The raw materials placed in the induction furnaces must be clean and have a known composition. Alternatively, the molten metal can be further treated at the ladle refining station.

Electrification of Pelletizing of Iron Ore

Electrical heating alternatives in the form of plasma torches and microwaves to pelletize iron ore are under investigation. This would replace the fossil fuel burners, providing potential for a CO_2-neutral production process for pelletizing magnetite ores. For pelletizing hematite ores, the carbon addition to the pellet feed needs to be replaced with biomass. Challenges include how process conditions are affected when switching to an electric heating source. Pilot trials at LKAB in Sweden have shown that implementation should be possible for both plasma torches and microwaves. One performance indicator that requires attention is the potential NOx emissions from plasma torches.[59] In 2023, Brazilian mining company Vale S.A. conducted pilot trials to replace anthracite coal with biomass to make pellets.[60]

Replacement of Coke With Electrolytically Generated Net-Zero-Carbon (NZC) Syngas

Syngas is generated by capturing the CO_2 from the furnace, bubbling it into water, and conducting co-electrolysis of the H_2O/CO_2 to generate H_2/CO. This could be accomplished with low-temperature electrolysis (LTE) in the shorter term and high-temperature steam electrolysis (HTSE) as technology matures. The furnace could provide the heat to drive the more efficient HTSE. With co-electrolysis and CO_2 looping, the energy to reduce the iron ore is electrical and there is limited loss of carbon. This is an emerging platform and an approach that could come close to net-zero carbon. The process is similar to using hydrogen generated by water electrolysis.[61]

Electrification of Reheat and Other Downstream Furnaces

Reheating furnaces have a high impact on CO_2 emissions in downstream steel processing. Reheating furnaces are used to heat and homogenize temperatures in semifinished cast products to be further processed in the mill. The CO_2 emissions of steel reheating furnaces with best available techniques are in the range of 63.2–76.0 kg CO_2/ton steel depending on steel quality and type of steel products.[62] Currently, the steel industry almost exclusively uses gas-fired reheating furnaces due to the lower energy costs. Slab reheating furnaces such as walking beam furnaces and tunnel furnaces use mainly natural gas. Alternatives are electrical induction heating, plasma heating or hydrogen combustion where hydrogen is produced by electrolyzers (indirect electrification). One example is Cleveland-Cliffs Inc. in Butler, PA, replacing two natural gas–fired reheat furnaces with electrical induction reheat furnaces.[57] Renewable energy can also replace fossil fuels at existing plants in the annealing, thermal treatment, coating, galvanizing and painting processes. Application of high-power laser diode technology may also be employed for the reheat furnace. High-power diode lasers provide a more flexible and precise surface treatment of steel components. Diode lasers offer a more economical method in heat treating metals over other heating sources, such as gas flames or induction coils, since they allow energy-efficient hardening of complex component geometries. These lasers are currently being used for surface hardening of steel components and for preheating steel alloys prior to friction stir welding to reduce tool wear and increase welding speeds.[63,64]

Examples of Ongoing Industrial Projects

In 2024, The U.S. Department of Energy announced the Industrial Demonstrations Program Selections for Award Negotiations: Iron and Steel, where six iron and steel projects were awarded US$1.5 billion to reduce a combined 2.5 million metric tons of CO_2 emissions annually.[65] The projects focus on hydrogen DRI fed to an EAF; hydrogen DRI fed to an ESF; induction reheat furnaces for slabs; replacing cupola furnaces with induction melting furnaces; replacing coke-fired foundry furnaces with induction melting furnaces; and cold-agglomerated iron ore briquette production. An overview of the six projects is shown in Table 3.

Challenges and Knowledge Gaps

More investments need to be directed to support process integration and optimization of electrification of industrial processes. Challenges include identifying the electrical power requirements of these facilities and the cost and reliability of supplying this power. Challenges also include strategies for managing the variability in renewable electricity generation, grid integration, capacity expansion and energy storage such that baseload energy requirements can be harmonized with intermittent energy availability. There is also a need for modeling, validation and optimization of these technologies. In addition, more investments are needed to support the scale-up of existing processes through testbed projects.

Challenges and knowledge gaps in electrolysis reactors for steelmaking include limitations with scale-up when considering surface area limited reduction and associated kinetic limitations owing to mass transport. Improving feedstock solubility of the reductant in electrolyte and electrode consumption are challenges that must be addressed prior to industrial adoption.

III. Alternative Low-Carbon Reductants and Energy Sources

The U.S. steel industry is less carbon-intensive than other major steel-producing regions due in part to increased use of natural gas, which is not as plentiful in other regions of the world. The most considered alternative for carbon-based (coke or natural gas) reduction of iron ore and overall energy generation has been hydrogen due to its potential to be produced at scale.[66] This requires new infrastructure

Table 3. Industrial Demonstrations Program Selections for Award Negotiations: Iron and Steel Projects (as of 2024).

Project Title	Hydrogen-Fueled Zero Emissions Steel Making
Company	SSAB Americas
Location	Perry County, MI, and Montpelier, IA
Budget	Federal cost share up to US$500 million
Description	SSAB will construct a HYBRIT® facility to produce fossil-free DRI using 100% green hydrogen. The project will also involve expanding SSAB's Montpelier, IA, steelmaking facility to melt the hydrogen DRI. SSAB has signed a statement of intent with HyStor Energy to provide green hydrogen and renewable power for the DRI operation. SSAB estimates that the emission reductions from the hydrogen DRI process will reduce emissions by 81% in comparison to conventional process route.
Project Title	Hydrogen-Ready Direct Reduced Iron Plant and Electric Melting Furnace Installation
Company	Cleveland-Cliffs Inc.
Location	Middletown, OH
Budget	Federal cost share up to US$500 million
Description	Cleveland-Cliffs is leading a project to install a hydrogen-ready flex-fuel DRI plant and two electric melting furnaces at Cleveland-Cliffs' Middletown Works mill in Ohio. The project would result in an estimated 1 million tons of GHG emissions reductions annually. In addition, this project intends to demonstrate critical hydrogen-based ironmaking technologies while also replacing one of Cleveland-Cliffs' seven operational blast furnaces.
Project Title	Steel Slab Electrified Induction Reheat Furnace Upgrade
Company	Cleveland-Cliffs Inc.
Location	Lyndora, PA
Budget	Federal cost share up to US$75 million
Description	Cleveland-Cliffs' project aims to electrify the United States' only high-silicon grain-oriented electrical steel (GOES) production plant. GOES is an important material for transformers and the electrical industry. Induction heating is a highly effective heating system that reduces energy losses while providing precise temperature control.

Table 3. Cont'd.

Project Title	Induction Melting Upgrade
Company	AMERICAN Cast Iron Pipe Co.
Location	Birmingham, AL
Budget	Federal cost share up to US$75 million
Description	The Induction Melting Upgrade ("Right Way" Next Generation Melt Project), led by AMERICAN Cast Iron Pipe Co., aims to electrify its process by replacing a cupola furnace with four induction furnaces. This will eliminate the usage of coke (derived from coal) for combustion and lower the carbon dioxide emissions at the melting process by an estimated 95% at its Birmingham, AL, facility. These improvements may be reproduced throughout the ductile iron pipe sector.
Project Title	Iron Electric Induction Conversion
Company	United States Pipe and Foundry Co.
Location	Bessemer, AL
Budget	Federal cost share up to US$75.5 million
Description	The project seeks to replace a coke-fired furnace with electric induction melting furnaces, eliminating the need for natural gas and coke (derived from coal) in the iron melting process and resulting in an estimated 73% reduction in carbon intensity at the Alabama Works ductile iron pipe production facility in Bessemer, AL. This project is projected to lower operational costs, increase production capacity and improve overall melting process dependability, showing the feasibility of electrifying a fundamental process in iron and steel manufacture. This project would significantly improve air quality by replacing coke combustion with electric induction, resulting in decreases in particulate matter, nitrogen oxides and sulfur oxides.
Project Title	Low-Emissions, Cold-Agglomerated Iron Ore Briquette Production
Company	Vale USA
Location	U.S. Gulf Coast
Budget	Federal cost share up to US$282.9 million
Description	Vale plans to build a first-of-its-kind manufacturing plant to produce low-emissions iron ore pellets in the United States. This transformational technique delivers significant emission reductions by decarbonizing iron ore processing and decreasing the demand for industrial heat, resulting in a versatile product that can be utilized in both direct reduced and blast furnace ironmaking processes. This would cut CO_2 emissions by an estimated 60% while also decreasing some critical air pollutants such as sulfur oxides by about 99%.

for production, storage, transport and utilization of clean hydrogen. Low-carbon-footprint hydrogen can be generated from renewable electricity using electrolysis or from natural gas through steam methane reforming coupled with CCS. Both produce clean hydrogen that has a significant advantage when used as combustion gas. The availability of cost-effective clean hydrogen can enable decarbonization and revenue opportunities across multiple sectors.

Hydrogen Hubs in the United States

On 13 October 2023, the Biden-Harris Administration announced US$7 billion to launch seven Regional Clean Hydrogen Hubs (H2Hubs) across the nation and accelerate the commercial-scale deployment of low-cost, clean hydrogen. The H2Hubs are planned to create 3 million metric tons of hydrogen per year, accounting for approximately one-third of the United States' 2030 output target. An overview of the seven Hydrogen Hubs is shown in Table 4. The Hydrogen Hubs with involvement with the steel industry are the Midwest Alliance for Clean Hydrogen (MachH2) with Nucor Steel West Virginia and Appalachian Regional Clean Hydrogen Hub (ARCH2) with Cleveland-Cliffs.[67,68]

The cost of hydrogen can vary between US$1.13 and US$8.62/kg H_2, dependent on electricity source.[69] A study by Mathew Humbert et al. compared CAPEX and operating expenses (OPEX) data for hydrogen DRI process with molten oxide electrolysis. For OPEX parity between both processes, the price of hydrogen needs to be US$1.5/kg, which is the current minimum cost of H_2.[70] Another study by V.V. Rajulwar et al. compared the cost of hydrogen-based and natural gas–based DRI technologies. The total cost of producing steel including carbon taxes of US$80/t CO_2 for H_2-DRI-EAF versus NG-DRI-EAF-CCUS was investigated. The parity in cost for producing steel between both processes showed the cost of green hydrogen needs to be around US$1.7/kg H_2 and US$3.84/thousand cubic feet (mcf) natural gas.[71] Both studies show the cost of green hydrogen needs to decrease to make it competitive with other green steelmaking routes.

Hydrogen-Based Direct Reduced Iron in Combination With the EAF Process

Hydrogen-based DRI production in combination with the EAF process powered by decarbonated electricity has the potential to provide an effective route to making green steel. The process replaces fossil fuels in the DRI production stage with hydrogen produced using renewable energy. Iron ore is reduced with hydrogen gas into sponge iron and then fed into the EAF process. The EAF process can use DRI, HBI and scrap as its main raw material inputs. The EAF process consumes electricity and melts the iron-bearing raw

Figure 13. Hydrogen power station. *Source and Image Credit: Audio und Werbung/Shutterstock.com, Germany*

Table 4. Overview of the Seven Hydrogen Hubs in the United States as of 2024

Hydrogen Hub	Region	Description
Appalachian Regional Clean Hydrogen Hub (ARCH2)	West Virginia, Ohio and Pennsylvania	The Appalachian Regional Clean Hydrogen Hub will use natural gas to produce low-cost clean hydrogen and permanently store the associated carbon emissions. The project will develop hydrogen pipelines, multiple hydrogen fueling stations and permanent CO_2 storage. The estimated amount of the project is up to US$925 million.
Alliance for Renewable Clean Hydrogen Energy Systems (ARCHES)	California	The California Hydrogen Hub will produce hydrogen exclusively from renewable energy and biomass. The project will provide renewable energy to decarbonize public transportation, heavy-duty trucking, port operations and other key emission drivers in the state that are hard to decarbonize. The estimated amount of the project is up to US$1.2 billion.
The Gulf Coast Hydrogen Hub (HyVelocity)	Centered in the Houston, Texas, region	HyVelocity plans to produce large-scale hydrogen using both natural gas with carbon capture and renewable-powered electrolysis. This project is estimated to be up to US$1.2 billion.
Heartland Hydrogen Hub	Minnesota, North Dakota and South Dakota	The Heartland Hydrogen Hub plans to decarbonize the agricultural sector's production of fertilizer, decrease the regional cost of clean hydrogen, and advance the use of clean hydrogen in electric generation and for cold-climate space heating. It also plans to offer unique opportunities of equity ownership to tribal communities through an equity partnership and to local farmers and farmer co-ops through a private sector partnership that will allow local farmers to receive more competitive pricing for clean fertilizer. The estimated amount of the project is up to US$925 million.
Mid-Atlantic Clean Hydrogen Hub (MACH2)	Pennsylvania, Delaware and New Jersey regions	The Mid-Atlantic Clean Hydrogen Hub plans to develop renewable hydrogen production facilities from renewable and nuclear electricity using both established and innovative electrolyzing technologies. The estimated amount is up to US$750 million.
Midwest Alliance for Clean Hydrogen (MachH2)	Illinois, Indiana and Michigan	The Midwest Hydrogen Hub will enable decarbonization through strategic hydrogen uses including steel and glass production, power generation, refining, heavy-duty transportation, and sustainable aviation fuel. This project plans to produce hydrogen by using renewable energy, natural gas and low-cost nuclear energy. The Midwest Hydrogen Hub estimated budget is up to US$1 billion.
Pacific Northwest Hydrogen Hub	Washinton, Oregon and Montana	The Pacific Northwest Hydrogen Hub plans to produce clean hydrogen exclusively via electrolysis. Its anticipated widescale use of electrolyzers will play a key role in driving down electrolyzer costs, making the technology more accessible to other producers and reducing the cost of hydrogen production.

materials with arcs generated by graphite electrodes. This path represents a technically proven production method that enables nearly emission-free steel production. However, some challenges remain relating to scalability: (1) the cost and availability of hydrogen; (2) the limits on iron ore quality for post-reduction processing; and (3) the competitiveness with natural gas. It is still desirable to have some carbon in steelmaking, as it is critical for operational processes such as foaming slag. Carbon is also easier to melt due to exothermal reactions, and the CO bubbles help stir the melt and remove dissolved gases. In contrast, the reduction of iron ore using H_2 gas is an endothermic reaction; some external heat source is required to maintain heat in the reduction furnace, as lowering the temperature can cause reversion of the iron back to iron oxide, which requires energy to occur. A thermodynamic study by Sara Hornby and Geoffrey Brooks showed that an optimal gas mixture would be around 75% H_2 and 25% CO.[72] When the reaction process is carried out with a mixture of CO and H_2 gas, the maximum rate of carbon deposition occurs between 500 and 600°C while no carbon deposition occurs above 900°C. This means that a reduction process of iron ore using H_2 + CO gas mixtures is favored by high temperatures, but this needs to be balanced with the desire to produce a DRI with some carbon in its structure.

It has been demonstrated on a pilot scale that the commercial ENERGIRON process can produce DRI utilizing hydrogen instead of natural gas. As mentioned above, hydrogen reduction of iron oxide is an endothermic reaction which requires energy, in contrast to reduction by natural gas which is an exothermic reaction and emits energy. The endothermic reaction may challenge the scale-up of the hydrogen-based DRI process. In early 2000s, hydrogen-based DRI was produced at commercial scale using a fluidized bed reactor in Trinidad and Tobago. The production route has already been demonstrated; however, the reactors are no longer in operation due to changes in ownership and economics.

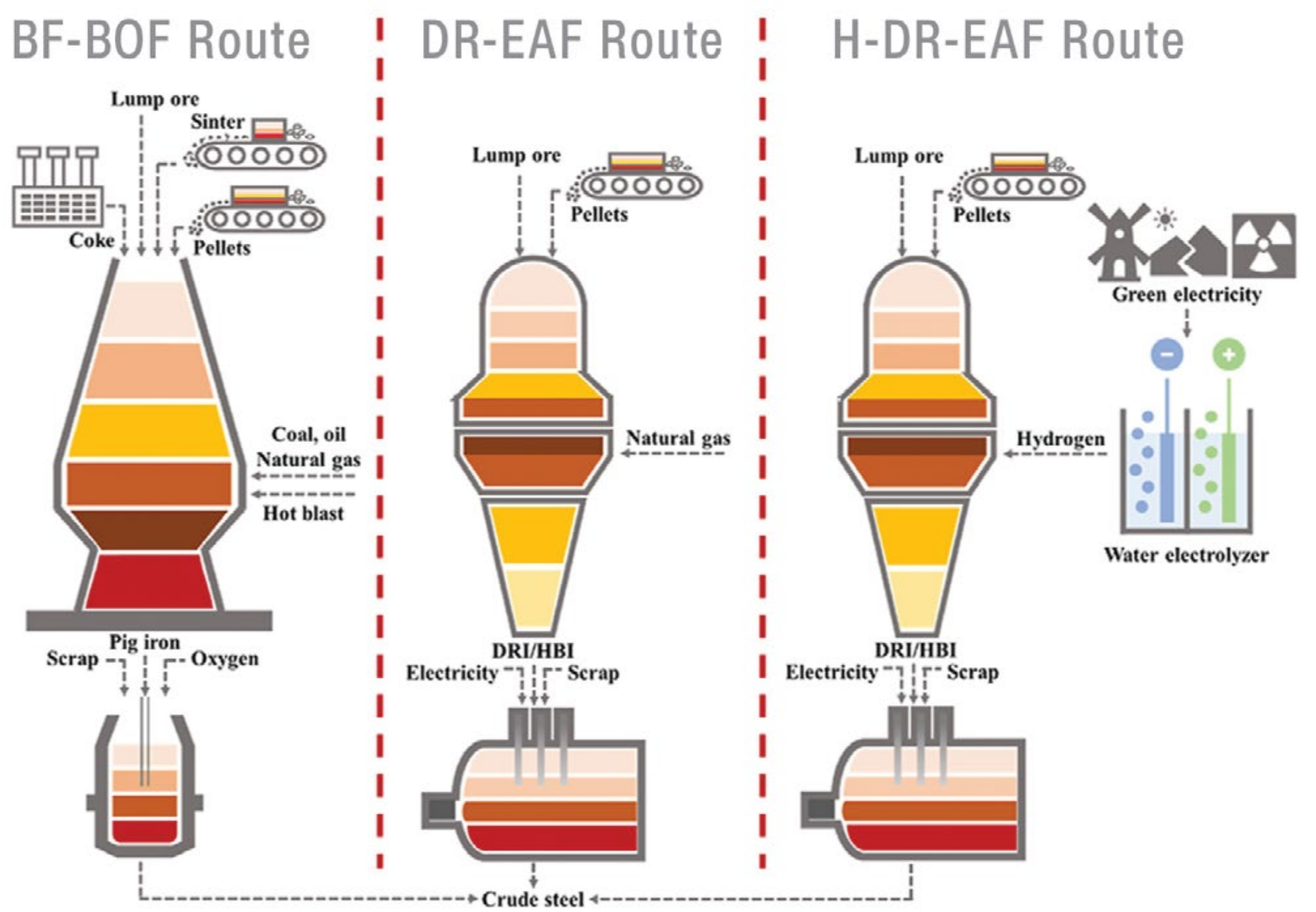

Figure 14. Conventional blast furnace–basic oxygen furnace (BF–BOF) route using coke and coal (left), direct reduction–electric arc furnace (DR–EAF) route using natural gas as energy source (center), and hydrogen–DR-EAF route.[73]

European steelmakers are already engaged in projects that employ H_2 in steelmaking. GrInHy[74] (Salzgitter in Germany) and H2FUTURE[75] (voestalpine in Austria) are focusing on electrolyzer development. The Swedish consortium HYBRIT[76] (SSAB, LKAB and Vattenfall) considers the entire fossil-free value chain for primary steel through H_2 electrolysis used for DRI and steelmaking in an EAF at the pilot plant scale (approximately 1 ton/hour). If successfully integrated with green electric grids, the impact would be cost-effective and could decarbonize ironmaking.

The GreenIron process, under evaluation in Sweden, is a low-temperature solid batch process at 600°C that uses hydrogen gas to reduce various input materials, such as mine tailings, iron ore (lump or pellets), and slags and deposits into 98–99% metallization grades. The GreenIron process can utilize materials that cannot be processed in commercial production routes, e.g., broken pellets. For example, approximately 5–10% of pellets used in conventional continuous DRI processes are broken down into smaller pieces which cannot be used in the process. The GreenIron pilot plant in Kumla has a capacity to process 20 kg of raw material, while the full-scale industrial facility in Sandviken can process 5 tons of raw material per batch. The process requires 2,100 kWh/ton hematite, with 400 kWh used toward heating. The full-scale industrial facility is planned to start-up in 2025.

Hydrogen Plasma Smelting Reduction

Iron ore can be melted and reduced simultaneously in a hydrogen plasma-based reduction process, which allows the production of liquid iron in one step. This process eliminates the need for intermediate agglomeration or refinement processing of iron ore. During hydrogen plasma reduction (HPR), a plasma arc zone is generated between the electrode and the iron ore under H_2 partial pressure. In the plasma arc zone, the iron ore can be melted and reduced by a hydrogen gas and plasma state.[78,79] There are not many publications available on the technology and more research needs to be conducted. Companies such as voestalpine (SuSteel),[80] Ferrum Decarb[81] and Hertha Metals[82] are currently conducting research on hydrogen plasma smelting reduction technologies.

Hydrogen Gas as a Replacement for Pulverized Coal in the Blast Furnace

Metallurgical coke is the primary fuel and reducing agent in the blast furnace process. Gas-based reductants cannot support the blast furnace burden; this limits the substitution of coke by all gas-based reductants including hydrogen. The amount of coke used in the BF can range between 260 and 500+ kg/ton hot metal (t HM) depending on the amount of auxiliary reducing agents (ARAs) injected and quality of coke used.[83] The world's lowest coke rate of 230 kg/tHM was reported by Kobe Steel #3 BF at its Kobe Works when hot briquetted iron was included in the ferrous charge.[84]

Typical fossil-based ARAs include pulverized coal, natural gas, heavy oil and, increasingly, coke oven gas. Hydrogen can be injected to replace coke and other injected ARAs, reducing fossil fuel use. Increasing the share of low-carbon-intensity hydrogen for the reduction of iron oxide in the BF will directly reduce greenhouse gas emissions. Major limiting factors for hydrogen use are the endothermic reduction of iron oxides by hydrogen and its impacts on the raceway flame temperature that must be above minimum values for the BF to operate.

Germany's thyssenkrupp Steel was the first steel company in the world to inject hydrogen into #9 BF at Hamborn Works during a test in 2019 where hydrogen, supplied by Air Liquide, was injected on a single tuyere. thyssenkrupp estimated that CO_2 emission could be reduced by up to 20% using hydrogen to partially replace pulverized coal.[85,86]

In 2023, Cleveland-Cliffs injected hydrogen gas into all 20 tuyeres at its #3 BF at Middletown Works.[87] Following the successful trial at Middletown Works, another trial was conducted at the Cleveland-Cliffs Indiana Harbor #7 BF with the hydrogen supplied by Linde. Indiana Harbor #7 BF is among the largest BFs in the world, both in size and production capacity, and is more than double the size of #3 BF at Middletown Works and thyssenkrupp's #9 BF.

Other hydrogen injection trials on an industry scale have been conducted in recent years. China's Jinnan Steel Group in collaboration with Shanxi Woneng Chemical Technology Co. Ltd. developed so-called "Steel-Coke-Chemical-Hydrogen" for co-production of chemicals and steel at Quwo Works. The chemical plant converts coke oven gas (COG) and basic oxygen furnace gas (BOFG) into ethylene glycol and liquified natural gas (LNG). The byproduct hydrogen from COG treatment has a purity greater than 75% and is injected into the BFs. [88] In 2021, Jinnan Steel and China Iron & Steel Research Institute Group carried out the COG injection tests to validate the hydrogen injection system on their two 1,860 m^3 BFs (inner volume).[89]

In 2021 and 2022, China Xingguo Precise Machine Parts in Qinhuadao and Shanghai University performed hydrogen injection tests on a 40 m^3 experimental BF and completed a furnace dissection.[89,90] In 2024, Xingguo Precise Machine Parts successfully commissioned a demonstration project on its 450 m^3 BF (inner volume) using the hydrogen produced from electrolyzers (300,000 Nm^3/day) built by Longi Green Energy Technology. The hydrogen injection rate reached 9.3 kg/t HM, achieving BF's CO_2 emission reduction by 8 to 11%. [91]

Tata Steel Jamshedpur in 2023 trialed hydrogen injection on its "E" BF using 40% tuyeres, the highest injection rate achieved was 6 kg/t HM, potentially reducing the coke rate by ~10%. Tata Steel invested a unique hydrogen production facility based on chemical looping technology. [92,93]

The Japanese Super Course50 (environmentally harmonious ironmaking) project also aims to replace some reductants in the BF with heated, externally sourced hydrogen. The latest trials on the 12 m^3 experimental BF confirmed a reduction in CO_2 emission by ~43%. [94,95]

Starting in 2017, China Baowu Group developed a low-carbon BF ironmaking technology known as "Hydrogen-enriched Carbonic-oxide Recycling Oxygenate Furnace" (HyCROF). The HyCROF process is a modified version of Top Gas Recycling-Oxygen Blast Furnace (TGR-OBF) trialed under ULCOS framework and offers an opportunity of introducing more hydrogen either as pure hydrogen or hydrogen-containing gas such as COG into the BF. In 2022, Baowu successfully commissioned a 380 m^3 (inner volume) HyCROF at the Bayi Iron & Steel Co. and used COG to enrich the recycled top gas. The preliminary test results showed a reduction in solid fuel rate by >30% and reduction in BF's CO_2 emissions by >21%. Following the successful test program at 380 m^3 HyCROF, Baowu converted to 2,500 m^3 (inner volume) "A" BF, also located at Bayi Iron & Steel Co., to the HyCROF configuration, and commissioned the furnace in 2023.

Biofuel as a Renewable Energy Source

Biofuel can partially replace coke and coal in the cokemaking process and BF production route and replace carbon injection in the EAF. A portion of the coal blend can be substituted with biocoke and used in the BF. The most common solid bioreducer in steelmaking is charcoal from wood. Biomass can also be used as an auxiliary fuel injected directly into the BF tuyeres. The amount of injected charcoal into the BF per produced ton of hot metal could be around 200 kg, with a coke rate of 260 kg/tHM.[102] Aço Verde do Brasil, a Brazilian integrated steel mill, achieved carbon-neutral steel production by reaching -0.04 metric ton of CO_2 per ton of steel in 2020. The 600,000 metric tons/year mill uses renewable power from eucalyptus charcoal to produce hot metal instead of traditional coking coal. The company has 50,000 hectares of planted eucalyptus trees for sustainable charcoal production. The Aço Verde do Brasil facility is certified by Société Générale de Surveillance (SGS).[103]

Utilizing Suppressed Combustion for EAF Production

In the suppressed-combustion system of a BOF, a ring-shaped hood is lowered onto the converter mouth prior to the blow, keeping air away from the hot offgases. This process offsets combustion and preserves the chemical heating value of the offgas. The application of such a system on an EAF could represent a potential energy source.

The Recovery and Reuse of Offgas, Waste Heat, and Steam to Generate Electricity

Within integrated steel production, there is energy-saving equipment that can be used, such as a top pressure recovery turbine (TRT) generating system and coke dry quenching (CDQ) system. The TRT helps control the top gas pressure in a blast furnace and converts the blast furnace gas into electric power via a turbine. The CDQ system is a waste heat recovery process that improves energy efficiency and reduces CO_2 emissions from coke plants. The CDQ generates power via steam from red-hot coke.

Approximately one-third of the energy input is lost via offgas in EAFs. Offgas heat recovery for EAF steelmaking is challenging because of high offgas velocity, fluctuating temperature and high dust content. In addition to these harsh conditions, a heat storage system must be used to balance power-off times of the EAF during tapping and charging. Waste heat recovery offers potential for further efficiency improvements in EAF steelmaking.[104] Offgases can also be used to preheat scrap from the EAF process, enabling energy saving and optimization.

Recovery and Utilization of Coproduct Gases (H_2, CO, CO_2) for Chemicals or Fuels

Flue gases, which are byproducts produced during the BF, BOF and coke oven process, can be utilized as feedstock in the chemical industry due to their high CO, CO_2, or H_2 content. Utilization of hydrocarbons from waste gases instead of fossil fuels reduces the carbon footprint of the chemical industry.[105]

Methane is an alternative energy source to carbon and can be extracted from natural gas. Methane can also be obtained from renewable carbon feedstock such as steelmaking gases.[106]

It is also possible to capture the carbon in CO_2 by permanently fixing it in the form of inorganic carbonates through accelerated mineralization/carbonation reaction between CO_2 and alkaline metals. Carbon in the form of inorganic carbonates is thermodynamically more stable than CO_2 gas and can be stored.[107]

Coke oven gas (COG) is a readily available and stable gas, which is one of several hydrogen sources used in industry. By utilizing waste heat recovery and a newly developed catalyst, the hydrogen content of COG can be increased into reformed COG (RCOG) before injection in the blast furnace shaft.

Hydrogen Gas as a Replacement for Natural Gas in the Reheat Furnace

There are ongoing trials to replace natural gas with hydrogen in reheat furnaces. By partial replacement from natural gas to H_2, the zoning of the reheat furnace will change. A possible alternative would be to use a combination of the gas-fired process and induction heating, called a hybrid reheating furnace.

In 2023, Ovako installed electrolyzer reactors at its steel plant in Hofors, Sweden, to produce hydrogen gas to power their reheat furnaces and rolling mills. In April 2024, the reheat furnaces and rolling mills were 100% run on hydrogen gas. The facility is equipped with 20-MW electrolyzer reactors which have the capacity to generate 3,880 cubic meters of hydrogen per hour.[108] The facility has the possibility to switch from hydrogen to liquified petroleum gas (LPG) in case electricity prices become too expensive. According to the mill, there are no differences in energy consumption by switching to hydrogen. Ovako is planning to expand the electrolyzer reactor project to its other facility in Smedjebacken, Sweden.

Alternately Fueled Mobile Equipment

Optimizing energy systems for mobile equipment will necessitate conversion and adaptation for alternate fuels such as hydrogen, natural gas, and electricity, including upgrading current systems to modern energy-efficient motors. These applications are relevant for equipment such as trucks, locomotives and ships that are used to ship materials.

Challenges and Knowledge Gaps

The costs of natural gas and CO_2 certificates (the price of emissions allowances) are expected to rise and remain high, while hydrogen (H_2) as an energy source is likely to be significantly more expensive than current natural gas prices. Steelmaking will need to adapt to new technologies and hydrogen usage, but this carries risks, such as water condensation and explosion hazards. Further research is needed on the impact of hydrogen and water on refractories and the challenges of using hydrogen-rich byproducts in steel production. Producing green hydrogen faces obstacles like the need for water, wind and solar power, along with difficulties in storage and transportation due to hydrogen's potential for causing hydrogen-induced cracking. More research is needed to assess the cost competitiveness of electrolytic hydrogen for ironmaking, its scalability, integration into smart grids and the efficiency of EAFs without carbon in the feedstock. Additionally, challenges remain in refining impurities and replacing pellets in blast furnaces with DRI.

IV. Carbon Capture, Utilization and Storage (CCUS)

Technological advancements in steelmaking processes will eventually reduce carbon emissions in the long term, ultimately leading to direct carbon avoidance. However, many of the mitigation technologies will require sufficient time for research and development to de-risk the significant investments necessary to convert existing steel manufacturing infrastructure. A transition era will be essential to sustaining the economic viability of the companies engaged in this effort.

One way to decarbonize existing steel plants during and beyond this transition era is through CCUS. Captured CO_2 emissions from iron- and steelmaking processes can either be used, such as in building materials (utilization), or permanently stored within the earth's subsurface (storage). Amongst the various technologies to reduce carbon emissions, CCUS remains one of the least invasive methods to achieve deep emission cuts. The technologies can be retrofitted onto existing furnaces and equipment without interfering with the BF–BOF production route. According to an International Energy Agency (IEA) forecast, by 2060, CCS will need to be implemented on about 21% of the world's crude steel production. This translates to a yearly CO_2 capture rate of 506 Mt.[109]

CCS technologies include point-source capture, which involves capturing CO_2 from large emissions sources, or direct air capture, which involves removing CO_2 from the atmosphere. Once the CO_2 gas has been isolated, it is compressed using high pressure to convert the gas into a supercritical liquid phase. The most common mode of transport of liquid CO_2 to the permitted geological storage site is through pipelines. Pipelines have been used for over 50 years to safely deliver CO_2 from production sites to storage facilities in the U.S. After the CO_2 has been transported, it is injected more than a mile underground into deep rock formations where it is safely and permanently stored. There are requirements for selecting CO_2 storage sites to ensure there is no significant risk of reversal or damage to health or the environment. The USGS published the National Geologic CO_2 Storage Assessment in 2013 where 36 sedimentary basins for potential CCS storage and their capacities were mapped and identified.[110] These geologic storage sites need to be able to safely contain a variety of liquids and pressured gases such as oil and natural gas for tens to hundreds of millions of years. The CCS costs depend on the process type, capture technology, CO_2 transport and storage location. The cost of carbon capture estimated by IEA in 2021 suggests costs can vary from US$5–25/t CO_2 for natural gas processing plants to US$40–120/t CO_2 for cement or power generation. The transport and storage cost can vary greatly and depends on CO_2 volumes, transport distances and storage conditions. In the United States, the cost of onshore pipeline transport is in the range of US$2–14/t CO_2.[111]

In an integrated steel mill, about 70% of the emissions come from flue gas produced in the BF hot stoves and in the power plant, while COG and BOF gas are responsible for approximately 9% and 7%, respectively. Top gas recycling technology with CCUS in the BF is mainly based on lowering the usage of coke and coal by reusing offgas. The CO_2 is first removed from the offgas to obtain the reducing agents CO and H_2. The ultralow-CO_2 steelmaking blast furnace process (ULCOS-BF) aims at minimizing the CO_2 emissions in the BF by at least 50%.[112] This process is based on the replacement of hot blast by oxygen, and recycling of top gas (CO and H_2) into the lower shaft and normal hearth tuyeres, and a full CO_2 capture and storage process. This process uses low-purity O_2 to produce the reducing gases from pulverized coal injection coal.

Natural gas and coal are the two main fuels used in DRI production. Natural gas DRI with postcombustion CCUS leads to lower CO_2 emissions, with emissions ranging from 0.77 to 1.10 tons of CO_2 per ton of iron, depending on the type of electricity used.[113] The most common technologies used for DRI production are MIDREX and HYL III, both using natural gas. The postcombustion CCUS process works by removing CO_2 from the flue gas before it is released into the atmosphere. Postcombustion CCUS can remove 89% of the CO_2 that would otherwise have been emitted.[114] DRI and HIsarna represent an alternative to BF–BOF steelmaking route and generate gas streams with increased concentration of CO_2 up to 90%, which is beneficial for CCUS applications.[115]

Existing DRI production requires high-purity iron ore with a Fe content of at least 67%. For this reason, iron ore mining firm BHP suggests most of the world's steel will still be produced in blast furnaces in 2050, as there is insufficient high-grade iron ore to allow the expansion of DRI-based output. There are ongoing projects to find technologies that can enable the use of lower-grade iron ores in DRI production. South Korea's POSCO is examining the possibility to use hydrogen-based fluidized bed reduction to utilize low-grade iron ore through its HyREX initiative. thyssenkrupp is planning to replace four BFs with new DRI-submerged-arc furnace installations by 2045.[116] The new steelmaking route will add a melting stage after DRI production before it is sent to the BOF. ArcelorMittal and BlueScope are planning similar projects.[114] thyssenkrupp's new production route is illustrated in Fig. 15.

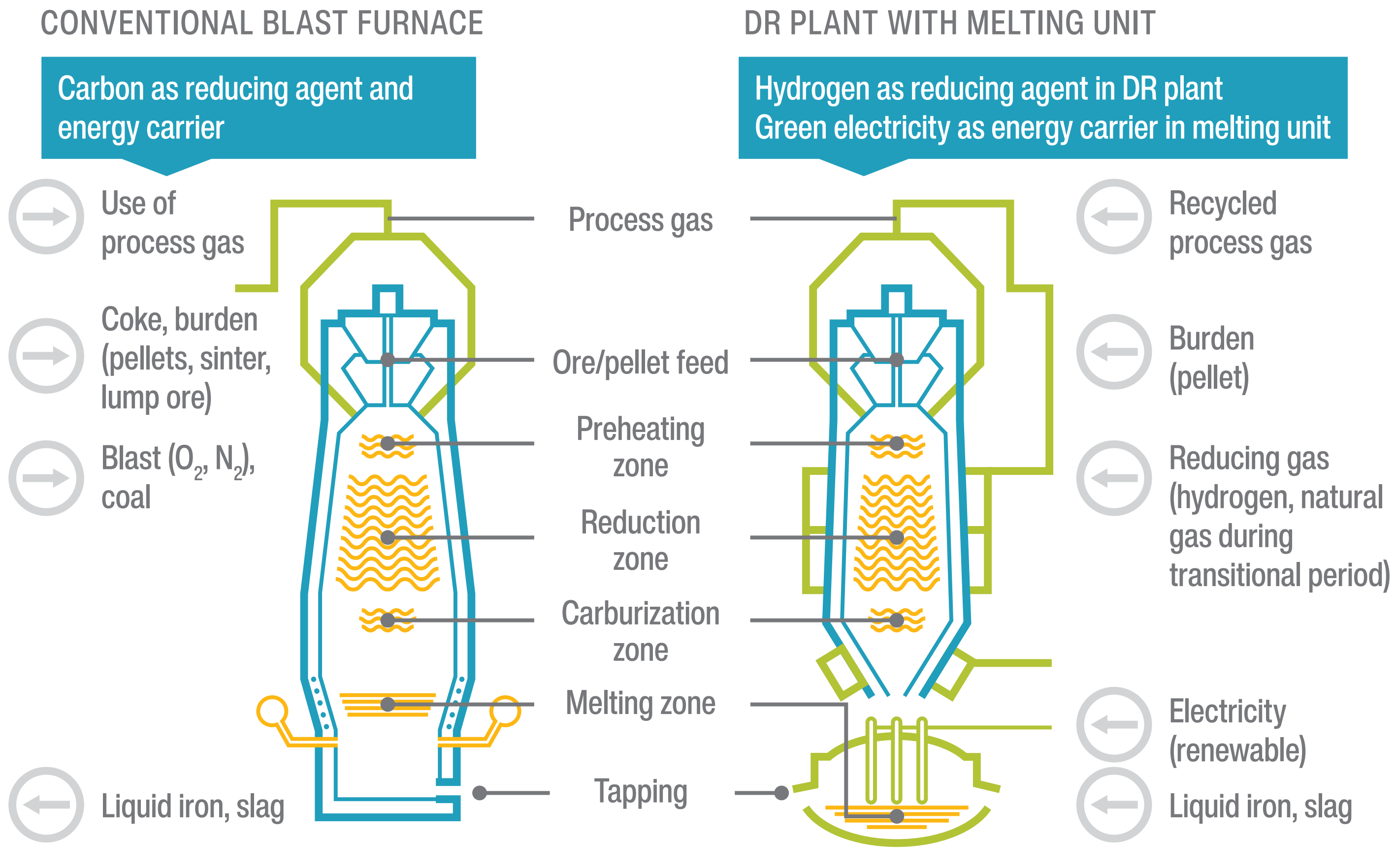

Figure 15. thyssenkrupp's technology pathway for transition from blast furnaces.[115]

In CCS processes, CO_2 has to be separated from the exhaust gas streams before subsequent transportation and storage. There are multiple CO_2 separation technologies available for steelmaking, such as amine scrubbing, pressure swing adsorption and membrane separation (filters).[117,118] Each technology needs to be evaluated according to the flue gas composition and economics for feasibility. There are four main CC technologies available for steelmaking processes: cryogenic separation, absorption, adsorption and membranes. The cryogenic separation process cools the gas to low temperatures so that CO_2 gets liquefied and separated. This technology is energy-intensive as it needs substantial power for refrigeration. The feedstock gas needs to be pretreated and dehydrated to avoid hydrate formation and CO_2 freezing in the equipment.[119] The absorption processes separate the gases based on the difference in affinity of substances in the gas. The substances can be absorbed through chemical reactions in liquid state and separated in a consecutive step by changing the pressure and/or the temperature of the liquid. The adsorption processes separate the gas based on one of the following effects: steric (molecular size and shape), kinetic (diffusion rates) or equilibrium (chemical interactions). The membrane process separates the gas based on filters and requires compression; therefore, it is not necessarily cost-effective.

There is an infrastructure needed for commercial-scale transport of gaseous and liquid CO_2 emissions via tanks, CO_2 trunk lines and ships. Gaseous CO_2 is typically compressed to a pressure above 8 MPa to avoid two-phased flow and increase the density of the gas, thereby making it easier and less costly to transport. Pipeline transportation of CO_2 over longer distances is most efficient and economical when the CO_2 is in the dense liquid phase. The Alberta Carbon Trunk Line is a 240-km-long, 16-inch-diameter pipeline that is currently being constructed in Alberta, Canada.[120] Once complete, the Alberta Carbon Trunk Line will be the largest integrated CCUS system in the world.

Carbon Capture Hubs in United States

As of November 2024, 19 CCS facilities were operating in the United States (see Table 5). Most CCS facilities are located at natural gas plants or ethanol for fuel, or ammonia for fertilizer facilities. Together, those 19 facilities have the capacity to capture more than 22 million metric tons of CO_2 per year, or 0.4% of the United States' total annual CO_2 emissions. Almost all those facilities provide the captured CO_2 to oil companies, which use it for enhanced oil recovery. In that process, CO_2 is injected into partially depleted oil wells, and the pressure from the gas pushes the remaining oil to the surface.[121,122]

In September 2023, JX Nippon restarted operations at the Petra Nova CCUS plant in Texas. Petra Nova remains the only operational carbon capture facility at a coal-fired power plant in the U.S. and one of only four operating at commercial coal-fired plants globally. If completed, Project Tundra in North Dakota will be the second such facility in the U.S. and was selected for award negotiations of up to US$350 million in funding from the Infrastructure Investment and Jobs Act in December 2023.[122]

As of July 2024, the United States had 276 projects in the commercial carbon capture and storage (CCS) facilities pipeline: 19 of these facilities were operational, while 132 were in the advanced development stage and an additional 13 were under construction. The U.S. has the highest number of CCS projects worldwide.[123] The total capacity of the 132 CCS facilities combined if completed would be more than 134 million metric tons of CO_2 per year.[124]

U.S. steel producers are also exploring carbon capture as a mitigation strategy, either through direct investment and experimentation or indirectly by way of participation in the DOE-funded hydrogen hubs program or other federally supported efforts.

Nucor Corp., for instance, finalized an agreement with ExxonMobil in June 2023 to implement a carbon capture and sequestration project at its Louisiana DRI plant. This initiative will allow the company to capture, transport and store up to 800,000 metric tons of CO_2 annually.

Throughout 2023, Cleveland-Cliffs continued to engage with developers of CCUS, primarily focused on reducing emissions from its ironmaking activities. The company also is a partner in the Midwest Alliance for Clean Hydrogen Hub project. Carbon capture and storage is a key element of the project's hydrogen production strategy. Cliffs is expected to become a major end user of hydrogen energy.

Meanwhile, United States Steel Corporation's Edgar Thomson plant has partnered with the DOE and GTI Energy to demonstrate a carbon capture technology utilizing a compact rotating bed packed with an advanced solvent. The technology has the potential to capture more than 95% of flue gases. At the same plant, U. S. Steel also is collaborating with the National Energy Technology Laboratory (NETL) to test a membrane-based carbon capture technology. Membrane-based carbon capture is most ideal compared to other carbon capture technologies and has the potential to reduce capital and maintenance costs, according to U. S. Steel.

Additionally, U. S. Steel's Gary, IN, facility is partnering with a company called CarbonFree to implement a commercialized carbon capture and reuse solution. Using CarbonFree's SkyCycle technology, U. S. Steel aims to capture and mineralize up to 50,000 metric tons of CO_2 annually. The technology converts blast furnace CO_2 into a pure form of limestone, which then can be used in products such as plastics, rubber and paints, adhesives, sealants, and caulks.

Reuse of Industrial Flue Gases (H_2, CO, CO_2) for Chemicals or Fuels

Flue gases, which are byproducts produced during the BF, BOF and coke oven process, can be utilized as feedstock in the chemical industry due to their high CO, CO_2 or H_2 content. Utilization of hydrocarbons from waste gases instead of fossil fuels reduces the carbon footprint of the chemical industry.[125]

Methane is an alternative energy source to carbon and can be extracted from natural gas. Methane can also be obtained from renewable carbon feedstock such as steelmaking gases.[126]

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Biological CO_2 Utilization/Transformation

CO_2 is generated through photosynthetic microorganisms such as microalgae, which convert inorganic carbon to organic carbon-based compounds via photosynthesis. The evolution of chloroplasts enabled microalgae to develop into CO_2-consuming biofactories that generate a wide variety of organic compounds. Microalgal biomass enriched with biochemicals can be upgraded to a diverse range of products, including food, biofuels, biopolymers, cosmetics, biomedicine and nutraceuticals.

Challenges and Knowledge Gaps

Challenges with carbon capture and storage involve making it economically viable and widely accessible. The main reason CCS is used to a limited extent is that the cost to implement CCS technology exceeds its value in most potential settings. These challenges can be overcome by, e.g., carbon taxes and financial aid toward RD&D scale-up projects where government and industry can develop CCUS hubs. Another challenge is enabling infrastructure such as shared transport pipelines and storage sites. Targeted RD&D projects toward next-generation CCUS technologies and other innovative solutions and business models are needed. Regulating and managing risks to ensure responsible and secure CCUS development, setting standards and regulations to ensure high CO_2 capture rates, as well as developing transparent best practice monitoring of CCUS are crucial. The current financial incentives and regulatory frameworks have not been sufficient to spur large-scale projects in the U.S. steel industry. To facilitate the development of CCS projects, the public sector may need to take a leading role in financing the transport and storage infrastructure.

Table 5. CCS Facilities in Operation in the United States in 2024[122]

Name of facility	Date CCS operations began	Location	Type of production	CO_2 used for	CO_2 capture capacity (Mton/year)
Occidental Terrell	1972	Texas	Natural gas processing	Enhanced oil recovery	0.500
Enid Fertilizer	1982	Oklahoma	Hydrogen/ammonia/fertilizer	Enhanced oil recovery	0.200
ExxonMobil Shute Creek Gas	1986	Wyoming	Natural gas processing	Enhanced oil recovery	7.000
Great Plains Synfuels Plant and Weyburn-Midale	2000	North Dakota	Hydrogen/ammonia/fertilizer	Enhanced oil recovery	3.000
Core Energy CO_2-EOR South Chester Plant	2003	Michigan	Natural gas processing	Enhanced oil recovery	0.350
Arkalon CO_2 Compression Facility	2009	Kansas	Bioenergy/ethanol	Enhanced oil recovery	0.500
Longfellow WTO Century Plant	2010	Texas	Natural gas processing	Enhanced oil recovery	5.000
Bonanza BioEnergy CCS	2012	Kansas	Bioenergy/ethanol	Enhanced oil recovery	0.100
Air Products Valero Port Arthur Refinery	2013	Texas	Hydrogen/ammonia/fertilizer	Enhanced oil recovery	0.900
Coffeyville Gasicifation Plant	2013	Kansas	Hydrogen/ammonia/fertilizer	Enhanced oil recovery	0.900
Contango Lost Cabin Gas Plant	2013	Wyoming	Natural gas processing	Enhanced oil recovery	0.900
Petra Nova Carbon Capture	2017	Texas	Power generation and heat	Enhanced oil recovery	1.400
ADM Illinois Industrial	2017	Illinois	Bioenergy/ethanol	Deep saline formation	1.000
Dark Horse Storage	2021	New Mexico	CO_2 transport/storage	Deep saline formation	N/A
Red Trail Energy Richardton Ethanol	2022	North Dakota	Bioenergy/ethanol	Deep saline formation	0.180
Heirloom DAC California	2023	California	Direct air capture	Mineral carbonation	0.001
Harvestone Blue Flint Ethanol	2023	North Dakota	Bioenergy/ethanol	Deep saline formation	0.200
Barnett Zero CCS	2023	Texas	Natural gas processing	Deep saline formation	0.185
Bantam DAC Oklahoma	2024	Oklahoma	Direct air capture	Enhanced oil recovery	0.005

Figure 16. Lightsource BP launches Bighorn Solar project in Colorado, powering the world's first steel mill to run almost entirely on solar power.

Three Cross-Cutting Themes

Cross-cutting technologies are versatile tools that support a wide range of industries, processes and techniques, rather than being designed for a specific application. These technologies have broad applicability across various sectors. In the materials manufacturing sector, the key cross-cutting technologies that were identified are: smart manufacturing, infrastructure, facilities and tools, and education and workforce. While these themes are discussed in detail elsewhere in the report, they are only briefly introduced in this chapter.

Smart Manufacturing

Smart manufacturing, leveraging AI and ML, can reduce energy consumption, enhance yield, and lower the carbon footprint in steel production and the broader materials manufacturing sector. Key technologies include:

- Micro-grid models integrating renewable energy and modular reactors to optimize local power use and improve voltage stability.
- Real-time tracking and automated inventory management, using intelligent systems to optimize orders and reduce in-house inventory.
- Computer simulation for improving material quality through local process control and modeling.
- Big data analytics to detect failures and improve efficiency.
- Predictive maintenance using real-time data to foresee and address failures in processes.
- Virtual reality for remote maintenance support and drones for operational inspections.
- Advanced sensors such as fiber optic applications or tunable diode laser.

Infrastructure, Facilities and Tools

Infrastructure, facilities and tools to decarbonize the iron and steel industry can also be transferred and utilized by the entire manufacturing sector. Some notable barriers for cross-discipline collaboration between industries to decarbonize their production processes are:

- The competitive nature of metals producers with their material versus other materials such as steel versus aluminum.
- The Technology Readiness Levels (TRL) and the economics of adoption.
- A continual need for a skilled labor force in all collaboration areas.
- The differences of corporate culture amongst organizations.
- Reluctance to share intellectual property.

Examples of tools that can be utilized by the entire manufacturing sector are life cycle analysis, techno-economic models, and supply chain analysis from raw materials, power usage, transport, and end-use markets.

Education and Workforce

There is an ongoing challenge for the manufacturing sector to attract, retain, and upskill or reskill their workforce. This challenge needs an industrywide effort to come together to accelerate deployment of new technologies and help bridge gaps in workforce training to expand and diversify the pipeline of workers entering the industry. There is a need to improve the perception of working in the manufacturing sector and to attract a new generation of workers. It is imperative to deploy partnerships with community colleges, trade schools and universities to provide qualified personnel and an infrastructure to develop a skilled, diverse and inclusive metals manufacturing workforce to meet evolving industry needs. The workforce needs and challenges are described more in detail in the Technology Process Adaptation chapter of this report.

U.S. Technology Areas on the Forefront of Decarbonization

Most manufacturing plants operate continuously. The challenge with utilizing renewable power (solar/wind/hydro) is the lack of sufficient energy storage and the resulting intermittent availability of that power, e.g., if the sun isn't shining, the power supply will be disrupted. Co-locating near continuous renewable power sources, e.g., hydroelectric, geothermal stations or nuclear power, is a viable option. The location also requires market access and takes into account competition from other sectors that require the same green power.

Electrifying the steel industry, whether directly or indirectly through hydrogen, will depend on the availability and cost of clean electric power. For example, Gareth Stace, director of UK Steel (the trade association for the U.K. steel industry), stated that due to increasing demand for electricity used in the steel sector, elevating prices of wholesale electricity has now made it uneconomical to produce steel, where the cost of electricity accounted for 20% of raw material prices used for steelmaking. There is a risk of overdependence on clean electric power, where the U.K. government now realizes they need to fix the structural weaknesses that lead to significant higher energy costs in relation to continental Europe.[128,129]

In Sweden, where the HYBRIT and H2GreenSteel projects are located, techno-economic feasibility is unclear due to electricity prices, [130,131] despite the abundance of continuous hydroelectric power and high-grade iron ore. The electricity demand is predicted to double in Sweden by 2045 in comparison to 2024. Furthermore, the strategy of decarbonizing the steel industry before the entire electric grid itself has been decarbonized is an ongoing debate. Every time electricity is converted to hydrogen and used to reduce iron ore, there is a loss in energy efficiency, whereas replacing it with fossil fuels is more economic. This situation will lead to a mismatch of competing interests between electricity supply and demand,[132] which will inevitably pose challenges during the transient period of the green energy transition.

In the U.S., the replacement of fossil-fueled combustion-based process heat and carbonaceous reductants with electric pathways will be challenged by the low cost of natural gas versus the limitations in renewable-based electric power. This is due to intermittency and competition with other industrial users as well as the transportation and residential sectors.

Several domestic EAF facilities have unveiled plans to collaborate with utility companies to take advantage of the benefits of their geographic location to integrate regionally generated green electricity into the local grid that supplies their facilities. Examples are EVRAZ North America's collaboration with Xcel Energy and Lightsource BP to develop a 300-MW solar facility in Pueblo, CO, and Nucor Steel Sedalia LLC's collaboration with local wind power company Evergy in Missouri. However, matching this supply with peaks in demand will remain a challenge, and new grid-balancing solutions or new operating paradigms for aligning steel production to off-peak power availability will be needed to make the transition to carbon-free steelmaking. Grid balancing using large-scale low-cost battery storage, such as FORM energy's iron air battery, or supplemental power generation using natural gas, may provide full or partial solutions. Off-peak energy storage in the form of DRI and HBI metallics to be used subsequently for EAF feedstock has also been proposed in the Grid-Interactive Steelmaking with Hydrogen (GISH) project.[133]

EVRAZ North America, which operates a scrap-based EAF facility in Pueblo, CO, for producing rails for railway lines and other products,[134] partnered with Lightsource BP and Xcel Energy to build the 300-MW Bighorn Solar project with the goal of lowering emissions for the mill. EVRAZ owns the solar plant, which is located on 1,800 acres of land adjacent to the Pueblo mill. Bighorn Solar is the largest on-site solar facility in the U.S. dedicated to a single customer.

North American steel producer Nucor and EDF Renewables North America have agreed to a virtual power purchase agreement for 400 MW of new solar energy that will be built in Texas. The US$452 million plant is a partnership between the steel company and Evergy, a local utility company.[135] Texas law allows utilities to apply for discounted electric rates for aluminum and steel producers that buy significant amounts of energy.[136] Nucor also signed a 10-year virtual power purchase agreement with Orsted Onshore North America LLC in 2021 for 100 MW of wind energy from Orsted's Western Trail wind farm in North Texas.[137] Sebree Solar LLC, a subsidiary of NextEra Energy Resources, together with Nucor has entered into a 250-MW power purchase agreement, which supports the company's net zero goal by 2050. The solar energy center will be constructed using low-embodied-carbon steel from Nucor divisions in the region, including Nucor Steel Gallatin in Ghent, KY.[138]

Pacific Steel Group anticipates starting a 380,000 tons/year rebar mill in Mojave, CA, integrating the facility with renewable energy from solar arrays. The MIDA Hybrid micro-mill is anticipated to start up in 2026.[139]

Hybar LLC is building a rebar facility in Osceola, AR, with a capacity of 630,000 tons of rebar annually. Hybar plans to utilize a direct connection to a nearby behind-the-meter solar installation to produce steel with 100% solar energy.[140]

Boston Metal has developed a molten oxide electrolysis (MOE) process that eliminates the need for coal in steel production. The MOE process is an electrochemical process that uses direct electric current to separate chemical compounds into their constituent parts and convert all iron ore grades to high-quality liquid metal. In the cell, an inert anode is immersed in an electrolyte containing iron ore. When the cell heats to 1,600°C, the electrons split the bonds in the iron ore and produce iron and oxygen. The output is a high-purity liquid metal that can be directly processed in the ladle.[141]

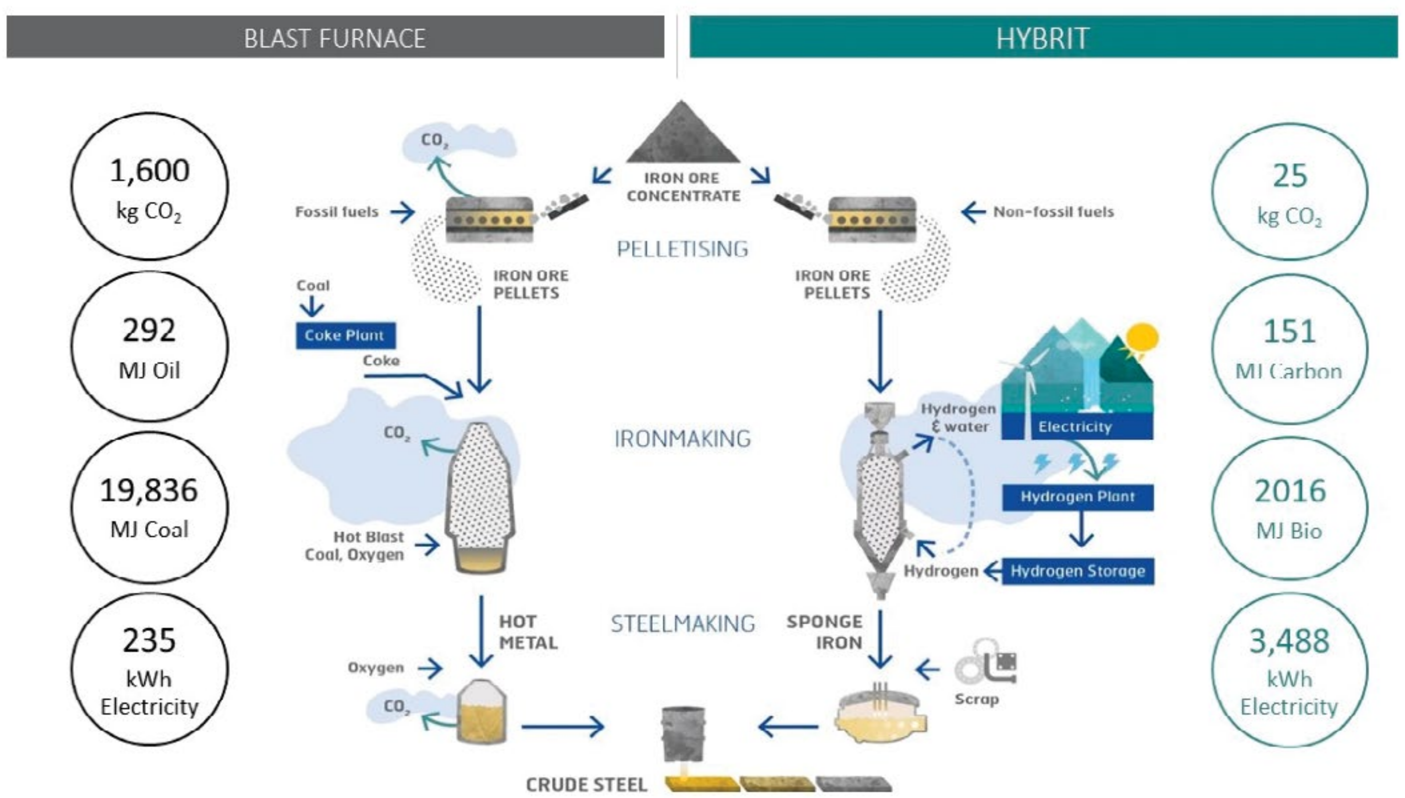


Figure 17. Comparison of some emission and consumption figures for the SSAB blast furnace route and the HYBRIT concept.[146]

Electra, a steel company in Boulder, CO, is investing in a steelmaking process that electrochemically refines iron ore into pure iron at 60°C (140°F). The low-temperature iron (LTI) process uses renewable electricity and converts the iron to steel using the existing infrastructure of electricity-powered arc furnaces. The LTI process will also be able to process commercial lower-grade ores that are not being used or are currently treated as waste today.[142]

International Steel Producers Innovating Decarbonization Technologies

Europe has led the charge in green technologies because of the massive amount of available government support — greater than any other region of the world.[143] There are several government-subsidized steel industry decarbonization projects occurring in Europe and Asia that provide local industry with the opportunity to focus on implementing innovative technologies that may otherwise not have been financially possible. While the U.S. steel industry leads the world in clean steel production, i.e., low carbon emissions, further innovation is essential. If the U.S. wants to lead the world in its pursuit of climate neutrality within the manufacturing sector, the U.S. federal government must aggressively subsidize research projects to de-risk technologies necessary to decarbonize the domestic steel industry.

The overall green electricity needed in the European steel sector is 400 TWh/year, including 230 TWh to produce 5.5 million tons of hydrogen. This is seven times more than what the steel sector purchases from the grid today. According to the European Steel Association (EUROFER), "green" steel will cost up to 35–100% more than regular steel. As of 2022, there were approximately 60 key low-CO_2 projects of the EU steel industry. Almost all of these projects anticipate launching before 2030. Potential CO_2 abatement from these projects in 2030 is estimated to be 81.5 million tons/year (representing more than one-third of current direct and indirect CO_2 emissions). The CAPEX needs are estimated to be EUR31 billion and OPEX needs EUR54 billion.

Table 6. Examples of Foreign Decarbonization Projects in the Iron and Steel Industry.

Company	Country	Project Description	Start
Europe			
47 Partners	15	▪ ULCOS: Develop new technologies to produce steel with reduced CO_2 emissions. The original project ended in 2010.	2004
thyssenkrupp	Germany	▪ tkH2Steel®: thyssenkrupp Steel in Germany is injecting hydrogen into one of their blast furnaces. The tkH2Steel project began in November 2019 as a trial on one tuyere, and expanded to the remaining tuyeres in the blast furnace. The program has expanded significantly to integrate a new plant combination into Europe's biggest steel mill. The 100% hydrogen-capable DR plant with two melters and a production capacity of 2.5 million metric tons of directly reduced iron per year (which will become 2.3 million metric tons of pig iron to feed the existing BOFs) is the first plant combination of its kind in the world in this technological concept.	2019

Table 6. Cont'd.

Company	Country	Project Description	Start
Salzgitter GmbH	Germany	▪ SALCOS®: Salzgitter GmbH is gradually replacing blast furnaces with direct reduction plants to avoid CO_2 emissions. The project aims at directly avoiding carbon usage in the steelmaking process by using hydrogen sourced from electrolyzers. The project started in 2015, currently commissioning electrolysis units powered by wind and recovering waste heat which will provide the required hydrogen for the direct reduced iron facility in 2022. The first of the SALCOS plants can go into operation in 2026. The SALCOS program aims at reducing CO_2 emissions by over 95%. The first stage will go into operation as early as the end of 2025 and consists of a direct reduction plant, an electric arc furnace and a 100 MW electrolysis plant for hydrogen production.	2015
Tata Steel Europe	Netherlands	▪ Zeremis®: Tata Steel Europe is shifting steel production from BF/BOF process to DRI/EAF process. Additionally, the Zeremis project will partner Tata Steel with their customers to work toward a carbon-neutral, circular world by accelerating projects that reduce carbon emissions. This will include carbon captured in a carbon bank to allow Tata to offer carbon credits through a range of solutions that enable the customer to reduce their carbon footprint as well. ▪ Everest: Tata Steel Europe in the Netherlands is developing carbon capture and storage of BF gas. The Everest project will utilize carbon monoxide and hydrogen byproducts from steel production. The project ended in 2021 and was replaced with the Zeremis project. ▪ ATHOS: The ATHOS project will convert the byproduct into chemicals and also capture waste CO_2 for storage in North Sea gas fields. The ATHOS project is developing a public CO_2 distribution network in the North Sea Canal area, enabling CCUS. The capture and transport of CO_2 will be used in the Everest project or be stored in empty gas fields under the North Sea. Reduction potential: 40%. The project ended in 2021 and was replaced with the Zeremis project. ▪ HIsarna: Tata Steel's HIsarna process is a novel method for making steel that was developed as part of the international ULCOS program. The HIsarna project started as a pilot plant trial in 2011 at the Tata Steel's IJmuiden facility in the Netherlands. The smelting reduction process involves the direct transformation of iron ore into liquid iron, thereby eliminating the need for coke and preparation of iron ore agglomerates. Without these preparatory steps, the HIsarna process can use raw materials more economically and can diminish CO_2 discharges by 20%. In 2018, the installation was integrated into the main production line and the pilot campaign was completed in 2019.	2010

Table 6. Cont'd.

Company	Country	Project Description	Start
Voestalpine Stahl GmbH	Austria	▪ H2FUTURE: voestalpine Linz GmbH in Austria is developing large-scale production of hydrogen for direct reduction facilities. In 2020, the industrial test phase of H2FUTURE began to produce hydrogen via electrolysis. ▪ SuSteel: The SuSteel project is using H_2 plasma smelting to directly transform iron ore into steel. The pilot plant operation in Donawitz, Austria, is currently operating a 500 kg furnace. ▪ HYFOR: Hydrogen-based fine ore reduction pilot facility.	2017
ArcelorMittal Europe	France	▪ Siderwin: ArcelorMittal Europe in France and Belgium is developing a smart hydrocarbon pathway to use more green electricity for electrolytic iron deposition. The Siderwin project has a pilot plant under operation in Maizières, France. Reduction potential 87%. ▪ Carbon2Value: The Carbon2Value projects in Belgium and France consist of carbon capture pilot projects to take blast furnace gas as a waste heat energy source to be exported to generate energy. The Torero plant converts waste biomass into biocoal and an industrial demo plant is under construction in Ghent, Belgium, with production to start in 2022 and another in 2024. The Carbalyst (Steelanol), scheduled for production in 2022 in Ghent, Belgium, is capturing carbon offgas and converting it into carbon ethanol. ▪ Torero: Waste wood into biocoal. ▪ Carbalyst: Capture carbon offgas and convert to carbon ethanol. ▪ IGAR: The IGAR project is capturing CO_2 waste and waste hydrogen from steelmaking, converting them into reductant gases. A demonstration plant is being built for production in 2024 at Ghent, Belgium. The 3D project on capturing offgas for storage and transport is building a large-scale demonstration plant in Dunkirk, France for 2024/2025.	2009
SSAB	Sweden	▪ HYBRIT: The HYBRIT project (see Fig. 15) was founded in 2017 to develop hydrogen-based production of fossil-free sponge iron (DRI). SSAB, LKAB and Vattenfall in Sweden are jointly working on eliminating CO_2 emissions in the iron- and steelmaking processes by replacing coal with fossil-free electricity and hydrogen. The HYBRIT R&D project is supported by the Swedish Energy Agency. So far, more than 5,000 metric tons of hydrogen-reduced iron have been produced at a pilot plant in Luleå. The project is now advancing into the industrialization phase of development. The transition from coal and blast furnace-based steelmaking to HYBRIT technology and the melting of iron in electric arc furnaces is expected to reduce Sweden's total carbon dioxide emissions by more than 10%.	2016

Table 6. Cont'd.

Company	Country	Project Description	Start
H2Green Steel	Sweden	▪ H2Green Steel: H2Green Steel is a EUR6.5 billion private startup company, located in Boden, Sweden. The facility will be a fully integrated steel mill, with hydrogen-based DRI, two EAFs and rolling mills. Production is expected to start in 2026. The production route is expected to reduce CO_2 emissions by 95% in comparison to traditional blast furnace steelmaking. The estimated production for this facility will be approximately 5 million tons by 2030.	2024
Asia			
POSCO	Korea	▪ GOAL: Establish a domestic hydrogen ecosystem for carbon neutrality, consisting of production, transport, storage and application. ▪ Grey hydrogen (CO_2 emitted while reforming fossil fuel) ▪ Blue hydrogen (Capturing and storing CO_2) ▪ Green hydrogen (Net-zero emission of CO_2) ▪ POSCO in Korea has a yearly hydrogen production capacity of 7,000 tons, which is produced by utilizing coke oven gas during the steelmaking process and natural gas. POSCO will study hydrogen-based steelmaking technology in the future and improve its capabilities to produce, transport, store, and use hydrogen, expanding facilities that produce byproduct hydrogen, and developing core technologies for hydrogen production. By 2030, POSCO plans to partner with global companies to produce up to 500,000 tons of "blue hydrogen" and increase its byproduct hydrogen production capacity to 70,000 tons by 2025. Additionally, the company intends to complete 2 million tons of "green hydrogen" production capacity by 2040 and 5 million tons by 2050.[144]	2020
KOBELCO, JFE Steel, Nippon Steel and Kobe Steel *(on behalf of NEDO, New Energy & Industrial Technology Development Organization)*	Japan	▪ COURSE50: Develop technologies to control reactions for reducing iron ore, to produce high-strength, high-reactivity coke for reduction with hydrogen, to capture, separate and recover CO_2 from BF gas and develop techniques for chemical absorption and physical adsorption to capture, separate and recover CO_2 from BF gas; and contribute to reduction in energy for capture, separation and recovery of CO_2 through enhanced utilization of unused waste heat. Phase II of the project will run between 2018 and 2025. Phase II of the program will develop technologies for reducing iron ore by amplifying the hydrogen included in the high-temperature coke oven gas generated during coking and using it as a partial substitute for coke and the development of innovative CO_2 separation and recovery technologies that utilize the unused waste heat of steel mills to separate CO_2 from blast furnace gas.[145]	2007

Table 6. Cont'd.

Company	Country	Project Description	Start
The Abu Dhabi CCS Project	United Arab Emirates	▪ The Abu Dhabi CCS Project, also known as the Emirates Steel Industries (ESI) CCS Project, is the first large-scale CCS-applicable iron and steel project in the world. Since 2016, it has captured approximately 0.8 million metric tons/year of CO_2 from the DRI reactor's gases in the United Arab Emirates. For the purpose of EOR, the CO2 is transported via a 43-km pipeline to the Rumaitha oilfield.[115]	2017
South America			
Vale	Brazil	▪ Following 20 years of development, Vale has begun producing a "green" iron ore briquette that can reduce carbon emissions in the overall steel value chain. The briquette is produced through a low-temperature agglomeration process that does not require nearly as much energy as the classic sintering process. The product also reduces emissions of particulates and gases such as sulfur dioxide (SOx) and nitrogen oxide (NOx), as well as eliminates the use of water in its production. Vale looks to eventually produce more than 50 million metric tons annually.	2004
Australia			
BlueScope Steel, BHP, Rio Tinto	Australia	▪ This project pairs Australia's largest steel producer and its two largest iron ore miners. Together, they aim to establish a pilot-scale facility that demonstrates the feasibility of producing molten iron from Pilbara ores using renewable power in the direct reduction process. If built, the facility could be commissioned as soon as 2024.	2024

09. Technology Process Adaptation

Eliminating GHG emissions in steel requires either (1) a change in the way iron is produced, i.e., direct carbon avoidance by replacing carbon with renewable derived reductant or electric power, or (2) the capture and possible use of the emitted CO_2. Both require innovation in diverse disciplines ranging from process design to supply chain, life cycle analysis and logistics to techno-economics. The capability gap is predicated on the historic and universal use of carbon to reduce iron ore into molten metallic iron, and the infrastructure to produce steel, i.e., locations, supply chain, raw materials and capital-intensive equipment.

The steel industry is continuously innovating technologies to improve productivity while decreasing energy consumption and now, more so, carbon emissions. Multiple technologies and solutions to decarbonize the iron and steel industry are identified within this Roadmap and are summarized in Fig. 18. Adoption of these varied technologies will be key to improving productivity, energy efficiency, yield and environmental sustainability in steel production.

Technological Advancements Needed to Decarbonize the U.S. Iron and Steel Industry by 2050

The main technologies to decarbonize the U.S. iron and steel industry for the four technology themes on an immediate, short-term, medium-term and long-term basis were identified based on a survey of industry experts representing production, research, academia and technology suppliers. AIST conducted a survey to establish industry consensus on the credibility of the decarbonization technologies and their impact on carbon emission reduction (Scope 1) expressed as kg CO_2/metric ton of crude steel produced and timeline of commercial implementation in the iron and steel industry for the technologies identified within this Roadmap. The results don't take into consideration the scalability of the technologies.

Only Scope 1 emissions are considered in this study, as these emissions are under direct control of the iron and steel industry. Scope 1 emissions are "direct emissions"

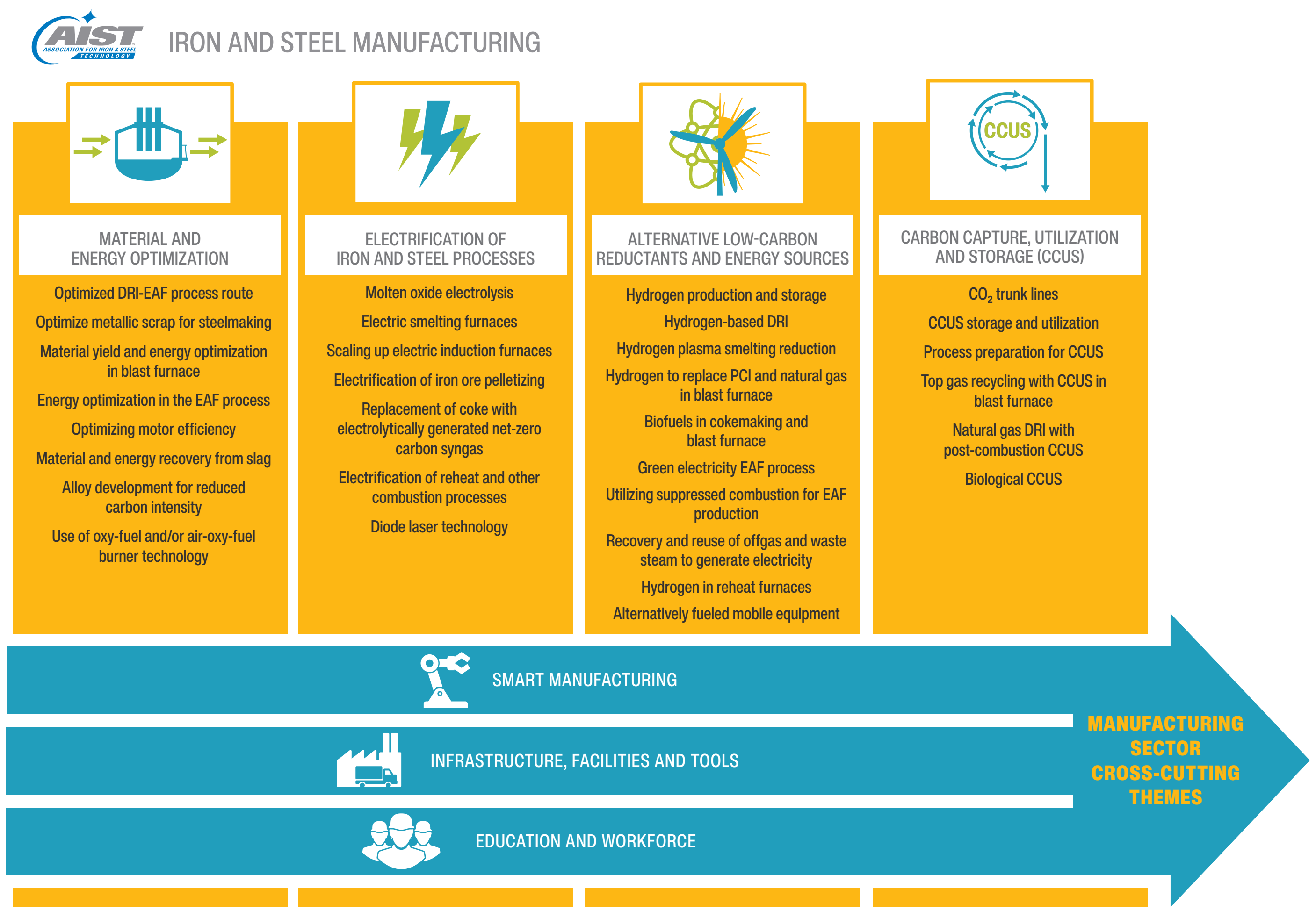


Figure 18. The four technology themes with the key decarbonization technologies and three cross-cutting themes.

Table 7. The Impact on Carbon Emission Reduction and Timeline of Commercial Implementation for the Decarbonization Technologies Identified Within This Roadmap

		Weighted average impact CO_2	Impact CO_2 max	Impact CO_2 min	Weighted average timeline	Timeline max	Timeline min
Technology theme	**Decarbonization technology**	**Unit: kg CO_2/metric ton of crude steel produced**			**Unit: Years from 2024 to commercial implementation**		
(1) Material and energy optimization	Optimized DRI-EAF process route	877.8	1,353.3	402.2	9.3	14.0	4.7
	Optimize metallic scrap for steelmaking	689.1	1,084.8	293.5	6.8	10.4	3.3
	Material yield and energy optimization in blast furnace	614.3	971.4	257.1	7.0	10.8	3.2
	Energy optimization in the EAF process	559.2	898.0	220.4	7.5	11.6	3.5
	Optimizing motor efficiency	365.2	623.9	106.5	7.2	11.1	3.3
	Material and energy recovery from slag	429.5	713.6	145.5	10.4	15.6	5.2
	Alloy development for reduced carbon intensity	464.4	764.4	164.4	11.7	17.3	6.1
	Use of oxy-fuel and/or air-oxy-fuel burner technology	504.7	820.9	188.4	7.4	11.4	3.5
	Smart manufacturing	588.9	944.4	233.3	7.5	11.5	3.5
(2) Electrification of iron and steel processes	Molten oxide electrolysis	1,195.5	1,820.5	570.5	16.9	24.4	9.4
	Electric smelting furnaces	974.1	1,488.9	459.3	9.1	13.7	4.4
	Scaling up electric induction furnaces	815.8	1,266.7	364.9	8.6	13.0	4.1
	Electrification of iron ore pelletizing	669.2	1,055.8	282.7	10.7	16.1	5.4

Table 7. Cont'd.

Technology theme	Decarbonization technology	Weighted average impact CO_2	Impact CO_2 max	Impact CO_2 min	Weighted average timeline	Timeline max	Timeline min
		Unit: kg CO_2/metric ton of crude steel produced			Unit: Years from 2024 to commercial implementation		
(2) Electrification of iron and steel processes *(cont'd.)*	Replacement of coke with electrolytically generated net-zero carbon syngas	966.7	1,487.5	445.8	15.9	23.0	8.8
	Electrification of reheat and other combustion processes	661.0	1,047.5	274.6	9.3	14.2	4.5
	Diode laser technology	626.3	1,010.5	242.1	17.8	25.6	10.1
(3) Alternative low-carbon reductants and energy sources	Hydrogen production and storage	1,072.9	1,641.7	504.2	11.6	17.1	6.0
	Hydrogen-based DRI	1,181.3	1,795.8	566.7	10.7	16.1	5.4
	Hydrogen to replace PCI and natural gas in blast furnace	725.0	1,133.3	316.7	10.2	15.3	5.1
	Biofuels in cokemaking and blast furnace	614.0	976.7	251.2	9.4	14.1	4.8
	Green electricity EAF process	928.3	1,428.3	428.3	10.2	15.2	5.1
	Utilizing suppressed combustion for EAF production	520.5	838.6	202.3	11.0	16.2	5.8
	Recovery and reuse of offgas and waste steam to generate electricity	569.2	909.6	228.8	8.7	13.2	4.2
	Hydrogen in reheat furnaces	649.0	1,027.5	270.6	11.8	17.6	6.1
	Alternatively fueled mobile equipment	414.9	697.9	131.9	8.5	12.9	4.1

Table 7. Cont'd.

Technology theme	Decarbonization technology	Weighted average impact CO_2	Impact CO_2 max	Impact CO_2 min	Weighted average timeline	Timeline max	Timeline min
		Unit: kg CO_2/metric ton of crude steel produced			Unit: Years from 2024 to commercial implementation		
(4) Carbon capture, utilization and storage (CCUS)	CO_2 trunk lines	617.4	987.0	247.8	15.4	22.4	8.4
	CCUS storage and utilization	946.9	1,456.3	437.5	14.9	21.9	8.0
	Process preparation for CCUS	540.9	877.3	204.5	12.5	18.4	6.7
	Top gas recycling with CCUS in blast furnace	894.1	1,376.5	411.8	13.7	20.0	7.4
	Natural gas DRI with postcombustion CCUS	894.3	1,380.0	408.6	11.5	16.9	6.1
	Biological CCUS	752.2	1,182.6	321.7	17.9	25.6	10.2

from sources that are owned or controlled by the company. Scope 2 emissions are "indirect emissions" released into the atmosphere from energy generated at another facility, such as a nuclear power plant. Scope 3 emissions include all other indirect emissions that occur across the value chain.

Decarbonization technologies and their applicability in the iron and steel industry are universally related to geographical location, availability of raw material and energy sources, regional politics and environmental regulation, and national or corporate sustainability goals. In recognition of the geopolitical sensitivity, the survey responses from the United States were analyzed separately from other regions of the world.

The survey results on the average impact on carbon emission reduction and timeline for commercial implementation for the decarbonization technologies were calculated according to Eqs. 1–4 and the results with ranges are summarized in Table 7.

The weighted average impact on carbon emission reduction was calculated according to the following formula:

$$\textbf{Weighted Average Impact } \mathbf{CO_2} = 200 * \%\ \text{responses} + 500 * \%\ \text{responses} + 1{,}000 * \%\ \text{responses} + 2{,}000 * \%\ \text{responses} \quad \text{(Eq. 1)}$$

The range on the impact of carbon emission reduction was calculated according to the following formulas.

$$\textbf{Range Impact } \mathbf{CO_2} = 200 * \%\ \text{responses} + 300 * \%\ \text{responses} + 500 * \%\ \text{responses} + 1{,}000 * \%\ \text{responses} \quad \text{(Eq. 2)}$$

The weighted average timeline of commercial implementation was calculated according to the following formula:

$$\textbf{Weighted Average Timeline} = 2 * \%\ \text{responses} + 6 * \%\ \text{responses} + 15 * \%\ \text{responses} + 26 * \%\ \text{responses} \quad \text{(Eq. 3)}$$

The range on the timeline of commercial implementation was calculated according to the following formula:

$$\textbf{Range Timeline} = 2 * \%\ \text{responses} + 3 * \%\ \text{responses} + 8 * \%\ \text{responses} + 10 * \%\ \text{responses} \quad \text{(Eq. 4)}$$

The survey results are illustrated in Fig. 2 and Figs. 19 and 20. Fig. 2 shows the overall U.S. results on the impact on

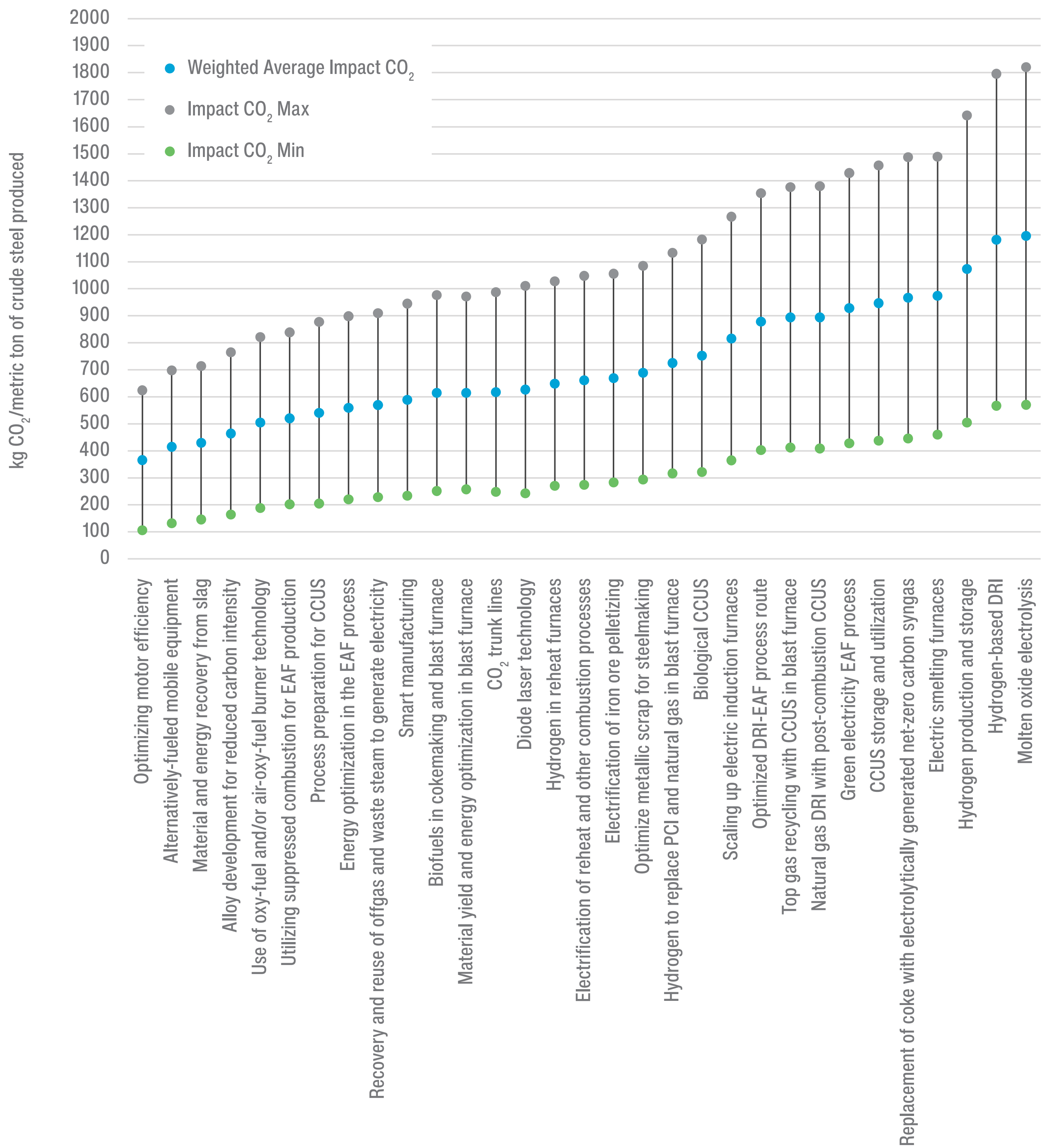


Figure 19a. Ranking of the impact on carbon emission reduction, expressed as kg CO_2/metric ton of crude steel, for the decarbonization technologies.

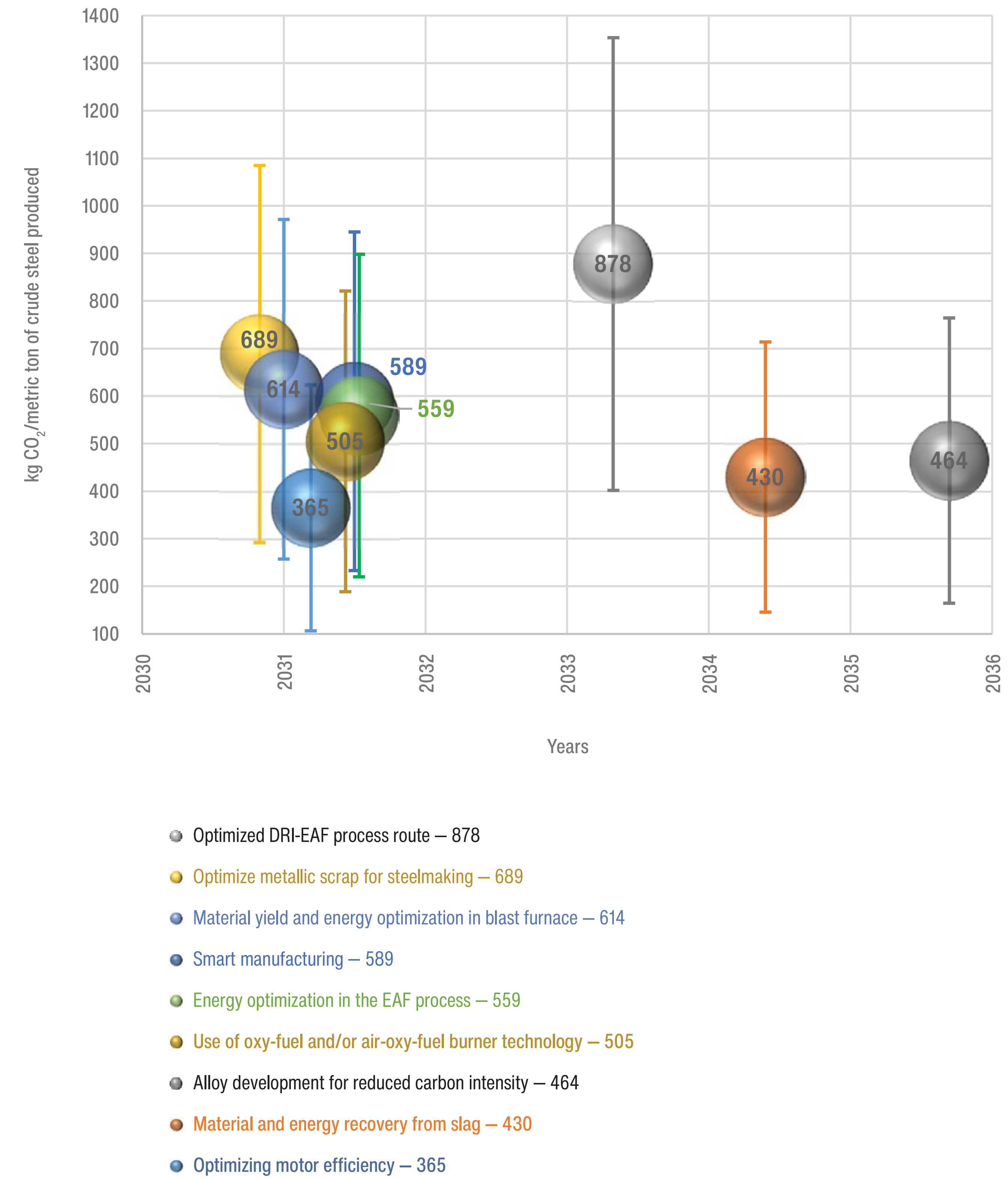
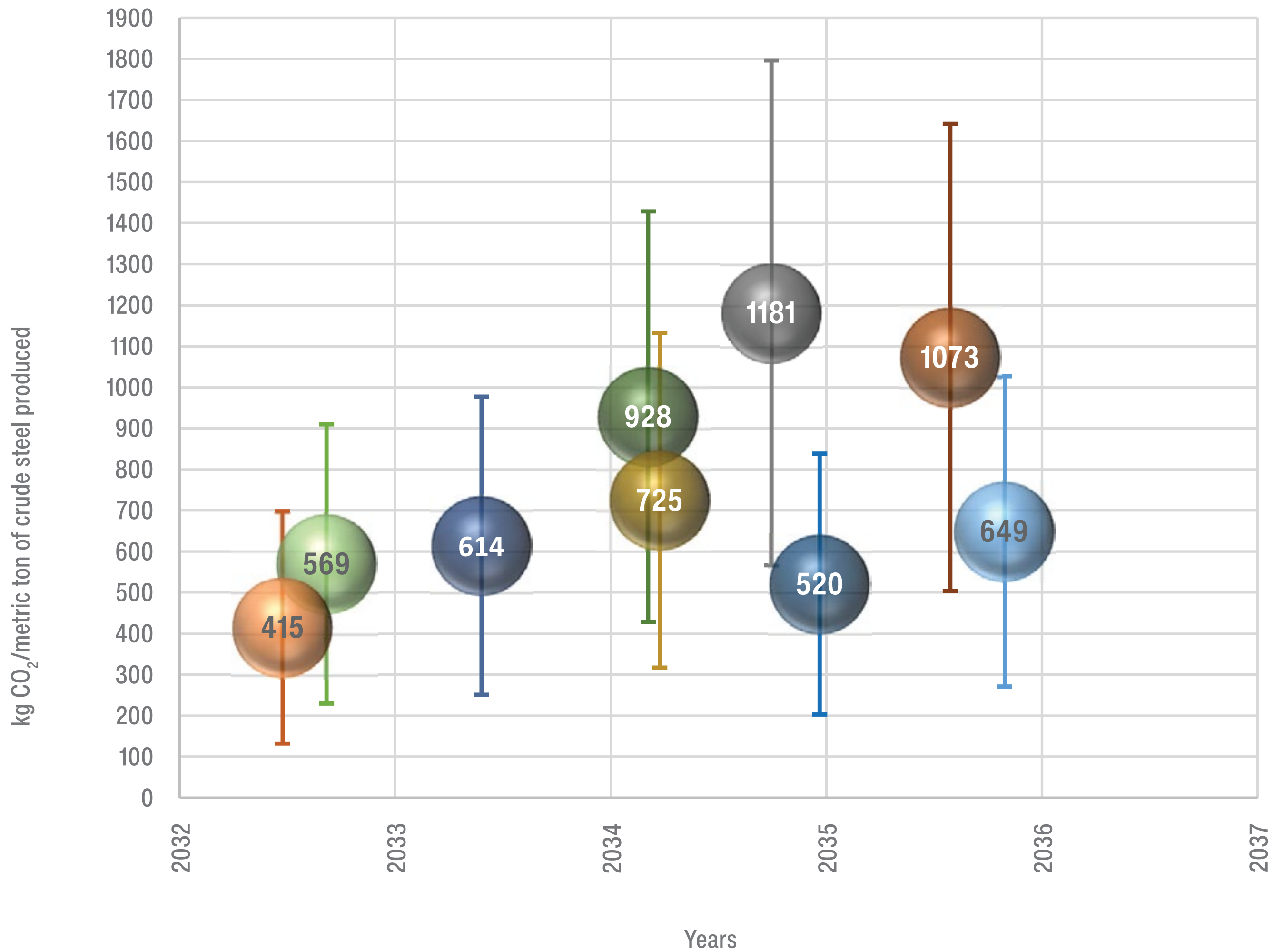
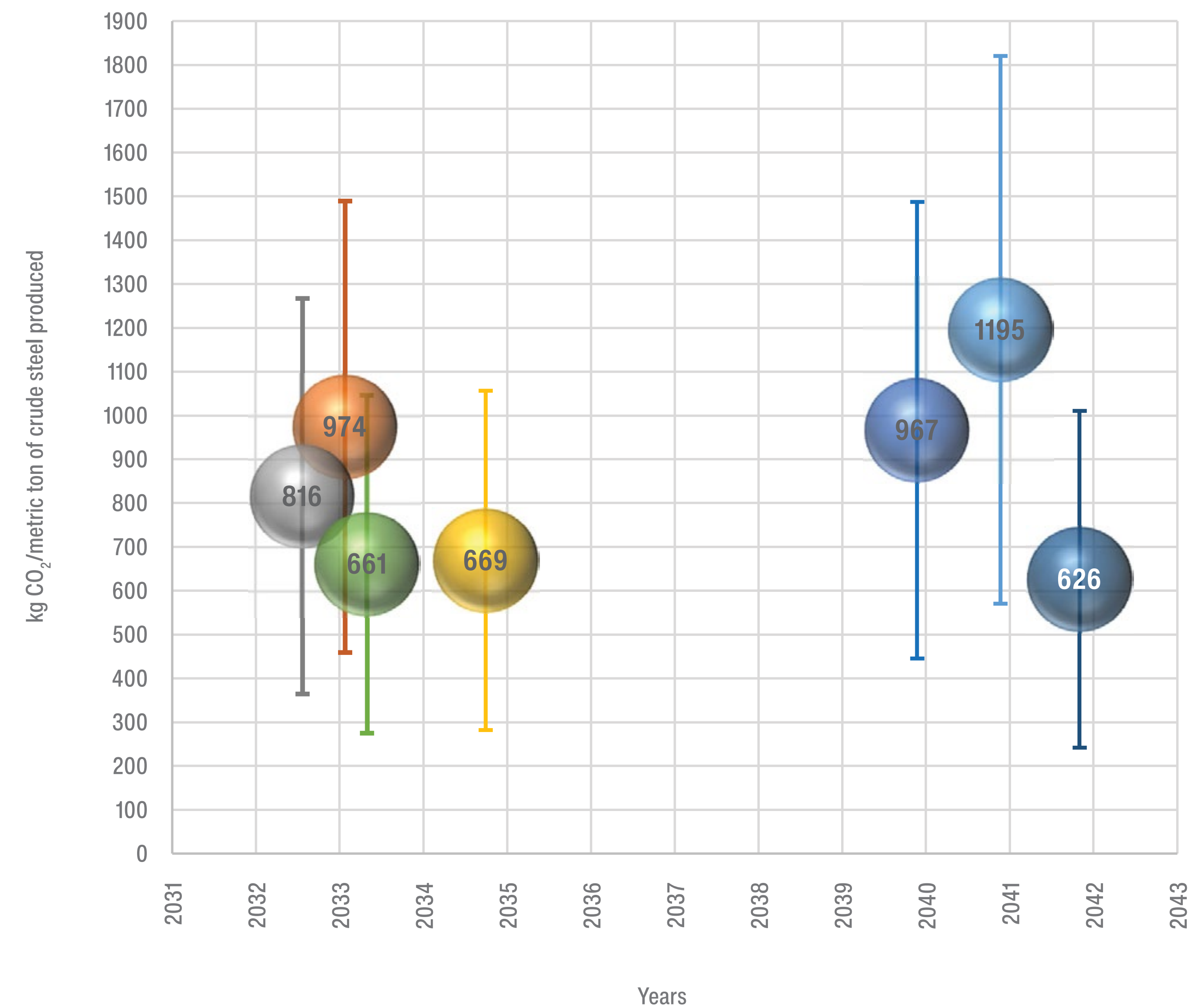


Figure 19b. Survey results on weighted average CO_2 reduction (Scope 1) with ranges for the decarbonization technologies identified within the technology theme Material and Energy Optimization.



- Hydrogen-based DRI – 1,181
- Hydrogen production and storage – 1,073
- Green electricity EAF process – 928
- Hydrogen to replace PCI and natural gas in blast furnace – 725
- Hydrogen in reheat furnaces – 649
- Biofuels in cokemaking and blast furnace – 614
- Recovery and reuse of offgas and waste steam – 569
- Utilizing suppressed combustion for EAF production – 520
- Alternatively fueled mobile equipment – 415

Figure 19c. Survey results on weighted average CO_2 reduction (Scope 1) with ranges for the decarbonization technologies identified within the technology theme Electrification of Iron and Steel Processes.



- Molten oxide electrolysis – 1195
- Electric smelting furnaces – 974
- Replacement of coke with electrolytically generated net-zero carbon syngas – 967
- Scaling up electric induction furnaces – 816
- Electrification of iron ore pelletizing – 669
- Electrification of reheat and other combustion processes – 661
- Diode laser technology – 626

Figure 19d. Survey results on weighted average CO_2 reduction (Scope 1) with ranges for the decarbonization technologies identified within the technology theme Alternative Low-Carbon Reductants and Energy Sources.

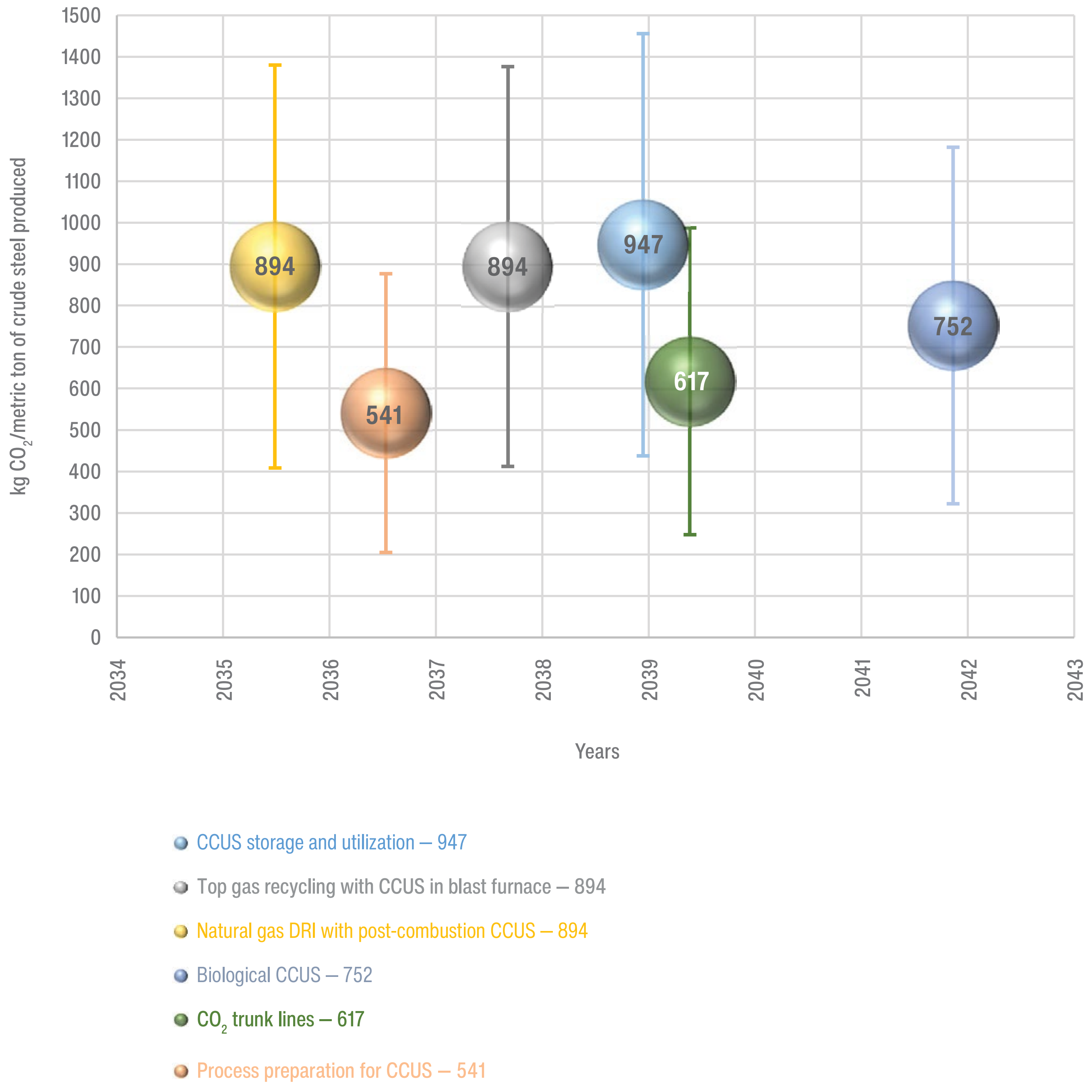


Figure 19e. Survey results on weighted average CO_2 reduction (Scope 1) with ranges for the decarbonization technologies identified within the technology theme Carbon Capture, Utilization and Storage (CCUS).

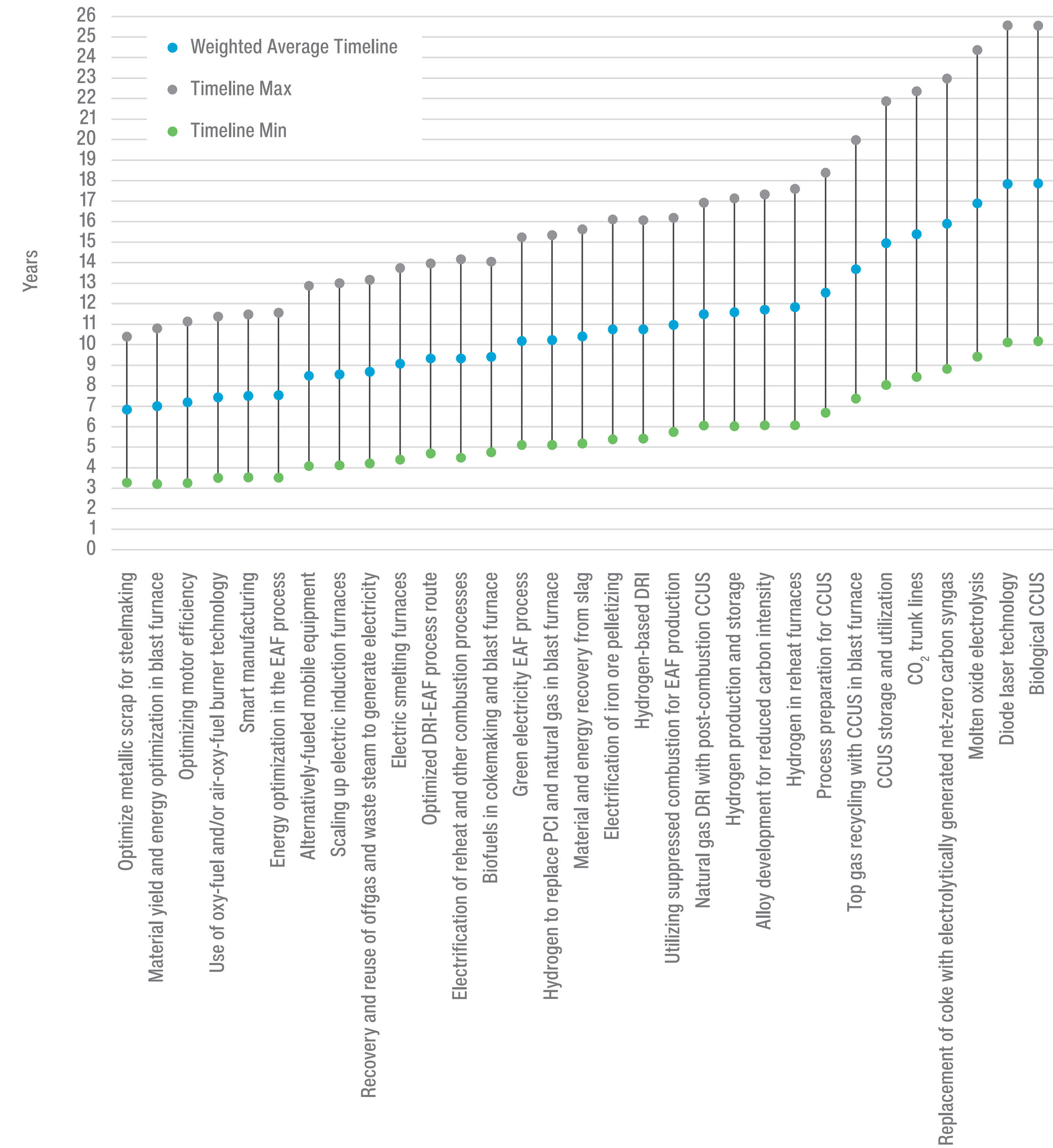


Figure 20a. Ranking of the timeline of commercial implementation, expressed as years from 2024, for the decarbonization technologies.

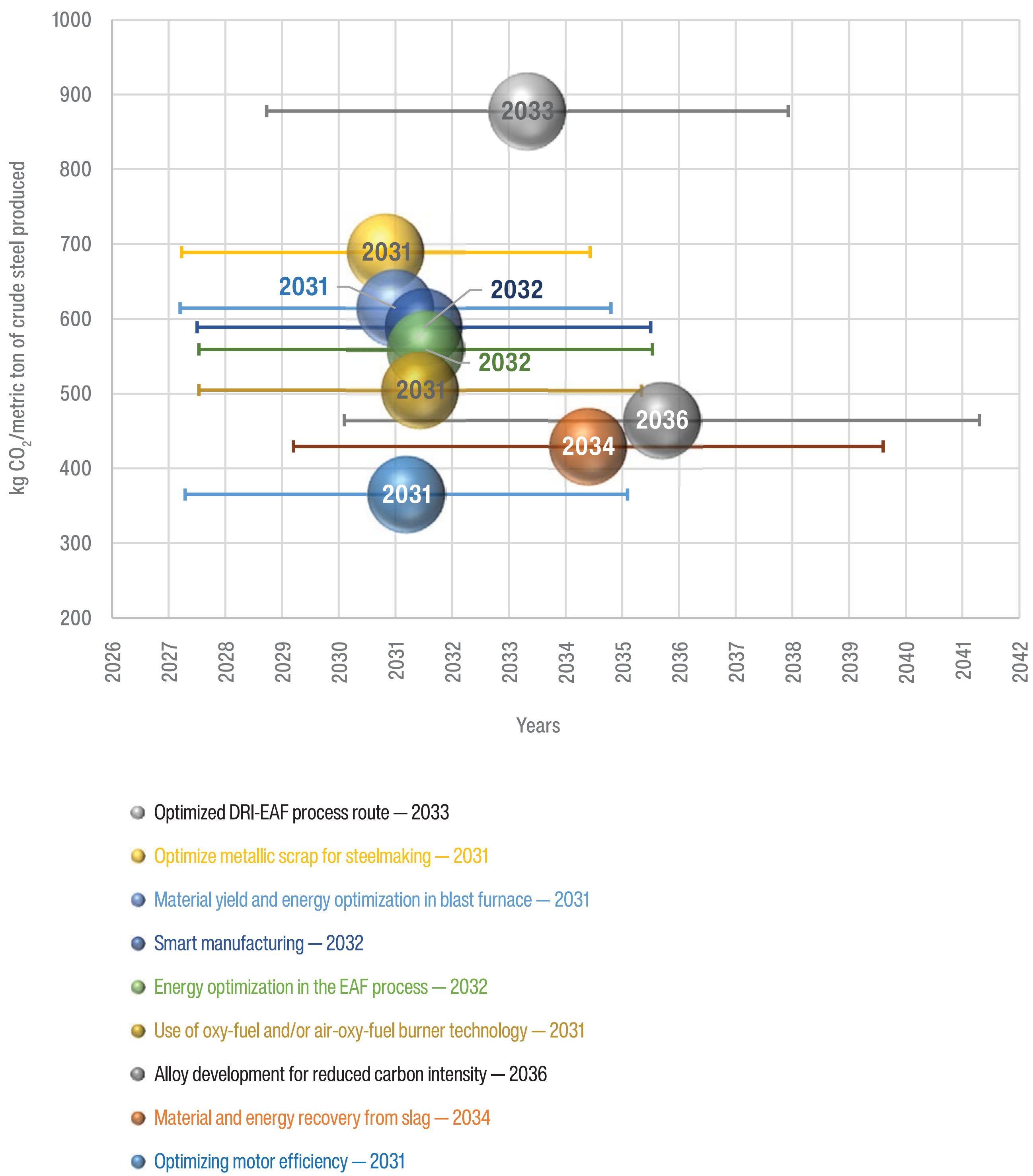


Figure 20b. Survey results on weighted average timeline of commercial implementation with ranges for the decarbonization technologies identified within the technology theme Material and Energy Optimization.

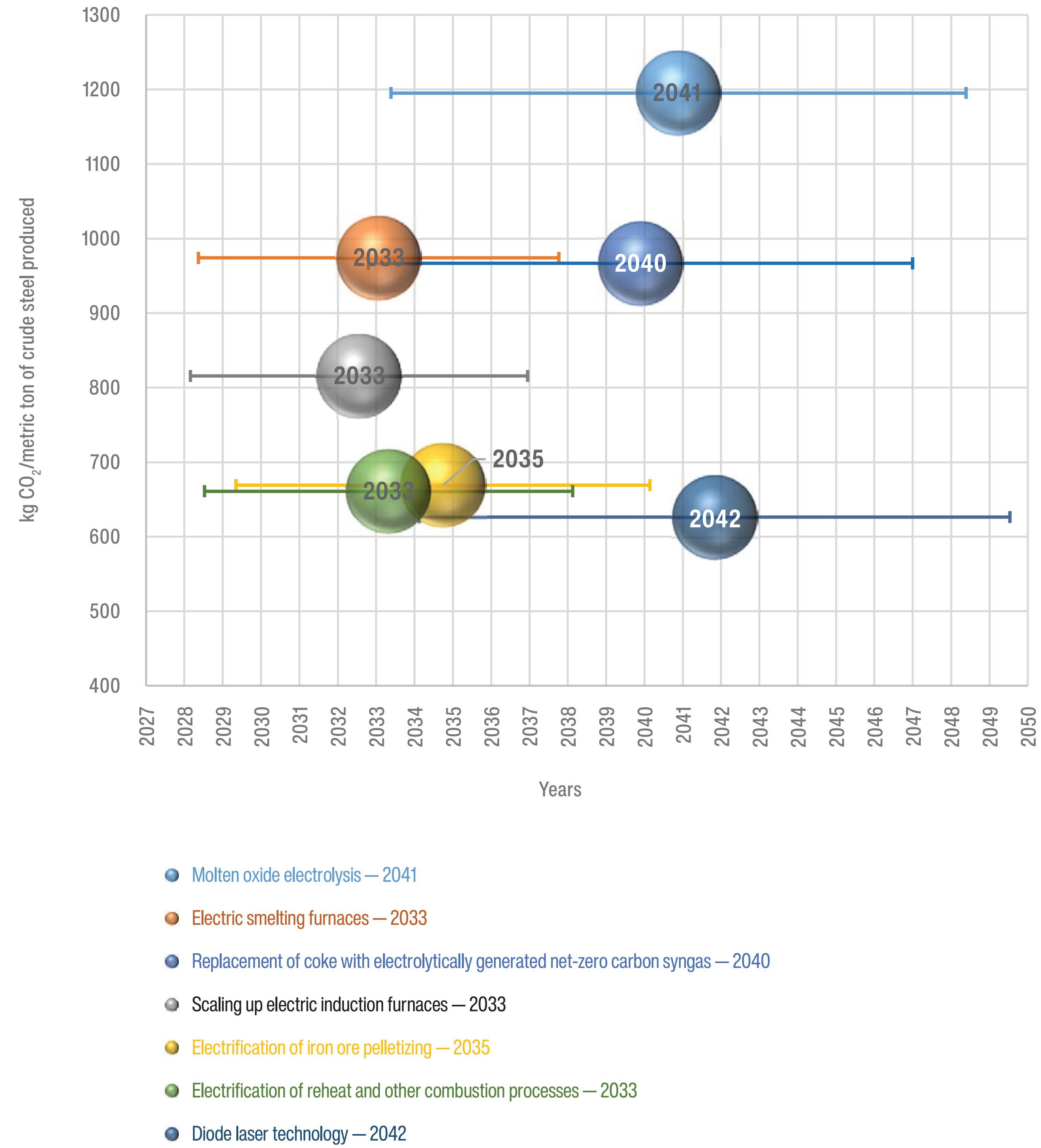


Figure 20c. Survey results on weighted average timeline of commercial implementation with ranges for the decarbonization technologies identified within the technology theme Electrification of Iron and Steel Processes.

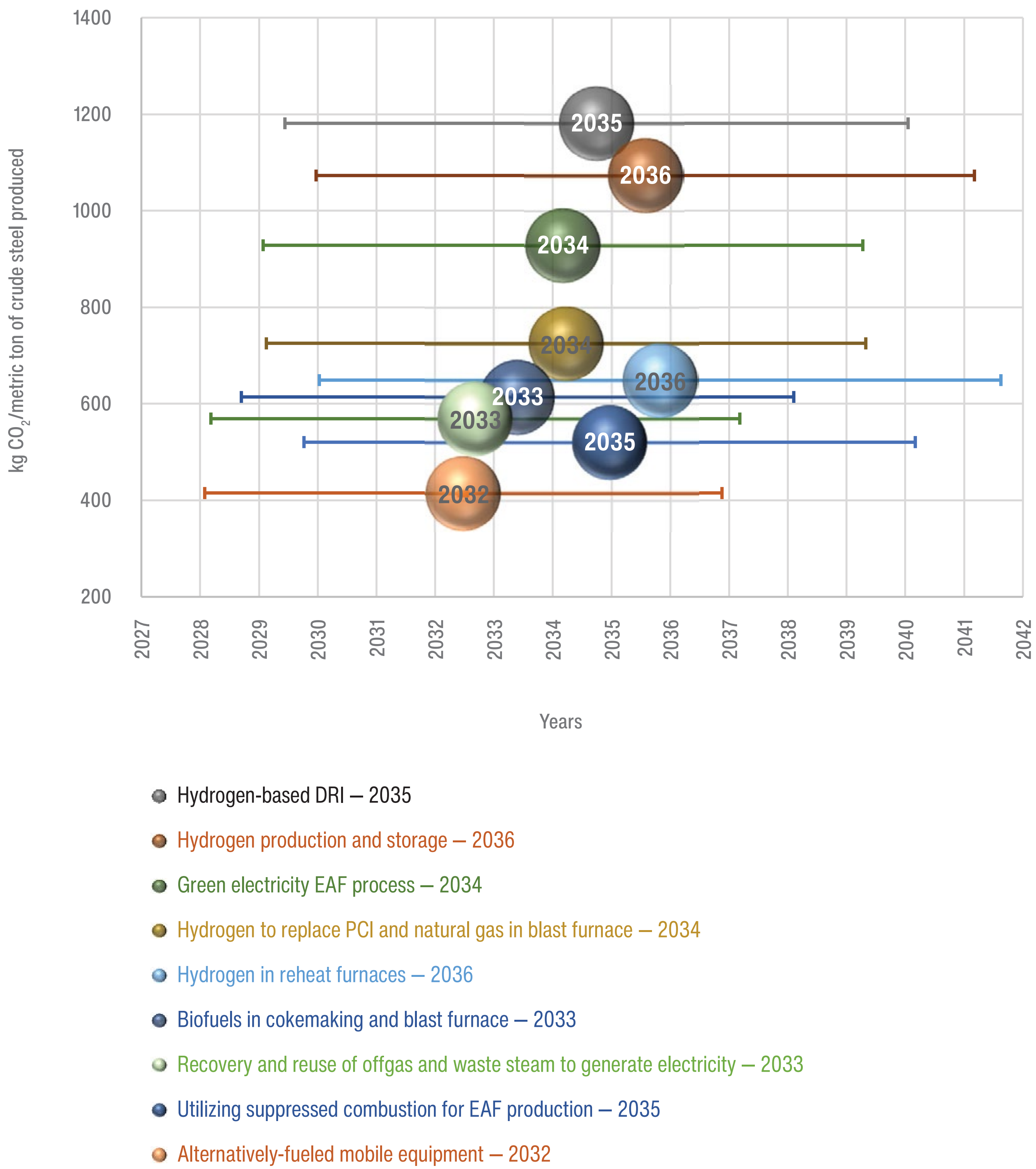


Figure 20d. Survey results on weighted average timeline of commercial implementation with ranges for the decarbonization technologies identified within the technology theme Alternative Low-Carbon Reductants and Energy Sources.

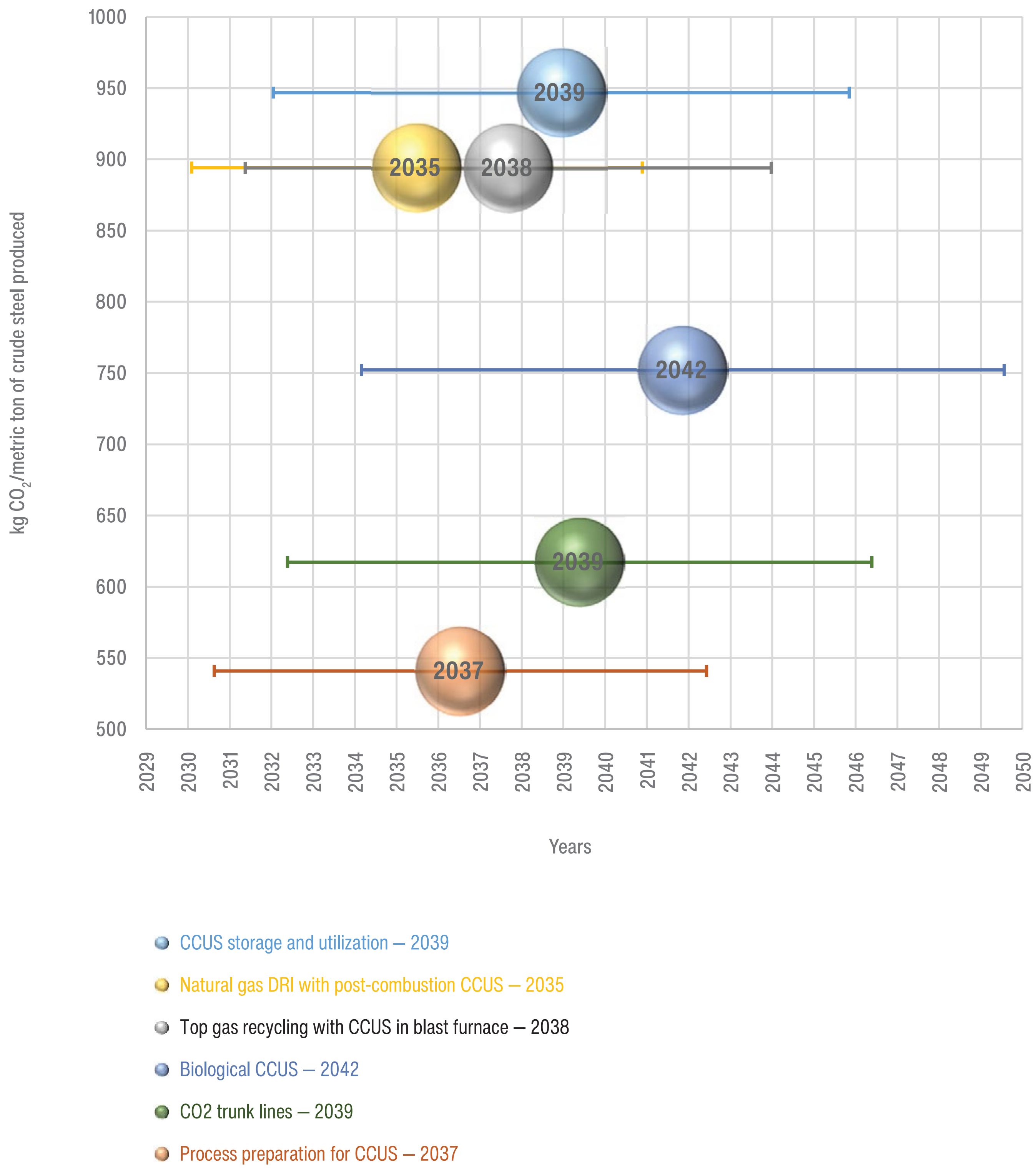


Figure 20e. Survey results on weighted average timeline of commercial implementation with ranges for the decarbonization technologies identified within the technology theme Carbon Capture, Utilization and Storage (CCUS).

Scope 1 carbon emission reduction for all decarbonization technologies. Fig. 19a shows the ranking of the impact on Scope 1 carbon emission reduction, expressed as kg CO_2/metric ton of crude steel produced for the decarbonization technologies. Figs. 19b–e show the results for the decarbonization technologies identified within the 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 (CCUS), respectively. The main technologies to decarbonize the U.S. iron and steel industry for the four technology themes on an immediate, short-term, medium-term and long-term basis, expressed as years from 2024, were identified and shown in Fig. 20a. Figs. 20b–e show the timeline of commercial implementation for the decarbonization technologies identified within the four technology themes.-

From the survey, more than 30 unique strategies were revealed, each of which can and will have an impact on reducing or eliminating carbon emissions. While the impact for each varies, the mitigating technologies to decarbonize the iron and steel industry with the largest potential impact were identified as: molten oxide electrolysis; hydrogen production and storage; hydrogen-based DRI; electric smelting furnaces; and replacement of coke with electrolytically generated net-zero carbon syngas, CCUS and green electricity EAF process (see Fig. 20).

The four decarbonization technologies with the lowest impact on carbon emission reduction were identified as optimizing motor efficiency, alternatively fueled mobile equipment, material and energy recovery from slag, and alloy development for reduced carbon intensity. Despite these technologies being considered the lowest impact on carbon emission reduction, they have on average a potential of reducing carbon emissions with 365, 415, 430 and 464 kg CO_2/metric ton of crude steel produced, respectively. When considering overall investment, these technologies have the potential to hasten the path to direct carbon avoidance.

This Roadmap provides a tool for the steel manufacturing industry to evaluate available technologies and their implementation stages, enabling the possibility to strategically evaluate best options to decarbonize their own processes on short-term, medium-term and long-term basis. Considering that the timeline of commercial implementation for these decarbonization technologies will vary widely and depend on many external factors, e.g., economical, political, geographical, etc., it is strategically important to invest in developing decarbonizing technologies and solutions in all iron- and steelmaking processes, along the entire value chain from raw material selection to finished products.

Table 8. Industry Priority for Iron and Steel Decarbonization Technologies (Rank 1–10)

Average rank	Industry priority for iron and steel decarbonization technologies (Rank 1–10)
4.2	Thermal Process Fuels
4.6	Electrification
4.6	Carbon Capture, Use and Sequestration
4.7	Metallic Scrap Feedstock
4.9	Smart Manufacturing
5.2	Effective Use of Existing Assets
5.8	Direct Carbon Avoidance
6.8	Alternative Iron Ore Reductants
7.1	Metallic Ore-Based Feedstock
7.6	Materials for Service

Table 9. Industry Priority for Related Government Initiatives (Rank 1–6)

Average rank	Industry priority for related government initiatives (Rank 1–6)
2.3	Develop supporting infrastructure for decarbonization technologies
2.9	Increase international co-operation and ensure a level global playing field
3.0	Support the demonstration of decarbonization technologies
4.2	Create a market for decarbonized steel
4.4	Track progress and improve data collection
4.5	Communicate the long-term importance for decarbonization efforts

Survey on Industry Priority on Decarbonization Topics

In February 2022, AIST surveyed the U.S. steel industry to prioritize 10 categories for steel decarbonization technologies and six categories for related government initiatives. Priorities are listed in descending order for each group, i.e., the highest priority category has the lowest average rank score. The data represents responses from 16 iron and steel companies and are shown in Tables 8 and 9 and Figs. 3 and 4. Examples of the technologies are described in Appendix C.

The three main priorities for decarbonizing the iron and steel industry, in order of importance, were identified as thermal process fuels, electrification of processes, and carbon capture utilization and storage, respectively.

The main priority for government initiatives was to develop supporting infrastructure for decarbonization technologies. Respondents indicate that the U.S. steel industry is willing to participate in public/private partnerships for research, development, and deployment programs for breakthrough decarbonization technologies.

Technology Process Adaptation Action Plan

This action plan outlines the short-term, medium-term and long-term goals for adapting steel manufacturing processes. By focusing on optimizing existing technologies, investing in new and transformational technologies, and aiming for breakthrough innovations, the steel industry can work toward achieving technological, economic, and environmental sustainability with a target of net-zero emissions by 2050.

Short-Term Outcomes

- Develop and Implement New Technologies
  - Action: Establish AIST-led working groups to coordinate government-supported funding for collaborative projects with steel industries, academia and national labs. Advance technologies for energy efficiency and emission reduction.
  - Objective: Optimize existing processes and workforce development. Transition to more sustainable practices.
  - Technologies to focus on:
    1. Optimize Metallic Scrap: Timeline 6.8 years (3.3–10.4 years). Carbon emission reduction 689 kg CO_2/metric ton of crude steel (293–1,085 kg).
    2. Material Yield and Energy Optimization in BF and EAF: Timeline BF: 7.0 years (3.2–10.8 years) and EAF: 7.5 years (3.5–11.6 years). Carbon emission reduction BF: 614 kg CO_2/metric ton of crude steel (257–971) and EAF: 559 kg CO_2/metric ton of crude steel (220–898).
    3. Optimize Motor Efficiency: Timeline 7.2 years (3.3–11.1 years). Carbon emission reduction 65 kg CO_2/metric ton of crude steel (107–624 kg).
    4. Use of Oxy-Fuel and/or Air-Oxy-Fuel Burner Technology: Timeline 7.4years (3.5–11.4 years). Carbon emission reduction 505 kg CO_2/metric ton of crude steel (188–821 kg).
    5. Expand Smart Manufacturing: Timeline 7.5 years (3.5–11.5 years). Carbon emission reduction 589 kg CO_2/metric ton of crude steel (233–944 kg).

6. Alternatively Fueled Mobile Equipment: Timeline 8.5 years (4.1–12.9 years). Carbon emission reduction 415 kg CO_2/metric ton of crude steel (132–698 kg).

7. Scaling Up Electric Induction Furnaces: Timeline 8.6 years (4.1–13.0 years). Carbon emission reduction 816 kg CO_2/metric ton of crude steel (365–1,267 kg).

8. Recovery and Reuse of Offgas/Waste Steam: Timeline 8.7 years (4.2–13.2 years). Carbon emission reduction 569 kg CO_2/metric ton of crude steel (229–910 kg).

9. Electric Smelting Furnaces: Timeline 9.1 years (4.4-13.7 years). Carbon emission reduction 974 kg CO_2/metric ton of crude steel (459–01,489 kg).

10. Optimized DRI-EAF Process Route: Timeline 9.3 years (4.7–14.0 kg). Carbon emission reduction 878 kg CO_2/metric ton of crude steel (402–1,353 kg).

11. Electrification of Reheat Processes: Timeline 9.3 years (4.5–14.2 years). Carbon emission reduction 661 kg CO_2/metric ton of crude steel (275–1,047 kg).

12. Biofuels in Cokemaking and Blast Furnace: Timeline 9.4 years (4.8–14.1 years). Carbon emission reduction 614 kg CO_2/metric ton of crude steel (251–977 kg).

Medium-Term Outcomes

- Invest in Transformational Technologies
  - Action: Develop and scale up advanced technologies with significant sustainability impacts.
  - Objective: Achieve major reductions in carbon emissions and energy use.
  - Technologies to focus on:
    1. Green Electricity EAF Process: Timeline 10.2 years (5.1–15.2 years). Carbon emission reduction 928 kg CO_2/metric ton of crude steel (428–1,428 kg).
    2. Hydrogen to replace PCI in Blast Furnace: Timeline 10.2 years (5.1–15.3 years). Carbon emission reduction 725 kg CO_2/metric ton of crude steel (317–1,133 kg).
    3. Material and Energy Recovery From Slag: Timeline 10.4 years (5.2–15.6 years). Carbon emission reduction 430 kg CO_2/metric ton of crude steel (145–714 kg).
    4. Electrification of Iron Ore Pelletizing: Timeline 10.7 years (5.4–16.1 years). Carbon emission reduction 669 kg CO_2/metric ton of crude steel (283–1,056 kg).
    5. Hydrogen-Based DRI: Timeline 10.7 years (5.4–16.1 years). Carbon emission reduction 1,181 kg CO_2/metric ton of crude steel (567–1,796 kg).
    6. Utilizing Suppressed Combustion for EAF: Timeline 11.0 years (5.8–16.2 years). Carbon emission reduction 520 kg CO_2/metric ton of crude steel (202–839 kg).
    7. Natural Gas DRI With Postcombustion CCUS: Timeline 11.5 years (6.1–16.9 years). Carbon emission reduction 894 kg CO_2/metric ton of crude steel (409–1,380 kg).
    8. Hydrogen Production and Storage: Timeline 11.6 years (6.0–17.1 years). Carbon emission reduction 1,073 kg CO_2/metric ton of crude steel (504–1,642 kg).
    9. Alloy Development for Reduced Carbon Intensity: Timeline 11.7 years (6.1–17.3 years). Carbon emission reduction 464 kg CO_2/metric ton of crude steel (164–764 kg).
    10. Hydrogen in Reheat Furnaces: Timeline 11.8 years (6.1–17.6 years). Carbon emission reduction 649 kg CO_2/metric ton of crude steel (271–1,027 kg).

Long-Term Outcomes

- Achieve Long-Term Sustainability Goals
  - Action: Develop and implement breakthrough technologies to support a net-zero-emission industry.
  - Objective: Reach full sustainability and carbon neutrality targets.
  - Technologies to focus on:
    1. Process Preparation for CCUS: Timeline 12.5 years (6.7–18.4 years). Carbon emission reduction 541 kg CO_2/metric ton of crude steel (205–877 kg).
    2. Top Gas Recycling With CCUS in Blast Furnace: Timeline 13.7 years (7.4–20.0 years). Carbon emission reduction 894 kg CO_2/metric ton of crude steel (412–1,376 kg).
    3. CCUS Storage and Utilization: Timeline 14.9 years (8.0–21.9 years). Carbon emission reduction 947 kg CO_2/metric ton of crude steel (438–1,456 kg).
    4. CO_2 Trunk Lines: Timeline 15.4 years (8.4–22.4 years). Carbon emission reduction 617 kg CO_2/metric ton of crude steel (248–987 kg).
    5. Replacement of Coke With Net–Zero Carbon Syngas: Timeline 15.9 years (8.8–23.0 years). Carbon emission reduction 967 kg CO_2/metric ton of crude steel (446–1,488 kg).
    6. Molten Oxide Electrolysis: Timeline 16.9 years (9.4–24.4 years). Carbon emission reduction 1,195 kg CO_2/metric ton of crude steel (570–1,820 kg).
    7. Diode Laser Technology: Timeline 17.8 years (10.1–25.6 years). Carbon emission reduction 626 kg CO_2/metric ton of crude steel (242–1,011 kg)
    8. Biological CCUS: Timeline 17.9 years (10.2–25.6 years). Carbon emission reduction 752 kg CO_2/metric ton of crude steel (322–1,183 kg).

Technology Process Adaptation Challenges

The steel industry faces a complex set of challenges as it navigates the transition to more sustainable and innovative practices. The following is a breakdown of these challenges and potential strategies to address them:

1. Global Steel Overcapacity
   - Issue: Excessive global steel production capacity (approaching 40%) exacerbates market instability, partly due to foreign government subsidies and market-distorting policies.
   - Impact: Low profit margins for U.S. steel producers, economic pressure and unstable pricing.
2. Economic Pressures
   - Issue: Narrow profit margins are compounded by fluctuating raw material prices and competition from alternative materials.
   - Impact: Limited investment in R&D as companies prioritize immediate financial stability over long-term innovation.
3. Underinvestment in R&D
   - Issue: Insufficient focus on research and development due to financial constraints.
   - Impact: Slow advancement in carbon-neutral technologies and other innovations.
4. Technology Innovation and Integration
   - Issue: The need to de-risk and accelerate the development of cutting-edge technologies like carbon capture and utilization, hydrogen-based DRI, and smart manufacturing.
   - Impact: Slower transition to sustainable practices and inefficient technology deployment.
5. The Fourth Industrial Revolution
   - Issue: Integration of advanced technologies (AI, machine learning, VR/AR, digital twins, etc.) into steel production.
   - Impact: High initial costs and the need for significant infrastructure changes.
6. Raw Material and Energy Constraints
   - Issue: Limitations in raw material availability and energy supply, combined with increasing emissions restrictions.
   - Impact: Pressure to innovate while managing costs and environmental impact.
7. Economic Viability and Accessibility of Green Energy
   - Issue: The challenge of balancing economic viability with the need for clean energy and innovative technologies.
   - Impact: Potential risk of overdependence on intermittent renewable energy sources and the need for reliable energy storage and grid integration.

Strategies to Address Technology Process Adaptation Challenges

Addressing these challenges requires a multifaceted approach that integrates technological innovation, strategic investments, and collaborative efforts across the industry and beyond. By focusing on these strategies, the steel industry can navigate its current obstacles and move toward a more sustainable and economically viable future.

1. Enhanced Collaboration
   - Strategy: Foster collaboration among industry, academia, technology suppliers and government entities to support precompetitive RD&D projects.
   - Outcome: Accelerate the development and commercialization of innovative technologies.

Table 10. List of CAPEX Investment in the U.S. Iron and Steel Melting Facilities Between 2012 and 2024.
*The list only includes melting facilities

Development	Facility	Plant	State	Census Region	Census Division	Date	Progress	Process	Capacity (tons/year)	Investment (in million US$)
New greenfield mills	Nucor Steel West Virginia	Apple Grove	WV	South	South Atlantic	Jan 2024	Under Construction	Slab/Sheet	3,000,000	3,100
New greenfield mills	Nucor Pacific Northwest	–	–	West	Pacific	Oct 2023	Site Selection	Rebar	650,000	860
New greenfield mills	Hybar LLC	Osceola	AR	South	West South Central	Nov 2022	Under Construction	Rebar	600,000	700
Brownfield expansion	Nucor Steel Kingman LLC	Kingman	AZ	West	Mountain	Aug 2022	Under Construction	Billet	600,000	100
New greenfield mills	Nucor Steel Lexington	Lexington	NC	South	South Atlantic	Apr 2022	Under Construction	Rebar	430,000	350
New greenfield mills	Pacific Steel Group	Mojave	CA	West	Pacific	Apr 2022	Permitted	Rebar	380,000	350
Brownfield expansion	U. S. Steel/Big River Steel	Osceola	AR	South	West South Central	Jan 2022	Under Construction	Slab/Sheet	3,000,000	3,000
New greenfield mills	CMC Arizona 2	Mesa	AZ	West	Mountain	Aug 2020	Completed, Jul 2023	Rebar/ Merchant Bar	500,000	300
New greenfield mills	CMC West Virginia	Martinsburg	WV	South	South Atlantic	Aug 2020	Under Construction	Rebar	500,000	450
Brownfield expansion	North Star BlueScope	Delta	OH	Midwest	East North Central	Aug 2019	Completed, May 2022	Slab/Sheet	940,000	770
New greenfield mills	Steel Dynamics Inc. – Flat Roll Group Southwest-Sinton Division	Sinton	TX	South	West South Central	Jul 2019	Completed, Jan 2022	Slab/Sheet	3,000,000	1,900
New greenfield mills	Nucor Steel Brandenburg	Brandenburg	KY	South	East South Central	Mar 2019	Completed, Dec 2022	Slab/Plate	1,200,000	1,700
Brownfield expansion	JSW Steel USA	Mingo Junction	OH	Midwest	East North Central	Jan 2019	Completed, Mar 2021	Slab/Sheet	1,500,000	250
Brownfield expansion	Big River Steel, Phase II	Osceola	AR	South	West South Central	Jun 2018	Completed, Nov 2022	Slab/Sheet	1,600,000	716
New greenfield mills	Nucor Steel Florida Inc.	Frostproof	FL	South	South Atlantic	Mar 2018	Completed, Dec 2020	Rebar	380,000	240
New greenfield mills	Nucor Steel Sedalia LLC	Sedalia	MO	Midwest	West North Central	Nov 2017	Completed, Feb 2020	Rebar	350,000	350
New greenfield mills	Cleveland-Cliffs Inc. Toledo HBI Plant	Toledo	OH	Midwest	East North Central	Jun 2017	Completed, Jun 2020	HBI	1,900,000	1,000
Brownfield expansion	U. S. Steel – Fairfield Works	Fairfield	AL	South	East South Central	Jul 2015	Completed, Oct 2020	Blooms	1,600,000	412
Brownfield expansion	CMC Steel Oklahoma	Durant	OK	South	West South Central	Jul 2015	Completed, May 2018	Rebar	390,000	250
New greenfield mills	Big River Steel, Phase I	Osceola	AR	South	West South Central	Jan 2013	Completed, Mar 2017	Slab/Sheet	1,650,000	1,300
New greenfield mills	ArcelorMittal Texas HBI	Corpus Christi	TX	South	West South Central	Dec 2012	Completed, Oct 2016	HBI	2,000,000	1,000

2. Focused R&D Investment
    - Strategy: Increase investments in research and development, particularly for technologies that enable carbon neutrality and advanced steelmaking processes.
    - Outcome: Drive technological advancements and improve competitive positioning.
3. Technology De-risking
    - Strategy: Engage in pilot projects and partnerships to de-risk new technologies such as carbon capture, hydrogen-based DRI, and electrolysis.
    - Outcome: Facilitate smoother transitions to commercial-scale applications.
4. Adoption of Smart Technologies
    - Strategy: Implement smart manufacturing technologies such as advanced sensors, AI, digital twins and automation.
    - Outcome: Improve operational efficiency, product quality and adaptability.
5. Optimizing Energy Use
    - Strategy: Develop strategies for integrating renewable energy sources, managing variability and optimizing energy storage.
    - Outcome: Enhance energy reliability and sustainability in steel production.
6. Policy Advocacy
    - Strategy: Work with policymakers to address trade imbalances, support subsidies for clean technologies and create favorable conditions for industry innovation.
    - Outcome: Improve the regulatory environment and level the playing field for domestic producers.
7. Building Ecosystems
    - Strategy: Create ecosystems that include diverse stakeholders — businesses, universities, national labs and energy companies — to drive industrial decarbonization and technological advancements.
    - Outcome: Foster a collaborative environment that supports breakthroughs and accelerates the transition to sustainable practices.

Scale-Up and Commercialization

To transition innovative steel decarbonization technologies from concept to commercialization an infrastructure and resources that support technology creation, development, demonstration, scale-up and commercialization will need to be developed. The focus will be on addressing the most challenging phases of this process, particularly for capital-intensive manufacturing like steel production. One approach could be to utilize multiphysics modeling and visualization technologies to reduce risks associated with scaling up new technologies, providing fundamental insights and practical guidance for rapid deployment. The following systemic research needs have been identified:

1. Carbon Measurement and Accounting:
    - Address challenges in measuring, accounting for and taxing carbon emissions accurately across various levels — from local to global. Ensure alignment of measurements and border transfers to improve net-zero steel production timelines.
2. Standardized Definitions:
    - Develop technical, measurable standards for various "green steel" grades and related inputs such as renewable power and fuels (e.g., hydrogen, biofuels).
3. Supply Chain and Investment:
    - Assess the impact of roadmap investments and required changes on existing supply chains. Explore technical, commercial and logistical resources, and evaluate supply and demand forces.
4. Supply Chain Upgrades:
    - Investigate current supply chain upgrades for cost reduction and shared costs, including potential cross-border subsidies. For example, consider U.S. government involvement in upgrading ores for DRI feedstock.
5. Research Program Coordination:
    - Align existing research programs to minimize duplication, share benefits and support national strategic goals while maintaining competitiveness. A Manufacturing Institute for Decarbonization of Iron and Steel could facilitate this coordination.

10. Workforce Development

Education and Outreach

Since 2021, the steel industry has seen a multigenerational investment cycle, one that has brought about US$26 billion in private investment by steel producers in North America. The industry is proactively investing in new technologies that will allow it to do more with less, and to do it better. In the meantime, domestic policy will encourage the development of a green energy grid and drive new steel demand over the long term.

Despite the optimism, steel struggles in the court of public opinion, which has impeded workforce development efforts. If you ask the average person about steel, you may hear that steel is obsolete and uses outdated technology or that it's bad for the environment and unsafe. What society does not realize, or perhaps takes for granted, is that steel is strong, durable, easily formed and machined; you can weld it and attach things to it; it can be magnetic or nonmagnetic; it is cost-effective; and it is the most recycled material on the planet.

What the public also doesn't see is that steel is an evolving engineered material that can improve the quality of life for every human being on Earth and perhaps beyond. Steel has an unbeatable value proposition, and the industry must shift the public mindset about an industry that is perceived to be unsafe, dirty and old to one that is safe, green and smart.

While there has been significant CAPEX investment in recent years, there is no such investment in a collaborative market outreach to educate the public about the vision for steel. The last concerted effort was the "Steel Alliance" which disbanded 20 years ago amidst myriad industry bankruptcies. In this regard, two fundamental facts exist:

- A green energy economy will be steel-intensive. Wind towers, solar farms, electric vehicles, hydrogen power plants and all forms of power transmission are all steel-intensive and cannot be constructed without steel.
- Steel is and will continue to be energy-intensive to produce. As an example, the steel industry in Ohio uses more energy than all other users in the state combined. If the steel industry is going to rely on green energy, it will need lots of it and it must be competitively available.

The vision is clear: A green energy economy will require a sustainable steel industry. Simply put, green energy needs steel and steel needs green energy. The industry must educate the public about this interdependence. Such outreach will undoubtedly enhance all workforce development efforts.

Manufacturing Skills Gap

Building a sustainable team of employees with the right mix of skill sets is a continuous challenge for the steel industry. Deloitte recently stated the U.S. manufacturing skills gap could leave as many as 3.8 million jobs unfilled between 2024 and 2033.[147] Of those 3.8 million open positions, roughly 1.9 million could go unfilled if manufacturers fail to address the skills shortage and applicant gap.

The main challenges within the manufacturing workforce are the high average age of workers where many existing employees are nearing retirement, changing technology demands that will require new skills, untapped and limited talent pools where the overall pool of potential engineering talent could be expanded, and inadequate training programs.

Financial burdens to manufacturing education are also a concern. Reduced federal funding and increasing costs of university education have contributed to the total outstanding student loans of US$1.08 trillion. The average student debt increased more than US$10,000 between 2005 and 2012, with tuition and college fees over the past decade growing faster than median household income.

The steel industry also faces the challenge of being perceived by society as a dirty, unsafe workplace with obsolete technology that is bad for the environment. According to Deloitte's survey, only 50% of respondents believed the working environments to be safe and clean and only 37% view manufacturing jobs as stable compared to other industries. The job security of professional staff in the steel industry is not as high as in other industries. Engineers, particularly in unionized steel mills, are priority targets for layoffs when the economy becomes unfavorable, as unions have negotiated job security clauses in their contracts. The reputation of the steel industry as an industry that lays off engineers has persisted since the 1980s, which coincides with the longest and most protracted decline in AIST's membership over the past 90 years, see Fig. 21.

To meet these national supply chain challenges, it is imperative to identify, prioritize and optimize the steel industry's manufacturing capabilities; improve efficiency in cost, performance and environmental sustainability; attract and educate a new, skilled and diverse pipeline of future engineers; and improve workforce training throughout the value chain.

In pursuing such strategic actions, and through strong industry support and philanthropy, the AIST Foundation has established programs to encourage student interest in the

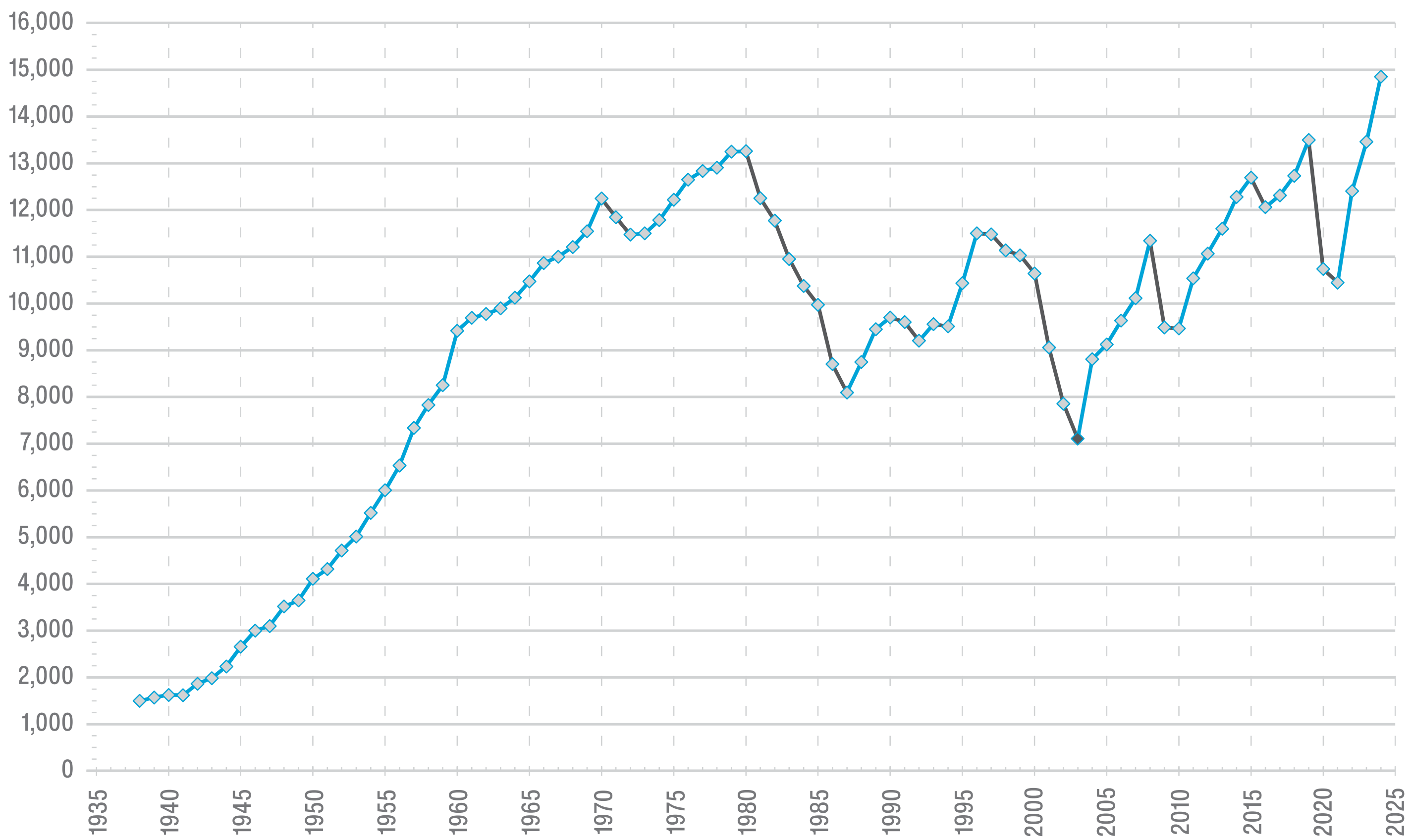


Figure 21. AIST professional membership from 1938 to 2024.

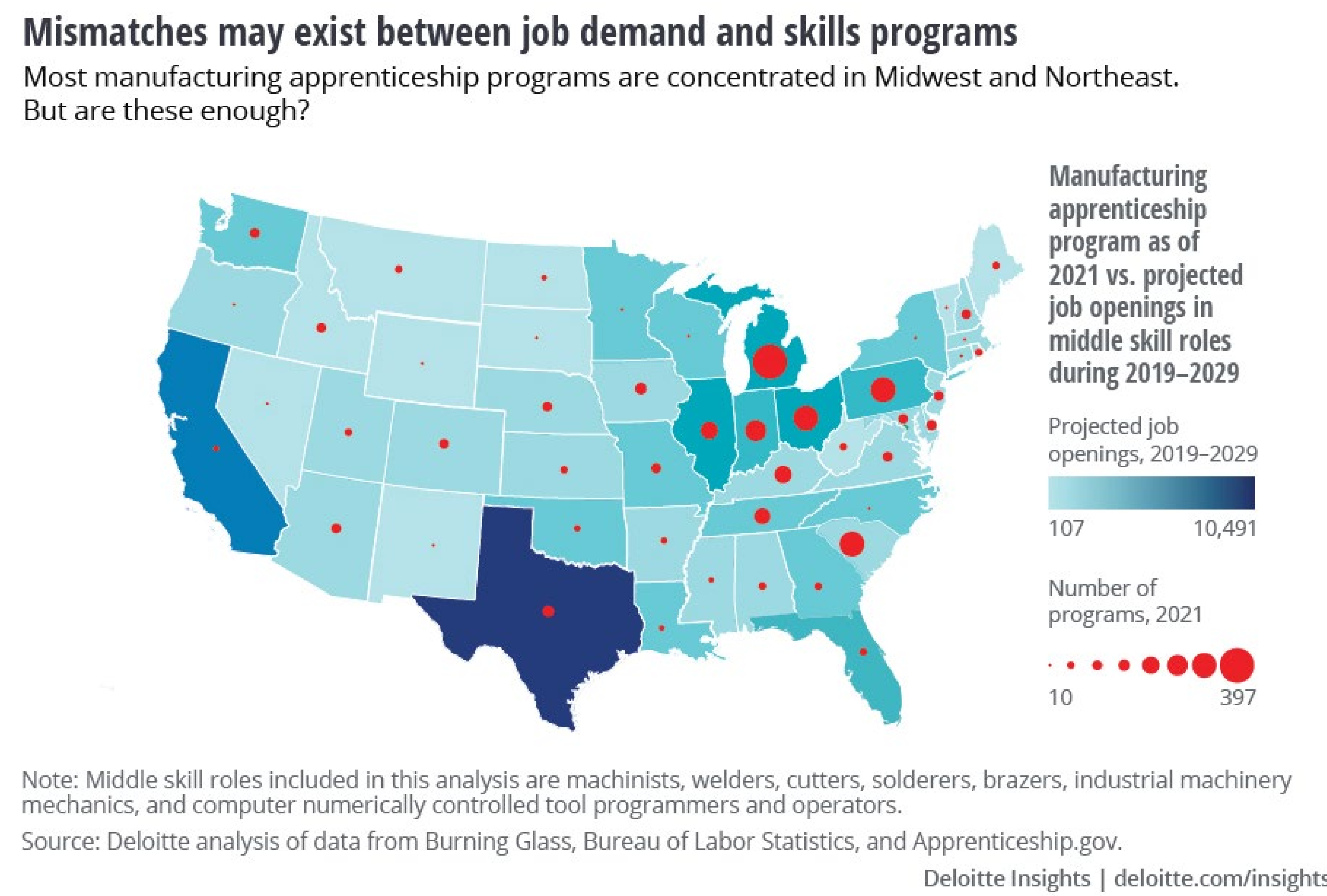


Figure 22. Deloitte's study on mismatch between job demand and skills programs in the U.S. manufacturing sector.[147]

steel industry. These programs promote the steel industry as a viable and rewarding career choice for young engineers, researchers, and others with technical skills or aptitude. The Foundation awards student scholarships, faculty grants and other student programs, including the Steel Intern Scholarship program, which awards annually up to 50 university students with a paid summer internship at a steel-related company and a US$7,500 scholarship for tuition support. In addition, the Foundation offers unique annual grants to university faculty to increase the number of engineering faculties with a vested interest in the industry and to increase the number of engineering students electing to pursue careers in the iron and steel industry. The annual funding for these programs exceeded US$1,200,000 in 2024.

According to Deloitte's article published in May 2021, a mismatch between job demand and skills programs exists for the manufacturing sector, see Fig. 22.[147] Research shows that more than 60% of steel industry investments are concentrated in the southern portion of the United States (see Table 10), but the demand for new engineers is not proportional to the amount of local talent graduating from southern universities. Generally, universities are behind in developing programs where they are needed, geographically. A list of materials science programs in United States with the numbers of undergraduate, master's and doctorate graduates are shown in Appendix D.

According to *U.S. News and World Report*, only one of America's top 10 materials science and engineering programs, Georgia Institute of Technology, is based in the southern region of the country. Moreover, students interested in the steel industry may be more likely to attend a university in the Midwest or Northeastern territories as this is where most universities with metallurgy concentrations lie. In this respect, historically black colleges and universities (HBCUs) and Hispanic-serving institutions (HSIs) may be strategically located for manufacturing jobs.

To bridge this gap, it is imperative to encourage engineering universities in southern states to evolve their current programs to ensure that engineering students are given the opportunity to explore and learn about the steel industry prior to graduation.

Although some southern universities may be behind in developing the necessary programs to foster the next generation of steel professionals, this realization is slowly coming to light for larger institutions in this area. In the steel industry, there is a shift where new programs are being developed to align with job opportunities. For example, Arkansas State University recently announced the U.S. Congress approved a US$10 million request to support the construction of a new Support Center for Advanced Materials and Steel Manufacturing. The university plans to invest in high-tech industry equipment and educate students about steel with the expectation to support what has become the biggest steel-producing region in the country. Investments like these are paramount to training young engineers and for creating programs involving universities and industry to showcase the significant industry growth in the south and to highlight the steel industry as a desirable and rewarding career for students.

There is also a need to define opportunities and challenges to retain and expand the talent pool, train and educate new employees, and upskill current employees. These new skills can be in AI, data analysis, automation, electric power systems, life cycle analysis, etc. Moreover, it is important to highlight today's modern steel industry by recognizing its advanced technology, energy conservation and environmental awareness to improve conventional perception. With this transition in mind, the steel industry must dispel its reputation as an industry with low job security. Specific tactics within a strategic framework could include:

- Actively introducing students and teachers to practical industry experience; for instance, through summer employment and internship programs.
- Collaborations with technical colleges to expand transferable skills certification programs.
- Investment into and strengthening of apprenticeship programs
- Retraining existing workers in innovation platforms.
- Utilizing digital technologies for authentic, engaged and interactive virtual training.
- Emulating innovative training and mentoring initiatives.

Such new learning has widespread impact and can be shared not only with the 120+ steel plants currently operating in the U.S., but with the entire manufacturing sector. These steel plants and their domestic suppliers directly and indirectly provide more than 2,000,000 jobs.

Minority-serving organizations (MSO), including business enterprises and institutions, are an important source of job creation and innovation in the U.S. economy, as well as economic development engines in their respective communities. There are nearly 700 minority-serving institutions (MSIs) providing pathways to STEM educational success and workforce development for millions of students of color. Barriers for these students can include financial circumstances, balancing requirements for work/family/education, resource availability and academic support. To eliminate barriers, it is important to learn the unique motivations, business strategies and community resources for each partnering MSO.

A diverse workplace allows for a more diverse suite of ideas, which inevitably increases the potential for transformative solutions in a complex and multidisciplinary problem such as decarbonization. Specific activities should be developed to bridge existing gaps in education, research, and public service to create career pathways for students at all levels and should include PIs from HBCUs and HSIs in RD&D projects.

Workforce Development Action Plan

Immediate Actions (0–2 years):

1. Improve Industry Image:
    - Launch Awareness Campaign: Develop and execute a campaign to highlight the steel industry's technological advancements and career opportunities.
    - Engage Influencers: Collaborate with industry influencers to change public perceptions.
2. Youth and Education Outreach:
    - Pilot Programs: Start pilot programs in high schools and trade schools to showcase steel industry careers and modern manufacturing techniques.
    - Virtual Tools Development: Begin creating and deploying educational tools, such as virtual plant tours and interactive process simulations.
3. Partnerships and Support:
    - Form Partnerships: Establish initial partnerships with educational institutions and industry organizations.
    - Advocate for Tech-Ed Funding: Lobby for increased support for technical education at the federal level.

Short-Term Actions (2–5 years):

1. Expand Outreach Programs:
    - Nationwide Initiative: Scale up outreach programs to include more schools and colleges, leveraging AIST Member Chapters for regional support.
    - Career Fairs and Workshops: Organize industry-specific career fairs and workshops for students and educators.
2. Enhance Training Programs:
    - Develop Training Modules: Create and implement new training modules that incorporate advanced technologies and processes.
    - Internship Programs: Expand internship and apprenticeship opportunities to provide hands-on experience in the industry.
3. Recruitment Strategy:
    - Refine Recruitment Practices: Based on research, adjust recruitment practices to better match candidates with industry needs.
    - Diversity Initiatives: Increase efforts to attract a diverse range of candidates.

Medium-Term Actions (5–10 years):

1. Sustainable Education and Training Infrastructure:
    - Strengthen Educational Ties: Deepen partnerships with educational institutions and industry to ensure a continuous pipeline of skilled workers.
    - Update Curriculum: Collaborate with schools to keep curricula relevant to current industry trends and technologies.
2. Evaluate and Adapt Programs:
    - Assess Program Impact: Regularly evaluate the effectiveness of outreach and training programs, making adjustments as needed.
    - Expand Virtual Tools: Enhance and expand the use of virtual tools and simulations to improve training and recruitment efforts.

Long-Term Actions (10–20 years):

1. Institutionalize Workforce Development:
    - Establish Enduring Programs: Ensure the sustainability of successful outreach, training and recruitment programs.
    - Continue Advocacy: Maintain advocacy efforts for federal and educational support to keep pace with industry needs.
2. Monitor and Evolve:
    - Ongoing Research: Continue researching workforce trends and adapt strategies to meet evolving industry demands.
    - Industry Leadership: Position the steel industry as a leader in workforce development by continuously improving and innovating educational and recruitment practices.

Workforce Development Challenges

1. Skill Shortages:
    - Lack of Engineers: Insufficient metallurgical, mechanical and electrical engineers.
    - High Competition: Many available manufacturing jobs face competition from more attractive sectors.
2. Impact of COVID-19:
    - Remote Work Transition: Difficulty in supporting real-time production operations due to remote work adjustments.
    - Work-Life Balance: Increased focus on work-life balance exacerbates aversion to shift work in the steel industry.
3. Perception Issues:
    - Stigmatization of Tech-Ed: Negative perceptions of technical education (tech-ed) and trade schools, leading to a preference for four-year college degrees.
    - Industry Misconceptions: Assumptions that steelmaking lacks high-tech opportunities, deterring younger generations
4. Educational and Recruitment Challenges:
    - Technical Education Stigma: Tech-ed classes are seen as less prestigious.
    - Attracting Talent: Need to better market the industry and engage with high school students and educators.

Strategies to Address Workforce Development Challenges

To develop a workforce strategic plan that establishes partnerships with community colleges, trade schools and universities, ensuring a skilled, diverse, and inclusive workforce for the steel industry, the following tactics are recommended:

1. Focused Working Groups
    - Strategy: Establish and solicit working groups within AIST.
    - Outcome: Address specific workforce development needs by creating targeted solutions and strategies for skills development and industry requirements.
2. Information Gathering
    - Strategy: Collect and analyze data on current recruitment programs and educational institutions.
    - Outcome: Assess and understand educational resources and needs, leading to informed decisions on improving recruitment and educational alignment with industry demands.
3. Curriculum Recommendations
    - Strategy: Create and distribute baseline curriculum recommendations for applied learning programs.
    - Outcome: Ensure educational programs across the U.S. are aligned with industry requirements, improving the relevance and effectiveness of training.
4. Recruitment Benchmarking
    - Strategy: Analyze existing recruitment programs to establish benchmarks and refine methods.
    - Outcome: Improve recruitment tactics and strategies, leading to more effective attraction and retention of talent in the steel industry.

5. Recruitment Skill Set Evaluation
    - Strategy: Implement aptitude testing and analyze successful employees' backgrounds.
    - Outcome: Match individuals with suitable roles more effectively and reduce miscasting, enhancing recruitment and retention strategies in the steel industry.
6. Educational Database
    - Strategy: Develop a comprehensive, accessible database of trade schools, colleges and universities.
    - Outcome: Facilitate networking and collaboration between AIST members and educational institutions, enhancing partnerships and resource sharing.
7. University and Industry Relations
    - Strategy: Develop and deploy tools for nationwide outreach and recruitment.
    - Outcome: Enhance engagement with educational institutions and potential candidates, increasing the effectiveness of recruitment efforts.
8. Collaborative Networks
    - Strategy: Foster collaboration among manufacturing industries to share educational resources.
    - Outcome: Build networks that connect educational institutions with industry needs, improving alignment and cooperation across sectors.
9. Internship and Scholarship Increases
    - Strategy: Increase internships and scholarships for steel industry careers.
    - Outcome: Expand practical training opportunities and financial support, attracting and retaining talent within the industry. Establish a nationwide scholarship fund to further support technical education.
10. Applied Learning Awareness
    - Strategy: Improve the perception of applied learning programs and educate high school students.
    - Outcome: Enhance awareness of career opportunities in the steel industry, encouraging more students to pursue relevant career paths.
11. Youth Engagement
    - Strategy: Engage youth through educational programs and collaboration with K–12 teachers.
    - Outcome: Increase interest in steel industry careers among individuals aged 15 to 19, improving future talent pipelines.
12. Trade School Engagement
    - Strategy: Engage trade schools improve the steel industry's collective reach into the network of trade and vocational schools
    - Outcome: Objective is to expand the pipeline for skilled trades and to recruit more people with skilled trades to the steel industry.
13. Virtual Tools and Visualization
    - Strategy: Develop educational tools such as animations, data visualizations and virtual tours.
    - Outcome: Aid understanding of steelmaking processes and complex scenarios through advanced digital tools, benefiting both newcomers and current employees.
14. Industry Image Enhancement
    - Strategy: Enhance the steel industry's image through targeted communication and outreach.
    - Outcome: Position steelmaking as a safe, clean, and high-tech sector, improving public perception and industry attractiveness.
15. Education on Sustainability
    - Strategy: Educate the public on the relationship between a green economy and a sustainable steel industry.
    - Outcome: Increase understanding of the industry's role in sustainability, supporting a positive public image and alignment with green initiatives.
16. Industry Promotion
    - Strategy: Market the steel industry as a high-tech sector with strong job prospects.
    - Outcome: Strengthen recruitment efforts and attract a diverse workforce, enhancing the industry's reputation and appeal.
17. Workforce Training
    - Strategy: Upgrade existing training programs to address new skills required for advancements in steel production and decarbonization technologies.
    - Outcome: Enhance the skills of the steel workforce, ensuring they are prepared for technological advancements and industry changes.
    - Skilled Workforce Attraction
    - Strategy: Attract and develop a skilled, diverse workforce.
    - Outcome: Drive innovation and adaptation to new technologies within the steel industry, fostering a more dynamic and capable workforce.
18. Cost Reduction and Competitiveness
    - Strategy: Improve production efficiency to reduce costs.
    - Outcome: Enhance the steel industry's global competitiveness by optimizing production processes and reducing operational expenses.
19. Transparency and Performance
    - Strategy: Track and publish data on industry performance and environmental sustainability.
    - Outcome: Improve industry transparency and build trust with stakeholders by showcasing progress and achievements in sustainability.
20. Government and Educational Support
    - Strategy: Advocate for increased federal funding and build partnerships with educational institutions.
    - Outcome: Secure additional support for technical education and align training programs with industry needs, strengthening the workforce development framework.

11. Concluding Remarks

The **Roadmap for Iron and Steel Manufacturing: Revolutionizing U.S. Global Leadership for a Sustainable Industrial Supply Chain** aims to transform the U.S. manufacturing sector by advancing research challenges in the iron and steel sector. The AIST Roadmap outlines the pathways for achieving the U.S. manufacturing vision in the steel industry by identifying the industry's grand challenges and priorities, and by identifying key milestones and performance targets for collaborative large-industry R&D. It is, and will continue to be, a work in progress with constant evolution and transformation.

To focus these grand challenges for iron and steel manufacturing, the AIST Roadmap utilizes a matrix consisting of four Technology Themes and three Cross-Cutting Themes. To facilitate crossover applications into other manufacturing sectors, the Technology Themes align with the DOE's "Industrial Decarbonization Roadmap" published in 2022.

Four Technology Themes

1. Material and Energy Optimization.
2. Electrification of Iron and Steel Processes.
3. Alternative Low-Carbon Reductants and Energy Sources.
4. Carbon Capture, Utilization and Storage (CCUS).

Three Cross-Cutting Themes

1. Smart Manufacturing.
2. Infrastructure, Facilities and Tools.
3. Education and Workforce.

This structure allows AIST to address challenges related to technical factors, such as raw material feedstock flexibility in ironmaking, improving recyclability, renewable energy sources and material efficiency. It addresses economic factors to bolster leadership and competitiveness by assessing technologies to insulate against global market distortions and to ensure a reliable return on the cost of capital for an industry with capital-intensive technologies. The work identifies pathways to develop industry-university-led innovation hubs to catalyze ideas in the marketplace and encourage innovation in the steel sector.

A critical aspect of the AIST Roadmap was to leverage the AIST Foundation with its programs and university partnerships. The AIST Foundation supports a mission to ensure the iron and steel industry of tomorrow will have qualified professionals by funding several significant initiatives to promote the steel industry as a viable and rewarding career choice for the next generation. These programs have been woven into the Roadmap.

The AIST Roadmap process has engaged stakeholders including raw material suppliers, steelmakers, equipment manufacturers, end users, government, academia and investors, with strategic goals intended to produce significant impacts for the U.S. steel industry and manufacturing supply chain.

The following goals and objectives were fulfilled within the project:

- Define a current baseline for the U.S. steel sector to decarbonize the iron and steel industry.
- Address high-priority technical research challenges to growing the U.S. manufacturing sector.
- Enhance innovation capacity and improve industrial competitiveness.
- Develop a plan through partnerships with community colleges, trade schools and universities for workforce development.
- Identify economically viable technical pathways to achieve a net-zero-emission iron and steel industry by 2050.

A Path Forward for an Iron and Steel Manufacturing Institute

To address the multifaceted challenges faced by the steel industry and to spearhead its transition toward a more sustainable future, the AIST Roadmap proposes a comprehensive set of strategies. These strategies are designed to tackle current barriers, drive technological advancement and enhance the overall competitiveness of the U.S. steel industry. A path forward to accelerate the implementation of these strategies could be through the creation of an iron and steel manufacturing institute.

A manufacturing institute would effectively drive innovation, collaboration and the implementation of technologies to accelerate the reduction of carbon emissions in steel production. The following benefits are anticipated:

1. Advanced Research & Development: The institute successfully spearheads cutting-edge R&D projects focused on developing and scaling innovative decarbonization technologies. This includes breakthroughs in carbon capture, utilization and storage; alternative low-carbon reductants; and electrification of steel production processes. The institute's research contributes to significant advancements in reducing the carbon footprint of steel production.
2. Collaborative Innovation Ecosystem: A robust network of industry stakeholders, including steel producers, technology developers, academic institutions and government agencies, is established. This collaborative ecosystem fosters knowledge sharing, joint research initiatives, and the codevelopment of solutions, accelerating the deployment of decarbonization technologies across the industry.
3. Successful Pilot Projects and Demonstrations: The institute oversees and successfully executes multiple pilot projects and demonstrations of new technologies. These projects showcase practical applications of innovative solutions, validate their effectiveness and provide a clear pathway for scaling up to commercial production. Successful demonstrations lead to the adoption of new technologies by steel producers.
4. Workforce Development and Training: The institute develops and delivers comprehensive training programs and educational resources for the steel workforce. These programs focus on the skills needed to operate and maintain new decarbonization technologies. Enhanced training efforts lead to a more skilled workforce capable of supporting the industry's transition to greener practices.
5. Policy and Industry Influence: The institute plays a pivotal role in shaping policies and standards related to steel decarbonization. By working closely with policymakers and industry leaders, the institute influences regulations and incentives that support the transition to a low-carbon steel industry. The institute's recommendations and findings are widely recognized and adopted.
6. Increased Industry Investment and Adoption: The successful implementation of the institute's initiatives leads to increased investment from both public and private sectors in steel decarbonization technologies. This investment accelerates the commercialization and widespread adoption of new technologies, contributing to a significant reduction in the industry's overall carbon emissions.
7. Transparent Reporting and Benchmarking: The institute establishes a system for transparent reporting and benchmarking of decarbonization progress. Regular updates and performance metrics are shared with stakeholders, demonstrating the institute's impact and providing a benchmark for industrywide progress. This transparency builds trust and accountability within the industry.
8. Enhanced Public Perception: Through effective outreach and education, the institute improves the public's understanding of the steel industry's commitment to sustainability. Positive media coverage and public awareness campaigns highlight the industry's advancements in decarbonization, leading to an enhanced public perception of steel as a green and innovative material.

Overall Impact

The successful implementation of the iron and steel manufacturing institute results in a significant reduction in carbon emissions from steel production, positions the industry as a leader in sustainable manufacturing, and supports the global transition to a green economy. The institute becomes a model for collaborative innovation and a key driver of progress in the steel industry's decarbonization journey.

12. Appendices

Appendix A. List of Contributors

Table A-1. AIST Technology Board I

Name	Technology Committee	Company
Alfaro, Jose L.	Cokemaking Technology Committee	Arch Resources
Baumgardner, Frank	Pipe & Tube Technology Committee	Nucor Steel–Decatur LLC
Bellai, Deni	Cold Sheet Rolling Technology Committee	Hugo MIEBACH GmbH
Brooks, Geoffrey	Oxygen Steelmaking Technology Committee	Swinburne University of Technology
Brunelli, Robert	Hot Sheet Rolling Technology Committee	TMEIC Corp. Americas
Cathcart, Chad	Metallurgy — Steelmaking & Casting Technology Committee	Stelco Inc.
Chapman, Russ	Member	Firebridge Inc.
Chevrier, Vincent	Direct Reduced Iron Technology Committee	Form Energy
Cox, Laurence	Transportation & Logistics Technology Committee	PGT Trucking
Cupp, Sara R.	Member	Steel Dynamics Inc.
d'Hubert, Xavier	Environmental Technology Committee	XDH Energy
Druciak, Matt	Plate Rolling Technology Committee	Tenova Inc.
Firsbach, Felix	Member	Badische Stahl-Engineering GmbH
Fountoulakis, Stavros	Galvanizing Technology Committee	ArcelorMittal Global R&D – East Chicago
Giglio, Alisha	Environmental Technology Committee	SINAI Technologies
Grant, Michael G.	Member	Air Liquide Global Management Services GmbH
Guidugli, Guilherme	Member	Primetals Technologies USA LLC

Table A-1. Cont'd.

Name	Technology Committee	Company
Hill, John	Energy & Utilities Technology Committee	Cleveland-Cliffs Inc.
Hornby, Sara A.	Member	Global Strategic Solutions Inc.
Jamieson, Brian J.	Member	Charm Industrial
Jampani, Megha	Ironmaking Technology Committee	Hatch
Kelly, Nate	Cranes Technology Committee	Virginia Crane — Foley Material Handling
Khajjayam, Ramesh	Electrical Applications Technology Committee	Primetals Technologies USA LLC
Kober, David	Digitalization Applications Technology Committee	IBA America
Komaragiri, Samrat	Continuous Casting Technology Committee	Vesuvius
Lapasin, Marco	Member	Danieli & C. Officine Meccaniche SpA
Lucas, William	Long Products Technology Committee	Fives ST
MacKinnon, Britt	Electric Steelmaking Technology Committee	Hatch
Makwana, Anand Kumar	Energy & Utilities Technology Committee	Air Products
Marshall, David	Energy & Utilities Technology Committee	Performance Improvement Inc.
Matson, Sam A.	Member	CMC
Morelato, Anderson Peter	Member	ArcelorMittal
Morey III, Joseph H	Member	Morey Industrial Consulting
Nimbalkar, Sachin U.	Member	Oak Ridge National Laboratory
Pathak, Hiranya M.	Member	Primetals Technologies USA LLC
Peintinger, Michael	Digitalization Applications Technology Committee	Smart Steel Technologies

Table A-1. Cont'd.

Name	Technology Committee	Company
Petrilena, Brenda Jean	Member	United States Steel Corporation
Pistorius, P. Chris	Member	Carnegie Mellon University
Poveromo, Joseph J.	Member	RMI Global Consulting
Quinn, Dennis	Galvanizing Technology Committee	Fives North American Combustion Inc.
Ranade, Madhukar G.	Member	Steel Dynamics Inc. – Flat Roll Group
Sgrò, Antonio	Member	Danieli & C. Officine Meccaniche SpA
Smith, Andrew	Plate Rolling Technology Committee	SSAB Alabama
Sukhram, Mitren	Member	Hatch
Tang, Dai	Ladle & Secondary Refining Technology Committee	Nucor Steel–Decatur LLC
Trzcinski, Richard E.	Project & Construction Management Technology Committee	Superior Engineering LLC
Tseitline, Alexander	Member	EVRAZ Inc. North America
Vachon, Michele	Member	Big River Steel – A U. S. Steel Co.
Valladares, Lewyn	Member	Stelco Inc.
Vanover, Kyle W.	Member	Steel Dynamics Inc. – Flat Roll Group Butler Division
Vieira, Igor	Metallurgy — Processing, Products & Applications Technology Committee	Nucor Steel–Arkansas

Table A-2. Business Board II

Universities		
Name	**Title**	**Institution**
Aglan, Heshmat	Dean and Professor, College of Engineering	Tuskegee University
Basit, Munshi	Assistant Professor, Department of Mechanical Engineering	Tuskegee University
O'Malley, Ronald	F. Kenneth Iverson Endowed Chair Professor and Director, Kent D. Peaslee Steelmaking Manufacturing Research Center	Missouri University of Science and Technology
Pistorius, P. Chris	POSCO Professor of Materials Science and Engineering	Carnegie Mellon University
Sanders, Paul	Patrick Horvath Endowed Professor of Materials Science and Engineering	Michigan Technological University
Seetharaman, Sridhar	Fulton Professor of Industrial Decarbonization and CEO of EPIXC	Arizona State University
Speer, John	John Henry Moore Distinguished Professor of Metallurgical and Materials Engineering, Director of Advanced Steel Processing and Products Research Center	Colorado School of Mines
Zhou, Chenn	NIPSCO Distinguished Professor of Engineering Simulation, Director of Center for Innovation Through Visualization and Simulation and Steel Manufacturing Simulation and Visualization Consortium	Purdue University Northwest

Table A-2. Cont'd.

National Laboratories		
Name	**Title**	**Institution**
Fisher, Aaron	Acting Director of the HPC for Energy Innovation Program	Lawrence Livermore National Laboratory
Ringer, Matthew	Laboratory Program Manager for Advanced Manufacturing	National Renewable Energy Laboratory
Snyder, Seth	Energy & Environment S&T, Relationship Manager – Advanced Manufacturing, Relationship Manager – Vehicle Technologies	Idaho National Laboratory (retired)
Van Buuren, Tony	Deputy Associate Director for S&T, Physical and Life Sciences Directorate	Lawrence Livermore National Laboratory
Associations		
Name	**Title**	**Institution**
Hengen, Tyler	Director, Sustainability and Environment	American Iron and Steel Institute
Sebastian, Brandie	Senior Director for Sustainability, Energy and Environment	American Iron and Steel Institute
Stuart, Eric	Vice President, Environment, Energy and Infrastructure Policy	Steel Manufacturers Association
AIST Key Personnel		
Name	**Title**	**Institution**
Ashburn, Ronald	Executive Director	Association for Iron & Steel Technology
Bliss, Brian	General Manager — Programs & Publications	Association for Iron & Steel Technology
Gauffin, Alicia	Staff Engineer	Association for Iron & Steel Technology
McKelvey, Chris	Board Services Administrator	Association for Iron & Steel Technology
Varmecky, Stacy	General Manager — Sales & Marketing	Association for Iron & Steel Technology
Voss, Anna	Manager — Technology Programs	Association for Iron & Steel Technology

Table A-2. Cont'd.

Industry Partners
ArcelorMittal North America
Cleveland-Cliffs Inc.
CMC
Danieli Corp.
Gerdau North America
Linde plc
Midrex Technologies Inc.
Nucor Corp.
SMS group Americas
SSAB Americas
Steel Dynamics Inc.
Tenova Inc.
United States Steel Corporation

Appendix B. List of Decarbonization Technologies

Material and Energy Optimization

- *Optimized DRI-EAF Process Route.* Optimizing the DRI-EAF process route will reduce the CO_2 emissions of the steel industry. The EAF process emits on average 600 kg CO_2/ton crude steel while the BF/BOF process emits 1,800 kg CO_2/ton crude steel on average. The co-location of DRI production facilities with EAF melting facilities enables the hot transfer of DRI to the EAF. Hot DRI transfer has been reported to save approximately 26 kWh/ton liquid steel for every 100°C increase in hot-charge DRI temperature in the EAF.

- *Optimize Steel Scrap for Steelmaking.* Optimize the utilization and efficiency of recycled steel scrap by collecting, sorting and blending. Technologies to sort and upgrade residual scraps must be developed to minimize tramp elements.

- *Material Yield and Energy Optimization in Blast Furnace.* Advanced automation and machine learning has great potential to increase the material yield and energy efficiency in the BF and auxiliary systems in the process route of steelmaking. Optimization of the smelting process so that the least-cost charge for iron specification can be obtained and still hit specifications. Increasing the hot blast temperature is the single remaining major step for those BFs not already maximizing stove output. Coke quality, most notably the coke cold crushing strength, coke stability, and coke CSR must be given special consideration to enable advanced blast furnace operations.

- *Energy Optimization in the EAF Process.* Depending on material recoveries and effective energy transfer, the EAF route can be 20–30% more energy efficient than the current state of the art.

- *Optimizing Motor Efficiency.* Optimize AC and DC motors, controls, and energy supply systems to improve overall electrical efficiency and power delivery.

- *Material and Energy Recovery From Slag.* Each year the iron and steel industry produces more than 300 million tons of liquid slag, the main waste product produced at steel mills. Approximately 1.7 GJ of thermal energy per ton of liquid slag is not being used, therefore the recovery of thermal heat from liquid slags and extraction of valuable metals are of great importance. Heat exchangers extract thermal energy from the slag and transfer it to water or oil. The captured energy can be used for various processes, such as gas preheating or generation of steam. Metals from slag can be extracted by magnetic separation and can also be further grinded whereafter the metals are selectively extracted by strainers.

- *Alloy Development for Reduced Carbon Intensity.* Higher-strength steels for auto bodies and other mobility applications have provided benefits in vehicle weight reduction and fuel efficiency. With a lower weight per application, the carbon footprint of the steel life cycle can be reduced in the manufacturing process and in use.

- *Use of Oxy-Fuel and/or Air-Oxy-Fuel Burner Technology.* Oxy-fuel and air-oxy-fuel combustion are established technologies that are used in diverse high-temperature melting processes including in the iron and steel industry. The use of oxy-fuel or air-oxy-fuel technology helps to improve the thermal efficiency of any high-temperature heating process. The major reasons for the improved thermal efficiency performance are the absence or reduction of nitrogen diluent in the oxidizer stream, which reduces the energy carried away with nitrogen in the exhaust flue, and the effective heat transfer rate from furnace gases to the melt or material increases.

- *Smart Manufacturing.* Smart manufacturing will transform the steel industry in the way raw materials are sourced, manufactured, and marketed through horizontal and vertical supply chain integration of digitalization, smart sensors, and data mining. Smart manufacturing may also include improved process optimization and control utilizing advanced digitalization technologies such as simulation, visualization and digital twins. Digitalization and smart manufacturing can further help production cycle integration with electricity needs, such that steel plants can have an optimal use of electricity.

Electrification of Iron and Steel Processes

- *Molten Oxide Electrolysis.* Reduction of iron ore via electrolytic cell technology instead of chemically via carbon in a blast furnace. The molten oxide electrolysis process uses an electrolytic cell, which produces an electric current to break down compounds, forcing the oxygen out of the iron ore without the use of coke and without creating carbon dioxide.

- *Electric Smelting Furnaces.* ESF technology is a long-established reduction process used in the nonferrous metals industry. The iron- and steelmaking route involves a DRI unit combined with an ESF and followed by the BOF process. There are two distinct designs for the ESF unit: the spherical shell design and the rectangular six-in-line furnace design. When converting the ESF to a steelmaking process, there are technical restrictions on the furnace's size that must be met to guarantee consistent thermal expansion of the refractory material.

- *Scaling Up Electric Induction Furnaces.* An electric induction furnace is a furnace that heats metal by electromagnetic induction. Induction heating equipment can be used by medium-frequency heating furnaces, melting furnaces, vacuum induction furnaces, metal quenching and tempering induction heating furnaces, etc.

- *Electrification of Iron Ore Pelletizing.* Electrical heating alternatives in the form of plasma torches and microwaves to pelletize iron ore are under investigation. Pilot trials have shown that implementation should be possible to eliminate fossil fuel burners. Pilot trials at LKAB have shown that implementation should be possible for both plasma torches and microwaves. For pelletizing hematite ores, carbon additions to the pellet feed need to be replaced by biomass materials.

- *Replacement of Coke With Electrolytically Generated Net-Zero-Carbon (NZC) Syngas.* Syngas is generated by capturing the CO_2 from a furnace, bubbling it into water, and conducting co-electrolysis of the H_2O/CO_2 to generate H_2/CO. Syngas may be generated via low-temperature electrolysis in the shorter term and high-temperature steam electrolysis as the technology matures. With co-electrolysis and CO_2 looping, energy to reduce the iron ore is electrical, and may come close to net-zero carbon. The process is similar to using hydrogen generated by water electrolysis.

- *Electrification of Reheat and Other Combustion Processes.* Reheating furnaces are used to heat and homogenize temperatures in semifinished cast products to be further processed in the mill. Reheating furnaces are almost exclusively gas-fired, typically natural gas, and are used due to the lower energy costs. Alternatives are electrical heating or hydrogen combustion. Electrification of reheating furnaces can be done by induction heating and direct or indirect resistance heating. Electrical energy can also replace fossil fuels in the annealing and thermal treatment processes, coatings, galvanizing, and paint processes.

- *Diode Laser Technology.* High-powered diode lasers provide a more flexible and precise surface treatment of steel components. Diode lasers offer a more economical method in heat treating metals over other heating sources such as gas flames or induction coils, since they allow energy-efficient hardening of complex component geometries. These lasers are currently being used for surface hardening of steel components and used on steel alloys as a preheating source prior to friction stir welding to reduce tool wear and increase welding speeds.

Alternative Low-Carbon Reductants and Energy Sources

- *Hydrogen Production and Storage.* The objective is to establish a hydrogen ecosystem for carbon neutrality, consisting of production, transport, storage and application. The development of hydrogen crack–resistant steels is needed to store and transport hydrogen in support of the evolving hydrogen economy.

- *Hydrogen-Based DRI.* The process replaces fossil fuels with renewable hydrogen in the DRI production stage to decarbonize iron ore reduction. It represents a technically proven production method that enables nearly emission-free production.

- *Hydrogen Plasma Smelting Reduction (HPR).* Iron ore can be melted and reduced simultaneously in a hydrogen plasma-based reduction process, which allows the production of liquid iron in one step. This process eliminates the need for intermediate agglomeration or refinement processing of iron ore. During HPR, a plasma arc zone is generated between the electrode and the iron ore under H_2 partial pressure. In the plasma arc zone, the iron ore can be melted and reduced by hydrogen gas and plasma state.

- *Hydrogen Replaces Pulverized Coal Injection and Natural Gas in Blast Furnace.* Hydrogen gas can replace some part of pulverized coal in the BF, which can reduce environmental pollution and energy consumption in molten iron production. The optimum H_2 content of gas injection into the BF is between 5 and 10%. Additionally, higher fossil fuel displacement, and therefore decarbonization, could be achieved using NZC syngas rather than hydrogen.

- *Biofuels in Cokemaking and Blast Furnace.* Biofuel can be used in two ways in the cokemaking-blast furnace production route. As coke prepared by substituting a portion of the coal blend (bio-coke) and as an auxiliary fuel injected directly into the blast furnace tuyere.

- *Green Electricity in the EAF Process.* Decarbonization may be achieved via the application of green electricity in the EAF process. Renewable intermittent and base-load energy sources located near the steel plant can ease the integration of a traditional electricity source.

- *Utilizing Suppressed Combustion for EAF Production.* In the suppressed-combustion system of a BOF, a ring-shaped hood is lowered onto the converter mouth before the blow, keeping air away from the hot offgases. This process offsets combustion and preserves the chemical heating value of the offgas. The application of such a system on an EAF could represent a potential energy source.

- *Recovery and Reuse of Offgas and Waste Steam to Generate Electricity.* Although most offgases present low calorific value, they can be recycled and reintroduced in the process or utilized to generate heat and electricity. Associated waste heat recovery system steam can be produced for electric power. Heat recovery facilities can be centralized to efficiently sequester offgas energy streams.

- *Recovery and Utilization of Waste Gases (H_2, CO, CO_2) for Chemicals or Fuels.* COG is a readily available and stable gas, which is one of several hydrogen sources used in industry. By utilizing waste heat recovery and a newly developed catalyst, the hydrogen content of COG can be increased into reformed COG before injection in the blast furnace shaft.

- *Hydrogen in Reheat Furnaces.* Partially switching from natural gas to H_2 changes the zoning of the reheat furnace, creating a hybrid furnace. In the short term, hybrid reheating furnaces may use a combination of the gas-fired process and induction heating.

- *Alternately Fueled Mobile Equipment.* Optimizing energy systems for mobile equipment to rely on alternate fuels such as hydrogen, natural gas and electricity, and upgrading current systems to modern energy-efficient motors. This includes equipment used to transport materials such as trucks, locomotives and ships.

Carbon Capture, Utilization and Storage (CCUS)

- *CO_2 Trunk Lines.* A network of CO_2 trunk lines will be critical to the integrated CCUS infrastructure.

- *CCUS Storage and Utilization.* Capture carbon dioxide emissions from iron- and steelmaking processes and either use them, such as in building materials (utilization), or permanently store them within the earth's subsurface thousands of feet below the surface (storage).

- *Process Preparation for CCUS.* In many processes, engineering and redesign is necessary for efficient carbon capture. An example is oxygen-enriched combustion to reduce or eliminate the nitrogen and consequently the volume of the gas. All processes that employ carbon will need to capture the exhaust streams.

- *Top Gas Recycling With CCUS in Blast Furnace.* Top gas recycling technology is based on lowering the usage of fossil carbon (coke and coal) with the reuse of the reducing agents (CO and H_2), after the removal of the CO_2 from the top gas. The ultralow-CO_2 blast furnace process (ULCOS-BF) aims to minimize the CO_2 emissions of the BF by at least 50%. This process is based on the replacement of hot blast by oxygen, the recycling of hot decarbonated top gas into the lower shaft and normal hearth tuyeres, and the capture of CO_2 and its storage in a geological trap (full CO_2 capture and storage process). This configuration uses high-purity O_2 to produce the reducing gases from pulverized coal injection coal. The coke ovens that supply the coke and the steel process that uses the hot metal should also be connected to a carbon capture system as well. These gases all have calorific content that can assist in powering a CCU process where a product is made from gases such as ethanol, precipitated calcium carbonate or carbon black.

- *Natural Gas DRI With Postcombustion CCUS.* Natural gas and coal are the two primary fuels used in DRI production. Natural gas–based DRI production leads to lower CO_2 emissions, with emissions ranging from 0.77 to 0.92 ton of CO_2 per ton of steel, depending on the type of electricity used. The postcombustion CCUS process works by removing CO_2 from the flue gas before it is released into the atmosphere. CO_2 is also removed from the top gas before the CO and H_2 are recycled. Postcombustion CCUS can remove 89% of the CO_2 that would otherwise have been emitted.
- *Biological CCUS.* Photosynthetic microorganisms such as microalgae convert inorganic carbon to organic carbon-based compounds via photosynthesis. The evolution of chloroplasts enabled microalgae to develop into CO_2-consuming bio-factories that generate a wide variety of organic compounds. Microalgal biomass enriched with biochemicals can be upgraded to a diverse range of products, including food, feed, biofuels, biopolymers, cosmetics, biomedicine and nutraceuticals.

Appendix C. Survey on Industry Priority on Decarbonization Topics

In February 2022, the Association for Iron & Steel Technology, in coordination with the Steel Manufacturers Association and the American Iron and Steel Institute, surveyed the U.S. steel industry to prioritize ten categories for steel decarbonization technologies and six categories for related government initiatives. This information is included in the Technology Process Adaptation Chapter under "Survey on Industry Priority on Decarbonization Topics" and with expanded definitions for the technologies presented below.

Description of Decarbonization Technologies:

- Thermal Process Fuels (e.g., hydrogen, natural gas, oxygen, biofuels, PCI, etc.).
- Electrification (e.g., electrolysis, nuclear, renewables, plasma, induction, converting combustion processes to electric, etc.).
- Carbon Capture, Use and Sequestration (e.g., use of waste gases, postcombustion, co-generation, use of slags, etc.).
- Metallic Scrap Feedstock (e.g., scrap sorting and optimization, reducing or mitigating the impact of residuals in scrap).
- Smart Manufacturing (e.g., modeling, advanced sensors, AI, etc., to improve energy and emission efficiencies).
- Effective Use of Existing Assets (e.g., application of retrofit and transition technologies vs. greenfield).
- Direct Carbon Avoidance (e.g., green hydrogen reduction of iron ore via DRI, molten oxide electrolysis, etc.).
- Alternative Iron Ore Reductants (e.g., hydrogen, natural gas, biochar, biofuels, etc.).
- Metallic Ore-Based Feedstock (e.g., supply and quality of iron ores: BF, DRI, etc.).
- Materials for Service (e.g., developing AHSS for lightweighting, electrical steels, steels resistant to hydrogen-induced cracking, etc.).

A series of follow-up questions and answers related to that survey are presented below:

What emerging decarbonization technologies could have the most impact in the steel industry over the next 5–10 years, and 10–20 years?

- Integrated Steelmaking (Blast Furnace/Basic Oxygen Furnace) Operations: The BF–BOF process is the most energy-intensive portion of the iron- and steelmaking route. Methods for reducing energy and carbon intensity in conjunction with CCUS will support leading to net-zero emissions.
    - 5–10 Years: Alternative injection technologies: natural gas, hydrogen, waste plastic, biofuel, biocoke, biochar, etc. (BF); metallic feedstock additions (DRI, HBI, scrap) (BF); oxygen enrichment (BF); CCUS (BF and BOF).
    - 10–20 Years: Plasma-assisted heating (BF); CCUS (BF and BOF).
- Electric Arc Furnace Steelmaking Operations: The EAF process is an energy-efficient process for producing steel from primarily recycled steel scrap, however the EAF process still produces GHG emissions. New technologies are needed to lead to net zero. The EAF process often requires the addition of varying volumes of virgin iron such as pig iron or DRI/HBI to dilute residual elements found in metallic scrap, such as Cu, Ni, Cr, Sn and Mo, which reduce product quality.
    - 5–10 Years: Energy generation and storage: natural gas, renewable and nuclear; raw materials: pig iron, DRI, HBI; injectants: biofuels, waste plastics, natural gas; scrap sorting, optimization and valorization (mitigating residuals); scrap pre-heating technologies (e.g., Consteel); alternative scrap preheating technologies (conduction, induction, radiation); direct hot charging technologies for temperature conservation; enhanced energy efficiency; smart sensors and control technologies.
    - 10–20 Years: Energy generation: nuclear, plasma heating; injectants: hydrogen, biocoke; alternative slag foaming technologies; CCUS.
- Direct Reduced Iron Operations: The co-location of DRI production facilities with steelmaking operations can enable significant energy savings via direct hot charging into the BF and EAF. DRI transfer has been reported to save approximately 26 kWh/ton liquid steel for every 100°C increase in hot-charge DRI temperature in the EAF. Hot charging may be an important enabling technology to improve the efficiency of melting carbon-free, high-melting-point, green hydrogen-produced DRI.
    - 5–10 Years: Synthetic gas reduction; replacement of hydrogen for iron ore reduction; fluidized process.
    - 10–20 Years: Plasma reduction; molten system reduction processes (direct smelting); metallic vapor exchange.
- Downstream Steel Mill Operations (e.g., Reheat Furnaces and Finishing Operations): Enhancing thermal process fuels with utilization efficiency and low-carbon fuels; recycling heat and waste energy effectively; alternatives to natural gas heating, e.g., hydrogen, induction heating or thermal radiation; avoidance of reheating through hot charging; and near-net-shape technologies.
- Other Operations or Opportunities: The challenges with modern steelmaking caused by raw material constraints, such as prime scrap scarcity, increasing restrictions on emissions, and renewable power and grid parity are pushing the frontiers of innovation. The industry must identify the pathways to merge smart solutions with advanced processes that enable raw material and energy flexibility, low-emission metallization, recycling and waste stream valorization, near-net-shape manufacturing, and lighter-weight, higher-performance steel products.
- Cross-Cutting Technologies (Affecting All or Some of the Above): Smart control technologies, e.g., ML, AI, robotics, big data analytics; advanced sensors including fiberoptics; electrolysis (water, molten oxide, etc.); synergistic production of carbon and hydrogen, e.g., natural gas pyrolysis; non-combustion heating; waste heat recovery; slag valorization; wastewater treatment/reuse.

Which promising technologies are most appropriate for demonstrating in the U.S. marketplace? Which technologies are ready for pilot plant scale-up, and which are ready for commercial demonstration?

Industry has begun to address several areas within the manufacturing value chain to achieve cost and efficiency improvements as well as emissions reductions. However, these efforts are not sufficiently mature for deployment and require further insights into complex phenomena through enhanced innovation and R&D, which is best achieved through a public-private partnership with the steel industry. There are several themes that emerge:

- Decarbonizing Existing BF Assets: The blast furnace is the most efficient technology to produce virgin metallic iron at scale. The need for pure metallic iron is essential for value-added steel products, such as those required by the automotive industry. Globally, roughly 1,800 kg of CO_2 per ton of steel is emitted by blast furnaces, making it the largest emitter of CO_2 within steelmaking although domestic BFs are typically lower in carbon intensity. To remain cost competitive through 2050 to a net-zero economy, it is essential to evolve BF mitigation technologies for reducing CO_2 emissions and energy consumption. Technologies related to CCUS, oxygen use in place of air, and injection of alternative reductants such as plastics and biocoke would be potential targets for demonstrations.
- Decarbonizing Existing Downstream Assets: There are myriad combustion processes within steel manufacturing that could be decarbonized through electrification, e.g., process preheating, heating, reheating, cutting, etc.
- Metallic Scrap Optimization: The primary challenge for scrap recycling is the presence of residual tramp elements, such as Cu, S, P or Sn, in scrap. These residual elements cannot easily be removed during liquid steel processing and require dilution via the addition of varying levels of virgin iron to prevent adverse effects downstream. This problem will become more significant with increasing global demand for quality scrap. Adoption of advanced sensors, automation and machine vision for scrap sorting would be suitable for demonstration.
- Low- or Non-Carbonaceous Iron Reductants: The U.S. steel industry is less carbon-intensive than other major steel-producing regions due in part to increased use of natural gas, which is not as plentiful in other regions of the world. The most-considered alternative for carbon-

based (coke or natural gas) reduction of iron ore has been H_2. European steelmakers are already engaged in projects that employ H_2 in steelmaking. GrInHy (Salzgitter in Germany) and H2FUTURE (voestalpine in Austria) are focusing on electrolyzer development. The Swedish consortium HYBRIT (SSAB, LKAB and Vattenfall) considers the entire fossil-free value chain for primary steel through H_2 electrolysis used for DRI and steelmaking in an EAF at the pilot plant scale (approximately 1 ton/hour). If successfully integrated with electric grids, the impact would be cost-effective and could decarbonize ironmaking. There are significant technical barriers to wide-scale adoption of hydrogen for steelmaking in the U.S. that will require further research, development and investment.

- Iron Smelting via Electrolysis: The use of electric power to produce metallic iron using an electrolysis reactor rather than the traditional BF offers an attractive route to replace carbon with electrons to produce iron electrolytically. This conversion process could be achieved through both low- and high-temperature electrolysis reactors, which have been proven in the laboratory. However, the process requires significant electrical power and is not yet a viable technology route for steelmaking.
- Creating Markets for Green Steel: Steel requires energy, but energy also requires steel. The interdependence for a transition to green energy and associated infrastructure will open new markets: (1) AHSS grades for lightweighting, transportation and mobility, renewable energy facilities, including wind turbine structures and solar fields, etc.; (2) Electrical steels for high-efficiency power generation and distribution; (3) Special steels resistant to hydrogen-induced cracking will be critical to the generation and storage of energy in a hydrogen-powered future.

What limiting factors or challenges does the steel industry face in broadly deploying decarbonization technologies in the United States?

The U.S. steel industry is among the world leaders in terms of safety, productivity, sustainability and product quality. To strengthen this leadership position, we must continue to evolve breakthrough technologies. With any such effort, there will always be strategic risks including those associated with decarbonization. Known concerns include:

- Creating competitive technologies which are cost effective and scalable.
- Closing knowledge gaps to de-risk capital-intensive investments in new technologies.
- New process technologies, e.g., utilizing different raw materials or energy sources and power infrastructure, need to maintain or improve product quality and properties.
- New technologies, when adopted, should continue to protect the health and safety of the workforce and related ESG imperatives.
- Promoting a skilled, diverse and inclusive workforce to address future workforce needs when new technologies are adopted.
- Developing appropriate supply chain economics for new feedstocks and clean energy markets, e.g., contracts, availability of raw materials, etc.

The steel industry is a capital-intensive, hard-to-decarbonize sector; therefore, additional investment in this sector is critical for de-risking future capital expenditures. Unlike some European and Asian countries, no nationally coordinated research effort for decarbonization of the steel industry is in place in the U.S. Coordinating such an effort between industry, academia and national labs in the U.S. would accelerate:

- Public-private investment in RD&D.
- Coordinated industrial and academic access to national lab expertise, e.g., HPC and renewable and nuclear energy development.
- Coordinated workforce development, diversification and training.
- Transformation through an innovation and investment ecosystem which includes utilities, steelmakers, raw material providers, equipment manufacturers, universities and emerging technology providers.

How can technologies leading toward decarbonization of the iron and steel industry be commercialized and deployed with positive impacts to the surrounding community?

Two key areas: decarbonization and infrastructure. Decarbonization will lead to an environmentally sustainable and socially acceptable industry. The required deployment of new technologies will lead to new manufacturing jobs and additional employment throughout the supply chain. Infrastructure will increase demand for steel consumption, catalyzing economic development and employment while also improving quality of life in adjacent areas, which may have particular impact in communities with aging steelmaking capacity and underprivileged populations.

What resources or actions could support improvement of areas surrounding iron and steel industry facilities, particularly those in areas of historical environmental injustice in the transition to a decarbonized energy economy?

The substantial economic activity supported by the steel industry provides major opportunities to invest in public services, thus generating prosperity and welfare. Over the past few decades, the steel industry has also transformed its manufacturing economy into one driven by knowledge and technology. This transition brings enormous potential to deliver jobs, economic opportunities and neighborhood improvements to disadvantaged communities. However, the benefits of new growth and development will not be automatically achieved without a focus on equitable development.

Initiatives could include the development of programs for management education and mentorship, best practice and benchmark reporting, and the establishment of strategic partnerships to create internships specifically for underrepresented groups. It will require a plan to partner with community colleges, trade schools, MSOs and universities to provide an infrastructure for workforce development to meet industry needs for a skilled, diverse and inclusive workforce by 2044. Collaboration is essential to identify effective and desirable opportunities for workforce development, especially around diversity and inclusion. Leaders in academia (intellectual leadership), industry (development leadership) and government (policy leadership) as the stakeholders in this effort must work together.

Investment in something such as an iron and steel manufacturing institute will provide stakeholders an opportunity to collaborate on a common goal: achieving climate neutrality by 2050. An institute would leverage each stakeholder's best strengths for the partnership to avoid breakdowns along the innovation value chain and to ensure the strategy to achieve climate-neutral steel includes equitable development.

Decarbonization solutions must be scalable, cost-effective and offer high performance for industrial adoption, and a manufacturing institute would address barriers for TRL 1–9 spectrum, innovations that no single company would tackle on its own. Capital intensity and technological risk represent significant barriers to entry for the many small- to medium-size enterprises that support the U.S. steel industry. A public-private partnership with the steel industry would be ideally suited to overcome these barriers.

Furthermore, there is no single technological solution for decarbonizing the nation's steel sector. Regional raw material sources and clean energy resources, logistics and markets will necessitate a range of solutions specific to each region. In addition to accelerating RD&D technologies for decarbonization, the U.S. steel industry is also motivated to reinforce and grow its workforce development infrastructure.

With steel being the engineered material solution for the manufacturing economy, the U.S. steel industry has key tailwinds to motivate its support for an institute. These forces include infrastructure readiness, decarbonization and ESG progress. There are mounting societal, customer and investment community expectations, and the steel industry is positioned to answer the call. Further, there are competitive pressures from significant decarbonization technology investments already underway globally. These breakthrough investments, if unanswered, will threaten U.S. leadership in the global production of clean steel.

What are the challenges in developing and retaining a skilled, diverse workforce to achieve industrial decarbonization?

The challenges include the following: lack of encouragement for trade careers; public perception in support of the steel industry; dwindling number of metallurgical institutes; a shrinking pool of skilled, diverse workers, compounded by interindustry competition; and unfair global competition, which undermines the national manufacturing base.

Appendix D. List of Materials Science and Engineering Programs in the United States

Table D-1. List of Materials Science and Engineering Bachelor's Degree Programs in the United States

School name	City	State	Website	Program name	Accreditation dates
Auburn University	Auburn	AL	www.auburn.edu	Materials Engineering	1975–Present
The University of Alabama	Tuscaloosa	AL	www.ua.edu	Metallurgical Engineering	1949–Present
University of Alabama at Birmingham	Birmingham	AL	www.uab.edu	Materials Engineering	1983–Present
Arizona State University	Tempe	AZ	www.asu.edu	Materials Science and Engineering	1996–Present
The University of Arizona	Tucson	AZ	www.arizona.edu	Materials Science and Engineering	1950–Present
California Polytechnic State University, San Luis Obispo	San Luis Obispo	CA	www.calpoly.edu	Materials Engineering	1971–Present
San Jose State University	San Jose	CA	www.sjsu.edu	Materials Engineering	1962–Present
University of California, Berkeley	Berkeley	CA	www.berkeley.edu	Materials Science and Engineering	2005–Present
University of California, Davis	Davis	CA	www.ucdavis.edu	Materials Science and Engineering	1990–Present
University of California, Irvine	Irvine	CA	www.uci.edu	Materials Science and Engineering	2003–Present
University of California, Los Angeles	Los Angeles	CA	www.ucla.edu	Materials Engineering	1985–Present
University of California, Merced	Merced	CA	www.ucmerced.edu	Materials Science and Engineering	2012–Present
University of California, Riverside	Riverside	CA	www.ucr.edu	Materials Science and Engineering	2011–Present

Table D-1. Cont'd.

School name	City	State	Website	Program name	Accreditation dates
Colorado School of Mines	Golden	CO	www.mines.edu	Metallurgical and Materials Engineering	1936–Present
University of Connecticut	Storrs	CT	www.uconn.edu	Material Science and Engineering	2005–Present
University of Central Florida	Orlando	FL	www.ucf.edu	Materials Science and Engineering	2021–Present
University of Florida	Gainesville	FL	www.ufl.edu	Materials Science and Engineering	1971–Present
Georgia Institute of Technology	Atlanta	GA	www.gatech.edu	Materials Science and Engineering	1942–Present
Iowa State University of Science and Technology	Ames	IA	www.iastate.edu	Materials Engineering	1999–Present
Boise State University	Boise	ID	www.boisestate.edu	Materials Science and Engineering	2005–Present
Illinois Institute of Technology	Chicago	IL	www.iit.edu	Materials Science and Engineering	1949–Present
Northwestern University	Evanston	IL	www.northwestern.edu	Materials Science and Engineering	1976–Present
University of Illinois at Urbana-Champaign	Champaign	IL	www.illinois.edu	Materials Science and Engineering	1994–Present
Purdue University at West Lafayette	West Lafayette	IN	www.purdue.edu	Materials Science and Engineering	1941–Present
University of Kentucky	Lexington	KY	www.uky.edu	Materials Engineering	1936–Present
Massachusetts Institute of Technology	Cambridge	MA	www.mit.edu	Materials Science and Engineering (Course 3)	1936–Present
The Johns Hopkins University	Baltimore	MD	www.jhu.edu	Materials Science and Engineering	1982–Present

Table D-1. Cont'd.

School name	City	State	Website	Program name	Accreditation dates
University of Maryland College Park	College Park	MD	www.umd.edu	Materials Science and Engineering	1998–Present
Michigan State University	East Lansing	MI	www.msu.edu	Materials Science and Engineering	1985–Present
Michigan Technological University	Houghton	MI	www.mtu.edu	Materials Science and Engineering	1965–Present
University of Michigan	Ann Arbor	MI	www.umich.edu	Materials Science and Engineering	1936–Present
University of Minnesota – Twin Cities	Minneapolis	MN	twin-cities.umn.edu	Materials Science and Engineering	1984–Present
Winona State University	Winona	MN	www.winona.edu	Composite Materials Engineering	1992–Present
Missouri University of Science and Technology	Rolla	MO	www.mst.edu	Metallurgical Engineering	1936–Present
University of Southern Mississippi	Hattiesburg	MS	www.usm.edu	Polymer Science and Engineering	2016–Present
Montana Technological University	Butte	MT	www.mtech.edu	Metallurgical and Materials Engineering	1937–Present
North Carolina State University at Raleigh	Raleigh	NC	www.ncsu.edu	Materials Science and Engineering	1969–Present
Rutgers, The State University of New Jersey	New Brunswick	NJ	www.rutgers.edu	Materials Science and Engineering	1949–Present
New Mexico Institute of Mining and Technology	Socorro	NM	www.nmt.edu	Materials Engineering	1991–Present
University of Nevada, Reno	Reno	NV	www.unr.edu	Materials Science and Engineering	1955–Present

Table D-1. Cont'd.

School name	City	State	Website	Program name	Accreditation dates
Alfred University	Alfred	NY	www.alfred.edu	Materials Science and Engineering	1976–Present
Cornell University	Ithaca	NY	www.cornell.edu	Materials Science and Engineering	1951–Present
Rensselaer Polytechnic Institute	Troy	NY	www.rpi.edu	Materials Engineering	1938–Present
Case Western Reserve University	Cleveland	OH	www.case.edu	Materials Science and Engineering	1936–Present
Case Western Reserve University	Cleveland	OH	www.case.edu	Polymer Science and Engineering	1936–Present
The Ohio State University	Columbus	OH	www.osu.edu	Materials Science and Engineering	1992–Present
Wright State University	Dayton	OH	www.wright.edu	Materials Science and Engineering	1979–Present
Carnegie Mellon University	Pittsburgh	PA	www.cmu.edu	Materials Science and Engineering	1936–Present
Drexel University	Philadelphia	PA	www.drexel.edu	Materials Science and Engineering	1953–Present
Lehigh University	Bethlehem	PA	www.lehigh.edu	Materials Science and Engineering	1936– Present
The Pennsylvania State University	University Park	PA	www.psu.edu	Materials Science and Engineering	1938–Present
University of Pennsylvania	Philadelphia	PA	www.upenn.edu	Materials Science and Engineering	1949–Present
University of Pittsburgh	Pittsburgh	PA	www.pitt.edu	Materials Science and Engineering	1988–Present
Brown University	Providence	RI	www.brown.edu	Materials Engineering	1967–Present
Clemson University	Clemson	SC	www.clemson.edu	Materials Science and Engineering	1955–Present

Table D-1. Cont'd.

School name	City	State	Website	Program name	Accreditation dates
South Dakota School of Mines and Technology	Rapid City	SD	www.sdsmt.edu	Metallurgical Engineering	1936–Present
University of Tennessee Knoxville	Knoxville	TN	www.utk.edu	Materials Science and Engineering	1964–Present
Rice University	Houston	TX	www.rice.edu	Materials Science and Nanoengineering	2015–Present
Texas A&M University	College Station	TX	www.tamu.edu	Materials Science and Engineering	2020–Present
University of North Texas	Denton	TX	www.unt.edu	Materials Science and Engineering	2012–Present
University of Texas at El Paso	El Paso	TX	www.utep.edu	Metallurgical and Materials Engineering	1947–Present
The University of Utah	Salt Lake City	UT	www.utah.edu	Materials Science and Engineering	1970–Present
The University of Utah	Salt Lake City	UT	www.utah.edu	Metallurgical Engineering	1936–Present
University of Virginia	Charlottesville	VA	www.virginia.edu	Materials Science and Engineering	2023–Present
Virginia Polytechnic Institute and State University	Blacksburg	VA	www.vt.edu	Materials Science and Engineering	1948–Present
University of Washington	Seattle	WA	www.engr.washington.edu	Materials Science and Engineering	1936–Present
Washington State University	Pullman	WA	www.wsu.edu	Materials Science and Engineering	1936–Present
Western Washington University	Bellingham	WA	www.wwu.edu	Polymer Materials Engineering	2015–Present
University of Wisconsin - Eau Claire	Eau Claire	WI	www.uwec.edu	Materials Science and Engineering	2018–Present

Table D-1. Cont'd.

School name	City	State	Website	Program name	Accreditation dates
University of Wisconsin – Madison	Madison	WI	www.wisc.edu	Materials Science and Engineering	1993–Present
University of Wisconsin – Milwaukee	Milwaukee	WI	www.uwm.edu	Materials Engineering	1969–Present

Table D-2. List of Universities with Metallurgical Majors in the United States and Number of Graduates in 2023

School name	City	State	Program name	Undergrad graduates	Master's and doctorate graduates	AIST MA Chapter
Colorado School of Mines	Golden	CO	Metallurgical and Materials Engineering	46	20	Yes
Missouri University of Science and Technology	Rolla	MO	Metallurgical Engineering	20	1	Yes
Montana Technological University	Butte	MT	Metallurgical and Materials Engineering	6	1	Yes
New Mexico Institute of Mining and Technology	Socorro	NM	Materials Engineering w/Metallurgical Engineering option	12	2	Yes
South Dakota School of Mines and Technology	Rapid City	SD	Metallurgical Engineering	18	N/A	Yes
The University of Alabama	Tuscaloosa	AL	Metallurgical Engineering	12	4	Yes
University of Nevada, Reno	Reno	NV	Metallurgical Engineering	2	1	Yes
University of Texas at El Paso	El Paso	TX	Metallurgical and Materials Engineering	16	4	
University of Utah	Salt Lake City	UT	Metallurgical Engineering	4	9	Yes
			TOTAL Graduates	136	42	

Appendix E. Tactics for Workforce Development

Several examples of tactics for the steel industry to recruit and retain qualified workers are shown in Table E-1.

Table E-1. List of Recommendations to Boost Interest in Working in the Steel Industry

Measure	Description
Internships, trainings and mentoring initiatives	• Collaborate with local high schools to start a steel-specific program that gives students insight into what it is like to work in the steel manufacturing industry. Internships can give students training and exposure to the field, which can further pique their interest in working in the steel industry. Also, working with universities in open innovation programs can help students gain indirect exposure to the steel industry along with gaining unique ideas. • Actively introduce students to practical industry experience, for instance, through summer employment and internship programs. In return, the student must work at one of the funding companies for a predetermined amount of time following graduation. There is no better way to understand if a career is right for you than hands-on experience in the field.
Awards and scholarships	• Investment in and strengthening of AIST's Awards and Recognition Program will provide a diverse group of students an opportunity to receive real-life training, attract more young talent to steel manufacturing and motivate K-16 students to pursue manufacturing careers. • Encourage entrepreneurs and innovators to implement breakthrough technologies focusing on decarbonization and digitalization. • Enhance AIST's current faculty grants and programs to support cross-cutting R&D for technological advancements. • Build internationally recognized, prestigious awards that researchers and students aspire to earn.
Competitions	• Organize steel-themed competitions for students and young professionals from different disciplines. The design challenge could revolve around creating innovative designs using steel as a primary material. This would attract a diverse range of participants and generate enthusiasm for the industry. For example, the company Epic Metals held a competition with the School of Architecture at Carnegie Mellon University for an innovative project incorporating metal deck systems. The competition informs young professionals about steel as a material. By generating excitement about steel, the competition promotes young professionals to work for the steel industry. • The Steel Founders' Society of America (SFSA) also organizes an annual competition called "Cast in Steel." The competition challenges university students to use modern casting tools to creatively design and produce a functioning version of a steel casting, e.g., a hammer, Celtic leaf sword or African spear point. The contest rules require each team to have at least one member who is a current college student, designated a faculty sponsor to help the team, and have an industrial partner familiar with steel castings. Teams perform all aspects of creating the steel casting and exploiting the casting manufacturing process from design conception to performance.

Table E-1. Cont'd.

Measure	Description
Plant tours	• Organize interactive plant tours for high school and trade schools. • Grant scholarships to students to attend in-person steel industry plant tours. • Steel companies can offer virtual tours and online exhibits, which will allow people who cannot physically visit the facility to still learn about the steel industry. • Virtual reality can be used to allow users to move freely around the facility and hover over equipment to understand its functions. • Offer interactive tours of museums that showcase the history and modern applications of steel. • The tours will provide positive aspects of the steel industry and its contributions to society and dispel the stereotype that the steel industry is an outdated, unsafe workplace.
Transferable skills certification programs	• Expand transferable skills certification programs. Collaborate with technical colleges to expand transferable skills certification programs. Foster collaboration between the steel industry and universities to create projects for students; this will further increase enthusiasm for the steel industry.
Educational lectures	• Partner with schools and universities to hold educational lectures that showcase the importance of steel in everyday life as well as career possibilities. It can also help diminish the stereotype that the steel industry is a dirty and unsafe workplace by highlighting the industry's unique opportunities and benefits, such as job security, good pay and potential for advancement.
Campus hiring events	• Host campus hiring events to attract potential employees and educate students on the career opportunities available in the steel industry. These events could include company presentations, panel discussions and networking opportunities with current employees. AIST can also provide information on the company's culture, values, and mission, as well as the benefits of working in the steel industry. By hosting campus hiring events, AIST can build relationships with students and potentially identify top talent for future employment opportunities.
Steel workshops	• The Festival of Combustion, an annual event hosted by the Rivers of Steel National Heritage Area in Pittsburgh, PA, celebrates the region's industrial heritage and the art of metalworking through demonstrations, performances and exhibits. It features artists and blacksmiths who use traditional and modern techniques to create metalwork pieces. The festival also includes live music, food and family-friendly activities, attracting thousands of visitors each year. The workshop is an excellent opportunity to show how steel is 100% recyclable by providing people with wasted steel to build something new. Also, consider educating the audience with the latest smart manufacturing technology and inviting some talented participants for potential job opportunities.

Table E-1. Cont'd.

Measure	Description
Career fairs	• Job fairs are important for awareness and visibility to potential future employees of the steel industry. Partner with university outreach programs and exhibit at career fairs to showcase the various career paths and opportunities available in the steel industry. Rather than focusing solely on the relevance of steel, the emphasis should also be on the range of roles and skills required to keep the industry running. This could include roles in engineering, R&D, operations, supply chain management, marketing and finance. AIST can also provide information on the training and development opportunities available for new hires, such as apprenticeships and mentoring programs. By participating in career fairs, AIST can connect with young professionals and students who may be interested in pursuing a career in steel.
Summer camps	• Major career interests are often developed during high school. Lack of exposure to industry fields is one of the factors disconnecting students from wanting to work in the steel industry. AIST can organize tangible projects for a week where students can come into the steel shop and make something by themselves under supervision. This will give them a chance to get to know the industry. The participating company(ies) or AIST can provide a certificate for the one-week industrial experience. By providing certified projects, AIST can promote career opportunities for the students within the steel industry and advocate for the steel industry to be a safe and high-tech workplace.
Videos and YouTube	• Using videos to advertise the steel industry is critical to attracting younger generation viewers. Informative documentary-style short videos could talk about the steel industry, its history and contribution in society. • Job seekers might also want to see a snippet of what their work life could be like and look for "a day in a life of..." or "working at [company name]" videos. Employers can use YouTube to showcase the variety of roles and career paths available in the steel industry. • To attract younger generations to the manufacturing industry, employers should highlight the benefits of working in the industry, offer flexible work arrangements and modernize their workplace culture. Employers can generate awareness of their commitment to creating a conducive work environment by showcasing the measures taken to improve safety, reduce physical demands and create a better work-life balance. Ultimately, by generating such awareness, employers can attract and retain the best talent, ensuring the industry remains strong and competitive in the years to come. • AIST can also create videos of success stories of young professionals in the industry so that the younger generation can relate to them and change their perception of the steel industry. Sharing stories of young professionals who have made significant contributions to the industry, achieved career goals, or improved safety and environmental practices can inspire young people and help them see the industry in a positive light. • New graduates want to work with exciting, emerging technologies. The steel industry's focus on investing in new technologies can be highlighted to attract these young graduates. Additionally, AIST and the industry can work to educate the public on the importance of steel and its role in the economy by streaming videos about the steel industry.

Table E-1. Cont'd.

Measure	Description
Social media platforms	• Social media channels like Instagram, X, LinkedIn and Facebook are very effective channels to reach the next generation of potential employees. Social media can be a powerful tool for reaching a diverse audience. More marketing campaigns that target the right audience via job boards and social media are needed. • To help people better understand the steel industry, the daily work content, working environment and working mode of the steel industry can be photographed and presented in the form of a vlog. In this way, it can spark willingness to understand the steel industry and lower the threshold for those who want to enter the steel industry. • A day in the life of an employee at a steel facility on social media would help potential candidates to see into the steel industry's day-to-day operations and what they are doing on a day-to-day basis. • Highlight the experiences of LGBTQ employees at a steel mill and share their stories to showcase the company's commitment to diversity and inclusion. AIST can use hashtags and targeted ads to reach young candidates. Social media "did you know" videos are popular among the younger generation. Social media is the source of information that younger generations trust. Topics that could be covered are: • Inventions or advancements that were made possible due to steel. • Information about how steel is helping to build a green energy economy. e.g., decarbonization, and how young engineers can help create an impact. • The impact steel has on communities and on the quality of life for all living beings. • History of steel industry and how technology has revolutionized steelmaking.
Reels	• Another powerful tool is posting short videos on Instagram Reels. Benefits for steel companies are exposure, brand building, promoting reputation as being a safe and high-tech industry, and access to job seekers. The following content could be featured: • Insights into company culture, work and benefits of working for the steel industry. • Showcasing the steel industry environment and its people. • Creative and energetic content about the steel industry could arouse curiosity, such as interesting facts about the steel industry and its impact on society. • Targeting the younger generation about how steel can be used in their daily life (e.g., medical applications, aerospace, infrastructure, appliances). • Certain processes of steelmaking. • Some challenges in the steel industry that make people want to discuss. This can be decarbonization of processes and environmental legislation, digitalization of processes and smart manufacturing.

Table E-1. Cont'd.

Measure	Description
Influencer collaborations	• According to a Bloomberg study, 86% of today's youth would like to be influencers. Popular engineering and design influencers include Simone Giertz (2.6 million subscribers on YouTube) and Matty Benedetto (3.3 million subscribers on YouTube). Giertz is known for her eccentric inventions, such as a Tesla she modified into a pickup truck. Benedetto is known for "unnecessary inventions," such as "I designed luggage for all my Apple products." Both channels succeed in increasing interest in their respective engineering/design fields. The steel industry could collaborate with influencers or celebrities to create and innovate with steel, opening the world to potential viewers.
Immersive technologies for training and education	• Utilize virtual reality, augmented reality and related technologies to create interactive educational and training modules based on real scenarios and real data from sensors and computational simulations to teach real jobs and activities performed in realistic virtual environments. Using these technologies serves multiple functions including providing a modernized method of introducing the steel industry to youth, building skills for new employees in a safe environment, and enhancing the educational and training aspects of existing steel industry personnel.
Gaming and simulation	• Gaming is an integral part of teen culture, serving not just as entertainment but as a platform for learning and socialization. With the rise of simulation and sandbox games that incorporate intricate processes and realistic scenarios, there is a unique opportunity to introduce young audiences to the steel industry. These games often include detailed terminology, materials science, and production processes that mirror real-world operations, making them valuable educational tools. Potential activities include: • Compiling a list of existing games that introduce steel production concepts and terminology. Host the list online for easy access by educators and students. • Sponsor eSports events featuring games like Minecraft and Factorio that incorporate elements of steel production. Offer industry-relevant prizes. • Host competitions to create realistic steel production simulations using sandbox games or game engines. Award cash prizes or internships to winners. • Organize annual contests using game engines like Unity and Unreal to develop steel industry training simulators. Integrate winning entries into educational curriculums and training programs.

Appendix F. Acronyms

AHSS — Advanced High-Strength Steels

AI — Artificial Intelligence

AIST — Association for Iron & Steel Technology

AR — Augmented Reality

BF — Blast Furnace

BOF — Basic Oxygen Furnace

BOS — Basic Oxygen Steelmaking

C — Carbon

CAPEX — Capital Expenditures

CCS — Carbon Capture Storage

CCUS — Carbon Capture, Utilization and Storage

CDQ — Coke Dry Quenching

CFD — Computational Fluid Dynamics

CHP — Combined Heat and Power

CO — Carbon Monoxide

CO_2 — Carbon Dioxide

COG — Coke Oven Gas

DC — Direct Current

DOE — U.S. Department of Energy

DR — Direct Reduction

DRI — Direct Reduced Iron

EAF — Electric Arc Furnace

EOR — Enhanced Oil Recovery

EPA — U.S. Environmental Protection Agency

ESF — Electric Smelting Furnace

ESP — Endless Strip Production

EUTC — Energy & Utilities Technology Committee

FIFR — Alterna Flash Iron-Fines Reduction

GHG — Greenhouse Gas

GISH — Grid Interactive Hydrogen Steelmaking

GOES — Grain-Oriented Electrical Steels

H_2DR — Hydrogen Direct Reduced

HBCU — Historically Black Colleges and Universities

HBI — Hot Briquetted Iron

HIS — Hispanic Serving Institutions

HPR — Hydrogen Plasma Reduction

HTSE — High-Temperature Steam Electrolysis

IEA — International Energy Agency

K-16 — Kindergarten Through Grade 16

LGBTQ — Lesbian, Gay, Bisexual, Transgender, Queer or Questioning Persons

LIBS — Laser-Induced Breakdown Spectroscopy

LLC — Limited Liability Company

LPG — Liquefied Petroleum Gas

LTE — Low-Temperature Electrolysis

LTI — Low-Temperature Iron

ML — Machine Learning

MOE — Molten Oxide Electrolysis

MS&T — Materials Science and Technology

MSI — Minority-Serving Institutions

MSO — Minority-Serving Organizations

NG — Natural Gas

NIST — National Institute of Standards and Technology

OEM — Original Equipment Manufacturer

OPEX — Operating Expenses

OSTC — Oxygen Steelmaking Technology Committee

PCI — Pulverized Coal Injection

PI — Philosophical Investigations

R&D — Research and Development

RCOG — Reformed Coke Oven Gas

RD&D — Research Development and Deployment

SFSA — Steel Founders' Society of America

STEM — Science, Technology, Engineering and Mathematics

TLS — Ton Liquid Steel

TMP — Thermomechanical Processing

TRL — Technology Readiness Level

TRT — Pressure Recovery Turbine

UIRR — University-Industry Relations Roundtable

ULCOS — Ultralow-CO_2 Steelmaking

USGS — U.S. Geological Survey

VR — Virtual Reality

XRF — X-Ray Fluorescence

XRT — X-Ray Transmission

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