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

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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. The Executive Summary of the AIST Roadmap is published herein; the entire publication will be available at AIST.org within the first quarter of 2025.

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 72.2% 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 71.4% of all steel produced globally in 2023 was from the iron ore-intensive blast furnace (BF) process. In comparison, the BF process has higher capital expenditure (CAPEX) requirements and 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.

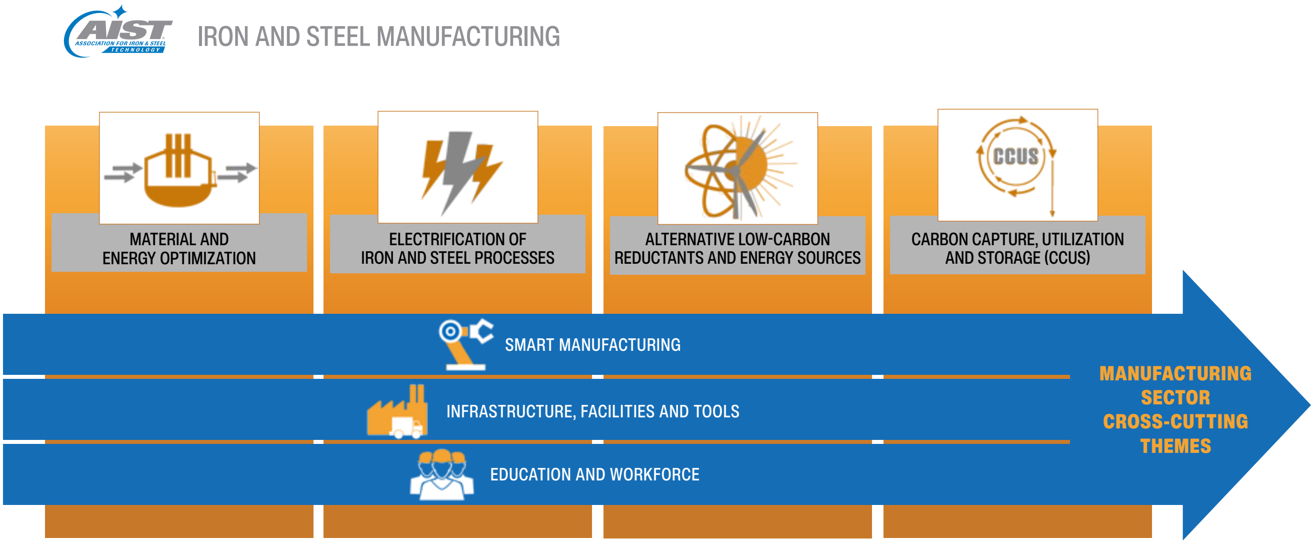


Figure 1. The four Technology Themes and three Cross-Cutting Themes for the AIST Roadmap.

Just as important, new training requirements for the workforce need to be introduced as we aggressively adopt more digitalization and decarbonization technologies.

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 (ML). 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

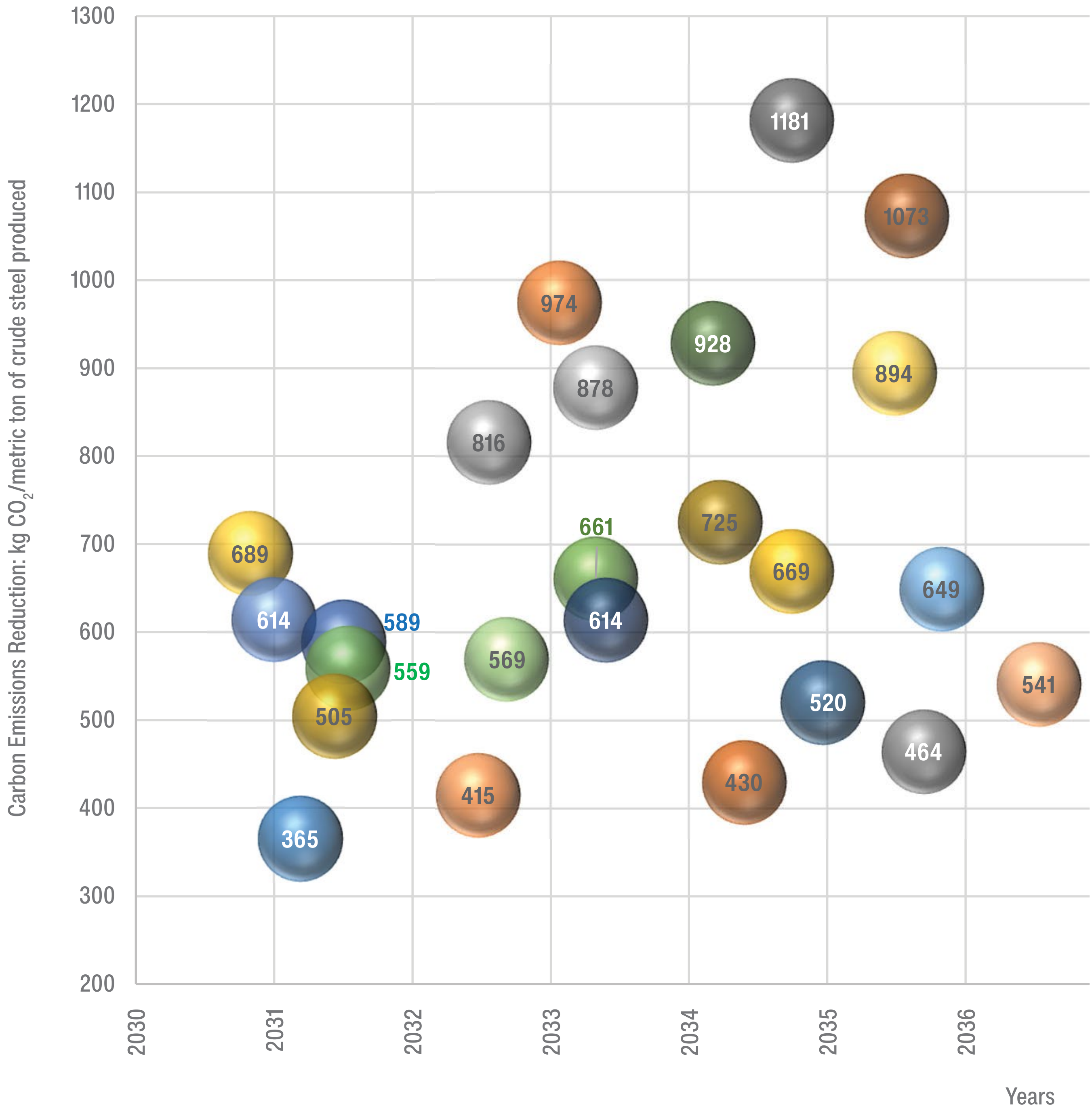
The Technology Baseline chapter describes the iron- and steelmaking processes and their carbon intensities, and provides a review of other roadmaps for the iron and steel industry in the United States. The chapter describes the status of current technologies and innovations, their challenges, and obstacles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



- Molten oxide electrolysis - 1195
- Hydrogen-based DRI - 1181
- Hydrogen production and storage - 1073
- Electric smelting furnaces - 974
- Replacement of coke with electrolytically generated net-zero carbon syngas - 967
- CCUS storage and utilization - 947
- Green electricity EAF process - 928
- Natural gas DRI with post-combustion CCUS - 894
- Top gas recycling with CCUS in blast furnace - 894
- Optimized DRI-EAF process route - 878
- Scaling up electric induction furnaces - 816
- Biological CCUS - 752
- Hydrogen to replace PCI and natural gas in blast furnace - 725
- Optimize metallic scrap for steelmaking - 689
- Electrification of iron ore pelletizing - 669
- Electrification of reheat and other combustion processes - 661

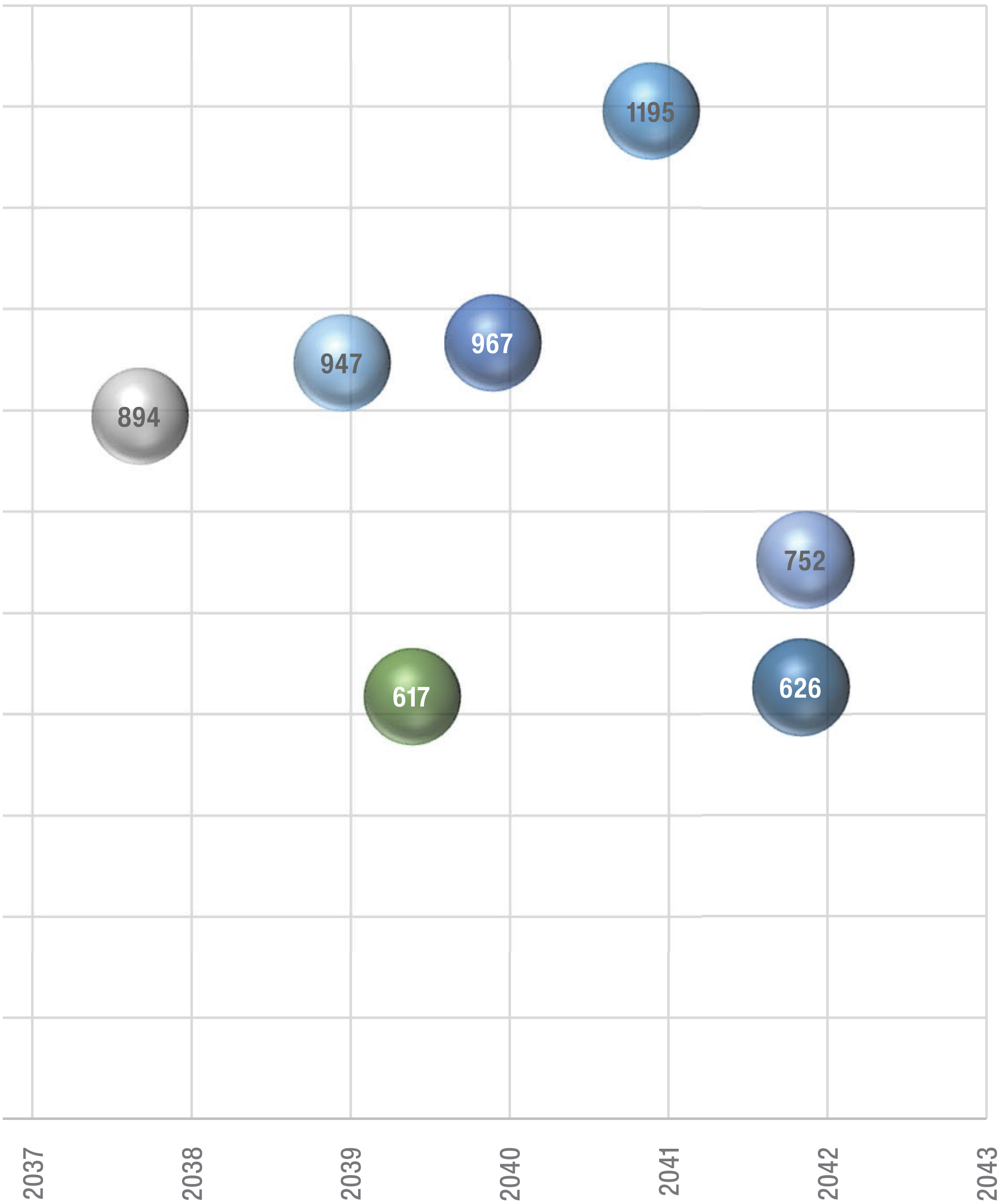


Figure 2. Iron and Steel Decarbonization Strategies: Impact on carbon emissions reduction and timeline to commercial implementation in the U.S. (Respondent data outside the U.S. reflects different results).

- Hydrogen in reheat furnaces - 649
- Diode laser technology - 626
- CO_2 trunk lines - 617
- Material yield and energy optimization in blast furnace - 614
- Biofuels in cokemaking and blast furnace - 614
- Smart manufacturing - 589
- Recovery and reuse of offgas and waste steam - 617
- Energy optimization in the EAF process - 559
- Process preparation for CCUS - 541
- Utilizing suppressed combustion for EAF production - 520
- Use of oxy-fuel and/or air-oxy-fuel burner technology - 505
- Alloy development for reduced carbon intensity - 464
- Material and energy recovery from slag - 430
- Alternatively fueled mobile equipment - 415
- Optimizing motor efficiency - 365

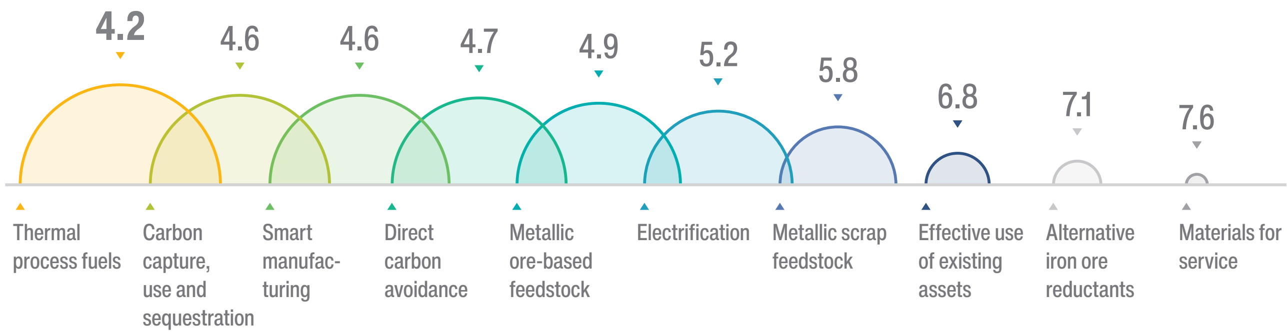


Figure 3. Industry priority for iron and steel decarbonization technologies *(Rank 1–10).*

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).

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.

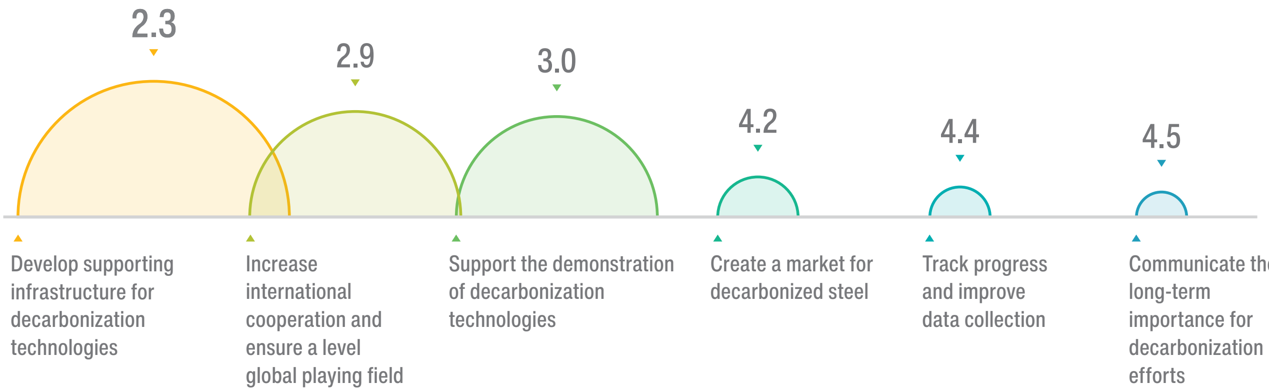


Figure 4. Industry priority for related government initiatives *(Rank 1–6).*

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:

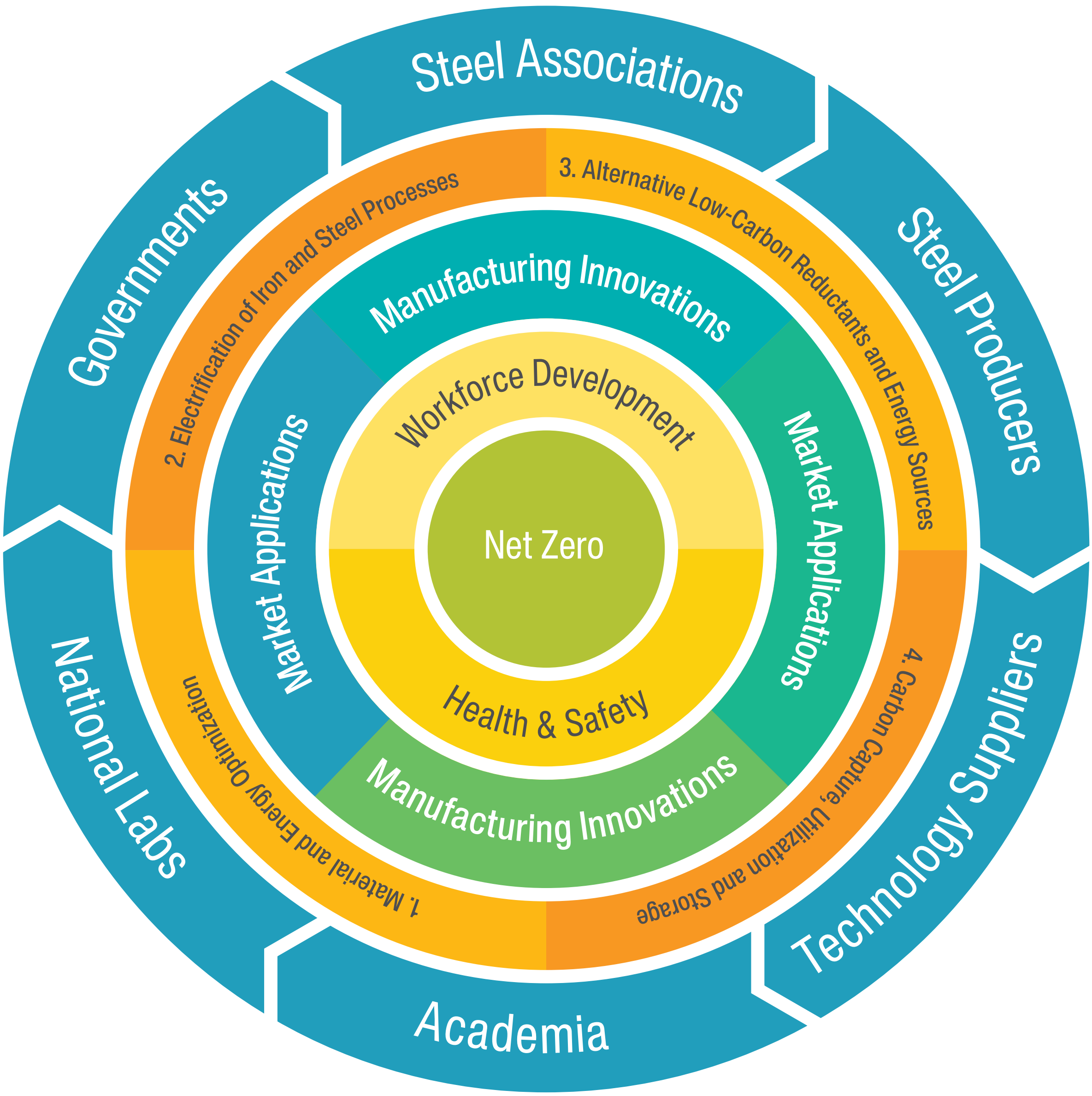


Figure 5. The engagement cycle leading to net-zero emissions for the U.S. steel industry.

- 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.

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 executive summary 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 material and energy sources, regional politics and environmental regulation, and national or corporate sustainability goals. The full AIST Roadmap will be available on AIST.org in the first quarter of 2025. ✦

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