DE-FOA-0002564: Request for Information on Establishing a New Manufacturing Institute

The Association for Iron & Steel Technology, headquartered near Pittsburgh, PA, is pleased to offer this response to the DOE RFI for the establishment of a Clean Energy Manufacturing Institute for Industrial Decarbonization.

We offer this response in strong support of an Institute focused on ***Decarbonization of Steel and Metals*** *versus Electrification of Industrial Processes. For AIST, our objective is to unify the entire U.S. steel industry — including steel producers, technology suppliers, academia and national labs — in support for the Institute. Collectively, the steel industry has the rigor of scale, impact and accountability to hasten the path to net zero carbon emissions for American manufacturing.*

The U.S. steel industry has tailwinds to motivate its support for this 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 steel decarbonization investments already underway in Europe, Asia and elsewhere. These breakthrough technology investments, if unanswered, could threaten U.S. leadership in the global production of clean steel.

The timing is right. The DOE working in direct cooperation with the U.S. steel industry would yield a significant impact to increase U.S. competitiveness within the grand challenge of industrial decarbonization.

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Category 1 Institute Scope

C1.1 As a highly engineered material, steel has been identified by the Biden administration as 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 infrastructure, transportation, power generation, energy transport, storage and many other applications.

In 2019, the U.S. steel industry produced approx. 90 million metric tons of steel, supported more than 85,000 direct jobs, and reached revenues of over US$100 billion. Advancements in steel manufacturing technologies over the last decade have enabled continuous improvements in property performance, energy efficiency and environmental stewardship.

The domestic industry's comparative advantage is derived by the fact that 72% of all steel produced in the U.S. in 2020 was via the recycled scrap-intensive electric arc furnace (EAF) process. This fact contrasts significantly with the rest of the world, whereby 70% of all steel produced globally in 2020 was from the coal-intensive blast furnace (BF) process. The industry is now positioning for pivotal growth to meet anticipated demand for U.S.-based steel production to support expected national infrastructure investments such as roads, bridges and buildings. American prosperity will indeed depend on a sustainable industrial supply chain for steel. Through U.S. innovation-based manufacturing, rapid cross-cutting technology advances, and the drive for carbon neutrality, the U.S. steel industry is determined to rise to the challenge.

Despite our 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 decarbonization expectations, will soon 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 completely foreign in nature. The misconception that steel is not advanced manufacturing must also 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.

To overcome these challenges and to bolster the U.S. steel industry's role as an innovation leader in industrial decarbonization, the Association for Iron & Steel Technology (AIST), based near Pittsburgh, PA, proposes to lead a large-scale industrially driven and consortia-based effort for the administration of a Clean Energy Manufacturing Institute (CEMI/MI) for Decarbonization of Steel and Metals. The objective of the CEMI would be to address high-priority challenges in decarbonization that are broadly deployable to a diverse set of metals manufacturing sectors. The key challenges include:

- **Technical Innovation:** Steel and metals manufacturing are reliant on fossil fuels, primarily due to the use of carbon for reduction of iron ore. In 2020, the U.S. steel industry produced 72.7 million tons of steel, where 29.4% (21.4 million tons) were produced by BF/BOF and 70.6% (51.3 million tons) by the EAF steelmaking process. The highest potential to reduce CO_2 emissions is in the integrated steelmaking route (BF/BOF), which remains an essential process to satisfy market demand, especially for automotive manufacturing. The BF/BOF process emits on average 1,800 kg CO_2/ton crude steel while the EAF process emits on average 600 kg CO_2/ton crude steel. EAF capacity is mainly restricted due to the availability of steel scrap and direct reduced iron (DRI). Due to its large percentage of EAF-based production, the U.S. steel industry is a global leader in clean steel production. However, our global leadership position is at risk as other nations take the lead in promoting RD&D efforts for breakthrough steel decarbonization technologies, as identified in Question 8.3.

Global steel production contributes significantly to the emission of CO_2, accounting for 7% of all CO_2 emissions, and while the global industry understands the importance for decarbonization, there is no coordinated effort industrywide within the U.S. for accelerating decarbonization RD&D. To improve productivity, competitiveness, energy efficiency and strengthening of the U.S. manufacturing workforce, a CEMI for Decarbonization of Steel and Metals led by AIST would engage industry, academia and labs across the country in the manufacturing supply chain to support pre-competitive industrial decarbonization research. Industrial innovation will always benefit from appropriate government support, as these efforts are capital-intensive and may take 10 to 20 years to realize broad commercialization. We need to start a coordinated effort now!

Currently, cutting-edge technologies to achieve carbon neutrality such as smelting reduction, carbon capture and utilization, hydrogen-based DRI, and electrolysis are at the RD&D stage. Many of the world's largest steel companies are exploring the possibilities of these technologies and need additional coordinated pre-competitive research and funding to become commercially viable. Additionally, the 4th Industrial Revolution (or Industry 4.0) is driving "smart" steel production, leveraging critical new technologies such as advanced sensors, 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.

- **Workforce Development:** There are precious few metallurgy institutes and universities in the U.S., which leads to a shrinking talent pool that will undermine the U.S. steel industry's future competitiveness. We need to attract and educate a skilled and diverse workforce and build the infrastructure pipeline to educate future engineers, scientists and technicians throughout the manufacturing supply chain. Workforce attrition is also a serious concern, and the capabilities, both physical and digital, are outdated when compared to other sectors, e.g., micro-electronics. There is a need to reduce the skills gap and increase diversity, equity and inclusion through new, focused training and retraining efforts, together with increased participation of SMEs in the steel sector supply chains.
- **Economic:** The U.S. steel industry has historically operated under narrow profit margins that are constantly challenged by varying raw material prices, product markets and underinvestment in R&D. These concerns can be attributed to unfair foreign trade, but also to alternative materials competition, much of which is carbon-intensive. To overcome these challenges and to bolster the U.S. steel and metals production industries' role as innovation leaders, a large-scale industrially driven and consortia-based CEMI for Decarbonization of Steel and Metals would revolutionize U.S. global leadership. It would bolster a sustainable industrial supply chain by de-risking technology innovation through the research development, demonstration and deployment phases.

C1.2 Current interest from the U.S. steel sector to support an institute is strong and coordinated through AIST. AIST is an 18,000-member non-profit organization, the global steel industry's largest association, focused on networking, education, and sustainability programs for advancing iron and steel technology. AIST has the unique ability to bring together the largest steel producers in the U.S., including core team industrial partners Nucor Corporation, Cleveland-Cliffs Inc., United States Steel Corporation, Steel Dynamics Inc., ArcelorMittal North America, Charter Steel Manufacturing, Commercial Metals Company, Gerdau Long Steel North America and SSAB Americas, with equipment and technology suppliers, universities, national labs, other materials and manufacturing societies, as well as Manufacturing Extension Partnerships. AIST would also convene its manufacturing experts from across this spectrum of industrially driven stakeholders, including expertise from our 30 Technology Committees and 22 regional Member Chapters.

The **capability gap** lies in the infrastructure to produce steel, i.e., locations, supply chain, raw materials and capital-intensive equipment, and products have historically been predicated on the use of carbon to reduce iron ore into molten metallic iron. The industry is also challenged by historic narrow profit margins and the false notion of being an outdated, dirty industry.

A **CEMI** would bridge this gap and aid competitive breakthrough technologies by creating the necessary ecosystem for bringing together diverse human talent, stakeholders, energy utility companies, medium and small businesses, universities and national labs to address the challenges for industrial decarbonization under the guidance of the steel industry. This means adopting emerging technologies, e.g., renewable feedstocks such as hydrogen, natural gas, biofuel, synthetic fuels for replacing coal, CCUS and CO_2 reuse for adoption in existing assets, as well as new innovative technologies such as H2DR, electrolysis and direct use of electric power. The institute would help close critical knowledge gaps and train the workforce, transition existing and bring in new diverse talents to de-risk investment from the steel sector and venture capitals.

C1.3 Current **steel RD&D investments** within the U.S. steel industry, inclusive of the five university-industry consortia, each focused on distinct and separate technical challenges, have budgets estimated at approx. US$2–3 billion in total, which pales in comparison to other industries. In contrast, Apple Inc. alone spends US$16 billion annually and the 10 largest semiconductor chip manufacturers spend over US$30 billion annually on research and development. Additionally, the federal government recognizes the need for semiconductor research by allocating US$250 billion in the 2021 U.S. Innovation and Competition Act to fund such research. The difference in asset allocation is significant considering the necessity of both industries to the U.S. economy. As the steel industry is also a key industry in the fight against climate change, additional investment in this sector is critical. While there is significant research underway in the steel sector, none of the steel-centered consortia are exclusively focused on decarbonization.

A CEMI for Decarbonization of Steel and Metals would address significant technical challenges through a set of industry-driven projects. Technical challenges include feedstock flexibility, improving recyclability, the use of alternative energy sources, waste management, improved yield, and material efficiency, etc.

Industry has started addressing several areas within the steel manufacturing value chain to achieve cost improvements and reductions in emissions and efficiency. However, many of these efforts are still not commercially deployable and will require further insights that can only come through enhanced innovation, research and development. Five key technology themes can be identified:

- **Advanced Materials and Process Development** — The use of an electrolysis reactor in place of the traditional blast furnace offers an attractive route for replacing carbon to produce elemental iron. Currently, low- and high-temperature electrolysis reactors have been proven in the laboratory; however, they are not yet viable for steelmaking. While there are several projects being conducted in Europe on this technology, in the U.S., Boston Metals has demonstrated a high-temperature electrolysis process using molten oxides, which has the potential for higher kinetics but at a much higher capital cost.
- **Carbon Emissions and Decarbonization: Low- or Non-Carbonaceous Reductants** — Hydrogen use as a primary reductant of iron (versus carbon) has become the most considered alternative on its potential to be produced at scale. Again, many European steelmakers have made considerable progress in the use of hydrogen as a reductant (See table in Q8.3).
- **Iron Recycling and Reuse** — Eliminating the need for ironmaking through the use of scrap would eliminate roughly 1,500 kg CO_2 emitted in blast furnaces per ton steel. Approx. 71% of steel in the U.S. is produced through scrap re-melting in EAFs. The primary challenge for EAF scrap charging and recycling is the presence of residual elements, such as Cu, Ni, Cr, Sn and Mo. These elements cannot be easily removed during liquid steel processing, resulting in deleterious effects downstream, such as hot shortness or cracking during thermomechanical processing (TMP). While all steel can be recycled, steel containing elevated levels of residual elements cannot be used for thin-gauged applications. The problem will worsen as residuals in the scrap “pool” continue to increase over time. Virgin iron from either the blast furnace or DRI module is the current method of diluting the residual content in the scrap system. Process control and deploying machine learning in scrap sorting have provided marginal improvement and continued efforts are necessary.
- **Product Properties: Quality and Cost** — Quality control and energy efficiency are impactful to the economics of the final product. Liquid steelmaking and refining serve as the gatekeeper for chemistry adjustment and quality control. Feedstock changes made in ironmaking or recycling have a significant impact on steel chemistry. Additionally, a modern EAF typically consumes 300–400 kWh of electricity per ton of liquid steel (TLS). 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 are predominantly through the EAF shell and through the water-cooled components. The theoretical minimum energy for melting steel and raising it to casting temperature is approximately 370 kWh/TLS. Thus, depending on material recoveries and effective energy transfer, the EAF can be 40–60% more energy efficient than the current state of the art. Data analytics of process data to optimize furnace conditions to account for variations in feedstock have shown improvements in economy and quality.(1,2) Digital technological pathways along with materials and engineering advancements can be utilized to develop the understanding to narrow the 40–60% gap and reduce/eliminate the chemical energy addition (coal and natural

[1] https://www.gcteng.com/wp-content/uploads/2006_AIST_2006_SmartGas_A_New_Approach_To_Optimizing_EAF_Operations.pd.

[2] A. Rahnama, Z. Li and S. Sridhar, “Machine Learning-Based Prediction of a BOS Reactor Performance From Operating Parameters,” Processes, 2020, 8, 371, doi:10.3390/pr8030371.

gas). Significant investment in new technologies such as sensors, robotics, data storage/data mining, high speed computing, AI, and ML will provide improved understanding of process systems and automation which would be applicable across all manufacturing sectors.

- **Product Properties: Valorization** — Product demands are changing because of societal expectations, e.g., lightweight applications, improved performance and competition from other materials. Steel has traditionally required (depending on grade and application) a series of solid-state, energy-intensive processes involving temperature adjustment and mechanical process to achieve the final properties required for the intended application. A variety of technological improvements can be deployed, such as near-net-shape casting, hydrogen-fueled combustion, hot charging and continuous rolling, improved furnace technologies and alternative heating methods. Each of these technologies has a presence in the industry but require additional research to bring them to widespread application.

C1.4 Eliminating greenhouse gas (GHG) emissions in steel requires either (I) a change in the way iron is produced, i.e., replacing carbon with renewable derived reductant or electric power, or (II) the capture and use of the emitted CO_2. Both require innovation in diverse disciplines ranging from process design to supply chain, life cycle analysis (LCA) and logistics to techno-economics. Due to the scale of production, its raw material intensity and diversified market, the steel sector's challenges are unique. A private-public partnership with strong support from a central industry such as steel (ranging from large steel producing enterprises to small and medium technology suppliers and to other manufacturing sectors such as automotive), in coordination with academia and government partnerships would allow for the leverage of the necessary resources and co-investment of human talent. To overcome these challenges and to bolster the U.S. steel industry's role as an innovation leader, AIST proposes a large-scale industrially driven and consortia-based CEMI for Decarbonization of Steel and Metals.

Category 2 Institute Organization

C2.1 A CEMI for Decarbonization of Steel and Metals would foster collaboration through the following organizational groups, many of which AIST already has established.

Steel Industry Producers — All major steel corporation in the U.S., including Nucor Corporation, Cleveland-Cliffs Inc., United States Steel Corporation, Steel Dynamics Inc., ArcelorMittal North America, Charter Steel Manufacturing, Commercial Metals Company, EVRAZ NA, Gerdau Long Steel North America and SSAB Americas, are already engaged in the pursuit of zero-carbon emissions at some level. The coordination of these stakeholders is key to advancing and accelerating technology proven to lower and eliminate CO_2 emissions.

Equipment and Technology Suppliers — Suppliers are already engaged in the development and advancement of technology. The steel producers rely on suppliers such as Danieli Corp., Linde plc, Midrex Technologies Inc., SMS group Inc. and Tenova Inc., all who are engaged in the reduction of CO_2 emissions in the industry. The suppliers, who are international corporations themselves, are active with AIST and are involved in steel manufacturing facilities around the world providing global resources to apply to domestic challenges.

Research Institutions — The U.S. steel industry is unique in the world, whereby most U.S. steel corporations do not have their own research and development facilities. Research institutions play a vital role in coordinating the research, design and deployment of new technology into the industry. Research consortia in the U.S. are already engaged with steel corporations, equipment and technology suppliers and AIST to develop and deploy new steel alloys, new technology and automation, as well as to advance efficiencies beyond current limitations. These research consortia are:

- Carnegie Mellon University — Center for Iron and Steel Research (CISR).
- Colorado School of Mines — Advanced Steel Processing and Products Research Center (ASPPRC) and Continuous Casting Consortium (CCC).
- Missouri University of Science & Technology — Peaslee Steel Manufacturing Research Center (PSMRC) and Kummer Institute.
- Purdue University Northwest — Center for Innovation Through Visualization and Simulation (CIVS) and Steel Manufacturing Simulation and Visualization Consortium (SMSVC).

National Laboratories — National laboratories working in collaboration with industry and research institutions are key contributors to advancing new technology and developing advanced alloys. LLNL, LANL, NETL, NREL, ORNL and Sandia all contribute research to the advancement of iron and steel technology. Their support in an industry-academia-national laboratory coordinated institute would be preferential.

Associations and Societies — Associations and societies provide the various industrial sectors with forums to discuss new technology and applications. Through association-organized conferences, seminars, meetings and conventions, individual stakeholders can discuss and disseminate the latest advancements for the improvement of all engaged. AIST routinely works in collaboration with the American Iron & Steel Institute (AISI), Steel Manufacturers Association (SMA), The Society for Mining, Metallurgy & Exploration (SME), American Institute for Chemical Engineers (AIChE) and numerous others which would provide cross-discipline engagement to ensure technology and advancements from the institute would disseminate across the entire metals manufacturing sector.

State and Regional Partnerships — AIST's 22 local Member Chapters centered in regional steelmaking hubs, colleges, universities and technical schools and regional Manufacturing Extension Partnerships; AIST currently has working relationships with PAMEP and SCMEP.

C2.2 A CEMI for Decarbonization of Steel and Metals would be fundamental for achieving the goal of net-zero carbon emissions by 2050, and would be an essential complement to existing CEMIs, notably RAPID, REMADE and CESMII.

To improve productivity, competitiveness, energy efficiency and strengthening of the U.S. manufacturing workforce, an AIST-led decarbonization institute would be bound by three key challenges:

- **Technical and Environmental Challenges:** It is essential to engage industry, academia and technology suppliers in the metals production supply chain to support pre-competitive RD&D projects that transition innovations into the commercial applications. An example would include the coordination and collaboration of the five existing U.S.-based university-industry steel consortia, each with distinct focus areas: CISR, ASPPRC and CCC, PSMRC, CIVS and SMSVC.
- **Workforce Challenges:** 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. An example would include leveraging and expanding the reach of the steel industry's AIST Foundation, including its platform of existing workforce and diversity development programs.

- **Economic Challenges:** It is vital to encourage entrepreneurship and innovation to attract future investment for economic sustainability of the institute. An example would include the development of pathways between steel and other metal producers, national labs and universities. These pathways would generate innovation hubs to catalyze ideas and encourage the creation of small and medium enterprises supporting industrial decarbonization and the MI.

These significant challenges are intertwined and underscore the important role of a CEMI for Decarbonization of Steel and Metals. The steel industry and AIST, the industry's technical association in Pittsburgh, PA, has the vigor of scale, impact and accountability for coordinating stakeholders to hasten the path toward net-zero carbon emissions.

C2.3 To improve productivity, competitiveness, energy efficiency and strengthening of the U.S. manufacturing workforce, a CEMI for Decarbonization of Steel and Metals led by AIST would succeed by:

- Organizing, coordinating and funding small, medium and large-scale collaborative projects in partnership with the steel and metals industries, academia, and national labs.
- Funding mission-driven decarbonization prototypes and deploying innovations generated by these prototypes to our network, and relevant industries, for adaptation of commercial applications.
- Utilizing AIST's 30 Technology Committee networks as a resource and to share information with all manufacturing stakeholders. The AIST Technology Committees represent the world's largest network of steel manufacturing expertise and are essential to the technological welfare of our industry.
- Engaging AIST's network of 22 local Member Chapters spreading across six continents and includes the United States, Canada, Mexico, Brazil, Australia, Korea, India, Middle East, North Africa and Europe. These local chapters provide bi-lateral dissemination of knowledge.
- Evolving our current technology training and workforce development programs, consisting of in-person events, webinars and online resources.
- Amplifying our current internship and scholarship programs to provide a diverse group of students an opportunity to receive real-life training, attract more young talent to steel manufacturing and motivate K-12 students to pursue manufacturing careers.
- Enhancing AIST's current faculty grants and programs to support cross-cutting research and development for decarbonization.
- Strengthening AIST current Awards and Recognition Program to encourage entrepreneurs and innovators to implement breakthrough technologies focused on decarbonization.

Through these efforts, an AIST-led MI will enhance innovation capacity for decarbonization and improve industrial competitiveness.

C2.4 A CEMI for Decarbonization of Steel and Metals would benefit from cross-discipline collaboration between CESMII, CYMANII, Power America, RAPID and REMADE as members of the Manufacturing USA network.

- Over 70% of the U.S. steel industry produces steel through the EAF route, which will continue to increase in its capacity whereby steel scrap will become scarcer, particularly in high production areas. Collaborations with Reducing Embodied-energy And Decreasing Emissions (REMADE) could provide substantial benefit.
- Steelmaking is a chemical process and is chemistry driven at its core. Teaming with Rapid Advancement in Process Intensification Deployment Institute (RAPID) and their expertise on

optimizing chemical reactions focused on hydrogen, natural gas and CCUS would be beneficial.

- Manufacturing times Digital's (MxD) advances in digital tools would benefit the steel industry as it embraces digitalization throughout its manufacturing processes. The steel industry is an energy-intensive manufacturing sector. The Cybersecurity Manufacturing Innovation Institute (CYMANII) can work to optimize production processes to sustain U.S. iron and steel manufacturing, benefiting smart supply chain logistics and secure factory automation. As smart manufacturing continues to evolve in the industry, high-performance computing (HPC) becomes essential for advanced machine learning considering innumerable data sets gathered from smart sensors throughout a mill. Here, CESMII can help to accelerate the adoption of these technologies.
- The core technologies in Industry 4.0, such as sensors, data analytics and simulation need to be integrated into steelmaking. This is challenged by the harsh and complex environments (high temperatures and multiphase and reactive materials) that make it difficult to implement. There is also a challenge related to a false perception that the sector is declining in economic importance. Thus, a cross-discipline collaboration between the aforementioned technologies and the steel industry would accelerate the path toward decarbonization.
- Cross-discipline collaboration comes with several barriers, though they do not outweigh the benefit to all involved with the cross-cutting theme of a CEMI for Decarbonization of Steel and Metals. Some notable barriers are the competitive nature of metals producers with their material versus other materials such as steel versus aluminum, the TRL and the economics facing ease of adoption, a continual need for a skilled labor force in all collaboration areas, the differences of corporate culture amongst organizations, and any reluctances to share intellectual property amongst all involved parties.

C2.5 A CEMI for Decarbonization of Steel and Metals would attract private sector investments on a large scale. The interest from the U.S. steel sector to support an institute is strong, as evidenced by the support of AIST's partners and members. AIST already brings the capacity to convene its manufacturing experts from across a spectrum of industrially driven stakeholders, including expertise from our 30 Technology Committees and 22 Member Chapters.

AIST's short-term indicators for success within the first 5 years: A defined current baseline for the U.S. steel sector would be essential, incorporating technological, economic, environmental, workforce and innovation accelerator requirements that identify the critical gaps and needs for preserving the U.S. economic and national security. A workforce strategic plan would also be essential to create partnerships with community colleges, trade schools and universities to provide for workforce availability and an infrastructure for workforce development to meet industry needs for a skilled, diverse and inclusive workforce by 2030. A defined decarbonization roadmap and strategic plan would also identify economically viable technical pathway(s) to achieve a net-zero-emission steel industry by 2050.

AIST's mid- and long-term strategic goals: To address high-priority technical research challenges needed to grow the U.S. manufacturing sector, the plan would need to address technologies and operations as summarized in sections C1.2 and C13.1. The development of the following technologies could be expected on a medium-term horizon: by 2026 converting exhaust emissions into chemicals, using biomass for partial coal replacement, using hydrogen to replace pulverized coal; by 2040: hydrogen-based DRI production, smelting reduction with carbon capture; and by 2050: CO_2 capture for storage and conversion, electrolysis processes to reduce iron ore to raw steel. AIST's strategic plan implementation will further lead to technological, economic and environmental sustainability for the steel industry and achieving a net-zero-emission iron and steel industry by 2050.

Category 3 Institute Benefit

C3.1 The expected impacts from the CEMI for Decarbonization of Steel and Metals are far-reaching, transformational manufacturing solutions that can be implemented by steel companies and suppliers across the supply chain.

Through collaborations enabled by a CEMI for Decarbonization of Steel and Metals, the consortium will identify and examine the critical pre-competitive gaps and challenges surrounding four key Technology Themes: (1) Advanced Materials and Process Development; (2) Carbon Emissions and Decarbonization; (3) Iron Recycling and Reuse; and (4) Product Properties and Valorization; and Three Cross-Cutting Themes: (1) Smart Solutions, including AI, ML, human-machine interface (HMI) and robotics; (2) Infrastructure, Facilities and Tools (including HPC); and (3) Education and Workforce. We expect the near-term projects identified for the strategic plan will focus on the optimization of existing processes and workforce development that can be implemented with existing steel plants, while longer-term projects and strategy will be to develop transformational feedstock materials and processes that might require significant investment for implementation.

Metrics from the steel industry that would be expected to have improved outcomes include: (1) improving fuel consumption, (2) reducing CO_2 and pollutant emissions, (3) decreasing downtime, (4) lowering production costs, (5) reducing the skills gap and increasing diversity, equity and inclusion both through focused new hire training and retraining efforts, and (6) increasing the participation and innovation of SMEs in the steel sector value and supply chains.

C3.2 The Biden administration is focused on two key areas that can unite the U.S. steel industry: decarbonization and infrastructure. For decarbonization, there is heightened interest both nationally and globally, which ignites competitive interests for RD&D that will lead to improving quality of life. Infrastructure will increase demand for steel consumption, catalyzing economic development and employment while also improving quality of life.

Further, the current financial strength of the steel industry offers healthy tailwinds for the unification of the industry in the grand challenges of net-zero carbon emissions and workforce development. Motivating factors include:

- Societal and investment community expectations for decarbonization is high.
- Technical solutions for carbon capture, utilization and storage, steel scrap beneficiation and availability of non-carbon fuels and reductants are all essential.
- The creation of a skilled, diverse and inclusive workforce through partnerships with community colleges, trade schools and universities is of paramount urgency.

A CEMI for Decarbonization of Steel and Metals could facilitate the commercial transition of innovative decarbonization technologies into scalable, cost-effective and high-performing manufacturing solutions. While industry has the capacity to evolve these technologies over time, an MI will coordinate and accelerate the effort to ensure global leadership is not lost.

The capability for the MI administration to engage industry at all levels will be critical for its long-term viability. The steel industry and AIST, the industry's technical association near Pittsburgh, PA, has the vigor of scale, impact and accountability for coordinating stakeholders to hasten the path towards net-zero carbon emissions.

C3.3 As identified in paragraph 1 of question C1.1, the steel industry generates prosperity and welfare. The substantial earnings and tax revenues created by the steel industry provide major opportunities to invest in public services.

Our industry has transformed its manufacturing economy into one driven by knowledge and technology over the past few decades. This brings enormous potential to deliver jobs, economic opportunities, and neighborhood improvements to low-income communities and communities of color across the U.S. However, the benefits of new growth and development will not be automatically achieved without a focus on equitable development. Leaders in academia (intellectual leadership), industry (development leadership) and government (policy leadership) must work together. Collaboration between these three is essential to identify effective and desirable opportunities for workforce development, especially around DEI.

A CEMI for Decarbonization of Steel and Metals will provide the stakeholders an opportunity to collaborate on a common goal — achieving climate neutrality by 2050. AIST has many steel industry partners within academia and at industry level, including access to national government laboratories and cross-discipline associations. The institute should work to leverage the DOE/AMO and 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.

The steel industry has come a long way in workforce development; however, the policy must be developed together with the industry and government if the journey of change is to be a success story. AIST's Foundation currently awards US$850,000 annually to develop the steel industry's next generation by collaborating with industry and academia. The groundwork is laid, but more work can be done to develop additional programs to support DEI efforts through collaboration with the new MI. Initiatives could include development of programs for management education and mentorships, development of best practices and benchmarks, establishment of strategic partnerships to create internships specifically for underrepresented groups, and development of a plan to partner with community colleges, trade schools, minority serving organizations and universities to provide an infrastructure for workforce development to meet industry needs for a skilled, diverse, and inclusive workforce by 2030.

C3.4 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 (3). Barriers for these students can include financial circumstances, balancing requirements for work/family/education, resource availability and academic support. To eliminate barriers to entry in the MI, it is important to learn the unique motivations, business strategies and community resources for each partnering MSO. In addition, steps outlined in paragraph 4 of section C3.3 can be implemented.

Category 4 Education and Workforce Development

C4.1 Building a sustainable team of employees with the right mix of skill sets is a continuous

[3] National Academies of Sciences, Engineering, and Medicine 2019. Minority Serving Institutions: America's Underutilized Resource for Strengthening the STEM Workforce. Washington, DC: The National Academies Press. https://doi.org/10.17226/25257.

challenge for the steel industry. In its report, [Creating pathways for tomorrow's workforce today: Beyond reskilling in manufacturing], Deloitte states that the U. S. manufacturing skills gap could leave as many as 2.1 million jobs unfilled by 2030. This is primarily due to an aging and reduced workforce and skill set changes required due to new technology.

The MI needs to define our opportunities and challenges to retain and expand the talent pool, train and educate new employees and upskill current employees. Moreover, the MI must highlight today's modern steel industry by recognizing our use of advanced technology, energy conservation and environmental awareness to improve conventional perception. AIST, through the AIST Foundation, has several of these platforms in place that could be scaled through an MI. Specific tactics within a strategic framework could include:

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

C4.2 A diverse workplace allows for a more diverse suite of ideas, which inevitably increases the potential for transformative solutions in a complex and multi-disciplinary problem such as decarbonization. The solutions are also likely to be more sustainable with regard to changing demographics and other grand challenges. The MI should engage with top-tier historically black colleges and universities (HBCUs), Hispanic-serving institutions (HSIs), MSOs, community colleges and vocational schools that have an interest in research and education related to manufacturing in general. HBCUs and HSIs that have historically been excluded from the mainstream of basic science and engineering research and collaboration. Specific activities should be developed such as: (I) Help bridge existing gaps in education, research and public service to create career pathways for students at all levels; and (II) Include PI's from HBCU and HSI's in RD&D projects.

Questions Addressing Decarbonization of Metal Manufacturing

Category 8 Productivity and Competitiveness

C8.1 The steel industry is continuously looking for new ways to improve productivity without increasing energy consumption or carbon emissions. With the rapid development of decarbonization technologies, advanced sensorization and digital technologies will become key to improving yield and energy efficiency in steel production.

A public-private MI would enable the application of new and growing expertise in digital technologies directed at impacting challenges in steel production. The use of data analytics, ML, physics-based computational simulation, visualization, HPC and other digital technologies in combination with sensors to analyze and improve the process of steel manufacturing at a multi-disciplinary MI would provide significant benefits to both producers and the entire metals manufacturing supply chain.

Iron and steel production is a complex multi-stage process route that requires effective planning, scheduling, real-time optimization and control to improve productivity and energy efficiency. Currently, there are digitalization tools and methodologies implemented in some processes in the steel industry(4). However, there is a critical need to further integrate and develop digitalization technologies within the metals manufacturing sector. These technologies can be domain-specific modeling, high-fidelity physics-based computational models, AI and ML.

Off-line high-fidelity physics-based computational models can provide fundamental understanding of complex physics and chemistry in a process as well as to identify optimum operation conditions for improving productivity without increasing energy efficiency and emissions. Such physics-based models can be integrated with AI and ML, HPC, and sensors to enable real-time optimization to improve process performance by adjusting their inputs in response to disturbances and process variations. Such integration can also be used for predictive maintenance, downtime prevention, enhanced plant logistics, improvement of product flow and efficiency of production lines. In addition, the application of such technologies for virtual training would assist in the promotion of safe and efficient operation, improving on-the-job outcomes and productivity and enhancing workforce development. These technologies can be applied to steel refining in ladle and other key processes in steelmaking that have significant impact on operational efficiency and performance of finished products by increasing productivity and reducing costs.

C8.2 This response is in strong support of Decarbonization of Steel and Metals versus Electrification of Industrial Processes. At this juncture, the DOE/AMO appear to be undecided as to which direction and focus the MI should take to garner the largest impact. For AIST, our objective would be to unify the entire U.S. steel industry — including steel producers, technology suppliers, academia and national laboratories — in support of an MI focused on decarbonization of steel and metal.

Globally, 7% of all CO_2 emissions originate from steel production, and the global industry is rising to the challenge of decarbonization. The U.S. steel industry, working in coordination with academia and the national labs, has the rigor of scale, impact and accountability to hasten the path to net-zero carbon emissions.

Decarbonization solutions must be scalable, cost-effective and offer high performance for industrial adoption, and the MI would address barriers for TRL 4-7 innovations that no single company or organization would tackle on its own; the MI will de-risk this effort. 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, and to support the long-term economic viability of such an institute. These challenges also represent favorable attributes in support of a steel-centric MI.

With steel being the engineered material solution for the manufacturing economy, the U.S. steel industry has key tailwinds to motivate its support for this 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 in Europe, Asia and elsewhere. These breakthrough investments, if unanswered, will threaten U.S. leadership in the global production of clean steel.

[4] [Backman et al., 2019] (Jere Backman, Vesa Kyllönen. Heli Helaakoski, "Methods and Tools of Improving Steel Manufacturing Processes: Current State and Future Methods", IFAC PapersOnLine 52-13 (2019) 1174–1179)

The timing is right, and perhaps overdue. The DOE/AMO working in direct cooperation with the U.S. steel industry would yield a significant impact to increase U.S. competitiveness within the grand challenge of industrial decarbonization. Technological advances in manufacturing will enable decarbonization for other sectors such as transportation, residential and commercial, which will carve the path to economy-wide net-zero emissions by 2050.

C8.3 Since 1990, Europe has been the only continent to reduce its carbon emission, whereas the U.S. has remained unchanged. Europe has been dominating green technologies, because of the massive amount of government support — greater than any other region of the world (5).

There are several government-subsidized steel industry decarbonization projects occurring in Europe and Asia that provide local industry the opportunity to focus on implementing innovative technologies that may otherwise not have been financially successful. If the U.S. wants to take the lead in attaining climate neutrality, our government should also support research into breakthrough technologies that lead to decarbonization for the U.S. steel industry. A CEMI for Decarbonization of Steel and Metals would be critical to support these investments.

Decarbonization Projects Outpacing U.S. Metals Industry

Company	Country	**Project** (Description)	Start
		Europe	
47 Partners	15	•**ULCOS** (Develop new technologies to produce steel with reduced CO_2 emissions)	2004
Thyssenkrupp	Germany	•**tkH2Steel** (Hydrogen injection into blast furnace, emitting water vapor vs. CO_2. Reduction potential: 20%)	2019
Salzgitter GmbH	Germany	•**SALCOS** (Hydrogen generation and the conversion of steel production from blast furnaces to direct reduction. Reduction potential: 95%)	2015
Tata Steel Europe	Netherlands	•**ATHOS** (Develop a public CO_2 distribution network in the North Sea Canal area, enabling CCUS. Reduction potential: 40%) •**EVEREST** (Utilize carbon monoxide and hydrogen byproducts for conversion into chemicals and capture waste CO_2 for storage in North Sea gas fields) •**HISARNA** (Alternative to blast furnace process, raw materials used in powder form and directly converted into liquid pig iron. Reduction potential: 20%)	2010
Voestalpine Stahl GmbH	Austria	•**H2FUTURE** ("Green" hydrogen pilot) •**SUSTEEL** (Research project for usage of hydrogen plasma) •**HYFOR** (Hydrogen-based fine-ore reduction pilot)	2017
ArcelorMittal Europe	France	•**SIDERWIN** (Steelmaking with electrochemical process. Reduction potential: 87%) •**Carbon2Value** (Carbon-neutral steelmaking route leveraging all clean energies) •**Torero** (Waste wood into biocoal)	2009

[5] https://www.home.saxo/content/articles/quarterly-outlook/decarbonisation-is-europe-last-chance-to-prosper-29062021

		•**Carbalyst** (Capture carbon offgas and convert to carbon ethanol) •**IGAR** (Capture CO_2 and hydrogen waste and convert to reductant gas)	
SSAB	Sweden	•**HYBRIT** (Create fossil-free value chain, from mine to end-product. Reduction potential: 25%)	2016
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)	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)	2007
South America			
Vallourec	Brazil	• **CDM** (Use of bio-coke in blast furnace)	2004

Category 9 Energy Efficiency and Energy Intensity

C9.1 The blast furnace process is the most energy-intensive portion of the iron and steelmaking route, with significant consumption of solid and gaseous fuels and a high carbon intensity. Based on a DOE/AMO-sponsored 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. Methods for reducing the energy and carbon intensity of the conversion process from iron ore to steel include operational efficiency improvements to the blast furnace, such as increased and alternative fuel injection techniques to reduce reliance on coke and the use of biofuels for coke replacement. Additionally, in the U.S. another means of increasing energy efficiency would be to explore alternative routes for reducing iron in combination with the electric arc furnace and hydrogen-based direct reduction ironmaking techniques.

The challenges presented in the use of such techniques are significant and will require the multiple approaches to determine feasibility and to scale-up the technology for wider implementation. Potential solutions to closing the gap include real-time sensing, rapid physics-based computer simulation and visualization, big data analysis and process control to allow for feedstock flexibility (reductants, scrap, energy source, etc.) without loss in process control or product quality. An energy efficiency increase of 10% in the blast furnace and basic oxygen furnace process would also lead to roughly 260,000 tons of CO_2/year reduction for a typical operation and 4.5 million tons of CO_2/year reduction across the entire U.S. steel industry. A

[6] Fruehan, R J, Fortini, O, Paxton, H W, and Brindle, R. Theoretical Minimum Energies to Produce Steel for Selected Conditions. United States: N. p., 2000. Web. doi:10.2172/769470.

public-private partnership would infuse the needed collaborative innovation in digital technologies to enable a transformative change.

C9.2 The EAF process route using recycled steel scrap eliminates 90% of the CO_2 emissions in comparison to the carbon embedded in blast furnace pig iron. The EAF process sometimes requires addition of pig iron to dilute impurity elements such as Cu, which is harmful for steel products, especially surface-sensitive grades such as automotive sheet by causing surface cracks (7). The Cu tolerance limit of automotive interstitial free steel is 0.03 wt.%, whereas typical automotive scrap contains over 0.2 wt.% Cu. Opportunities to produce high-value products, such as automotive sheet from steel scrap, would decrease need for virgin iron ore and CO_2 emission and improve the competitiveness of the U.S. steel sector. Potential routes to achieving this are: (I) improved sorting and separation of Cu(8), (II) removal of Cu during liquid steelmaking and/or (III) mitigating process conditions during casting and thermo-mechanical processing to ameliorate the effects of Cu (9).

C9.3 The co-location of DRI production facilities with EAF melting facilities provides an opportunity for significant energy savings by enabling 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(10). This may be an important enabling technology for improving the efficiency of melting carbon-free, high-melting-point, hydrogen-produced DRI. Similar benefits could also be envisioned using hot DRI additions in the blast furnace through co-location.

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 might be utilized for DRI feedstock production with a low CO_2 footprint. Collocation of coke plants with blast furnace facilities would also enable bridging technologies for improved utilization of offgas streams between processes and allow for the centralization of sequestration and heat recovery facilities. Collocation of DRI and blast furnace facilities could also provide similar benefits.

A public-private institute for steel decarbonization is needed to serve as a bridge between the steel industry and other metals manufacturing industries, universities and national laboratories to facilitate and catalyze the next wave of breakthrough technologies for decarbonization of the steel industry and bring them to market. This proposed MI would also serve to facilitate the creation of new small and medium enterprises supporting industrial decarbonization innovation for U.S. industry through institute partners such as the Kummer Institute for Entrepreneurship and Innovation at Missouri S&T.

C9.4 Enhancing fuel utilization efficiency and enabling significant use of low-carbon fuels while maintaining productivity (BF, RF, EAF). Recycling waste energy and heat effectively throughout

[7] EAF-Based Flat-Steel Production Applying Secondary Metallurgical Processes, October 2006
Conference: Ironmaking Steelmaking, Linz Austria, Markus Huellen, Christian Schrade, Uwe Wilhelm, Zulfiadi Zulhan
[8] Gao, Zhijiang & Sridhar, S. & Spiller, D. & Taylor, Patrick. (2020). Applying Improved Optical Recognition with Machine Learning on Sorting Cu Impurities in Steel Scrap. Journal of Sustainable Metallurgy. 6. 785-795. 10.1007/s40831-020-00300-8.
[9] E.M. Nick, B. A. Webler, S. Sridhar, "The influence of cooling and reheating on the evolution of separated Cu in high-residual-low-carbon steels", Iron & Steelmaking, 2008, 35:473-480
[10] Duarte, P.E. & Becerra, J. & Lizcano, C. & Martinis, A. (2010). Energiron direct reduction ironmaking - Economical, flexible, environmentally friendly. 34. 25-30.

the mill to enable high productivity with minimized carbon emissions. Study of new technologies and techniques for iron and steelmaking which could be effectively trialed for feasibility and explored for scale-up, including novel alternative ironmaking, and plasma-based heating techniques.

Category 10 Material Performance and Alloy Development

C10.1 Alloy development will impact decarbonization of the metals industry by increasing efficiency of material usage (lightweighting, performance under harsh conditions, etc.) within the manufacturing economy, thereby reducing the amount of metals that are consumed. This approach would lead to a reduction in energy consumption and overall environmental impact.

A public/private partnership MUST ensure that alloy development and process development occur in synergy. This is essential as the development of innovative and advanced metals involve combined alloy and process development. These two aspects are inseparable because high-performance microstructures are obtained by control of both alloy composition and sophisticated processing.

There are clear opportunities to develop alloys whose processing will be less carbon intense. For example, alloys that can tolerate greater concentrations of impurities from scrap would enable production of these alloys using electric arc furnace of recycled materials, rather than needing to generate “virgin” iron units. From a processing standpoint, another example might be alloys designed to respond to induction heat treatment thermal signatures, rather than conventional furnace technologies. These two examples would both replace carbon-based processing technologies with electrically powered options.

C10.2 Steel development profoundly enables innovations in a variety of industries to reduce the carbon intensity of the overall economy, and this aspect underpins the foundational role of a CEMI for Decarbonization of Steel and Metals. For example, higher-strength steels for auto bodies have provided benefits in vehicle weight reduction and fuel efficiency, which are critical to decarbonization of the economy at low cost while maintaining crashworthiness and human safety. In addition, development of structural steels for construction is essential for affordable and sustainable housing. These improvements have increased, but much work remains to be done. 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, wear-resistant, fatigue-resistant steels, etc., for life extension and enhanced performance/efficiency. New hydrogen-cracking resistant steels are also needed to store or transport hydrogen in support of the evolving “hydrogen economy.” Each of these examples represents critical areas of manufacturing competitiveness for the U.S. to consider. Developments of entire new classes of iron-based materials may be on the horizon, using greater alloy concentrations than are typical today, such as medium or high-manganese steels, iron-based MPEAs (multiple principal element alloys, or “high entropy” alloys), and using new manufacturing technologies such as additive methods that will enable additional innovations for niche applications that are not possible using homogeneous bulk materials in combination with conventional “shaping” technologies such as forming or machining.

The important aspects of alloy performance are highly dependent on the application. Most steels are used in structural applications where higher strength is desired while improving other critical characteristics like fracture toughness, formability and weldability. The ability to produce and further process products are critical aspects of alloy development. Thus, it is important that researchers have access to deep knowledge of industrial processing and manufacturing in combination with materials science that would be available with a MI for the Decarbonization of Steel and Metal.

C10.3 This question is especially important. This RFI has a broad focus covering the entire metals industry, but steel is *the* most strategically important material in terms of prosperity of the metals industry, participation in the broad manufacturing economy, and its importance toward decarbonizing the economy. Steel's carbon intensity is magnified by its significantly higher production volumes when compared to other metals. Of course, refractory metals, rare earth metals, copper and aluminum-based alloys also have important roles in the economy, but these metals are produced at much lower volumes than steel. Alloy developments for materials are well supported by federal funding including defense, such as refractory metals—high-temperature applications in rocket engines, hypersonics—light metals (Al, Mg, Ti) for aerospace, and critical minerals. In fact, there are existing manufacturing institutes such as ONR's LIFT (Lightweight Innovations for Tomorrow) and DOD's CMI (Critical Materials Institute) that already incorporate specific missions for development of these alloy families.

Category 11 Decarbonization and Environmental Justice

C11.1 Answered in sections C1.1, C8.1, 9.1, 9.3 (1st question), C2.3 (2nd question), C1.3 (3rd question).

C11.2 The challenge with intermittent renewable power (solar/wind) is the lack of sufficient energy storage and ability to operate fossil free operation during downtimes. A manufacturing plant must operate continuously 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., hydro-electric or geothermal stations or nuclear power, is a viable option, but the location requires 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). For example, U.K. Steel Gareth Stace Works 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 Europe (11).

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 to develop a new 240-megawatt solar facility in Pueblo, CO, and Nucor Steel Sedalia's collaboration with local wind power company Evergy in MO. 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

[11] https://www.bbc.com/news/uk-wales-58628721

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 (GISH).

C11.3 Electric power may be used to substitute fossil reductants and fossil fuels for heating. Substituting the reductant would have the far greatest impact. In the case of reduction, Al, many rare earth metals, Ti and Mg can be produced (more or less) cost-effectively through direct electrolysis. Iron could potentially be produced through direct electrolysis (ArcelorMittal's SIDERWIN and molten oxide electrolysis) but the processes have not been scaled up and will be limited by mass transport, electrode stability and available plant area.

Electric power can be used to produce H_2 at sufficient quantities for iron and steel production. This can be used in reduction, melting (arc furnace technologies and induction melting) and re-heating for thermo-mechanical processing.

C11.4 Aside from contributing to the worlds 7-8% GHG (12), the steel supply chain emits:

I. Significant other harmful elements to the air, where the primary emitter is coke facilities through coke oven gas, naphthalene, ammonium compounds, light oil and coke dust. NOx and SOx are emitted from every stage of the steelmaking process, where burning or use of fossil materials is involved.
II. Wastewater, from quenching, cooling and pickling, out of which the latter may be most challenging. Advanced water treatment projects within the DOE NAWI water HUB (13) may cover this in collaboration with the proposed MI.
III. Enormous amounts of slag are generated within the steel industry and have historically been sent to landfills.

Category 12 Transition and Adoption of New Technologies

C12.1 Answered in Section C1.3. The journey from concept to commercialization of any innovative technology, including steel decarbonization technologies, requires an infrastructure and resources that support technology creation, development, demonstration, scale-up and commercialization at each stage of the process. A CEMI for Decarbonization of Steel and Metals would provide the infrastructure, resources, communications platforms and networking opportunities needed to bring together the resources from industry, academia, government laboratories, producers, technology providers and business incubators that are needed to tackle the decarbonization challenges facing our domestic steel industry. The institute would also be positioned to provide resources for enabling innovation, entrepreneurship, workforce development, economic development, and equity and inclusion through its supporting members.

The demonstration and scale-up phases of a new technology to move it to commercialization is normally the most difficult part of this process, particularly in capital-intensive manufacturing processes such as steel. An institute that provides support for securing the resources and facilities needed for this phase of technology development would greatly accelerate the process of technology commercialization and adoption.

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[12] https://www.mckinsey.com/industries/metals-and-mining/our-insights/decarbonization-challenge-for-steel
[13] https://www.nawihub.org/about

C12.2 We envision that our institute partners would provide support to the institute's mission in a variety of ways. For example, Missouri S&T has pledged to support an AIST-led CEMI for Decarbonization of Steel and Metals with resources from its newly formed Kummer Institute for Entrepreneurship and Economic Development. This pledge would include support in the form of 10 student fellowships, an endowed professor position, 22,000 ft^2 in its new Missouri manufacturing protoplex facility, and support for new business incubation through the institute. Instrumented pilot test beds, such as the H_2DR reactor at Hazen or the experimental blast furnace at MEFOS could be utilized to accelerate decarbonization developments. The operation and maintenance of such facilities are not possible to support by a single company's R&D laboratory and broad access of such a facility to universities, small businesses and government labs would accelerate deployment of new technologies and help bridge gaps in workforce training.

C12.3 New technology startups that support steel industry decarbonization will provide significant economic benefits to the U.S. and local economies by expanding manufacturing workforce employment and tax revenue base and by positioning the U.S. to be a global provider of decarbonization technologies for the steel and metals industries.

Category 13 Disruptive Technology

C13.1 The greatest potential disruption from technology development in the steel industry is one that is economical and eliminates the use of fossil fuel or energy sources in the reduction of iron ore. There are a variety of possibilities in this respect, including hydrogen, biomass, electrowinning, closed loop carbon sequestration, etc. A truly disruptive technology would be the development of a combined H2 plasma reduction and melting technology that could take advantage of unpelletized ore, utilized enhanced reduction kinetics of plasma ionized/dissociated hydrogen, produce liquid steel while directly separating the gangue as slag, with hydrogen managing the slag FeO content. All these possibilities are difficult and require extensive R&D with deep interaction between industry practitioners and researchers in a variety of disciplines and are perhaps only achievable through a public-private partnership.