U.S. DEPARTMENT OF ENERGY

Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

Advanced Manufacturing Office

Steel Industry Roundtable

Summary Report

November 6, 2019

Washington, DC

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The DOE Office of Energy Efficiency and Renewable Energy (EERE) Advanced Manufacturing Office (AMO) partners with industry, small business, universities, and other stakeholders to identify and invest in emerging technologies with the potential to create high-quality domestic manufacturing jobs and enhance the global competitiveness of the United States.

This document was prepared as a collaborative effort between DOE AMO, Boston Government Services, and Energetics.

Disclaimer

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1. Executive Summary

The U.S. Department of Energy's Advanced Manufacturing Office (AMO) hosted a Steel Industry Roundtable on November 6, 2019. Representatives from the steel industry, Department of Energy (DOE) National Laboratories, academia, and non-governmental organizations gathered in Washington, DC to hear expert speakers and participate in facilitated discussions regarding steel technology needs and opportunities. Discussion topics focused on foundational/enabling technologies for iron and steelmaking, cross-cutting foundational/enabling technologies, and workforce and collaboration needs.

Background

The steel industry is an important part of the U.S. economy. According to a recent industry-sponsored report, in 2017 the iron and steel industry generated more than $520 billion in economic output and nearly two million domestic jobs. About 387,000 jobs worth $34 billion dollars are directly linked to domestic iron and steel manufacture, with workers in steelmaking, steel mill and other steel products, processing, distribution, and materials and mill services.[1] Steel is a vital material for many economic sectors, with uses in transportation, homes, commercial buildings and industrial equipment, as well as many other applications that touch everyday life. Steel is also a critical component in electricity infrastructure, machine tools, and many aspects of defense.

Steelmaking is a relatively energy-intensive process, consuming nearly 1.6 quadrillion Btu of energy in 2014 when incorporating offsite generation and transmission losses – or 1.6% of total U.S. energy consumption that year.[2] Onsite fuel used for heat and power in 2014 was estimated at 1,084 trillion Btu (Figure 1-1). The industry has a history of pursuing technology innovations and advances to foster energy efficiency and optimization of its diverse processes.

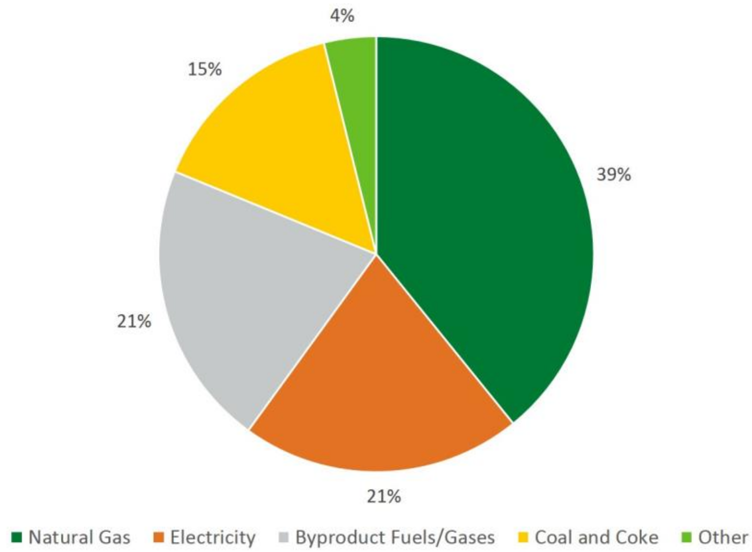

Figure 1-1. U.S. Steel Industry Onsite Energy Use for Heat and Power, 2014 (Total = 1,084 Trillion Btu)

Workshop Overview

Manufacturing remains the essential core of the U.S. innovation infrastructure and is critical to economic growth and national defense. Experts point to a gap in the innovation continuum that exists between research and development (R&D) activities and the deployment of technological innovations in the domestic production of goods. Concerns have been raised that

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[1] John Dunham & Associates, Inc. May 2018. "The Economic Impact of the American Iron and Steel Industry; Methodology and Documentation" Accessed November 20,2019. https://www.steel.org/-/media/doc/steel/policy/reports/economicimpact/dunham-methodology.ashx?la=en&hash=143B7B196B37FEFED363FFC013E60E90D1ED9780

[2] Department of Energy, Advanced Manufacturing Office. 2014. "Manufacturing Energy and Carbon Footprint"https://www.energy.gov/sites/prod/files/2018/10/f56/2014_mecs_iron_steel_energy_footprint.pdf.

this gap could have long-term negative consequences for the economy and the defense industrial base. As global competition to manufacture advanced products intensifies, the performance of the country's innovation ecosystems must improve. Industry, academia, and government partners need to leverage existing resources, collaborate, and co-invest to nurture manufacturing innovation and accelerate commercialization.

The Advanced Manufacturing Office (AMO) within DOE's Office of Energy Efficiency & Renewable Energy (EERE) partners with private and public stakeholders to improve U.S. competitiveness, save energy, create high-quality domestic manufacturing jobs and ensure global leadership in advanced manufacturing and clean energy technologies. AMO invests in cost-shared research, development and demonstration (RD&D) of innovative, next generation manufacturing processes and production technologies that will improve efficiency and reduce emissions, reduce industrial waste, and reduce the life-cycle energy consumption of manufactured products. The results of this investment include having manufacturing energy efficiency harnessed as a competitive advantage, and cutting-edge clean energy products competitively manufactured in the United States. AMO is particularly interested in the challenges associated with advanced manufacturing technology related to the energy-intensive steel industry.

The Steel Industry Roundtable was held on November 6, 2019 to collect steel industry perspectives on future research priorities. Representatives from the steel industry, DOE National Laboratories, academia, and non-governmental organizations gathered in Washington, D.C. to hear expert speakers and participate in facilitated discussions regarding steel technology needs and opportunities. Discussion topics focused on foundational/enabling technologies for iron and steelmaking, cross-cutting foundational/enabling technologies, and workforce and collaboration needs.

Highlights of Results

Facilitated discussions identified several foundational and enabling R&D areas that could be opportunities for continued advances in the steel industry. These are outlined in Table 1-1.

Table 1-1. Summary of Foundational and Enabling Needs Identified for Steel

Technologies for Iron and Steelmaking	Cross-cutting Technologies
Electric Arc Furnace • Alternative electrodes, non-consumable electrodes • Efficient use of chemical energy	**Carbon Capture/Storage** • Carbon storage and infrastructure • Carbon dioxide capture in calcium carbonate; carbon capture to produce formic acid • Integrated steelmaking/carbon capture products
Steel Recycling & Waste Heat Recovery • Low cost, low-grade waste heat recovery • Recycling/sorting sensors for steel wastes • Reformation of slag to byproducts • Useful recycling of all steel wastes and byproducts • Recycling of off-gases such as argon and hydrogen	**Properties Testing & Characterization** • Expansion of Integrated Computational Materials Engineering (ICME) for chemistry/validated process and properties models • Online chemistry/properties sensors • Multi-physics, multi-scale flow models for electric arc furnaces
Iron & Steelmaking Processes • Acceleration of hydrogen-based processes • Use of direct reduced iron • All viable forms of ironmaking • Synthetic materials to replace/enhance mined materials	**Sensors & Analytics** • Robust sensors for steelmaking processes • Soft sensors, e.g., simulations and visualization, digital twins of processes • Artificial intelligence for steelmaking
Workforce and Collaboration Needs	
Workforce • Workforce development (virtual training, curriculum, etc.) • Augmented Workers	**Collaboration** • User facilities at national laboratories for characterization testing • User facility to support accelerated insertion of materials • Support for technology pilot and near-commercial scale deployment

2. Overview and AMO Steel Activities

An overview of DOE AMO technology activities relevant to the steel industry was provided by Isaac Chan, Program Manager, R&D Projects. Technology innovation through applied research and development in advanced manufacturing and energy is a foundation for economic growth and jobs in the United States. The mission of AMO is to catalyze R&D and adoption of energy-related advanced manufacturing technologies and practices to drive U.S. economic competitiveness and energy productivity. As part of its mission, AMO supports a range of projects addressing steel industry energy challenges, through a three-pronged approach (see Figure 2-1, below).

The results of a previous Steel Industry Roundtable conducted in 2015 were noted as identifying R&D needs in data management/analytics (Big Data), smart steel manufacturing, predictive modeling and visualization, alternative feedstocks, and electric arc furnace technology. Collaborative R&D projects supported by AMO since 2015 cover improvements in electrical steels, developing electrical process for carbon free iron, and low-density steels, as well as advanced computational capabilities. Notable successes include a quenching and partitioning approach to mass-produce 3rd generation advanced high strength steel (AHSS) sheet material, and a novel Flash Ironmaking Process with significant reduction in energy use and carbon emissions.

Many steel stakeholders are taking advantage of the High Performance Computing for Manufacturing Program, which began in 2015, and are using modeling and simulation resources to improve processes for energy and cost savings. The purpose of the pilot was to introduce companies to large computational resources so that they have a better understanding of what these capabilities can achieve, including higher resolution and capture of true physics; new material design at the atomic to continuum levels; and methods not commercially available but needed by industrial R&D and production.

Mr. Chan concluded his presentation by stating the purpose of the 2019 Steel Industry Roundtable was an opportunity to identify and prioritize current and future priorities for the steel industry, particularly those related to energy and the mission of AMO.

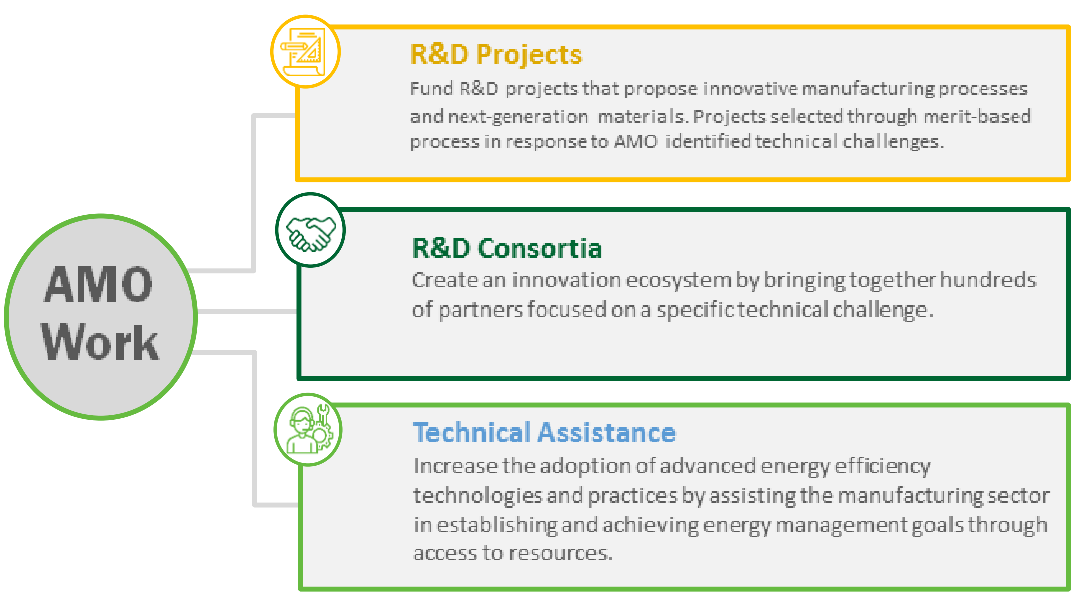

Figure 2-1. Three Pillars of the AMO Program

3. Steel Industry Perspectives

To set the stage for discussion, representatives from various segments of the steel industry gave perspectives on some of the technologies emerging in iron and steelmaking as well as R&D needs. The steel industry presentations identified multiple areas of further R&D:

- Innovations for Low-Emissions and Sustainable Steelmaking,
- Sustainable Integrated Steel Plants,
- New and Recycled Materials,
- Sensors and High-Performance Computing, and
- Advanced Technologies for Measuring Performance.

Highlights of R&D areas and other perspectives presented by industry stakeholders are summarized below.

Innovations for Low-emission Steelmaking

Mark Atkinson and Tom Dower provided background on ArcelorMittal and the Climate Action Report ArcelorMittal released in May 2019, which described technology pathways to reduce carbon dioxide (CO_2) emissions. ArcelorMittal's European operations have a goal of achieving carbon neutrality by 2050.

There was substantial discussion around the use of hydrogen as a replacement for fossil fuels in making iron or steel. All recognized such technologies presume the availability of low-cost hydrogen at the steel plant, either made on-site or delivered via a future hydrogen-based infrastructure.

Ben Kowing described lifecycle carbon savings from high strength steels produced by SSAB. The company specializes in advanced steels for many applications, with an emphasis on efficiency in its production processes. SSAB will convert one steel mill (in Sweden) to use hydrogen for direct reduction of iron ore for fossil free steel and will likely use hydropower to make hydrogen on-site without any carbon emissions.

Francesco Memoli of Tenova notes that some U.S. steel companies have already invested in gas-based iron ore reduction, and European companies are following, some with the introduction of hydrogen in the process. The HYBRIT concept is one such process, enabling the decoupling of energy carriers and reduction agents generating carbon dioxide. Future mini mills are also expected to incorporate continuous charge and heat recovery which can reduce emissions.

The recent Flash Smelting project co-funded by DOE and the American Iron and Steel Institute (AISI) was reported as having validated reduction of iron ore fines and can use natural gas or hydrogen as the reducing agent. It was further reported that this technology could help with transition from blast furnace to electric arc furnace (EAF) in the United States, as metallic iron will still be required. The technology is potentially scalable to site-specific needs.

In addition to hydrogen-based processes, molten oxide electrolysis, an ironmaking technology under development using electrolysis rather than fossil fuels to separate iron from iron ore, was noted as having the potential to reduce CO_2 emissions.

Finally, several attendees noted the "Circular Economy" concept should not be limited to recycling of steel products and by-products but includes the important point that use of steel in other sectors of the economy (e.g., manufacture of automobiles) lowers CO_2 emissions in such sectors due to steel's low life cycle emissions.

Sustainable Integrated Steel Plants

Francesco Memoli of Tenova provided insight on the overall environmental footprint for steel, new technologies that reduce emissions, sustainable heat recovery, potential carbon tag/tax impacts, and a perspective on the future integrated steel plant. For example, integrated future steel plants could incorporate gas-based iron ore reduction plus hot charge in a smelting type furnace or EAF, such as natural gas-based to produce hot metal/pig iron or hydrogen-based to produce steel.

Plants can also increase the use of waste heat recovery, whose application is often limited by payback associated with existing methods. The payback in the U.S. of waste heat capture in EAFs was noted to be about 10 years. It was further noted that in the European Union, 50% of the heat recovery equipment cost has been supported by government funding. More cost-effective technologies for waste heat recovery and reuse are needed to foster use of waste heat.

In addition, there are opportunities to reduce process costs by recovering and reusing other process gases such as argon. If recovered cost-effectively, these byproducts can add significant value to the overall process.

New and Recycled Materials

Representatives from both Tenova and AK Steel suggested using steel plant slags in combination with CO_2 to make calcium carbonate ($CaCO_3$) as a means of sequestering CO_2. Slag can also be used to make light aggregates for use in a high-end cement application, i.e., calling for a lighter and stronger material than regular cement. A pilot plant that can make $CaCO_3$ and light aggregates from steel plant slags was noted as a desirable research pathway. It was suggested that other economical, environmentally friendly uses for steelmaking slag and dust could be explored. SSAB noted they use a lot of tires as a carbon source and questioned whether spent plastics could also be used.

Tom Richter described the perspective of HarbisonWalker, a refractory supplier to the steel industry. From his view, Industry 4.0 improvements are needed to limit operational swings that affect refractories; including real-time sensor technology, improved connectivity, and advanced data analytics. Alternative feedstocks are needed for several supplies/critical minerals needed for high temperature refractories. In particular, the supply chain is now reliant on imports. Magnesia and bauxite are of the most interest.

Others noted that the recycling of spent refractories needs to be improved (i.e., quality of scrap, sorting/segregating scrap). Such gains are enabled by sensors to identify refractory types for sorting to appropriate recycling streams. Recycling will also alleviate pressure on materials such as magnesia for refractory production, which is sourced outside the USA.

The development of substitutes for graphite electrodes used in steelmaking is another material R&D need. Graphite is currently the only viable material with the high levels of electrical conductivity and high heat capacity needed to operate in an electric arc furnace; no commercially viable substitutes are currently available.

Increasing the competitiveness and efficiency of domestically produced electrical steels is needed to achieve energy infrastructure savings. This includes for example steels used in electric vehicles, power industry transformers, and raw materials for rare earth magnets used in motors and generators.

Sensors and High-Performance Computing

Buddy Damm briefly described Timken's history as a company focused on producing high-strength and clean steels, both of which can result in energy savings in use. Key supporting technologies include predictive models, which include integrated computational materials engineering (ICME) fatigue analysis, such as the prediction of gear fatigue. Another application is the study of problems caused by liquid metal embrittlement in emerging AHSS.

John Catterall of the Auto/Steel Partnership described the Partnership's technology roadmap and noted interest in the use of ICME for advancing materials with specific properties to address liquid metal embrittlement of AHSS. Non-destructive evaluation techniques for welds and welding simulations are also needed.

Several stakeholders noted that the concept of "Industry 4.0/Digitalization" needs to be fed by data from advanced sensors and process models, thereby enabling high performance computing to be used more fully by the steel industry. A wide variety of steel sensors still need to be developed for:

- Detecting the chemistry of liquid steel in real-time (several under development)
- Detecting the chemistry of solids for sorting of steel plant wastes including scales, sludges and used refractories
- Online determination of weld quality, possibly as part of the welding machine
- Measurement of steel cleanliness

Ben Kowing of SSAB noted other opportunities exist to enhance process performance and efficiency through computing and simulation. Process modeling is needed as well as improvements to measurement technologies, including advanced sensors.

Advanced Technologies for Measuring Performance

Janice Bolen provided insights from Hatch, an engineering company that works mostly with the steel industry. Technologies under development that were highlighted include real-time measurement of molten material composition, digital capabilities to improve performance monitoring, and a plasma blast air heating technology.

Vijay Madi of AK Steel noted several areas of opportunity, including the potential role of information technology for product performance, measurement and control, with interest in high performance computing (HPC) and artificial intelligence (AI). Some of the challenges noted in deployment of AI include modeling and simulation using HPC and read-only memory (ROM); sensor development and integration; process data wrangling and security; and overcoming the limitations of legacy systems.

Flash Ironmaking

Chris Ravenscroft described Berry's role in the advancement of the flash ironmaking technology. Berry was the engineering contractor for the recently completed AMO-funded project (awarded to AISI with activities conducted at the University of Utah). The recent project validated reduction of iron ore fines; and can use natural gas or hydrogen as the reducing agent. This technology could help with transition from blast furnace to EAF in the United States, as metallic iron will still be required. The technology is scalable and can be a site-specific solution. The industry is interested in continuing this project, although the estimated cost for the next phase is significant. Additional public funding could help accelerate implementation of the next phase.

R&D Programs at AISI

Michael Sortwell provided an overview of AISI's collaborative R&D program, including some past successes and insight on current research priorities of its members, notably:

- Advanced Measurement Technologies
- Recycling of Steel Plant Co-products
- CO_2 Reduction

- Additive Manufacturing

Some of the challenges faced when responding to recent AMO funding opportunities were noted, as well as recommendations for the future. Collaboration between the industry and federal agencies that provide R&D funding could be beneficial, and better support national energy and environmental goals.

21st Century Steel – Steel Manufacturers Association (SMA)

Eric Stuart briefly described the Steel Manufacturers Association (SMA) as the North American voice of the EAF steel industry and some of their concerns. The organization facilitates the exchange of information and ideas and promotes public policies that support the global competitiveness of North American steelmakers.

Other Sources

OAK RIDGE NATIONAL LABORATORY (ORNL)

Xin Sun described some of the capabilities and recent activities at ORNL, a National Laboratory supported by the U.S. Department of Energy. ORNL includes user facilities funded by the DOE Office of Science with world-leading high performance computing, modeling and analytics capabilities. National Laboratories also include advanced measurement capabilities for future collaboration.

PURDUE UNIVERSITY NORTHWEST

Chenn Zhou described the technology roadmap of Purdue Northwest’s Center for Innovation through Visualization and Simulation and its Steel Manufacturing Simulation and Visualization Consortium, which has provided digital visualization and “digital twinning” of steelmaking processes with the facilities and expertise on hand to extend this work through many more steelmaking processes.

4. Foundational Technologies and R&D Gaps

A series of questions were posed to gain insights on how the technology and process landscape is expected to change in iron and steelmaking, as well as the need for important ancillary systems and infrastructure (e.g., information technology, training, etc.). These questions are outlined in the text box at right.

A wide spectrum of technologies and R&D gaps were identified, from processing technologies to computing and data analytics platforms and sustainable practices. The results of the moderated discussions have been categorized into three primary areas summarized below. Appendix B provides detailed results from this discussion.

Moderated Questions

- What are the "next big things" and what R&D is needed to enable their development? Which technologies have the greatest potential?
- What are some of the foundational R&D needs to enable breakthroughs and accelerate development of emerging steel product and processing technologies?
- What are the technological needs for cross-cutting capabilities, e.g., high-performance computing (HPC), smart/advanced sensing and controls, modeling/simulation, sustainable manufacturing technologies?

Foundational/Enabling Technologies for Iron and Steelmaking

In foundational and enabling technologies for iron and steelmaking, concepts were focused primarily within two major R&D topic areas including iron and steelmaking, and steel recycling and waste heat recovery. These are summarized below, with additional details provided in Appendix B, Table B-1.

IRON AND STEELMAKING PROCESSES

Advancements related to ***electric arc furnace*** (EAF) steelmaking include alternative electrodes, such as those made from different materials, or non-consumable electrodes. Artificial graphite electrodes are currently the standard in EAF operations. Different (or renewable) methods for supplying electricity are also needed.

Retrofittable and cost-effective heat recovery is one approach for providing heat as well as power; new technologies may be needed to realize heat recovery. This is true for integrated as well as EAF steelmaking.

More efficient application of chemical energy may be one way to alleviate electrode and electricity use in EAF. Multi-physics, multi-scale and multi-phase reacting flow models for the EAF process are also needed. Flash Ironmaking was noted as one technology that could help companies transition from the blast furnace to EAF. It requires metallic iron and is scalable.

Research needs for ***hydrogen-based iron and steelmaking*** include acceleration of hydrogen-based processes currently under development. Hydrogen (instead of coal) can be used for the direct reduction of iron oxide/ore and when combined with an electric arc furnace (EAF) or in integrated steelmaking, the process can be nearly fossil-free. Ancillary but critical issues for H_2-based steel include lowering the cost of delivered hydrogen and improving the hydrogen distribution infrastructure.

Advances in ***ironmaking processes and inputs*** include a broad exploration of all ironmaking options with emphasis on low-cost solutions, including economically viable and scalable hydrogen-based iron and direct reduced iron (DRI). DRI (also called sponge iron) is produced by direct reduction of iron ore to iron by a reducing gas or elemental carbon produced from natural gas or coal. There are still technical and economic hurdles to making hydrogen-based DRI that need to be addressed.

There is also a need to explore synthetic materials to replace or enhance natural mined materials for use in ironmaking. The use of recycled plastics in integrated or H_2-based steelmaking is another potential topic for exploration.

STEEL RECYCLING AND WASTE HEAT RECOVERY

Various advancements are needed in ***steel recycling***. These include, for example, sensors for recycling/sorting for steel plant wastes, including refractories. In general, there is a need to explore many types of recycling processes to enable reuse and recovery of all parts of the steel product as well as byproducts. An example is recycling of steel plant co-products to reduce or eliminate product components going to landfills. Other possibilities are reformation of slag and other byproducts into light construction aggregates and process off-gas recycling (argon and hydrogen).

Effective use of ***waste heat recovery*** could reduce energy use and associated costs. Efficient technologies at a realistic capital investment for the use of low-grade waste heat needs to be explored. There is a need to understand how to best co-locate waste heat sources and sinks and devise strategies for using waste heat sources.

Cross-cutting Foundational/Enabling Technologies

In cross-cutting foundational and enabling technologies, concepts focused primarily under three R&D topic areas including carbon capture and storage, properties testing and characterization, and sensors and analytics. These are summarized below, with additional details provided in Appendix B, Table B-2.

CARBON CAPTURE AND STORAGE

Several areas for research were identified for carbon capture and storage. One is fully integrating steelmaking, carbon capture processes, heat integration and synthesis, and production of value-added products. For example, an integrated process might include capturing carbon to make useful products such as formic acid that can be used in pickling or producing calcium carbonate from CO_2. Research may be needed to improve the reformation efficiency of calcium to optimize carbon capture from $CaCO_3$. Another area of research includes developing general solutions for carbon storage and infrastructure that could be applied more universally (but also in steel).

From a sustainability perspective, there is interest in understanding the life cycle of steel in terms of how it impacts greenhouse gases (GHG) in other sectors. Broader research topics might encompass advanced ‘coal to carbon’ technology where the carbon in coal is used to manufacture useful high value products (rather than using coal strictly for energy).

PROPERTIES TESTING AND CHARACTERIZATION

Properties testing and characterization advancements include pushing the boundaries of ICME to develop next generation products. This requires better validated chemistry and process properties models and data, as well as understanding fundamental properties mechanisms such as liquid metal embrittlement in AHSS.

Other testing/characterization technologies include development of online chemistry sensors, and non-destructive evaluation (NDE) technologies for quality assessment. An example of NDE is testing of welds. Studies and technologies are needed to check weld quality in real-time, non-destructively, possibly even in the weld machine. In general, research is needed to ensure development of accessible, affordable in-house testing and characterization tools.

SENSORS AND ANALYTICS

Sensor and analytic advancements include more robust sensors for operating in harsh steelmaking process environments, soft sensors that support simulations and visualization, and AI for steelmaking to link in-situ measurements. Digital twins (where a multi-dimensional digital representation of the equipment is created) have great potential for creating tools for modeling of steelmaking processes. These require the use of visualization tools as well as computational fluid dynamic modeling and failure analysis models – combined with high performance computing (HPC).

Workforce and Collaboration Needs

Workforce, training, and productive cost-effective collaborations are all important to a growing and vibrant steel industry. Some key issues within each area are outlined below. Details of discussions are provided in Table B-3.

WORKFORCE AND EDUCATION

Within workforce, discussion focused on skills and educational needs, augmenting workers through the use of with technology, and outreach to the public to raise awareness of the steel industry as an attractive employment environment. Greater training and development of metallurgy and digital skills is needed to better equip the industry workforce. Training can include new virtual tools, internships, curricula development, and promotional materials.

COLLABORATIONS

Within collaboration, discussion focused on leveraging DOE national laboratories and their capabilities and expertise in AI and machine learning. User facilities at national laboratories could help to perform steel characterization tests and support accelerated insertion of new materials. An Accelerated Insertion of Materials (AIM)-type effort for steel technology would greatly benefit the industry. This would enable testing of specific materials for applications and accelerate commercial use.[3]

In general, there is a need for more pilot and near-commercial demonstration scale activities to help in moving newly developed technologies into practice. Additional details are provided in Appendix B, Table B-3.

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[3] The AIM program is a strategic initiative spearheaded by the U.S. Defense Advanced Research Projects Agency and the Office of Naval Research. The AIM program initiative created a new materials development methodology to accelerate the insertion of new materials to achieve parity with development/design cycles.

Appendix A: Agenda

Steel Industry Roundtable

American Iron and Steel Institute

25 Massachusetts Ave, NW, #800, Washington, DC

November 6, 2019

Time	Activity
10:00 AM – 10:30 AM	**Welcome** • EERE AMO – Introduction and Objectives (Isaac Chan, U.S. Department of Energy) • Progress since 2015 Roundtable
10:30 AM – 12:15 PM	**Overview of Steel Industry Stakeholder Research Priorities – Steel Representatives** • Representatives provide 10-minute overview of organization's perspective on advanced steel technologies needed in the future *(PowerPoint slides preferred)*
12:15 PM – 1:15 PM	**Light Lunch and Refreshments (Provided by AISI)**
1:15 PM – 2:30 PM	**R&D Gaps and Opportunities** *Facilitated Discussion* What are the Next Big Things and what R&D is needed to enable their development? Which technologies have the greatest potential? *Steel Product/Processing Technologies* • What are some of the foundational R&D needs to enable breakthroughs and accelerate development of emerging steel product and processing technologies? ***Cross-Cutting Capabilities*** • What are the technological needs for cross-cutting capabilities, e.g. High-Performance Computing (HPC), smart/advanced sensing and controls, modeling/simulation, sustainable manufacturing technologies?
2:30 PM – 2:45 PM	**General Understanding of Top R&D Needs** *Facilitated Discussion* Have we identified/covered the most important technology needs?
2:45 PM – 3:00 PM	**Next Steps and Adjourn**

Appendix B. Summary of Results

Table B-1. Foundational/Enabling Technologies for Iron and Steelmaking

Electric Arc Furnace

- Non-consumable electric arc electrodes/ substitutes
- EAF heat recovery – retrofittable and cost-effective solutions
- More efficient application of chemical energy in EAF processes to alleviate electrode and electric usages

Steel Recycling & Waste Heat Recovery

- Capital expenditure-efficient low-grade waste heat use
- Waste heat use from other processes
- Recycling/sorting sensors or technology for steel plant wastes and refractories
- Reformation of slag and other byproducts into light construction aggregates
- Overall recycling – all parts of the products/ byproducts
- Recycling of steel plate co-products (i.e., no products to landfill)
- Recycling of H_2 and argon in process

Hydrogen-Based Iron and Steelmaking

- Hydrogen distribution, infrastructure, and transportation
- Lowest cost hydrogen delivered to the steel mill
- Accelerate hydrogen-based processes currently under development

Iron and Steelmaking Processes

- Low-cost solutions, economically viable and scalable H_2-based iron
- Ironmaking – all forms – exploration of all options
- Synthetic materials to replace/enhance natural (mined) materials
- Use of recycled plastics in H_2-based steelmaking

Table B-2. Cross-Cutting Foundational/Enabling Technologies
Carbon Capture and Storage
• Developing carbon storage solutions and infrastructure • Calcium reformation efficiency to optimize carbon dioxide capture in $CaCO_3$ • Carbon capture to make formic acid; the acid can be used for pickling steel • Advanced 'coal to carbon' technology (not coal to energy) • Integrated steelmaking/carbon capture processes/value added products, with heat integration and synthesis • Analysis of how steel's use in other sectors impacts greenhouse gases (GHG) in those sectors
Properties Testing and Characterization
• ICME: validated chemistry/process properties models and data • Using ICME: Understanding fundamental mechanisms of liquid metal embrittlement in third generation AHSS and all steels; expand ICME in general (requires HPC) • Online chemistry sensors and funding for plant trials • Multi-physics, multi-scale, multi-phase reacting flow models for EAF • Study and technologies to check spot weld quality in real time, possibly in the weld machine; address NDE needs and develop models • Accessible, affordable, in-house characterization tools and models
Sensors and Analytics
• Sensors – robust to withstand steelmaking processes: high temperature, continuous, and with energy savings • Soft Sensors: simulations (using computational fluid dynamics and finite element analysis) and visualization plus big data (digital twins); creating realistic digital twins of steelmaking processes • AI for steelmaking – linking in-situ measurements at different stages for final product performance and equipment maintenance

** Notes: Direct reduced iron (DRI), also called sponge iron, is produced from the direct reduction of iron ore (in the form of lumps, pellets, or fines) to iron by a reducing gas or elemental carbon produced from natural gas or coal. Many ores are suitable for direct reduction.*

Table B-3. Workforce and Collaboration Needs

Workforce and Education

- Augmented workers (robotics, virtual reality)
- Workforce development (virtual training, internships, curriculum, promotional materials)
- People development – metallurgy and digital skills
- Educate the public (address not-in-my-backyard attitude)

Collaborations

- Leverage National Laboratory AI and machine learning experts for steel applications
- User facility at National Laboratory capable of performing all steel characterization tests for simulation and material models
- National Laboratory assistance with additive manufacturing
- Development of a DOE-AISI user facility to support accelerated insertion of materials (e.g., DOE/AISI AIM)
- DOE support for pilot and near-commercial scale deployment
- DOE study whether H_2 fuel cells in cars or H_2-based ironmaking yields greater energy savings

Appendix C. List of Roundtable Participants

Name	Organization
Mark Atkinson	ArcelorMittal USA
Paul Balserak	American Iron and Steel Institute
Philip Bell	Steel Manufacturers Association
Janice Bolen	Hatch
John Catterall	Auto/Steel Partnership
Isaac Chan	DOE Advanced Manufacturing Office
Martha Collins	Harbison Walker International
E. Buddy Damm	Timken Steel
Kevin Dempsey	American Iron and Steel Institute
Tom Dower	ArcelorMittal USA
Thomas Gibson	American Iron and Steel Institute
Chris Hovanec	DOE Advanced Manufacturing Office
Keith Jamison	Energetics
Lawrence Kavanagh	Steel industry consultant
Ben Kowing	SSAB Americas
Nick Lalena	Redhorse (DOE Advanced Manufacturing Office, onsite contractor)
Jay Larson	American Iron and Steel Institute
Vijay Madi	AK Steel Research and Innovation Center
Tommi Makila	Energetics (DOE Advanced Manufacturing Office, onsite contractor)
Francesco Memoli	Tenova Inc.
Theresa Miller	Energetics (DOE Advanced Manufacturing Office, onsite contractor)
Joan Pellegrino	Energetics
Chris Ravenscroft	Berry Metal Company
Tom Richter	Harbison Walker International
Steve Sikirica	DOE Advanced Manufacturing Office
Brett Smith	American Iron and Steel Institute
Michael Sortwell	American Iron and Steel Institute
Eric Stuart	Steel Manufacturers Association
Xin Sun	Oak Ridge National Laboratory
David Werner	Berry Metal Company
Travis Wheeler	Office of Congressman Pete Visclosky
Chenn Zhou	Purdue University Northwest

Appendix D. List of Acronyms

AHSS	Advanced high strength steels
AI	Artificial Intelligence
AIM	Accelerated Insertion of Materials
AISI	American Iron and Steel Institute
AMO	Advanced Manufacturing Office (of the Department of Energy)
$CaCO_3$	Calcium carbonate
CO_2	Carbon dioxide
DOE	U.S. Department of Energy
DRI	Direct reduced iron
EAF	Electric Arc Furnace
EERE	Office of Energy Efficiency and Renewable Energy
GHG	Greenhouse gases
H_2	Hydrogen
HPC	High performance computing
ICME	Integrated computational materials engineering
NDE	Non-destructive evaluation
ORNL	Oak Ridge National Laboratory
R&D	Research and development
RD&D	Research, development and demonstration
SMA	Steel Manufacturers Association

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