

Industrial Decarbonization Roadmap, Part 2, Iron & Steel

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October 2022

1. Introduction

The first part of this post is described and linked below:

Industrial Decarbonization Roadmap, Part 1, Overview: Occasionally I come across a document that is overwhelming in scope and information-content. This requires me to adjust how I post papers based on this document if it falls within the scope of subjects that I normally write about and contains information my readers would want to read. The DOE Industrial Decarbonization Roadmap is one of those documents. It also covers subjects that I spent far more time researching and writing about several years ago, than I do currently.

I decided pretty quickly that this would require multiple papers to cover, and thus a series. I will start with this post, and post other papers in this series as I complete them. These will be interleaved with other posts covering other subjects, but all parts of this series will start with “Industrial Decarbonization Roadmap.”

<https://energycentral.com/c/cp/industrial-decarbonization-roadmap-part-1-overview>

Part 2 is about Iron and Steel Production Industries. I intend start with the primary document (referenced at the end of this paragraph), and also use prior posts as they interject useful information into the narrative.¹

In this case I have previously posted three papers on the iron and steel industries. I reference the most recent two of these in the body of this paper.

2. Paths to Decarbonization

The crosscutting decarbonization pillars identified in this work are energy efficiency, industrial electrification, low-carbon fuels, feedstocks, and energy sources (LCFFES) from non-fossil fuel or low-carbon emitting sources, and carbon capture, utilization, and storage (CCUS), where electrification and LCFFES are highly connected and evaluated together for this roadmap. There is a range of iron and steel products and some adaptation of how the pillars are applied across the products and the facilities that are tailored to make them may be relevant. The amount of carbon and how it is used to attain the desired performance characteristics would be the focus of these adjustments. The source of the carbon and transitioning to lower-carbon sources would be an end goal. Improving technologies to recover the carbon as part of recycling or reuse efforts would also be part research development and demonstration (RD&D) challenges that need to be considered. There are several approaches in various stages of development and commercialization that could be considered. While a review of those methodologies is outside the scope of this work, the reader is referred to the literature for additional

¹ Full List of authors, reviewers and supporting groups is contained on this document’s front-matter pages xi -- xiv, U.S. Department of Energy, “Industrial Decarbonization Roadmap,” September 2022, <https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf>

information.² Managing the carbon and managing its GHG emissions impact is the goal, not eliminating the carbon, as it is vital to the performance of products.

The U.S. steel industry produced 87 million metric tons (MT) of crude steel in 2018, of which 33% was produced by primary steelmaking plants using blast furnace-basic oxygen furnace (BF-BOF) and 67% was produced by the electric arc furnace (EAF) production route (typically called secondary steelmaking), which mainly uses steel scrap but can also use direct reduced iron (DRI).³ The United States also imported 31 million MT and exported 8 million MT of steel mill products in 2018.

The value of products produced by the U.S. iron and steel industry and ferrous foundries in 2018 was about \$137 billion.⁴ The U.S. BF-BOF plants that produced pig iron and crude steel as of 2018 were operated by three companies with integrated steel mills in nine locations.³ Also in 2018, EAF steel plants were owned by 51 companies producing crude steel at 99 minimills.⁵

BF-BOF and EAF steel plants together employed around 81 thousand people, and iron and steel foundries employed an additional 64 thousand people in the United States in 2018. Indiana accounted for 27% of total crude steel production, followed by Ohio (12%), Michigan (6%), and Pennsylvania (6%). The construction subsector is the largest consumer of steel in the United States (43%) followed by transportation, predominantly the automotive industry (27%), machinery and equipment (10%), the energy sector (7%), appliances (5%), and other consumers (8%). Overall, U.S. steel production has been declining in the past two decades (Figure 11, next page).

The key message from Figure 11 (next page) is that electric arc furnaces (EAF) have been growing their share of manufacturing for at least two decades, and now are the dominant technology.

2.1. Energy Use and GHG Emissions

Iron and steel manufacturing is one of the most energy-intensive industries worldwide. In addition, the use of coal as the primary fuel and feedstock for the chemical reduction of iron oxide, coupled with the sheer volume of iron and steel produced, means the industry has among the highest GHG emissions of any industry. The iron and steel industry accounts for around a fifth of industrial energy use and about a quarter of direct industrial GHG emissions in the world.⁶ Iron and steel production accounts for over 7%

² Zhiyuan Fan and S. Julio Friedmann, “Low-carbon production of iron and steel: Technology options, economic assessment, and policy,” *Joule* 5, no. 4 (April 2021): 829-862.

<https://www.sciencedirect.com/science/article/pii/S2542435121000957>

³ Cris Candice Tuck, 2018 Minerals Yearbook: Iron and Steel [Advance Release], U.S. Geological Survey, October 2021, <https://pubs.usgs.gov/myb/vol1/2018/myb1-2018-iron-steel.pdf>

⁴ Christopher A. Tuck, Iron and Steel Statistics and Information, Minerals Commodity Summaries, U.S. Geological Survey, February 2019, <https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/atoms/files/mcs-2019-feste.pdf>

⁵ Steel mills that produce steel using scrap and directly reduced iron (DRI) via an electric arc furnace (EAF) are commonly called minimills.

⁶ International Energy Agency, Iron and Steel Technology Roadmap, October 2020, <https://www.iea.org/reports/iron-and-steel-technology-roadmap>

of global GHG emissions. Additionally, steel production generates significant air pollutants (such as sulfur dioxide, nitrous oxide, or non-methane volatile organic compounds), which contribute to adverse health effects and can negatively impact their local communities (typically in low-income, disadvantaged communities).⁷ These air pollutants should be considered alongside GHG emissions as the steel industry decarbonizes.

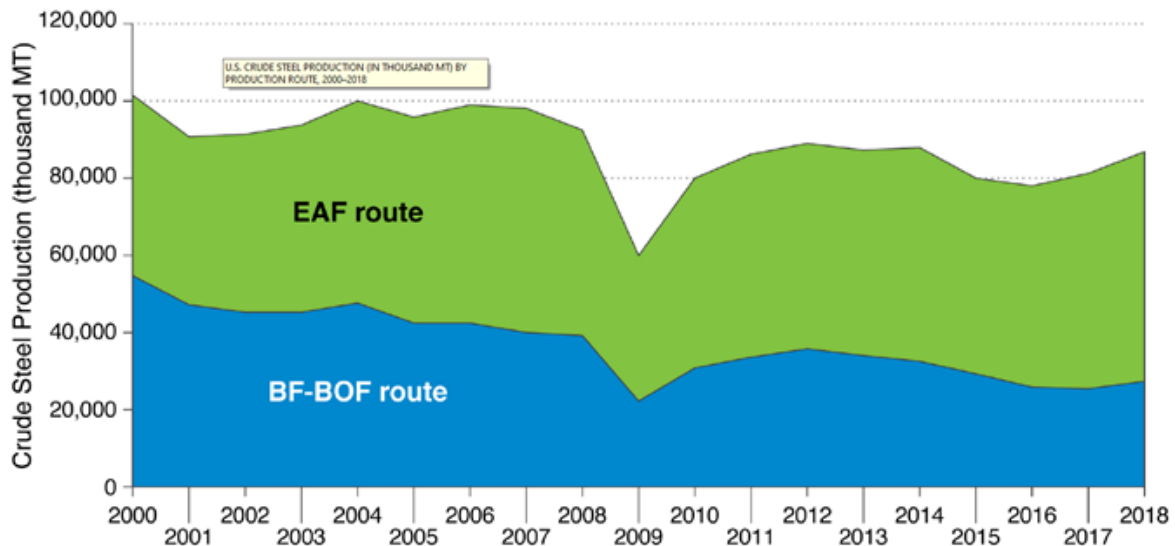


FIGURE 11. U.S. CRUDE STEEL PRODUCTION (IN THOUSAND MT) BY PRODUCTION ROUTE, 2000–2018¹²⁷

The U.S. steel industry accounted for around 8% of total fuel used in the U.S. manufacturing sector in 2018.⁸ ... Natural gas had the largest share and accounted for 37% of the U.S. steel industry's final energy use in 2018. This is significantly higher than many other countries where coal is the dominant fuel used in the steel industry...

A recent study⁹ conducted benchmarking of the energy intensity and CO₂ emissions intensity of the U.S. iron and steel industry against that of the steel industry in 15 other major steel-producing countries/regions. Figure 13 shows the CO₂ emissions intensity of the steel industry in these countries/regions.¹⁰

⁷ Ali Hasanbeigi, Navdeep Bhadbhade, and Ahana Ghosh, Air Pollution from Global Steel Industry: An International Benchmarking of Criteria Air Pollutants Intensities, August 2022, <https://www.globalefficiencyintel.com/air-pollution-from-global-steel-industry>

⁸ "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data," U.S. Energy Information Administration, released 2021, <https://www.eia.gov/consumption/manufacturing/data/2018/> See Table 3.2. Energy Consumption as a Fuel By Manufacturing Industry and Region

⁹ Ali Hasanbeigi, Steel Climate Impact: An International Benchmarking of Energy and CO₂ Intensities, Global Efficiency Intelligence, April 2022, <https://www.globalefficiencyintel.com/s/Steel-climate-impact-benchmarking-report-7April2022.pdf>

¹⁰ These values include Scope 1, Scope 2, and imported pig iron/DRI emissions.

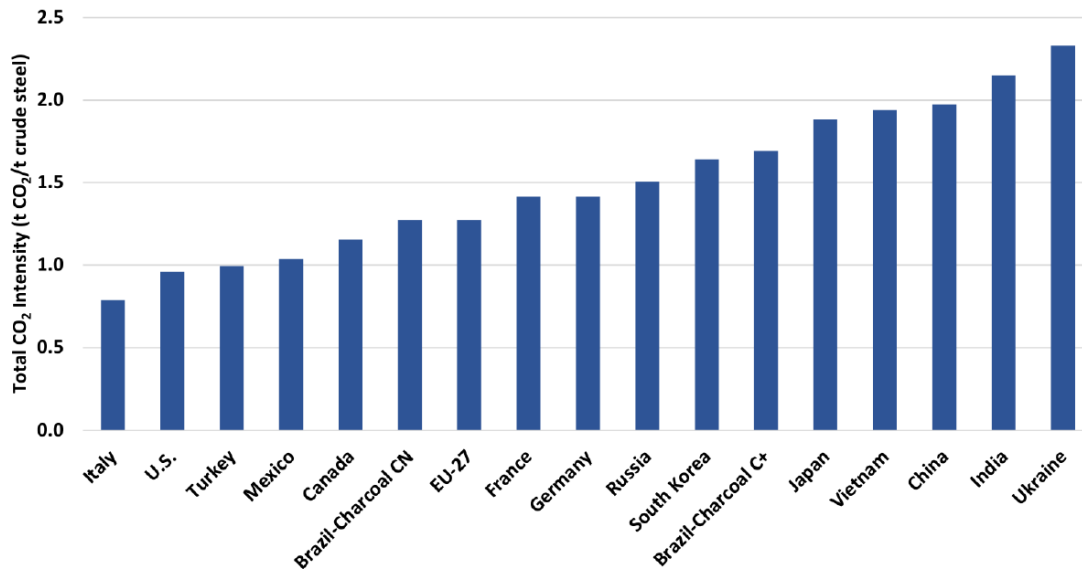


FIGURE 13. TOTAL CO₂ EMISSIONS INTENSITY OF THE STEEL INDUSTRY IN 16 COUNTRIES/REGIONS IN 2019.¹³⁹

Author's comment: A main reason that the U.S. is doing so well in the above comparison is that we aggressively recycle steel. See the section 3 in prior post referenced below.

I Like Smoke & Lightning, Heavy Metal Thunder, Part 2: This paper is the second in a series about the metals industrial subsector, how these industries use energy and how they are evolving.

<https://energycentral.com/c/ec/i-smoke-lightning-heavy-metal-thunder-part-2>

Some of the key factors influencing the energy and carbon intensity of the steel industry include:

- *Share of electric arc furnaces (EAF, a.k.a. minimills) steel in total steel production:* The EAF process uses steel scrap to produce steel and is less energy and carbon intensive. A higher share of EAF steel production would lead to a lower overall steel industry energy intensity in a country.
- *Fuel shares in the iron and steel industry:* Natural gas has a significantly lower emissions factor per unit of energy compared to coal and coke which are the primary type of energy used in the steel industry in many countries (e.g., China and India). The higher share of natural gas used in the United States, Mexico, and Canada has helped to lower the CO₂ emissions of BF-BOF steel production in these three countries.
- *Electric grid GHG emissions factor:* The fuel mix for power generation in a country, and as a result the emissions factor of the grid (kg CO₂/kWh), plays an important role when comparing the CO₂ emissions of the iron and steel industry with other countries.
- *Blast furnace-basic oxygen furnace (BF-BOF) and EAF feedstock types:* The overall energy and carbon intensity of EAF steel production changes depending upon the type of feedstocks in EAFs (scrap steel vs. DRI vs. pig iron). The DRI (sponge iron) and pig iron production processes are highly energy and carbon intensive, which results in higher energy use and CO₂ emissions for EAF

operations when used as feedstock materials in EAFs. In the case of BF-BOF, the quality of iron ore (iron content, impurities, etc.) influences the energy use and carbon intensity of steel production.

- *Penetration level of energy efficient technologies: Energy efficiency technologies such as coke dry quenching (CDQ) for the coking process, top-pressure recovery turbines (TRTs) for blast furnaces, pulverized coal injection, and continuous casting help to reduce the energy and carbon intensities of BF-BOF steel production. The penetration of these technologies in different countries is different.*
- *Each country's steel product mix: Different steel products have different energy requirements in the rolling, casting, and finishing processes. Therefore, the product mix could influence the CO₂ intensities in different countries.*
- *Steel manufacturing facility age in each country: Even though basic oxygen furnace (BOF) vessels in the United States have been relined and other upgrades have been made, they are overall older than most of the steel production facilities in China and therefore could be less energy-efficient than the Chinese facilities.*
- *Capacity utilization: Higher capacity utilization improves overall energy and carbon performance compared to lower capacity utilization if all other factors remain constant. Since it takes a long time and is costly to shut down and restart blast furnaces, operators avoid shutting down for short periods and instead reduce production rates so that the BF's continue to work at less than full capacity. This impacts their energy and carbon intensity.*
- *Environmental regulations: Environmental regulations can affect industry CO₂ emissions by incentivizing different operational and equipment choices. At the same time, the operation of some pollution control equipment requires additional energy, which can add CO₂ emissions.*
- *Energy and raw materials cost: Changing energy and materials sources to optimize costs can affect the CO₂ and energy intensities of a plant.*
- *Steel industry boundary definitions (i.e., which inputs and intermediary products are included in the analysis and whether the embodied energy and carbon in those products are included in the analysis): For example, some countries may report the energy use of the coke-making within the steel industry while some others may report it separately.*

2.2. Decarbonization Pathways

To understand how the application of the decarbonization pillars (energy efficiency, industrial electrification, low-carbon fuels, feedstocks, and energy sources (LCFFES), and carbon capture, utilization, and storage (CCUS)) could help phase out net GHG emissions, the potential GHG emissions reductions possible for the steel industry were examined. This work was also pursued to provide guidance on where research, development, and demonstration (RD&D) could significantly enable reductions. The topics of where to start on reductions, the relative impact of the decarbonization pillars, and priorities for RD&D were also of common interest across the stakeholder meetings. The scenarios used are described in Part 1 of this series.

For this work, DOE forecasted the CO₂ emissions of the U.S. steel industry to 2050. For the business as usual (BAU) scenario, the CO₂ emissions of the U.S. steel industry

decreases by 37% between 2015 and 2050, primarily driven by a decrease in the U.S. electric grid CO₂ emissions factors. As already mentioned, around 67% of U.S. steel is produced by EAF and most of the energy used in EAF is electricity. In the Advanced scenario, the CO₂ emissions of the steel industry decreases by 80% from 86 million MT CO₂ per year in 2015 to 17 million MT CO₂ per year in 2050. The drop is mainly because of the increased share of EAF steel production and substantial decarbonization of the U.S. electric grid in addition to the adoption of CCUS technologies. This decrease in emissions occurs while U.S. steel production increases by 12% during the same period to meet the needs of a growing population and expanding economy. In the Near Zero GHG scenario, the most ambitious assumptions were made across all the decarbonization pillars (energy efficiency, industrial electrification, LCFES, and CCUS) to get the U.S. steel industry's CO₂ emissions to near zero.

To achieve Near Zero GHG scenario results, in addition to ambitious deployment of current commercialized technologies, more-ambitious RD&D is needed by public and private sector entities, especially to make substantial adoption of transformative and CCUS technologies possible in the steel industry. These are discussed in detail in the following section on RD&D needs and opportunities.

Several factors contribute to the realization of significant CO₂ emissions reductions in the Near Zero GHG scenario. Figure 15 shows the contribution of each of the decarbonization pillars to the reduction of the U.S. steel industry's CO₂ emissions between 2015 and 2050. It should be noted that the impact of electrification includes the reduction in electric grid CO₂ emissions. DOE assumed less than 10% of the steel will be produced by BF-BOF process in 2050 under Near Zero GHG scenarios. In this scenario, most steel will be produced by scrap-based EAF and a small portion with hydrogen-based DRI-EAF process and electrolysis of iron ore process. Because all these processes are electricity-intensive, the U.S. electric grid CO₂ emissions and its projection to 2050 significantly influence the CO₂ emissions projection results under the electrification and LCFES pillars. Further research is needed to understand how the transition to low-carbon energy generation in the electrical grid will impact industrial decarbonization.

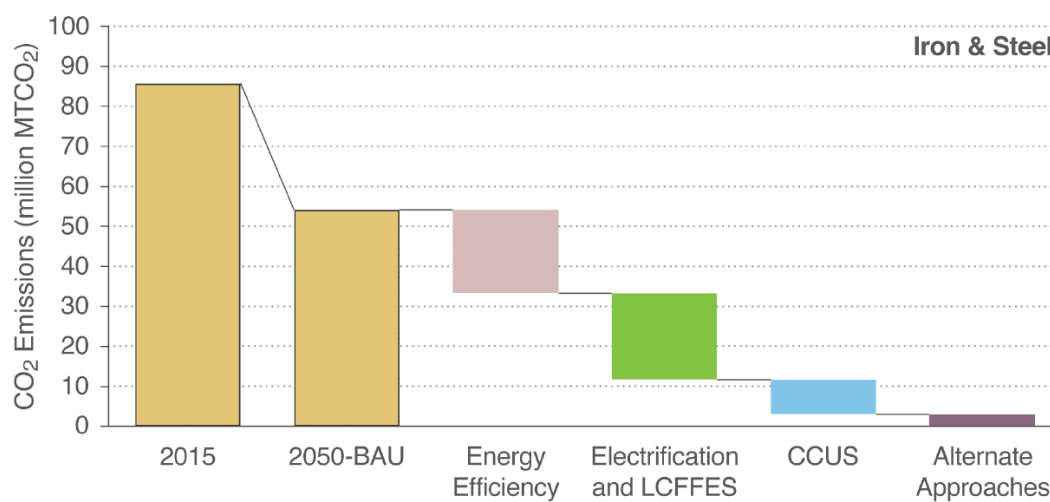


FIGURE 15. IMPACT OF THE DECARBONIZATION PILLARS ON CO₂ EMISSIONS (MILLION MT/YEAR) FOR THE U.S. IRON & STEEL INDUSTRY, 2015–2050.

2.3. RD&D Needs and Opportunities

This section explores the research development and demonstration (RD&D) challenges and opportunities of the decarbonization pillars (energy efficiency, industrial electrification, LCCFES, and CCUS) and what should be the priority approaches. The technologies covered in this section represent a wide range of technological maturity and market readiness. Figure 16 maps steel decarbonization technologies along these axes...

Author's comment: The rest of this subsection seemed to jump ahead in the narrative. Each of the applicable “pillars” are explored in the following subsections, so, hopefully we will put together a reasonable description of our path there.

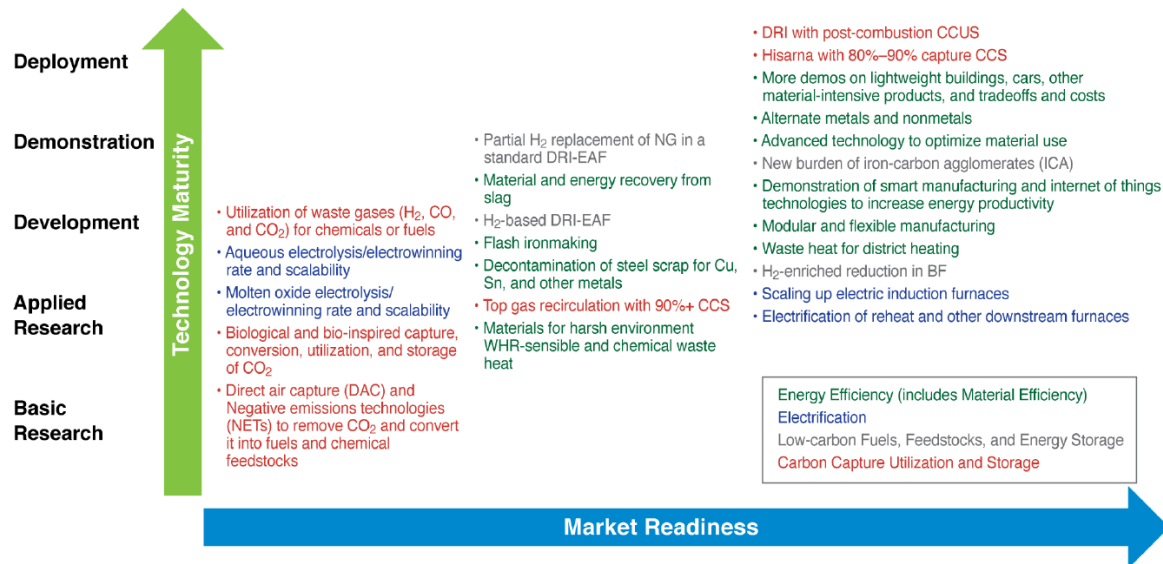


FIGURE 16. TECHNICAL MATURITY LEVELS OF SELECT DECARBONIZATION TECHNOLOGIES DISCUSSED DURING ROADMAP VIRTUAL MEETINGS FOR THE U.S. STEEL MANUFACTURING INDUSTRY.

2.3.1. Energy Efficiency

Because energy efficiency technologies could reduce—but not eliminate—GHG emissions, other decarbonization technologies and strategies are needed. There are many energy efficiency technologies and the World Steel Association estimates there is a significant potential for a further reduction in energy intensity for the global steel industry.¹¹ However, challenges with the deployment of these technologies remain, and RD&D could help address them. A 2010 energy efficiency and cost savings guide¹² describes a list of commercialized energy efficiency measures and technologies for the iron and steel industry and a 2013 report¹³ describes 56 emerging technologies for energy efficiency improvement in the steel industry.

¹¹ ArcelorMittal, Climate Action Report 1, May 2019, https://corporate-media.arcelormittal.com/media/hs4nmyya/am_climateactionreport_1.pdf

¹² Ernst Worrell et al., Energy Efficiency Improvement and Cost Saving Opportunities for the U.S. Iron and Steel Industry: An ENERGY STAR Guide for Energy and Plant Managers, Lawrence Berkeley National Laboratory, 2010, <https://doi.org/10.2172/1026806>

¹³ Ali Hasanbeigi, Lynn Price, and Marlene Arens, Emerging Energy Efficiency and Carbon Dioxide Emissions-Reduction Technologies for the Iron and Steel Industry, Lawrence Berkeley National Laboratory, BNL-6106E, January 2013, <https://eta-publications.lbl.gov/sites/default/files/6106e-steel-tech.pdf>

Energy efficiency technologies that are either already available or will be available in the next few years include various measures to optimize the blast furnace, such as reducing the coke rate through pulverized coal injection or using coke dry quenching to promote heat recovery. Alternative injection materials to pulverized coal could also be used, such as hydrogen. And the use of such alternatives would decrease the emissions associated with the coking process and improve the performance of conventional blast furnaces. For such technologies, the primary barriers are economic.

Waste heat and gas recovery (WHR) could also benefit from RD&D. Coke gas, blast furnace gas, and furnace gas can be recycled back into the process or be used to produce hot water, steam, and electricity. For commercialized WHR technologies, the primary challenge is economic viability. There is also room for technological advancement of WHR, such as developing materials for application in harsh environments. RD&D could drive innovation in phase-stable materials, functional surfaces, and embrittlement-resistant materials that can resist material aging effects. There could also be WHR from oxy-fired rehear furnaces. Also, RD&D is needed to reduce the initial investment cost for waste heat to power (WHP) systems, such as organic Rankine cycle and supercritical CO₂ power cycles.

Cutting-edge technologies could assist with energy management systems, drawing from smart manufacturing and the Internet of Things; such technologies include predictive maintenance and machine learning or digital twins to improve process control. More RD&D could scale-up and adapt these technologies for use by steel plants.

RD&D for energy efficiency should focus on the economic feasibility of these technologies by demonstrating potential costs and benefits to plant managers. Attention to systems efficiency and strategic energy management is vital for continuous improvements in energy efficiency. RD&D could cover both analytical work, such as better characterizing the energy saving potential of different technologies and combinations of technologies, as well as practical tools that could help plant managers simulate and understand energy efficiency opportunities. However, as noted earlier it is important that additional cutting-edge low-emissions technologies are developed to further reduce GHG emissions.¹⁴

2.3.2. Electrification, Low-Carbon Fuels, Feedstocks, & Energy Sources

Several fuels can replace coal or petroleum coke as a reducing agent in the smelting process. These alternative fuels include natural gas, biomass, or biogas, and on a longer time horizon, hydrogen. The use of natural gas and charcoal already represents commercialized technologies for use in steel production.

RD&D could help map timelines for switching to fuels with lower-carbon footprints, such as using natural gas and biomass in the short-term as transition fuels to a longer-term option (i.e., hydrogen). And research could identify just how much hydrogen could be used in existing BF-BOF and DRI-EAF facilities.¹⁵

¹⁴ Energy Transitions Commission, Mission Possible: Achieving Net-Zero Carbon Emissions from Harder-to-Abate Sectors, November 2018, <https://www.energy-transitions.org/publications/mission-possible>

¹⁵ Chris Bataille, Low and Zero Emissions in the Steel and Cement Industries: Barriers, Technologies, and Policies, (paper presented at OECD Green Growth and Sustainable Development Forum, Paris, November 26-27, 2019), https://www.oecd.org/greengrowth/GGSD2019_Steel%20and%20Cemement_Final.pdf

More RD&D on preparing agricultural waste for use in blast furnaces is also needed, including economic considerations, such as resource constraints and availability for different plants. Biomass may only be feasible for certain plants in specific locations, and more research needs to be done on the availability and life cycle impacts of local biomass resources. Also, there could be benefits of using biochar in a blast furnace, such as a reduction in harmful gases from the combustion that occurs in an incinerator.

2.3.2.1. Process Heat Electrification

Globally, the main pathway to the electrification of the steel industry is the use of EAF—not BF-BOF—steel production. In the United States, however, over 67% of the steel is already produced by EAFs and limited opportunity remains for increased use of EAF technology. Another major pathway to electrification is the use of hydrogen that is produced from near zero emissions energy (e.g., renewable or nuclear), instead of natural gas in direct reduced iron (DRI) production and the electrolysis of iron ore; these two emerging technologies are discussed in Sections 2.3.2.2 (Hydrogen DRI-EAF) and 2.3.2.3 (Electrolysis of Iron Ore) respectively.

Several different process heating pathways in steel production could be decarbonized by switching to low-carbon electricity. Reheating furnaces could be electrified, and electric induction furnaces could be scaled up. Ladle and tundish heating could be switched to resistance, infrared, or plasma heating. There could also be reallocation or onsite generation of low-carbon electricity for secondary steel plants.

Electrification of these processes presents several technical challenges. For example, the production environment has many corrosive gases that could result in frequent failure of electrical heating equipment. For reheating equipment, switching from fuel-fired burners to an induction heater might only work for thin slabs or billets with current technologies, and plants might need some significant redesign to electrify this process, which requires temperatures over 2,000°F (1100°C).

Scale-up of technology to meet demand and the high capital cost involved are the biggest barriers to implementing electro-technologies in the iron and steel industry. Though many of the technologies under consideration perform well for small-scale applications, systems that can process a million MT of steel per year using electrolysis of iron ore are not yet as economical as traditional systems, given the high capital cost. Large-scale testing and process optimization are needed to improve operational efficiency and bring down costs before such technologies could be adopted.¹⁶ More RD&D is needed to improve furnace design so that resistance heating can be scaled up in batch and continuous furnaces. Given that electrification will increase electricity demand, RD&D could investigate the best ways to meet the capacity needs of industrial zones or clusters where high-voltage electricity transmission infrastructure can deliver electricity for steel production. Also, some emerging technologies could save energy and materials for steel galvanizing and heat treatment...

2.3.2.2. Hydrogen DRI-EAF

Hydrogen, especially low-carbon hydrogen, can be used in several ways to decarbonize steel production. In addition to its potential to produce heat when burned as fuel,

¹⁶ Kiran Thirumaran et al., “Energy Implications of Electro-Technologies in Industrial Process Heating Systems,” (paper presented at ACEEE Summer Study on Energy Efficiency in Industry, Portland, Oregon, August 12-14, 2019), <https://www.osti.gov/servlets/purl/1564150>

hydrogen can be used as an alternative reductant to produce iron that is then processed into steel in an EAF. One of the most advanced pathways to iron refining with hydrogen is known as direct reduction with iron (DRI) and is already commercial with natural gas and in demonstration stages with hydrogen internationally.

Author's comment: See subsection 2.2 in the prior post described and linked below. This describes a Pilot Plant in the EU that is using green hydrogen for producing DRI. The graphic below is the world's first greenhouse gas free steel produced in the HYBRIT pilot plant in Luleå, Sweden. Section 2.2 in the post below covers the process used to produce this, which is basically the same process covered by this subsection.

I Like Smoke & Lightning, Heavy Metal Thunder, Part 3: *This post is the third in the series. This series is about the metals subsector, and more specifically this post, is about the Iron and Steel Mills and Ferroalloy Manufacturing Industry Group.*

<https://energycentral.com/c/ec/i-smoke-and-lightning-heavy-metal-thunder-part-3>



A plant in Oxelösund produces the world's first fossil-fuel-free steel made using sponge iron from SSAB's new pilot facility in Luleå, Sweden, in August 2021. Jan Lindblad Jr.—SSAB

Key RD&D barriers to the use of hydrogen in iron refining include:

- *Cost of hydrogen production,*
- *Understanding of the kinetics of DRI, which influence the reliability and efficiency of DRI processes,*
- *Systems engineering of hydrogen-based processes to reduce capital cost and energy consumption and optimize iron quality,*
- *Foundational understanding of early-stage pathways to iron reduction, such as use of hydrogen plasmas.*

2.3.2.3. Electrolysis of Iron Ore

The technical viability of iron electrolysis has been demonstrated in laboratory settings, and it could even use less electricity than is needed to synthesize hydrogen.¹⁷ Direct electrolysis of iron would be a transformative technology in the long term, and it could be fully decarbonized if no-carbon electricity were used. Several routes for electrolysis are being investigated, including molten oxides at high temperatures (1,600°C) (Figure 17) and aqueous electrowinning¹⁸ at low temperatures (110 °C). Aqueous electrolysis technology, such as Siderwin under a European Union (EU) Horizon2020-funded project, will be demonstrated as a prototype by 2022 and will then be ready for further scale-up.¹⁹

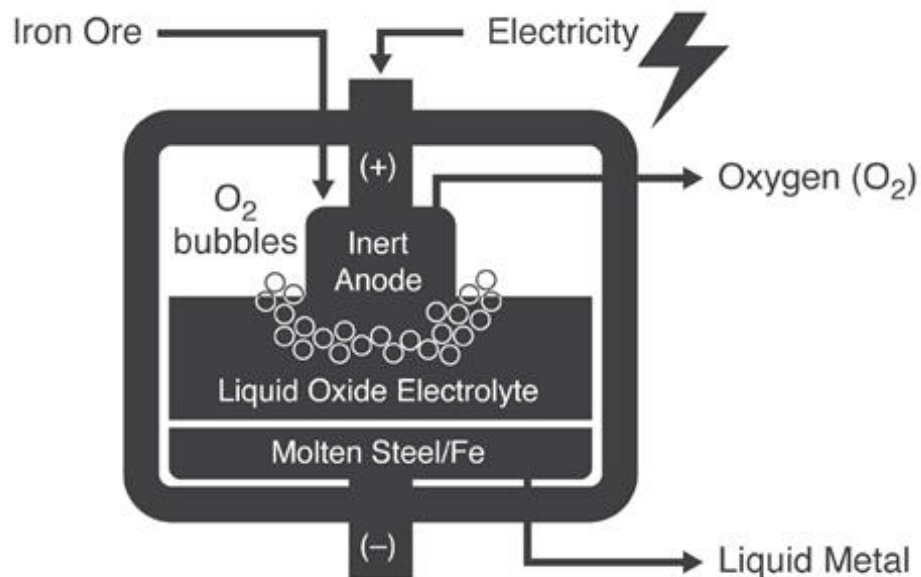


FIGURE 17. SCHEMATIC OF MOLTEN OXIDE ELECTROLYSIS¹⁵³

The yield and scalability of electrolysis of iron ore are currently not at a commercial scale, and the technology is still in the basic RD&D stage. Fundamental questions about the energy footprint of this process remain, including whether the iron ore would need energy-intensive preprocessing before undergoing electrolysis. In addition, further research is needed on inexpensive, no-carbon inert anodes that can resist the corrosive conditions of high-temperature molten oxide electrolysis...

¹⁷ ArcelorMittal, Climate Action Report 1, May 2019, https://corporate-media.arcelormittal.com/media/hs4nmyya/am_climateactionreport_1.pdf

¹⁸ Electrowinning from aqueous solutions using insoluble anodes is a well-established process for metals like zinc, copper, nickel, cobalt, cadmium, manganese and others. The metal is electrodeposited at the cathode from a solution of one of its salts, most commonly a sulfate. See <https://www.911metallurgist.com/electrowinning/> for more information.

¹⁹ Siderwin project aims to develop a technology to produce steel by electrolysis of iron ore at low temperature. ArcelorMittal supported by 11 additional innovative European partners, aims at developing a 3-meter-long new experimental pilot to validate the technology at the demonstration level. See “Development of new methodologies for Industrial CO₂-free steel production by electrowinning,” TECNALIA, accessed May 2022, <https://www.siderwin-spire.eu/>

2.3.3. Carbon Capture, Utilization, and Storage

2.3.3.1. Carbon Capture and Storage

Carbon capture and storage (CCS) could decarbonize different processes of iron and steel production, such as top-gas recycling in blast furnaces, directly reduced iron (DRI), oxygen-rich smelt reduction, bath smelting reduction, HIsarna,²⁰ and direct smelting reduction. These pathways vary greatly in their commercialization status, with blast furnace CCS being at the pilot stage, DRI CCS in the development stage, and smelting reduction CCS in the pilot stage. The top-gas recirculation blast furnace process with CCS could also reduce coal inputs and increase the percentage of CO₂ in the exhaust gas, which would also lower the cost of carbon capture. Also, CCS could be combined with oxy-fuel combustion in reheat, sintering, or pelletizing furnaces, though this combination has not yet been demonstrated.

The main challenges for CCS technologies are achieving further reductions in costs and improving operational efficiencies. Building out the CO₂ transport and storage infrastructure near the iron and steel facilities which are dispersed across the United States is another challenge. Also, better materials and process designs are needed to improve carbon capture operations and lower costs.

By helping to address these challenges, RD&D could help further develop the efficacy of CCS. RD&D could focus on design innovations, such as for blast furnace-basic oxygen furnace, to increase the purity and concentration of the CO₂ stream, which would make capture more efficient and less costly. This would also decrease compression costs for liquification of the supercritical CO₂ for transport.

The DOE Office of Fossil Energy and Carbon Management recently funded an RD&D project by Cleveland Cliffs (formerly ArcelorMittal) in collaboration with Dastur Energy and ION Clean Energy to conduct the engineering feasibility research on an industrial-scale solution for CCS from blast furnace (BF) to capture 50-70% of CO₂ emissions from blast furnace gas.²¹ Their proposed scheme includes a compositional shift of the BF gas by passing it through a series of water gas shift (WGS) reactors, which convert about 55% of the carbon monoxide (CO) in the BF gas to CO₂, thus enabling enhanced capture of up to 70% CO₂ from the available BF gas.²²

Also, RD&D could address economic challenges by focusing attention on CCS technologies with the greatest techno-economic potential. Some CCS technologies,

²⁰ HIsarna is an alternative to the blast furnace process. To be able to make liquid pig iron in a blast furnace, it is necessary to pre-process ores and metallurgical coal (the raw materials) into sinter (light chunks of iron ore), pellets (marbles of iron ore) and coke. The HIsarna process makes these steps superfluous: in the HIsarna installation, the raw materials can be used in powder form and be directly converted into liquid pig iron. The following site has more information on this: <https://www.tatasteeleurope.com/sites/default/files/TS%20Factsheet%20Hisarna%20ENG%20jan2020%20Vfinal03%204%20pag%20digital.pdf>

²¹ “FOA 2187 and FOA 2188 Project Selections,” U.S. Department of Energy Office of Fossil Energy and Carbon Management, September 1, 2020, <https://www.energy.gov/fecm/articles/foa-2187-and-foa-2188-project-selections> ; Cleveland Cliffs and Dastur International Inc., 2021, personal communication.

²² “Department of Energy Invests \$72 Million in Carbon Capture Technologies,” U.S. Department of Energy, September 1, 2020, <https://www.energy.gov/articles/department-energy-invests-72-million-carbon-capture-technologies>

such as calcium-looping lime production can capture CO₂ emissions at lower cost, and RD&D should further explore these opportunities...

2.3.3.2. Carbon Utilization

CO₂ emissions from iron and steel production can be captured and used for chemicals or fuel production (e.g., alcohol). Costs of doing this can vary widely depending on the product to be made and the site. Another utilization option, which is already commercialized, is carbonation of slag for use either in cement as a clinker substitute or in concrete as a cement substitute, which would displace the CO₂ emissions associated with cement production.

In general, carbon utilization technologies have not been demonstrated at scale, and there are technical barriers to developing carbon utilization, which RD&D could help address. More research is needed to characterize the utilization potential at steel plants and address whether carbon utilization technologies can utilize carbon on the scale at which it would be captured from a steel plant. In addition, RD&D should characterize the performance and durability of carbon utilization-based materials. There is also an opportunity for developing new carbon utilization technologies and applications.

Cost barriers for carbon utilization are significant because some of the materials carbon utilization technologies are trying to substitute for are already very inexpensive. RD&D could investigate specific standards and codes that could promote increased use of materials produced by carbon utilization technologies, and it could seek to understand policy options to incentivize uptake. The amount of energy needed could also be an issue because it could result in higher costs. Developing carbon utilization technologies that require lower temperatures can help reduce the cost. A better understanding of how the chemical manufacturing industry and the steel industry might work together for CO₂ utilized for chemicals production is also needed...

Final author's comment: There is a final iron & steel section on developing an R&D Plan, but I'm not going there. We are past the preferred-length for a post, and, at this point in any process, there are just too many variables and unknowns.