Potential Decarbonization Strategies and Challenges for the U.S. Iron & Steel Industry

Sachin Nimbalkar, PhD

Oak Ridge National Laboratory

Acknowledgement

Workshop Core Team (Iron & Steel Sector)

- Joe Cresko, DOE AMO – Report Lead, Sponsor
- Edward Rightor, ACEEE - Co-Chair
- Alberta Carpenter, NREL - Co-Chair
- Sachin Nimbalkar, ORNL – Iron & Steel Sector Lead
- Ali Hasanbeigi, Global Efficiency Intelligence, LLC. - Iron & Steel Sector Co-Lead

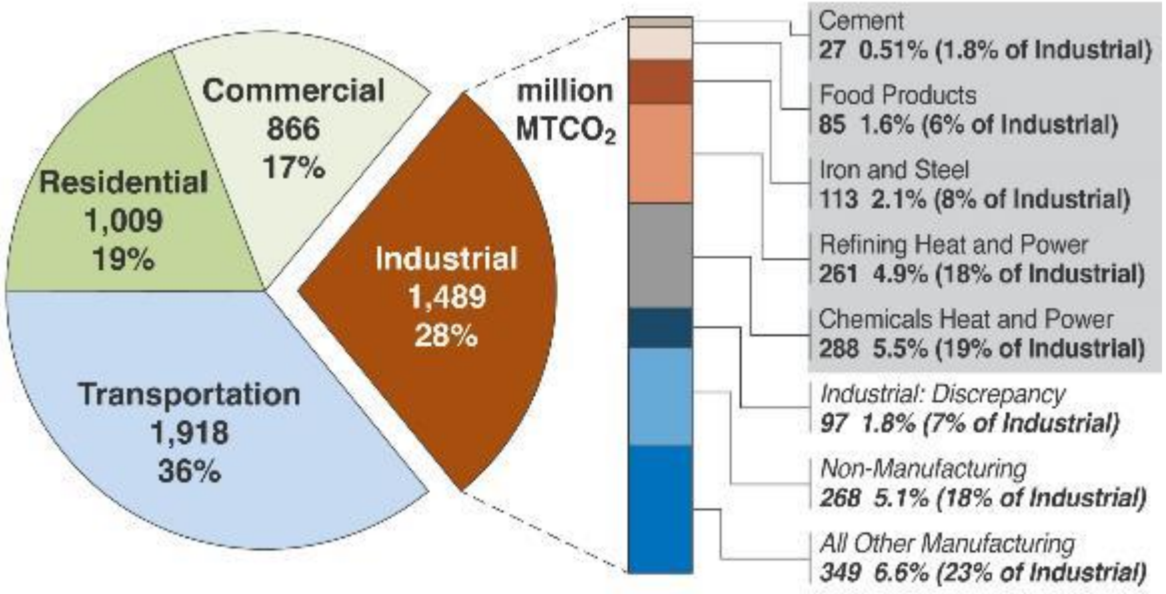
Iron and Steel Sector Chapter Reviewers

- Marlene Arens, Fraunhofer Institute for Systems and Innovation Research
- Jan Mares, Resources for the Future
- Lawrence Fabina and Rishabh Bahel, Cleveland Cliffs

The industrial sector is a major contributor to U.S. CO_2 emissions

- Decarbonization of the industrial sector is key to addressing the climate crisis and achieving economy-wide net zero emissions by 2050.
- The U.S. industrial sector accounts for 32% of the nation’s primary energy use and 28% of its annual CO_2 emissions.
  - **52% of industrial CO_2 emissions are attributed to the five top sectors analyzed in the *Decarbonization Roadmap***
- Without intervention, anticipated 30% growth in industrial sector energy demand by 2050 may increase CO_2 emissions by 15%.

U.S. CO_2 Emissions by Sector and Subsector (2018)



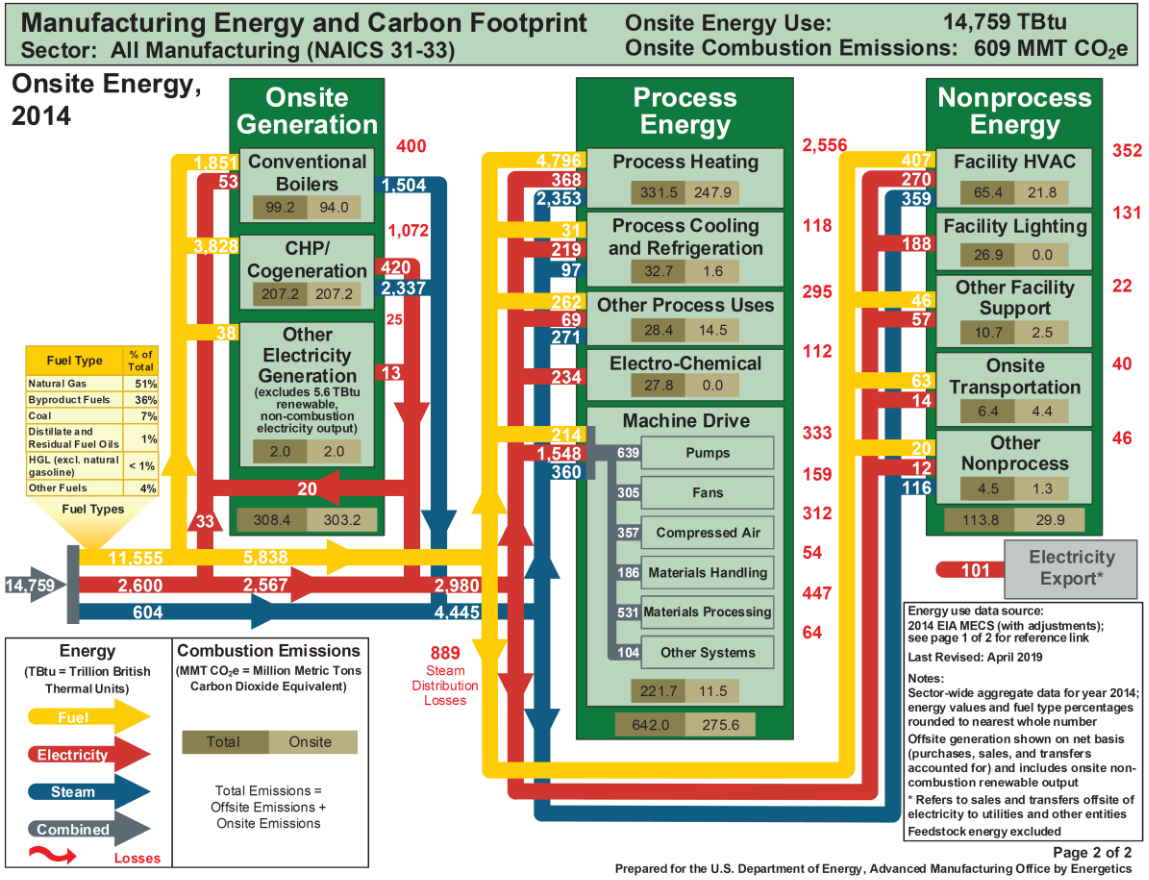
Share of the **5,282 million metric tons of CO_2** emitted by the U.S. in 2018 (EIA 2021)

Key message: *U.S. industry accounts for 28% of the energy-related CO_2 emissions, with the five top industrial sectors responsible for 52% of the industrial contribution.*

Data source: Energy Information Administration (EIA) *Annual Energy Outlook 2021 with Projections to 2050.*

U.S. Manufacturing Combustion Emissions

Industrial Sector Energy & Emissions



Fuel Type	% of Total
Natural Gas	51%
Byproduct Fuels	36%
Coal	7%
Distillate and Residual Fuel Oils	1%
HGL (excl. natural gasoline)	< 1%
Other Fuels	4%

Energy use data source:
2014 EIA MECS (with adjustments); see page 1 of 2 for reference link

Last Revised: April 2019

Notes:
Sector-wide aggregate data for year 2014; energy values and fuel type percentages rounded to nearest whole number

Offsite generation shown on net basis (purchases, sales, and transfers accounted for) and includes onsite non-combustion renewable output

* Refers to sales and transfers offsite of electricity to utilities and other entities

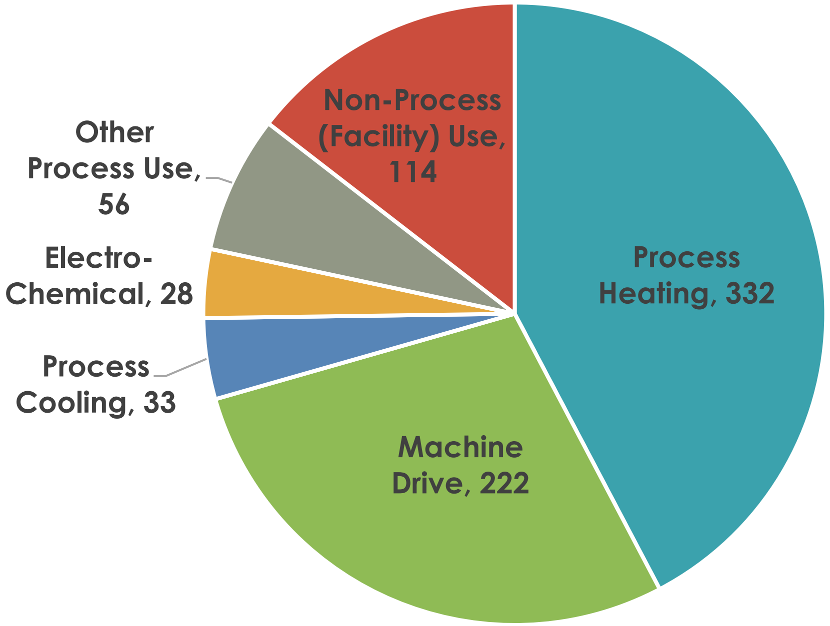
Feedstock energy excluded

Prepared for the U.S. Department of Energy, Advanced Manufacturing Office by Energetics

Data source: DOE *Manufacturing Energy and Carbon Footprint*, based on EIA Manufacturing Energy Consumption Survey (MECS) data for 2014.

Emissions Breakdown by Major Operation

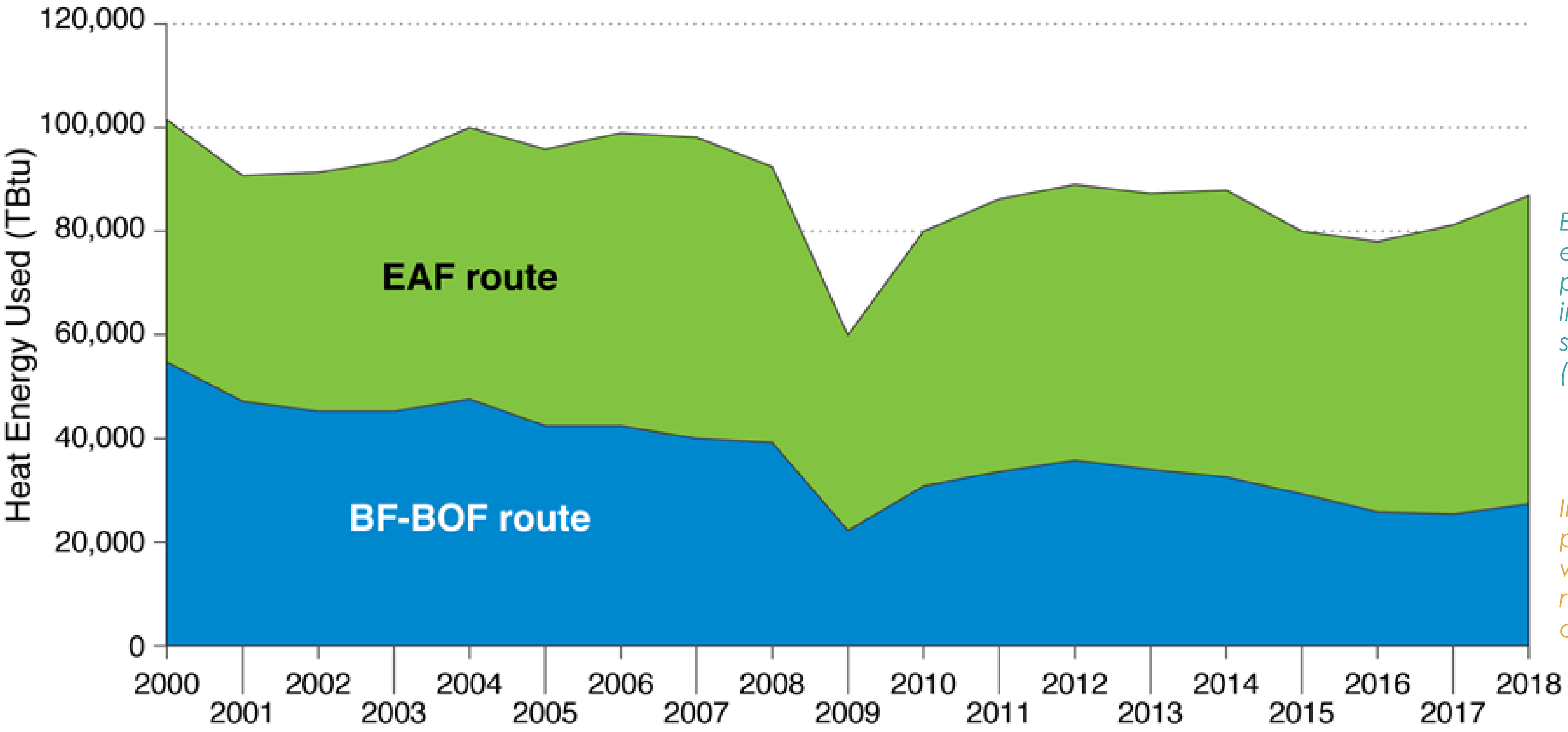
- Most combustion emissions in the industrial sector are driven by process heating (42%) and motor-driven process operations (28%).



Industrial CO_2-Equivalent Combustion Emissions by End-Use (million metric tons, 2014)

Steel Production Methods: Blast Furnace and Electric Arc Furnace

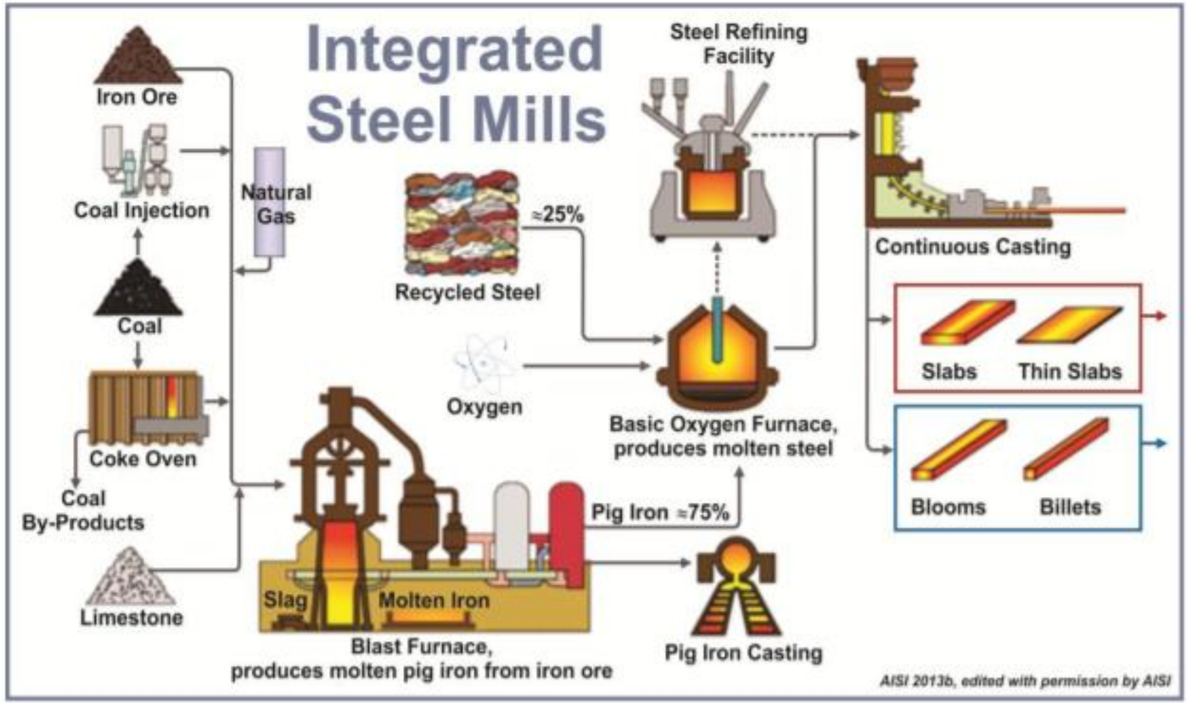
In 2018, 33% of crude steel was produced via the blast furnace / basic oxygen furnace (BF-BOF) route and 67% was produced via the electric arc furnace (EAF) route.



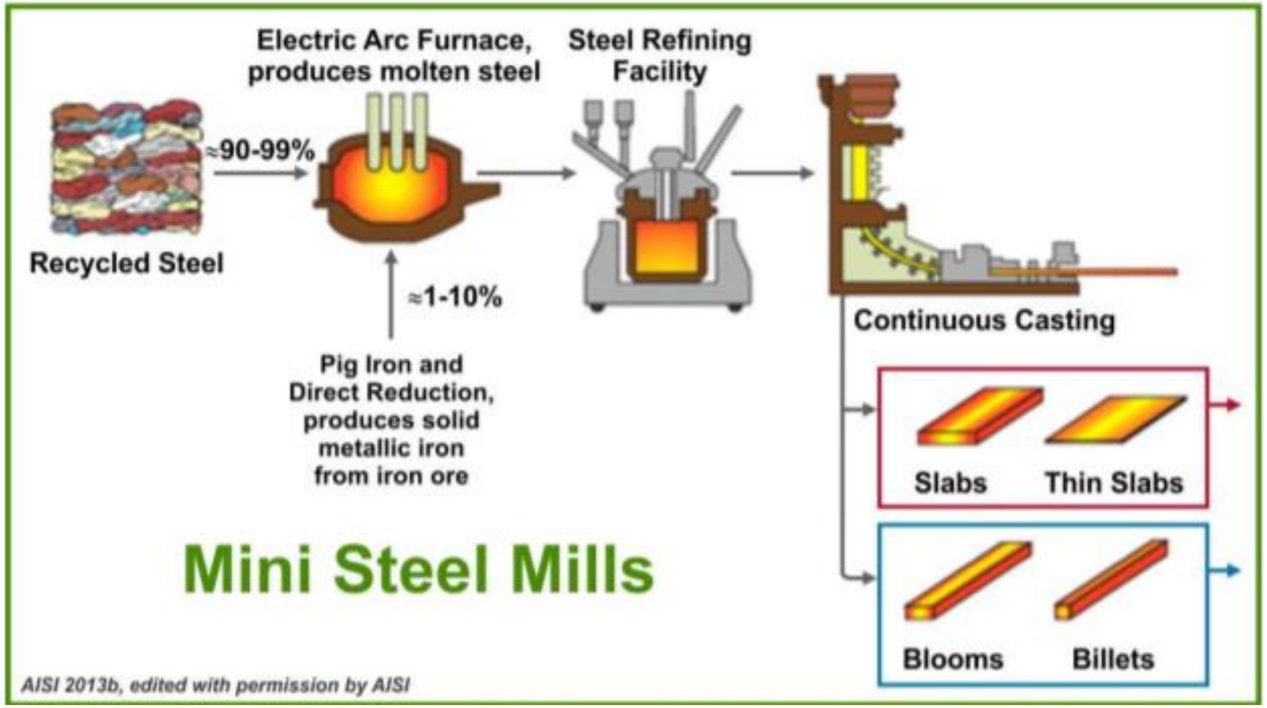
EAF steel producers use an electrified process to produce steel from raw input materials of steel scrap or direct reduced iron (DRI).

Integrated BF/BOF mills produce steel from iron ore with coal coke used as a reductant, relying on mostly combustible fuel energy

Steelmaking Flowlines for Integrated and Mini Mills



AISI 2013b, edited with permission by AISI

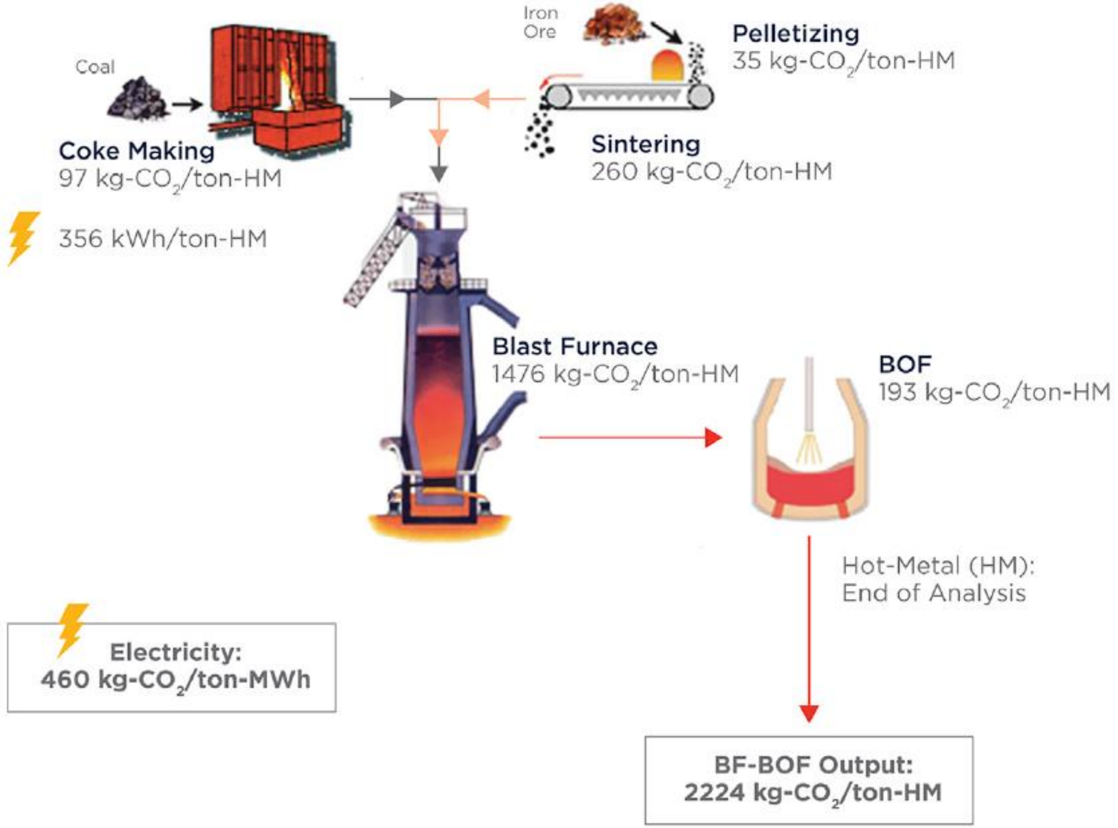


AISI 2013b, edited with permission by AISI

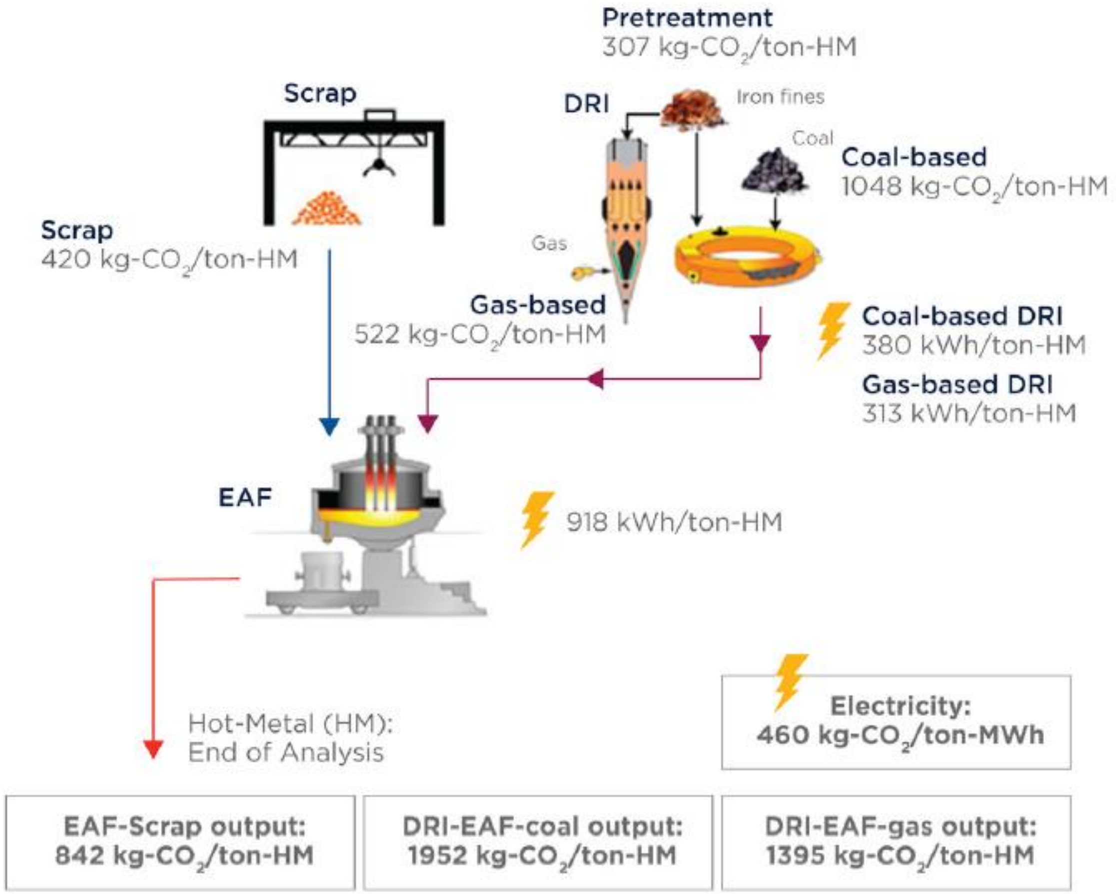
Source: "Steelmaking Flowlines." American Iron and Steel Institute (AISI). 2013.

Global Average CO_2 Emissions for Integrated and Mini Mills

BF-BOF pathway flow diagram, electricity consumption, and CO2 emission sources

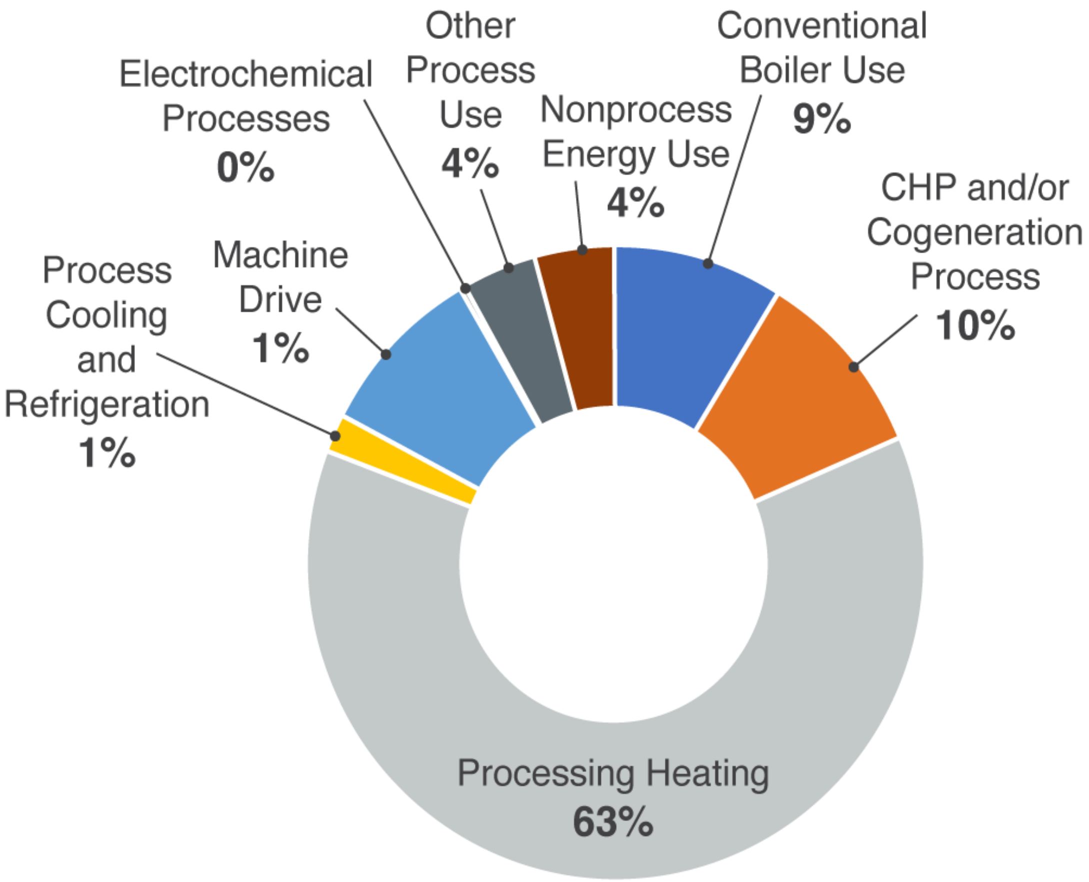


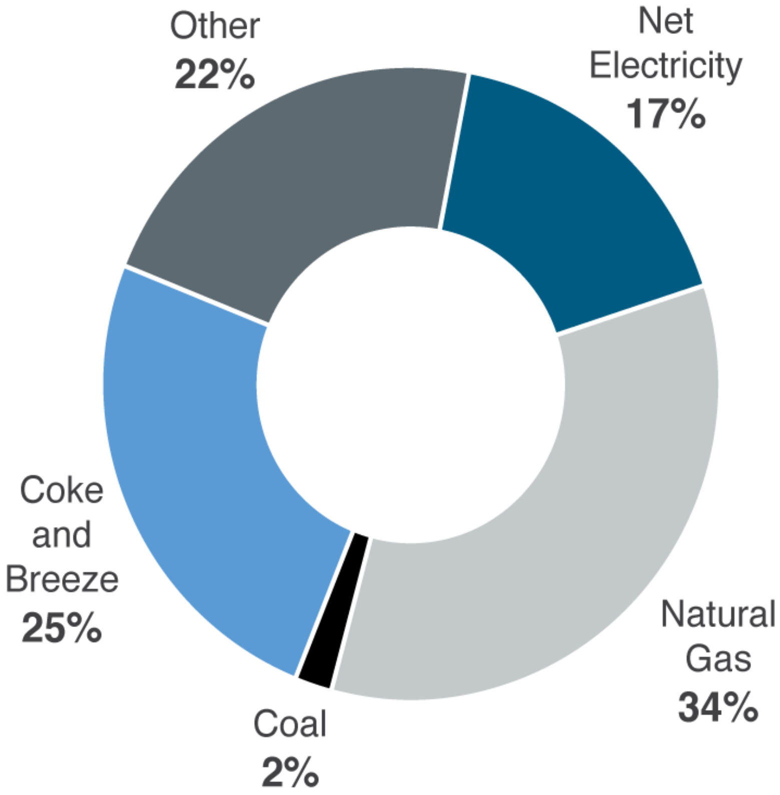
EAF-scrap and DRI-EAF pathways flow diagrams, electricity consumption, and CO2 emission sources



Source: Fan, Zhiyuan, and S. Julio Friedmann. "Low-carbon production of iron and steel: Technology options, economic assessment, and policy." Joule (2021).

Thermal processes (process heating, CHP, and boilers) accounted for around 82% of total energy used in the U.S. steel industry

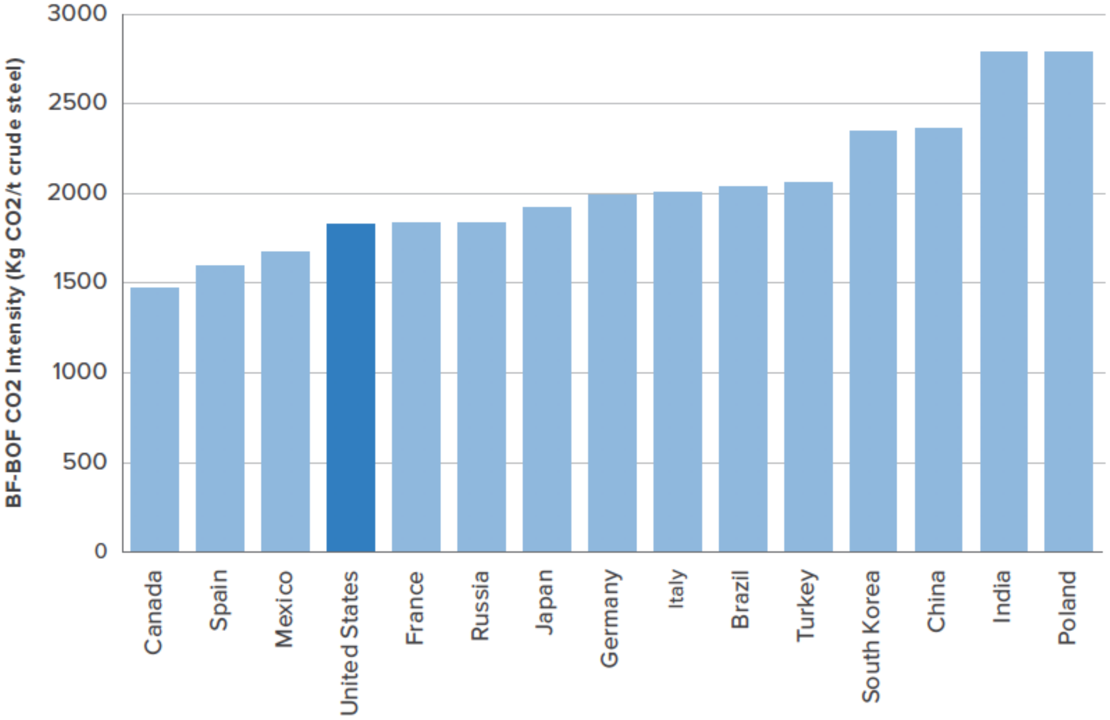




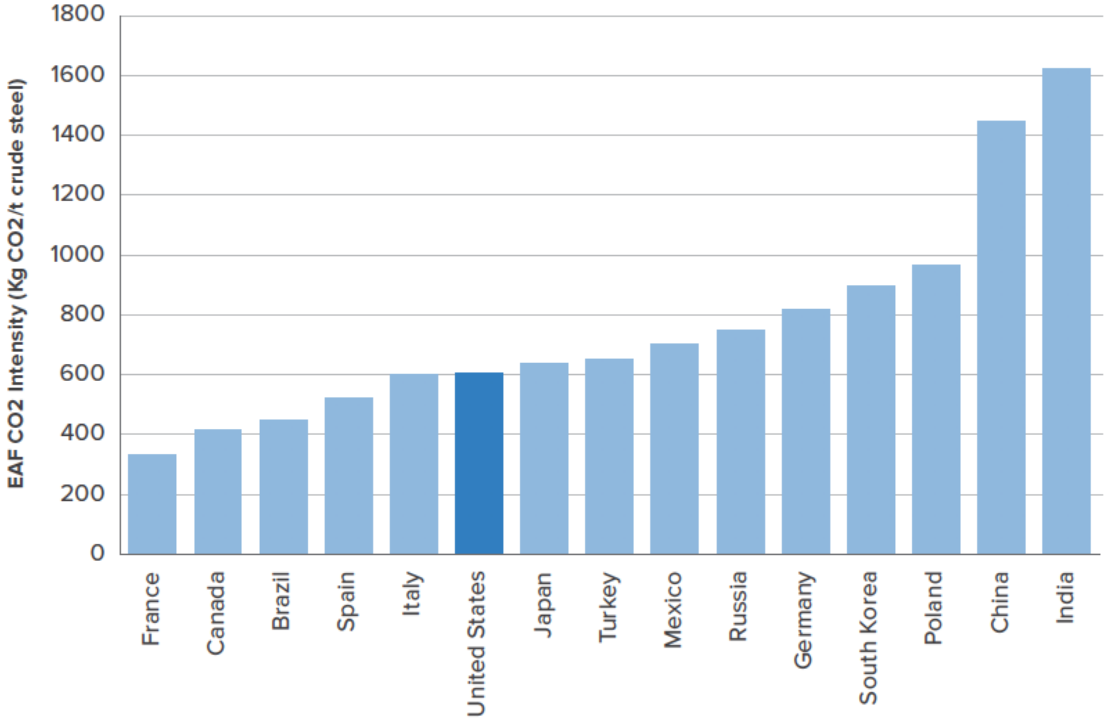
IEA (International Energy Agency), Energy Technology Perspectives 2020.

Emissions intensity of BF-BOF and EAF steelmaking

The U.S. performs better than average in emissions intensity for both steel production routes. Pound-for-pound, the cleaner EAF process emits a third of the CO2 of the BF-BOF process.

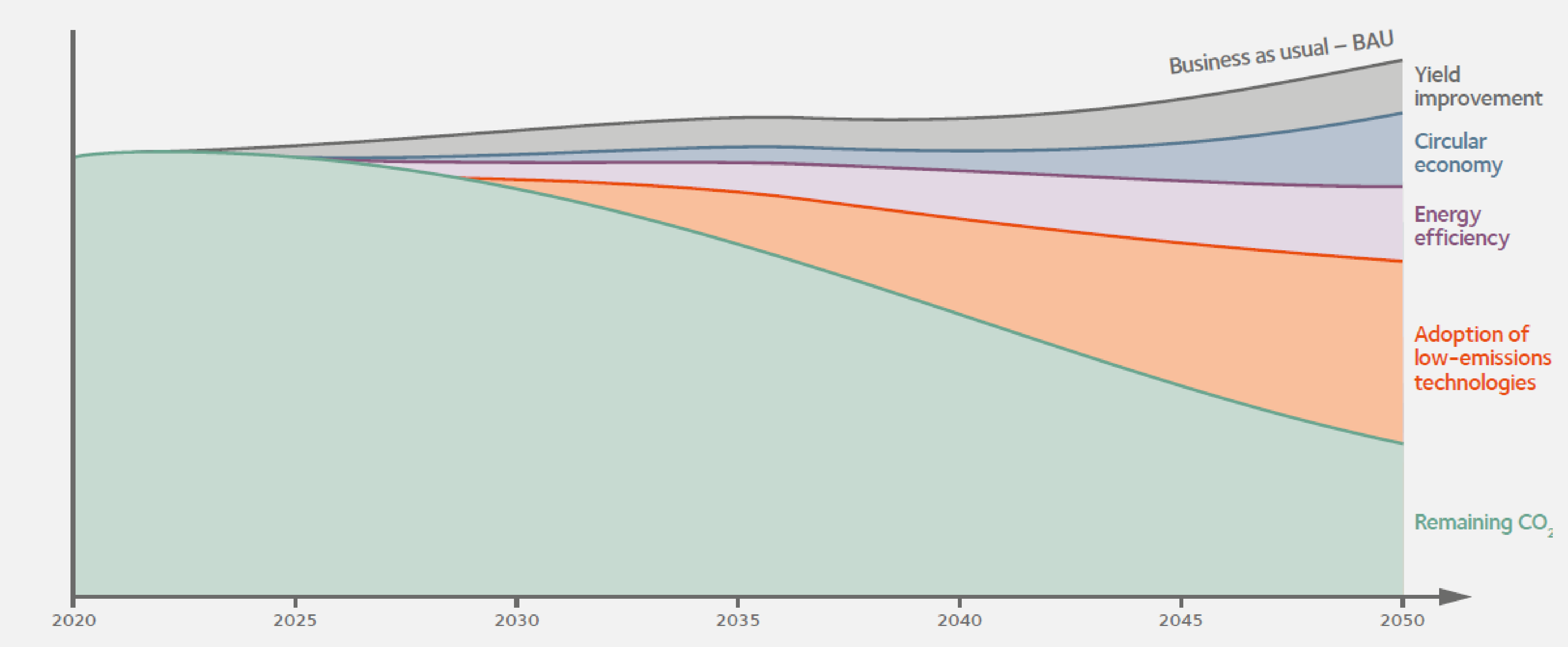


The CO_2 intensity of BF-BOF steel production in the studied countries in 2016 (Hasanbeigi et al. 2019)



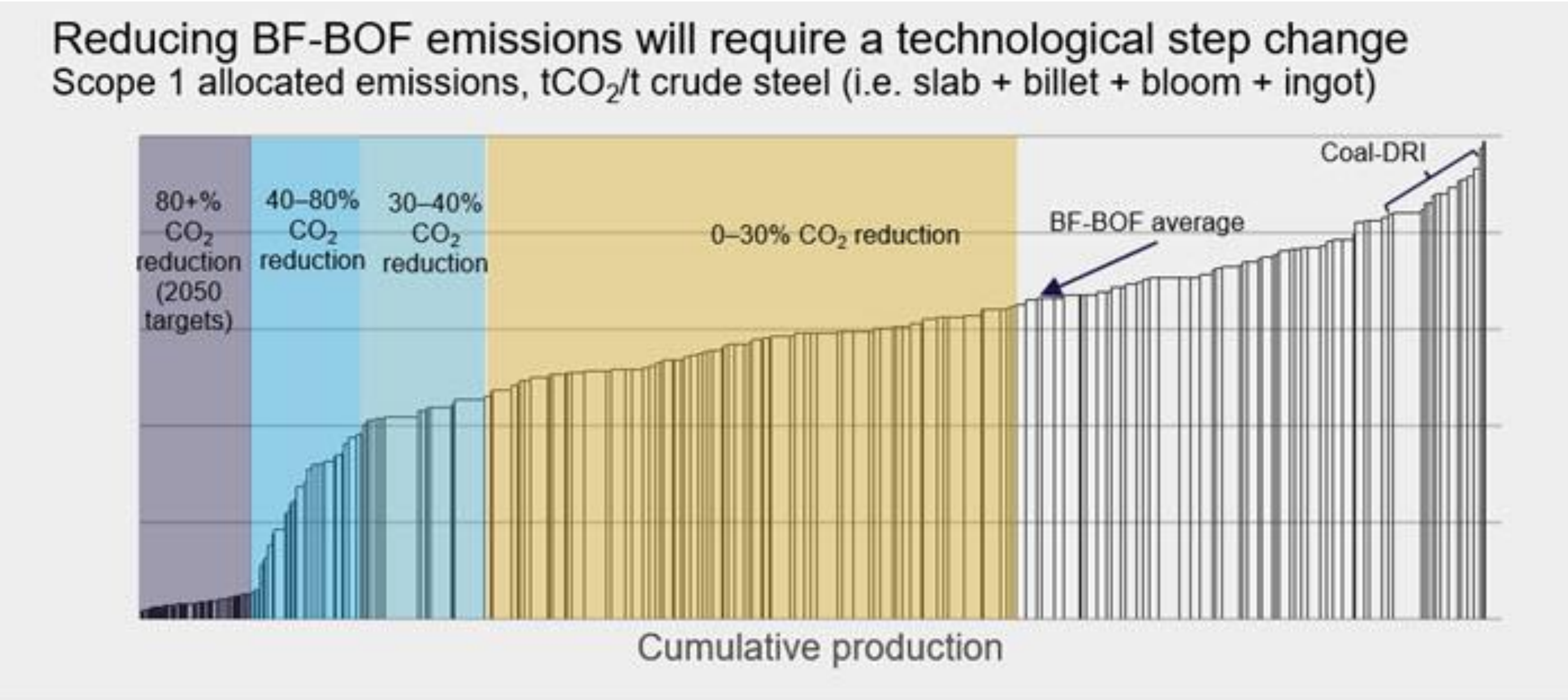
The CO_2 intensity of EAF steel production in the studied countries in 2016 (Hasanbeigi et al. 2019)

Meeting the carbon challenge for steel will require continued energy and yield improvements, a shift to a circular economy, and the adoption of low-emissions technologies.



Reference: ArcelorMittal Climate Action Report, 2019

Blast Furnace – Basic Oxygen Furnace (BF-BOF) Technology Options



Reducing BF-BOF emissions will require a technological step change

Scope 1 allocated emissions, tCO_2/t crude steel (i.e. slab + billet + bloom + ingot)

DATA: CRU Steel Carbon Curve—Steel Cost Model 2019

	CO_2 reduction	Technology options
🟨	0–30% reduction	BF-BOF Best Practice (i.e. minimum coke rates), BF Natural Gas injection, BF H_2 injection
🟦	30–40% reduction	Corex, Hisarna
🟦	40–80% reduction	Natural gas-DRI-EAF
🟪	>80% reduction	Scrap-based EAF, H_2-DRI-EAF

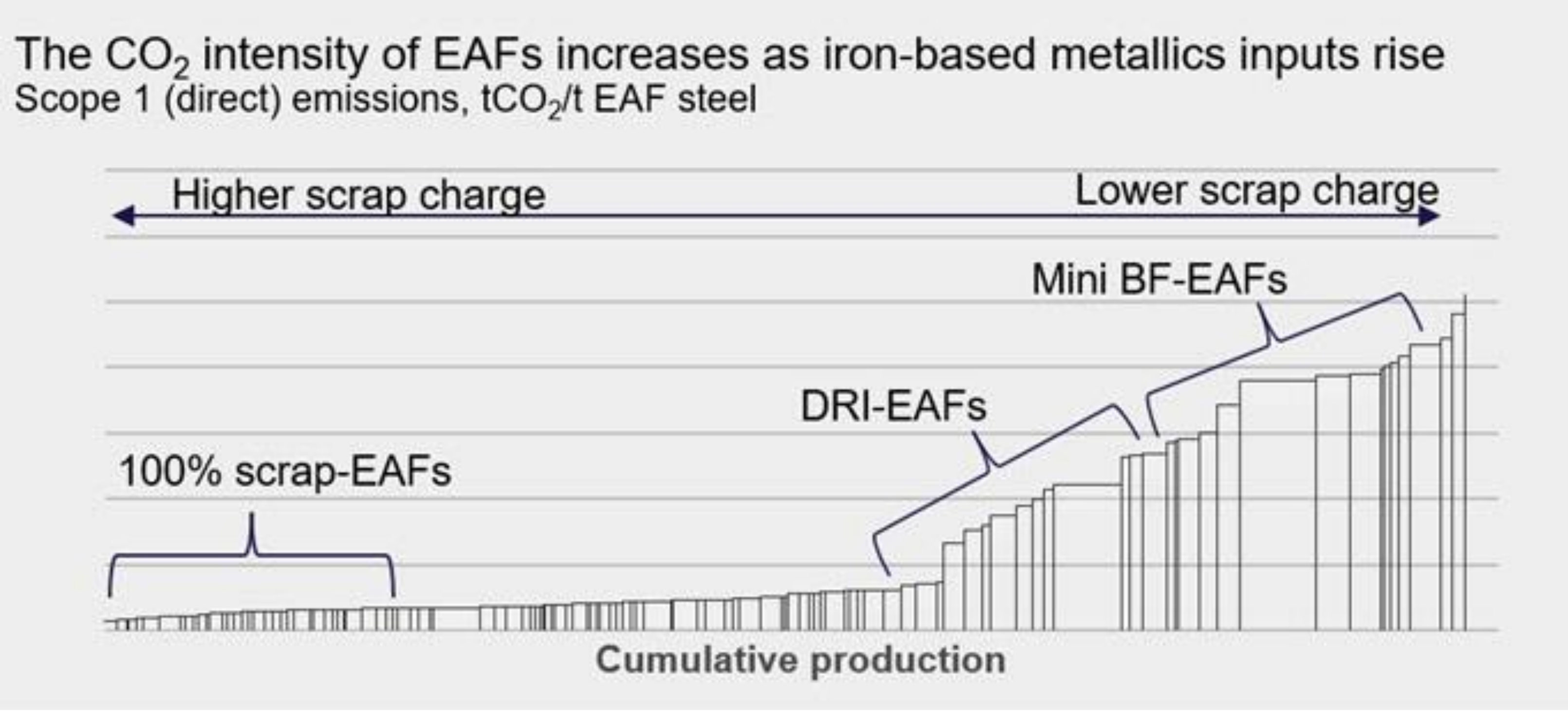
U.S. BF-BOF production is relatively cleaner than BF-BOF production in other countries due to relining, use of pulverized coal injection (PCI), improving burden compositions, and other upgrades.

Further reducing BF-BOF emissions will require step-change technology advancements and abatement strategies.

Data sources: A. Hasanbeigi and C. Springer, How Clean is the U.S. Steel Industry? An International Benchmarking of Energy and CO2 Intensities (San Francisco, CA: Global Efficiency Intelligence, November 2019).

R. Smith and S. MacNaughton, The immense decarbonization challenge facing the steel industry, CRU 2020

Electric Arc Furnace (EAF) Technology Options



Data sources:

R. Smith and S. MacNaughton, *The immense decarbonization challenge facing the steel industry,* CRU 2020

- ***Where are U.S. EAFs on this chart?***
- ***Why can't the U.S. move to 100% scrap-based steelmaking? Challenges producing quality grades and limits to prime scrap supply***
- ***Higher quality flat and long products require a 'clean' iron input***
- ***In case of DRI-EAFs and mini-BF-EAFs, we need lower carbon DRI and mini BFs***
- ***Capture CO_2***

Barriers to Low-Carbon Transition

- Low profit margins
- Significant initial investment & risk
- Facilities last 25-50 years with proper maintenance
- Significant existing capacity (~20% more than demand)
- No market for more expensive but less GHG intense materials

Deep Decarbonization Pillars and Technologies for the Steel Industry

Energy Efficiency	Electrification & Low-C Fuels and Feedstocks	CCUS
• Strategic energy management • Waste heat management including COG & BFG utilization • System optimization • Pulverized coal or H_2 injection • Top pressure recovery turbine (TRT), coke dry quenching, and BOF gas recovery	• Renewable energy Hydrogen in DRI and blast furnaces¥ • Electrification of reheating furnace • Hydrogen DRI¥ • Producing iron by electrolysis of iron ore • Hydrogen plasma smelting reduction	• Post-combustion carbon capture and storage • Top-gas recycling in blast furnaces with CCS¥ • DRI with CCS • Carbon utilization • Carbon to ethanol and carbon to chemical

¥ Hybrid emerging/near commercial technologies could, once commercialized, be retrofitted into existing plants.

Not for publication

R&D Needs and Opportunities

Deployment

Demonstration

Development

Applied Research

Basic Research

Technology Maturity

- Utilization of waste gases (H_2, CO, and CO_2) for chemicals or fuels (TRL 3-6)
- Aqueous electrolysis/ electrowinning rate and scalability (TRL 3-4)
- Molten oxide electrolysis/ electrowinning rate and scalability (TRL 3-4)
- Biological and bio-inspired capture, conversion, utilization, and storage of CO_2 (TRL 3-4)
- Direct air capture (DAC) and Negative emissions technologies (NETs) to remove CO_2 and convert it into fuels and chemical feedstocks (TRL 3-6)

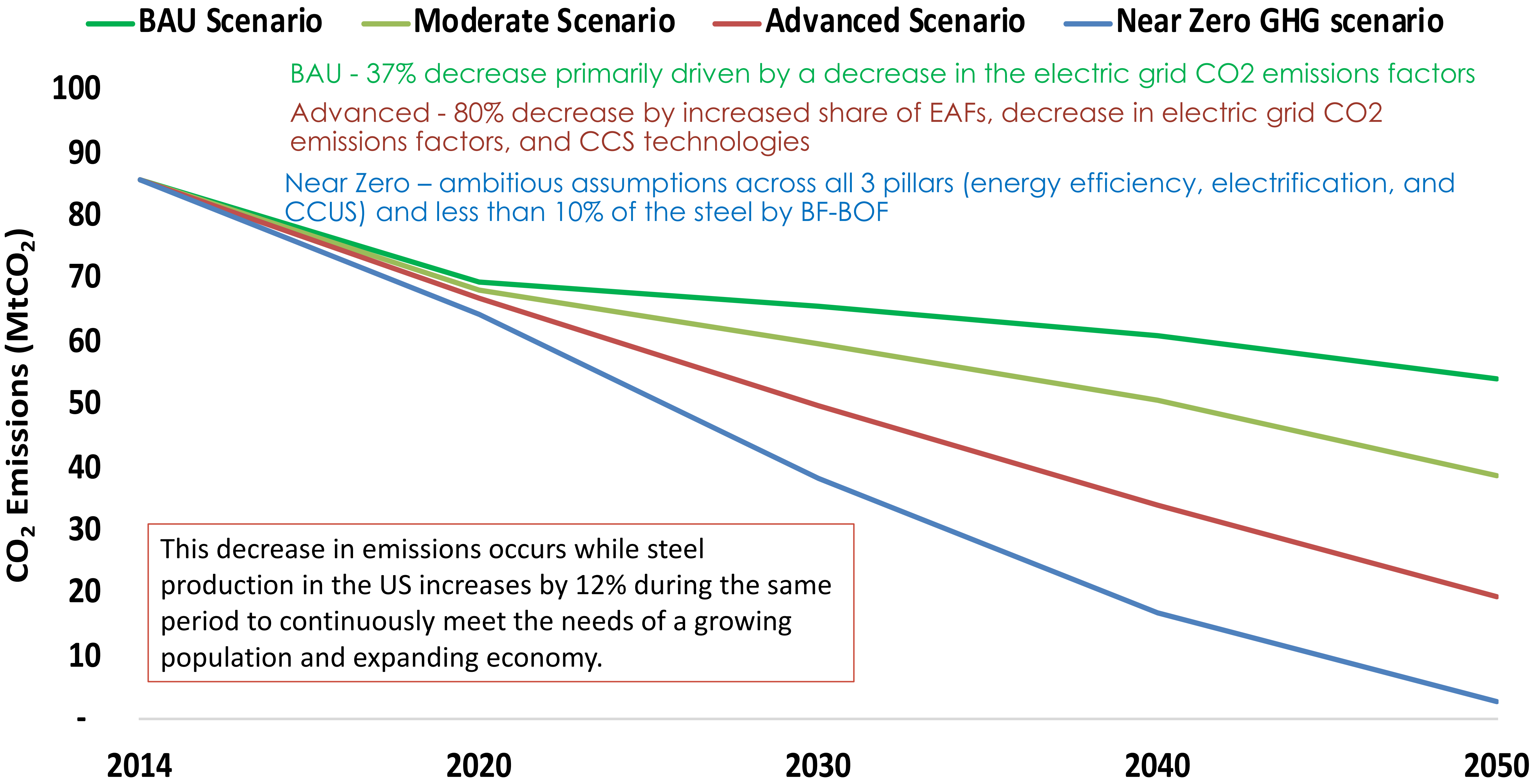
- H_2-based DRI-EAF (TRL 5-7)
- Flash ironmaking (TRL 4-5)
- Partial H_2 replacement of NG in a standard DRI-EAF (TRL 6-7)
- Top gas recirculation with 90%+ CCS (TRL 5)
- Decontamination of steel scrap for Cu, Sn, and other metals (TRL 4-6)
- Materials for harsh environment WHR-sensible and chemical waste heat (TRL 4-6)
- Material and energy recovery from slag (TRL 6-7)

- DRI with post-combustion CCUS (TRL 9)
- Hisama with 80%-90% capture CCS (TRL 7-8)
- More demos on lightweight buildings, cars, other material-intensive products and tradeoffs and costs (TRL 6-9)
- Alternate metals and nonmetals (TRL 7-9)
- Advanced technology to optimized material use (TRL 5-9)
- New burden of iron-carbon agglomerates (CA) (TRL 8-9)
- Demonstration of smart manufacturing and internet of things technologies to increase energy productivity (TRL 7-9)
- Modular and flexible manufacturing (TRL 7-9)
- Waste heat for district heating (TRL 7-9)
- H_2-enriched reduction in BF (TRL 6-9)
- Scaling up electric induction furnaces (TRL 6-9)
- Electrification of reheat and other downstream furnaces (TRL-5-9)

Market Readiness

Not for publication

CO_2 Emissions Forecast for the US Steel Industry



BAU - 37% decrease primarily driven by a decrease in the electric grid CO2 emissions factors

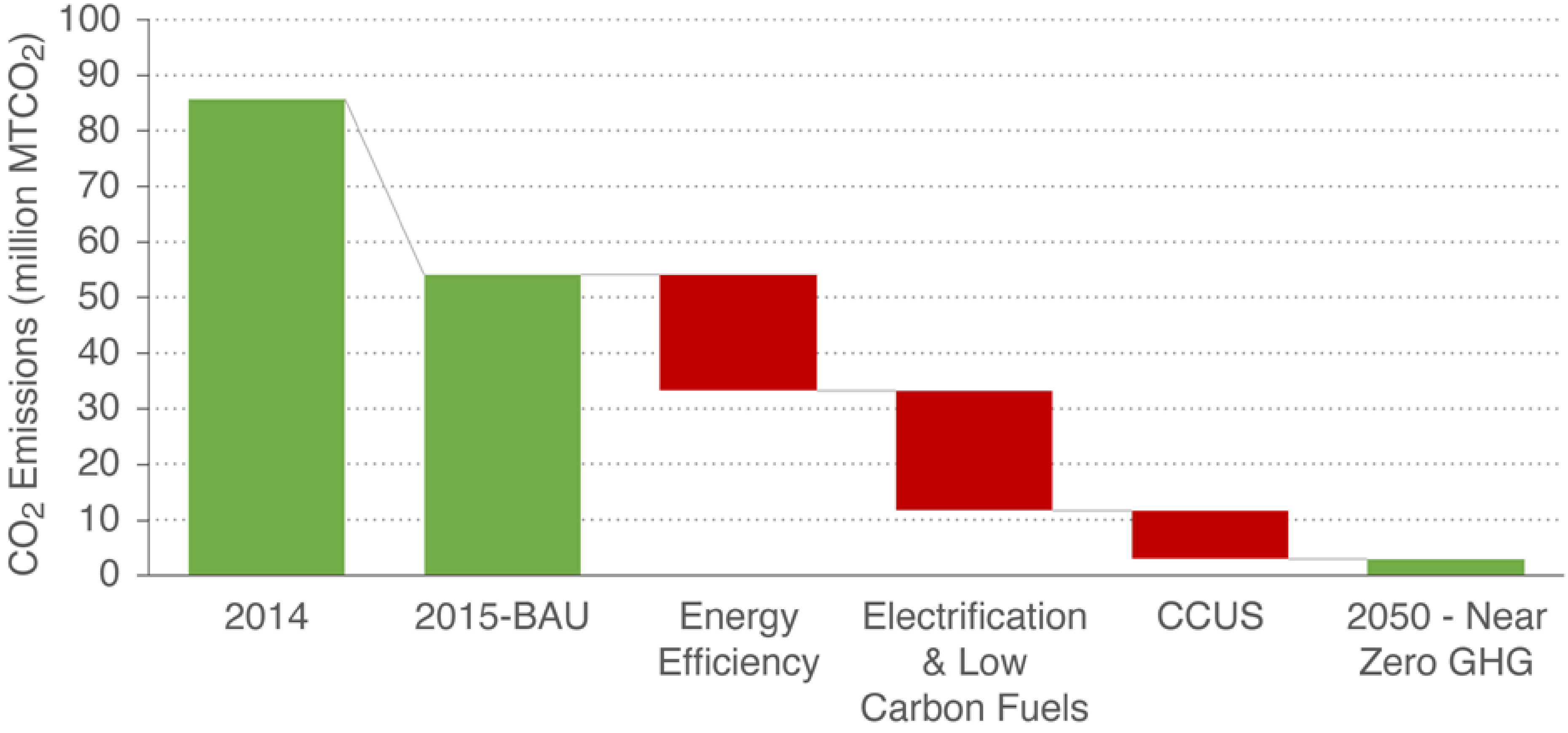
Advanced - 80% decrease by increased share of EAFs, decrease in electric grid CO2 emissions factors, and CCS technologies

Near Zero – ambitious assumptions across all 3 pillars (energy efficiency, electrification, and CCUS) and less than 10% of the steel by BF-BOF

This decrease in emissions occurs while steel production in the US increases by 12% during the same period to continuously meet the needs of a growing population and expanding economy.

Not for publication

Impact of Decarbonization Pillars on CO_2 Emissions from the US Steel Industry (BAU Vs Near Zero)

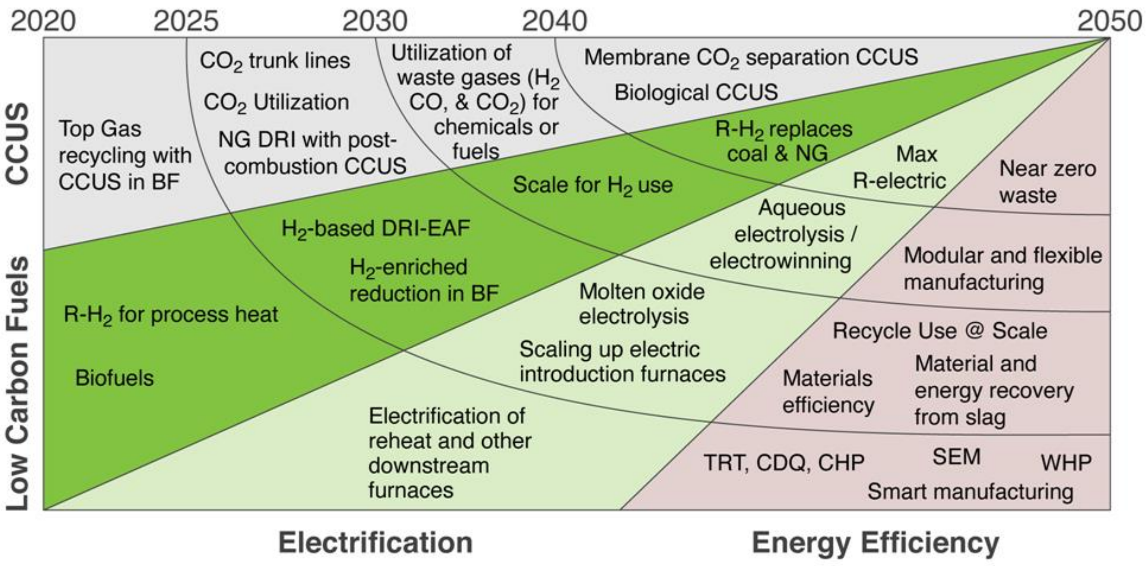


- The impact from electrification includes the reduction in electric grid CO_2 emissions.
- Assumed <10% of the steel will be produced by BF-BOF process in 2050.

Not for publication

Proposed RD&D and Action Plan for Iron and Steel

Landscape of needs/opportunities in the U.S. steel industry for RD&D investments

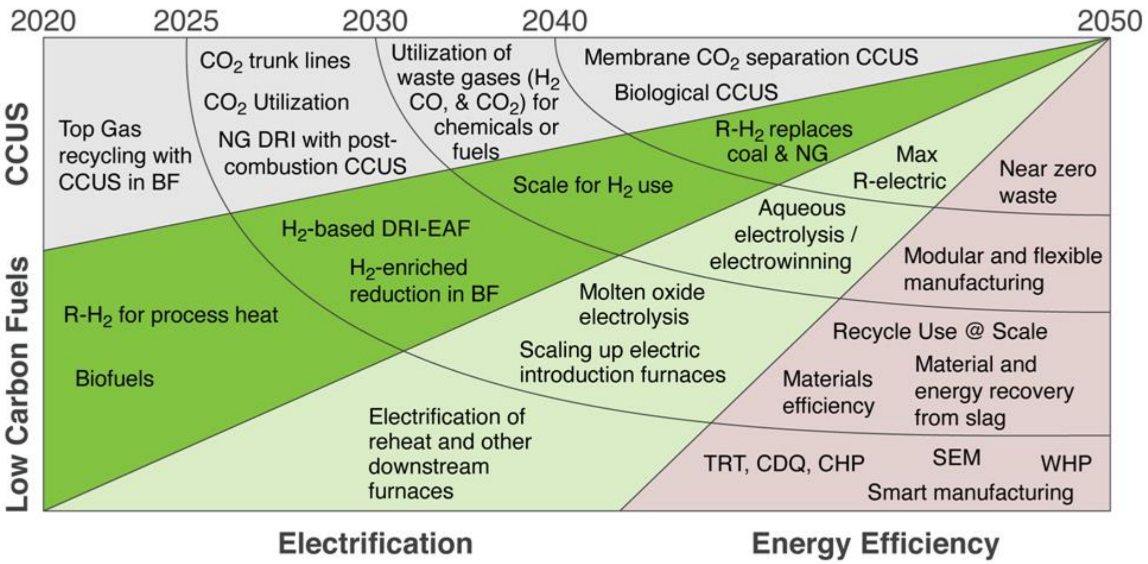


RD&D needs with near-term (2020–2025) impacts include to:

- Help leverage relatively low-capital solutions (energy efficiency, strategic energy management (SEM)) and waste reduction/recovery solutions (waste heat to power (WHP), TRT, CDQ that provide additional nonenergy benefits,
- Enable the transition to lower carbon fuels and process heat solutions (e.g., electrification of reheat and downstream furnaces, renewable hydrogen (R-H_2) for process heat, biofuels),
- Continue advancing integration of CCUS with hard to abate sources (e.g., top gas recycling in BF furnaces).

Proposed RD&D and Action Plan for Iron and Steel

Landscape of needs/opportunities in the U.S. steel industry for RD&D investments

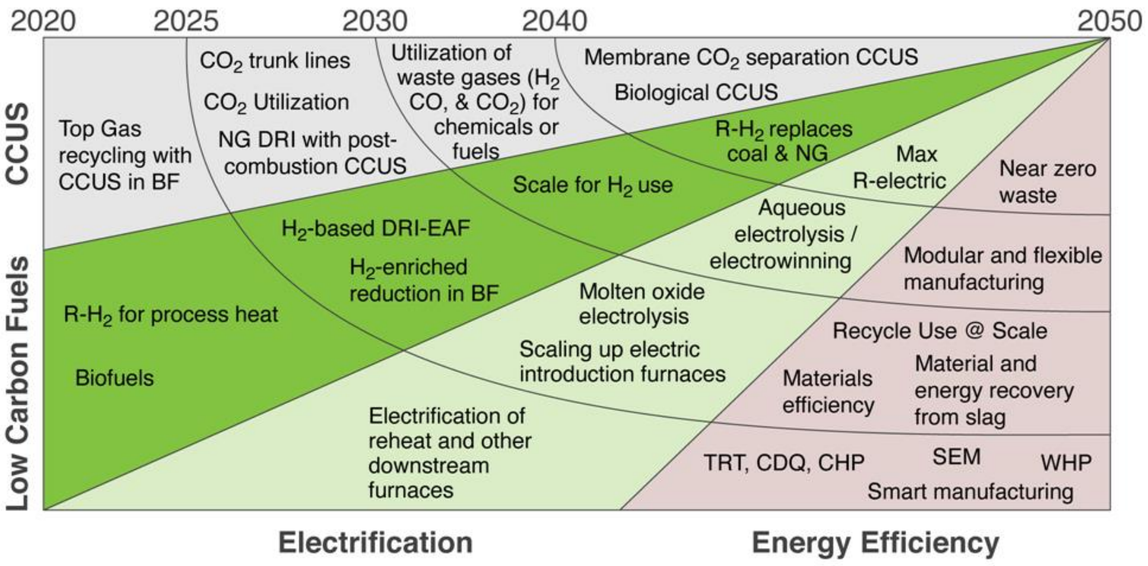


RD&D needs with mid-term (2025–2030) impacts include to:

- Probe routes to continue improving materials efficiency and flexibility including reuse/recycle/refurbishment (including materials and energy recovery from slag),
- Invest in lower-carbon process adaptations/ routes (e.g., molten oxide electrolysis, scaling up electric induction furnaces, renewable hydrogen based direct reduction iron -electric arc furnace (DRI-EAF)),
- Expand the infrastructure and integration capabilities and knowledge to capture, transport, and reuse where possible (in the steel process, or nearby uses), CO_2 from hard to abate sources with the highest efficiency and best economics possible.

Proposed RD&D and Action Plan for Iron and Steel

Landscape of needs/opportunities in the U.S. steel industry for RD&D investments



RD&D needs with longer-term (2030–2050) impacts include to:

- Advance modular approaches for manufacturing to greater scale and proportion of market
- Lower technical and economic challenges for transformative approaches to making steel and accelerate development timeline (e.g., aqueous electrolysis/electrowinning)
- Develop additional routes for utilizing waste gases (hydrogen, CO, CO_2 etc.) on-site or in nearby facilities, improve the efficiency of separations of these and other gases so their energy and resource needs are significantly decreased

Iron & Steel Industry - Summary

- The U.S. steel industry GHG emissions can go down to almost zero in 2050, under our Near Zero GHG emissions scenario, while steel production in the United States increases by 12% during the same period.
- More than 2/3 of total GHG emissions reduction needed to get to near zero in 2050 comes from improvement in energy efficiency and switching to low/no-carbon fuels and electrification.
- Aggressive RD&D and pilot and demonstration is needed for transformative technologies such as H_2-based steel production, electrolysis of iron ore, and CCUS to realize near zero GHG emissions goal by 2050.
- The demand for green H_2 and low-carbon electricity use in steel making will increase significantly by 2050. R&D efforts will be needed to improve the efficiency of electrolyzers along with reliable infrastructure to produce low-cost low-carbon electricity.
- Although this was not in the scope of this report, material efficiency strategies could help reduce industry GHG emissions for steel while delivering the same material services. This pathway needs to be explored further with defensible LCA and TEA analyses.

Q&A

Sachin Nimbalkar, PhD

Email: nimbalkarsu@ornl.gov

Phone: 865.576.3590