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

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The industrial sector is a major contributor to U.S. CO₂ 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 CO₂ emissions.
  - 52% of industrial CO₂ 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 CO₂ emissions by 15%.

**Key message:** U.S. industry accounts for 28% of the energy-related CO₂ 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.
Most combustion emissions in the industrial sector are driven by process heating (42%) and motor-driven process operations (28%).
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.

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

EAF steel producers use an electrified process to produce steel from raw input materials of steel scrap or direct reduced iron (DRI).
Steelmaking Flowlines for Integrated and Mini Mills

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

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

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 CO2 intensity of BF-BOF steel production in the studied countries in 2016 (Hasanbeigi et al. 2019)

The CO2 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, tCO₂/t crude steel (i.e. slab + billet + bloom + ingot)

- 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: CRU Steel Carbon Curve—Steel Cost Model 2019

<table>
<thead>
<tr>
<th>CO₂ reduction</th>
<th>Technology options</th>
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</thead>
<tbody>
<tr>
<td>0–30% reduction</td>
<td>BF-BOF Best Practice (i.e. minimum coke rates), BF Natural Gas injection, BF H₂ injection</td>
</tr>
<tr>
<td>30–40% reduction</td>
<td>Corex, Hisarria</td>
</tr>
<tr>
<td>40–80% reduction</td>
<td>Natural gas-DRI-EAF</td>
</tr>
<tr>
<td>&gt;80% reduction</td>
<td>Scrap-based EAF, H₂-DRI-EAF</td>
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R. Smith and S. MacNaughton, The immense decarbonization challenge facing the steel industry, CRU 2020
Electric Arc Furnace (EAF) Technology Options

The CO₂ intensity of EAFs increases as iron-based metallics inputs rise
Scope 1 (direct) emissions, tCO₂/t EAF steel

Higher scrap charge  Lower scrap charge

Mini BF-EAFs

DRI-EAFs

100% scrap-EAFs

Cumulative production

• 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 CO₂

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

<table>
<thead>
<tr>
<th>Energy Efficiency</th>
<th>Electrification &amp; Low-C Fuels and Feedstocks</th>
<th>CCUS</th>
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</thead>
<tbody>
<tr>
<td>• Strategic energy management</td>
<td>• Renewable energy Hydrogen in DRI and blast furnaces¥</td>
<td>• Post-combustion carbon capture and storage</td>
</tr>
<tr>
<td>• Waste heat management including COG &amp; BFG utilization</td>
<td>• Electrification of reheating furnace</td>
<td>• Top-gas recycling in blast furnaces with CCS¥</td>
</tr>
<tr>
<td>• System optimization</td>
<td>• Hydrogen DRI¥</td>
<td>• DRI with CCS</td>
</tr>
<tr>
<td>• Pulverized coal or H₂ injection</td>
<td>• Producing iron by electrolysis of iron ore</td>
<td>• Carbon utilization</td>
</tr>
<tr>
<td>• Top pressure recovery turbine (TRT), coke dry quenching, and BOF gas recovery</td>
<td>• Hydrogen plasma smelting reduction</td>
<td>• Carbon to ethanol and carbon to chemical</td>
</tr>
</tbody>
</table>

¥ Hybrid emerging/near commercial technologies could, once commercialized, be retrofitted into existing plants.
R&D Needs and Opportunities

- Deployment
  - Utilization of waste gases (H₂, CO, and CO₂) for chemicals or fuels (TRL 3-6)
  - Aqueous electrolysis/electrowinning rate and scalability (TRL 3-4)

- Demonstration
  - Molten oxide electrolysis/electrowinning rate and scalability (TRL 3-4)
  - Biological and bio-inspired capture, conversion, utilization, and storage of CO₂ (TRL 3-4)
  - Direct air capture (DAC) and Negative emissions technologies (NETs) to remove CO₂ and convert it into fuels and chemical feedstocks (TRL 3-6)

- Development
  - H₂-based DRI-EAF (TRL 5-7)
  - Flash ironmaking (TRL 4-5)
  - Partial H₂ 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 WHRSensible and chemical waste heat (TRL 4-6)
  - Material and energy recovery from slag (TRL 6-7)

- Applied Research
  - DRI with post-combustion CCS (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)
  - H₂-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
CO₂ Emissions Forecast for the US Steel Industry

- **BAU Scenario**: 37% decrease primarily driven by a decrease in the electric grid CO₂ emissions factors.
- **Advanced Scenario**: 80% decrease by increased share of EAFs, decrease in electric grid CO₂ emissions factors, and CCS technologies.
- **Near Zero Scenario**: 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.
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.
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-H2) 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, CO₂ 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 H₂-based steel production, electrolysis of iron ore, and CCUS to realize near zero GHG emissions goal by 2050.

- The demand for green H₂ 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

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