The Costs and Distributional Impacts of Decarbonizing the Iron and Steel Industry in the United States

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U.S. iron and steel production, imports, exports, and emissions in a global context

<table>
<thead>
<tr>
<th>Country</th>
<th>Production in 2022 (thousand tons)</th>
<th>Share</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>1,017,959</td>
<td>54%</td>
</tr>
<tr>
<td>India</td>
<td>125,377</td>
<td>7%</td>
</tr>
<tr>
<td>Japan</td>
<td>89,227</td>
<td>5%</td>
</tr>
<tr>
<td><strong>United States</strong></td>
<td><strong>80,535</strong></td>
<td><strong>4%</strong></td>
</tr>
<tr>
<td>Russia</td>
<td>71,469</td>
<td>4%</td>
</tr>
<tr>
<td>South Korea</td>
<td>65,846</td>
<td>3%</td>
</tr>
<tr>
<td>Germany</td>
<td>36,849</td>
<td>2%</td>
</tr>
<tr>
<td>Türkiye</td>
<td>35,134</td>
<td>2%</td>
</tr>
<tr>
<td>Brazil</td>
<td>34,090</td>
<td>2%</td>
</tr>
<tr>
<td>Iran</td>
<td>30,593</td>
<td>2%</td>
</tr>
<tr>
<td>Other</td>
<td>298,658</td>
<td>16%</td>
</tr>
</tbody>
</table>

7% of global energy related CO₂ emissions
2% of U.S. GHG emissions

Source: World Steel Association (2022, 2023)
Iron and steel production: Two major routes

**Integrated (BF-BOF) route**
- Iron ore
- Coke, fluxes
- Ladle metallurgy, Steel
- ~ 2.2 t CO$_2$/tcs
- 72% of production
- 30% in U.S.

**Electric arc furnace route**
- Iron ore
- Electricity
- Steel scrap
- ~ 0.5 t CO$_2$/tcs
- 28% of production
- 70% in U.S.

**Blast Furnace (BF)**
- Coal, natural gas, hydrogen
- Pig iron
- Ladle metallurgy, Steel

**Basic Oxygen Furnace (BOF)**
- Liquid iron

**Direct Reduced Iron (DRI)**
- Coal, natural gas, hydrogen

**Electric Arc Furnace (EAF)**
- Steel scrap
- Ladle metallurgy, Steel

Iron and steel processes, in living color

Integrated Route

Basic oxygen furnace, Pittsburgh, PA, USA
Mon Valley Works, Pittsburgh, PA, USA
Blast furnace, Valencia, Spain

Electric Arc Furnace Route

Direct reduced iron, Corpus Christi, TX, USA
Big River Steel, Osceola, AR, USA
Electric arc furnace, Osceola, AR, USA
The steel production supplied by the EAF route has increased since the early 1990s.
We compared the cost of pathways for decarbonizing both BF-BOF and EAF production.
Key assumptions used to estimate cost and CO₂ emissions

- Emissions scopes: Scope 1 (direct from production), Scope 2 (mainly electricity), Scope 3 (mainly upstream ore extraction and processing)
- BF-BOF represents Best Available Technology in 2023.
- Electricity CO₂ based on US 2021 grid average, except for H₂ / CCS, which are assumed to only be deployed if they can be operated on zero C electricity.
- The 100% NG DRI, 50% H₂ and 100% H₂ DRI assume the input gas stream is partially used for pre-heating.
- Prices are fixed: cost of H₂ is $4.68/kg (Pistorius, 2022), electricity price of 4 cents/kWh, + 3 cents/kWh for zero CO₂ electricity.
However, direct comparisons may be misleading because...

• Today, BF-BOF and EAF steel are not perfect substitutes – used to make different grades (exposed automotive vs. rebar)

• “Decarbonizing” the EAF route may require considering a higher-emissions counterfactual – increasing share of DRI in the EAF charge (ore-based metallics such as pig iron or DRI are more GHG-intensive than scrap, but necessary to make higher-grade products)

• Our 100% DRI-EAF estimates should be considered as benchmarks that can be used in weighted averages to assess emissions as a function of DRI share in an EAF charge
Our analysis considers two scenarios to evaluate cost of decarbonization

• A “route-specific” (RS) scenario: A scenario that maintains BF-BOF and EAF technology shares and deeply reduces CO$_2$ emissions at least cost (often favored by labor and BF-BOF producers).

• A “substitution-in-place” (SP) scenario: A scenario that replaces BF-BOF steelmaking with DRI-EAF steelmaking, with higher ore-based metallics than today’s scrap-EAF steelmaking (often favored by EAF producers, climate advocates).
Our scenario analysis holds production fixed, uses literature values for inputs.

Table 1: Assumptions for CO$_2$ reduction scenarios

<table>
<thead>
<tr>
<th>Measure</th>
<th>Quantity</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S. BF-BOF capacity (2021)</td>
<td>40 mtpa</td>
<td>WSA (2022)</td>
</tr>
<tr>
<td>U.S. BF-BOF production (2021)</td>
<td>26 mtpa</td>
<td>WSA (2022)</td>
</tr>
<tr>
<td>U.S. EAF capacity (2021)</td>
<td>89 mtpa</td>
<td>WSA (2022)</td>
</tr>
<tr>
<td>U.S. EAF production (2021)</td>
<td>59 mtpa</td>
<td>WSA (2022)</td>
</tr>
<tr>
<td>Pig iron input for EAF, 15% of charge</td>
<td>8.9 mtpa</td>
<td>Assumption</td>
</tr>
</tbody>
</table>

Notes: This table reports current capacity and production for the BF-BOF and EAF production separately. Given the relative stability of U.S. steel production around 80 mtpa, we assume in our scenarios that abatement actions address CO$_2$ emissions from existing production.
Costs of deeply reducing CO₂ emissions from iron and steel production in the U.S. – “back of the envelope”

<table>
<thead>
<tr>
<th>Estimate</th>
<th>RS Scenario</th>
<th>SP Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF-BOF incremental capital cost</td>
<td>$16 billion</td>
<td>$0 billion</td>
</tr>
<tr>
<td>DRI incremental capital cost</td>
<td>$7.2 billion</td>
<td>$11.2 billion</td>
</tr>
<tr>
<td>EAF incremental capital cost</td>
<td>$0 billion</td>
<td>$12.4 billion</td>
</tr>
<tr>
<td>Total capital cost</td>
<td>$23.2 billion</td>
<td>$22.6 billion</td>
</tr>
<tr>
<td>BF-BOF incremental variable cost per year</td>
<td>$2.3 billion</td>
<td>$0 billion</td>
</tr>
<tr>
<td>EAF incremental variable cost per year</td>
<td>$2.5 billion</td>
<td>$3.5 billion</td>
</tr>
<tr>
<td>Total incremental variable cost per year</td>
<td>$5.8 billion</td>
<td>$3.5 billion</td>
</tr>
<tr>
<td>EAF zero CO₂ electricity cost per year</td>
<td>$0.8 billion</td>
<td>$1.2 billion</td>
</tr>
<tr>
<td>Average CO₂ emissions per tcs</td>
<td>0.289 t CO₂ per tcs</td>
<td>0.213 t CO₂ per tcs</td>
</tr>
<tr>
<td>% reduction in CO₂ emissions per tcs</td>
<td>71%</td>
<td>80%</td>
</tr>
</tbody>
</table>
Takeaways so far...

• Overall, if DRI-EAF can meet product requirements, it may represent the most cost effective approach to reducing CO$_2$ emissions.

• Models that do not recognize the potential to accomplish reductions with more limited DRI may reach the opposite conclusion.

• Important to compare options on both aggregate cost as well as local costs/benefits:
  • Jobs (-)
  • Public revenue generation (?)
  • Air quality (+)
Motivation

• Environmental Justice (EJ) concerns: siting of polluting plants
  • exposure to fine particulate matter of diameters <2.5 μm (PM2.5)
  • PM2.5 identified as the 5th-highest risk factor for mortality globally

• Colmer et al. (Science, 2020): absolute disparities in exposure to PM2.5 have fallen, but relative disparities persist
  • the most polluted census tracts in 1981 remained the most polluted in 2016
  • the most exposed pop subgroups in 1981 remained the most exposed in 2016
Particulate Matter (PM2.5)
Motivation

• Jbaily et al. (Nature, 2022): develop a data platform linking demographic to PM2.5 data across the U.S. from 2000-2016
  • zip codes with >avg Black, Asian and Hispanic/Latino populations more exposed to PM2.5 than zip codes with >avg white and Native American populations
  • zip codes with low-income populations exposed to higher PM2.5 levels than zip codes with high-income groups
  • disparities in exposure relative to safety standards set by US EPA and WHO have been increasing over time

• Decarbonization may generate co-benefit of PM2.5 reductions
    • lowered GHG, PM2.5, PM10, and NOx emissions by 3-9% annually between 2012-2017
    • caused EJ gaps in PM2.5, PM10, and NOx from those facilities to narrow by 6-10% annually
This Work: Decarbonizing Steel and Iron Industry

U.S. Steel's Gary Works, on the Lake Michigan shore in Lake County, is the largest steel mill in North America. - Center crews ain't cutting it. Bad news is not...
Map of Current U.S. BF-BOF and EAF Facilities
Data

• Location of U.S. furnaces used in iron and steel production
  • Global Energy Monitor (GEM)

• Demographic and socioeconomic variables
  • median household income (2019 USD)
  • share of population below the poverty line
  • share of 25+ pop. w/ or w/o college degree
  • share of African Americans (or nonwhites)
  • share of 16+ pop. unemployed
  • share of 16+ pop. out of labor force
  • population (total and density)

• American Community Survey (ACS): 5-year averages
  • 2010-2014, and 2015-2019
  • data at census tract level: 600-3,000 people

• PM2.5: van Donkelaar et al. (EST, 2021)
  • annual mean in µg/m3 at 0.01° x 0.01° resolution (0.7 x 0.7 miles)
  • satellite + chem transport model + calibration (ground-based obs.)
Empirical Strategy

• World steel production capacity: 72% BF-BOF & 28% EAF
  • March 2022: planned capacity mirrored those proportions
  • March 2023: notable change in plans – 57% BF-BOF & 43% EAF

• U.S. current steel production capacity: 30% BF-BOF & 70% EAF
  • this reflects the setting the world is moving toward
Operating steelmaking capacity by technology type

<table>
<thead>
<tr>
<th>Country</th>
<th>Basic oxygen furnace</th>
<th>Electric arc furnace</th>
<th>Open hearth furnace</th>
<th>Unspecified</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>1112</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>India</td>
<td>121</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td>115</td>
<td></td>
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<tr>
<td>United States</td>
<td>115</td>
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<td></td>
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<tr>
<td>Russia</td>
<td>86</td>
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<td>South Korea</td>
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<td>Germany</td>
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<td>Brazil</td>
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<td>Ukraine</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Vietnam</td>
<td>26</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Empirical Strategy

• Descriptive analysis
  • average outcomes across varying distances from steel plants stratified by
  • steelmaking technologies (BF-BOF vs. EAF) & time (2010-2014 vs. 2015-2019)
  • distance bins: 0-2 miles, 2-5 miles, 5-10 miles, 10-20 miles, and 20-30 miles

• Difference in differences analysis
  • \( \Delta \) outcome within BF-BOF & EAF areas relative to 0-2 miles from plants
  • DiD: BF-BOF difference minus EAF difference – for each distance bin
Distance Bins

furnace
Results: Avg PM2.5 Levels by Distance to Steel Plants

A. BF-BOF

B. EAF

2010-2014  
2015-2019

2021 WHO Annual PM2.5 Guidelines: 5µg/m³
Results: Estimated PM2.5 Differences Relative to 0-2 Miles from Steel Plants

Comparison: Currie et al. (2023)'s estimated effects of “2005” NAAQS for PM2.5:

0.73 µg/m³
Results: Estimated PM2.5 Differences Relative to 0-2 Miles from Steel Plants *With Additional Controls*

Comparison: Currie et al. (2023)'s estimated effects of “2005” NAAQS for PM2.5:

0.73 µg/m³
Results: Median Household Income (2019 USD)
Results: Median Household Income (2019 USD)
Results: Share of Pop. 25+ with College Degree

A. BF-BOF

B. EAF

Distance to Furnace (miles)

Share of Pop. 25+ w/ College Degree

2010-2014

2015-2019
Results: Share of Pop. 25+ with College Degree
Results: Share of African Americans
Results: Share of African Americans
Results: Share of Pop. 16+ Out of Labor Force

A. BF-BOF

B. EAF

Distance to Furnace (miles)

Share of Pop. 16+ Out of Labor Force

2010-2014 2015-2019
Results: Share of Pop. 16+ Out of Labor Force
Results: Population Density (1K)

A. BF-BOF

B. EAF

Population Density (1K) vs. Distance to Furnace (miles) for 2010-2014 and 2015-2019.
Results: Population (100K)

A. BF-BOF

B. EAF

Population (100K)

Distance to Furnace (miles)

0-2  2-5  5-10  10-20  20-30

2010-2014  2015-2019

0  40  80  120  160  200  240  280  320  360  400

Population (100K)

Distance to Furnace (miles)

0-2  2-5  5-10  10-20  20-30

2010-2014  2015-2019

0  40  80  120  160  200  240  280  320  360  400
Results: Share of Pop. Below the Poverty Line

A. BF-BOF

B. EAF

2010-2014

2015-2019
Results: Share of Pop. Below the Poverty Line
Results: Share of Nonwhites

A. BF-BOF

B. EAF
Results: Share of Nonwhites
Results: Share of Pop. 16+ Unemployed

A. BF-BOF

B. EAF

2010-2014  2015-2019
Results: Share of Pop. 16+ Unemployed

The graph shows the estimated share differences in unemployment rates across different distance categories from a furnace. The categories are 2-5, 5-10, 10-20, and 20-30 miles. The data includes BF-BOF Diff, EAF Diff, and DiD (Difference-in-Differences) comparisons.
Concluding Remarks

• Communities experience worse air quality near BF-BOF vs. EAFs
  • CCS installation may not address local air quality issues

• Transition from BF-BOF to EAF (DRI-EAF, or even DRI-BOF): co-benefits of PM2.5 reductions
    • lowered GHG, PM2.5, PM10, and NOx emissions by 3-9% annually between 2012-2017
    • EJ gaps in PM2.5, PM10, and NOx from those facilities narrowed by 6-10% annually
  • Counterfactual evidence from Clean Power Plan regulatory impact analysis

• Currie, Voorheis, and Walker (AER, 2023): >60% of convergence in Black-White PM2.5 exposure since 2000 attributable to Clean Air Act
  • areas with larger Black populations saw greater CAA-related declines in PM2.5
THANK YOU!

Questions? Comments?
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edsons@andrew.cmu.edu
Comparison of magnitude: Currie et al. (AER, 2023)

**Figure 1. Trends in Pollution Exposure by Race**
### Table 3—The Impact of the 2005 Implementation of PM2.5 Standards on PM2.5 Levels

<table>
<thead>
<tr>
<th></th>
<th>PM2.5</th>
<th>PM2.5</th>
<th>ln(PM2.5)</th>
<th>ln(PM2.5)</th>
<th>PM2.5</th>
<th>PM2.5</th>
<th>ln(PM2.5)</th>
<th>ln(PM2.5)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
<td>(6)</td>
<td>(7)</td>
<td>(8)</td>
</tr>
<tr>
<td>PM2.5 nonattain</td>
<td>-1.230</td>
<td>-1.237</td>
<td>-0.075</td>
<td>-0.076</td>
<td>-0.727</td>
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<td>-0.036</td>
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<td>× post</td>
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<td>(0.334)</td>
<td>(0.020)</td>
<td>(0.020)</td>
<td>(0.080)</td>
<td>(0.082)</td>
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<td>(0.006)</td>
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<tr>
<td>PM2.5 non</td>
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<td>0.008</td>
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<tr>
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<td>County FE</td>
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<td>Observations</td>
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<td>32,360,000</td>
<td>32,360,000</td>
<td>32,360,000</td>
<td>32,360,000</td>
<td>32,360,000</td>
</tr>
</tbody>
</table>

**Notes:** This table presents regression coefficients from 8 separate versions of equation (3), one per column, where the dependent variable consists of PM2.5 or ln(PM2.5) for an individual in a given year. Columns 2, 4, 6, and 8 add an additional interaction for African Americans to test for heterogeneity in regulatory impacts for African Americans. Regressions are weighted by census survey weights and errors are clustered by CZ. FE = fixed effects.
Challenges to keep in mind when evaluating industrial decarbonization pathways

• **Industrial production involves multiple interdependent steps**, with interdependencies in decarbonization decisions across steps.
  - Important to disaggregate – within 3312 - Steel Works, Blast Furnaces (Including Coke Ovens), and Rolling Mills, 30-fold difference in CO₂ intensity.

• **Abatement options are not always additive**: efficiency of a given process (low capex, limited reduction potential) versus replacing that process (high capex, greater reduction potential).

• **Multiple margins for innovation**: (1) ability to substitute toward scrap-based (less GHG intensive) pathways over pathways requiring virgin material or (2) innovation across the supply chain to support decarbonization of a particular process step.