Low-Carbon Steel Production: Options and Assessment

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1. Today’s Iron and Steel Production
   • BF-BOF dominates 71%
   • EAF-scrap 24%, DRI-EAF 5%

2. Decarbonization Approaches
   • Hydrogen, Biomass, Zero-Carbon Electricity, CCS

3. Potentials and Costs Summary
   • Moving towards net-zero
   • $/ton-HM v.s. $/ton-CO₂

4. Findings and Suggestions
   • Pathways and approaches
   • Policy Implications

5. Future Work
   • Longer term and more options
Iron and Steel:
Massive global industry
Globally traded, small margin commodity
Iron and Steel: 6% of global CO$_2$-eq emissions (same as cars)

In 2018:
1807 Mt/yr hot metal (HM)
1.85 ton-CO$_2$/ton-HM
$400/ton-HM

→ 3.34 Gt-CO$_2$/yr
*Source: Worldsteel Association*
Iron and Steel Production Pathways: Blast Furnace + Basic Oxygen Furnace

BF-BOF Pathway: 71%

- Coke Making: 97 kg-CO₂/ton-HM
- 356 kWh/ton-HM
- Iron Ore
- Pelletizing: 35 kg-CO₂/ton-HM
- Sintering: 260 kg-CO₂/ton-HM

Blast Furnace: 1476 kg-CO₂/ton-HM

Hot-Metal (HM): End of Analysis

BOF: 193 kg-CO₂/ton-HM

Electricity: 460 kg-CO₂/ton-MWh

BF-BOF Output: 2224 kg-CO₂/ton-HM
Iron and Steel Production Pathways: Electric Arc Furnace & Direct Reduction Iron

**EAF-Scrap Pathway: 24%**

- **Scrap**
  - 420 kg-CO$_2$/ton-HM

- **EAF**

- **Hot-Metal (HM): End of Analysis**

- **EAF-Scrap output:** 842 kg-CO$_2$/ton-HM

**DRI-EAF Pathway: 5%**

- **Pretreatment**
  - 307 kg-CO$_2$/ton-HM

- **DRI**

- **Coal-based DRI**
  - 1048 kg-CO$_2$/ton-HM
  - 380 kWh/ton-HM

- **Gas-based DRI**
  - 522 kg-CO$_2$/ton-HM
  - 313 kWh/ton-HM

- **Electricity:**
  - 460 kg-CO$_2$/ton-MWh

- **DRI-EAF-coal output:** 1952 kg-CO$_2$/ton-HM

- **DRI-EAF-gas output:** 1395 kg-CO$_2$/ton-HM
1. Zero-C Hydrogen injection
   • Blue (with CCS) & Green (electrolysis) options
   • Fuel injection into furnaces or DRI unit

2. Biomass substitution
   • Charcoal, “biocoke”, biogas (not assessed)
   • Life-cycle (LCA) and land use change (LUC) terms dominate

3. Zero-carbon electricity replacement
   • No retrofit existing plants on reactors
   • Mostly focused on EAF and DRI

4. CCS
   • Retrofits to existing plants with conventional tech
   • Mostly focused on top-gas capture

5. Combination options
   • Only way to get deep decarbonization
   • Only one way to make net-negative emissions steel

Technology Options to Decarbonize Iron & Steel

• Not many options
• All have challenges
• Potential to decarbonize limited
Hydrogen Injection: ~20% limit for BF-BOF

Decarbonization potential:
DRI > BF

Costs ($/ton-HM & $/ton-CO₂):
DRI > BF
Green H₂ > Blue H₂

Hydrogen injection:
Practical reduction close to theoretical limits.
Biomass Substitution with Charcoal: Moderate potential; highly sensitive to LUC

**Ideal**: No C-footprint

**LCA**: Life cycle analysis C-footprint

**LUC**: Land-use change C-footprint

Biomass:

**Ideal** → **Best**

**Real** → **Worst**

**Uncertainty** is huge for biomass.

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**Decarbonization percentage (%)**

0% | 10% | 20% | 30% | 40% | 50% | 60% | 70% | 80% | 90% | 100%

**Cost ($)**

0 | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800

**BF-BOF (Biomass Ideal)**

- Decarbonization potential (%)
- Practical reduction (%)
- HM Cost increase ($/ton)
- CO₂ abatement cost ($/ton-CO₂)

**BF-BOF (Biomass LCA)**

**BF-BOF (Biomass LCA + LUC)**
# Zero-Carbon Electricity Penetration

## Replacing BF with DRI for Electrification and Deep Decarbonization

<table>
<thead>
<tr>
<th>Iron/steel production pathways and share (%)</th>
<th>Current Baseline</th>
<th>Medium DRI Replacement</th>
<th>High DRI Replacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF-BOF</td>
<td>71%</td>
<td>51%</td>
<td>26%</td>
</tr>
<tr>
<td>EAF-scrap</td>
<td>24%</td>
<td>24%</td>
<td>24%</td>
</tr>
<tr>
<td>DRI-EAF</td>
<td>5%</td>
<td>25%</td>
<td>50%</td>
</tr>
<tr>
<td>Weighted average CO2 intensity (kg-CO2/ton-HM)</td>
<td>1857</td>
<td>1713</td>
<td>1534</td>
</tr>
<tr>
<td>Electricity related CO2 emission (kg-CO2/ton-HM)</td>
<td>246</td>
<td>328</td>
<td>430</td>
</tr>
<tr>
<td>Non-Elec CO2 intensity (kg-CO2/ton-HM)</td>
<td>1611</td>
<td>1385</td>
<td>1104</td>
</tr>
<tr>
<td>Added electricity demand (TWh/yr) &amp; capacity (GW)</td>
<td>N/A</td>
<td>449.7 TWh 146.7 GW (35% capacity factor)</td>
<td>1011.9 TWh 330.0 GW (35% capacity factor)</td>
</tr>
</tbody>
</table>

DeCar potential (%) from Electricity

- BF-BOF: 0%
- EAF-scrap: 10%
- DRI-coal: 20%
- DRI-gas: 30%

Carbon intensity lower

Electricity emission higher

Significant zero-carbon electricity supply required.
Finding 1:

For deep iron/steel decarbonization we need all commercial options in combination.
Finding 2:

BF-BOF faces deep technical challenges.
1. BF-BOF has high carbon intensity
2. Decarbonization approaches for BF-BOF are limited.

Deep decarbonization potential better for EAF-Scrap & DRI+EAF systems

Suggests replacement agenda
Finding 3: enormous range of costs by option

1. Lowest cost options ($/ton CO$_2$): CCS and Zero-C electricity
2. Green H2 and non-ideal biomass are very expensive
Finding 4: Almost all options result in substantial production cost increases

![Graph showing cost increase per ton of hot metal production for different options.](Image)
Policy implications: Hard but important

**US Policy**

- High abatement costs limit conventional policy value
  - Broad infrastructure (zero-c power & CO2 pipeline) gets <50%
  - Insensitive to most carbon price policy proposals
  - Border tariffs must be very high
- **Must consider an asset replacement policy strategy**

- Potential policies to assist deployment & cost competitiveness
  - Replacement grants (GND?)
  - Govt. procurement
  - Incentives for early adopters

**International Policy**

- Most production not in US
  - Will require international standards
  - Will require sectoral participation from companies (including SOEs)
- Not clear what is best model to engage
  - Border tariffs (EU): Unlikely to deliver abatement
  - **Proactive club of nations & companies**
  - Sectoral effort parallel to Paris & G20
- Innovation agenda (possible Mission Innovation target)
Towards a Low-Carbon Future

Future for Iron/Steel

• Policies needed to assist deployment & cost competitiveness.

• Local decarbonization:
  - Design around local geography, economies, infrastructure, etc.
  - Engage local labor, communities, lawmakers, etc.

• Long-term future (>15 years) heavy on innovation agenda:
  - Overcoming technical challenges
  - MOE (electricity energy only)
  - HIsarna (<50% C-intense of BF)

Future for CaMRI Team

• Working on Iron/Steel
  - Specific geography cases (China, India)
  - More novel approaches (e.g., LanzaTech, new CCS)
  - More detailed analysis (e.g., ASPEN model)

• Component of broader on Industrial Decarbonization
  - Hydrogen production
  - Ammonia, Chemicals,
  - Cement & concrete
  - Etc……
Thank You