Pathways to Commercial Liftoff: Industrial Decarbonization

Interim Webinar

June 28, 2023
Overview: Pathways to Commercial Liftoff

Pathways to Commercial Liftoff represents a new DOE-wide approach to deep engagement between the public and private sectors.

The initiative’s goal is catalyzing commercialization and deployment of technologies critical to our nation’s net-zero goals.

Pathways to Commercial Liftoff started in 2022 to:

• collaborate, coordinate, and align with the private sector on what it will take to commercialize technologies
• provide a common fact base on key challenges (e.g., cost curve)
• establish a live tool and forum to update the fact base and pathways

Publications and webinar content can be found at Liftoff.energy.gov

Feedback is eagerly welcomed via liftoff@hq.doe.gov
Industrial decarbonization webinar

What this webinar is

- high-level overview of potential decarbonization pathways for U.S. industrial sectors
- preliminary perspective
- part of an upcoming set of industrial decarbonization liftoff reports
- Open for questions and comment via liftoff@hq.doe.gov

What this webinar is not

- a discussion of any specific programs or funding opportunities
- a technical overview of decarbonization technologies

Disclaimer:
- DOE is only communicating public and non-privileged information during this webinar.
- DOE will not be discussing the details of any specific program opportunity in this webinar (e.g., Request for Information, Notice of Intent, Funding Opportunity Announcement).
This analysis considered the processing and production steps in eight industrial sector value chains.

### Industrial Sector

#### Simplified value chains

1. **O&G upstream**
2. **Oil & Gas midstream**
3. **Refining**
4. **Processing**
5. **Fabrication/Storage**
6. **Distribution**

#### Chemicals

- **Raw material development**
  - Refining

#### Refining

- **Raw material development**
  - Storage

#### Iron & Steel

- **Raw material development**
  - Fabrication/conversion

#### Food & Beverage

- **Raw material development**
  - Storage

#### Cement

- **Raw material development**
  - Construction

#### Pulp & Paper

- **Raw material development**
  - Distribution

#### Aluminum

- **Raw material development**
  - Distribution

#### Glass

- **Raw material development**
  - Distribution

---

1. Given the share of U.S. emissions from this sector, further production stage emissions were included.
2. "Well-to-gate" emissions are not discussed in this presentation.
Based on DOE’s Industrial Decarbonization Roadmap and prior Liftoff Reports, we identified nine decarbonization levers for focus

Decarbonization levers are groups of technologies used to abate emissions from different sources…

- Carbon Capture and Storage (CCS)
- Industrial Electrification
- Energy Efficiency
- Electrolytic Hydrogen
- Raw Material Substitution
- Alternative Fuel – Non-H2
- Alt. production methods
- Clean onsite electricity + storage
- Grid Decarbonization

…with impact potential evaluated via a Marginal Abatement Cost Curve (MACC)

- On the path to net-zero, MACCs provide one scenario for decarbonization in the year 2030.
- The analysis selects for every ton of emissions studied which decarbonization levers may offer the lowest cost abatement in 2030.
- The MACC is informed by today’s best available public information for:
  - 2021 emissions baseline for US industries
  - Estimates of 2030 costs for technologies, including assumptions from prior Liftoff Reports (H2, CCS)
  - Technology readiness and applicability for addressable emissions across industries

Notes: 1. For the purposes of this analysis, CCS category also includes H2 production via Reforming + CCS.
Key Messages for Industrial Decarbonization

- **U.S. industrial players are at risk of lagging** behind net-zero targets; however, this narrative is changing with public sector support in BIL / IRA, increasing customers’ expectations to address emissions, and early private sector movers.

- **Emerging decarbonization levers** including energy efficiency, industrial electrification, carbon capture and storage (CCS), and alternative fuels are estimated to be least-cost to abate a portion of industrial emissions in 2030.

- **Continued research, development, and demonstration** of additional decarbonization levers (e.g., novel low-carbon production methods) is needed to fully abate emissions, lower overall costs, and de-risk decarbonization by 2050.

- **Potential capital deployment of $700B–$1.1T** from public and private sector investment and leverage of industrial materials’ small portion of end-products price would be required to decarbonize with emerging technologies.

- **Early commercial deployments** of decarbonization technologies in sector-specific applications could drive cost reductions and cross-sector learnings to boost the value proposition of similar, future projects.

- **Clear end-customer demand** would speed industrial decarbonization requiring action across supplier value chains to compete for market share and customer segments that value low-carbon products.
Agenda

• Introduction

• Cross-sector insights
  • Overview of industrial emissions targeted by Inflation Reduction Act (IRA)
  • Estimated role of decarbonization levers
  • Cross-sector challenges and potential solutions

• Sector-level insights
Liftoff report focuses on industrial sectors highlighted by IRA which represent ~14% (876 MT) of U.S. emissions

<table>
<thead>
<tr>
<th>U.S. total CO₂e emissions² Million tonnes of CO₂e in 2021</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat, electricity &amp; processing emissions for industrial sectors in IRA¹</td>
</tr>
<tr>
<td>Other industrials⁴</td>
</tr>
<tr>
<td>~6,330</td>
</tr>
<tr>
<td>~600</td>
</tr>
<tr>
<td>~5,200</td>
</tr>
</tbody>
</table>

Remaining U.S. emissions³

2021

---

1. Excluding ceramics
2. Includes other greenhouse gas emissions and non-industry sectors using GWP100
3. Includes agriculture, where emissions are largely methane and nitrous oxide from on the farm activities and is not within scope for DOE
4. Remaining industries include construction, computers & electronics, transportation and electrical equipment, production and use of fluorinated gasses among others
5. O&G upstream is not considered here by DOE since it is often addressed by EPA due to fugitive emissions

**Geography:** CO$_2$e emissions come from thousands of facilities, but 80% are concentrated in the South & Midwest$^1$

**Map of select U.S. point source CO$_2$ emissions by sector, 2021**

**Sectors**
- Cement
- Pulp & Paper
- Aluminum
- Iron & Steel
- Glass
- Chemicals
- Refining
- Food & Beverage

**GHG emissions (metric tons CO$_2$e)**
- <50k
- 50-200k
- >200k

1. Regions are defined using U.S. Census guidance.
2. Includes natural gas processing, refineries, chemicals (various), food processing, cement production, glass production, lime manufacturing, aluminum production, iron & steel production, pulp and paper manufacturers, and other paper products. EPA flight only records GHG emissions from facilities with reported emissions or quantity of GHG > 25,000 metric tons CO$_2$e.

**Share of U.S. industrial emissions for sectors in IRA, %, 100% = 876 Million tonnes of U.S. 2021 CO2e emissions**

- South: 56% (80%)
- Midwest: 24%
- Other regions: 20%

South & Midwest regions represent ~80% of point source emissions.
**Emissions source:** ~70% of CO2e emissions are heat- and process-related

**PRELIMINARY – VALUES SUBJECT TO CHANGE**

Emissions breakdown for industrial sectors of focus (2021), MT CO2e

<table>
<thead>
<tr>
<th>Emissions source</th>
<th>Emission breakdown</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low temp heat</td>
<td>15%</td>
<td>Low heat (-30-200C) emissions, where heating is end use</td>
</tr>
<tr>
<td>Mid temp heat</td>
<td>7%</td>
<td>Medium heat (200-400C) emissions, where heating is end use</td>
</tr>
<tr>
<td>High temp heat</td>
<td>30%</td>
<td>High heat (400C+) emissions, where heating is end use</td>
</tr>
<tr>
<td>Process</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process</td>
<td>18%</td>
<td>Process-related emissions from chemical transformation of raw materials and fugitive emissions</td>
</tr>
<tr>
<td>Electricity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>On-site power</td>
<td>9%</td>
<td>Electricity emissions for power produced on-site</td>
</tr>
<tr>
<td>Off-site power</td>
<td>18%</td>
<td>Electricity emissions for power from the grid</td>
</tr>
<tr>
<td>Other</td>
<td>3%</td>
<td>Other emissions sources1</td>
</tr>
</tbody>
</table>

1. Includes quarry and logistics emissions (Cement)

**Sector**: Chemicals and Refining together represent 60%+ of CO₂e emissions, while other U.S. sectors contribute to larger global footprints.

<table>
<thead>
<tr>
<th>Sector</th>
<th>Sector share of 2021 CO₂e emissions from eight industrial sectors of focus in IRA¹, %</th>
<th>U.S. 2021 emissions MT CO₂e</th>
<th>Global 2021 emissions MT CO₂e</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemicals²</td>
<td>36.0%</td>
<td>315</td>
<td>~1,000</td>
</tr>
<tr>
<td>Refining</td>
<td>27.7%</td>
<td>243</td>
<td>~1,400</td>
</tr>
<tr>
<td>Iron &amp; Steel</td>
<td>10.2%</td>
<td>89</td>
<td>~3,200</td>
</tr>
<tr>
<td>Food &amp; Beverage³</td>
<td>9.7%</td>
<td>85</td>
<td>~400</td>
</tr>
<tr>
<td>Cement³</td>
<td>7.9%</td>
<td>69</td>
<td>~3,500</td>
</tr>
<tr>
<td>Pulp &amp; Paper³</td>
<td>5.5%</td>
<td>48</td>
<td>~200</td>
</tr>
<tr>
<td>Aluminum</td>
<td>1.8%</td>
<td>16</td>
<td>~1,100</td>
</tr>
<tr>
<td>Glass</td>
<td>1.3%</td>
<td>11</td>
<td>~100</td>
</tr>
</tbody>
</table>

1. Includes other greenhouse gas emissions and non-industry sectors using GWP100
2. Split into natural gas processing (56 MT), ammonia (43 MT), ethylene steam cracking (39 MT), chlor-alkali (24 MT), other downstream chemical processes (112 MT)
3. Does not reflect biogenic emissions of the sector. Paper has estimated biogenic emissions of ~104 MT. Cement biogenic emissions resulting from use of alternative fuels.

Agenda

• Introduction

• Cross-sector insights
  • Overview of industrial emissions targeted by Inflation Reduction Act (IRA)
  • Estimated role of decarbonization levers
    • Cross-sector challenges and potential solutions

• Sector-level insights
Recall: Based on DOE’s Industrial Decarbonization Roadmap and prior Liftoff Reports, we identified nine decarbonization levers for focus

Decarbonization levers are groups of technologies used to abate emissions from different sources

- **Carbon Capture and Storage** – 45Q tax credit and cost estimates for 2030 capture, transport, and storage from Carbon Management Liftoff report
- **Energy Efficiency** – Cost estimates for a suite of available sector-specific technologies
- **Electrolytic Hydrogen** – 45V tax credit\(^2\) and cost estimates for 2030 production, transport, and storage from the H2 Liftoff Report
- **Alternative production methods** – Costs are not estimated; the role for 2050 is assessed by sector
- **Clean onsite power + storage** – Cost estimates based on onsite solar with long duration storage (LDES) with costs from the LDES Liftoff report
- **Grid Decarbonization** – Estimated based on linear progress of 100% clean power by 2035 goal

Notes: 1. For the purposes of this analysis, CCS includes H2 production via Reforming + CCS | 2. Assumptions for 45V based publicly available policy and guidance as of June 2023

Levers aligning to Low Carbon Fuels, Feedstocks, and Energy Sources pillar in Industrial Decarbonization Roadmap

Technologies also discussed in prior Liftoff reports from DOE
On the path to net-zero, a set of decarbonization levers are estimated to be the least-cost including tax credits like 48C and 45V in 2030.

### Industrial decarbonization lever

<table>
<thead>
<tr>
<th>Emissions category</th>
<th>Industrial decarbonization lever</th>
<th>Estimated abatement potential, MT CO₂</th>
<th>Share of abatement, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat and process</td>
<td>CCS (with H₂ production)</td>
<td>~210</td>
<td>~30%+</td>
</tr>
<tr>
<td></td>
<td>Reforming + CCS to produce H₂</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Industrial electrification</td>
<td>~85</td>
<td>~10%+</td>
</tr>
<tr>
<td></td>
<td>Energy efficiency</td>
<td>~75</td>
<td>~9%+</td>
</tr>
<tr>
<td></td>
<td>Electrolytic hydrogen</td>
<td>~35</td>
<td>~4%+</td>
</tr>
<tr>
<td></td>
<td>Raw material substitution</td>
<td>~25</td>
<td>~3%+</td>
</tr>
<tr>
<td></td>
<td>Alternate fuel - Non hydrogen</td>
<td>~20</td>
<td>~2%+</td>
</tr>
<tr>
<td></td>
<td>Alternative production methods</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>Clean onsite electricity + storage</td>
<td>~120</td>
<td>~14%+</td>
</tr>
<tr>
<td></td>
<td>Grid decarbonization</td>
<td></td>
<td>~17%</td>
</tr>
</tbody>
</table>

**Estimated capex needed:** $700B-1.19T

**Emerging technologies will be needed to abate 4% of emissions with no near-term lever and could reduce capex of full abatement.**

---

1. Based on 2021 emissions baseline | 2. Includes LDES / TES for storage of energy generated from renewables; subset of this abatement also includes electric boilers replacing natural gas boilers | 3. Unabated emissions account for ~30MT of CO₂, about ~4% share of total emissions. Additional external factors that reduce emissions by ~60 MT about ~8% of total emissions include mechanical recycling (Chemicals) and transport sector electrification (Refining) | 4. Includes alternative chemistries, production processes, and technologies | 5. Reforming + CCS H₂ falls under the total abatement potential for CCS (~40 MT CO₂). IRA credits are used for all CCS levers and electrolytic hydrogen production levers | 6. Reflects total of current least cost abatement potentials for each sector | 7. IRA credits are indirectly reflected in calculation of least cost abatement levers for each industry | 8. Industrial electrification use cases include transition to EAF (Steel), switching NG boilers with electric boilers (cross multiple industries, and electrifying high-temp heat processes (Cross-sector)) | 9. Reflects total of sector-level capex requirements. Details to follow in sector overviews | 10. Figure does not include unabated emissions or external factors (e.g., demand reduction) | 11. The split between electrolytic and reforming + CCS hydrogen was assumed based on currently announced projects; however, there is uncertainty around split in the long run. This analysis does not evaluate methane emissions trade-offs for chemicals and refining sectors. 75MT of CO₂ abatement for H₂ ties to ties to H₂ roadmap estimates for H₂ use in ammonia and refining by 2030.

Source: Industrials sector integrated MACC, DOE Chemicals & Refining Decarbonization Pathway
Today, ~15% of emissions studied can be abated with net-positive levers, while other levers could abate emissions with additional cost

**PRELIMINARY – VALUES SUBJECT TO CHANGE**

<table>
<thead>
<tr>
<th>Decarbonization lever</th>
<th>Net positive</th>
<th>$1 to 50</th>
<th>$51 to 100</th>
<th>$101 to 150</th>
<th>$151 to 250</th>
<th>$250+</th>
</tr>
</thead>
</table>
| CCS (with H2 production)

<table>
<thead>
<tr>
<th>Estimated abatement potential by economic impact ($/tCO₂ including 45Q and 45V)</th>
<th>~15</th>
<th>~70</th>
<th>~95</th>
<th>~70</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industrial electrification</td>
<td>~20</td>
<td>~10</td>
<td>~35</td>
<td>~151</td>
</tr>
<tr>
<td>Energy efficiency</td>
<td>~70</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Electrolytic hydrogen assumes accessible pipelines / storage</td>
<td>Electrolytic H2 costs uncertain; assumptions based current policy and guidance as of June 2023</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raw material substitution</td>
<td>~20</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Alternate fuel - Non hydrogen</td>
<td>~10</td>
<td>~10</td>
<td>~10</td>
<td>~10</td>
</tr>
<tr>
<td>Clean onsite electricity + storage</td>
<td>~20</td>
<td>~70</td>
<td>~35</td>
<td>~35</td>
</tr>
</tbody>
</table>

**Share of abatement potential, %**

| ~15% | ~5% | ~20% | ~15% | ~10% | <1% |

---

1. Based on 2021 emissions baseline | 2. Cost after applying levelized 45Q tax incentive from the Inflation Reduction Act; includes reforming + CCS applications as well (~40 MT overlap with Electrolytic H2) | 3. Includes costs associated with heating equipment for steam generation | 4. Cost after applying 45Q and 45V tax incentives from the Inflation Reduction Act for hydrogen production via reforming + CCS and electrolysis, respectively. Transport and Storage costs assumptions based on successful large-scale infrastructure buildout | 5. Factors include grid decarbonization, transport sector electrification, and mechanical recycling | 6. Cost based on estimated 2030 prices for decarbonization levers. 45Q and 45V are not stacked in this analysis

Source: Industrials sector integrated MACC, DOE Chemicals & Refining Decarbonization Pathway

Without swift, new technology development, in 2030, CCS could be the lowest cost to abate 30+% of emissions, due to:

- **Long asset lifetime**, infrequent downtime
- **Higher cost** of other decarbonization levers
- **Absence and/or limitations** of commercially available alternative decarbonization technologies
- **Majority of CCS abatement potential** in Chemicals and Refining sectors

To accelerate net-zero goals and lower costs, we need a range of cost-effective solutions via cost reductions and demand-side pull

Note: Unabated emissions (~30 MT), external factors (~200 MT) not shown
With continued cost reductions, other decarbonization levers may address the same emissions as CCS including electrification, electrolytic H2, and utilization opportunities.

**Industrial Sectors**

- **Refining**
  - Process heat
  - Fluid catalytic cracker
  - Steam methane reformer/Syngas
- **Chemicals**
  - Ethylene cracker (post combustion)
  - Other chemicals - cracking furnace
  - NGP – CO2
  - Blast Furnace/Basic Oxygen Furnace
- **Steel**
  - NG DRI/HBI
- **Cement**
  - Rotary kiln

**Stage of decarbonization lever development**

- **Deployable**
- **Demo**
- **R&D / Pilot**

**Emissions source**

- Process heat
- Fluid catalytic cracker
- Steam methane reformer/Syngas
- Ethylene cracker (post combustion)
- Other chemicals - cracking furnace
- NGP – CO2
- Blast Furnace/Basic Oxygen Furnace
- NG DRI/HBI
- Rotary kiln

**Decarbonization lever**

- Electrification: Low & High temp heat
- Alternative Fuel: Oxyfuel or Clean H2 (fuel)
- Electrolytic H2
- Electrification: Electric cracker
- Electrification: Transition to EAF
- Utilization
- H2-HBI
- Alternative ironmaking processes
- Alternative fuels
- Raw Material Substitution: Clinker substitution
- Alternative production / chemistry
- Electrification: Electric rotary kiln
- Hydrogen fuel

Source: Press search, expert interviews
Industrial materials are often a small portion of the price of end-products, even after decarbonization costs

Demand-side pull is building up… … and a small increase in end-product cost could enable industrial decarbonization today

2015 🟢 No significant pull for low-carbon products

2023 🟢 Early movers from both private and public-sector pushing demand for low-carbon products

2030 🟢 Consolidated demand for low-carbon products to meet short-term targets

End-Consumer willingness to pay for decarbonized products is highly product-specific and market-specific

Material producer 🟢 Face higher cost of production to decarbonize operations and production methods

Component manufacturer 🟢 Dilute increase in bill of materials costs due to share of spend on other inputs and non-material costs

Goods manufacturer 🟢 Absorb smaller increases in end-product costs (varies by product and market, e.g., auto, building & construction)

End consumer 🟢
Technology readiness and adoption readiness will drive cost reductions and technology improvement to accelerate net-zero and lower costs

- **Technology Readiness Levels (TRL)** assess the maturity level of a particular technology (e.g., R&D vs. Commercial)

- TRL does not capture essential tech commercialization risk factors, such as product-market fit, demand pull, supply chain, workforce, siting & permitting, etc.

- DOE’s new “Adoption Readiness Level (ARL)” describes and assesses key adoption risks beyond technology risks that impede commercialization

Source: [https://www.energy.gov/technologytransitions/adoption-readiness-levels-arl-complement-trl](https://www.energy.gov/technologytransitions/adoption-readiness-levels-arl-complement-trl)
Industrial decarbonization pathways will evolve as decarbonization levers and underlying technologies mature across both TRL and ARL

DOE has characterized technologies in **three stages of commercialization** based on both Technology and Adoption Readiness Levels

Reaching net-zero will require:

Without development of new and existing technologies a portion of industrial emissions may remain unabated in the industrial sectors of focus
Exact decarbonization levers and capital for net-zero varies by sector

<table>
<thead>
<tr>
<th>Industrial Sector Lens</th>
<th>Chemicals</th>
<th>Refining</th>
<th>Iron &amp; Steel</th>
<th>Food &amp; Beverage</th>
<th>Cement</th>
<th>Pulp &amp; Paper</th>
<th>Aluminum</th>
<th>Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCS (with H2 production)</td>
<td>Various</td>
<td>FCC2, process heat, SMR2</td>
<td>BF-BOF4, NG-DRI/HBI5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Industrial electrification</td>
<td>Low-high temp heat alternatives</td>
<td>Low-high temp heat alternatives</td>
<td>EAF6 transition</td>
<td>Low-temp heat alternatives</td>
<td>Pre-calc, kiln</td>
<td>Low-mid temp heat alternatives</td>
<td>Low-temp, high temp, process</td>
<td>High temp melting</td>
</tr>
<tr>
<td>Electrolytic Hydrogen</td>
<td>Clean ammonia production</td>
<td>Hydrocracking, hydrotreating8</td>
<td>H2-HBI</td>
<td>Boiler</td>
<td>Rotary kiln</td>
<td>Boilers, burners</td>
<td>Calciner</td>
<td>Melting</td>
</tr>
<tr>
<td>Raw material substitutions</td>
<td>Recycling</td>
<td>Bio-based feedstock</td>
<td>NG-DRI/HBI6</td>
<td></td>
<td>Clinker substitution</td>
<td>Recycling</td>
<td>Recycling</td>
<td>Recycling, silica alternatives</td>
</tr>
<tr>
<td>Alt. fuel (non-H2)</td>
<td></td>
<td>Boilers, various equipment</td>
<td></td>
<td>Rotary kiln</td>
<td>Boilers, burners</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alt. production methods</td>
<td>Bio-based plastics1</td>
<td>Ironmaking processes</td>
<td>Various8</td>
<td></td>
<td>Electrochemical7</td>
<td>Carbochlorination, inert anode</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Agenda

• Introduction

• Cross-sector insights
  • Overview of industrial emissions targeted by Inflation Reduction Act (IRA)
  • Estimated role of decarbonization levers
  • Cross-sector challenges and potential solutions

• Sector-level insights
Industrial decarbonization can be accelerated today with public sector support, demand-side pressure, and early private sector action

Today, U.S. industry is at risk of lagging net-zero targets...

- Across sectors, goals of top U.S. industrial companies only represent only a ~15% reduction of scope 1 and 2 U.S. industrial emissions by 2035
- Market players cite common concerns driving reluctance to be a first mover:
  - Value Proposition
  - Resource Maturity
  - Limited Technologies
  - Market Acceptance
  - Additional sector-specific challenges

...However, this narrative is changing including:

Public sector support in BIL\(^1\), IRA\(^1\), and more:
- OCED’s ~$6.2B for industrial decarbonization demonstration-to-deployment program
- 48C Advanced Manufacturing Tax Credit
- R&D and transformative solutions (e.g., Energy Earthshots)

Customers expect companies to address emissions:
- Federal Buy Clean Initiative
- Demand signals for low-carbon products (e.g., First Movers Coalition, Frontier)

Some companies making bold moves:
- Accelerating commercialization of decarbonization technologies with public sector support
- Building low-carbon domestic products and exports
- Capturing low-carbon technology premiums

---

1. BIL = Bipartisan Infrastructure Law (formally called the Infrastructure Investment and Jobs Act); IRA = Inflation Reduction Act

---

NOT EXHAUSTIVE
Challenges across the value chain must be addressed for industrial decarbonization to liftoff

ILLUSTRATIVE PRELIMINARY NOT EXHAUSTIVE

Suppliers

- Raw material development
- Processing & production
- Fabrication & storage
- Distribution

High delivered cost of technology

Lack of enabling infrastructure

High complexity to adopt

Capital flow challenges

Limited high-TRL\(^1\) technologies

Consumers

Customer

Limited Demand Maturity

Emerging demand-side pull for decarbonized products could increase pressure for robust decarbonization action across the supplier value chain

---

1. Technology Readiness Level
## Targeted solutions can address challenges across the value chain

<table>
<thead>
<tr>
<th>Challenges</th>
<th>Solutions</th>
<th>Example tactics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Value Proposition</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High delivered cost of technology</td>
<td>Close cost gap between incumbent and decarbonized technology for producers</td>
<td>• Demonstration projects</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Create buy-side consortia</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• R&amp;D on technology costs</td>
</tr>
<tr>
<td>High complexity to adopt</td>
<td>Integrate decarbonization strategy into <em>near- and long-term capital planning</em></td>
<td>• Opportunistic use of downtime</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Operational best-practices</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• R&amp;D on manufacturing and system integration</td>
</tr>
<tr>
<td><strong>Resource Maturity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lack of enabling infrastructure</td>
<td>Build ecosystem to support <em>infrastructure</em> and assets</td>
<td>• Expedited permitting</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Regional hubs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Common-carrier infrastructure</td>
</tr>
<tr>
<td>Capital flow challenges</td>
<td>Improve access to <em>equity and debt financing</em> for low-carbon assets</td>
<td>• Transition risk in business case development</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Offtake agreements</td>
</tr>
<tr>
<td><strong>Technology readiness</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limited high-TRL(^1) technologies</td>
<td>Diversify decarbonization portfolios with <em>high-potential alternative technologies</em></td>
<td>• Pilot projects</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Sector-specific niches</td>
</tr>
<tr>
<td><strong>Market Acceptance</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limited demand maturity</td>
<td>Activate <em>demand-side pull</em> through coalitions and individual procurement deals</td>
<td>• Offtake agreements with defined green premiums</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Supplier assessments</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Voluntary or statutory requirements</td>
</tr>
</tbody>
</table>

---

1. Technology Readiness Level
• Introduction

• Cross-sector insights

• Sector-level insights
  – Sector leadership opportunities
    – Chemicals
    – Refining
    – Iron & Steel
    – Food & Beverage
    – Cement
    – Pulp & Paper
    – Aluminum
    – Glass
Every sector has unique opportunities to lead industrial decarbonization

<table>
<thead>
<tr>
<th>Industrial sector</th>
<th>Leadership opportunities include…</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemicals</td>
<td>Demonstrate <strong>world class, low-carbon chemicals processing domestically</strong> in pursuit of competitive advantage internationally</td>
</tr>
<tr>
<td>Refining</td>
<td>Make the U.S. a <strong>global leader in the production, usage and export of lower-carbon intensity fuels</strong>, to preserve industrial base and retain social license to operate</td>
</tr>
<tr>
<td>Iron &amp; Steel</td>
<td>Scale low-carbon ironmaking inputs to further <strong>solidify U.S. position as a global leader of low-carbon steel products</strong></td>
</tr>
<tr>
<td>Food &amp; Beverage</td>
<td>Activate consumer-side pull and grow business by educating consumers on the benefits of decarbonization and scale promising options for decarbonized <strong>low-temperature heat</strong></td>
</tr>
<tr>
<td>Cement</td>
<td>Transform U.S. cement into a pioneer for <strong>net-zero cement</strong>, capitalizing on already economic levers, low-carbon government procurement, and development of innovative cement-making</td>
</tr>
<tr>
<td>Pulp &amp; Paper</td>
<td>Achieve economic <strong>low-temperature heat decarbonization</strong> and reach <strong>carbon-negative operations</strong> with CCS retrofits</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Reach infinite recycling and <strong>build out cost-effective clean power to produce carbon-free aluminum and de-risk U.S. import reliance</strong></td>
</tr>
<tr>
<td>Glass</td>
<td>Unlock decarbonized <strong>high-temperature heat</strong> and set a precedential roadmap for other heat-intensive industrial processes</td>
</tr>
</tbody>
</table>
Agenda

• Introduction
• Cross-sector insights

• Sector-level insights
  − Sector leadership opportunities
  − Chemicals
    − Refining
    − Iron & Steel
    − Food & Beverage
    − Cement
    − Pulp & Paper
    − Aluminum
    − Glass
Chemicals: Industry Overview

Sub-sectors:
Ammonia, ethylene\(^5\), Natural Gas Processing (NGP), and chlor-alkali

\(~315\) MT CO\(_2\)e  
2021 U.S. emissions

\(~1,000\) MT CO\(_2\)e  
2021 Global emissions

Industry Context

- Chemicals is the largest exporting sector in the U.S., accounting for more than 9% of total U.S. exports
- U.S. demand for Chemicals is expected to grow \(~1.5\)% p.a. through 2030, creating opportunities to decarbonize new production capacity
- Chemicals decarbonization levers to-date have focused on energy efficiency & clean electricity\(^7\)
- Electrolytic H2 for ammonia and CCS on concentrated NGP\(^6\) streams have been deployed\(^8\)
- Industry Scope 1 & 2 reduction targets by 2035\(^4\) range between 15-50%

Source: EIA, EPA, IEDO Industrial Decarbonization Roadmap, U.S. Cybersecurity and Infrastructure Security Agency, IEA, press search, company sustainability reports, expert interviews

---

1. Includes other greenhouse gas emissions and non-industry sectors using GWP20 | 2. Split into natural gas processing (56 MT), ammonia (43 MT), ethylene steam cracking (39 MT), chlor-alkali (24 MT), other downstream chemical processes (112 MT) | 3. Does not reflect biogenic emissions of the sector | 4. Reflects range for largest U.S. chemicals players by market share | 5. Represents ethylene, propylene, and BTEX plastics precursor chemicals | 6. NGP = Natural gas processing | 7. Players are starting to cover a portion of their power consumption needs through renewable (V)PPAs | 8. There are announced deployments for Electrolytic H2 for ammonia in the U.S.
# Chemicals: Emissions baseline

**Emissions breakdown**

<table>
<thead>
<tr>
<th>Emissions source</th>
<th>CO₂e</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat¹</td>
<td>291 MT</td>
</tr>
<tr>
<td>Low temp heat</td>
<td>11%</td>
</tr>
<tr>
<td>Mid temp heat</td>
<td>18%</td>
</tr>
<tr>
<td>High temp heat</td>
<td>11%</td>
</tr>
<tr>
<td>Production</td>
<td>24%</td>
</tr>
<tr>
<td>Process</td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>24%</td>
</tr>
<tr>
<td>On-site power</td>
<td>12%</td>
</tr>
<tr>
<td>Off-site power</td>
<td>17%</td>
</tr>
<tr>
<td>Other</td>
<td>7%</td>
</tr>
<tr>
<td>Other</td>
<td></td>
</tr>
</tbody>
</table>

**Chemicals production has fragmented emission sources ...**

1. Temperature ranges: low-temperature heat is from \(-30\) C to 200 C, medium heat is from 200 C to 400 C, and high heat is 400+ C | 2. Breakdown of 2020 Chemicals production emissions

## Chemicals: Decarbonization levers

Decarbonization pathway (with IRA 45Q and 45V), based on 2030 cost estimates

<table>
<thead>
<tr>
<th>Lever</th>
<th>Description</th>
<th>Current lowest cost abatement, MT</th>
<th>Share of sector abatement potential</th>
<th>Abatement cost, $/tCO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat</td>
<td>Clean power [Other chem]: Onsite RES with LDES and e-boiler with TES</td>
<td>~50</td>
<td>~20%</td>
<td>~40-60</td>
</tr>
<tr>
<td></td>
<td>Energy efficiency [Ethylene]: Fuel use reduction</td>
<td>&lt;5</td>
<td>&lt;5%</td>
<td>~(100)-(80)²</td>
</tr>
<tr>
<td>Heat</td>
<td>Clean power [Chlor-alkali, Other chem]: Onsite RES with LDES and e-boiler with TES</td>
<td>~35</td>
<td>~10%</td>
<td>~40-70</td>
</tr>
<tr>
<td></td>
<td>CCS [Ethylene, Other chem]: Steam cracking furnace</td>
<td>~35</td>
<td>~10%</td>
<td>~140-180</td>
</tr>
<tr>
<td></td>
<td>CCS [Ammonia]: Dilute flue gas from SMR</td>
<td>&lt;5</td>
<td>&lt;5%</td>
<td>~110-140</td>
</tr>
<tr>
<td>Process</td>
<td>CCS [NGP¹]: Associated CO₂ emissions</td>
<td>~15</td>
<td>~5%</td>
<td>~(20)-(10)</td>
</tr>
<tr>
<td></td>
<td>CCS [Ammonia]: Dilute flue gas from SMR</td>
<td>~15</td>
<td>~5%</td>
<td>~110-140</td>
</tr>
<tr>
<td></td>
<td>Electrolytic Hydrogen [Ammonia]: Electrolyzer powered by RES</td>
<td>~15</td>
<td>~5%</td>
<td>Costs uncertain; assumptions based current policy and guidance as of June 2023</td>
</tr>
<tr>
<td>Power</td>
<td>Electrification [NGP¹]: Compressor electrification with power generation by renewables</td>
<td>~20</td>
<td>~5%</td>
<td>~(50)-(30)</td>
</tr>
<tr>
<td></td>
<td>Clean power [Ammonia, Chlor-alkali, Ethylene, Other chem]: Power generation with RES and LDES</td>
<td>~40</td>
<td>~15%</td>
<td>~30-70</td>
</tr>
</tbody>
</table>

1. RES = Renewable energy sources; TES = Thermal energy storage; NGP = Natural gas processing; LDES = Long-duration energy storage | 2. (X) indicates negative cost or net-positive lever

Chemicals: Operational decarbonization momentum (varies by subsector)

**U.S. stage of decarbonization lever development**

- **Deployable**
- **Demo**
- **R&D / Pilot**

### Energy efficiency

- **On-site low-carbon electricity**

### CCS with H2 production

1. Deployed for NGP and ammonia, pilot/demo for ethylene, limited deployment for chlor-alkali
2. Not exhaustive
3. Not applicable for NGP and ammonia
4. Limited deployment only including NGP and ammonia
5. Such as biobased plastics (ethanol dehydration)

### Electrification

2. (R&D: electric cracker, Demo: NGP Compressor)

### Recycling

3.

### Alternative production methods

4.

Source: EIA, EPA, IEDO Industrial Decarbonization Roadmap, IEA, press search, company sustainability reports, expert interviews

---

**PRELIMINARY**  **NOT EXHAUSTIVE**  **ILLUSTRATIVE**
Chemicals liftoff pathway: Demonstrate world class, low-carbon chemicals processing domestically in pursuit of competitive advantage internationally

**Technology examples**
- **Deployable**
  - Energy efficiency
  - Electrification [NGP]
  - Electrolytic H2 [Ammonia]
  - Clean electricity [Chlor-alkali]
  - CCS in concentrated streams [NGP]
  - Grid decarbonization

- **Demo**
  - Low temp. heat electrification
  - CCS on dilute streams
  - Bio-based feedstocks and chemicals

- **R&D/Pilot**
  - Electrification (e.g., Electric cracker, catalytic cracker [Ethylene])
  - Alternative production methods (e.g., low-carbon feedstocks²)

**Net-zero pathway enablers**
- **Deployable**
  - Adopt best available technology at large chemical plants
  - Adopt electric compressors at 400+ NG processing plants
  - Produce and use Electrolytic H2 in ammonia production, enabled by 45V
  - Retrofit NG processing plants with CCS, enabled by 45Q

- **Demo**
  - Reach ~$15/MWh² cost of low temp. heat electrification to be competitive with fossil fuel boilers/burners enabled by demonstrations and cost downs
  - Close the CCS cost gap on dilute streams after 45Q incentives with demonstrations, CCS infrastructure, and emerging green premium for decarbonized chemical products
  - Adopt advanced bio-feedstocks for chemicals after green premium develops

- **R&D/Pilot**
  - Reach ~$35/MWh⁴ cost of alternative steam cracker technologies to be competitive with fossil fuel
  - Mature alternative decarbonized production methods (e.g., bio-plastics and enzyme engineering) to be cost competitive with incumbent methods

**Timeline**
- 2023
- 2030
- 2040
- 2050

**Investment**
- $400 – 600B

1. Current ranges consider how abatement potential might evolve if all CCS applications (e.g., dilute streams) do not reach full maturity/scale. Abatement share ranges are constrained and based on two alternative decarbonization pathways | 2. Includes bio-based or captured CO₂ | 3. Estimated as breakeven point on the MACC levelized cost of heat to reach $0/CO₂e abatement cost for ethylene steam generation | 4. Estimated as breakeven point on the MACC levelized cost of heat to reach $0/CO₂e abatement cost for ethylene steam cracking furnace | 5. Refer to DOE Chemicals & Refining for further detail on capex methodology

Source: EIA Natural Gas Processing Plants (Count of NGP plants)
Agenda

- Introduction
- Cross-sector insights
- Sector-level insights
  - Sector leadership opportunities
  - Chemicals
  - Refining
    - Iron & Steel
    - Food & Beverage
    - Cement
    - Pulp & Paper
    - Aluminum
    - Glass
Sector share of 2021 CO₂e emissions from eight industrial sectors of focus in IRA¹, %

<table>
<thead>
<tr>
<th>Sector</th>
<th>Share (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemicals²</td>
<td>36.0</td>
</tr>
<tr>
<td>Refining</td>
<td>27.7</td>
</tr>
<tr>
<td>Iron &amp; Steel</td>
<td>10.2</td>
</tr>
<tr>
<td>Food &amp; Beverage³</td>
<td>9.7</td>
</tr>
<tr>
<td>Cement³</td>
<td>7.9</td>
</tr>
<tr>
<td>Pulp &amp; Paper³</td>
<td>5.5</td>
</tr>
<tr>
<td>Aluminum</td>
<td>1.8</td>
</tr>
<tr>
<td>Glass</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Industry Context

- U.S. refining sector produces transport fuels⁴ and petrochemical feedstocks
- U.S. transport sector electrification will reduce domestic fuel consumption
- Domestic production of diesel and gasoline⁵ may remain via potential shift to export and renewable fuels
- Though U.S. refineries have been transitioning towards renewable fuels, this segment is expected to represent limited U.S. refining capacity in 2030⁶
- Industry Scope 1&2 reduction targets by 2035⁷ range between 30-50%

~243 MT CO₂e 2021 U.S. Emissions
~1,400 MT CO₂e 2021 Global Emissions

1. Includes other greenhouse gas emissions and non-industry sectors using GWP20 | 2. Split into natural gas processing (56 MT), ammonia (43 MT), ethylene steam cracking (39 MT), chlor-alkali (24 MT), other downstream chemical processes (112 MT) | 3. Does not reflect biogenic emissions of the sector | 4. Such as gasoline, diesel, and jet fuel | 5. Demand for U.S. refined products is expected to decrease 0.7% per annum through 2030 but may be offset by an increase in exports | 6. Sustainable fuels production can emit more emissions than fossil fuel production and still requires operational decarbonization | 7. Reflects range for largest U.S. refining players by market share; Target values with Low N excluded
Almost half of refining emissions are from high-temp heating ...

1. Temperature ranges: low-temperature heat is from -30 C to 200 C, medium heat is from 200 C to 400 C, and high heat is 400+ C. 2. Breakdown of 2020 Refining emissions

# Refining: Decarbonization levers

Decarbonization pathway (with IRA 45Q and 45V), based on 2030 cost estimates

<table>
<thead>
<tr>
<th>Lever</th>
<th>Energy Efficiency Measures</th>
<th>CCS on Process Heat</th>
<th>CCS on FCC&lt;sup&gt;1&lt;/sup&gt;</th>
<th>CCS on SMR&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Electrolytic H&lt;sub&gt;2&lt;/sub&gt;</th>
<th>Onsite Clean Electricity and Storage</th>
<th>Grid Decarbonization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finishing: Treating products to achieve desired mix</td>
<td>~20</td>
<td>~50</td>
<td>~25</td>
<td>~20</td>
<td>~15</td>
<td>~15</td>
<td></td>
</tr>
<tr>
<td>Atmospheric distillation: Boils and separates crude oil residuals</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FCC&lt;sup&gt;1&lt;/sup&gt;: Cracks heavy products to generate lighter products in presence of catalyst</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrotreating: Removes sulfur or nitrogen</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam methane reforming: Production of hydrogen for hydrotreating and hydrocracking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power: CHP for onsite power and steam generation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power: Grid decarbonization</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. SMR = steam methane reformer; FCC = Fluidized catalytic cracking; CHP = Combined heat and power; LDES = Long-duration energy storage | 2. An additional 9% of abatement potential can be gained from energy efficiency measures including reducing fuel consumption and repurposing flare gas | 3. (X) indicates negative cost or net-positive lever | 4. Displayed cost estimates based on EUI Foundation capture costs with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10-40/tonne, except where noted. All in 2022 dollars. All CCS figures represent retrofits, not new-build facilities. The lower bound costs represents a NOAK plant in a low cost retrofit scenario with low inflation. The higher bound costs represents a FOAK plant in a high cost retrofit scenario with high inflation. |

Costs uncertain; assumptions based on current policy and guidance as of June 2023

~10% Share of sector abatement potential

## Introduction

Cross-sector Insights

Sector-level Insights

---

**PRELIMINARY – VALUES SUBJECT TO CHANGE**

**ABATEMENT FIGURES ONLY REFLECT CO<sub>2</sub> (NO OTHER GHG)**

<table>
<thead>
<tr>
<th>% Share of sector abatement potential</th>
<th>Current lowest cost abatement&lt;sup&gt;2&lt;/sup&gt;, MT</th>
<th>Abatement cost, $/tCO&lt;sub&gt;2&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>~10%</td>
<td>~20</td>
<td>~10%</td>
</tr>
<tr>
<td>~20%</td>
<td>~50</td>
<td>~10%</td>
</tr>
<tr>
<td>~10%</td>
<td>~25</td>
<td>~10%</td>
</tr>
<tr>
<td>~5%</td>
<td>~20</td>
<td>~5%</td>
</tr>
<tr>
<td>~15%</td>
<td>~15</td>
<td>~15%</td>
</tr>
<tr>
<td>N/A</td>
<td>~15</td>
<td>N/A</td>
</tr>
</tbody>
</table>

---

Refining: Operational decarbonization momentum

**U.S. stage of decarbonization lever development**

- **Deployable**
- **Demo**
- **R&D / Pilot**

1. **Energy efficiency**
2. **CCS with H2 production** (e.g., SMR¹)
3. **Raw material substitution** (e.g., bio-based feedstocks)²
4. **Industrial electrification** (e.g., cracker)

---

¹. SMR = Steam methane reformers
². Such as bio-based feedstocks for fuel production and sustainable aviation fuels with decarbonized production facility
³. Refers to H2 use in traditional processes

Source: EIA, EPA, IEDO Industrial Decarbonization Roadmap, IEA, press search, company sustainability reports, expert interviews
Refining liftoff pathway: Make the U.S. a global leader in the production, usage and export of clean fuels, to preserve industrial base and retain social license to operate

<table>
<thead>
<tr>
<th>Technology examples</th>
<th>Net-zero pathway enablers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deployable</td>
<td>Scale</td>
</tr>
<tr>
<td>Energy efficiency</td>
<td>Adopt best available technology at 130+ refineries</td>
</tr>
<tr>
<td>Electrolytic H₂</td>
<td>Produce and use Electrolytic H₂, enabled by 45V</td>
</tr>
<tr>
<td>Grid decarbonization</td>
<td>Scale production of sustainable fuels (e.g., renewable diesel) with existing production methods</td>
</tr>
<tr>
<td>Bio-based feedstocks with current production methods</td>
<td>Large-scale production of sustainable fuels (e.g., renewable diesel) with existing production methods</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Demo</th>
<th>Commercialize Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low temp. heat electrification</td>
<td>Achieve &lt;$30/MWh² cost of electrifying CHP unit to be competitive vs. fossil-fuel-powered CHP enabled by demonstrations and cost downs</td>
</tr>
<tr>
<td>CCS on dilute streams</td>
<td>Close the CO₂ cost gap on dilute streams (e.g., FCC, process heat) after 45Q incentives with demonstrations and CCS infrastructure build out</td>
</tr>
<tr>
<td>CHP + modular nuclear reactor</td>
<td>Mature CHP + modular nuclear reactor through R&amp;D and demonstrations to achieve &lt;$30/MWh cost to compete with fossil-fuel-powered CHP</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>R&amp;D/Pilot</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternative production methods (e.g., sustainable fuels)</td>
<td>Mature sustainable fuels (e.g., renewable diesel, sustainable aviation fuel) made with decarbonized production methods and capture emerging green premium for low-carbon fuels</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Timeline</th>
<th>2023</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment</td>
<td>$200 – 300B</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. Regardless of transport electrification goals, this breakdown of decarbonization technologies will be required to reach Net-zero refining in the U.S. at varying scales. Current ranges consider how abatement potential might evolve if all CCS applications (e.g., FCC, process heat) do not reach full maturity/ scale. Abatement share ranges are constrained and based on two alternative decarbonization pathways. 2. Estimated as breakeven point on the MACC levelized cost of heat to reach $0/MCO₂e abatement cost for refining CHP. 3. Refer to DOE Chemicals & Refining for further detail on capex methodology.
Chemicals & Refining: 2030 Marginal Abatement Cost Curve with IRA

1. Electrification analysis includes IRA 48E incentive assuming the projects meet the prevailing wage and apprenticeship requirements and half of projects meet for the domestic content adder. Other policies are not considered in this analysis due to unclear economic impact (e.g., downstream impact of policies) and local impact (e.g., state and local policies). Asset and geography-specific consideration of policies could significantly impact choice of technology and resulting abatement costs. (2) Operation of compressor results in significant efficiency improvements over steam turbines (95% vs. 35% efficiency). (3) CCS assumptions based on EFI Foundation capture costs with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10/tonne (representing the lower and upper bounds of the displayed range) assuming the chemical engineering plant cost index (CEPCI) for base construction that meets the prevailing wage an efficiency improvements over steam turbines (95% vs. 35% efficiency). (5) Ethylene process assumes the costs associated with charging and TES as an archetypal setup; however, asset-specific heat generation can be achieved with other technologies such as heat pumps and resistance heaters. Technology development and asset-specific considerations could significantly impact the choice of heat generation technologies. (6) Ethylene feedstock assumptions used to model propylene and BTEX processes (e.g., feedstock and catalysts). (7) Displayed CCS cost estimates based on EFI Foundation capture costs with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10/tonne (representing the lower and upper bounds of the displayed range) except where noted. All ACC figures represent retrofits, not new-build facilities. The inflation variance on each cost estimate represents the range of cost increases on a generic chemical processing facility due to inflation from 2020 to 2030. (8) Demand reduction consists of primarily transport sector electrification as well as the impact of a mechanical recycling rate of 25% of all plastics. (9) Split of emissions streams assumed to be ~60% concentrated and ~40% dilute in SMR unit. Portion of SMR on associated CO2 (NGP) 2030 Abatement cost, USD/ton CO2

Unabated emissions ~3% remaining emissions due to incomplete CCS capture (~90%)

Abatement potential, Mt CO2

Agenda

• Introduction

• Cross-sector insights

• Sector-level insights
  - Sector leadership opportunities
  - Chemicals
  - Refining
  - Iron & Steel
    - Food & Beverage
    - Cement
    - Pulp & Paper
    - Aluminum
    - Glass
Iron & Steel: Industry Overview

<table>
<thead>
<tr>
<th>Sector share of 2021 CO₂e emissions from eight industrial sectors of focus in IRA¹, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemicals²</td>
</tr>
<tr>
<td>Refining</td>
</tr>
<tr>
<td>Iron &amp; Steel</td>
</tr>
<tr>
<td>Food &amp; Beverage³</td>
</tr>
<tr>
<td>Cement³</td>
</tr>
<tr>
<td>Pulp &amp; Paper³</td>
</tr>
<tr>
<td>Aluminum</td>
</tr>
<tr>
<td>Glass</td>
</tr>
</tbody>
</table>

~89 MT CO₂e 2021 U.S. Emissions

~3,200 MT CO₂e 2021 Global Emissions

Industry Context

- There are two primary steelmaking pathways: integrated Blast Furnace/Basic Oxygen Furnaces (BF-BOF) & Electric Arc Furnaces (EAF)
  - EAF production has grown 172% in the U.S. since 1970
  - EAF (70% of domestic production) is low-carbon but will likely face domestic resource constraints (e.g., scrap, DRI/HBI)
  - BF-BOF (30% of domestic production) represent 70% of U.S. sector CO₂ emissions
- Analysis focuses on primary steelmaking which accounts for >95% of value chain emissions
- U.S. steel production relies on the import of essential raw materials such as pig iron and DRI/HBI
- Industry Scope 1 & 2 reduction targets by 2035 range⁴ between 20-50%

1. Includes other greenhouse gas emissions and non-industry sectors using GWP20 | 2. Split into natural gas processing (56 MT), ammonia (43 MT), ethylene steam cracking (39 MT), chlor-alkali (24 MT), other downstream chemical processes (112 MT) | 3. Does not reflect biogenic emissions of the sector | 4. Reflects range for largest U.S. chemicals players by market share
Iron & Steel: Five primary production routes for net-zero steel in the U.S.

Comparison of opex, capex, and emissions intensity for low-carbon steel production routes

<table>
<thead>
<tr>
<th>Production Route</th>
<th>Opex Breakdown, $/ton liquid steel</th>
<th>Emissions Intensity, kg CO2/ton steel</th>
<th>Capex – Decarb Retrofit, $B</th>
<th>Capex – New Facility, $B</th>
<th>Decarbonization Challenges</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF-BOF + CCS</td>
<td>~$500-600</td>
<td>~0.3</td>
<td>~0.6</td>
<td>N/A</td>
<td>Limited demonstration of CCS on coke oven, BF-BOF</td>
</tr>
<tr>
<td>Scrap + EAF</td>
<td>$460</td>
<td>&lt;0.1</td>
<td>N/A</td>
<td>0.3</td>
<td>Can only produce long steel products</td>
</tr>
<tr>
<td>Scrap + NG-DRI/HBI + CCS + EAF</td>
<td>~$470-700</td>
<td>&lt;0.1</td>
<td>~0.3</td>
<td>~0.1</td>
<td>No commercial demonstrations of CCS retrofit for NG-DRI/HBI plants</td>
</tr>
<tr>
<td>Scrap + H2-DRI/HBI + EAF</td>
<td>~$550-800</td>
<td>&lt;0.1</td>
<td>~0.1</td>
<td>~0.9</td>
<td>No H2-DRI/HBI plants in the U.S.</td>
</tr>
<tr>
<td>Scrap + AIU – EAF</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>0.16</td>
<td>Technology still nascent, may take years to reach commercial scale</td>
</tr>
</tbody>
</table>

**Opex 1, Iron Units 8, Scrap 7, Energy - Electricity, Energy - NG, Energy - H2, CCS opex**

*There are emerging production technologies for low-carbon iron units including:*  
- Molten oxide electrolysis  
- Ammonia DRI  
- Hlsmelt process  
- …

*Emissions intensity and economics are unclear*  

**Introduction**  
Cross-sector Insights  
Sector-level Insights

1. Largely labor and mill maintenance | 2. Emissions intensity per ton liquid steel assumes that grid decarbonization reaches 100% by 2050 and contingent on carbon capture rate of 90% | 3. Assume scrap ratio of 60% combined with iron units in EAF and scrap ratio of 20% in BF-BOF | 4. Reflects costs for 1.2 MT facility. Retrofit reflects cost of CCS or H2 installation on existing facility | 5. There are no plans to build addition BF-BOF mills domestically | 6. Cost of retrofitting NG-DRI/HBI to H2 | 7. Scrap use is highly variable, many steelmakers will fluctuate use of iron ore and scrap as cost of these inputs change due to external conditions | 8. Assumes range uses cost difference between merchant and integrated DRI/HBI production | 9. Range assumes a Electrolytic H2 price of $2-$4/kg | 10. Includes new NG-DRI/HBI built with CCS | 11. Includes cost of electrolyzer | 12. Alternative iron units | 13. Cost to build new EAF | 14. Recent announcement by Nucor to deploy
Iron & Steel: Emissions baseline

Most of BF-BOF emissions are from high temp heat …

### Emissions breakdown\(^2\), CO\(_2\)e

<table>
<thead>
<tr>
<th>Emissions source</th>
<th>(\text{CO}_2)e</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat(^1)</td>
<td></td>
</tr>
<tr>
<td>Low temp heat</td>
<td></td>
</tr>
<tr>
<td>Mid temp heat</td>
<td></td>
</tr>
<tr>
<td>High temp heat</td>
<td></td>
</tr>
<tr>
<td>Production</td>
<td></td>
</tr>
<tr>
<td>Process</td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td></td>
</tr>
<tr>
<td>On-site power</td>
<td></td>
</tr>
<tr>
<td>Off-site power</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td></td>
</tr>
</tbody>
</table>

- **56 MT**: Steel (BF-BOF)
- **78%**
- **22%**

---

1. Temperature ranges: low-temperature heat is from -30 C to 200 C, medium heat is from 200 C to 400 C, and high heat is 400+ C.
2. Breakdown of 2021 BF-BOF Steel emissions

Source: McKinsey, Mission Possible Partnership Net-zero Steel, “Decarbonizing the iron and steel industry: A systematic review of sociotechnical systems, technological innovations, and policy options” (Kim et al., July 2022), World steel association, Steelmakers annual report
## Iron & Steel: Decarbonization Levers

Decarbonization pathway (with IRA 45Q and 45V), based on 2030 cost estimates

<table>
<thead>
<tr>
<th>Value chain step responsible for emissions</th>
<th>Lever</th>
<th>Current lowest cost abatement, MT</th>
<th>Abatement cost, $/tCO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coking Oven:</strong> Coal heated to produce coke</td>
<td>Raw material substitution (e.g., Add DRI/HBI to charge mix¹)</td>
<td>~5</td>
<td>~5%</td>
</tr>
<tr>
<td><strong>Blast Furnace:</strong> Iron ore pellets melted with coke &amp; limestone</td>
<td>CCS on coking oven, BF heat, BOF, NG-DRI/HBI</td>
<td>~30</td>
<td>~50%</td>
</tr>
<tr>
<td><strong>Basic Oxygen Furnace:</strong> Pig iron melted &amp; refined</td>
<td>Electrification (e.g., EAF¹)</td>
<td>~20²</td>
<td>~35%²</td>
</tr>
</tbody>
</table>

1. As more U.S. steelmakers shift to DRI/HBI-EAF there could be constrains on scrap metal availability as a key material input in U.S. EAFs (~0.7t/t of steel). Abatement reflects decarbonized grid scenario.  
2. Note that this reflects difference in furnace emissions and increased scrap consumption |  
3. NG DRI-EAF is estimated to be ~$100-150/ton whereas H2 DRI-EAF is ~$150-250/ton |  
4. Can only make up ~10-15% of material input |  
5. Varies by application. BF-BOF applications are expected to be $40-110/tCO₂ with 45 Q and NG-DRI/HBI applications are expected to be $140-290/tCO₂ |  
6. Displayed cost estimates based on EFI Foundation capture costs with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10-40/tonne, except where noted. All in 2022 dollars. All CCS figures represent retrofits, not new-build facilities. The lower bound costs represents a NOAK plant in a low cost retrofit scenario with low inflation. The higher bound costs represents a FOAK plant in a high cost retrofit scenario with high inflation.  

Source: McKinsey, Mission Possible Partnership Net-zero Steel, “Decarbonizing the iron and steel industry: A systematic review of sociotechnical systems, technological innovations, and policy options” (Kim et al., July 2022), World steel association, Steelmakers annual report
Iron & Steel: Operational decarbonization momentum (varies by subsector)

Deployable R&D / Pilot Demo

Energy efficiency

Industrial electrification (e.g., EAF)

Raw material substitution (e.g., DRI/HBI)

CCS (e.g., BF-BOF, NG DRI/EAF)

Alternative production methods (e.g., alternative ironmaking)

Electrolytic Hydrogen (e.g., H2-DRI/HBI)

1. Includes ammonia direct reduced iron, molten oxide electrolysis, liquid sodium reduction, hydrogen plasma direct reduction, aqueous electrolytic reduction

Iron & Steel liftoff pathway: Scale low-carbon ironmaking inputs to further solidify U.S. position as a global leader of low-carbon steel products

**Introduction**

**Cross-sector Insights**

**Sector-level Insights**

**Net-zero pathway enablers**

**Deployable**

- Energy efficiency
- Transition to EAF
- Raw material substitution (scrap, H2 DRI/HBI)
- Grid decarbonization
- Adopt best available technology at 8 remaining U.S. BF-BOF and increased use of DRI/HBI and ferrous scrap
- Continue migration of flat steel to EAF steelmaking route
- Increase U.S. DRI/HBI production enabled by stable supply of low-carbon DR pellets

**Demo**

- BF-BOF + CCS
- NG-DRI/HBI + CCS
- Electrolytic H2-DRI/HBI
- Reduce cost of CCS on BF-BOF by $75/tCO₂ via demonstrations, 45Q incentives, and buildout of CCS infrastructure
- Reduce CCS costs on NG-DRI/HBI, enabled by emerging green premium of low-carbon DRI/HBI in U.S. and by stable supply of low-carbon DR pellets
- Build FOAK Electrolytic H2-DRI/HBI in the U.S., supported by 45V incentives, cost downs for on-site electrolyzers, and domestic Electrolytic H2 infrastructure

**R&D/Pilot**

- Alternative production method (e.g., electrowinning, molten oxide electrolysis)
- Increase EAF production
- Scale alternative ironmaking processes to reach $350-400/ton and be cost competitive with DRI/HBI and pig iron through continued R&D and demos
- Expand EAF production to all flat products (e.g., exposed galvanized sheet) through continued R&D

**Timeline**

- 2023
- 2030
- 2040
- 2050

**Investment**

- $25 – 40³ B

---

1. To reach Net-zero steel will require development of CCS on EAF or bio-based cathode | 2. Abatement share ranges are constrained and based on alternative decarbonization pathways, varying on factors such as the number for BF-BOF mills that transition to EAF and evolution of CCS on BF-BOF and NG-DRI/HBI | 3. Reflects multiple decarbonization scenarios considering cost of CCS retrofits on 2-8 remaining BF-BOF, potential environmental clean-up shut down costs for 2-6 BF-BOF, building additional domestic 2.5 to 10MT NG based DRI/HBI, CCS to 5-15MT NG based DRI/HBI, CCS retrofits for EAF capacity, and FOAK U.S. Electrolytic H2 DRI/HBI – EAF | 4. Based on estimate merchant cost of pig iron, DRI/HBI | 5. Reflects cost gap for BF-BOF CCS as published in carbon management report
Agenda

- Introduction
- Cross-sector insights

- **Sector-level insights**
  - Sector leadership opportunities
  - Chemicals
  - Refining
  - Iron & Steel
  - Food & Beverage
    - Cement
    - Pulp & Paper
    - Aluminum
    - Glass
Food & Beverage: Industry Overview

| Sector share of 2021 CO₂e emissions from eight industrial sectors of focus in IRA¹, % |
|---------------------------------|---------------------|---------------------|
| Chemicals²                      | 36.0                |
| Refining                        | 27.7                |
| Iron & Steel                    | 10.2                |
| Food & Beverage³               | 9.7                 |
| Cement³                        | 7.9                 |
| Pulp & Paper³                   | 5.5                 |
| Aluminum                        | 1.8                 |
| Glass                           | 1.3                 |

~85⁴ MT CO₂e 2021 U.S. Emissions

~400 MT CO₂e 2021 Global Emissions

Industry Context

- F&B processing emissions are in scope for IRA but account for <10% of total value chain emissions across major product categories⁶
  - On-farm, transport, packaging, retail and post-consumer activities are out of scope
- There is substantial variation across F&B production processes
  - Deployment of decarbonization levers will need to be product- and geography-specific
- Industry Scope 1 & 2 reduction targets by 2035⁵ range between 10-40%

---

1. Includes other greenhouse gas emissions and non-industry sectors using GWP20 | 2. Split into natural gas processing (56 MT), ammonia (43 MT), ethylene steam cracking (39 MT), chlor-alkali (24 MT), other downstream chemical processes (112 MT) | 3. Does not reflect biogenic emissions of the sector | 4. Figures based on EIA 2021 energy-related emissions by end-use | 5. Scope 1 & 2 targets of largest U.S. F&B players for meat, dairy, and grain processing by market share. This reflects sustainability ambitions across all facilities which can also include farms and retail facilities | 6. Major product categories include meat processing, dairy processing, grain milling, fruits & vegetables
Food & Beverage: Emissions baseline

~50% of F&B processing emissions are from low temp heating

Emissions source

<table>
<thead>
<tr>
<th>Emissions Breakdown $^{2}$, CO$_{2}$e</th>
</tr>
</thead>
<tbody>
<tr>
<td>Food and Beverage</td>
</tr>
<tr>
<td>85 MT</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Heat$^{1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low temp heat</td>
</tr>
<tr>
<td>Mid temp heat</td>
</tr>
<tr>
<td>High temp heat</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Electricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-site power</td>
</tr>
<tr>
<td>Off-site power</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Other</td>
</tr>
</tbody>
</table>

1. Temperature ranges: low-temperature heat is from -30 C to 200 C, medium heat is from 200 C to 400 C, and high heat is 400+ C. 2. Breakdown of 2021 Food & Beverage processing emissions

## Food & Beverage: Decarbonization levers

Decarbonization pathway (with IRA 45Q and 45V), based on 2030 cost estimates

**PRELIMINARY – VALUES SUBJECT TO CHANGE**

<table>
<thead>
<tr>
<th>Value chain step responsible for emissions</th>
<th>Lever</th>
<th>Current lowest cost abatement, MT</th>
<th>Abatement cost, $/tCO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Steam generation</strong>: Boilers and CHP</td>
<td>Energy efficiency, e.g., reduced steam losses</td>
<td>~5</td>
<td>~5%</td>
</tr>
<tr>
<td></td>
<td>Electrification, e.g., e-boiler + TES³ with RES³</td>
<td>~20</td>
<td>~30%</td>
</tr>
<tr>
<td><strong>Process heating</strong>: Various equipment for different sub-sectors (e.g., ovens, fryers)</td>
<td>Energy efficiency, e.g., electric oven, electric fryers</td>
<td>~10</td>
<td>~10%</td>
</tr>
<tr>
<td></td>
<td>Alternative fuels, (e.g., biomass)</td>
<td>&lt;1</td>
<td>&lt;5%</td>
</tr>
<tr>
<td><strong>Process cooling⁵, conveyor belts, and other facility operations</strong>: Electricity consumption</td>
<td>Energy efficiency, e.g., efficient process cooling/refrigeration</td>
<td>~2</td>
<td>&lt;5%</td>
</tr>
<tr>
<td></td>
<td>Grid decarbonization</td>
<td>~40</td>
<td>~51%⁴</td>
</tr>
</tbody>
</table>

Reducing food loss is an indirect lever to reduce F&B processing emissions⁵

---

1. Wide range due to diverse products, processes, and facility sizes | 2. Figures for steam generation with electric boiler / TES and heat pumps / TES powered by on-site solar are $70-110 / tCO₂ | 3. RES = Renewable energy sources; TES = Thermal energy storage | 4. Based on White House – Long-term strategy of the U.S. Pathways to Net-zero | 5. Process cooling is a significant portion of current F&B processing electrical load and there are a range of levers that could be used to reduce electricity consumption | 6. Manufacturing is the largest source of food waste/loss

**Food & Beverage: Operational decarbonization momentum (varies by subsector)**

**U.S. stage of decarbonization lever development**

- **Deployable**
- **Demo**
- **R&D / Pilot**

---

**Efficiency**
(e.g., waste energy recovery)

**Alternative fuel – non-hydrogen**
(e.g., Deployable: Biomass in boilers, R&D: Biomass in other equipment\(^1\))

**Industrial electrification**
(e.g., Deployable: Electric boilers, R&D: Other equipment\(^1\))

**Alternative production methods\(^2\)**

**Electrolytic Hydrogen\(^1\)**
(e.g., H2 boilers)

---

Water usage is particularly intensive in F&B processing - wastewater treatment, recovery, and reuse could reduce facility’s water consumption and carbon footprint

---

1. Equipment varies by subsegment, product, and facility with some applications in different stages. | 2. E.g., absorption chillers, ejector refrigeration, deep waste energy and water recovery, alternative protein manufacturing

F&B liftoff pathway: Activate consumer-side pull and grow business by promoting decarbonization and scale options for low-temperature heat

**Technology examples**

**Deployable**
- Energy efficiency (e.g., energy mgmt. systems, increase CHP, efficient refrigerators, etc.)
- Grid decarbonization
- Electrification (boiler, heat pump)

**Demo**
- Alternative fuel for low temp heating equipment

**R&D/Pilot**
- Electrolytic H2 (e.g., boilers)
- Electrification (other equipment)
- Alternative production methods

**Net-zero pathway enablers**
- **Adopt best available technology across F&B processing facilities**
- Increase awareness of F&B processing emissions and solutions and proper food storage practices
- Co-create holistic emissions reduction plans with F&B players that tackle Scope 1-3 emissions
- **Reach ~$15/MWh**\(^3\) cost of low temp. heat electrification (e.g., electric boilers/heat pumps) to be competitive vs. fossil fuel boilers and other heating equipment (e.g., dryers, ovens), enabled by demonstrations and cost downs

**Timeline**
- 2023
- 2030
- 2040
- 2050

**Investment**
- $5-15B\(^2\)

**Sector abatement share**\(^1\) (excluding biogenic from process heat), %
- 70% (including grid decarb.)

**5-10+\%**

**20-25+\%**

---

1. Abatement share ranges are constrained and based on alternative decarbonization pathways, varying on factors such as the evolution of Electrolytic H2 boilers | 2. Capex estimate for Food and Beverage processing was based on assuming a) fossil-fuel based boilers are replaced with electric boilers and b) given the wide range of alternative equipment needed across F&B facilities the boiler estimate would represent roughly half of the total investment needed to decarbonize the industry | 3. Estimated as breakeven point on the MACC levelized cost of heat to reach $0/tCO\(_2\)e abatement cost for ethylene steam generation (used as a proxy for low-temperature heat) | 4. Includes electrification or alternative fuel use
Agenda

• Introduction
• Cross-sector insights

• Sector-level insights
  − Sector leadership opportunities
  − Chemicals
  − Refining
  − Iron & Steel
  − Food & Beverage
  − Cement
  − Pulp & Paper
  − Aluminum
  − Glass
Cement: Industry Overview

<table>
<thead>
<tr>
<th>Sector share of 2021 CO2e emissions from eight industrial sectors of focus in IRA¹, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemicals²</td>
</tr>
<tr>
<td>Refining</td>
</tr>
<tr>
<td>Iron &amp; Steel</td>
</tr>
<tr>
<td>Food &amp; Beverage³</td>
</tr>
<tr>
<td>Cement³</td>
</tr>
<tr>
<td>Pulp &amp; Paper³</td>
</tr>
<tr>
<td>Aluminum</td>
</tr>
<tr>
<td>Glass</td>
</tr>
</tbody>
</table>

~69 MT CO2e  2021 U.S. Emissions

~3,500 MT CO2e  2021 Global Emissions⁴

Industry Context

- Government procurement accounts for ~50% of the market, giving public sector an outsized role to play in accelerating decarbonization, but multiple tiers and fragmentation in value chain make it challenging to create clear demand signal
- 98 active cement plants in U.S. (96 in 34 states, 2 in PR)
- Significant opportunity for U.S. to expand use of low-carbon approaches compared to international peers:
  - Approximately 15% alternative fuels mix vs. Europe's average ~50%
  - 90% clinker-to-binder ratio vs. global average of ~70%
- Industry Scope 1 & 2 reduction targets by 2035 range⁵ between 10-65%


¹ Includes other greenhouse gas emissions and non-industry sectors using GWP20
² Split into natural gas processing (56 MT), ammonia (43 MT), ethylene steam cracking (39 MT), chlor-alkali (24 MT), other downstream chemical processes (112 MT)
³ Does not reflect biogenic emissions of the sector
⁴ Cement is the third largest CO2 emitter globally
⁵ Reflects range for major U.S. cement players by market share
Cement: Emissions baseline

Most cement emissions are from process and high-temp heat sources...

Emissions breakdown\(^2\), CO\(_2\)e

<table>
<thead>
<tr>
<th>Emissions source</th>
<th>CO(_2)e</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat(^1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low temp heat</td>
<td>69 MT</td>
<td>51%</td>
</tr>
<tr>
<td>Mid temp heat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High temp heat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Process</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>On-site power</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Off-site power</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1. Temperature ranges: low-temperature heat is from -30 C to 200 C, medium heat is from 200 C to 400 C, and high heat is 400+ C. 2. Breakdown of 2021 Cement emissions

# Cement: Decarbonization levers

Decarbonization pathway (with IRA 45Q and 45V), based on 2030 cost estimates

**PRELIMINARY – VALUES SUBJECT TO CHANGE**

<table>
<thead>
<tr>
<th>Lever</th>
<th>Current lowest cost abatement, MT</th>
<th>Abatement cost, $/tCO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy efficiency</td>
<td>~10%</td>
<td>Net Positive</td>
</tr>
<tr>
<td>Clinker substitution – e.g., fly ash, calcined clay</td>
<td>Up to 25%</td>
<td>Net Positive</td>
</tr>
<tr>
<td>Alternative fuel – waste, biomass</td>
<td>Up to 34%</td>
<td>~0-100</td>
</tr>
<tr>
<td>Alternative fuel - hydrogen</td>
<td>Up to 34%</td>
<td>~50-80²</td>
</tr>
<tr>
<td>Heat electrification</td>
<td>Up to 34%</td>
<td>Emerging economics</td>
</tr>
<tr>
<td>CCS on combustion and remaining emissions⁴</td>
<td>Up to 80%</td>
<td>~25-90⁶</td>
</tr>
<tr>
<td>Alternative production methods</td>
<td>TBD</td>
<td>Emerging economics</td>
</tr>
<tr>
<td>Alternative chemistries</td>
<td>TBD</td>
<td>Emerging economics</td>
</tr>
<tr>
<td>Grid decarbonization</td>
<td>~10%</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Reducing cement use in concrete and concrete consumption in construction can further reduce emissions

1. Average based on several different types of feedstocks | 2. Cost after applying levelized 45V tax credit | 3. Assuming 50% clinker to binder ratio with clinker substitution embodied emissions 50% lower | 4. Assuming 90% capture rate for all heat and production emissions | 5. Low figure based on low NETL estimate of $109 per ton including $10 T&S cost, assuming 30-year payback period; high figure based on NETL estimate of $132 per ton with $40 T&S cost and 15-year period.


Note: Use of alternative fuels and clinker substitutes in the U.S. lags behind EU averages, resulting in opportunity to close gap. See Excel backup for further detail
Cement: Operational decarbonization momentum (varies by subsector)

U.S. stage of decarbonization lever development

- Energy efficiency
- Alternative fuel (e.g., biomass, waste)
- Raw material substitution (e.g., clinker alternative)
- CCS
- Alternative production methods
- Alternative chemistry
- Industrial electrification (e.g., pre-calcination and kiln electrification)
- Alternate fuel – hydrogen

**Cement liftoff pathway:** Transform U.S. cement into a pioneer for net-zero cement, capitalizing on already economic levers, low-carbon government procurement, and development of innovative cement-making

### Technology examples

<table>
<thead>
<tr>
<th>Deployable</th>
<th>Pathway to commercial liftoff</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Deployable</strong></td>
<td><strong>Commercialize</strong></td>
<td><strong>Scale</strong></td>
</tr>
<tr>
<td>• Energy efficiency</td>
<td><strong>Scale currently deployable measures rapidly</strong>, enabled by accelerated testing &amp; validation of clinker substitution and low-carbon procurement standards</td>
<td><strong>Accelerate buildout of CCS</strong> at existing plant footprint, enabled by 45Q, cost-downs from FOAK to NOAK, and coordinated procurement to create investable demand signal</td>
</tr>
<tr>
<td>• Clinker substitutes (e.g., fly ash, steel slag, calcined clay)</td>
<td><strong>Demonstrate CCS on existing plants</strong>, enabled by 45Q and government support</td>
<td><strong>Accelerate buildout of greenfield plants</strong>, enabled by coordinated procurement to create investable demand signal</td>
</tr>
<tr>
<td>• Alternative fuels (waste, biomass)</td>
<td><strong>Build FOAK plants</strong>, enabled by government support</td>
<td><strong>Accelerate buildout of CCS</strong> at existing plant footprint, enabled by 45Q, cost-downs from FOAK to NOAK, and coordinated procurement to create investable demand signal</td>
</tr>
</tbody>
</table>

### Demo

<table>
<thead>
<tr>
<th>Demo</th>
<th><strong>Pilots/FOAK</strong></th>
<th><strong>Scale</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• CCS retrofits of existing plants</td>
<td><strong>Commercialize</strong></td>
<td><strong>Scale</strong></td>
</tr>
<tr>
<td>• Alternative production methods</td>
<td><strong>Build FOAK plants</strong>, enabled by government support</td>
<td><strong>Accelerate buildout of greenfield plants</strong>, enabled by coordinated procurement to create investable demand signal</td>
</tr>
<tr>
<td>– Noncarbonate feedstocks</td>
<td></td>
<td></td>
</tr>
<tr>
<td>– Electrochemical production</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### R&D/Pilot

<table>
<thead>
<tr>
<th>R&amp;D/Pilot</th>
<th><strong>R&amp;D</strong></th>
<th><strong>Scale</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>• Alternative chemistries requiring updated standards</td>
<td><strong>Achieve initial market share with alternative chemistries in non-structural niches</strong></td>
<td><strong>Expand supply chain to meet increased demand</strong></td>
</tr>
<tr>
<td><strong>Update standards and build customer trust</strong> to enable wider deployment</td>
<td></td>
<td>****</td>
</tr>
</tbody>
</table>

### Timeline

<table>
<thead>
<tr>
<th>Investment</th>
<th><strong>$50-110B</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2023</strong></td>
<td><strong>2030</strong></td>
</tr>
</tbody>
</table>

### Source:

1. Abatement share ranges are constrained and based on alternative decarbonization pathways, varying on factors such as the emergence of alternative production methods and chemistries | 2. Capex figures based on expert syndication

NOT EXHAUSTIVE

---

**PRELIMINARY – VALUES SUBJECT TO CHANGE**

**ILLUSTRATIVE**

**~30-60%** (including grid decarb)

**~40-70+%**

**TBD**

**Net-zero**
Agenda

- Introduction
- Cross-sector insights

**Sector-level insights**

- Sector leadership opportunities
- Chemicals
- Refining
- Iron & Steel
- Food & Beverage
- Cement
- **Pulp & Paper**
- Aluminum
- Glass
Pulp & Paper: Industry Overview

<table>
<thead>
<tr>
<th>Sector share of 2021 CO\textsubscript{2}e emissions from eight industrial sectors of focus in IRA\textsuperscript{1}, %</th>
<th>~48</th>
<th>MT CO\textsubscript{2}e</th>
<th>2021 U.S. Emissions\textsuperscript{4}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemicals\textsuperscript{2}</td>
<td>36.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Refining</td>
<td>27.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron &amp; Steel</td>
<td>10.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Food &amp; Beverage\textsuperscript{3}</td>
<td>9.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cement\textsuperscript{3}</td>
<td>7.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulp &amp; Paper\textsuperscript{3}</td>
<td>5.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>1.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td>1.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>~200 MT CO\textsubscript{2}e for 2021 Global Emissions</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Industry Context

- Paper demand is expected to grow <1% from 2021 to 2030
  - Packaging is expected to grow faster and printing to decrease
- Most paper mills are focusing on transitioning from remaining coal-fired boilers to natural gas and biomass boilers
  - The industry currently supplies >60% of their fuel needs from biomass
- Most U.S. paper producers are not implementing decarbonization levers beyond energy efficiency, renewable energy and recycling
- U.S. is a net exporter of Pulp & Paper products
- Industry Scope 1 & 2 reduction targets\textsuperscript{5} by 2035 range between 20-50%

\textsuperscript{1} Includes other greenhouse gas emissions and non-industry sectors using GWP20 | \textsuperscript{2} Split into natural gas processing (56 MT), ammonia (43 MT), ethylene steam cracking (39 MT), chlor-alkali (24 MT), other downstream chemical processes (112 MT) | \textsuperscript{3} Does not reflect biogenic emissions of the sector | \textsuperscript{4} Biogenic emissions account for an additional 104MT CO2e in 2020 | \textsuperscript{5} Scope 1 and 2 target of largest U.S. Pulp and Paper players
Pulp & Paper: Emissions baseline

**Emissions source**

<table>
<thead>
<tr>
<th>Type</th>
<th>Low temp heat</th>
<th>Mid temp heat</th>
<th>High temp heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Emissions breakdown^2, CO\textsubscript{2}e**

<table>
<thead>
<tr>
<th>Source</th>
<th>Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
<td>54%</td>
</tr>
<tr>
<td>On-site power</td>
<td>12%</td>
</tr>
<tr>
<td>Off-site power</td>
<td>20%</td>
</tr>
<tr>
<td>Other</td>
<td>0%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>On-site power</td>
<td>7%</td>
</tr>
<tr>
<td>Off-site power</td>
<td>7%</td>
</tr>
<tr>
<td>Other</td>
<td>0%</td>
</tr>
</tbody>
</table>

1. Temperature ranges: low-temperature heat is from -30 C to 200 C, medium heat is from 200 C to 400 C, and high heat is 400+ C. 2. Breakdown of 2021 Pulp & Paper production emissions

Source: FisherSolve Next 4.0.23.0301, expert interviews
## Decarbonization levers

Decarbonization pathway (with IRA 45Q and 45V), based on 2030 cost estimates

### Value chain step responsible for emissions

<table>
<thead>
<tr>
<th>Heat</th>
<th>Lever</th>
<th>Current lowest cost abatement, MT</th>
<th>Abatement Cost, $/tCO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drying: Uses a multi-cylinder dryer, drying is the most energy-intensive phase within the papermaking process</td>
<td>Energy efficiency¹ e.g., real time energy management systems</td>
<td>~10</td>
<td>~20% Net Positive</td>
</tr>
<tr>
<td></td>
<td>Alternative fuels² e.g., biomass</td>
<td>~10</td>
<td>~20% ~100 – 130</td>
</tr>
<tr>
<td></td>
<td>Electrification e.g., heat pumps, electric boiler, CHP</td>
<td>~10</td>
<td>~20% ~110 – 160</td>
</tr>
<tr>
<td></td>
<td>Electrolytic Hydrogen e.g., hydrogen burners, hydrogen boilers</td>
<td>Emerging economics</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alternative fuels e.g., biomass gasification, pyrolysis</td>
<td>Emerging technology, economics unclear</td>
<td></td>
</tr>
<tr>
<td>Burners: Supports drying process</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Evaporators: Evaporates and concentrates black liquor</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boilers: Produces steam and electricity</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Onsite electricity: burning fossil fuels on site to produce power</td>
<td>Clean onsite electricity e.g., biomass, onsite solar</td>
<td>~5</td>
<td>~15% ~50 – 100</td>
</tr>
<tr>
<td>Offsite electricity</td>
<td>Grid decarbonization</td>
<td>~7.5</td>
<td>~15% N/A</td>
</tr>
</tbody>
</table>

1. Energy efficiency levers could include real-time energy management systems, air dryers, variable speed drivers, turbo blower pump, new-technology pulper, radial blowers, mechanical vapor recompression, stationary siphon & drying bar | 2. Includes biomethane boilers (brownfield), biomass burner, RDF boiler, biomass boiler, biomethane burner (brownfield). Biogenic emissions could be decarbonized by post-combustion CCS

Source: FisherSolve Next 4.0.23.0301, DOE Chem and refining liftoff report, DOE hydrogen liftoff
Pulp & Paper: Operational decarbonization momentum

U.S. stage of decarbonization lever development

- **Deployable**
- **Demo**
- **R&D / Pilot**

**Energy efficiency**
(e.g., RTEM\(^1\))

**Alternate fuel – non hydrogen**
(e.g., biomass)

**Raw material substitution**
(e.g., recycling)

**Industrial electrification**
(e.g., heat pumps, boilers)

**Electrolytic Hydrogen**
(e.g., burners, boilers)

**CCS**
(e.g., black liquor boiler)

---

1. Real Time Energy Management
**Pulp & Paper liftoff pathway**: Achieve economic low-temperature heat decarbonization and reach carbon-negative operations with CCS retrofits

**Technology examples**
- **Deployable**
  - Energy efficiency
  - Clean electricity and alternative fuels (e.g., biomass)
  - Grid decarbonization
- **Demo**
  - Low temp. heat electrification
- **R&D/Pilot**
  - Alternative technology (e.g., gasification, pyrolysis)\(^1\)

**Net-zero pathway enablers**
- Adopt best available technology at 200+ aging paper mills, including mills with dwindling demand like printing
- Reach 80+% share of sustainable biomass fuel consumption for steam and electricity generation, enabled by stable long-term supply
- Reach ~$15/MWh\(^4\) cost of low temp. heat electrification to be competitive vs. fossil fuel boilers/burners, enabled by demonstrations and cost downs
- Commercialize biomass gasification and pyrolysis technology to create new revenue streams from production of H2 and SAF fuels, enabled by stable long-term supply of biomass

**Timeline**
- **2023**
- **2030**
- **2040**
- **2050**

**Investment**
\(\$10 - 15B\)

---

1. Biogenic emissions account for an additional 104MT CO2e in 2020 (over 2x the sector's energy related emissions) | 2. Abatement share ranges are constrained and based on alternative decarbonization pathways, varying on factors such as the use of alternative fuels | 3. Based on assumption that fossil-fuel based boilers are replaced with electric boilers. Capex is scaled for adoption of other levers such as electrification and alternate fuels | 4. Estimated as breakeven point on the MACC levelized cost of heat to reach $0/tCO\(_2\) e abatement cost for ethylene steam generation (used as a proxy for low-temperature heat)

Source: FisherSolve Next 4.0.23.0301, expert interviews
Agenda

• Introduction
• Cross-sector insights

• Sector-level insights
  - Sector leadership opportunities
  - Chemicals
  - Refining
  - Iron & Steel
  - Food & Beverage
  - Cement
  - Pulp & Paper
  - Aluminum
  - Glass
Aluminum: Industry Overview

<table>
<thead>
<tr>
<th>Sector</th>
<th>2021 U.S. Emissions</th>
<th>2021 Global Emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>~16 MT CO₂e</td>
<td>~1,100 MT CO₂e</td>
</tr>
<tr>
<td>Glass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sector share of 2021 CO₂e emissions from eight industrial sectors of focus in IRA¹, %</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chemicals²</td>
<td>36.0</td>
<td></td>
</tr>
<tr>
<td>Refining</td>
<td>27.7</td>
<td></td>
</tr>
<tr>
<td>Iron &amp; Steel</td>
<td>10.2</td>
<td></td>
</tr>
<tr>
<td>Food &amp; Beverage³</td>
<td>9.7</td>
<td></td>
</tr>
<tr>
<td>Cement³</td>
<td>7.9</td>
<td></td>
</tr>
<tr>
<td>Pulp &amp; Paper³</td>
<td>5.5</td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>1.8</td>
<td></td>
</tr>
<tr>
<td>Glass</td>
<td>1.3</td>
<td></td>
</tr>
</tbody>
</table>

Industry Context

- U.S. aluminum demand expected to increase due to energy transition and EV uptake
- U.S. currently relies significantly on imports of primary aluminum
  - U.S. primary aluminum supply has been historically shrinking due to high power costs with no near-term reversal expected
  - U.S. imports ~2Mt of primary aluminum (~66% of domestic primary aluminum demand), largely from Canada
- U.S. secondary aluminum supply has been increasing recycled content usage and has recently announced additional recycling capacity
- Industry Scope 1 & 2 reduction targets by 2035 range⁴ between 20-50%

1. Includes other greenhouse gas emissions and non-industry sectors using GWP20
2. Split into natural gas processing (56 MT), ammonia (43 MT), ethylene steam cracking (39 MT), chlor-alkali (24 MT), other downstream chemical processes (112 MT)
3. Does not reflect biogenic emissions of the sector
4. Scope 1 and 2 target of largest U.S. Pulp and Paper players

Source: International Aluminum Association, USGS, MPP – Net-zero aluminum, IEA
# Aluminum: Emissions baseline (1/2)

| Source | International Aluminum Association, USGS, MPP – Net-zero aluminum |

## U.S. aluminum production 2021, mt

<table>
<thead>
<tr>
<th>Process</th>
<th>CO₂ emission intensities, tCO₂e/t</th>
<th>CO₂ emission from aluminum production 2021, MT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alumina refining</td>
<td>1.4</td>
<td>1.1 (≈5% of total)</td>
</tr>
<tr>
<td>Smelting</td>
<td>0.9</td>
<td>2.7 (≈70% of total)</td>
</tr>
<tr>
<td>Rolling, extrusion, &amp; casting</td>
<td>4.1</td>
<td>3.8 (≈25% of total)</td>
</tr>
<tr>
<td>Total</td>
<td>7.7</td>
<td>8.2 ~16</td>
</tr>
</tbody>
</table>

Smelting accounts for the majority (~70%) of aluminum industry emissions, despite having lower U.S. production volumes than refining and secondary aluminum production.

Smelting is significantly more energy intensive than refining and casting.
**Aluminum: Emissions baseline (2/2)**

**Emissions source**

<table>
<thead>
<tr>
<th>Heat1</th>
<th>Low temp heat</th>
<th>Mid temp heat</th>
<th>High temp heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Production</td>
<td>Process</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electricity</td>
<td>On-site power</td>
<td>Off-site power</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>Other</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Emissions breakdown\(^2\), CO\(_2\)e**

<table>
<thead>
<tr>
<th>Source</th>
<th>Aluminum</th>
</tr>
</thead>
<tbody>
<tr>
<td>16 MT</td>
<td>5%</td>
</tr>
<tr>
<td></td>
<td>26%</td>
</tr>
<tr>
<td></td>
<td>17%</td>
</tr>
<tr>
<td></td>
<td>31%</td>
</tr>
<tr>
<td></td>
<td>21%</td>
</tr>
</tbody>
</table>

---

1. Temperature ranges: low-temperature heat is from -30 C to 200 C, medium heat is from 200 C to 400 C, and high heat is 400+ C. 2. Breakdown of 2021 Aluminum production emissions

Source: International Aluminum Association, USGS, MPP – Net-zero aluminum, IEA
### Aluminum: Decarbonization levers

Decarbonization pathway (with IRA 45Q and 45V), based on 2030 cost estimates

**PRELIMINARY – VALUES SUBJECT TO CHANGE**

<table>
<thead>
<tr>
<th>Production segment</th>
<th>Lever</th>
<th>Current lowest cost abatement, MT</th>
<th>Abatement cost, $/tCO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Alumina refining:</strong> digestion and calcination</td>
<td>Electrification (e.g., electric boiler, e-caliner)</td>
<td>&lt;1</td>
<td>&lt;5%</td>
</tr>
<tr>
<td></td>
<td>Energy efficiency (e.g., waste heat recovery)</td>
<td>&lt;1</td>
<td>&lt;5%</td>
</tr>
<tr>
<td><strong>Smelting:</strong> carbon anode consumption and electricity</td>
<td>Energy efficiency</td>
<td>~1</td>
<td>~10%</td>
</tr>
<tr>
<td></td>
<td>Grid decarbonization</td>
<td>~5</td>
<td>~35%</td>
</tr>
<tr>
<td></td>
<td>CCS on Hall-Heroult/Electrolysis</td>
<td>&lt;2</td>
<td>~15%</td>
</tr>
<tr>
<td><strong>Rolling, extrusion, and casting</strong></td>
<td>Energy efficiency</td>
<td>~2</td>
<td>~15%</td>
</tr>
<tr>
<td></td>
<td>Electrification (e.g., e-reheater)</td>
<td>&lt;1</td>
<td>~5%</td>
</tr>
<tr>
<td></td>
<td>Raw material substitution (recycling)</td>
<td>&lt;1</td>
<td>~5%</td>
</tr>
</tbody>
</table>

1. U.S. aluminum smelters are largely very old resulting in residual emissions of perfluorocarbons which are highly potent greenhouse gases from equipment leaks and disrepair | 2. Despite relatively small abatement potential, recycling has other ancillary benefits including de-risking U.S. aluminum exposure. | 2. (X) indicates negative cost or net-positive lever

Source: International Aluminum Association, USGS, MPP – Net-zero aluminum
Aluminum: Operational decarbonization momentum

U.S. stage of decarbonization lever development

- **Deployable**
- **Demo**
- **R&D / Pilot**

**Energy efficiency**
(e.g., heat recovery)

**Raw material substitution**
(Demo: Zorba processing,
Deployable: Increase scrap usage)

**Alternative production methods**
(R&D: Carbochlorination,
Demo: Inert anode)

**CCS**
(e.g., smelting process)

**Electrolytic Hydrogen**
(e.g., H2 calciner)

**Industrial electrification**
(R&D: High temp heat,
Deployable: Low temp heat)

---

1. Planned international deployment | 2. Select feasibility studies | 3. International pilots and deployments
Source: International Aluminum Association, USGS, MPP – Net-zero aluminum, expert interviews, IEA
Aluminum liftoff pathway: Reach infinite recycling and build out cost-effective clean power to produce carbon-free aluminum and de-risk U.S. import reliance

1. Reflects a) alumina refinery retrofit of fossil-fuel based boiler and calciner in digestion and calcination to electric boiler and electric/hydrogen calciner, b) retrofit of remaining 6 aluminum smelters, and 50+ rolling/extrusion/casting plants; 2. Estimated as breakeven point on the MACC levelized cost of heat to reach $0/tCO₂ abatement cost for ethylene steam generation (used as a proxy for low-temperature heat); 3. Abatement share ranges are constrained and based on alternative decarbonization pathways, varying on factors such as use of raw material substitution (e.g., Zorba processing); 4. Estimated as breakeven point on the MACC levelized cost of heat to reach $0/tCO₂ abatement cost for ethylene steam generation (used as a proxy for low-temperature heat); 5. Cost estimates based on [EFI Foundation capture costs] with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10-40/tonne

Source International Aluminum Association, USGS, MPP – Net-zero aluminum, expert interviews
Agenda

• Introduction
• Cross-sector insights

• Sector-level insights
  - Sector leadership opportunities
  - Chemicals
  - Refining
  - Iron & Steel
  - Food & Beverage
  - Cement
  - Pulp & Paper
  - Aluminum
  - Glass
**Glass: Industry Overview**

<table>
<thead>
<tr>
<th>Sector share of 2021 CO₂e emissions from eight industrial sectors of focus in IRA¹, %</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Chemicals</strong>²</td>
</tr>
<tr>
<td><strong>Refining</strong></td>
</tr>
<tr>
<td><strong>Iron &amp; Steel</strong></td>
</tr>
<tr>
<td><strong>Food &amp; Beverage</strong>³</td>
</tr>
<tr>
<td><strong>Cement</strong>³</td>
</tr>
<tr>
<td><strong>Pulp &amp; Paper</strong>³</td>
</tr>
<tr>
<td><strong>Aluminum</strong></td>
</tr>
<tr>
<td><strong>Glass</strong></td>
</tr>
</tbody>
</table>

~11 MT CO₂e 2021 U.S. Emissions

~100 MT CO₂e 2021 Global Emissions

**Industry Context**

- **U.S. is the leading glass importer worldwide, importing $8B+ in 2018**
- Flat glass and container glass are the largest segments by volume
  - Flat glass growth is driven by increase in solar panel and construction glass demand
  - Container glass growth is partially driven by sustainability and premium perception of glass containers vs. other substrates
  - Currently, the industry is focused on increasing cullet usage; however, U.S. container glass recycled content is 30% vs. 60% in Europe
- **Industry Scope 1 & 2 reduction targets by 2035 range⁴ between 15-50%**

---

1. Includes other greenhouse gas emissions and non-industry sectors using GWP20 | 2. Split into natural gas processing (56 MT), ammonia (43 MT), ethylene steam cracking (39 MT), chlor-alkali (24 MT), other downstream chemical processes (112 MT) | 3. Does not reflect biogenic emissions of the sector | 4. Reflects range for largest U.S. Glass players by market share

Glass: Emissions baseline

Most Glass emissions are from heat...

<table>
<thead>
<tr>
<th>Emissions source</th>
<th>CO₂e (MT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat¹</td>
<td></td>
</tr>
<tr>
<td>Low temp heat</td>
<td></td>
</tr>
<tr>
<td>Mid temp heat</td>
<td></td>
</tr>
<tr>
<td>High temp heat</td>
<td>11</td>
</tr>
<tr>
<td>Production</td>
<td></td>
</tr>
<tr>
<td>Process</td>
<td>47%</td>
</tr>
<tr>
<td>Electricity</td>
<td></td>
</tr>
<tr>
<td>On-site power</td>
<td>9%</td>
</tr>
<tr>
<td>Off-site power</td>
<td>40%</td>
</tr>
<tr>
<td>Other</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>47%</td>
</tr>
</tbody>
</table>

1. Temperature ranges: low-temperature heat is from -30 C to 200 C, medium heat is from 200 C to 400 C, and high heat is 400+ C. 2. Breakdown of 2021 Glass emissions

## Glass: Decarbonization levers

Decarbonization pathway (with IRA 45Q and 45V), based on 2030 cost estimates

**PRELIMINARY – VALUES SUBJECT TO CHANGE**

<table>
<thead>
<tr>
<th>Value chain step responsible for emissions</th>
<th>Lever</th>
<th>Potential abatement, MTCO$_2$</th>
<th>Abatement Cost, $/tCO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annealing: Cooling hot glass objects after they have been formed</td>
<td>Alternate fuel – non hydrogen (biomethane)</td>
<td>&lt;1</td>
<td>~5%</td>
</tr>
<tr>
<td>Melting: Heating mixture of materials in a furnace until it melts</td>
<td>Electrification – electric melting, electric boost</td>
<td>~1</td>
<td>~10%</td>
</tr>
<tr>
<td>Fining: Removing bubbles and impurities from molten glass by subjecting it to high-temperatures and controlled cooling to achieve a clear and uniform product</td>
<td>Energy efficiency – waste heat recovery</td>
<td>&lt;1</td>
<td>~5%</td>
</tr>
<tr>
<td></td>
<td>Energy efficiency - oxyfuel</td>
<td>&lt;1</td>
<td>~5%</td>
</tr>
<tr>
<td></td>
<td>Electrolytic Hydrogen – forming and post forming</td>
<td>&lt;1</td>
<td>~5%</td>
</tr>
<tr>
<td></td>
<td>CCS – melting and forming</td>
<td>~1</td>
<td>~15%</td>
</tr>
<tr>
<td>Batch and Mix: Weighing and mixing raw materials in specific proportions</td>
<td>Raw material substitution and recycling</td>
<td>~1</td>
<td>~10%</td>
</tr>
<tr>
<td>Forming: Shaping molten glass according to the desired end-product</td>
<td>Grid decarbonization</td>
<td>~5</td>
<td>~40%</td>
</tr>
</tbody>
</table>

---

1. Lower bound represents estimates for biomethane forming in container glass and higher bound represents estimates for biomethane melting in container glass

Glass: Operational decarbonization momentum

U.S. stage of decarbonization lever development

**Deployable**

- Energy efficiency (e.g., Oxyfuel, waste heat recovery)
- Raw material substitution (e.g., Deployable: recycling\(^1\), R&D: silica alternatives)
- Industrial electrification (e.g., electric melting)
- CCS (e.g., melting and forming)

**Demo**

- Alternative fuels (e.g., biomethane forming/postforming)

**R&D / Pilot**

- Electrolytic Hydrogen (e.g., H2 melting)

---

1. Increase cullet usage

Glass liftoff pathway: Unlock decarbonized high-temperature heat and set a precedential roadmap for other heat-intensive industrial processes

**Technology examples**

**Deployable**
- Raw material substitution – cullet usage
- Energy efficiency (e.g., Oxyfuel, waste heat recovery)
- Grid decarbonization

**Net-zero pathway enablers**
- Increase adoption of oxyfuel and waste heat recovery\(^4\), enabled by decreasing technology costs, increasing energy costs, and updated regulatory requirements
- Increase cullet usage\(^2\) at glass plants (container) enabled by better cullet collection, increased MRF\(^1\) capacity and improved MRF\(^1\) sorting

**Demo**
- CCS
- Alternative fuel (biomass)
- Electrification (preheating cullet)
- Raw material substitution – cullet usage

**Pilots/FOAK**
- Reduce CCS cost in glass plants (flat and container), enabled by 45Q tax credit incentives, emerging green premium for low-carbon glass and CCS infrastructure
- Increase cullet usage at flat glass plants, enabled by building supply chain for PV recycling and support building demolition recycling

**R&D/Pilot**
- Electrolytic Hydrogen
- Raw material substitution (e.g., silica alternatives)
- Electrification (melter)

**Timeline**
- **2023**
- **2030**
- **2040**
- **2050**

**Investment**
- **$5-15B**

---

1. Material recovery facility
2. EU's average cullet usage is 60% compared to the U.S. average of 30% 
3. Estimated as breakeven point on the MACC levelized cost of heat to reach $0/tCO2e abatement cost for ethylene steam cracking furnace (used as a proxy for low-temperature heat)\(4\). Use of oxyfuel will diminish potential for waste heat recovery (due to much lower flue gas volumes)\(5\). Abatement share ranges are constrained and based on alternative decarbonization pathways, varying on factors such as the evolution of CCS\(6\). Reflects oxyfuel, CCS and hydrogen levers being implemented for both flat and container glass. Per ton capex values were multiplied with total glass production. The model assumes growth rate of 2% p.a. from 2022 through 2030 for volume of glass produces in the U.S.