# 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**

# Based on DOE's Industrial Decarbonization Roadmap and prior Liftoff Reports, we identified nine decarbonization levers for focus

***Decarbonization pillars: inter-related, cross-cutting strategies to pursue in parallel***

**Energy Efficiency**

**Industrial Electrification**

**Low-Carbon Fuels, Feedstocks, and Energy Sources (LCFFES)**

- Electrolytic Hydrogen 🚀
- Raw Material Substitution
- Alternative Fuel – Non-H2
- Clean onsite electricity + storage 🚀
- Alternative production methods

**Carbon Capture, Utilization, and Storage (CCUS)** 🚀

**Grid Decarbonization and other external factors**

Key

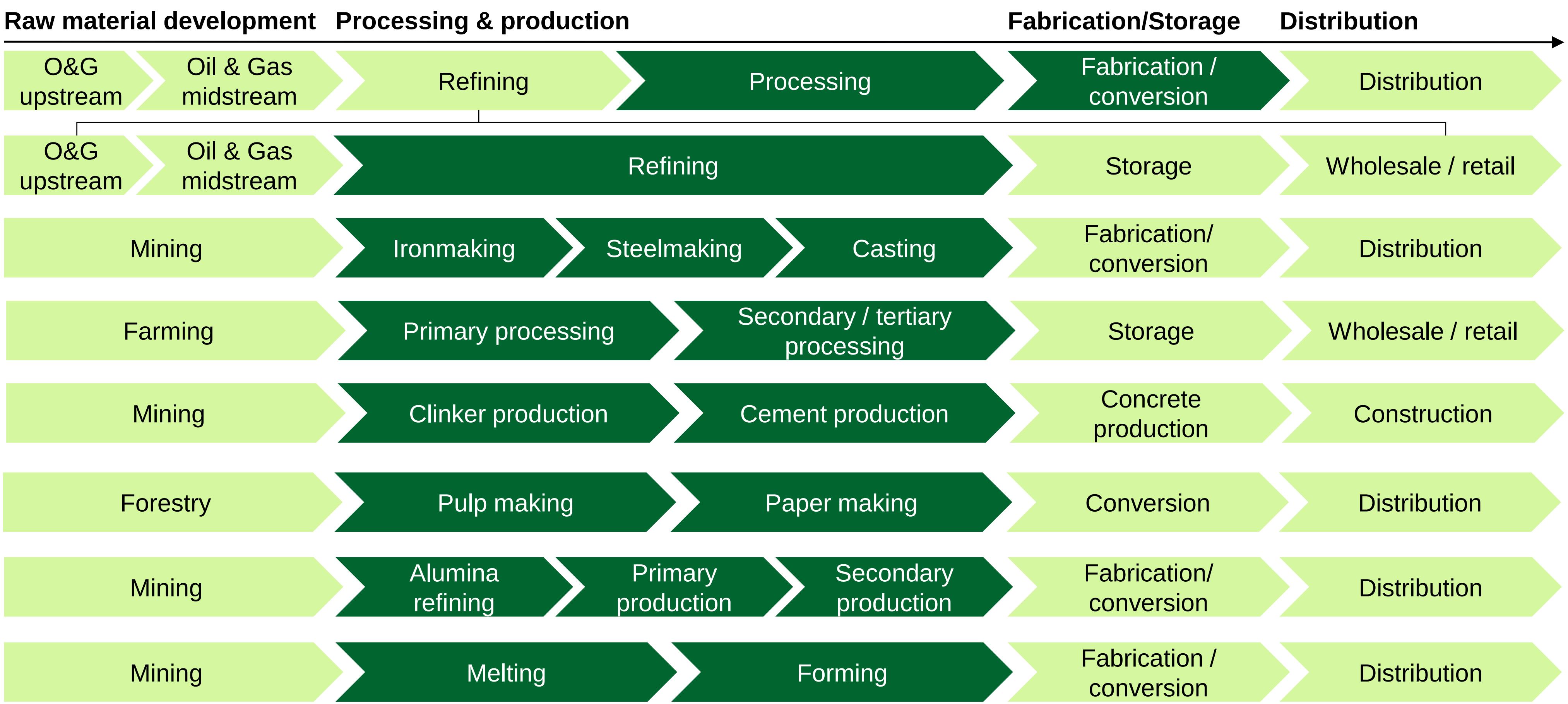
🚀 Technologies also discussed in prior Liftoff reports from DOE

Notes: 1. For the purposes of this analysis, CCS includes reformation-based H2. Utilization is included in overall discussions; however; MACC analysis focuses on CCS due to limited expected market for utilization.

# This analysis considered the processing and production steps in eight industrial sector value chains

■ In-scope □ Out-of-scope

**PRELIMINARY** **ILLUSTRATIVE** **TRANSPORTATION EMISSIONS NOT STUDIED**



**Simplified value chains[2]**

| Industrial Sector | Raw material development | Processing & production | Fabrication/Storage | Distribution |
|---|---|---|---|---|
| Chemicals[1] | □ O&G upstream<br>□ Oil & Gas midstream | □ Refining<br>■ Processing | ■ Fabrication / conversion | □ Distribution |
| Refining | □ O&G upstream<br>□ Oil & Gas midstream | ■ Refining | □ Storage | □ Wholesale / retail |
| Iron & Steel | □ Mining | ■ Ironmaking<br>■ Steelmaking<br>■ Casting | □ Fabrication/ conversion | □ Distribution |
| Food & Beverage | □ Farming | ■ Primary processing<br>■ Secondary / tertiary processing | □ Storage | □ Wholesale / retail |
| Cement | □ Mining | ■ Clinker production<br>■ Cement production | □ Concrete production | □ Construction |
| Pulp & Paper | □ Forestry | ■ Pulp making<br>■ Paper making | □ Conversion | □ Distribution |
| Aluminum | □ Mining | ■ Alumina refining<br>■ Primary production<br>■ Secondary production | □ Fabrication/ conversion | □ Distribution |
| Glass | □ Mining | ■ Melting<br>■ Forming | □ Fabrication / conversion | □ Distribution |

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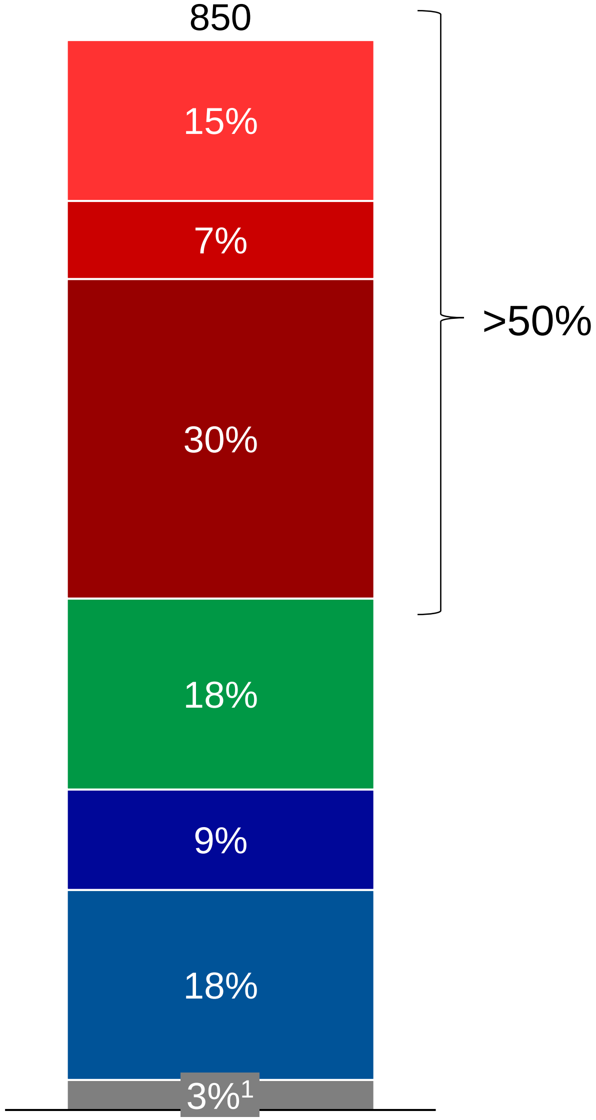
1. Given the share of U.S. emissions from this sector, further production stage emissions (e.g., natural gas processing) were included | 2. "Well-to-gate" emissions are not discussed in this presentation

# Majority of emissions in sectors of focus are from heat

| Emissions source | | Definition |
|---|---|---|
| **Heat**[3] | 🟥 Low temp heat | Low heat (-30-200ºC) emissions, where heating is end-use |
| | 🟥 Mid temp heat | Medium heat (200-400ºC) emissions, where heating is end-use |
| | 🟥 High temp heat | High heat (400ºC+) emissions, where heating is end-use |
| **Process** | 🟩 Process | Process-related emissions from chemical transformation of raw materials and fugitive emissions |
| **Electricity** | 🟦 On-site power | Electricity emissions for power produced on-site |
| | 🟦 Off-site power | Electricity emissions for power from the grid |
| **Other** | ▨ Other | Other emissions sources[1] |

**Emission breakdown,** MT $CO_2$



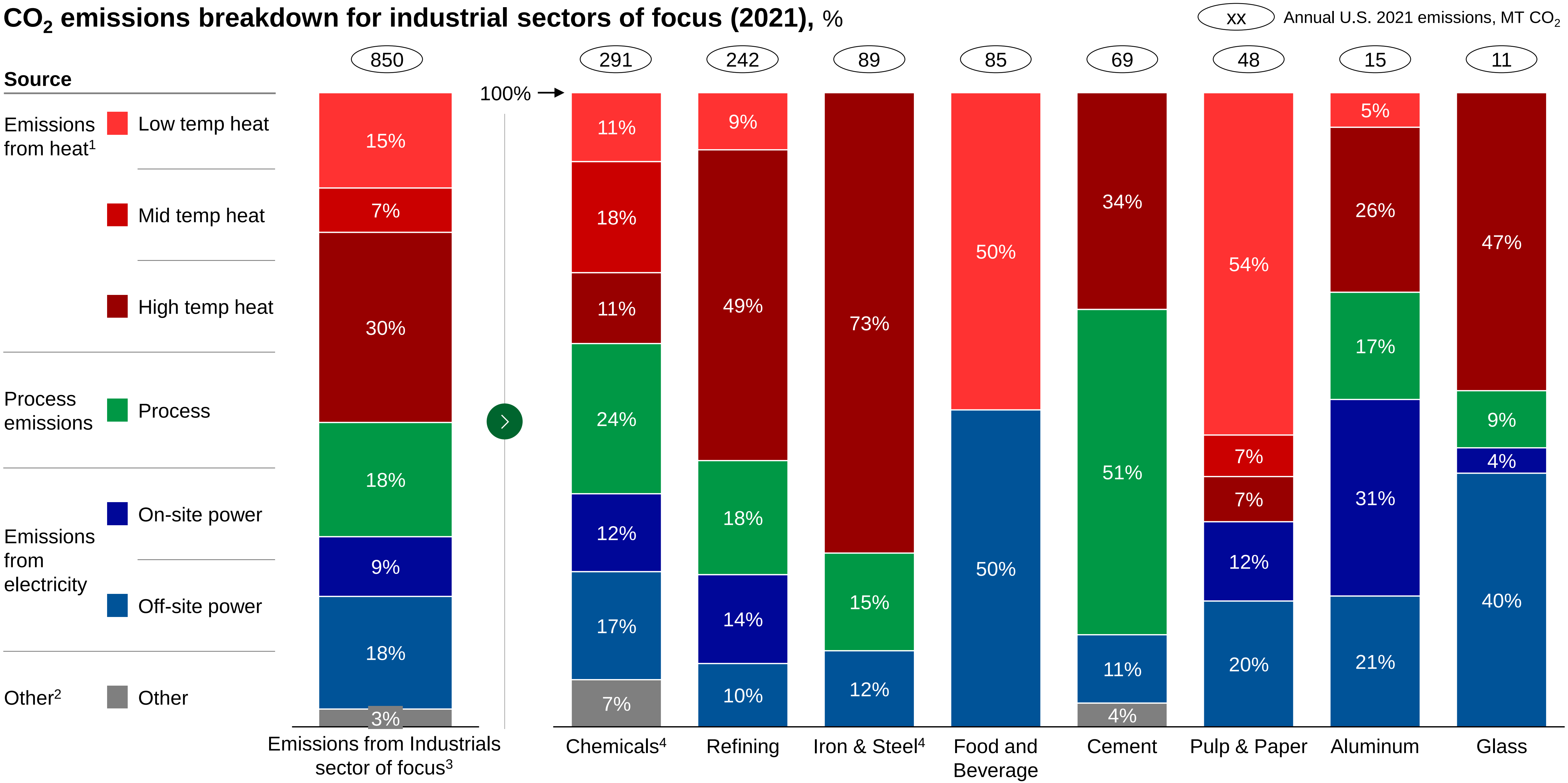
**Emissions from Industrials sector of focus**[2]

*Notes: 1. Incl. electrochemical processes, refrigeration, and cooling for ethylene / propylene; cooling, heat loss for ammonia, fugitives or leakage emissions from NG processing, and quarry and logistics emissions (e.g., cement) | 2. Estimate based on available data*

*Source: 2018 EPA Flight, 2018 EERE Manufacturing Energy and Carbon Footprints report, 2022 IEDO Report, Energy Environ. Sci., 2020,13, 331-344, EIA, 2020 USGS, DOE Natural Gas Supply Chain report*

# Emissions sources across sectors of focus are highly variable

## $CO_2$ emissions breakdown for industrial sectors of focus (2021), %



*Notes: 1. Temperature ranges: low temperature heat is from -30ºC to 200ºC, medium heat is from 200ºC to 400ºC, and high heat is 400+ºC | 2. Includes electrochemical processes, refrigeration, and cooling for ethylene / propylene; cooling, heat loss for ammonia, fugitives or leakage emissions from NG processing, and quarry and logistics emissions | 3. Includes Scope 1 and Scope 2 emissions for U.S. industry only; Estimate based on available data | 4. Weighted average of in-scope subsegments*

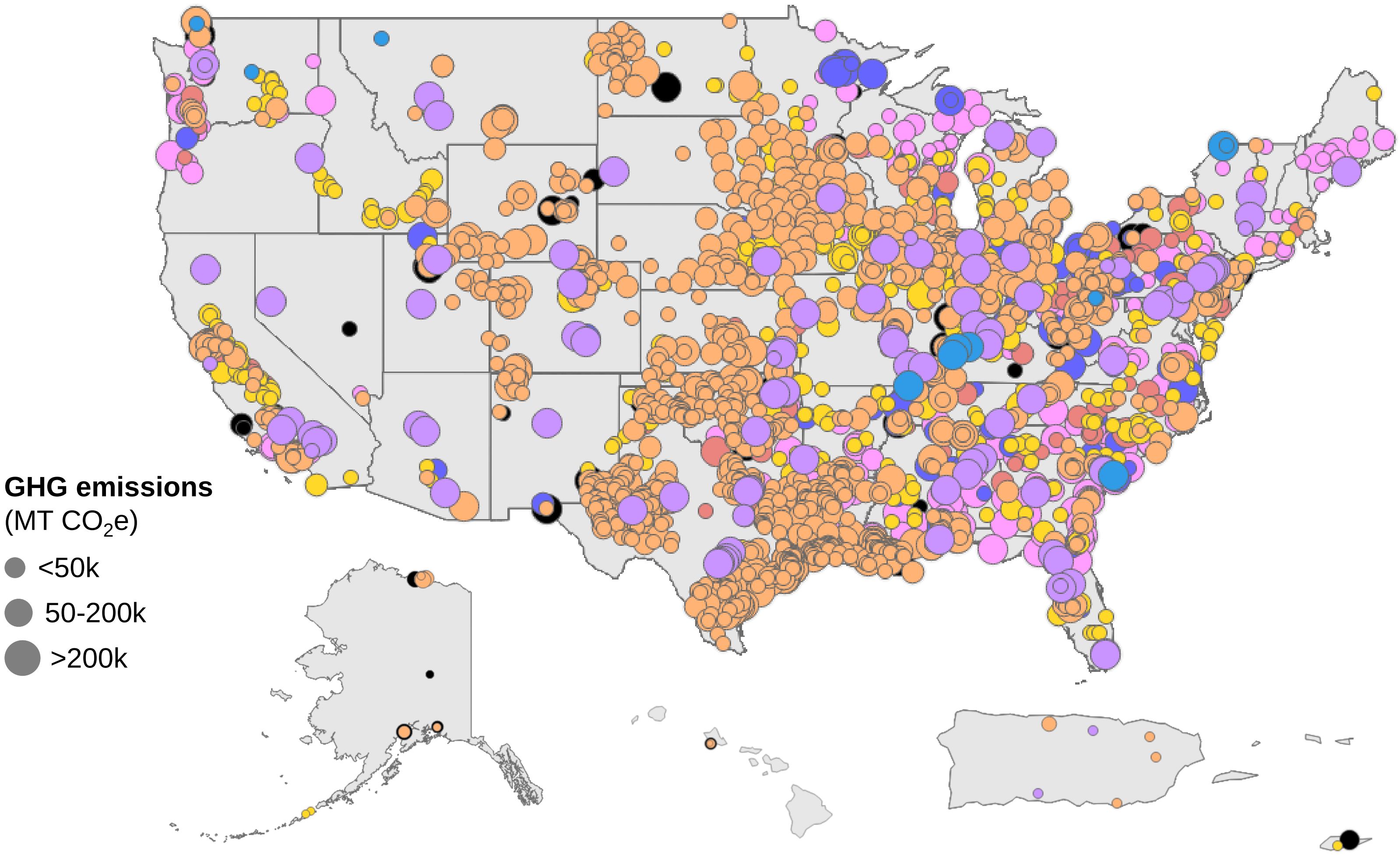
*Source: 2018 EPA Flight, 2018 EERE Manufacturing Energy and Carbon Footprints report, 2022 IEDO Report, Energy Environ. Sci., 2020,13, 331-344, EIA, 2020 USGS, DOE Natural Gas Supply Chain report*

ILLUSTRATIVE NOT EXHAUSTIVE

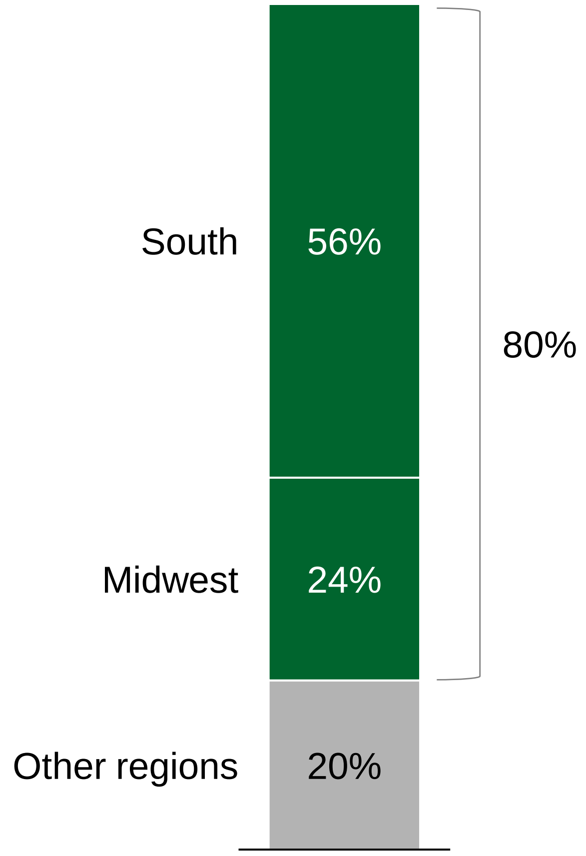
# Emissions are dispersed across 2,500+ facilities across the U.S.

**Sectors** 🟪 Cement 🟧 Chemicals 🟪 Pulp & Paper ⬛ Refining 🟦 Aluminum 🟦 Iron & Steel 🟥 Glass 🟨 Food & Beverage

**Map of select U.S. point source CO$_2$ emissions by sector,** 2021[2]



**Share of U.S. industrial emissions for sectors in IRA,** %, 100% = 876 MT of U.S. 2021 CO2e emissions[3]



South & Midwest regions[1] represent ~80% of U.S point source emissions

*Notes: 1. Regions are defined using U.S. Census guidance | 2. Includes natural gas processing, refineries, chemicals production (various), food processing, cement production, glass production, aluminum production, iron & steel production, pulp and paper manufacturers, and other paper products. EPA FLIGHT data only records GHG emissions from facilities with reported emissions or quantity of GHG emissions > 25,000 MT CO$_2$e/year and does not include emissions from land use, land use change, or forestry | 3. Includes 850 MT CO$_2$ emissions in addition to other non-CO2 GHG emissions*

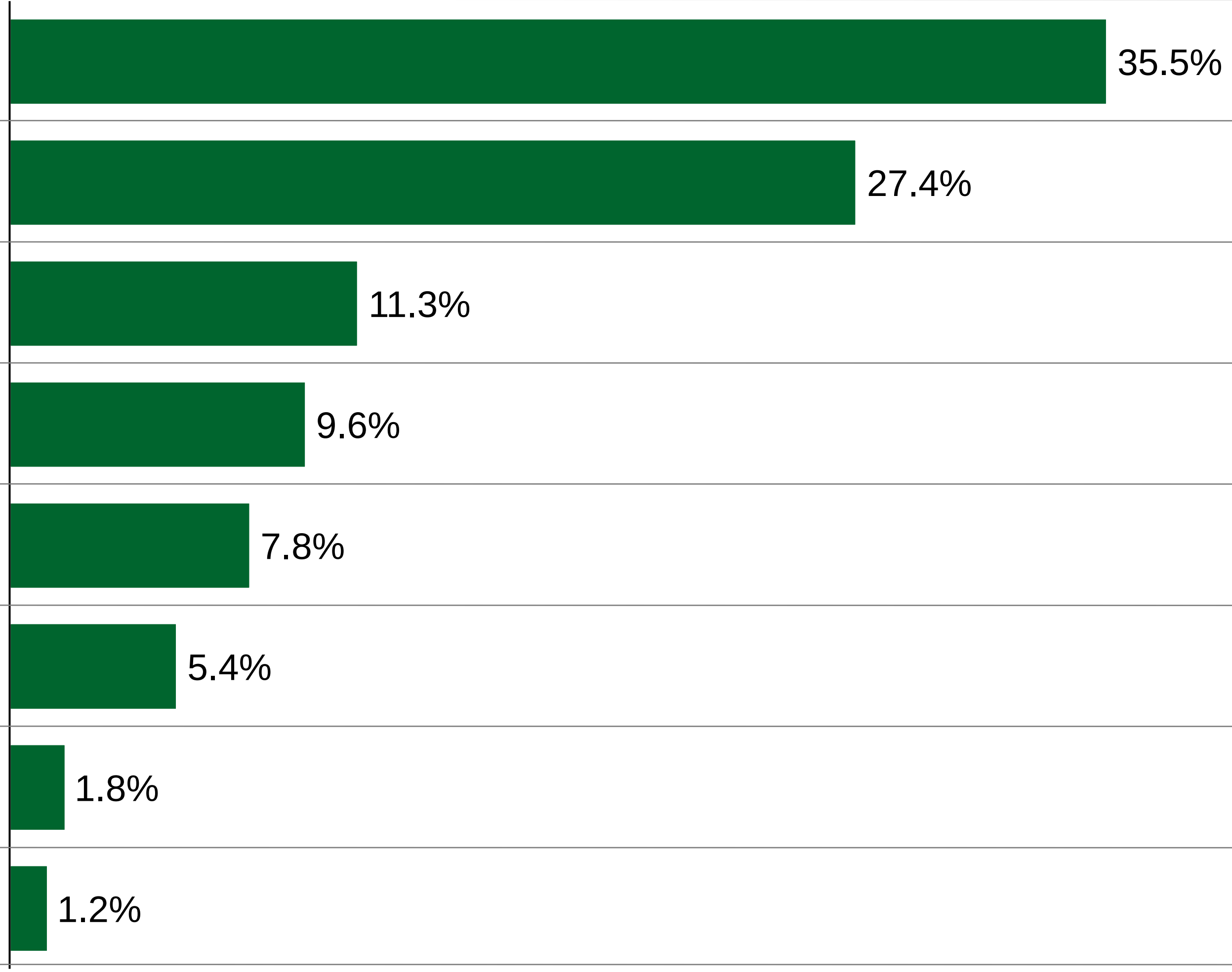
*Source: EPA FLIGHT*

# Sectors of focus are 14% of U.S. CO2e emissions

🍃 Biogenic emissions in sector (not included in share)[3]

**Sector share of 2021 $CO_2e$ emissions from eight industrial sectors of focus,**[1]

%, 100% = ~876 MT of U.S. 2021 $CO_2e$ emissions (14% of total U.S. $CO_2e$ emissions)

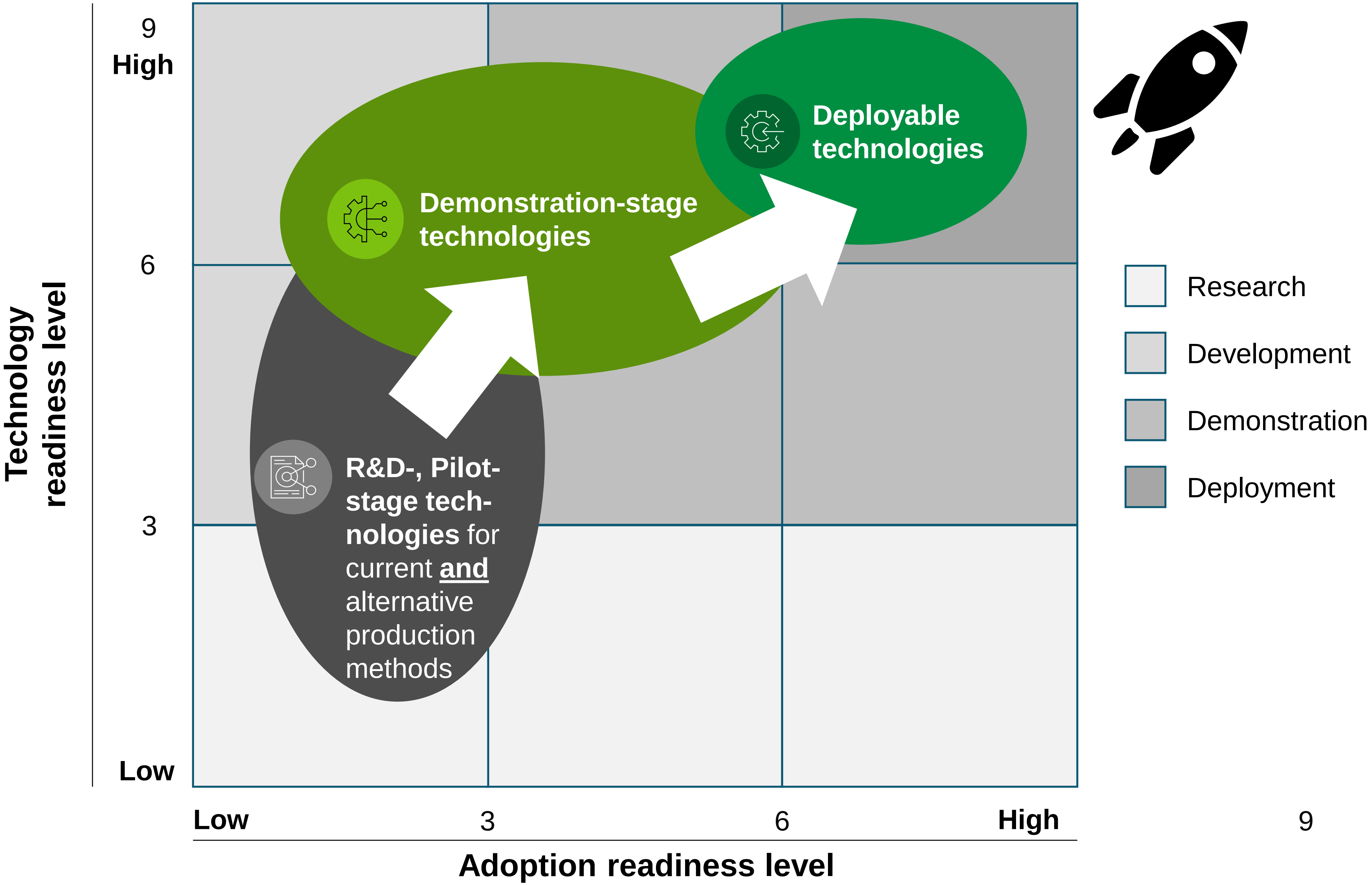


| | Sector | Share | **U.S. 2021 emissions** MT $CO_2e$ | **U.S. 2021 emissions** MT $CO_2$[4] | **Global 2021 emissions** MT $CO_2$ |
|---|---|---|---|---|---|
| | Chemicals[2] | 35.5% | 315 | 291 | ~1,000 |
| | Refining | 27.4% | 243 | 242 | ~1,400 |
| | Iron & Steel | 11.3% | 89 | 89 | ~3,100 |
| 🍃 | Food & Beverage[3] | 9.6% | 85 | 85 | ~400 |
| 🍃 | Cement[3] | 7.8% | 69 | 69 | ~2,500 |
| 🍃 | Pulp & Paper[3] | 5.4% | 48 | 48 | ~200 |
| | Aluminum | 1.8% | 16 | 15 | ~1,100 |
| | Glass | 1.2% | 11 | 11 | ~100 |
| | **Total** | | 876 | 850 | ~9,800 |

*Notes: 1. Includes other greenhouse gas emissions and non-industry sectors using GWP100 | 2. Split into $CO_2$ from natural gas processing (59 MT $CO_2$), ammonia (46 MT $CO_2$), ethylene steam cracking (41 MT $CO_2$), chlor-alkali (26 MT $CO_2$), other downstream chemical processes (119 MT $CO_2$), as well non-$CO_2$ GHG emissions (24 MT $CO_2e$) | 3. Does not reflect biogenic emissions of the sector. Paper has estimated biogenic emissions of ~104 MT. Cement has some biogenic emissions resulting from use of alternative fuels. | 4. For all assessment of decarbonization in the remainder of this report, analysis considers $CO_2$ rather than $CO_2e$.*

*Source: EIA data for energy-related emissions with bottom-up modeling of select chemicals, EPA data for total U.S. emissions, IEDO Industrial Decarbonization Roadmap, Life Cycle Carbon Footprint Analysis of Pulp and Paper Grades in the United States using production-lined-based data and integration - Tomberlin et al (2020).*

# Industrial decarbonization will evolve as decarbonization levers and underlying technologies mature across both TRL and ARL



**Deployable technologies**

**Demonstration-stage technologies**

**R&D-, Pilot-stage technologies** for current **and** alternative production methods

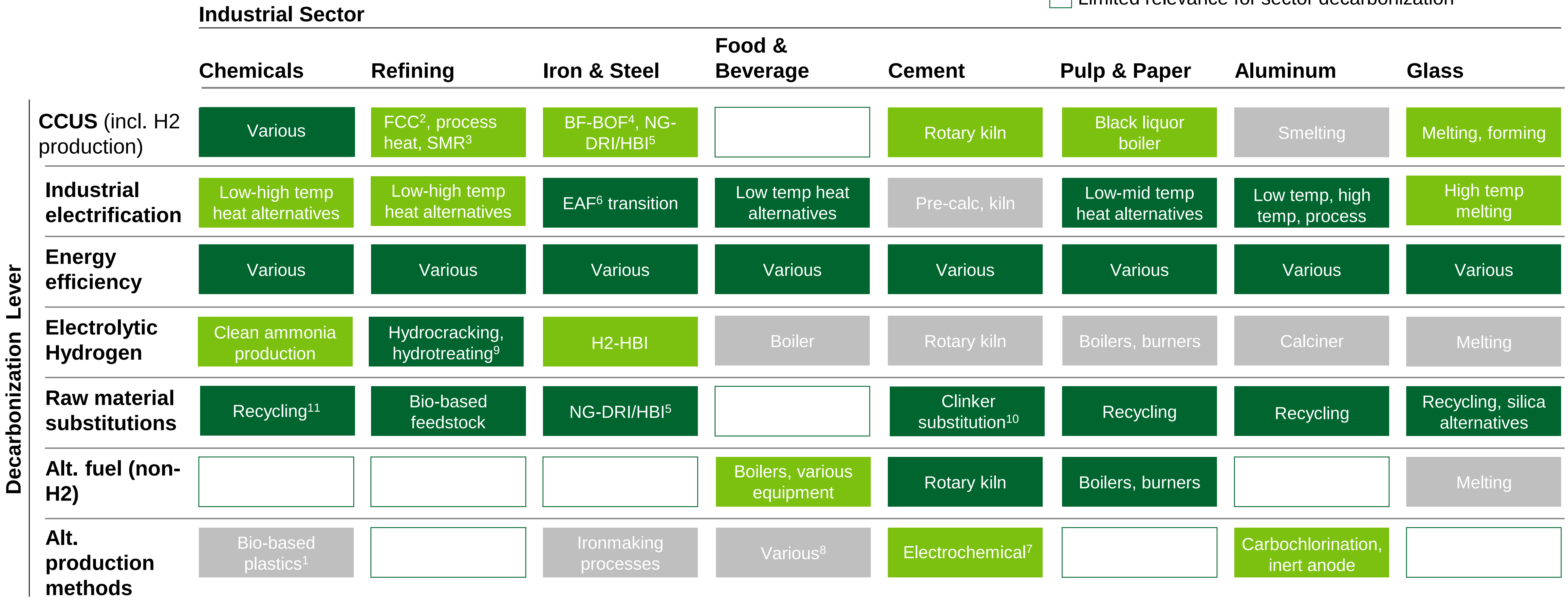
# Decarbonization levers: Opportunities to implement deployable levers exist across all sectors

**NOT EXHAUSTIVE** **ILLUSTRATIVE**

**Highest stage of U.S. development***

■ Deployable ▣ Demo ▨ R&D / Pilot

☐ Limited relevance for sector decarbonization



**Industrial Sector**

| Decarbonization Lever | Chemicals | Refining | Iron & Steel | Food & Beverage | Cement | Pulp & Paper | Aluminum | Glass |
|---|---|---|---|---|---|---|---|---|
| **CCUS** (incl. H2 production) | ■ Various | ▣ FCC[2], process heat, SMR[3] | ▣ BF-BOF[4], NG-DRI/HBI[5] | ☐ | ▣ Rotary kiln | ▣ Black liquor boiler | ▨ Smelting | ▣ Melting, forming |
| **Industrial electrification** | ▣ Low-high temp heat alternatives | ▣ Low-high temp heat alternatives | ■ EAF[6] transition | ■ Low temp heat alternatives | ▨ Pre-calc, kiln | ■ Low-mid temp heat alternatives | ■ Low temp, high temp, process | ▣ High temp melting |
| **Energy efficiency** | ■ Various | ■ Various | ■ Various | ■ Various | ■ Various | ■ Various | ■ Various | ■ Various |
| **Electrolytic Hydrogen** | ▣ Clean ammonia production | ■ Hydrocracking, hydrotreating[9] | ▣ H2-HBI | ▨ Boiler | ▨ Rotary kiln | ▨ Boilers, burners | ▨ Calciner | ▨ Melting |
| **Raw material substitutions** | ■ Recycling[11] | ■ Bio-based feedstock | ■ NG-DRI/HBI[5] | ☐ | ■ Clinker substitution[10] | ■ Recycling | ■ Recycling | ■ Recycling, silica alternatives |
| **Alt. fuel (non-H2)** | ☐ | ☐ | ☐ | ▣ Boilers, various equipment | ■ Rotary kiln | ■ Boilers, burners | ☐ | ▨ Melting |
| **Alt. production methods** | ▨ Bio-based plastics[1] | ☐ | ▨ Ironmaking processes | ▨ Various[8] | ▣ Electrochemical[7] | ☐ | ▣ Carbochlorination, inert anode | ☐ |

Notes: *Stage of development determined using both Technology and Adoption Readiness Level | 1. Ethanol dehydration | 2. Fluid Catalytic Cracker | 3. Steam Methane Reformer | 4. Blast Furnace – Basic Oxygen Furnace | 5. Natural Gas – Direct Reduced Iron / Hot Briquetted Iron; Refers to substitution of natural gas as a reductant in place of coal | 6. Electric Arc Furnace | 7. Geopolymers | 8. E.g., absorption chillers, ejector refrigeration, deep waste energy and water recovery, alternative protein manufacturing | 9. Refers to H2 use in traditional processes | 10. While substitution of limestone and fly ash are deployed today, other clinker substitutes are more nascent. See the following sources for additional detail: a.) U.S. Department of Energy - Office of Energy Efficiency & Renewable Energy. (n.d.). Industrial Efficiency and Decarbonization Office (IEDO) FY23 Multi-Topic FOA. *Novel cements*. Cembureau. (2018, September 28). | 11. Mechanical recycling widely deployed while chemical/advanced recycling is more nascent. Additional details can be found in the Chemicals and Refining Liftoff report

# Net-positive or external levers could abate up to 40% of studied emissions

## Emissions abatement potential by 2030 by decarbonization lever costs (incremental to IRA incentives)[1]

MT $CO_2$

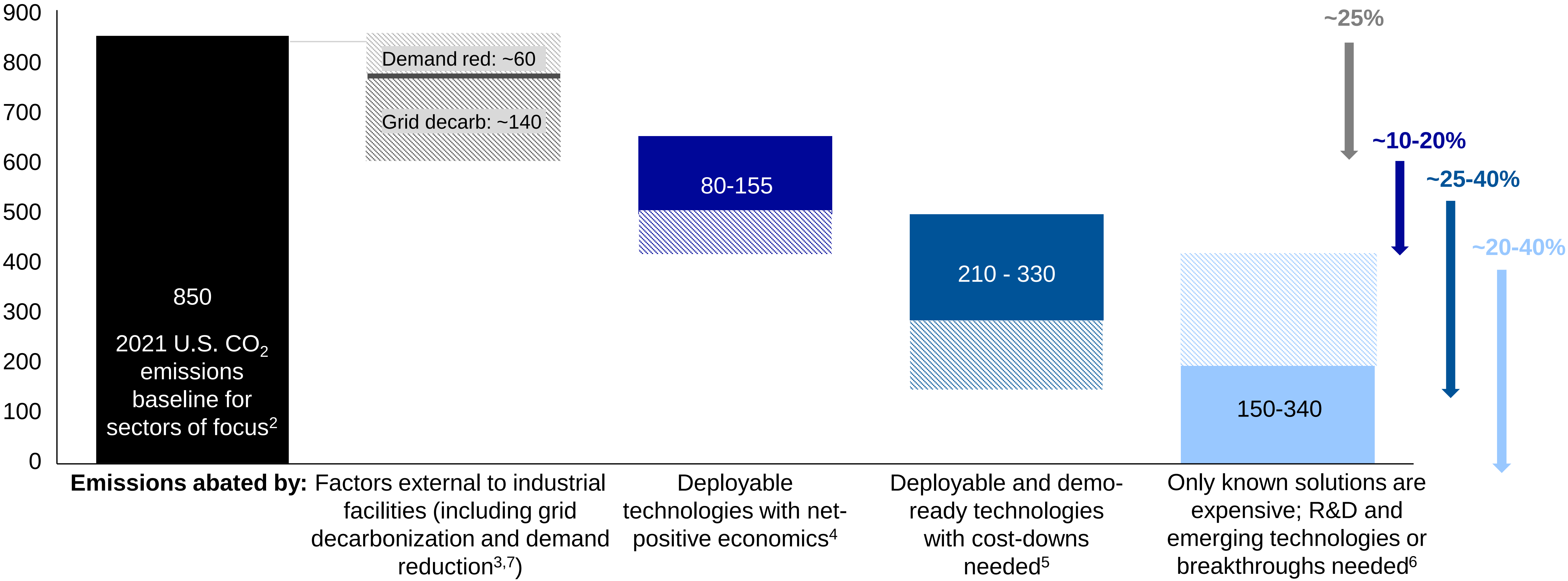


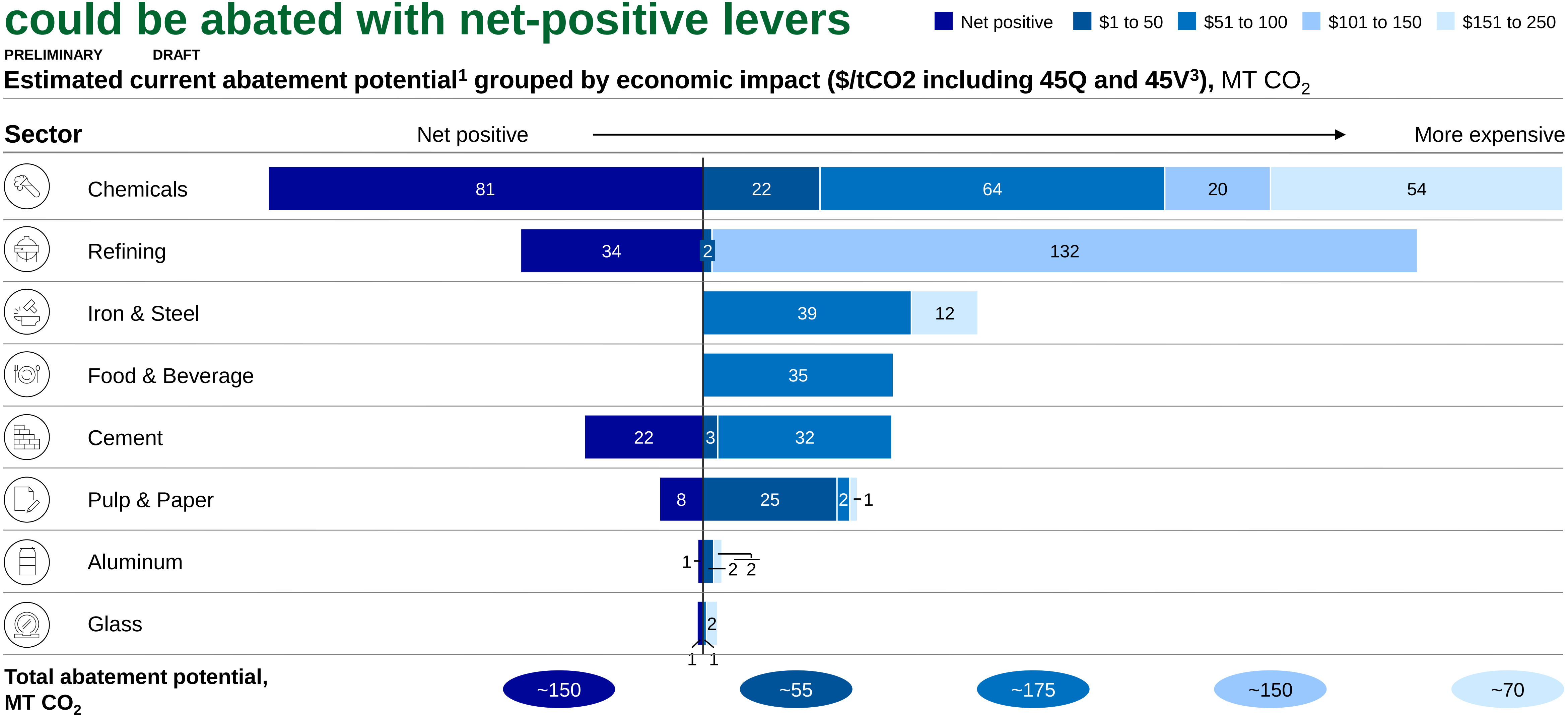
*Figure 3.1: Industrial emissions abatement is split between external factors (i.e., grid decarbonization, transport sector electrification, and mechanical recycling), net-positive levers, and uneconomic levers (>$0/t CO2e), with up to 40% of abatement achievable at- or below-cost | 1. Current ranges consider how abatement potential might evolve if abatement cost curve is higher or lower than anticipated. Abatement potential ranges are based on high and low scenarios for abatement cost. Ranges are not meant to represent a statistical accounting of confidence intervals but depict uncertainty in the range of cost estimates for decarbonization levers. | 2. Heat, electricity, and process emissions for industrial sectors included in IRA, excluding ceramics | 3. Emissions abated by external levers (e.g., grid decarbonization) | 4. Emissions abated by net-positive levers (< $0/t) | 5. Emissions abated by levers approaching breakeven ($0-$100/t) | 6. Emissions abated by levers >$100/t or that require further R&D | 7. Assumes Biden administration target of zero emissions from grid in 2035 and goals for transport decarbonization and EPA goals for recycling for this analytical exercise. Entire bar shaded to indicate uncertainty around factors external to industrial facilities*

*Source: EIA data for energy-related emissions, EPA data for total U.S. emissions, IEDO Industrial Decarbonization Roadmap, Life Cycle Carbon Footprint Analysis of Pulp and Paper Grades in the United States using production-lined-based data and integration - Tomberlin et al (2020), White House Long-Term 2050 Roadmap*

# ~27% of chemicals, ~14% of refining, and ~32% of cement emissions could be abated with net-positive levers

**PRELIMINARY** **DRAFT**

**Estimated current abatement potential[1] grouped by economic impact ($/tCO2 including 45Q and 45V[3]),** MT $CO_2$



Note: Unabated emissions (~40 MT), external factors[3] (~200 MT), and abatement potential with costs $250+ /$tCO_2$ (~5 MT) are not shown in this figure

1. Based on 2021 emissions baseline for all industries except for Chemicals, Refining, and Cement where emissions were projected through 2050. All costs represented here took the midpoint of cost ranges | 2. Factors include grid decarbonization, transport sector electrification, and mechanical recycling | 3. Cost based on estimated 2030 prices for decarbonization levers. 45Q and 45V are not stacked in this analysis

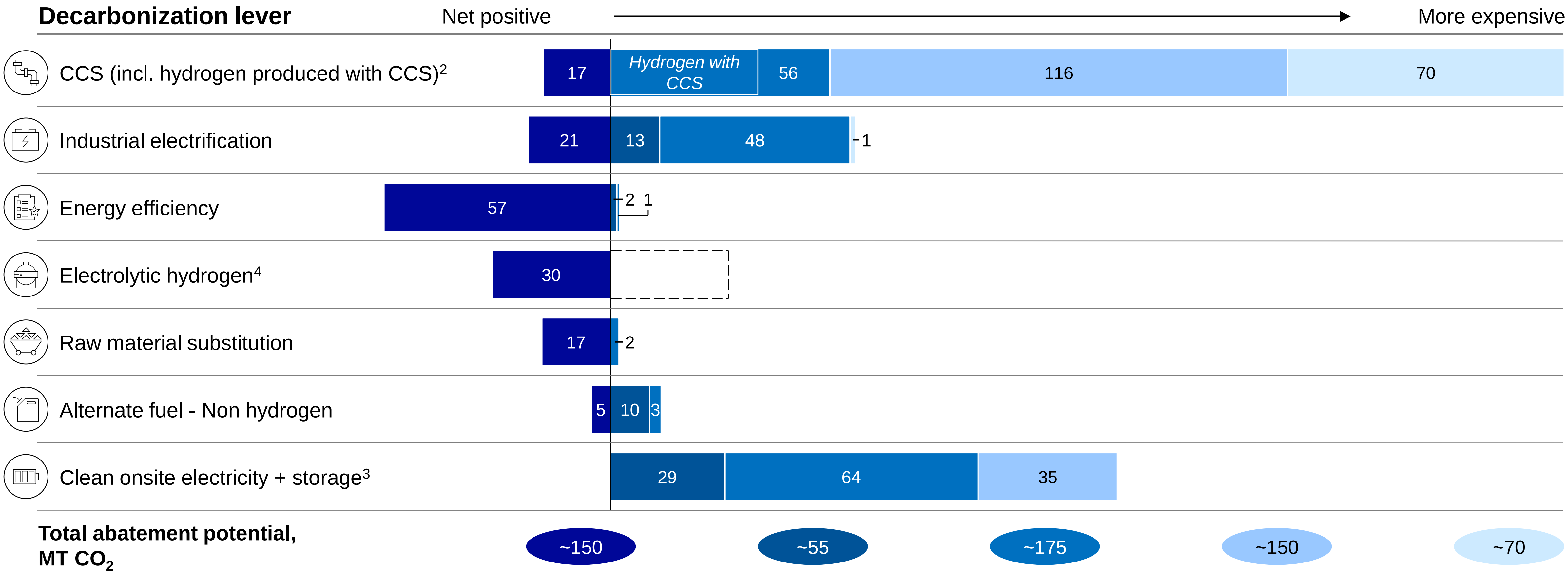
Source: Industrials sector integrated MACC, DOE Chemicals & Refining Decarbonization Liftoff Report, DOE Cement Decarbonization Liftoff Report

# ~15% of CO2 emissions studied could be abated with net-positive decarbonization levers

■ Net positive ■ $1 to 50 ■ $51 to 100 ■ $101 to 150 ■ $151 to 250 ⬚ Range from uncertainty of transport & storage and electrolyzer costs

PRELIMINARY DRAFT

**Estimated current abatement potential[1] grouped by economic impact ($/tCO2 including 45Q and 45V[6]),** MT $CO_2$



Note: Unabated emissions (~40 MT), external factors[5] (~200 MT), and abatement potential with costs $250+ /$tCO_2$ (~5 MT) are not shown in this figure

1. Based on 2021 emissions baseline for all industries except for Chemicals, Refining, and Cement where emissions were projected through 2050. All costs represented here took the midpoint of cost ranges | 2. Costs estimated after applying levelized 45Q tax incentive from the Inflation Reduction Act; includes 41MT of emissions abated with hydrogen produced with CCS (2030 Hydrogen with CCS costs range from x-X) | 3. Includes costs associated with heating equipment for steam generation | 4. Costs estimated after applying 45V tax incentives from the Inflation Reduction Act for hydrogen production via electrolysis. Cost estimates for 2030 range from $2.02-3.02/kg H2 including capital expenditure, operating expenditures and transport and storage costs. Overall electrolytic hydrogen costs are uncertain – assumptions based on current policy guidance and commercial cost estimates as of June 2023 and could change as more data emerges. Estimated abatement by clean hydrogen in line with Hydrogen Roadmap estimates for 2030 ammonia and refining use cases.| 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

# With continued cost reductions, other decarbonization levers may address the same emissions as CCS including electrification, electrolytic H2, and utilization opportunities

**Stage of decarbonization lever development** 🟩 Deployable 🟩 Demo ⬜ R&D / Pilot

International example

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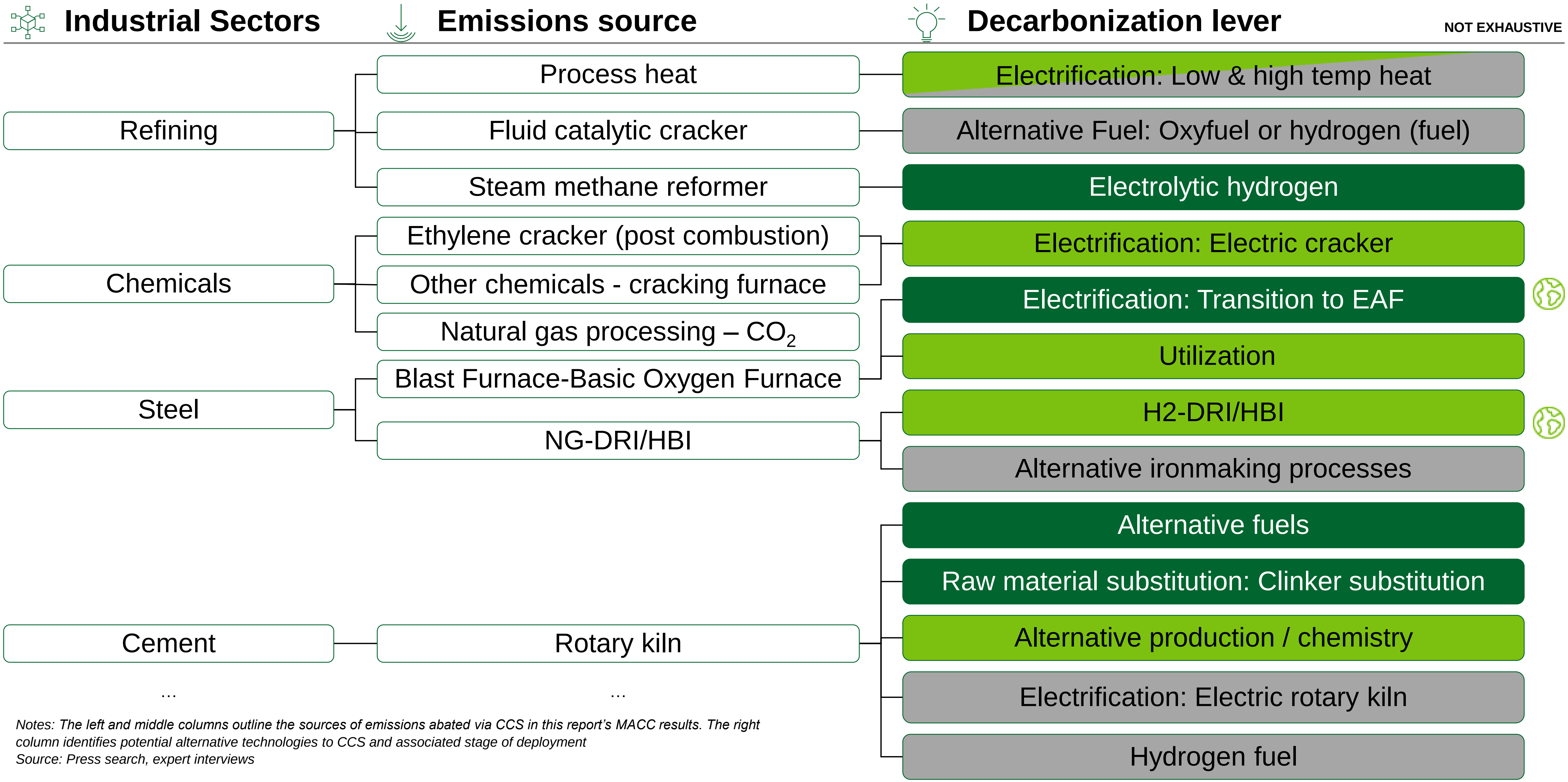


**Industrial Sectors**

- Refining
- Chemicals
- Steel
- Cement
- …

**Emissions source**

- Process heat
- Fluid catalytic cracker
- Steam methane reformer
- Ethylene cracker (post combustion)
- Other chemicals - cracking furnace
- Natural gas processing – $CO_2$
- Blast Furnace-Basic Oxygen Furnace
- NG-DRI/HBI
- Rotary kiln
- …

**Decarbonization lever**

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

*Notes: The left and middle columns outline the sources of emissions abated via CCS in this report's MACC results. The right column identifies potential alternative technologies to CCS and associated stage of deployment*

*Source: Press search, expert interviews*

# High Temperature Heat Deep Dive

NOT EXHAUSTIVE

| Decision criteria | Chemicals | Refining | Iron & Steel[8] | Cement | Pulp & Paper | Aluminum | Glass |
|---|---|---|---|---|---|---|---|
| Highest heat requirement,[10] degrees | 1,000°C | 800°C | 1,600°C | 1,450°C | 1,100°C | 1,000°C | 1,600°C |
| High grade heat share of industry emissions[11] | 11% | 49% | 73% | 34% | 7% | 26% | 47% |
| Most applicable technologies with implementation tradeoffs | ■▨ **Small modular nuclear reactor**<br>💰 | ▨ **CCS**<br>💵 💰 🔧 | ■ **Electrification**<br>💵 📋 🔌 | ■ **Biomass; waste fuels**<br>⚙ 🚚 | ■ **Biofuels**<br>⚙ 🚚 | □ **Hydrogen[9]**<br>💵 | ▨ **Electrification**<br>💵 🔧 🔌 |
| | □▨ **Electrification +TES**<br>💵 🔧 🔌 | □ **Electrification +TES**<br>💵 🔧 🔌 | ▨ **CCS**<br>💵 💰 | ▨ **CCS**<br>💵 💰 | ■ **Electrification**<br>💵 🔧 🔌 | □ **CCS**<br>💵 💰 | ▨ **CCS**<br>💵 💰 🔧 |
| | □▨ **Hydrogen[9]**<br>💵 | □ **Hydrogen[9]**<br>💵 | □ **Hydrogen[9]**<br>💵 | □ **Electrification +TES**<br>💵 🔧 🔌 | ▨ **(BE)CCS**<br>💵 💰 | □ **Electrification**<br>💵 🔧 🔌 | □ **Biofuels**<br>⚙ 🚚 |
| | ▨ **CCS**<br>💵 💰 🔧 | □ **Biofuels**<br>💵 🔧 🚚 | | | | | □ **Hydrogen[9]**<br>💵 |

■ Deployable ▨ Demo
□ R&D / Pilot

**Key challenges/tradeoffs[1]**

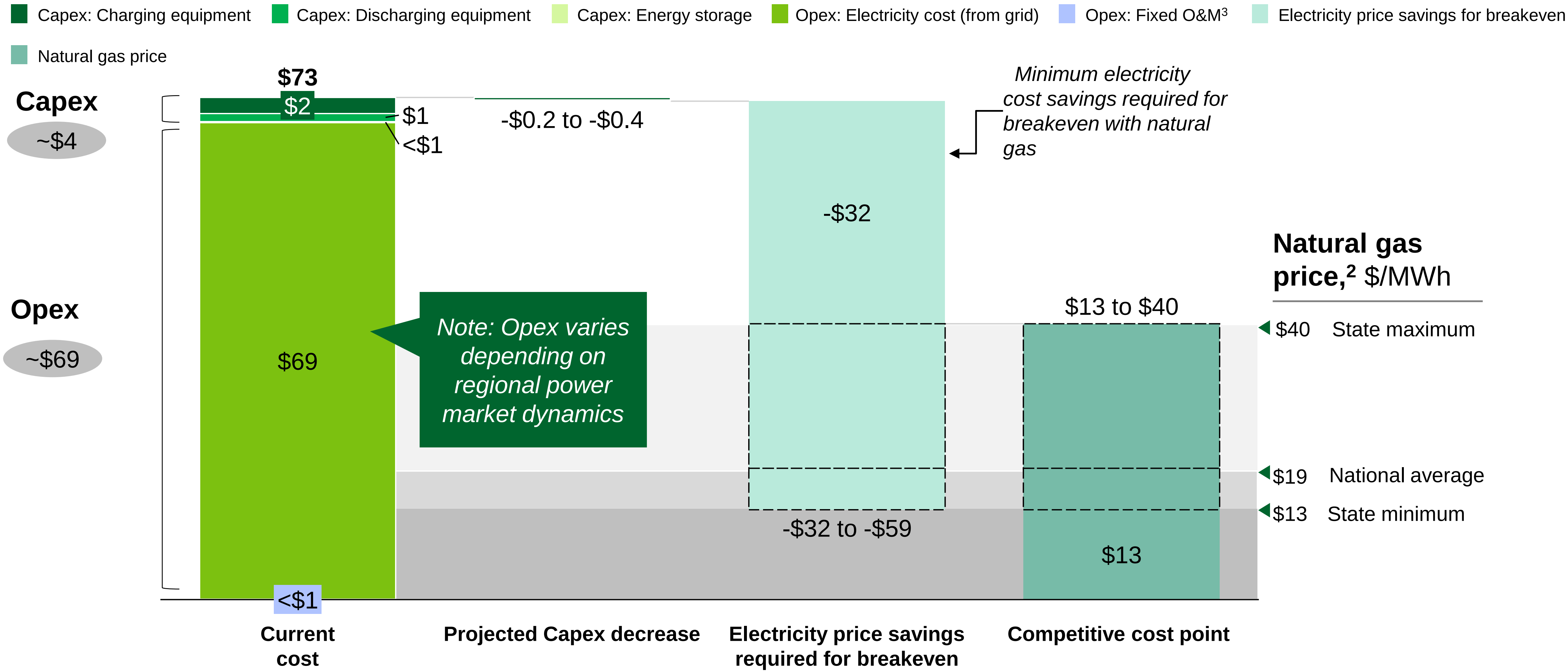
- 💵 High opex cost
- 💰 High capex cost
- ⚙ Operational challenges[2]
- 🔧 Retrofit challenges[3]
- 📋 Product limitations[4]
- 🔌 Access to low carbon electricity [5]
- 🚚 Supply challenges[6]

Notes: 1. Highest priority challenges/tradeoffs for each technology in each sector listed in figure. Other challenges could apply but may not be as critical a decision factor for industry | 2. Operational challenges refer to difficulty in meeting the heat or other technical requirements for the process with the decarbonization technology. For example, the use of biomass in cement presents operational challenges as it has a lower heat value than fossil fuels and therefore cannot replace 100% of fuel and reach sufficient temperatures | 3. Retrofit challenges are difficulty in implementing the decarbonization technology. For example, the number of emissions sources in refining and chemicals is a retrofit challenge for CCS as emissions sources could need to be rerouted to combine multiple streams to be captured within the facility | 4. Product quality challenges refer to when the decarbonization technology impacts the quality of the product being produced. For example, EAF produces steel that does not meet technical requirements for some end-uses (e.g., automotive)| 5. Refers to challenges in accessing sufficient low carbon electricity either from the grid or onsite | 6. Supply challenges arise when the decarbonization technology relies on an input that has a limited or localized supply chain. For example, access to biomethane for use in melting glass will depend on the location of the glass production and if there is availability of sufficient biomethane within range | 7. High temperature (HT) | 8. Weighted average of in-scope subsegments | 9. Assumes purchase of electrolytic hydrogen. Production of electrolytic hydrogen has its own set of challenges (e.g., access to low carbon electricity for electrolytic hydrogen) | 10. The general maximum heat requirement for current processes; excludes a consideration of new processes | 11. High temperature heat emissions data is estimated from this combination of sources.

# Case study on heat decarbonization through thermal energy storage

## Cost components of high temperature thermal energy storage (TES),[1] $/MWh of thermal energy delivered

**ILLUSTRATIVE**



*Minimum electricity cost savings required for breakeven with natural gas*

*Note: Opex varies depending on regional power market dynamics*

*Notes: Electricity price in comparison to fossil fuel is the largest determinant of TES's economic viability | 1. Capex figures are based on anonymized industry data from LDES council members; technology agnostic, assumes 16h storage, 8h charging, 365 cycles per year, 8% WACC, 30-year lifetime, and 5,840 MWh heat discharge per year | 2. EIA annual Natural Gas Prices: Industrial (2021); minimum represents the lowest (West Virginia) and highest (Delaware) annual natural gas price by state; note that the natural gas price doesn't include a small efficiency loss from combustion | 3. Assumes that fixed O&M cost is 2% of capex, in line with similar energy technologies; no data is available from the LDES council*

*Source: LDES Council, EIA Monthly Electric Power Industry Report*

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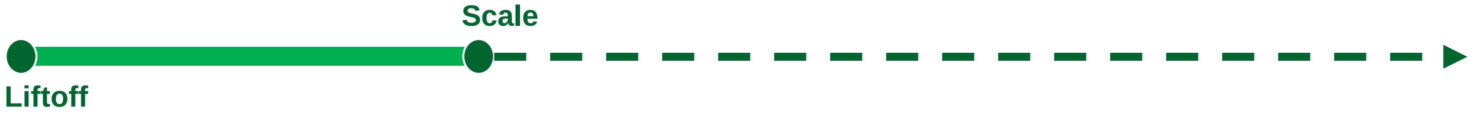
# Pathway to commercial liftoff – Priority decarbonization actions[1]

## Selected technology examples

### Deployable

- **Energy management systems** (energy efficiency)
- **Cullet in glass** (raw material substitution)
- **Ammonia and refining** (clean hydrogen)
- **EAF in steel** (electrification)
- **Biomass in pulp & paper** (alt. fuel)
- **CCS on Natural Gas Processing** (CCS)



**Investment in deployable technologies must overcome remaining adoption hurdles and rapidly scale:**

- Clarify and strengthen end-customer demand to speed action across supplier value chains to compete for market share and customer segments
- Leverage all available downtime to rapidly implement economic levers, significantly expand enabling infrastructure, and achieve cost-downs through scale

### Demonstration-stage

- **Industrial CCS retrofits** (e.g., hydrogen, cement, ethylene, refining)
- **Clean onsite electricity and storage**
- **Heat pumps in pulp & paper** (electrification)

**Accelerated liftoff of demo-stage technologies could address technical barriers and reduce costs:**

- Pursue cost-downs and proof of readiness through demonstrations of decarbonization technologies in sector-specific applications to drive cost reductions, replicability, and cross-sector learnings to boost the value proposition of similar, future projects.

### R&D/Pilot

- **Alternative chemistries in cement** (alt. production methods)
- **Steam e-crackers in ethylene** (Electrification)
- **Biomethane forming in glass** (alt. fuels)
- **Carbon utilization** (CCUS)

**Continued research, development, and demonstration of R&D, Pilot stage technologies:**

- Targeted R&D and pilots focused on technical hurdles on high-potential decarbonization technologies that could close the cost gap or address emissions with limited abatement options today to de-risk decarbonization by 2050

Net-zero ●

**Timeline** 2023 2030 2040 2050

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1. *Indicative timeline presented for R&D, FOAK, liftoff, and scale. Actual timelines will vary by technology based on technological maturity and barriers to adoption*

| Cross-sector challenges | | Solutions | Example tactics |
|---|---|---|---|
| **Value Proposition** | **High delivered cost of technology** | **Close cost gap** between incumbent and decarbonized technology for producers | Demonstration projects<br>Create buy-side consortia<br>R&D on technology costs |
| | **High complexity to adopt** | Integrate decarbonization strategy into **near- and long-term capital planning** | Opportunistic use of downtime<br>Operational best practices<br>R&D on manufacturing and system integration |
| **Technology Readiness** | **Limited high-TRL technologies** | Diversify industrial decarbonization portfolios with **high-potential alternative technologies** | Pilot projects<br>Sector-specific niches |
| **Resource Maturity** | **Lack of enabling Infrastructure** | Build ecosystem to support **infrastructure** and assets | Expedited permitting<br>Regional hubs<br>Common carrier infrastructure |
| | **Capital flow challenges** | Improve access to **equity and debt financing** for low-carbon assets | Transition risk in business case development<br>Offtake agreements |
| **Market Acceptance** | **Limited demand maturity** | Activate **demand-side pull** through coalitions and individual procurement deals | Offtake agreements with defined green premiums<br>Supplier assessments |
| **License to Operate** | **Community perception** | **Engaging with communities** and addressing their reasons for concern | Community Agreements<br>Mitigating Technologies |

# Maintenance frequency, requirements, and duration, vary by industry

**Equipment lifetime**

- - - - - - Practically indefinite —— Finite number (estimated years)

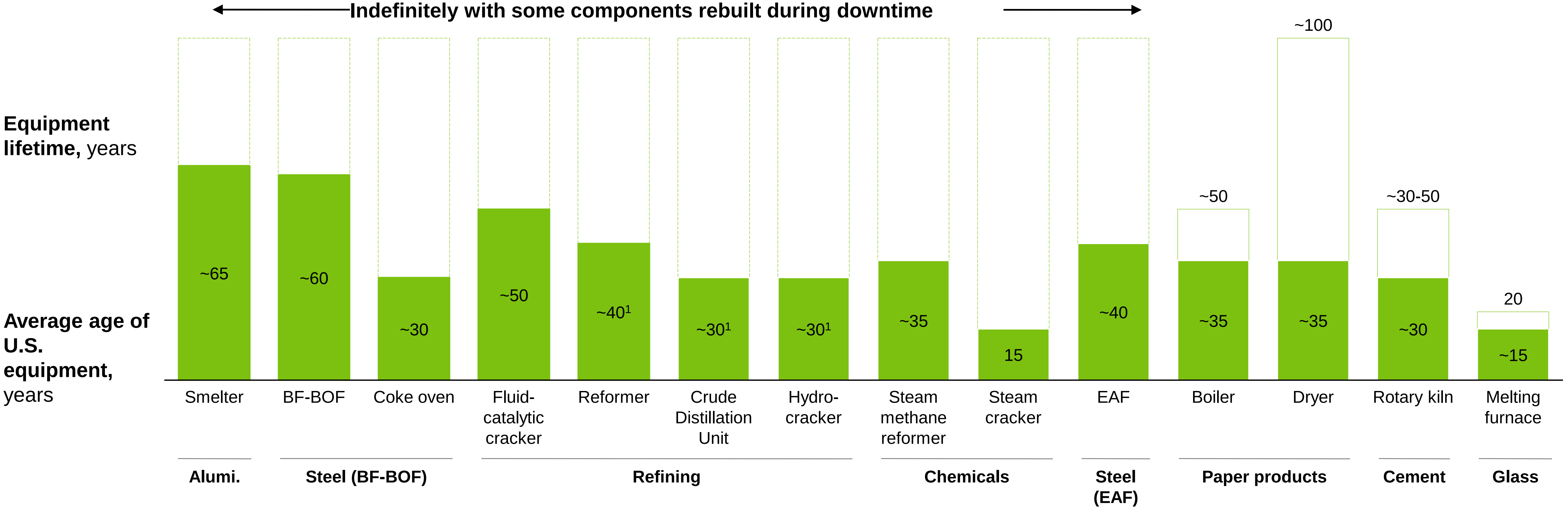
**Downtime frequency** (years)

⬜ Very infrequent ▨ Infrequent ⬛ Regular

**Downtime duration** (weeks)

● Long ● Short ● Very short

## Average age, lifetime, and downtime frequency & duration of key equipment by U.S. industrial sector

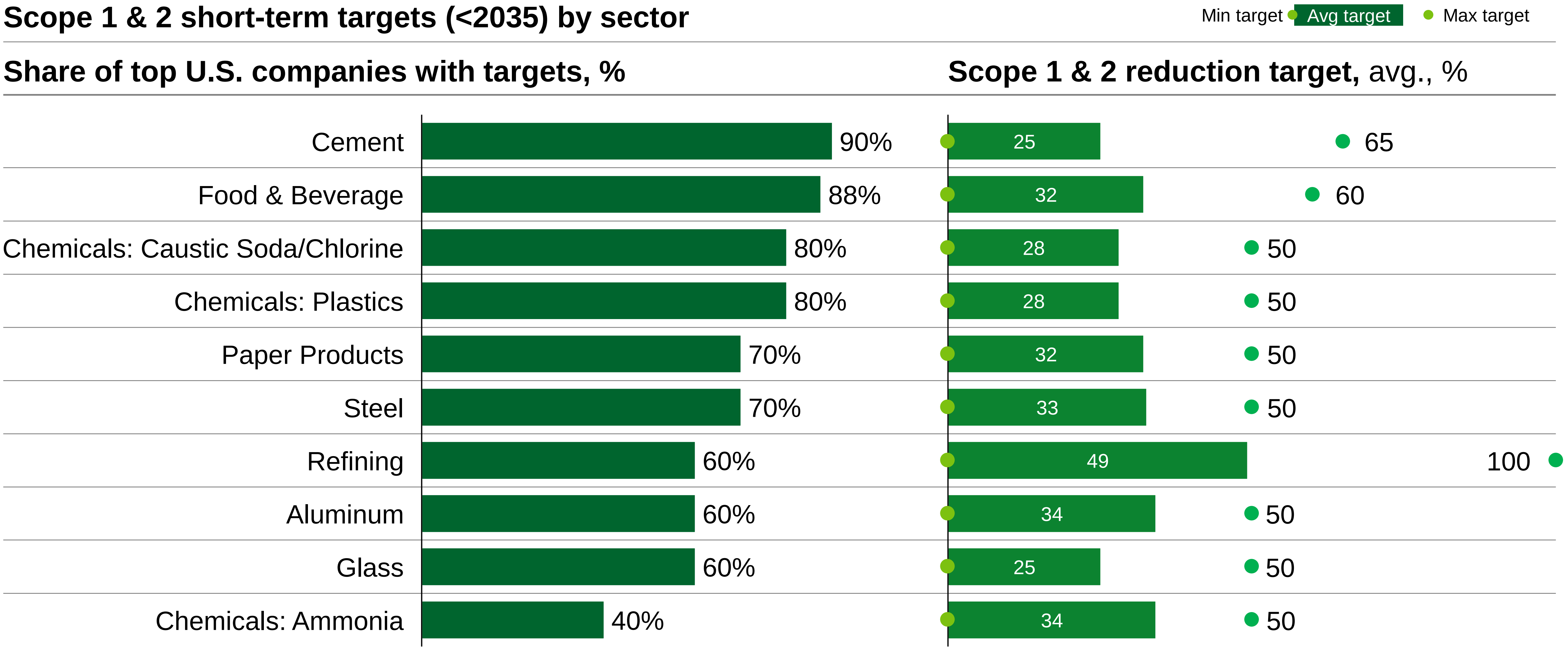


| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Downtime frequency,** years | 4-5 | 10-15 | 10-15 | 5 | 5 | 5 | 1-1.5 | 5 | 5 | ~0 | 1-2 | 1-2 | 1 | 15-20 |
| **Downtime duration,** weeks | 0.1 | 16-20 | 20-30 | 8-12 | 8-12 | 8-12 | 3-5 | 2-8 | 2-8 | 0.1 | 1-2 | 1-2 | 4-8 | 25-30 |

*Source: Press search, Annual reports, Expert interviews, International Aluminum Association, World Steel Association, IHS, Fertecon*

# Cement, Food & Beverage and Chemicals sectors have the largest share of top U.S. companies with Scope 1 & 2 short-term targets; however, the average target is < 30%

## Scope 1 & 2 short-term targets (<2035) by sector



*Note: Average Industry targets by sector.  | Specific companies included listed in Liftoff report Chapter 4.*

ILLUSTRATIVE NOT EXHAUSTIVE

# Every sector has unique opportunities to lead industrial decarbonization

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

*Notes: Sector-specific leadership opportunities based on a sector's industrial context, current momentum, and available technologies. Activities outlined in each sector's Pathway to Liftoff could support achieving these leadership opportunities.*

# Chemicals: Industry Overview

**Sub-sectors:** Ammonia, ethylene/propylene/BTX, natural gas processing, chlor-alkali processes

**~291** MT $CO_2$ 2021 U.S. missions

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**~315** MT $CO_2e$ 2021 U.S. Emissions

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**~1,000** MT $CO_2$ 2021 Global Emissions

**Industry Context**

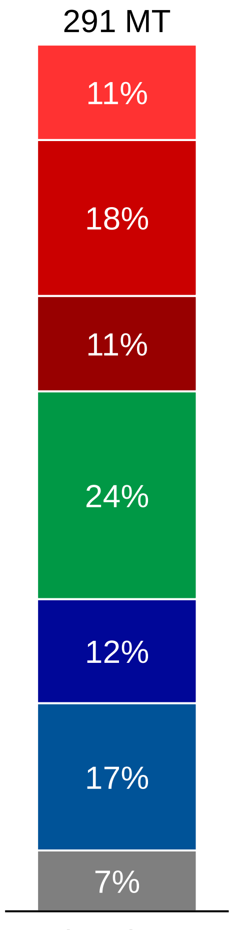
- Chemicals is the largest exporting sector in the U.S., accounting for more than 9% of total U.S. exports
- U.S. demand for Chemicals is expected to grow ~1.5% p.a. through 2030, creating opportunities to decarbonize new production capacity
- Chemicals decarbonization levers to-date have focused on 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%

# Chemicals: Decarbonization levers

% Share of sector abatement potential

NON-EXHAUSTIVE

| Emissions source | | Emissions breakdown,[2] MT $CO_2$ |
|---|---|---|
| **Heat[1]** | 🟥 Low temp heat | 11% |
| | 🟥 Mid temp heat | 18% |
| | 🟫 High temp heat | 11% |
| **Production** | 🟩 Process | 24% |
| **Electricity** | 🟦 On-site power | 12% |
| | 🟦 Off-site power | 17% |
| **Other** | ⬜ Other | 7% |



| Value chain step responsible for emissions | Lever | Current lowest cost abatement, MT $CO_2$ | % | Abatement Cost, $/t $CO_2$ |
|---|---|---|---|---|
| **[Ethylene]:** Switch steam generation to low carbon electricity with electric boiler and thermal storage | Electrification | ~10 | <5% | ~40-70 |
| **[Ethylene]:** Fuel use reduction | Energy efficiency | <5 | <5% | ~(120)-(80) |
| **[Chlor-alkali, Other chem]:** Onsite clean energy with electrification and storage | Clean power | ~70 | ~25% | ~40-60 |
| **[Ethylene, Other chem]:** Steam cracking furnace | CCS[5] | ~55 | ~20% | ~145-180 |
| **[Ammonia]:** Dilute flue gas from SMR (process and combustion emissions) | CCS[4,5] | ~20 | ~5% | ~110-140 |
| **[NGP[3]]:** Associated $CO_2$ emissions | CCS[5] | ~15 | ~5% | ~(25)-(10) |
| **[Ammonia]:** Electrolyzer powered by clean energy | Clean hydrogen | ~15 | ~5% | ~(60)-50 |
| **[Ammonia, Other chem]:** Power generation with clean energy and LDES[3] | Clean power | ~5 | <5% | ~30-70 |
| **[NGP[3]]:** Compressor electrification with power generation from clean energy | Electrification | ~20 | ~5% | ~(50)-(30) |

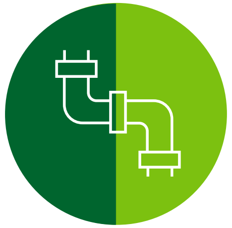
*Notes: Chemicals production has fragmented emissions sources that can be abated using a variety of levers | 1. Temperature ranges: low temperature heat is from -30ºC to 200ºC, medium heat is from 200ºC to 400ºC, and high heat is 400+ºC | 2. Breakdown of 2021 chemicals production emissions | 3. Natural gas processing (NGP); Long-duration energy storage (LDES) | 4. Blended cost of applying CCS to SMR unit (concentrated and dilute flue gas streams), 5. Displayed cost estimates based on capture costs from various sources (see appendix for detail) with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10-40/t. 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: 2018 EPA Flight, 2018 EERE Manufacturing Energy and Carbon Footprints report, 2022 IEDO Report, DOE Natural Gas Supply Chain report, Energy Environ. Sci., 2020,13, 331-344, 2020 USGS, IHSMarkit data, Chemical Emissions Model*

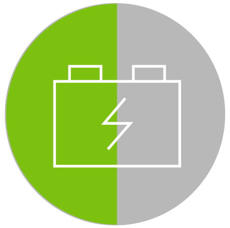
# Chemicals: Operational decarbonization momentum (varies by subsector)

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

■ Deployable ■ Demo ■ R&D / Pilot

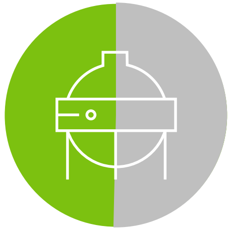


**CCS**[1] (Deployment: NGP, Ammonia, Chlor-Alkali, Demo: Ethylene)

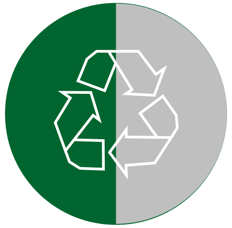


**Industrial electrification** (Demo: NGP Compressor, R&D: Steam cracker)[2]

**Energy efficiency**



**Electrolytic hydrogen**[4]



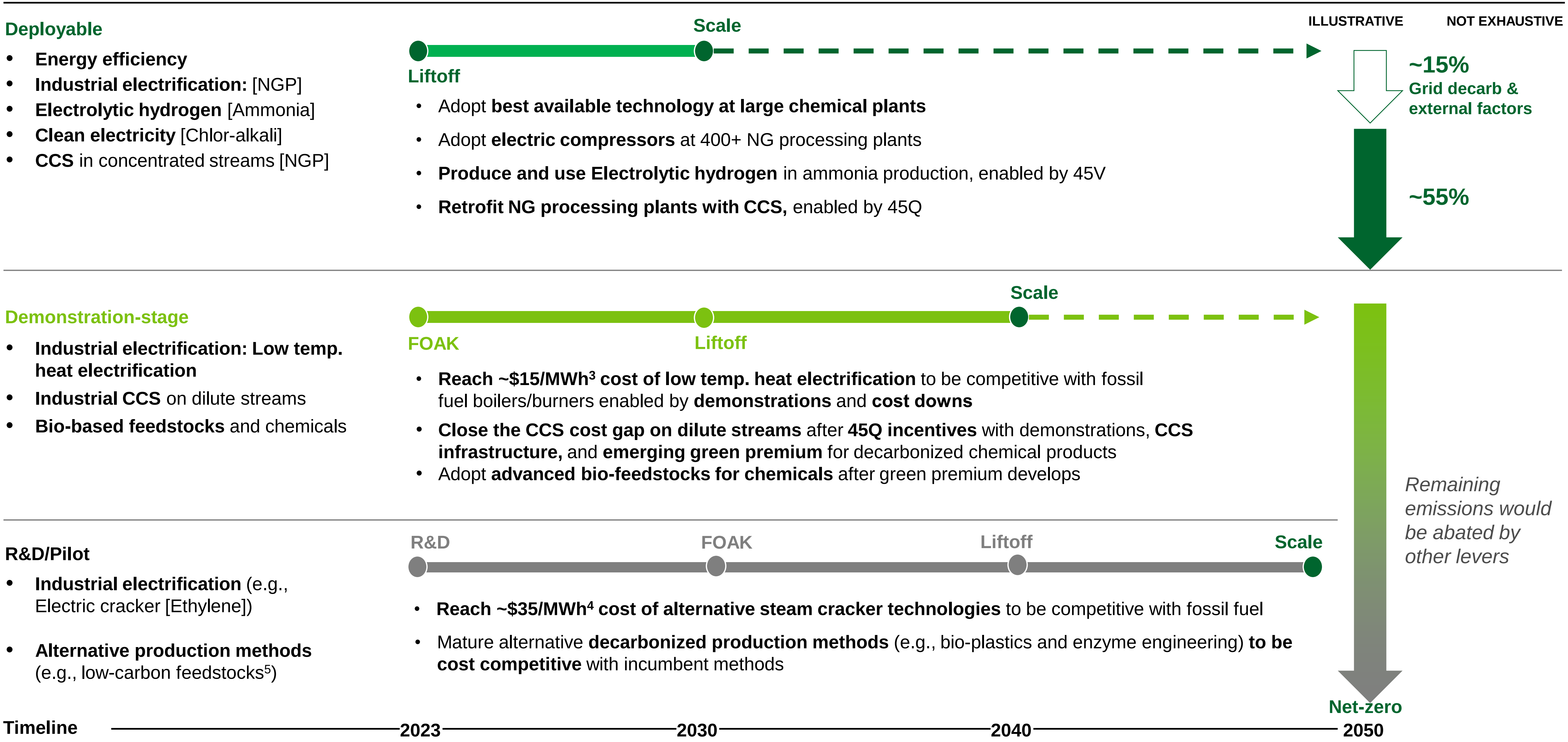
**Raw material substitutions**[3]

**Alternative production methods**[5]

*Notes: Stage of lever deployment within the chemicals sector | 1. Deployed for natural gas processing and ammonia, pilot/demo for ethylene, limited deployment for chlor-alkali | 2. Not exhaustive | 3. Not applicable for natural gas processing and ammonia, mechanical recycling widely deployed while chemical/advanced recycling is more nascent. Additional details can be found in the Chemicals and Refining Liftoff report | 4. Limited deployment only (e.g., ammonia) | 5. Such as biobased plastics (ethanol dehydration)*

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

# Chemicals: Liftoff pathway



**Technology examples**

**Pathway to commercial liftoff – Priority decarbonization actions**[1]

**2030 estimated emissions abatement in Chemicals, %**

ILLUSTRATIVE NOT EXHAUSTIVE

**Deployable**

- **Energy efficiency**
- **Industrial electrification:** [NGP]
- **Electrolytic hydrogen** [Ammonia]
- **Clean electricity** [Chlor-alkali]
- **CCS** in concentrated streams [NGP]

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

**Demonstration-stage**

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

- **Reach ~$15/MWh[3] 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

*Remaining emissions would be abated by other levers*

**R&D/Pilot**

- **Industrial electrification** (e.g., Electric cracker [Ethylene])
- **Alternative production methods** (e.g., low-carbon feedstocks[5])

- **Reach ~$35/MWh[4] 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

*Figure [3.1.3]: Liftoff pathway for decarbonization technologies within the chemicals sector | 1. Indicative timeline presented for R&D, FOAK, liftoff, and scale. Actual timelines will vary by technology based on technological maturity and barriers to adoption | 3. Estimated as breakeven point on the MACC levelized cost of heat to reach \$0/tCO$_2$ abatement cost for ethylene steam generation | 4. Estimated as breakeven point on the MACC levelized cost of heat to reach \$0/tCO2 abatement cost for ethylene steam cracking furnace | 5. Includes bio-based or captured CO$_2$*

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

# Agenda

# Refining: Industry Overview

**~242**

MT $CO_2$ 2021 U.S. Emissions

**~243**

MT $CO_2e$ 2021 U.S. Emissions

**~1,400**

MT $CO_2$ 2021 Global Emissions

**Industry Context**

- U.S. refining sector produces transport fuels[4] and petrochemical feedstocks
- U.S. transport sector electrification will reduce domestic fuel consumption
- Domestic production of diesel and gasoline[5] 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 2030[6]
- Industry Scope 1&2 reduction targets by 2035[7] range between 30-50%

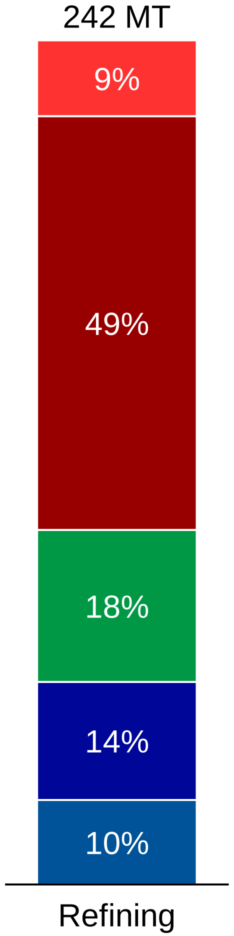
# Refining: Decarbonization levers

% Share of sector abatement potential

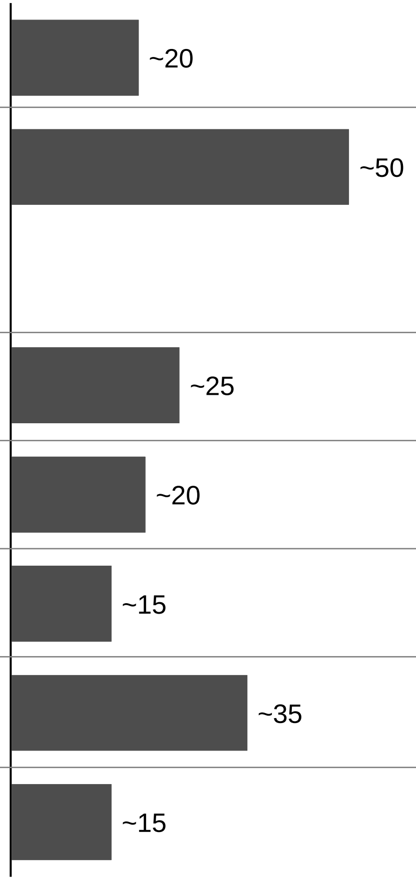
**NON-EXHAUSTIVE**

| Emissions source | | |
|---|---|---|
| **Heat[1]** | 🟥 | Low temp heat |
| | 🟥 | Mid temp heat |
| | 🟥 | High temp heat |
| **Production** | 🟩 | Process |
| **Electricity** | 🟦 | On-site power |
| | 🟦 | Off-site power |
| **Other** | ⬜ | Other |

## Emissions breakdown,[2] MT $CO_2$



## Decarbonization pathway (with IRA)



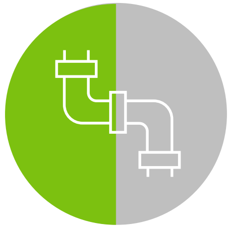
| | Value chain step responsible for emissions | Lever | Current lowest cost abatement,[4] MT $CO_2$ | % | Abatement cost, $/t $CO_2$ |
|---|---|---|---|---|---|
| 🟥 | **Finishing:** Treating products to achieve desired mix | Energy efficiency measures | ~20 | ~10% | ~(100)-(10) |
| 🟥 | **Atmospheric distillation:** Boils and separates crude oil residuals<br>**FCC[3]:** Cracks heavy products to generate lighter products in presence of catalyst<br>**Hydrotreating:** Removes sulfur or nitrogen | CCS on process heat | ~50 | ~20% | ~90-130[5] |
| | | CCS on FCC[3] | ~25 | ~10% | ~90-130[5] |
| 🟩 | **Steam methane reforming:** Production of hydrogen for hydrotreating and hydrocracking | CCS on SMR[3] | ~20 | ~10% | ~80-120[5] |
| | | Clean hydrogen | ~15 | ~5% | ~(65)-45 |
| 🟦 | **Power:** CHP[3] for onsite power and steam generation | Onsite clean electricity and storage | ~35 | ~15% | ~110-130 |
| 🟦 | **Grid decarbonization** | | ~15 | ~5% | N/A |

*Notes: Almost half of refining emissions come from high-temperature heat and can be addressed with CCS on process heating and fluid catalytic crackers (FCCs) | 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 refining emissions | 3. steam methane reformer (SMR); Fluidized catalytic cracking (FCC); Combined heat and power (CHP); Long-duration energy storage (LDES) | 4. An additional 9% of abatement potential can be gained from energy efficiency measures including reducing fuel consumption and repurposing flare gas | 5. Displayed cost estimates based on capture costs from various sources (see appendix for detail) with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10-40/t. 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.*

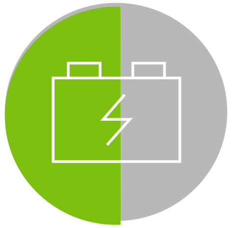
*Source: 2018 EPA Flight, 2018 EERE Manufacturing Energy and Carbon Footprints report, 2022 IEDO Report, White House – Long-term strategy of the U.S. Pathways to Net-zero, Refining MACC*

# Refining: Operational decarbonization momentum

**U.S. stage of decarbonization lever development** ■ Deployable 🟩 Demo ▨ R&D / Pilot

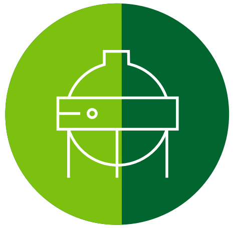


**CCS** (e.g., SMR[1])



**Industrial electrification**
(e.g., cracker)

**Energy efficiency**



**Electrolytic hydrogen[3]**

**Raw material substitution**
(e.g., bio-based feedstocks[2])

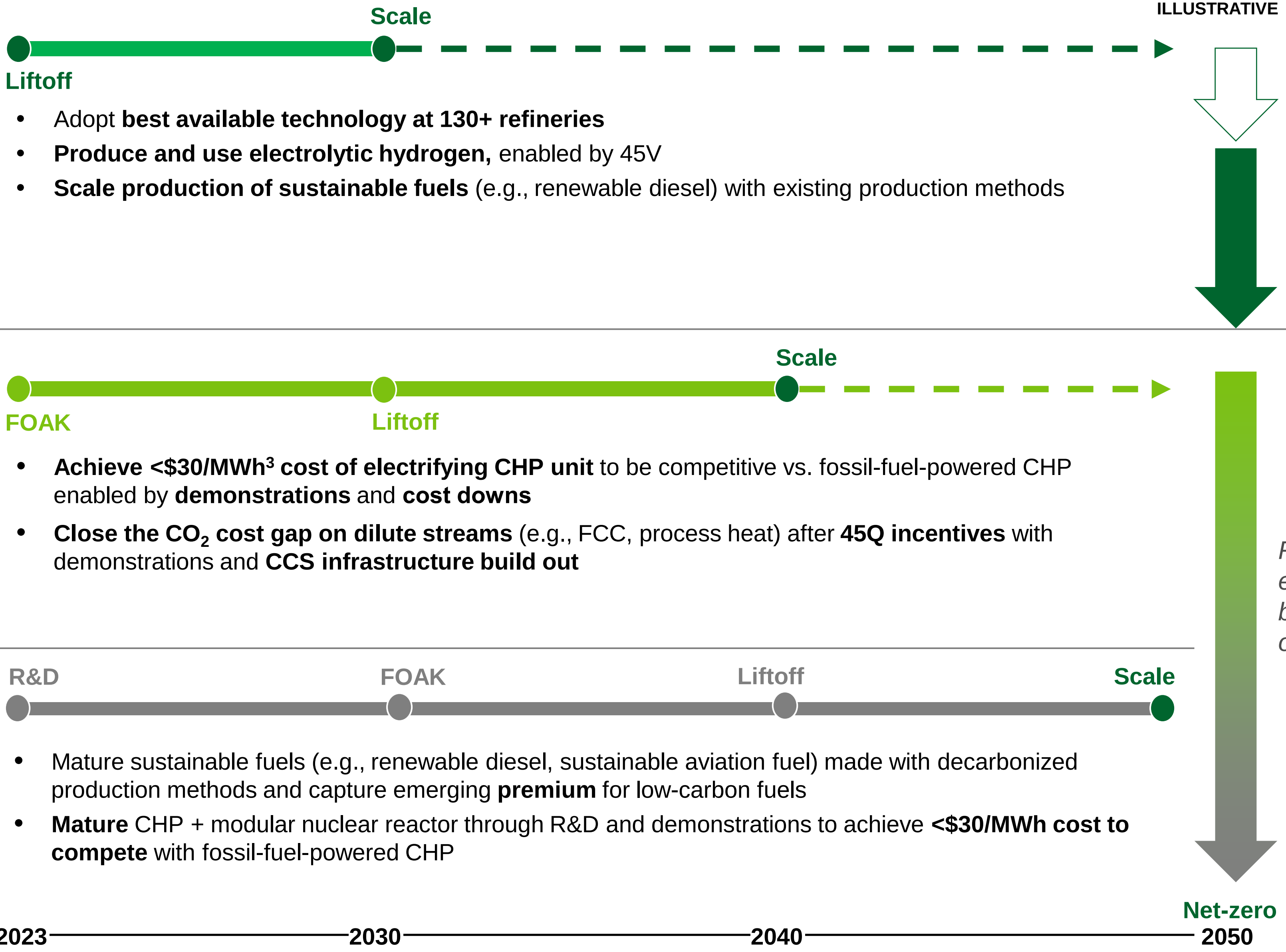
*Notes: Stage of lever deployment within the refining sector | 1. SMR = Steam methane reformers | 2. Such as bio-based feedstocks for fuel production and sustainable aviation fuels with decarbonized production facility | 3. Refers to hydrogen use in traditional processes as a feedstock*

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

# Refining: Liftoff pathway

**Technology examples** | **Pathway to commercial liftoff – Priority decarbonization actions[2]** | **2030 estimated emissions abatement in Refining[1], %**

ILLUSTRATIVE NOT EXHAUSTIVE



## Deployable

- **Energy efficiency**
- **Electrolytic hydrogen** (i.e., in ammonia and refining processes)
- **Raw material substitution:** Bio-based feedstocks with current production methods[4]

Liftoff → Scale

- Adopt **best available technology at 130+ refineries**
- **Produce and use electrolytic hydrogen,** enabled by 45V
- **Scale production of sustainable fuels** (e.g., renewable diesel) with existing production methods

~30% Grid decarb & external factors

15%

## Demonstration-stage

- **Industrial electrification:** Low temp. heat **electrification**
- **Industrial CCS** on dilute streams

FOAK → Liftoff → Scale

- **Achieve <\$30/MWh[3] cost of electrifying CHP unit** to be competitive vs. fossil-fuel-powered CHP enabled by **demonstrations** and **cost downs**
- **Close the $CO_2$ cost gap on dilute streams** (e.g., FCC, process heat) after **45Q incentives** with demonstrations and **CCS infrastructure build out**

*Remaining emissions would be abated by other levers*

## R&D/Pilot

- **Alternative production methods** (e.g., sustainable fuels)
- **CHP + modular nuclear reactor**

R&D → FOAK → Liftoff → Scale

- Mature sustainable fuels (e.g., renewable diesel, sustainable aviation fuel) made with decarbonized production methods and capture emerging **premium** for low-carbon fuels
- **Mature** CHP + modular nuclear reactor through R&D and demonstrations to achieve **<\$30/MWh cost to compete** with fossil-fuel-powered CHP

**Timeline** 2023 — 2030 — 2040 — Net-zero 2050

*Notes: 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. | 2. Indicative timeline presented for R&D, FOAK, liftoff, and scale. Actual timelines will vary by technology based on technological maturity and barriers to adoption | 3. Estimated as breakeven point on the MACC levelized cost of heat to reach \$0/t$CO_2$ abatement cost for refining combined heat and power | 4. Bio-based feedstocks not included in estimated emissions abatement due to focus on process and production emissions vs. lifecycle emissions. See Chemicals and Refining Liftoff Report for more detail.*

# 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

**~89**

MT $CO_2$ 2021 U.S. Emissions

---

**~3,100**

MT $CO_2$ 2021 Global Emissions

**Industry Context**

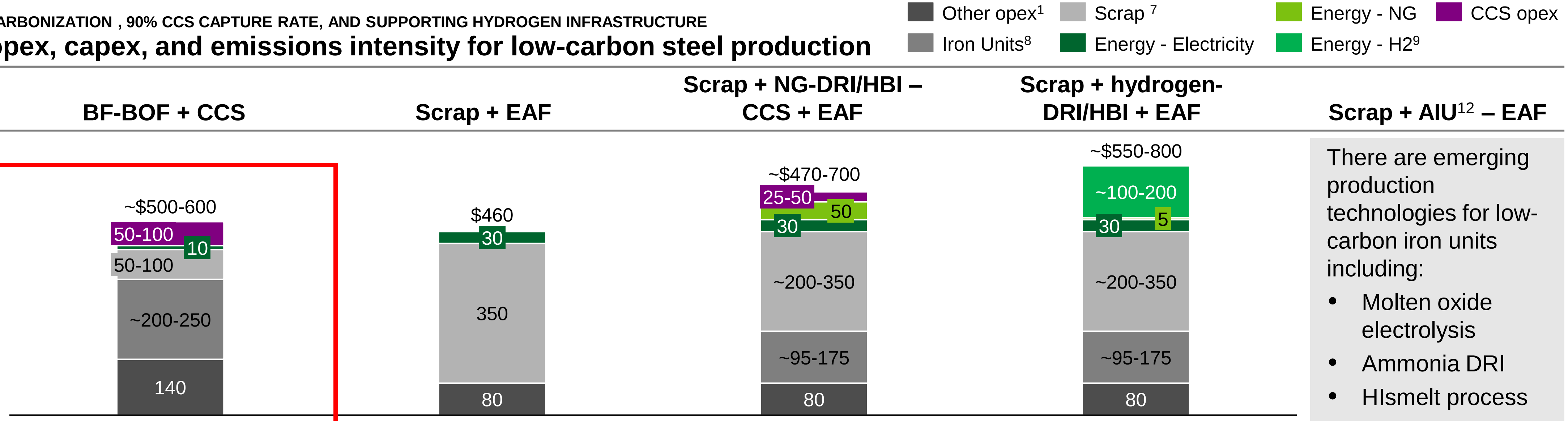
- There are two primary steelmaking pathways: integrated Blast Furnace/Basic Oxygen Furnaces (BF-BOF) & Electric Arc Furnaces (EAF)
  - EAF production has grown 172% in the U.S. since 1970
  - EAF (70% of domestic production) is low-carbon but will likely face domestic resource constraints (e.g., scrap, DRI/HBI)
  - BF-BOF (30% of domestic production) represent 70% of U.S. sector $CO_2$ 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 range[4] between 20-50%

# Iron & Steel: Five primary production routes for net-zero steel in the U.S.

ASSUMING FULL GRID DECARBONIZATION , 90% CCS CAPTURE RATE, AND SUPPORTING HYDROGEN INFRASTRUCTURE

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

**Opex breakdown,** $/ton liquid steel[3]



| | BF-BOF + CCS | Scrap + EAF | Scrap + NG-DRI/HBI – CCS + EAF | Scrap + hydrogen-DRI/HBI + EAF | Scrap + AIU[12] – EAF |
|---|---|---|---|---|---|
| **Emissions intensity,**[2] kg $CO_2$/ton steel | **~0.3** | **<0.1** | **<0.1** | **<0.1** | There are emerging production technologies for low-carbon iron units including:<br>- Molten oxide electrolysis<br>- Ammonia DRI<br>- HIsmelt process<br>- Others<br>Emissions intensity and economics are unclear |
| **Capex – decarb retrofit**[4], $B | **~0.6** | **N/A** | **~0.3** | **~0.1**[6] | |
| **Capex – new facility**[4], $B | **N/A**[5] | **0.3**[13] | **~1.2**[10] | **~0.9**[11] | |
| **Decarbonization challenges** | - Limited demonstration of CCS on coke oven, BF-BOF<br>- CCS is cost additive<br>***Detail on all BF-BOF decarb levers (beyond CCS) follows*** | - Near 100% scrap is predominately used to produce long products<br>- Scrap availability and quality drives production capacity | - No commercial demonstrations of CCS retrofit for NG-DRI/HBI plants[14]<br>- CCS is cost additive<br>- DRI/HBI price not competitive w/pig iron | - No hydrogen-DRI/HBI plants in the U.S.<br>- Limited Electrolytic hydrogen infrastructure<br>- Price of material & energy inputs (e.g., Electrolytic hydrogen price vs. NG[6], DRI/HBI vs. pig iron) | - Technology still nascent, may take years to reach commercial scale |

*Notes: Costs above represent perspective of steel producer | 1. Largely labor and mill maintenance | 2. Emissions intensity per ton liquid steel assumes that grid decarbonization reaches 100% 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 steel facility. Retrofit reflects cost of CCS or hydrogen installation on existing facility | 5. There are no plans to build additional BF-BOF mills domestically | 6. Cost of retrofitting NG-DRI/HBI to hydrogen | 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 an electrolytic hydrogen 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*

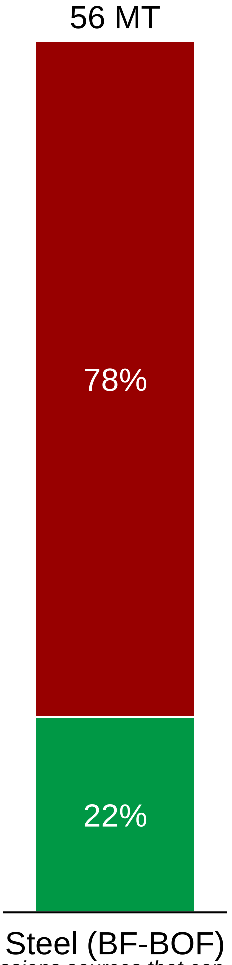
NON-EXHAUSTIVE

# Iron & Steel: Decarbonization levers

% Share of sector abatement potential

| Emissions source | | |
|---|---|---|
| **Heat**[1] | 🟥 | Low temp heat |
| | 🟥 | Mid temp heat |
| | 🟥 | High temp heat |
| **Production** | 🟩 | Process |
| **Electricity** | 🟦 | On-site power |
| | 🟦 | Off-site power |
| **Other** | ⬜ | Other |

**Emissions breakdown,**[2] MT $CO_2$



| | Value chain step responsible for emissions | Lever | Current lowest cost abatement, MT $CO_2$ | | Abatement Cost, $/t $CO_2$ |
|---|---|---|---|---|---|
| 🟥 | **Coking Oven:** Coal heated to produce coke | **Raw material substitution** (e.g., Add DRI/HBI to charge mix[6]) | <5 | ~5% | ~50-100 |
| 🟥 | **Blast Furnace:** Iron ore pellets melted with coke & limestone | **CCS** on coking oven, BF heat, BOF, NG-DRI/HBI | ~30 | ~55% | ~40-290[7,8] |
| 🟥 | **Basic Oxygen Furnace:** Pig iron melted & refined | **Electrification** (e.g., EAF[3]) | ~15[4] | ~25% | ~50-100[5] |
| 🟩 | **Rolling & Casting:** Molten steel casted and cooled | **Electrolytic hydrogen** (e.g., NG-DRI/HBI to hydrogen-DRI/HBI) | <5 | <5% | ~500-750[6] |

*Notes: BF-BOF steel production has two primary emissions sources that can be abated using a variety of levers (e.g., CCS, raw material substitution, electrification) | 1. Temperature ranges: low temperature heat is from -30ºC to 200ºC, medium heat is from 200ºC to 400ºC, and high heat is 400+ºC | 2. Breakdown of 2021 BF-BOF steel emissions | 3. 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 | 4. Note that this reflects difference in furnace emissions and increased scrap consumption | 5. NG DRI-EAF is estimated to be ~$100-150/ton whereas hydrogen DRI-EAF is ~$150-250/t | 6. Can only make up ~10-15% of material input | 7. 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.| 8. Displayed cost estimates based on capture costs from various sources (see appendix for detail) with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10-40/t. 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

**U.S. stage of decarbonization lever development** ■ Deployable 🟩 Demo ▨ R&D / Pilot

🟩 **CCUS**
(e.g., BF-BOF[2], NG DRI/HBI[3], Utilization)

■ **Industrial electrification**
(e.g., EAF[4])

■ **Energy efficiency**

🟩 **Electrolytic hydrogen**
(e.g., hydrogen-DRI/HBI[5])

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

▨ **Alternative production methods**
(e.g., ironmaking[1])

Notes: 1. Includes direct reduced iron and molten oxide electrolysis from companies such as Boston Metal | 2. Blast furnace-basic oxygen furnace (BF-BOF) | 3. Natural gas direct reduced iron / hot briquetted iron (NG DRI/HBI) | 4. Electric arc furnace (EAF) | 5. Direct reduced iron / hot briquetted iron (DRI/HBI)

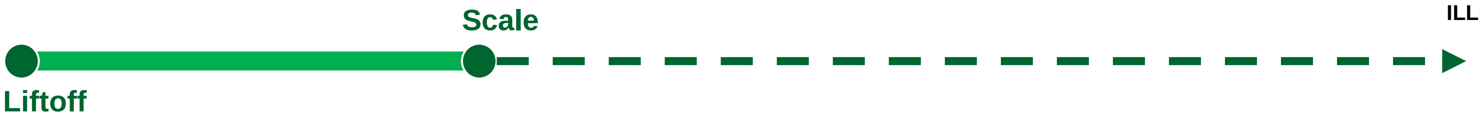
# Iron & Steel: Liftoff pathway

**Technology examples** | **Pathway to commercial liftoff – Priority decarbonization actions[1]** | **2030 estimated emissions abatement in Iron & Steel[2], %**

ILLUSTRATIVE NOT EXHAUSTIVE

## Deployable

- **Energy efficiency**
- **Industrial electrification:** Transition to EAF
- **Raw material substitution** (scrap, hydrogen DRI/HBI)



- 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

## Demonstration-stage

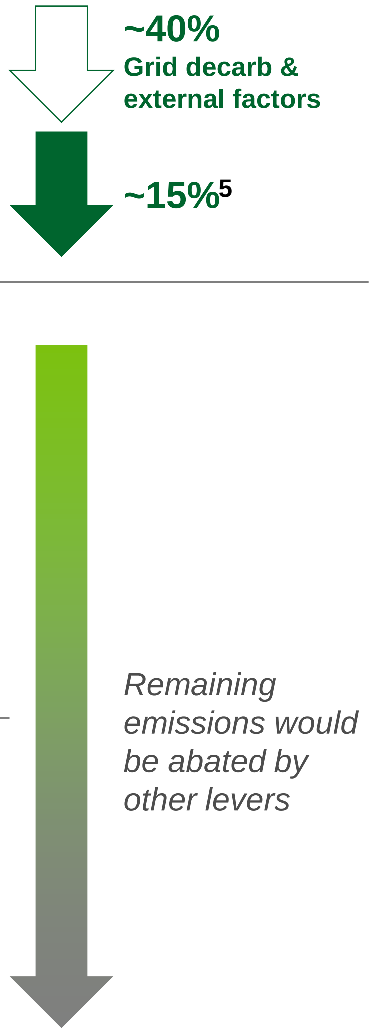
- **CCS:** BF-BOF + CCS
- **CCS:** NG-DRI/HBI + CCS
- **Electrolytic hydrogen:** Electrolytic hydrogen-DRI/HBI
- **CCUS:** Utilization retrofits

- **Reduce cost** of CCS on BF-BOF by **$75/tCO2[4]** via **demonstrations, 45Q incentives,** and buildout of **CCS infrastructure**
- **Reduce CCS costs on NG-DRI/HBI, enabled by emerging premium** of low-carbon DRI/HBI in U.S. and by stable supply of low-carbon DR pellets
- **Build FOAK Electrolytic hydrogen-DRI/HBI in the U.S.,** supported by 45V incentives, cost downs for on-site electrolyzers, and domestic Electrolytic hydrogen infrastructure

## R&D/Pilot

- **Alternative production method** (e.g., electrowinning, molten oxide electrolysis)
- **Increase EAF production**

- **Scale alternative ironmaking processes** to reach $350-400[3]/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 Net-zero 2050

*Notes: 1. Indicative timeline presented for R&D, FOAK, liftoff, and scale. Actual timelines will vary by technology based on technological maturity and barriers to adoption | 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-DRIHBI | 3. Based on estimate merchant cost of pig iron, DRI/HBI | 4. Reflects cost gap for BF-BOF CCS as published in carbon management report | 5. Calculated based on transition to electrification and raw material substitution does not evaluate energy efficiency levers.*

# 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

**~85** MT $CO_2$ 2021 U.S. Emissions

**~400** MT $CO_2$ 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 categories[6]
  - – 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 2035[5] range between 10-40%

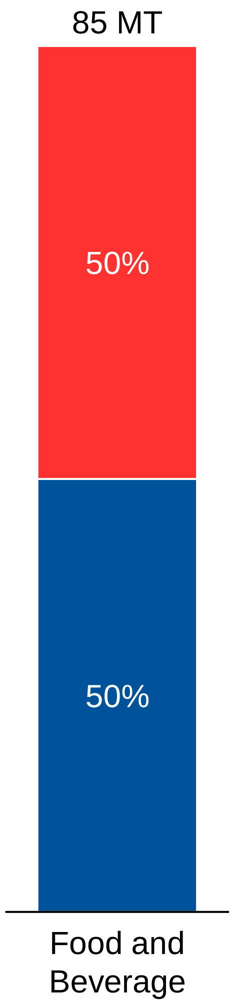
NON-EXHAUSTIVE

# Food & Beverage: Decarbonization levers

% Share of sector abatement potential

| Emissions source | | |
|---|---|---|
| **Heat**[1] | 🟥 | Low temp heat |
| | 🟥 | Mid temp heat |
| | 🟥 | High temp heat |
| **Production** | 🟩 | Process |
| **Electricity** | 🟦 | On-site power |
| | 🟦 | Off-site power |
| **Other** | ⬜ | Other |

**Emissions breakdown,**[2] $MT\ CO_2$



| Value chain step responsible for emissions | Lever | Current lowest cost abatement, $MT\ CO_2$ | Share of sector abatement potential | Abatement Cost, $/t $CO_2$[4] |
|---|---|---|---|---|
| **Steam generation:** Boilers and CHP | **Energy efficiency,** e.g., reduced steam losses | ~4 | ~5% | Net positive |
| | **Electrification,** e.g., e-boiler + TES[5] with clean energy | ~25 | ~30% | ~40-70[3] |
| **Process heating:** Various equipment for different sub-sectors (e.g., ovens, fryers) | **Electrification,** e.g., electric oven, electric fryers | ~10 | ~10% | ~60-105[3] |
| | **Alternative fuels (non-hydrogen)** (e.g., biomass) | <1 | <5% | TBD |
| **Process cooling,**[7] **conveyor belts, and other facility operations:** Electricity consumption | **Energy efficiency,** e.g., efficient process cooling/refrigeration | ~2 | <5% | Net positive |
| | **Grid decarbonization**[6] | ~45 | ~51% | N/A |

Reducing food loss is an indirect lever to reduce food and beverage processing emissions[8]

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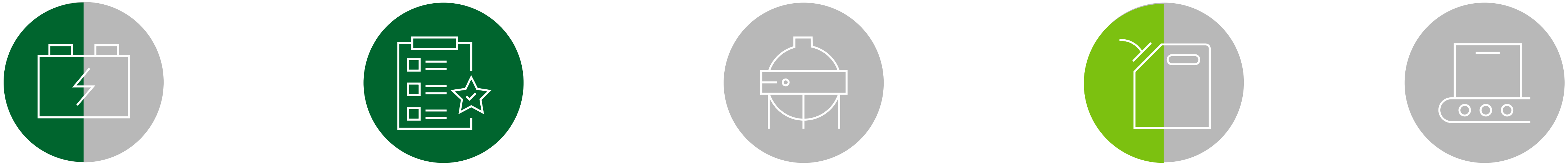
1. Temperature ranges: low temperature heat is from -30ºC to 200ºC, medium heat is from 200ºC to 400ºC, and high heat is 400+ºC | 2. Breakdown of 2021 food & beverage processing emissions | 3. Assumed to be 1.5x cost of electrified steam generation | 4. Wide range due to diverse products, processes, and facility sizes | 5. Thermal energy storage (TES) | 6. Biden Administration goal of reaching 100% clean electrical grid by 2035 | 7. Process cooling is a significant portion of current food & beverage processing electrical load and there are a range of levers that could be used to reduce electricity consumption | 8. Manufacturing is the largest source of food waste/loss

*Source: 2018 EPA Flight, 2018 EERE Manufacturing Energy and Carbon Footprints report, 2022 IEDO Report, McKinsey Global Energy Perspective, Communications, Earth & Environment (2022)*

# Food & Beverage: Operational decarbonization momentum

**U.S. stage of decarbonization lever development** 🟩 Deployable 🟩 Demo ⬜ R&D / Pilot



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

**Energy efficiency**
(e.g., waste energy recovery)

**Electrolytic hydrogen**[1]
(e.g., hydrogen boilers)

**Alternative fuel (non-hydrogen)**
(e.g., Demo: Biomass in boilers, R&D: Biomass in other equipment[1])

**Alternative production methods**[2]

**Water usage is particularly intensive in food & beverage processing - wastewater treatment, recovery, and reuse could reduce facility's water consumption and carbon footprint**

*Notes: 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*

*Source: 2018 EPA Flight, 2018 EERE Manufacturing Energy and Carbon Footprints report, 2022 IEDO Report, McKinsey Global Energy Perspective, Communications, Earth & Environment (2022)*

# Food & Beverage: Liftoff pathway

**Technology examples**

**Pathway to commercial liftoff – Priority decarbonization actions[3]**

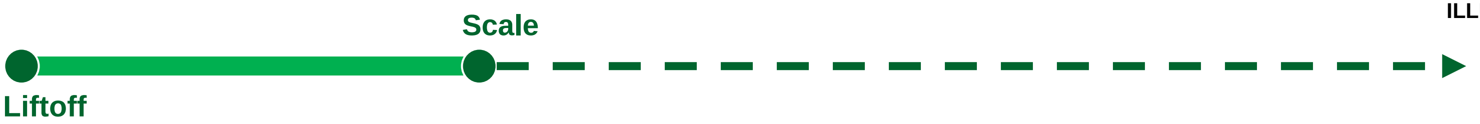
**2030 estimated emissions abatement in Food & Beverage %**

ILLUSTRATIVE

NOT EXHAUSTIVE

**Deployable**

- **Energy efficiency** (e.g., energy mgmt. systems, increase CHP**, efficient refrigerators, etc.)**
- **Industrial electrification** (boiler, heat pump)



- Adopt **best available technology across food & beverage processing facilities**
- Increase awareness of food & beverage processing emissions and solutions and proper food storage practices
- Co-create holistic emissions reduction plans with food & beverage companies that tackle Scope 1-3 emissions
- **Reach ~$15/MW[2] 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**

**Demonstration-stage**

- **Alternative fuel (non-hydrogen)** for low temp heating equipment

- **Increase use of alternative fuels in boilers and other heating equipment** (e.g., biomass, renewable natural gas, etc.)

**R&D/Pilot**

- **Electrolytic hydrogen** (e.g., boilers)
- **Industrial electrification** (other equipment)
- **Alternative production methods**

- Make alternative **low-carbon, low temp. heat methods** such as hydrogen boilers cost competitive with incumbent methods
- Develop cost-effective electric alternatives to other process heating equipment (specific to product)
- **Make alternatives to conventional food & beverage processing equipment** (e.g., absorption chillers, ejector refrigeration, deep waste energy and water recovery, alternative protein manufacturing, etc.) **cost competitive** with incumbent methods

**~50%**
**Grid decarb & external factors**

**~35%**

*Remaining emissions would be abated by other levers*

**Timeline** 2023 — 2030 — 2040 — 2050

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*1. Abatement share ranges are constrained and based on alternative decarbonization pathways, varying on factors such as the evolution of Clean hydrogen boilers | 2. Estimated as breakeven point on the MACC levelized cost of heat to reach $0/tCO2e abatement cost for ethylene steam generation (used as a proxy for low-temperature heat) | 3. Indicative timeline presented for R&D, FOAK, liftoff, and scale. Actual timelines will vary by technology based on technological maturity and barriers to adoption*

# 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

**~69**

MT $CO_2$ 2021 U.S. Emissions

---

**~2,500**

MT $CO_2$ 2021 Global Emissions

### Industry Context

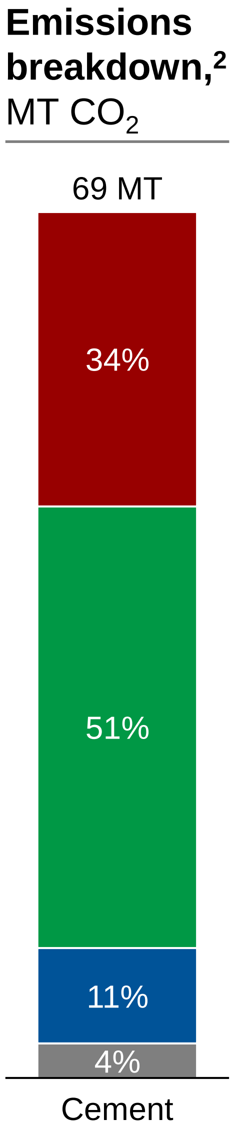
- Government procurement accounts for ~50% of the market, giving public sector an outsized role to play in accelerating decarbonization, but multiple tiers and fragmentation in value chain make it challenging to create clear demand signal
- 98 active cement plants in U.S. (96 in 34 states, 2 in PR)
- 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 range[5] between 10-65%

NON-EXHAUSTIVE

# Cement: Decarbonization levers

% Share of sector abatement potential

| Emissions source | | |
|---|---|---|
| **Heat**[1] | 🟥 | Low temp heat |
| | 🟥 | Mid temp heat |
| | 🟥 | High temp heat |
| **Production** | 🟩 | Process |
| **Electricity** | 🟦 | On-site power |
| | 🟦 | Off-site power |
| **Other** | ⬛ | Other |
| | 🟨 | Cross-cutting |



| Lever | Current lowest cost abatement, MT $CO_2$ | % | Abatement Cost, $/t $CO_2$ |
|---|---|---|---|
| 🟨 Energy efficiency | <5 | <5% | ~(40)-(20) |
| 🟨 Clinker substitution[3] | ~15 | ~25% | ~(75)-(20) |
| 🟥 Alternative fuel – waste[4] | ~5 | ~5% | ~(15)-5 |
| 🟥 Alternative fuel – biomass | <5 | <5% | ~25-45 |
| 🟥 Heat electrification | Emerging technology not included in MACC | | Emerging economics |
| 🟩 CCS on combustion and remaining emissions[5] | ~30 | ~45% | ~35-65 |
| 🟩 Alternative production methods | Emerging technology not included in MACC | | Emerging economics |
| 🟩 Alternative chemistries | Emerging technology not included in MACC | | Emerging economics |
| 🟦 Grid decarbonization | <5 | ~5% | N/A |

*Notes: 1. Temperature ranges: low temperature heat is from -30ºC to 200ºC, medium heat is from 200ºC to 400ºC, and high heat is 400+ºC | 2. Breakdown of 2021 cement emissions | 3. Assuming 65% clinker ratio | 4. Average based on several different types of waste feedstocks | 5. Displayed cost estimates based on capture costs from various sources (see appendix for detail) with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10-40/t. 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 – "Laying the foundation for zero-carbon cement", Portland Cement Association, DOE Carbon Management Liftoff Report, GCCA, Cemnet, IFC, GNR, IEA "Low-Carbon Transition in the Cement Industry"*

# Cement: Operational decarbonization momentum

**U.S. stage of decarbonization lever development** ■ Deployable 🟩 Demo ▨ R&D / Pilot

🟩

**CCS**
(e.g., rotary kiln)

▨

**Industrial electrification**
(e.g., pre-calcination and kiln electrification)

■

**Energy efficiency**

▨

**Electrolytic hydrogen**

■/▨

**Raw material substitution[2]**
(e.g., clinker alternative)

■

**Alternative fuel (non-hydrogen)**
(e.g., biomass, waste)

🟩/▨

**Alternative production methods[1]**
(e.g., electrochemical calcination, calcium silicate)

*Notes: 1. Geopolymers | 2. While substitution of limestone and fly ash are deployed today, other clinker substitutes are more nascent. See the following sources for additional detail: a.) U.S. Department of Energy - Office of Energy Efficiency & Renewable Energy. (n.d.). Industrial Efficiency and Decarbonization Office (IEDO) FY23 Multi-Topic FOA. Novel cements. Cembureau. (2018, September 28.*

*Source: McKinsey – "Laying the foundation for zero-carbon cement", Portland Cement Association, DOE Carbon Management Liftoff Report, GCCA, Cemnet, IFC, GNR, IEA "Low-Carbon Transition in the Cement Industry"*

# Cement: Liftoff pathway

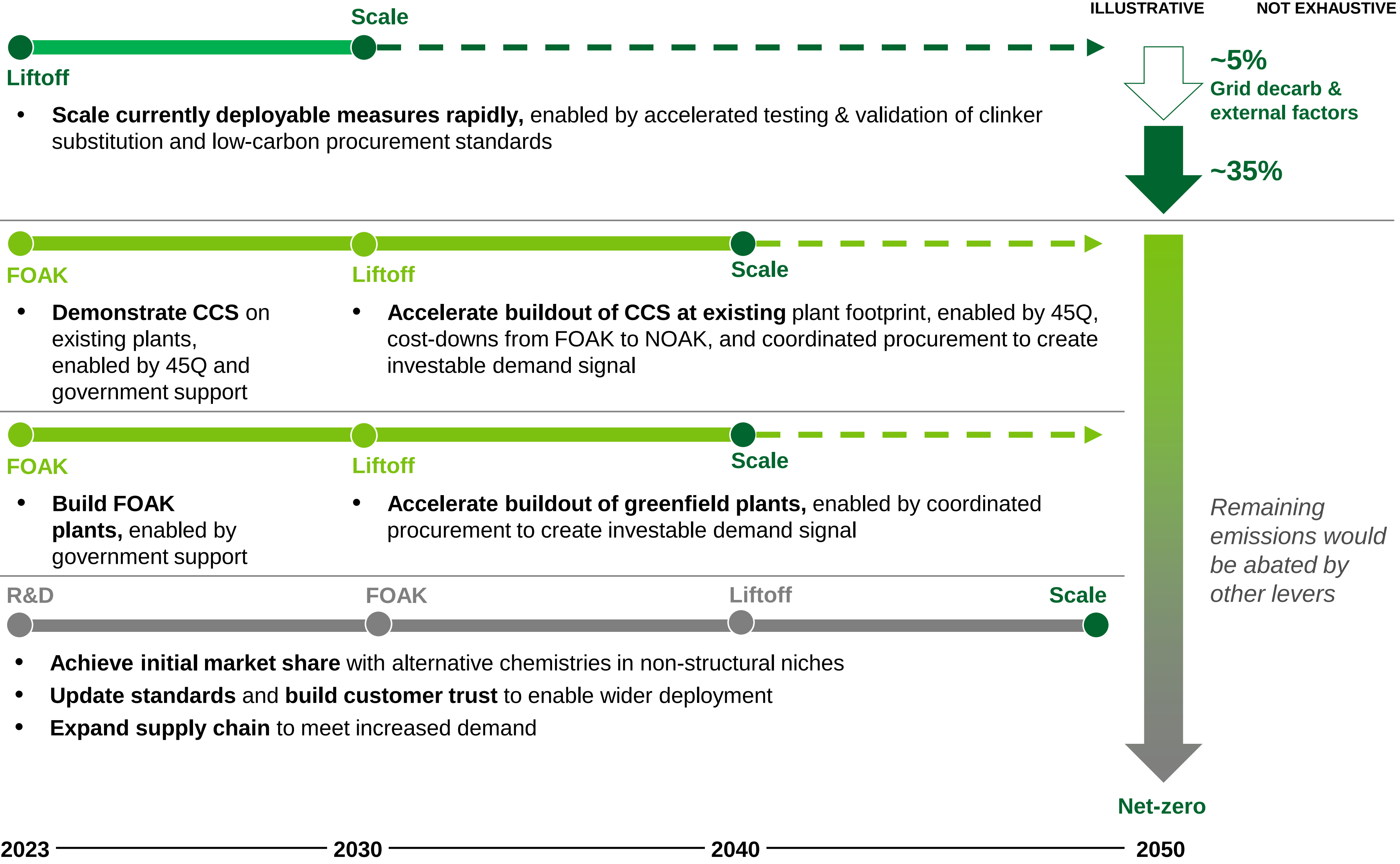
**Technology examples**

**Pathway to commercial liftoff – Priority decarbonization actions**[2]

**2030 estimated emissions abatement in Cement %**

ILLUSTRATIVE

NOT EXHAUSTIVE



**Deployable**

- **Energy efficiency**
- **Raw material substitutions:** Clinker substitutes (e.g., fly ash, GGBFS, calcined clay)
- **Alternative fuel (non-hydrogen)** (waste, biomass)

Liftoff → Scale (2023–2030)

- **Scale currently deployable measures rapidly,** enabled by accelerated testing & validation of clinker substitution and low-carbon procurement standards

**Demonstration-stage**

- **CCS** retrofits of existing plants

FOAK (2023)

- **Demonstrate CCS** on existing plants, enabled by 45Q and government support

Liftoff (2030) → Scale (2040)

- **Accelerate buildout of CCS at existing** plant footprint, enabled by 45Q, cost-downs from FOAK to NOAK, and coordinated procurement to create investable demand signal

- **Alternative production methods** (e.g., Noncarbonate feedstocks, Electrochemical production)

Compatible with existing standards

FOAK (2023)

- **Build FOAK plants,** enabled by government support

Liftoff (2030) → Scale (2040)

- **Accelerate buildout of greenfield plants,** enabled by coordinated procurement to create investable demand signal

**R&D/Pilot**

- **Raw material substitutions:** Earlier-stage novel SCMs and binders, alternative chemistries requiring updated standards
- **Hydrogen:** Higher-hydrogen fuel blends and electrification
- **CCS:** Alternative CCS approaches

R&D (2023) → FOAK (2030) → Liftoff (2040) → Scale (2050)

- **Achieve initial market share** with alternative chemistries in non-structural niches
- **Update standards** and **build customer trust** to enable wider deployment
- **Expand supply chain** to meet increased demand

*Remaining emissions would be abated by other levers*

**Timeline** 2023 — 2030 — 2040 — 2050

*Notes: 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. Indicative timeline presented for R&D, FOAK, liftoff, and scale. Actual timelines will vary by technology based on technological maturity and barriers to adoption*

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  - Cement
  - **Pulp & Paper**
  - Aluminum
  - Glass

# Pulp & Paper: Industry Overview

**~48** MT $CO_2$ 2021 U.S. Emissions

---

**~200** MT $CO_2$ 2021 Global Emissions

**Industry Context**

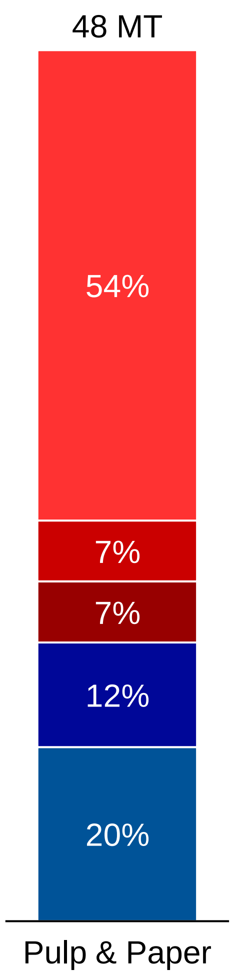
- Paper demand is expected to grow <1% from 2021 to 2030
  - Packaging is expected to grow faster and printing to decrease
- Most paper mills are focusing on transitioning from remaining coal-fired boilers to natural gas and biomass boilers
  - The industry currently supplies >60% of their fuel needs 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[5] by 2035 range between 20-50%

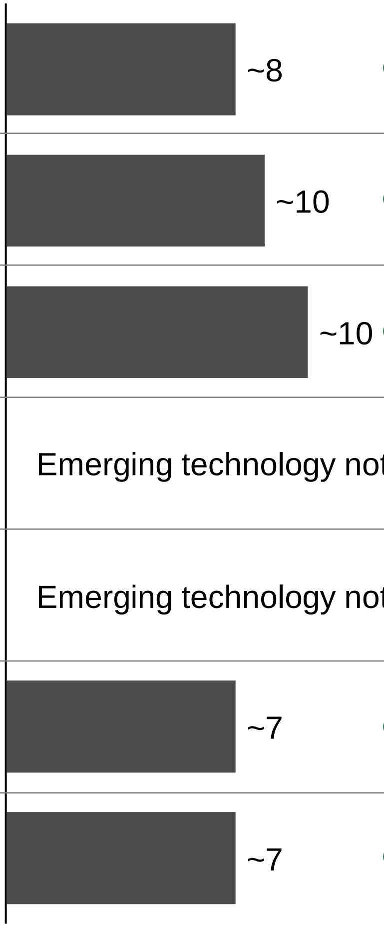
NON-EXHAUSTIVE

# Pulp & Paper: Decarbonization levers

(%) Share of sector abatement potential

| Emissions source | | | Emissions breakdown[2], MT CO2 |
|---|---|---|---|
| **Heat[1]** | 🟥 | Low temp heat | 54% |
| | 🟥 | Mid temp heat | 7% |
| | 🟥 | High temp heat | 7% |
| **Production** | 🟩 | Process | |
| **Electricity** | 🟦 | On-site power | 12% |
| | 🟦 | Off-site power | 20% |
| **Other** | ⬜ | Other | |





| Value chain step responsible for emissions | Lever | Current lowest cost abatement, MT CO$_2$ | | Abatement Cost, $/t CO$_2$ |
|---|---|---|---|---|
| **Drying:** Uses a multi-cylinder dryer, drying is the most energy-intensive phase within the papermaking process<br>**Burners:** Supports drying process<br>**Evaporators:** Evaporates and concentrates black liquor<br>**Boilers:** Produces steam and electricity | **Energy efficiency[3]** e.g., real time energy management systems | ~8 | ~15% | Net Positive |
| | **Alternative fuels (non-hydrogen)[4]** e.g., biomass boilers & burners | ~10 | ~20% | ~10 – 130 |
| | **Electrification** e.g., heat pumps, electric boiler, CHP | ~10 | ~25% | ~0 – 70 |
| | **Clean hydrogen** e.g., hydrogen burners, hydrogen boilers | Emerging technology not included in MACC | | |
| | **Alternative fuel (non-hydrogen)** e.g., biomass gasification, pyrolysis | Emerging technology not included in MACC | | |
| **Onsite electricity:** Burning fossil fuels on site to produce power | **Clean onsite electricity** e.g., biomass, onsite solar | ~7 | ~15% | ~30 – 70 |
| **Offsite electricity** | **Grid decarbonization** | ~7 | ~15% | N/A |

Biogenic emissions could be decarbonized by post combustion CCS

*Notes: 1. Temperature ranges: low temperature heat is from -30ºC to 200ºC, medium heat is from 200ºC to 400ºC, and high heat is 400+ºC | 2. Breakdown of 2021 pulp and paper production emissions | 3. 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 | 4. Includes biomethane boilers (brownfield), biomass burner, RDF boiler, biomass boiler, biomethane burner (brownfield).*

*Source: FisherSolve Next 4.0.23.0301, expert interviews*

# Pulp & Paper: Operational decarbonization momentum

**U.S. stage of decarbonization lever development** 🟩 Deployable 🟩 Demo ⬜ R&D / Pilot

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

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

**Energy efficiency**
(e.g., RTEM[1])

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

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

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

*Note: 1. Real time energy management (RTEM)*

# Pulp & Paper: Liftoff pathway

**Technology examples**

**Pathway to commercial liftoff – Priority decarbonization actions**[4]

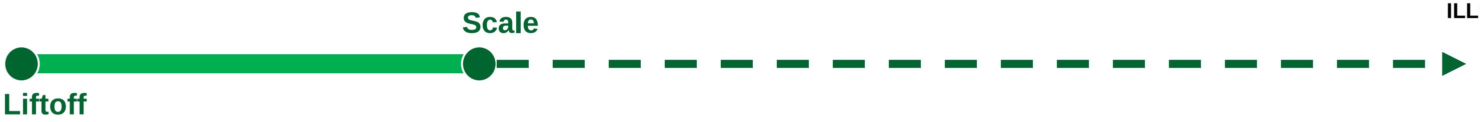
**2030 estimated emissions abatement in Pulp and Paper %**

ILLUSTRATIVE

NOT EXHAUSTIVE

**Deployable**

- **Energy efficiency**
- **Clean electricity and alternative fuels** (e.g., biomass)
- **Industrial electrification:** Low temp. heat electrification



- 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[3] cost of low temp. heat electrification** to be competitive vs. fossil fuel boilers/burners, enabled by **demonstrations** and **cost downs**

**Demonstration-stage**

- **CCS** (black liquor boiler)

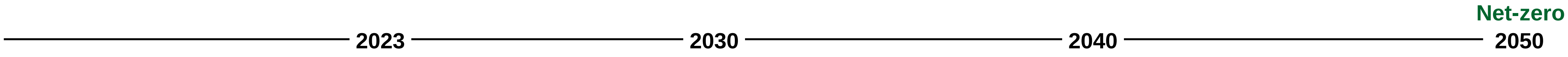
- **Cost-downs to reach breakeven with available incentives** with potential to **abate biogenic emissions**[1]

**R&D/Pilot**

- **Alternative technology** (e.g., gasification, pyrolysis)
- **Electrolytic hydrogen** (e.g., Boilers)

- Commercialize biomass gasification and pyrolysis technology to create **new revenue streams from production of hydrogen and SAF fuels,** enabled by **stable long-term supply of biomass**
- **Install FOAK clean hydrogen boiler in a P&P mill in the U.S.,** supported by domestic clean hydrogen infrastructure

*Remaining emissions would be abated by other levers*



*Notes: 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. Indicative timeline presented for R&D, FOAK, liftoff, and scale. Actual timelines will vary by technology based on technological maturity and barriers to adoption*

# 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

**~15**

MT $CO_2$ 2021 U.S. Emissions

**~16**

MT $CO_2e$ 2021 U.S. Emissions

**~1,100**

MT $CO_2$ 2021 Global Emissions

**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 range[4] between 20-50%

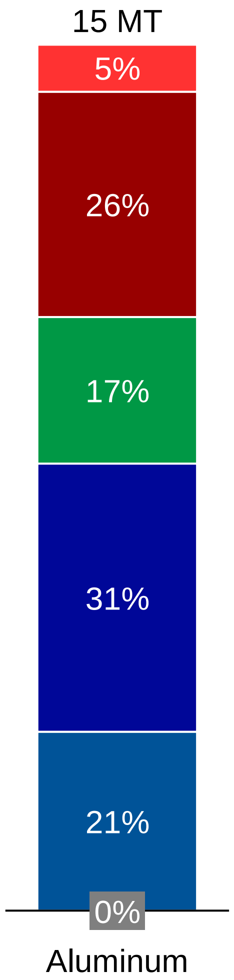
NON-EXHAUSTIVE

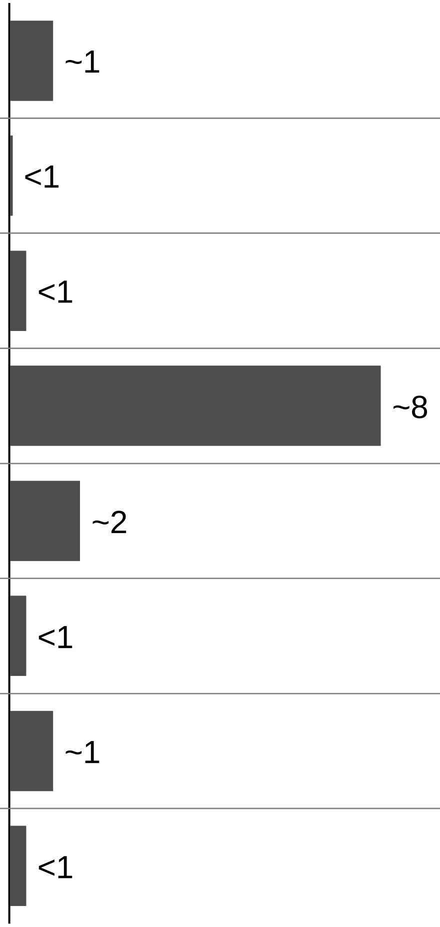
# Aluminum: Decarbonization levers

% Share of sector abatement potential

| Emissions source | | |
|---|---|---|
| **Heat**[1] | 🟥 | Low temp heat |
| | 🟥 | Mid temp heat |
| | 🟥 | High temp heat |
| **Production** | 🟩 | Process |
| **Electricity** | 🟦 | On-site power |
| | 🟦 | Off-site power |
| **Other** | ⬜ | Other |

**Emissions breakdown,**[2] MT $CO_2$





| Value chain step responsible for emissions | Lever | Current lowest cost abatement, MT $CO_2$ | % | Abatement Cost, \$/t $CO_2$ |
|---|---|---|---|---|
| **Alumina refining:** digestion and calcination | **Electrification** (e.g., electric gas heating) | ~1 | ~5% | ~(10)-10 |
| | **Energy efficiency** (e.g., waste heat recovery) | <1 | <5% | ~(10)-10 |
| **Smelting:** carbon anode consumption and electricity | **Energy efficiency**[3] | <1 | <5% | ~(15)-5 |
| | **Grid decarbonization** | ~8 | ~50% | N/A |
| | **CCS** on Hall-Héroult/Electrolysis[5] | ~2 | ~10% | ~140-290 |
| **Rolling, extrusion, and casting** | **Energy efficiency** | <1 | <5% | ~(15)-5 |
| | **Electrification** (e.g., e-reheater) | ~1 | ~5% | ~20-40 |
| | **Raw material substitution** (recycling)[4] | <1 | <5% | ~(40)-(20) |

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*1. Temperature ranges: low temperature heat is from -30ºC to 200ºC, medium heat is from 200ºC to 400ºC, and high heat is 400+ºC | 2. Breakdown of 2021 aluminum production emissions | 3. 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 | 4. Despite relatively small abatement potential, recycling has other ancillary benefits including de-risking U.S. aluminum exposure | 5. Displayed cost estimates based on capture costs from various sources (see appendix for detail) with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~\$10-40/t. 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: International Aluminum Association, USGS, MPP – Net zero aluminum, IEA*

# Aluminum: Operational decarbonization momentum

**U.S. stage of decarbonization lever development** 🟩 Deployable 🟢 Demo ⬜ R&D / Pilot

⬜ **CCS**
(e.g., smelting process[2])

⬜🟩 **Industrial electrification**
(R&D: high temp heat,[3]
Deployable: low temp heat)

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

⬜ **Electrolytic hydrogen**
(e.g., hydrogen calciner)

🟢🟩 **Raw material substitution**
(Demo: Zorba processing and yield improvement, Deployable: Increase scrap usage)

🟢⬜ **Alternative production methods**
(Demo: inert anode,[1]

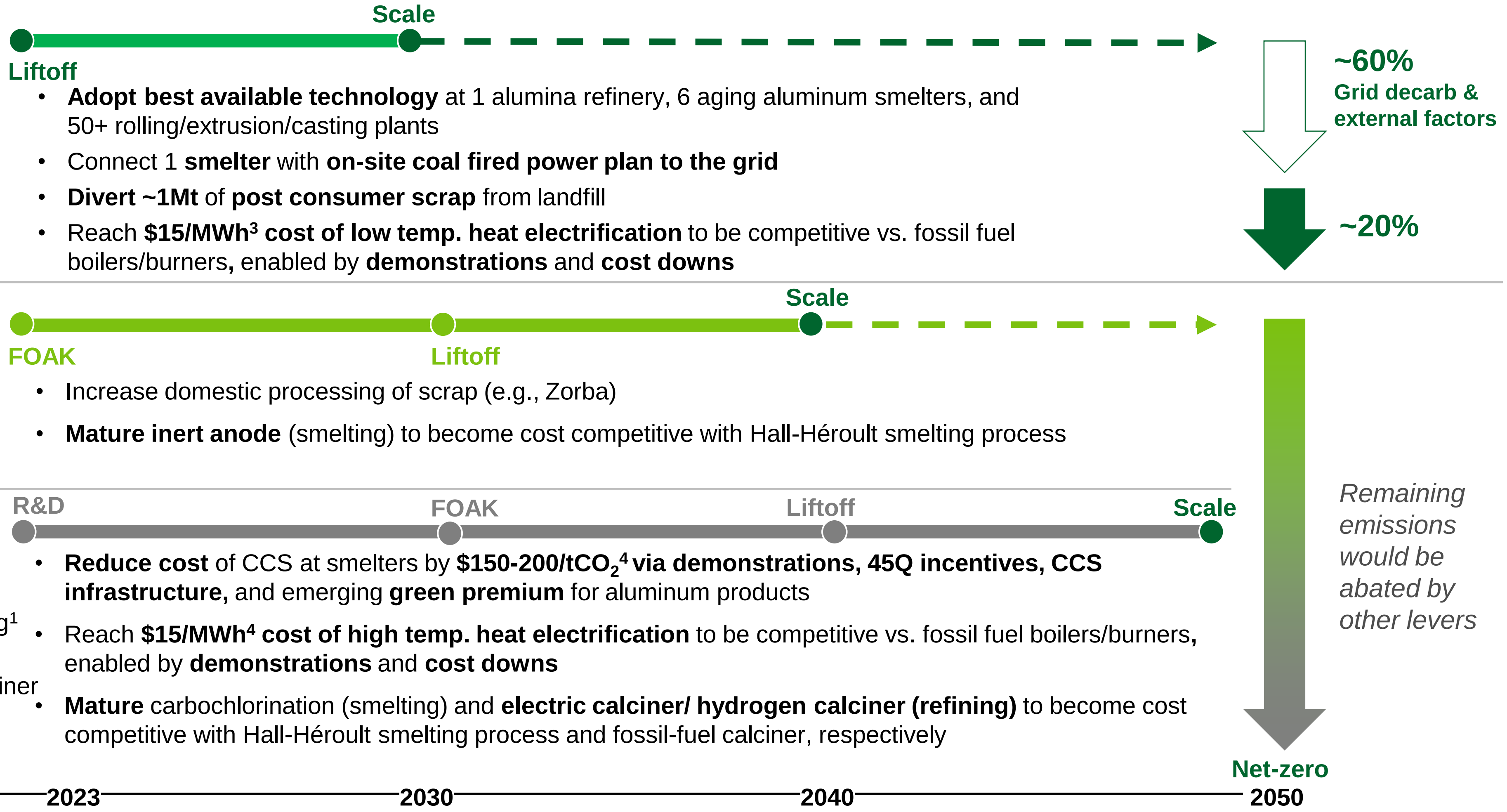
RD&D: carbochlorination)

*Notes: 1. Planned international deployment | 2. Select feasibility studies | 3. International pilots and deployments*

# Aluminum: Liftoff pathway

**ILLUSTRATIVE NOT EXHAUSTIVE**

**Technology examples** | **Pathway to commercial liftoff – Priority decarbonization actions[6]** | **2030 estimated emissions abatement in Aluminum %**



**Deployable**

- **Energy efficiency**
- **Raw material substitution**: Increase scrap usage
- **Low temp heat electrification**

Priority actions:

- **Adopt best available technology** at 1 alumina refinery, 6 aging aluminum smelters, and 50+ rolling/extrusion/casting plants
- Connect 1 **smelter** with **on-site coal fired power plan to the grid**
- **Divert ~1Mt** of **post consumer scrap** from landfill
- Reach **$15/MWh[3] cost of low temp. heat electrification** to be competitive vs. fossil fuel boilers/burners**,** enabled by **demonstrations** and **cost downs**

**Demonstration-stage**

- **Raw material substitution**: Increase Zorba processing
- **Alternative production methods**: Inert anode

Priority actions:

- Increase domestic processing of scrap (e.g., Zorba)
- **Mature inert anode** (smelting) to become cost competitive with Hall-Héroult smelting process

**R&D/Pilot**

- **CCS** on smelters
- **Industrial electrification:** High heat electrification in rolling/extrusion/casting[1]
- **Industrial electrification**: E-calciner
- **Electrolytic Hydrogen**: hydrogen-calciner
- **Alternative production methods**: Carbochlorination

Priority actions:

- **Reduce cost** of CCS at smelters by **\$150-200/$tCO_2$[4] via demonstrations, 45Q incentives, CCS infrastructure,** and emerging **green premium** for aluminum products
- Reach **$15/MWh[4] cost of high temp. heat electrification** to be competitive vs. fossil fuel boilers/burners**,** enabled by **demonstrations** and **cost downs**
- **Mature** carbochlorination (smelting) and **electric calciner/ hydrogen calciner (refining)** to become cost competitive with Hall-Héroult smelting process and fossil-fuel calciner, respectively

**Timeline** 2023 – 2030 – 2040 – 2050

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*Notes: 1. Electrical furnace – resistance, electrical furnace – induction, plasma furnace | 2. 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) | 3. Estimated as breakeven point on the MACC levelized cost of heat to reach \$0/$tCO_2$ abatement cost for ethylene steam generation (used as a proxy for low-temperature heat) | 4. Displayed cost estimates based on capture costs from various sources (see appendix for detail) with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~\$10-40/t. 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. | 5. Estimated as breakeven point on the MACC levelized cost of heat to reach \$0/$tCO_2$ abatement cost for ethylene steam generation (used as a proxy for low-temperature heat) | 6. Indicative timeline presented R&D, FOAK, liftoff, and scale. Actual timelines will vary by technology based on technological maturity and barriers to adoption*

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

# Agenda

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- **Sector-level insights**
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  - Food & Beverage
  - Cement
  - Pulp & Paper
  - Aluminum
  - **Glass**

# Glass: Industry Overview

| | | |
|---|---|---|
| **~11** | MT $CO_2$ | 2021 U.S. Emissions |
| **~100** | MT $CO_2$ | 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 range[4] between 15-50%

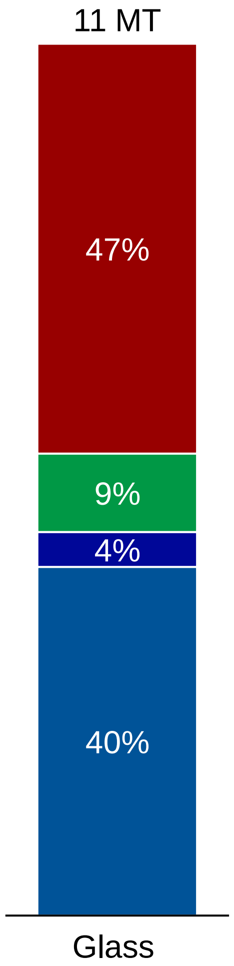
NON-EXHAUSTIVE

# Glass: Decarbonization levers

% Share of sector abatement potential

| Emissions source | | |
|---|---|---|
| **Heat[1]** | 🟥 | Low temp heat |
| | 🟥 | Mid temp heat |
| | 🟥 | High temp heat |
| **Production** | 🟩 | Process |
| **Electricity** | 🟦 | On-site power |
| | 🟦 | Off-site power |
| **Other** | ⬜ | Other |

**Emissions breakdown[2],** MT $CO_2$



| **Value chain step responsible for emissions** | **Lever** | **Current lowest cost abatement,** MT $CO_2$ | % | **Abatement Cost,** \$/t $CO_2$ |
|---|---|---|---|---|
| **Annealing:** Cooling hot glass objects after they have been formed<br>**Melting:** Heating mixture of materials in a furnace until it melts<br>**Fining**: Removing bubbles and impurities from molten glass by subjecting it to high temperatures and controlled cooling to achieve a clear and uniform product | **Alternate fuel – non hydrogen** (biomethane) | <1 | ~5% | ~125 - 550[3] |
| | **Electrification –** electric melting, electric boost | ~1 | ~10% | ~300 - 400 |
| | **Energy efficiency –** waste heat recovery | <1 | ~5% | Net positive |
| | **Energy efficiency -** oxyfuel | <1 | ~5% | ~10 - 140 |
| | **Clean hydrogen –** forming and post forming | <1 | ~5% | ~190 - 550 |
| | **CCS[4] –** melting and forming | ~2 | ~15% | ~140 - 290 |
| **Batch and Mix:** Weighing and mixing raw materials in specific proportions | **Raw material substitution and recycling** | ~1 | ~10% | ~(40) - 50 |
| **Forming:** Shaping molten glass according to the desired end-product | **Grid decarbonization** | ~5 | ~40% | N/A |

*Notes: 1. Temperature ranges: low temperature heat is from -30ºC to 200ºC, medium heat is from 200ºC to 400ºC, and high heat is 400+ºC | 2. Breakdown of 2021 glass production emissions | 3. Lower bound represents estimates for biomethane forming in container glass and higher bound represents estimates for biomethane melting in container glass | 4. Displayed cost estimates based on capture costs from various sources (see appendix for detail) with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~\$10-40/t. 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: Manufacturing Energy and Carbon Footprint: Glass and Glass Production U.S. DOE, Glass International 'Could carbon capture work in the glass manufacturing sector?', Zier 2021 A review of decarbonization options for the glass industry, Technical analysis – Glass sector (NACEC23.1),*

# Glass: Operational decarbonization momentum

**U.S. stage of decarbonization lever development** 🟩 Deployable 🟩 Demo ⬜ R&D / Pilot

**CCS**
(e.g., melting and forming)

**Industrial electrification**
(e.g., electric melting)

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

**Electrolytic hydrogen**
(e.g., hydrogen melting)

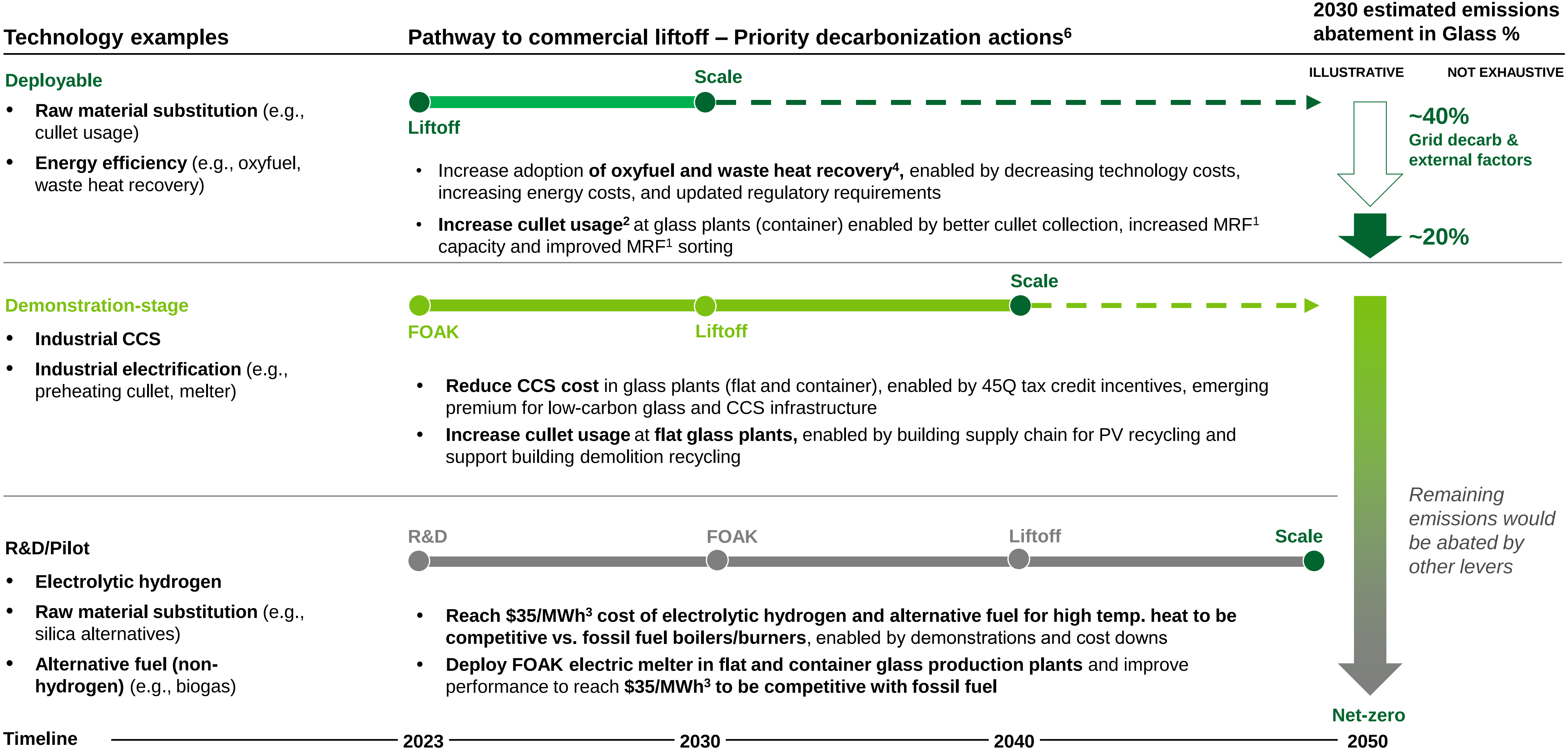
**Raw material substitution**
(e.g., Deployable: recycling,[1] R&D: silica alternatives)

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

*Note: 1. Increase cullet usage*

*Source: Manufacturing Energy and Carbon Footprint: Glass and Glass Production U.S. DOE, Glass International 'Could carbon capture work in the glass manufacturing sector?', Zier 2021 A review of decarbonization options for the glass industry, Technical analysis – Glass sector (NACEC23.1),*

# Glass: Liftoff pathway



**Technology examples**

**Pathway to commercial liftoff – Priority decarbonization actions[6]**

**2030 estimated emissions abatement in Glass %**

ILLUSTRATIVE

NOT EXHAUSTIVE

**Deployable**

- **Raw material substitution** (e.g., cullet usage)
- **Energy efficiency** (e.g., oxyfuel, waste heat recovery)

- 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

**~40%** **Grid decarb & external factors**

**~20%**

**Demonstration-stage**

- **Industrial CCS**
- **Industrial electrification** (e.g., preheating cullet, melter)

- **Reduce CCS cost** in glass plants (flat and container), enabled by 45Q tax credit incentives, emerging 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

*Remaining emissions would be abated by other levers*

**R&D/Pilot**

- **Electrolytic hydrogen**
- **Raw material substitution** (e.g., silica alternatives)
- **Alternative fuel (non-hydrogen)** (e.g., biogas)

- **Reach $35/MWh[3] cost of electrolytic hydrogen and alternative fuel for high temp. heat to be competitive vs. fossil fuel boilers/burners**, enabled by demonstrations and cost downs
- **Deploy FOAK electric melter in flat and container glass production plants** and improve performance to reach **$35/MWh[3] to be competitive with fossil fuel**

**Net-zero**

**Timeline** — **2023** — **2030** — **2040** — **2050**

*Notes: 1. Material recovery facility (MRF) | 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. Indicative timeline presented R&D, FOAK, liftoff, and scale. Actual timelines will vary by technology based on technological maturity and barriers to adoption*