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

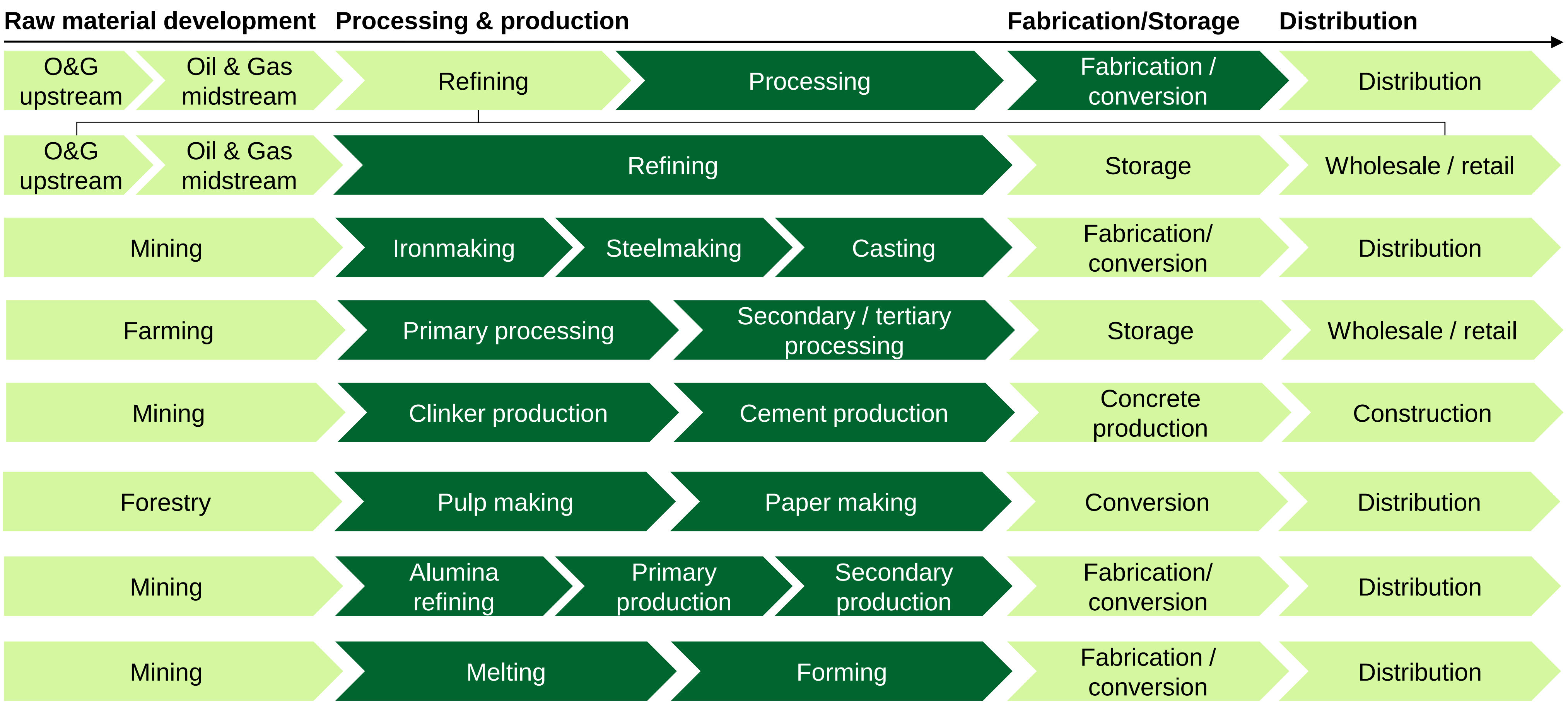
🚀 Technologies also discussed in prior Liftoff reports from DOE

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



Industrial Sector	Simplified value chains[2] Raw material development	Processing & production	Fabrication/Storage	Distribution
Chemicals[1]	O&G upstream Oil & Gas midstream	Refining Processing	Fabrication / conversion	Distribution
Refining	O&G upstream Oil & Gas midstream	Refining	Storage	Wholesale / retail
Iron & Steel	Mining	Ironmaking Steelmaking Casting	Fabrication/ conversion	Distribution
Food & Beverage	Farming	Primary processing Secondary / tertiary processing	Storage	Wholesale / retail
Cement	Mining	Clinker production Cement production	Concrete production	Construction
Pulp & Paper	Forestry	Pulp making Paper making	Conversion	Distribution
Aluminum	Mining	Alumina refining Primary production Secondary production	Fabrication/ conversion	Distribution
Glass	Mining	Melting Forming	Fabrication / conversion	Distribution

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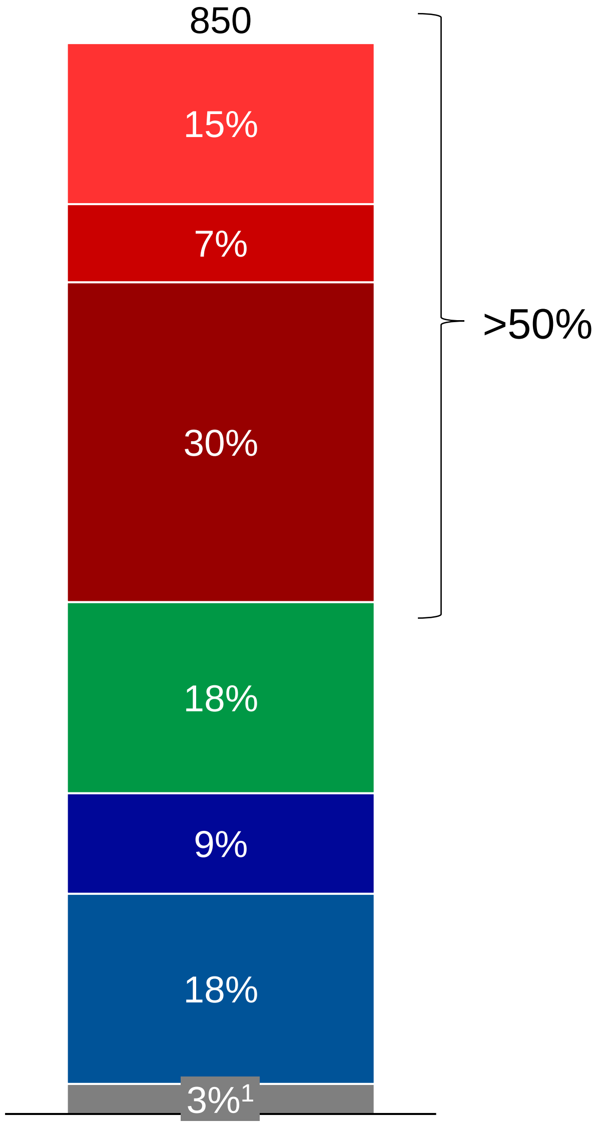
1. Given the share of U.S. emissions from this sector, further production stage emissions (e.g., natural gas processing) were included | 2. "Well-to-gate" emissions are not discussed in this presentation

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



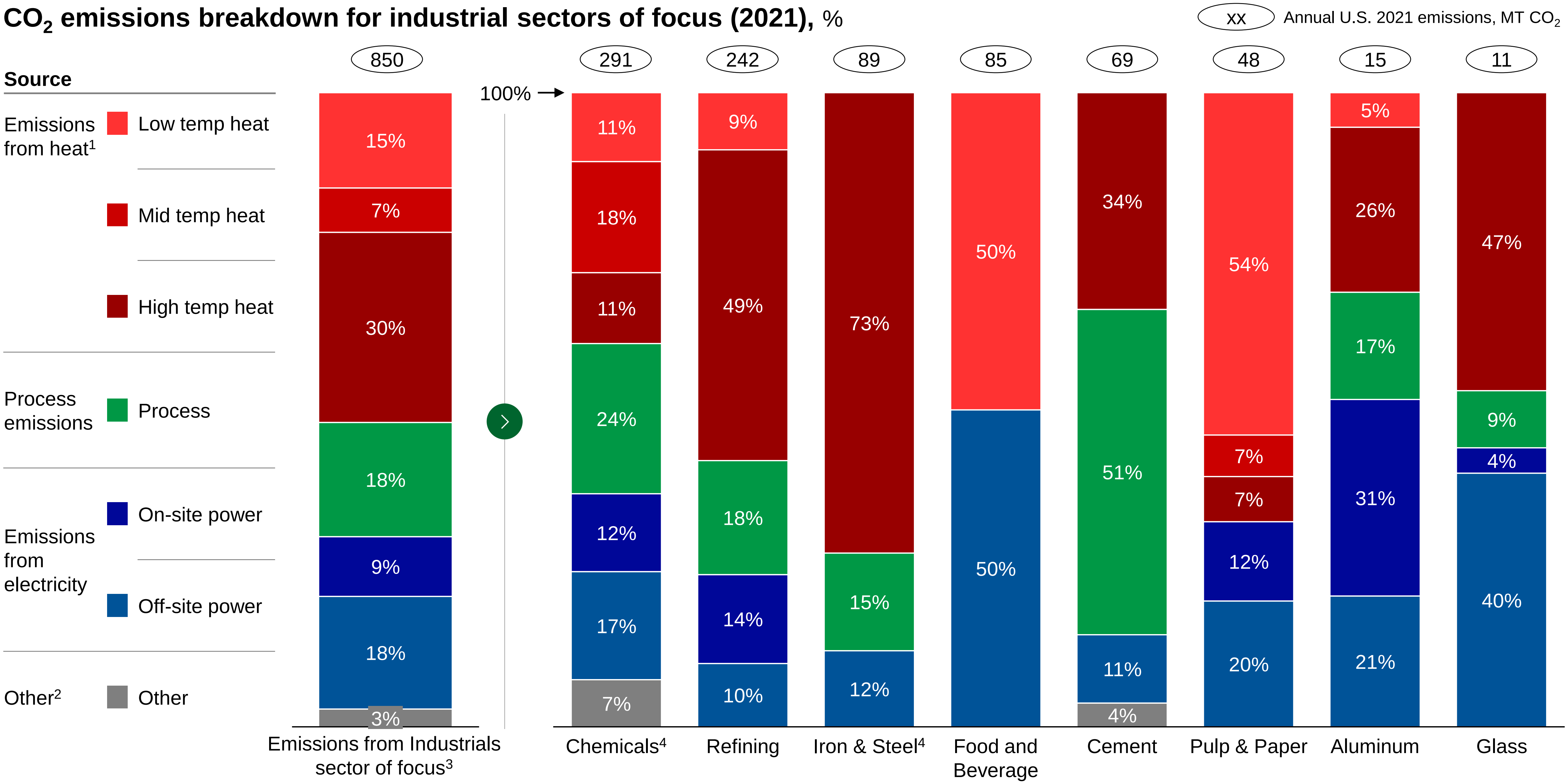
Emissions from Industrials sector of focus[2]

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

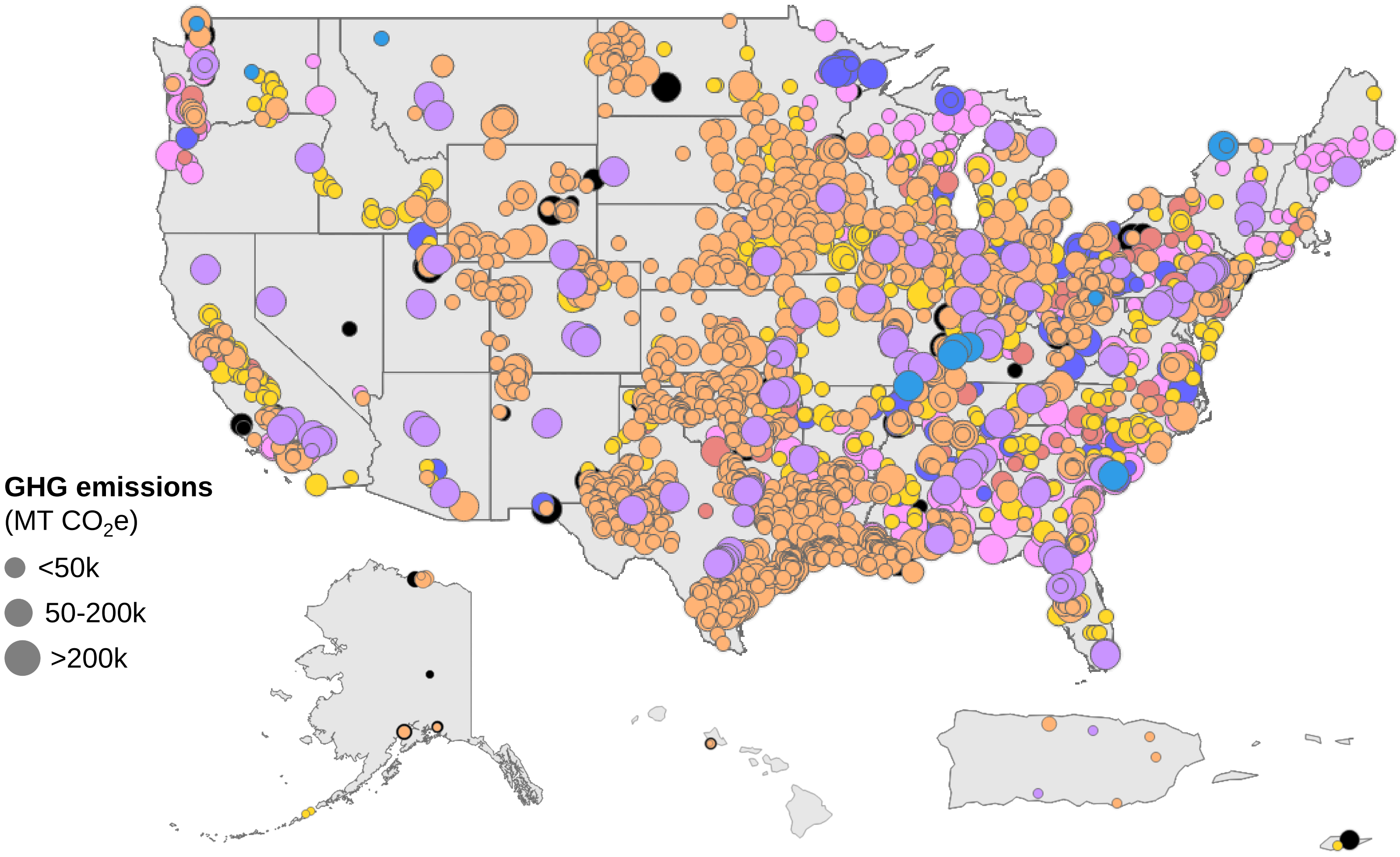
Source: 2018 EPA Flight, 2018 EERE Manufacturing Energy and Carbon Footprints report, 2022 IEDO Report, Energy Environ. Sci., 2020,13, 331-344, EIA, 2020 USGS, DOE Natural Gas Supply Chain report

ILLUSTRATIVE **NOT EXHAUSTIVE**

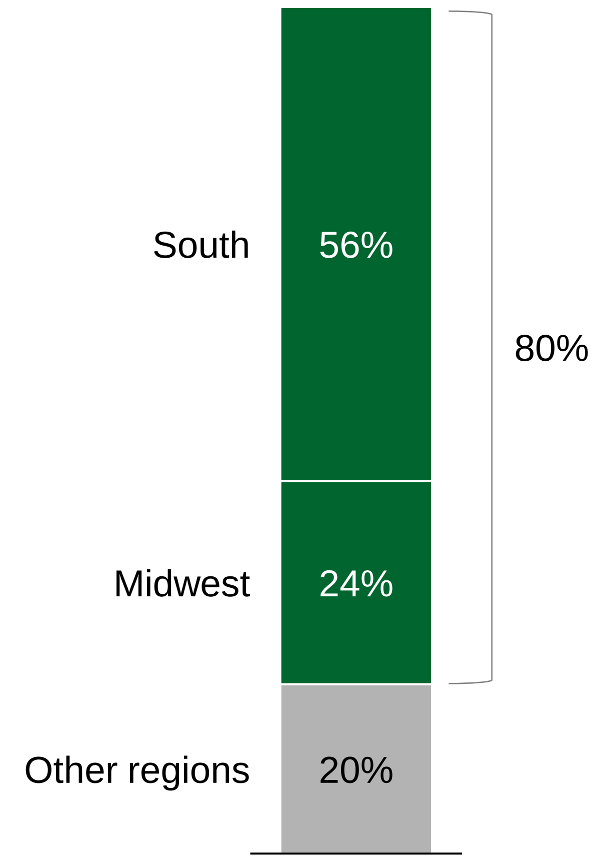
Emissions are dispersed across 2,500+ facilities across the U.S.

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_2e/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

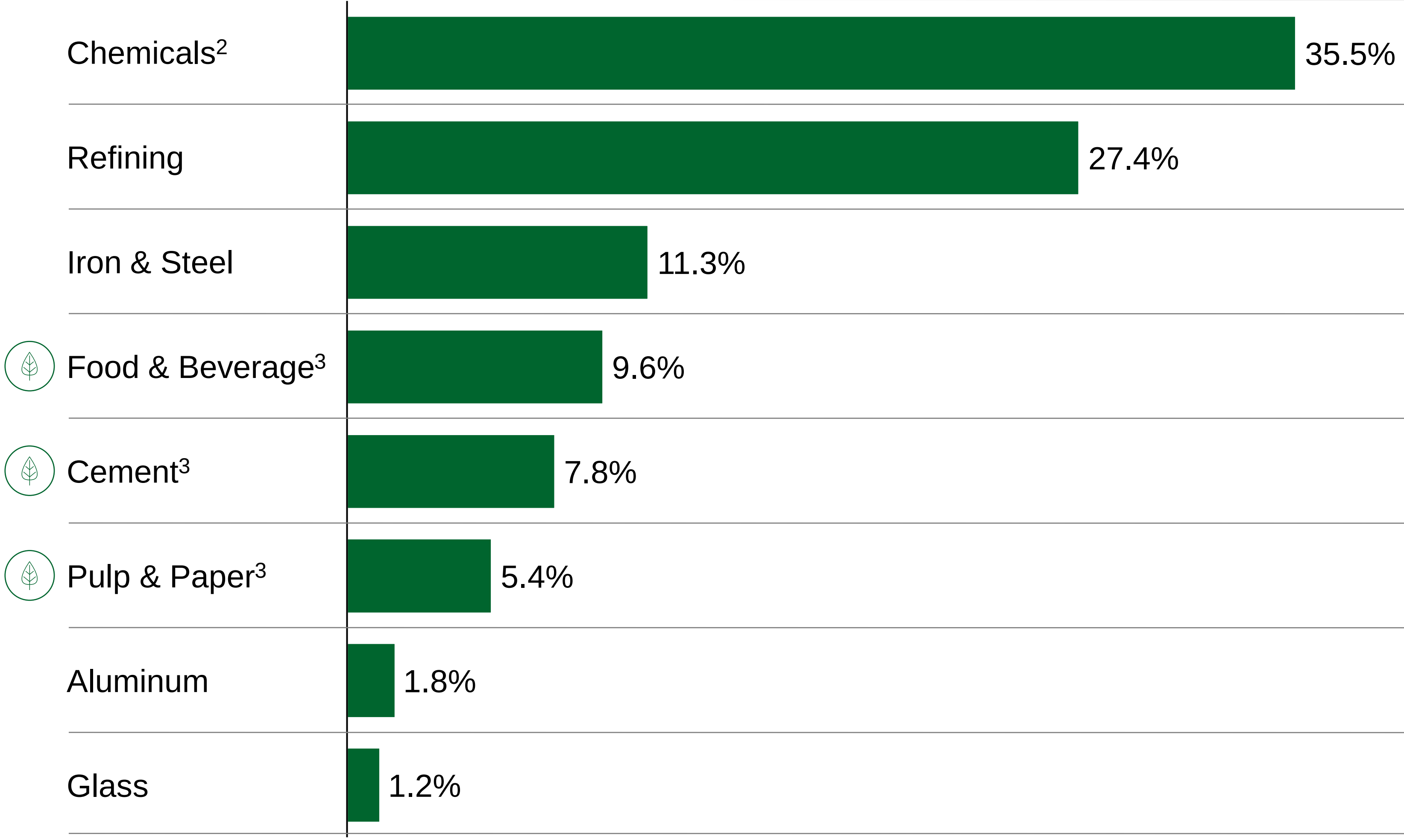
Source: EPA FLIGHT

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)

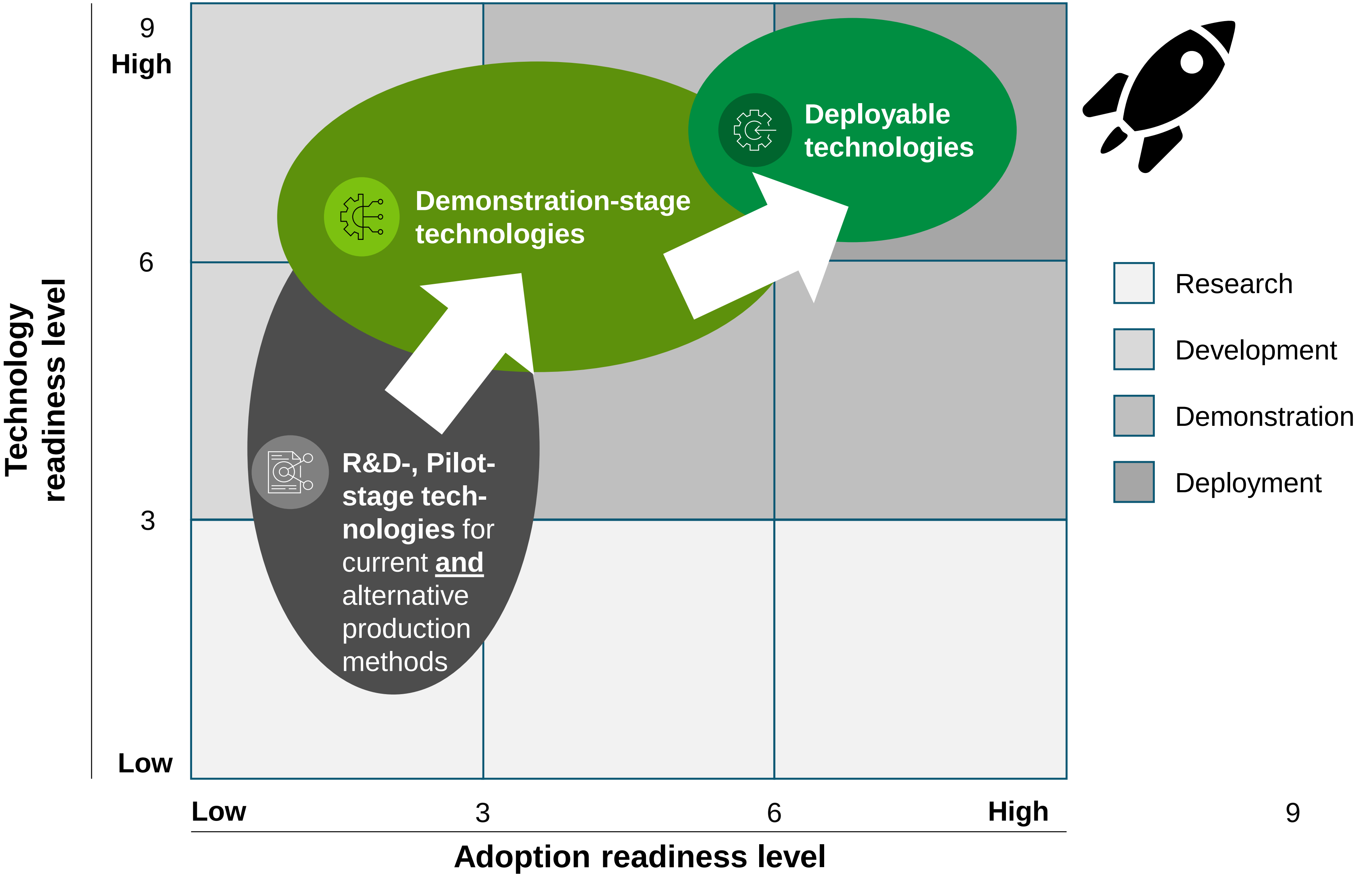


		U.S. 2021 emissions MT CO_2e	**U.S. 2021 emissions** MT CO_2[4]	**Global 2021 emissions** MT CO_2
Chemicals[2]	35.5%	315	291	~1,000
Refining	27.4%	243	242	~1,400
Iron & Steel	11.3%	89	89	~3,100
🍃 Food & Beverage[3]	9.6%	85	85	~400
🍃 Cement[3]	7.8%	69	69	~2,500
🍃 Pulp & Paper[3]	5.4%	48	48	~200
Aluminum	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



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

Demonstration-stage technologies

Deployable technologies

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

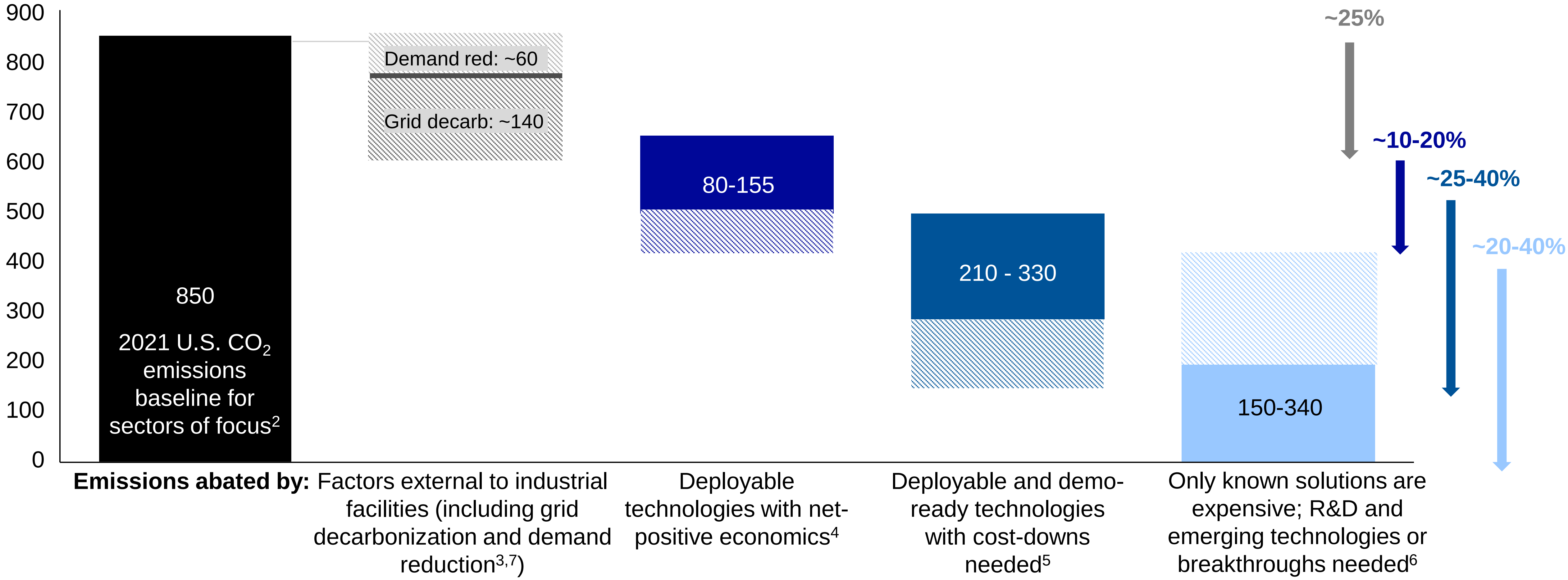


Figure 3.1: Industrial emissions abatement is split between external factors (i.e., grid decarbonization, transport sector electrification, and mechanical recycling), net-positive levers, and uneconomic levers (>$0/t CO2e), with up to 40% of abatement achievable at- or below-cost | 1. Current ranges 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

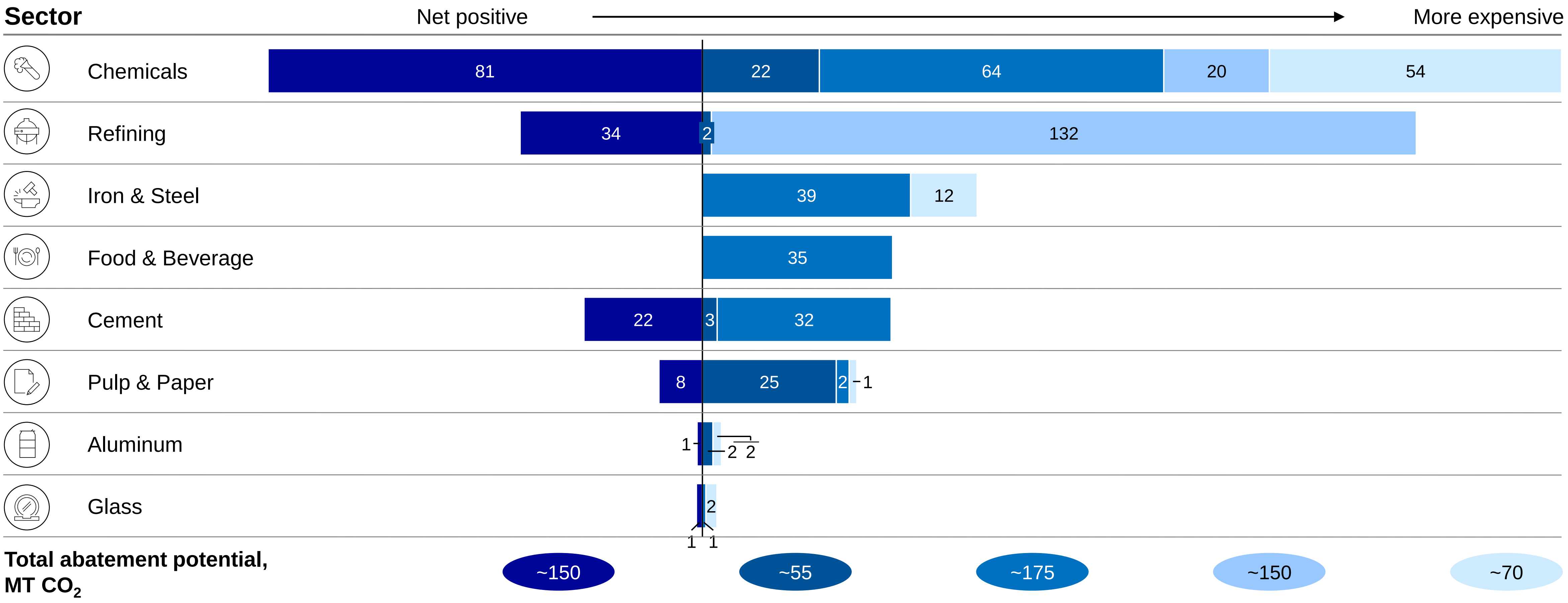
Source: EIA data for energy-related emissions, EPA data for total U.S. emissions, IEDO Industrial Decarbonization Roadmap, Life Cycle Carbon Footprint Analysis of Pulp and Paper Grades in the United States using production-lined-based data and integration - Tomberlin et al (2020), White House Long-Term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

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

■ Net positive ■ $1 to 50 ■ $51 to 100 ■ $101 to 150 ■ $151 to 250

PRELIMINARY **DRAFT**

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



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

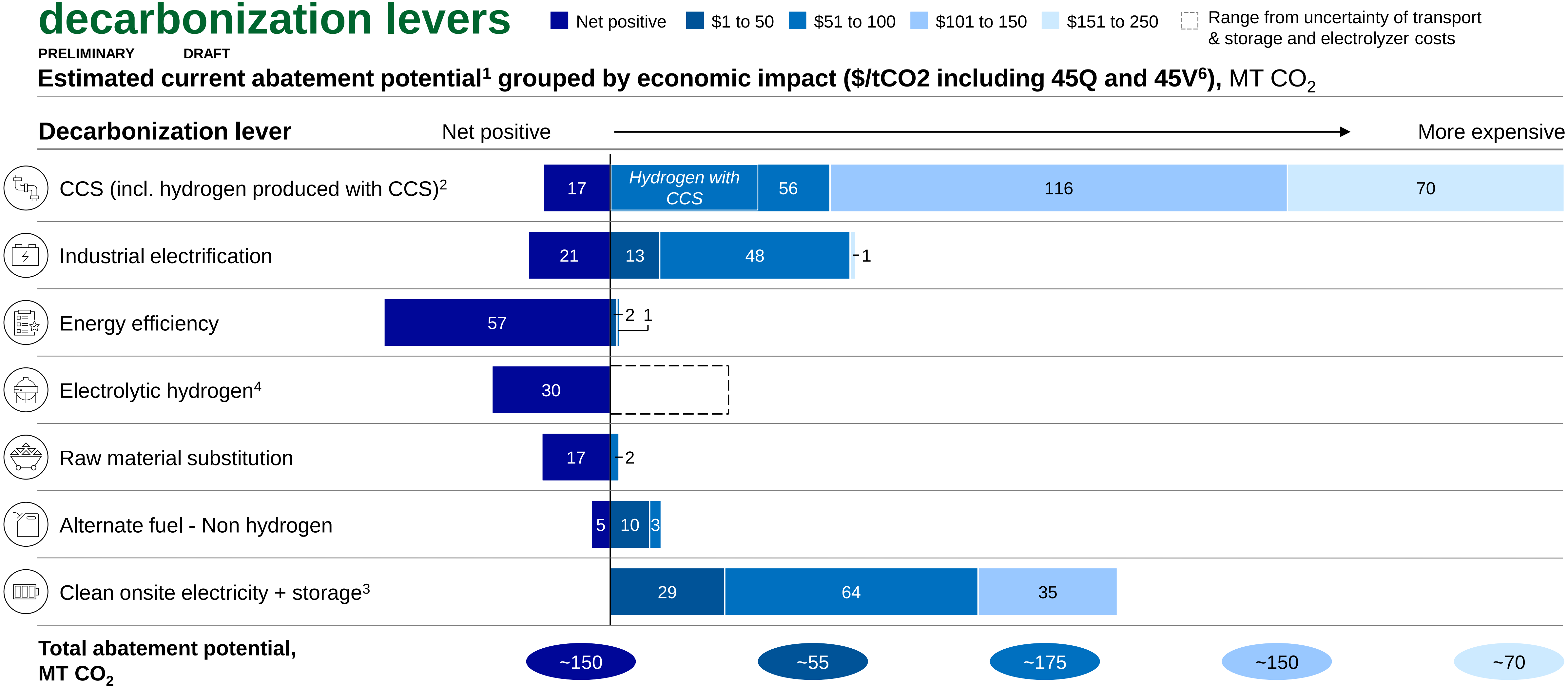
Source: Industrials sector integrated MACC, DOE Chemicals & Refining Decarbonization Liftoff Report, DOE Cement Decarbonization Liftoff Report

Note: Unabated emissions (~40 MT), external factors[3] (~200 MT), and abatement potential with costs $250+ /t$CO_2$ (~5 MT) are not shown in this figure

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

PRELIMINARY DRAFT

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



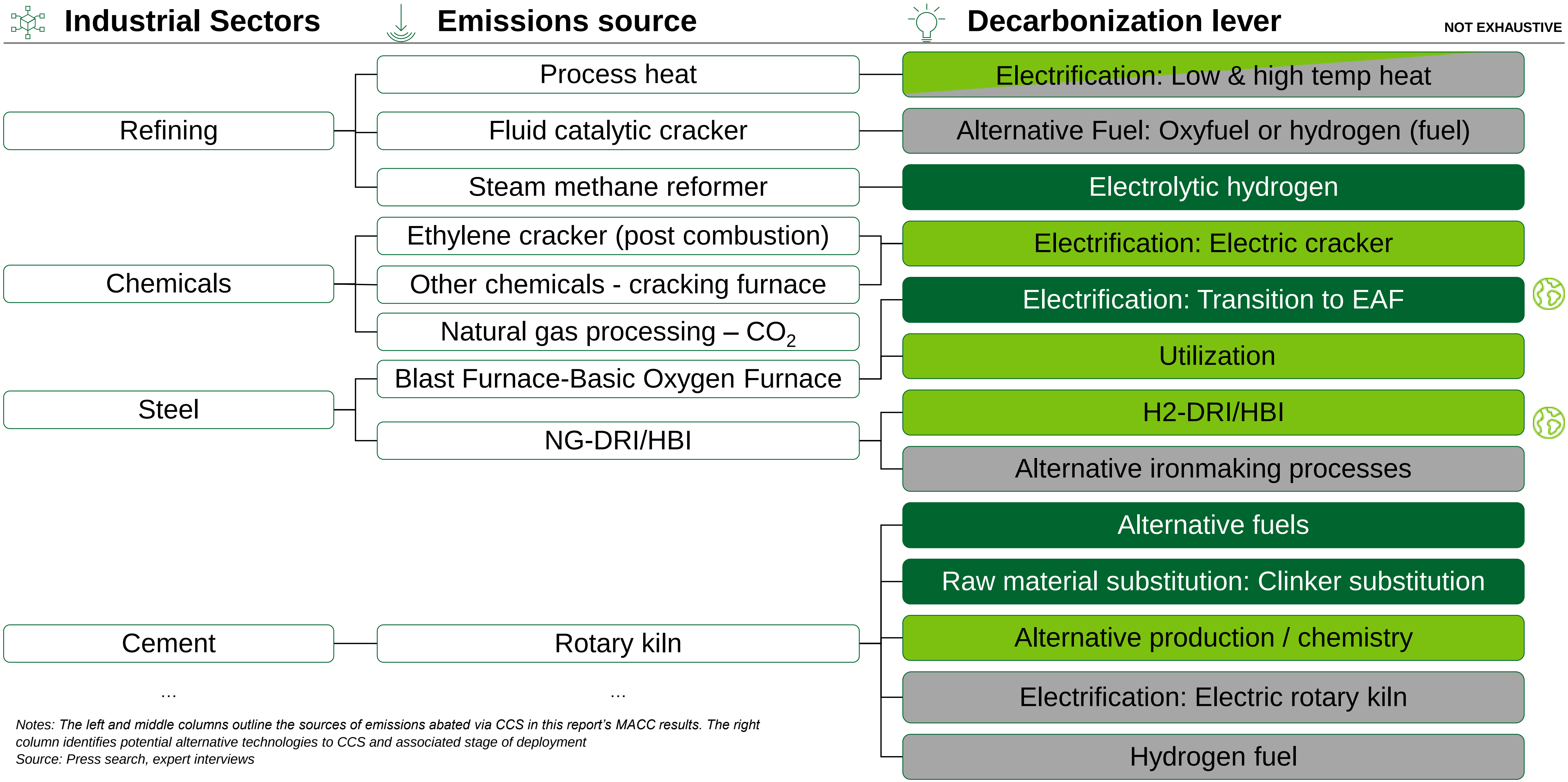
Note: Unabated emissions (~40 MT), external factors[5] (~200 MT), and abatement potential with costs $250+ /$tCO_2$ (~5 MT) are not shown in this figure

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

🌐 International example

Stage of decarbonization lever development ■ Deployable ▨ Demo □ R&D / Pilot



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

NOT EXHAUSTIVE

▨ / □ 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	1,000ºC	800ºC	1,600ºC	1,450ºC	1,100ºC	1,000ºC	1,600ºC
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** 💰 ◩ **Electrification +TES** 💵 🔧 🔌 ◩ **Hydrogen[9]** 💵 ▣ **CCS** 💵 💰 🔧	▣ **CCS** 💵 💰 🔧 □ **Electrification +TES** 💵 🔧 🔌 □ **Hydrogen[9]** 💵 □ **Biofuels** 💵 🔧 🚚	■ **Electrification** 💵 📋 🔌 ▣ **CCS** 💵 💰 □ **Hydrogen[9]** 💵	■ **Biomass; waste fuels** ⚙ 🚚 ▣ **CCS** 💵 💰 □ **Electrification +TES** 💵 🔧 🔌	■ **Biofuels** ⚙ 🚚 ■ **Electrification** 💵 🔧 🔌 ▣ **(BE)CCS** 💵 💰	□ **Hydrogen[9]** 💵 □ **CCS** 💵 💰 □ **Electrification** 💵 🔧 🔌	▣ **Electrification** 💵 🔧 🔌 ▣ **CCS** 💵 💰 🔧 □ **Biofuels** ⚙ 🚚 □ **Hydrogen[9]** 💵

■ 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

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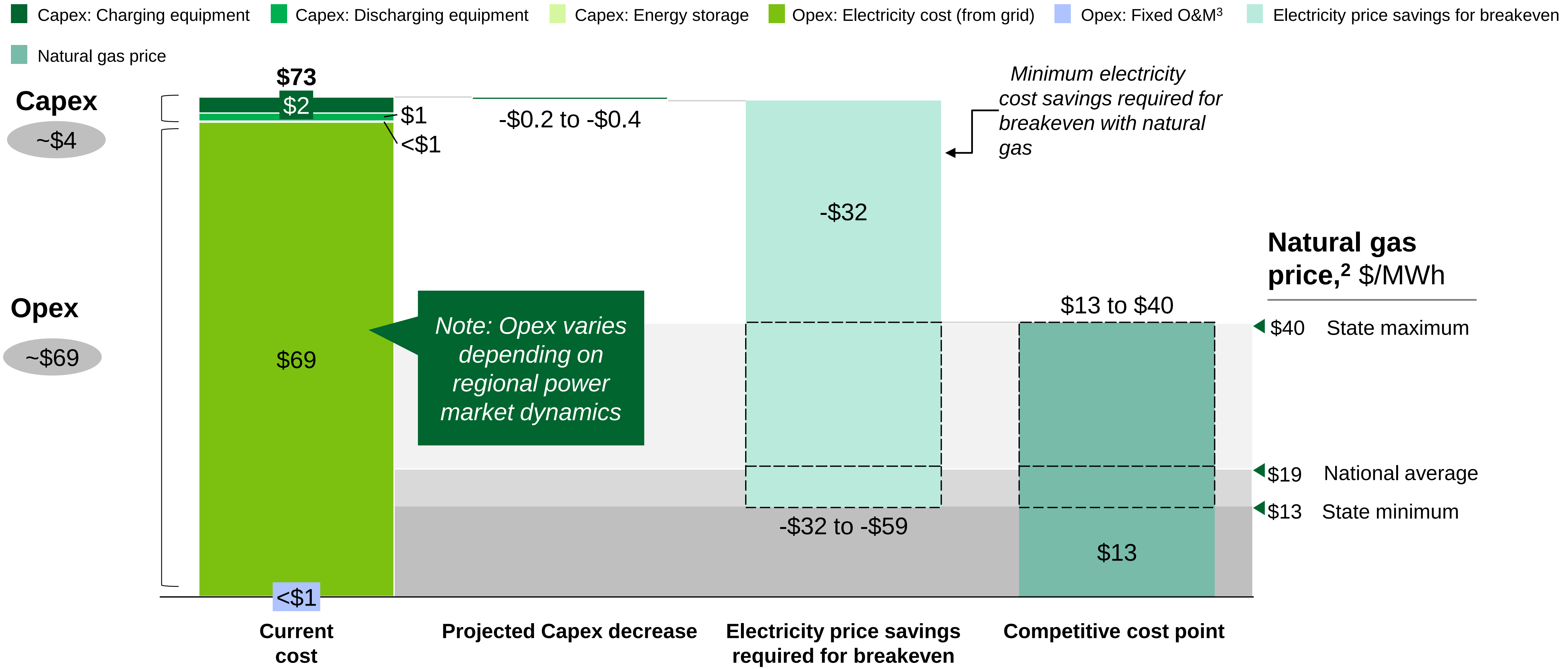


Notes: Electricity price in comparison to fossil fuel is the largest determinant of TES's economic viability | 1. Capex figures are based on anonymized industry data from LDES council members; technology agnostic, assumes 16h storage, 8h charging, 365 cycles per year, 8% WACC, 30-year lifetime, and 5,840 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

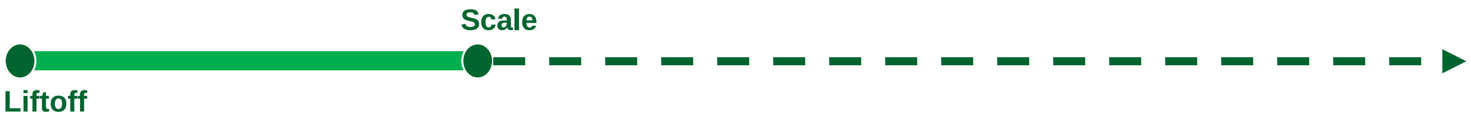
ILLUSTRATIVE NOT EXHAUSTIVE

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

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

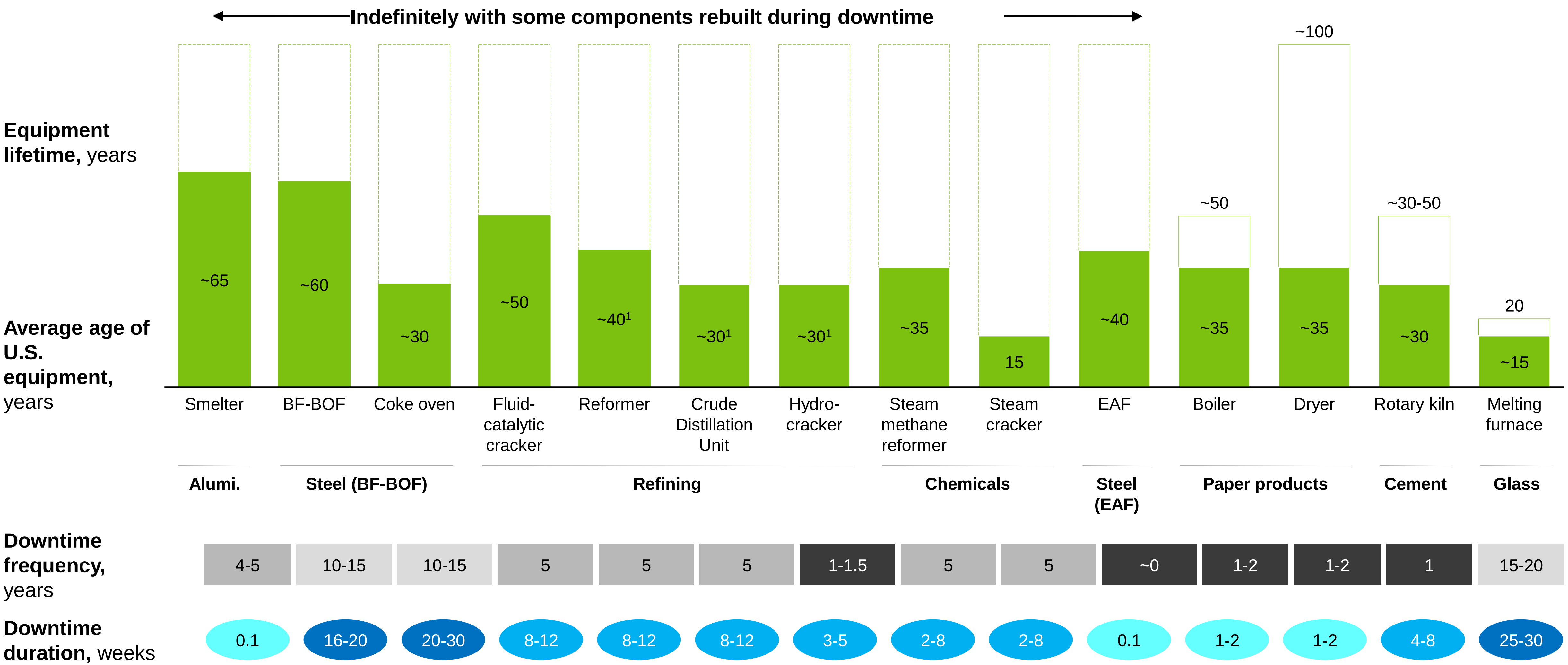
Maintenance frequency, requirements, and duration, vary by industry

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

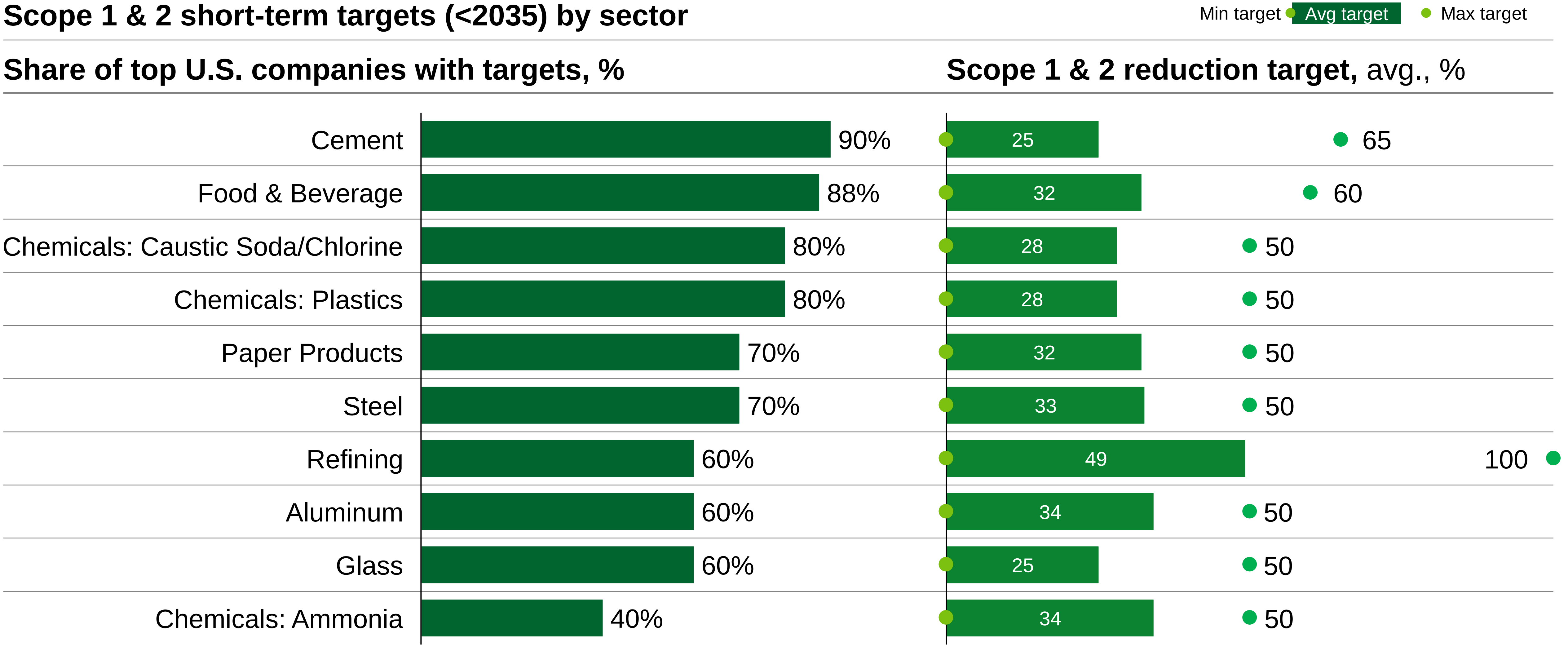


		Equipment lifetime, years	Average age of U.S. equipment, years	Downtime frequency, years	Downtime duration, weeks
Alumi.	Smelter		~65	4-5	0.1
Steel (BF-BOF)	BF-BOF		~60	10-15	16-20
	Coke oven		~30	10-15	20-30
Refining	Fluid-catalytic cracker		~50	5	8-12
	Reformer		~40[1]	5	8-12
	Crude Distillation Unit		~30[1]	5	8-12
	Hydro-cracker		~30[1]	1-1.5	3-5
Chemicals	Steam methane reformer		~35	5	2-8
	Steam cracker		15	5	2-8
Steel (EAF)	EAF		~40	~0	0.1
Paper products	Boiler	~50	~35	1-2	1-2
	Dryer	~100	~35	1-2	1-2
Cement	Rotary kiln	~30-50	~30	1	4-8
Glass	Melting furnace	20	~15	15-20	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%

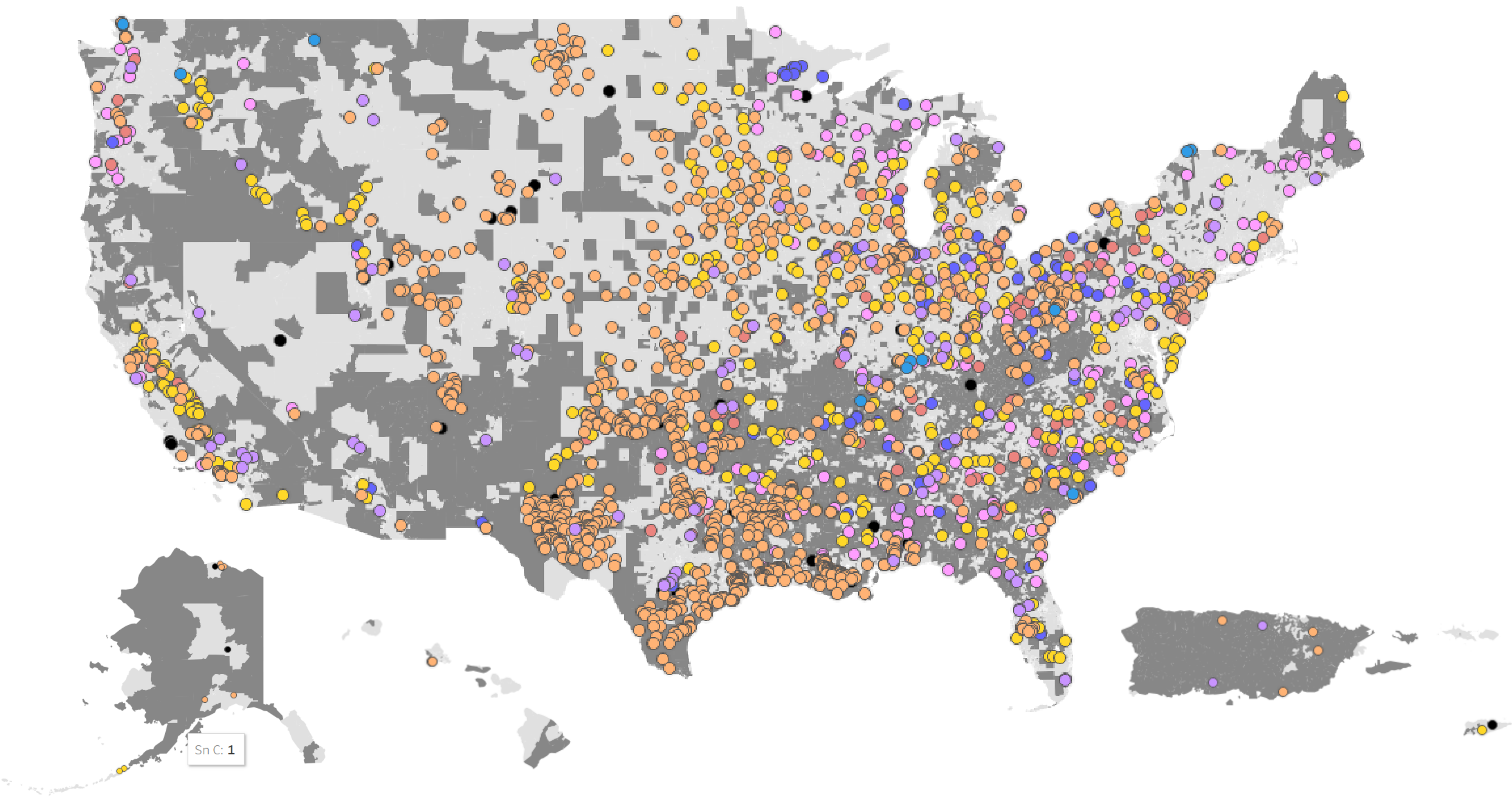
Scope 1 & 2 short-term targets (<2035) by sector



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

Facilities across industrial sectors of focus affect fence-line communities across the U.S., often located in disadvantaged communities.

Map of select U.S. point source CO_2 emissions and US Disadvantaged Communities, 2021[1]



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

⬜ Non-DAC Community ⬛ DAC Community

2,500+

Industrial facilities in sectors of focus[1]

1,145+

Studied sector's industrial facilities located within U.S. Disadvantaged Communities

Notes: *1. Includes natural gas processing, refineries, chemicals production (various), food processing, cement production, glass production, lime manufacturing, 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_2e/year and does not include emissions from land use, land use change, or forestry*

Source: EPA Flight, Climate and Economic Justice Screening Tool (CEJST)

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
~315	MT CO_2e	2021 U.S. Emissions
~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%

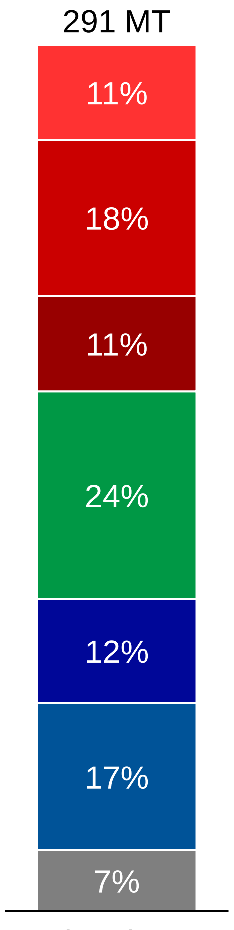
Chemicals: Decarbonization levers

○ % Share of sector abatement potential

NON-EXHAUSTIVE

Emissions source	
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
🟥 **[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

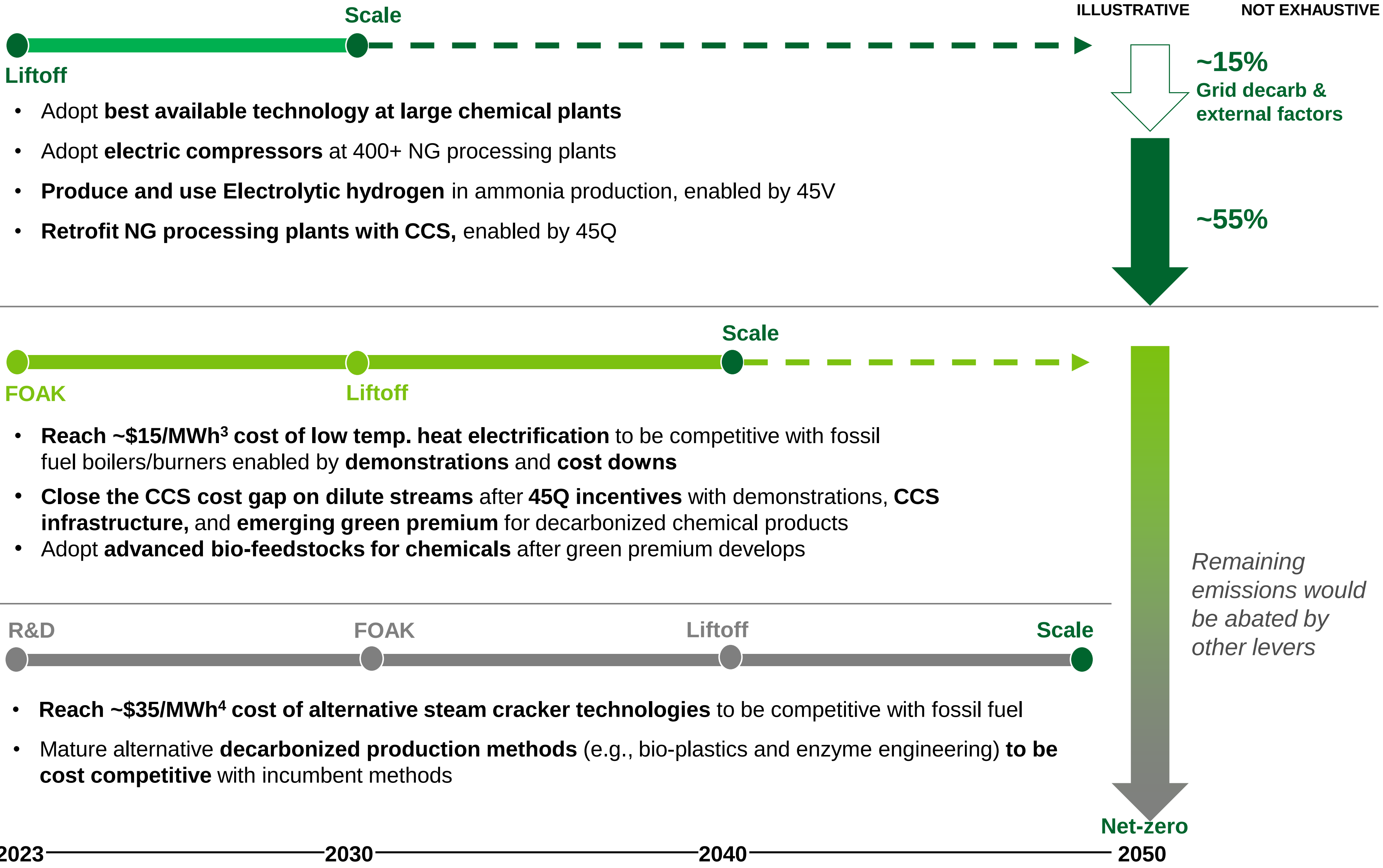
Chemicals: Liftoff pathway

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]

Liftoff → Scale

- 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

~15% Grid decarb & external factors

~55%

Demonstration-stage

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

FOAK → Liftoff → Scale

- **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])

R&D → FOAK → Liftoff → Scale

- **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

Net-zero

Timeline 2023 2030 2040 2050

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

- Introduction
- Cross-sector insights
- **Sector-level insights**
  - Sector leadership opportunities
  - Chemicals
  - **Refining**
  - Iron & Steel
  - Food & Beverage
  - Cement
  - Pulp & Paper
  - Aluminum
  - Glass

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%

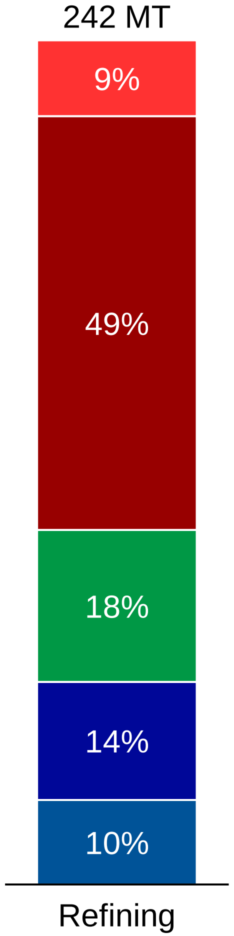
Refining: Decarbonization levers

(%) Share of sector abatement potential

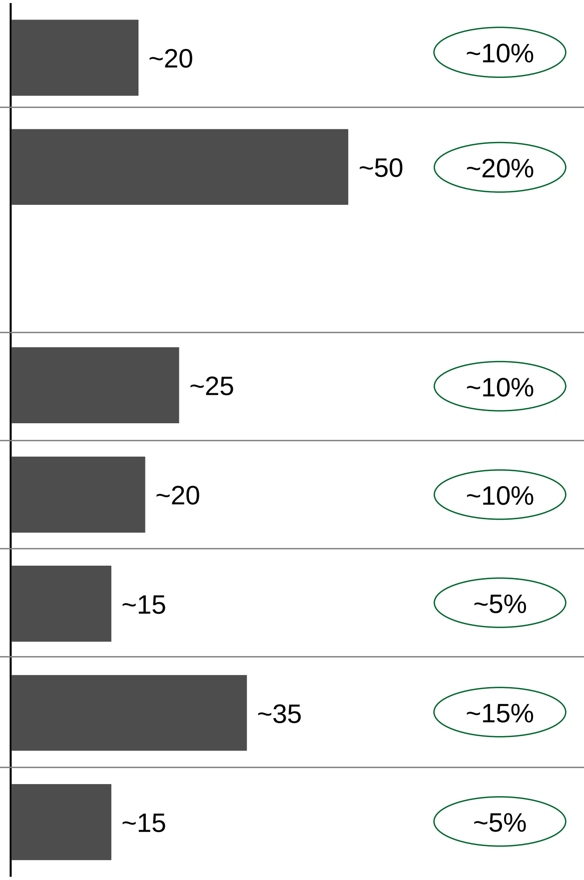
NON-EXHAUSTIVE

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)



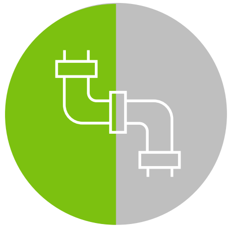
Value chain step responsible for emissions	Lever	Current lowest cost abatement,[4] MT CO_2	%	Abatement cost, $/t CO_2
Finishing: Treating products to achieve desired mix	Energy efficiency measures	~20	~10%	~(100)-(10)
Atmospheric distillation: Boils and separates crude oil residuals **FCC[3]:** Cracks heavy products to generate lighter products in presence of catalyst **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 -30ºC to 200ºC, medium heat is from 200ºC to 400ºC, and high heat is 400+ºC | 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.

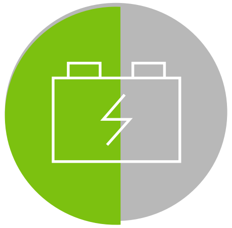
Source: 2018 EPA Flight, 2018 EERE Manufacturing Energy and Carbon Footprints report, 2022 IEDO Report, White House – Long-term strategy of the U.S. Pathways to Net-zero, Refining MACC

Refining: Operational decarbonization momentum

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

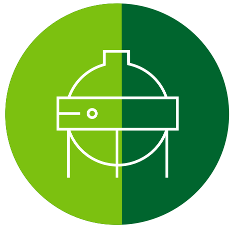


CCS (e.g., SMR[1])



Industrial electrification
(e.g., cracker)

Energy efficiency



Electrolytic hydrogen[3]

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

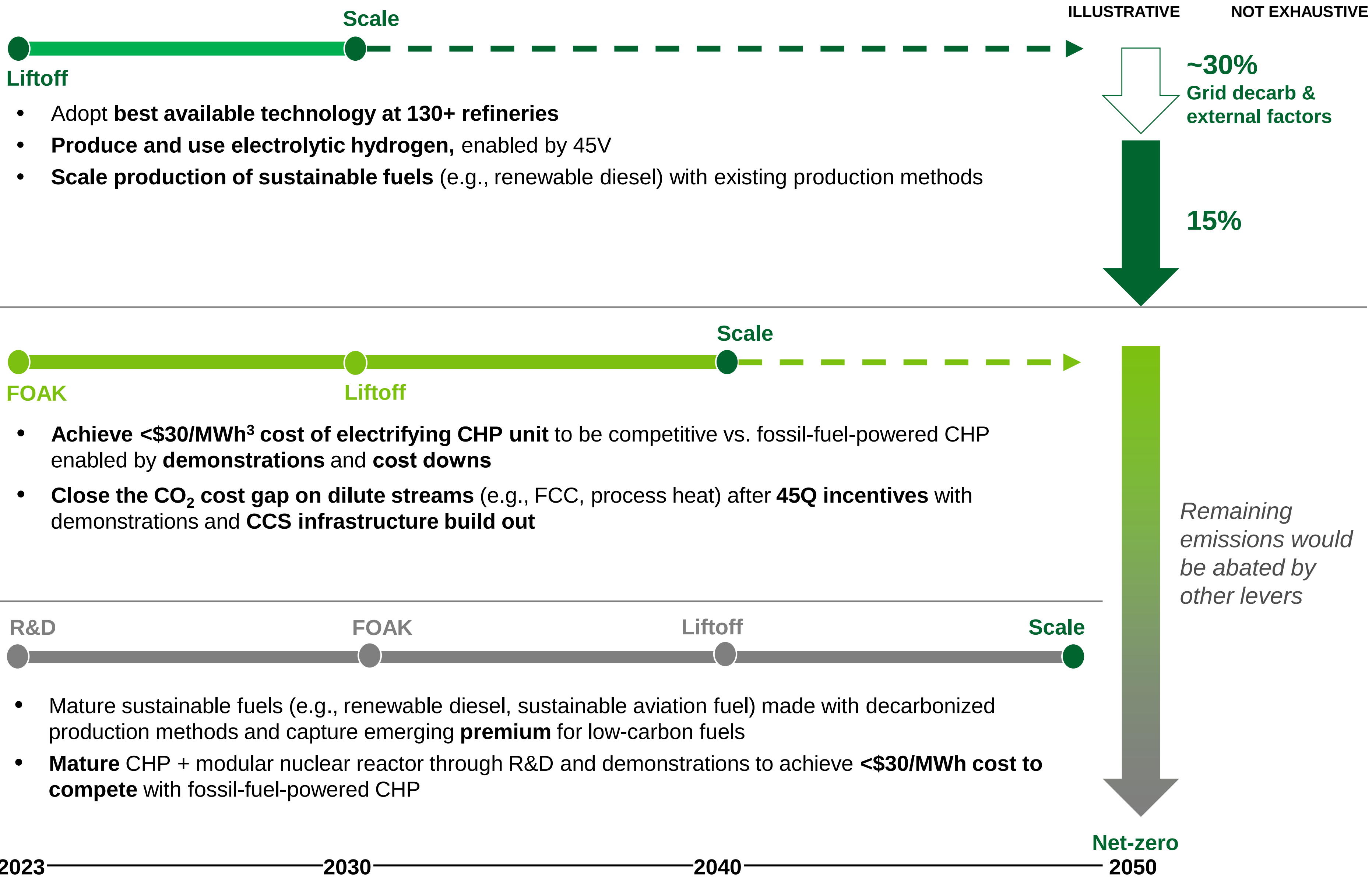
Notes: Stage of lever deployment within the refining sector | 1. SMR = Steam methane reformers | 2. Such as bio-based feedstocks for fuel production and sustainable aviation fuels with decarbonized production facility | 3. Refers to hydrogen use in traditional processes as a feedstock

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 $\$0/tCO_2$ 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.

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    - **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

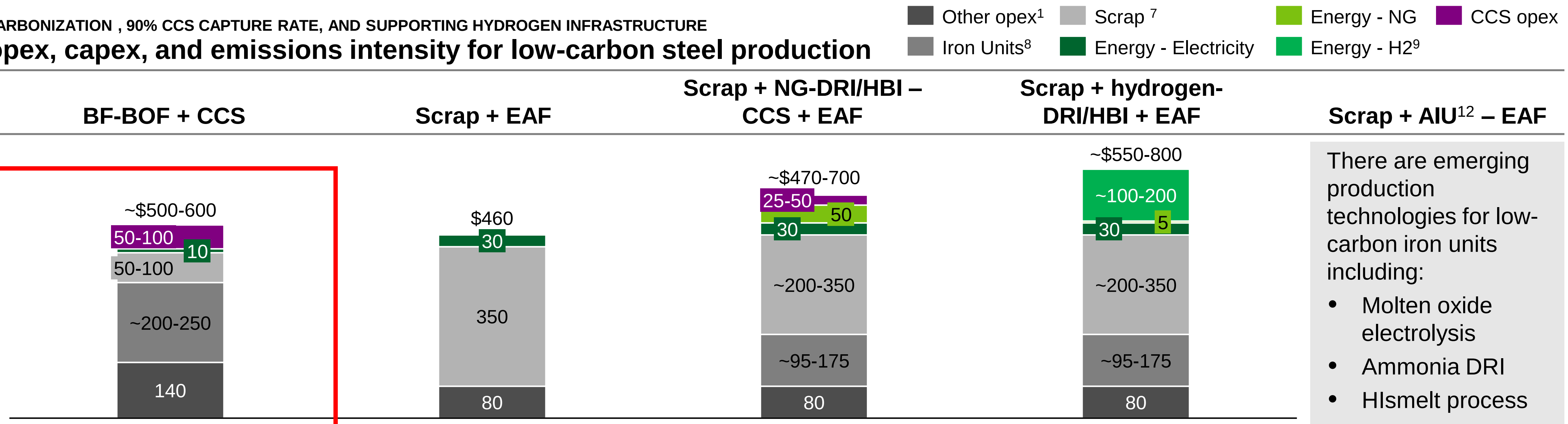
Industry Context

- 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



	BF-BOF + CCS	Scrap + EAF	Scrap + NG-DRI/HBI – CCS + EAF	Scrap + hydrogen-DRI/HBI + EAF	Scrap + AIU[12] – EAF
Opex breakdown, $/ton liquid steel[3]	~$500-600	$460	~$470-700	~$550-800	There are emerging production technologies for low-carbon iron units including: - Molten oxide electrolysis - Ammonia DRI - HIsmelt process - Others Emissions intensity and economics are unclear
Emissions intensity,[2] kg CO$_2$/ton steel	**~0.3**	**<0.1**	**<0.1**	**<0.1**	
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 - CCS is cost additive ***Detail on all BF-BOF decarb levers (beyond CCS) follows***	- Near 100% scrap is predominately used to produce long products - Scrap availability and quality drives production capacity	- No commercial demonstrations of CCS retrofit for NG-DRI/HBI plants[14] - CCS is cost additive - DRI/HBI price not competitive w/pig iron	- No hydrogen-DRI/HBI plants in the U.S. - Limited Electrolytic hydrogen infrastructure - 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

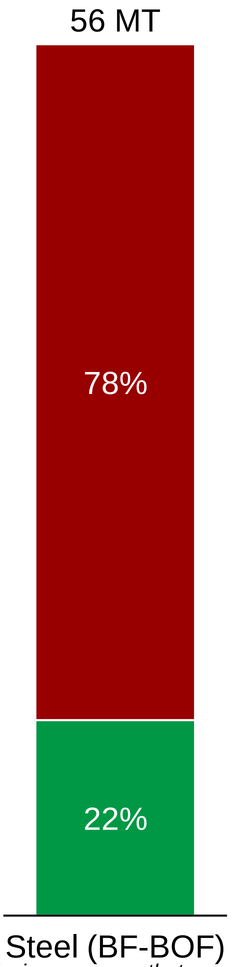
NON-EXHAUSTIVE

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

2030 estimated emissions abatement in Iron & Steel[2], %

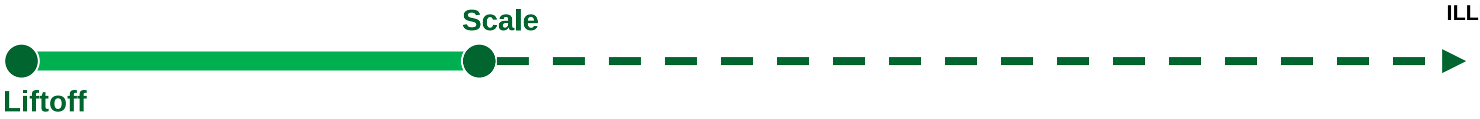
ILLUSTRATIVE NOT EXHAUSTIVE

Technology examples

Pathway to commercial liftoff – Priority decarbonization actions[1]

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**

~40% Grid decarb & external factors

~15%[5]

Remaining emissions would be abated by other levers

Net-zero

Timeline 2023 — 2030 — 2040 — 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%

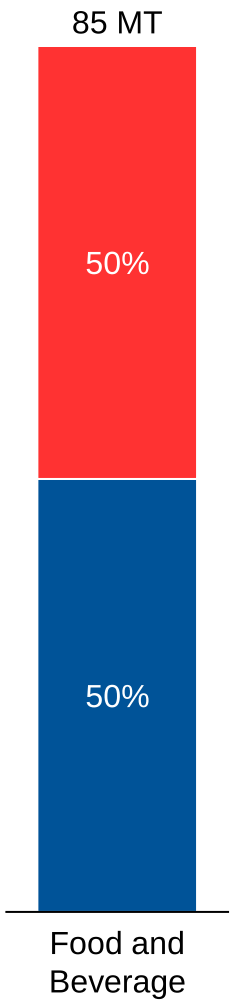
NON-EXHAUSTIVE

Food & Beverage: Decarbonization levers

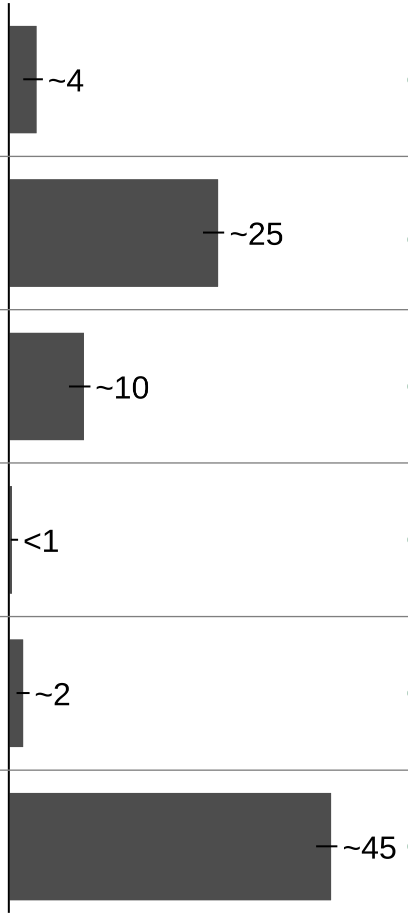
(%) Share of sector abatement potential

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	%	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]

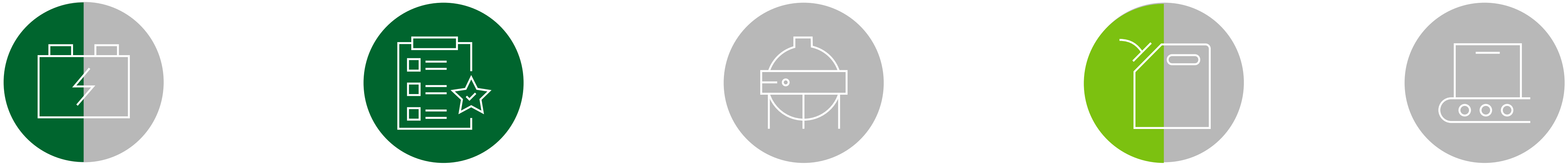
1. Temperature ranges: low temperature heat is from -30ºC to 200ºC, medium heat is from 200ºC to 400ºC, and high heat is 400+ºC | 2. Breakdown of 2021 food & beverage processing emissions | 3. Assumed to be 1.5x cost of electrified steam generation | 4. Wide range due to diverse products, processes, 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

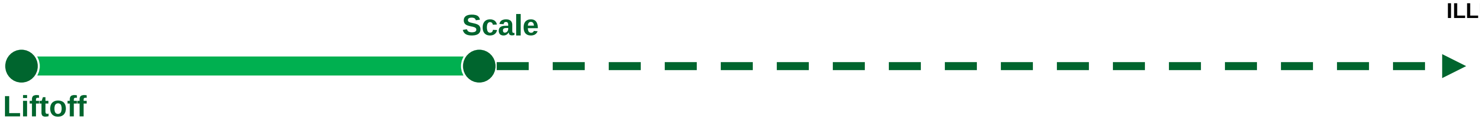
Pathway to commercial liftoff – Priority decarbonization actions[3]

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

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

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

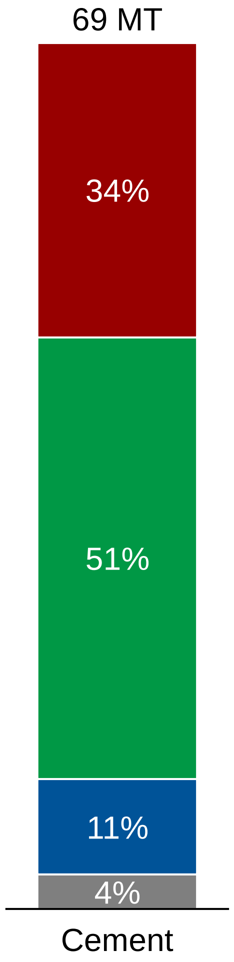
Cement: Decarbonization levers

% 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

Emissions breakdown,[2] MT CO_2



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 -30°C to 200°C, medium heat is from 200°C to 400°C, and high heat is 400+°C | 2. Breakdown of 2021 cement emissions | 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"

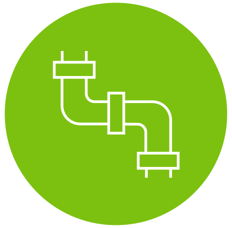
Cement: Operational decarbonization momentum

U.S. stage of decarbonization lever development

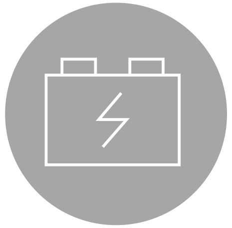
Deployable

Demo

R&D / Pilot



CCS
(e.g., rotary kiln)



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

Energy efficiency

Electrolytic hydrogen

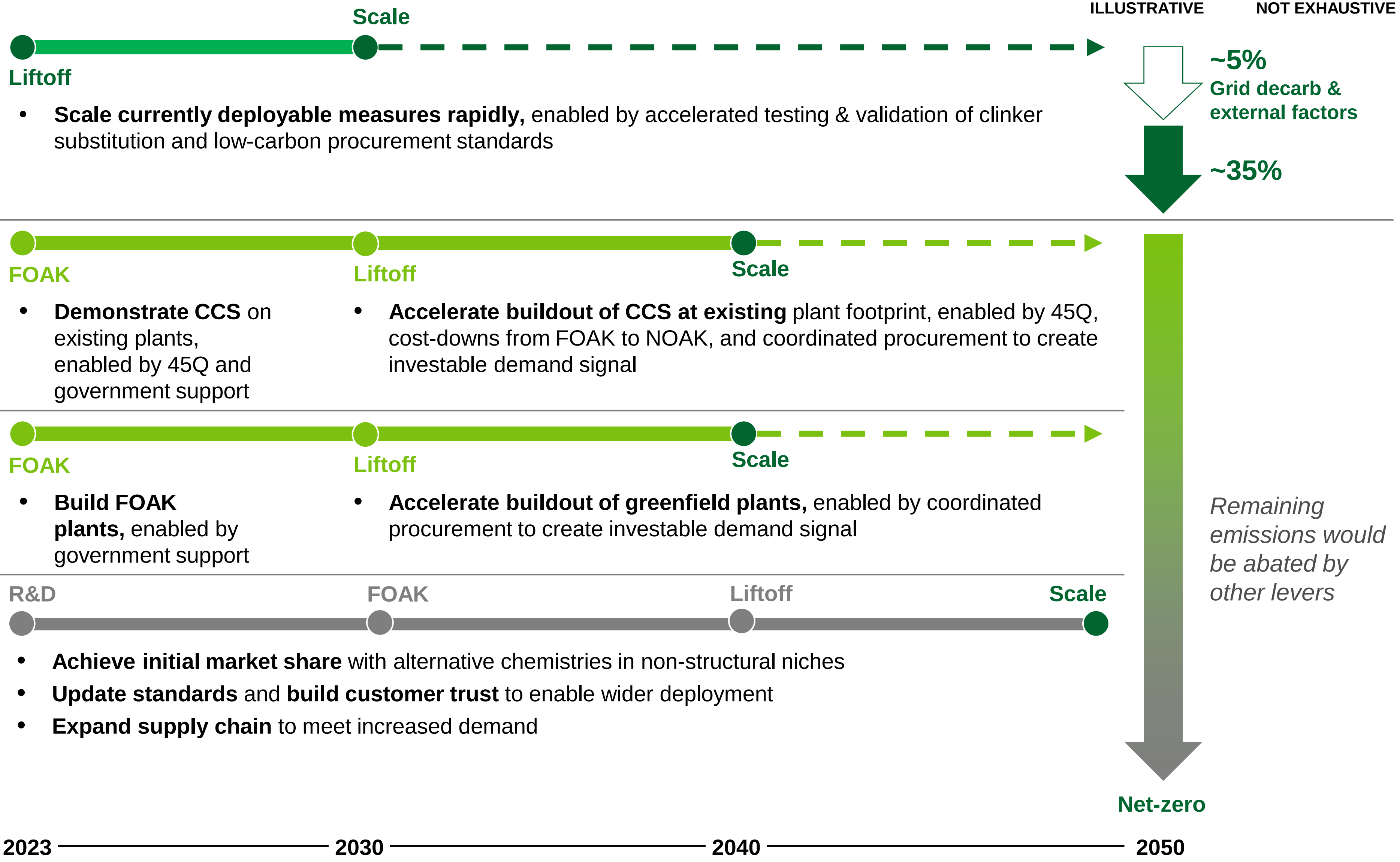
Raw material substitution[2]
(e.g., clinker alternative)

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)

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

~5%
Grid decarb & external factors

~35%

Demonstration-stage

- **CCS** retrofits of existing plants

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

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

Compatible with existing standards

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

Remaining emissions would be abated by other levers

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

- **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

Net-zero

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

Agenda

- Introduction
- Cross-sector insights
- **Sector-level insights**
  - Sector leadership opportunities
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  - Refining
  - Iron & Steel
  - Food & Beverage
  - 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%

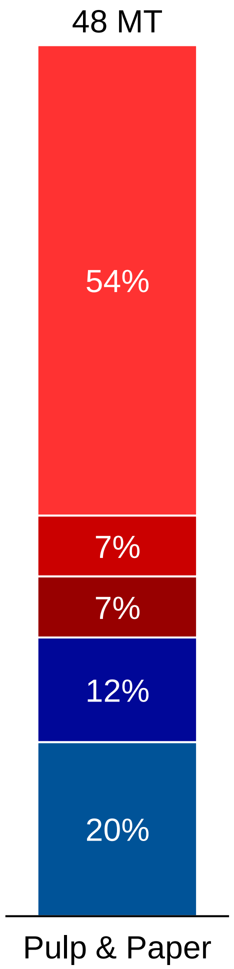
NON-EXHAUSTIVE

Pulp & Paper: Decarbonization levers

% Share of sector abatement potential

Emissions source		
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 CO2



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 **Burners:** Supports drying process **Evaporators:** Evaporates and concentrates black liquor **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

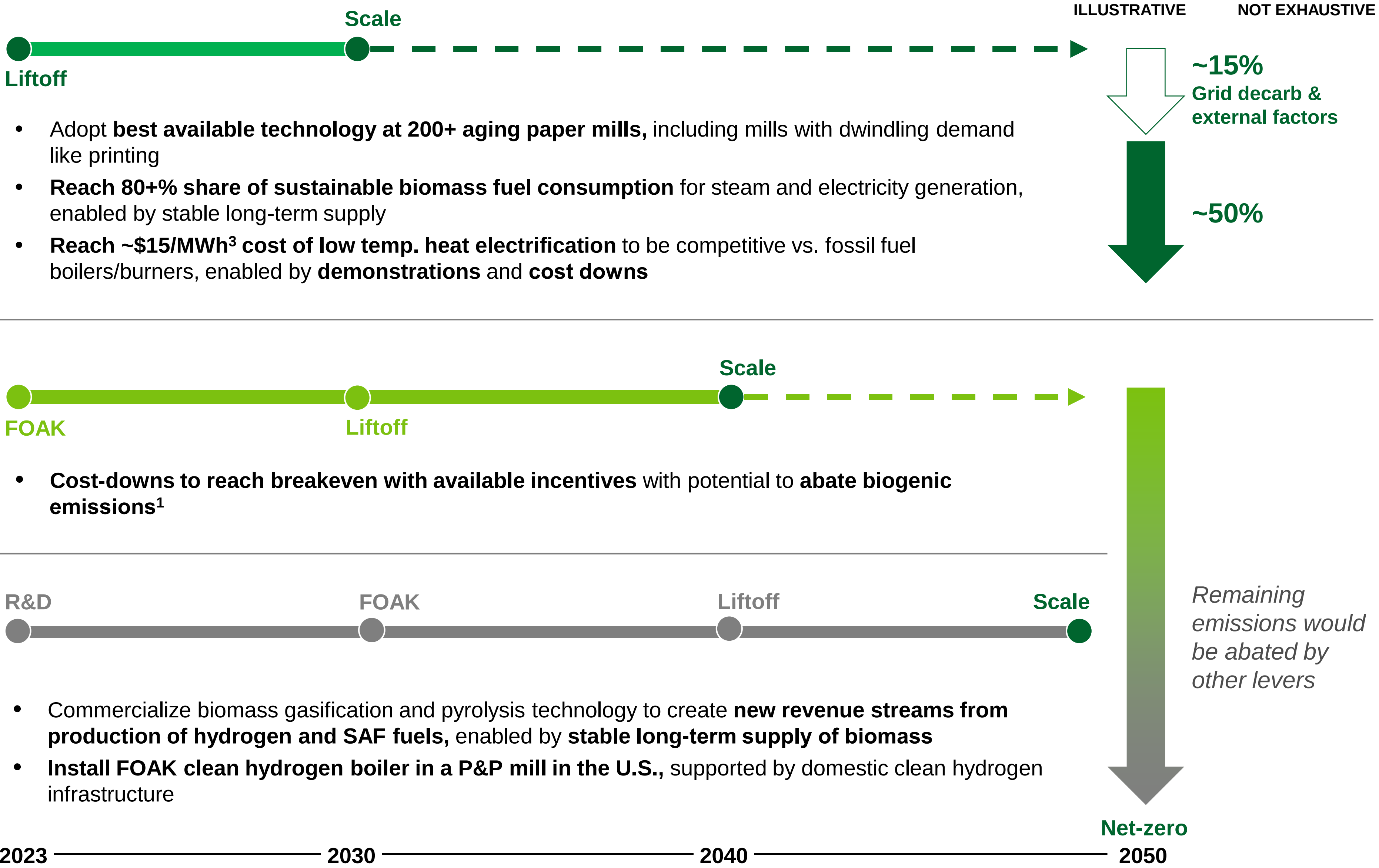
Technology examples

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

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

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  - 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%

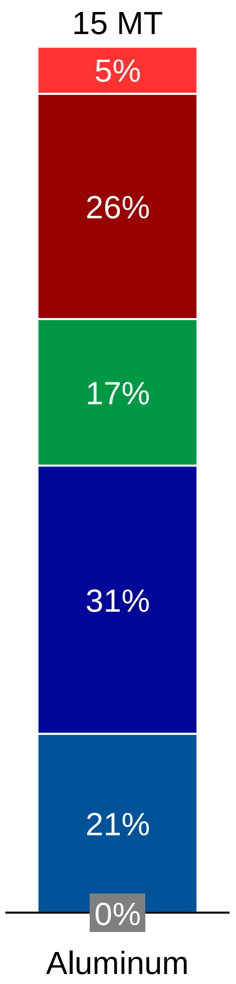
NON-EXHAUSTIVE

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



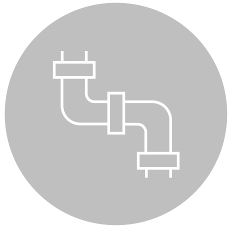
Value chain step responsible for emissions	**Lever**	**Current lowest cost abatement,** MT CO_2		**Abatement Cost,** $/t CO_2
Alumina refining: digestion and calcination	**Electrification** (e.g., electric gas heating)	~1	~5%	~(10)-10
	Energy efficiency (e.g., waste heat recovery)	<1	<5%	~(10)-10
Smelting: 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)

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.

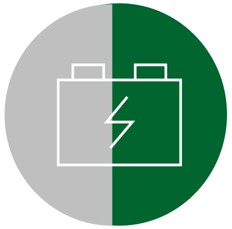
Source: International Aluminum Association, USGS, MPP – Net zero aluminum, IEA

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}

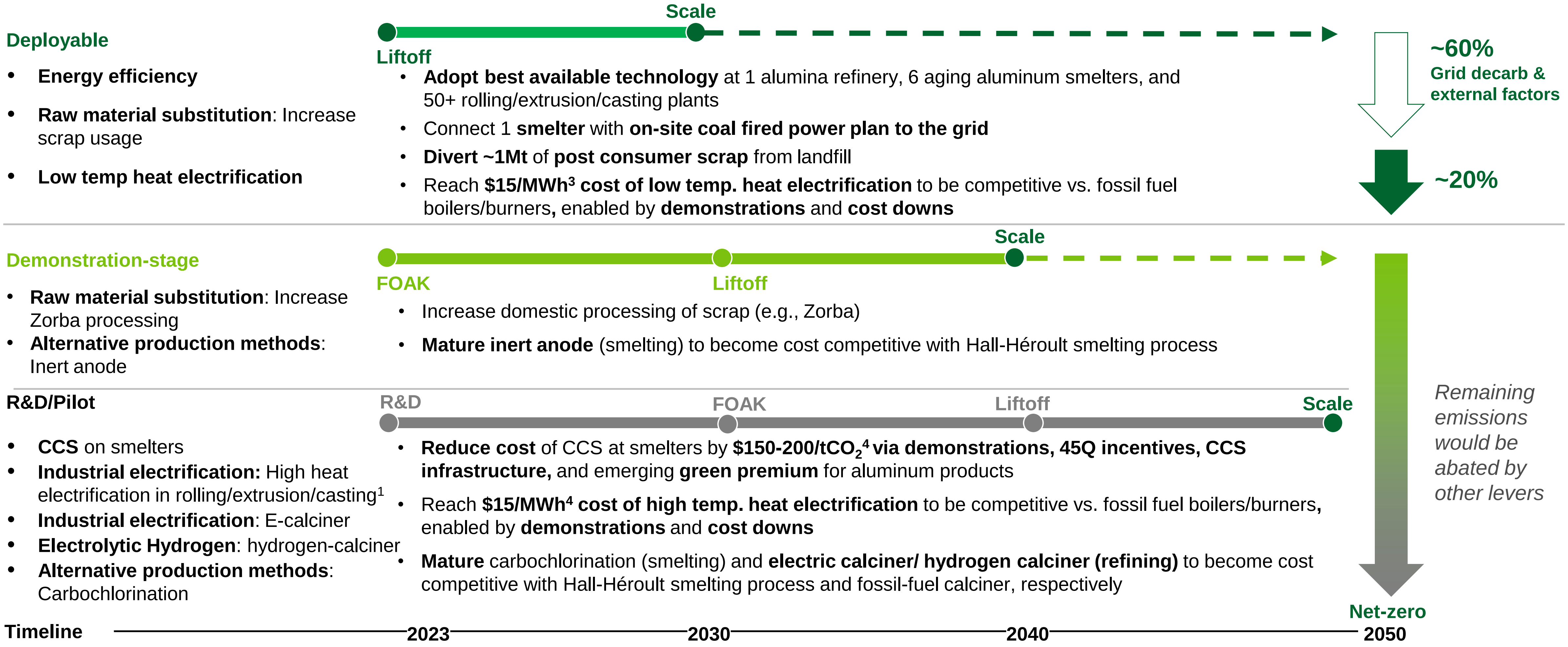
RD&D: carbochlorination)

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**

Liftoff — Scale

- **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**

~60% **Grid decarb & external factors**

~20%

Demonstration-stage

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

FOAK — Liftoff — Scale

- 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

R&D — FOAK — Liftoff — Scale

- **Reduce cost** of CCS at smelters by **$150-200/t$CO_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

Remaining emissions would be abated by other levers

Net-zero

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

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 $0/t$CO_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 $0/t$CO_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

- Introduction
- Cross-sector insights
- **Sector-level insights**
  - Sector leadership opportunities
  - Chemicals
  - Refining
  - Iron & Steel
  - 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%

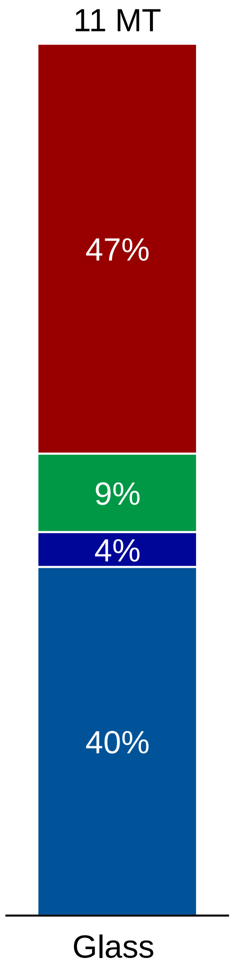
NON-EXHAUSTIVE

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 **Melting:** Heating mixture of materials in a furnace until it melts **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

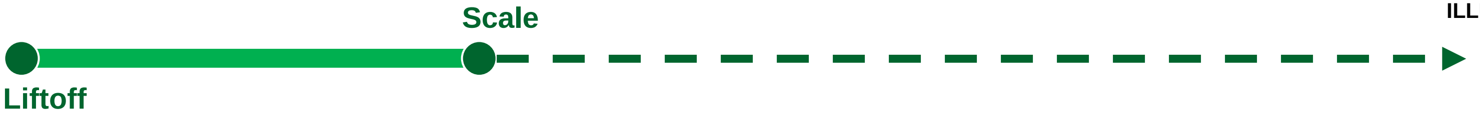
Technology examples | **Pathway to commercial liftoff – Priority decarbonization actions[6]** | **2030 estimated emissions abatement in Glass %**

ILLUSTRATIVE

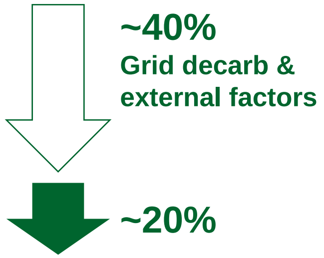
NOT EXHAUSTIVE

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



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

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**

Remaining emissions would be abated by other levers

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