U.S. DEPARTMENT OF ENERGY

Pathways to Commercial Liftoff: Industrial Decarbonization

Interim Webinar

June 28, 2023

DRAFT. PRELIMINARY. UNDER ONGOING DEVELOPMENT.

Overview: Pathways to Commercial Liftoff

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

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

Pathways to Commercial Liftoff started in 2022 to:

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

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

Feedback is eagerly welcomed via **liftoff@hq.doe.gov**

Industrial decarbonization webinar

What this webinar is

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

What this webinar is not

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

Disclaimer:

- DOE is only communicating public and non-privileged information during this webinar.
- DOE will not be discussing the details of any specific program opportunity in this webinar (e.g., Request for Information, Notice of Intent, Funding Opportunity Announcement).

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

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 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

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

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

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

- Carbon Capture and Storage (CCS)[1]
- Industrial Electrification
- Energy Efficiency
- Electrolytic Hydrogen
- Raw Material Substitution
- Alternative Fuel – Non-H2
- Alt. production methods
- Clean onsite electricity + storage
- Grid Decarbonization

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

Technologies also discussed in prior Liftoff reports from DOE

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

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

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

Key Messages for Industrial Decarbonization

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

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

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

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

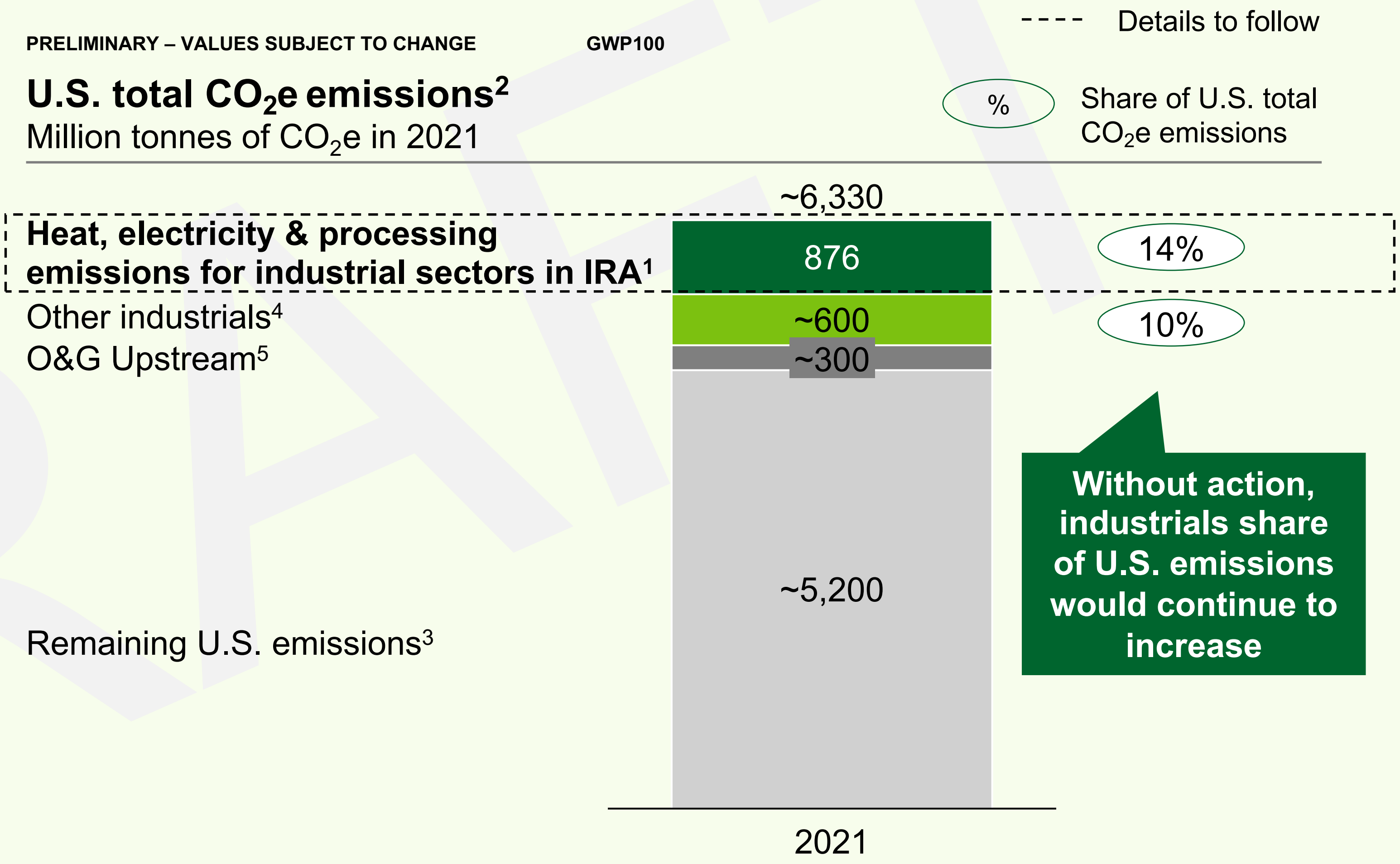
Early commercial deployments of decarbonization technologies in sector-specific applications could drive cost reductions and cross-sector learnings to boost the value proposition of similar, future projects.

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

Agenda

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

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



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

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

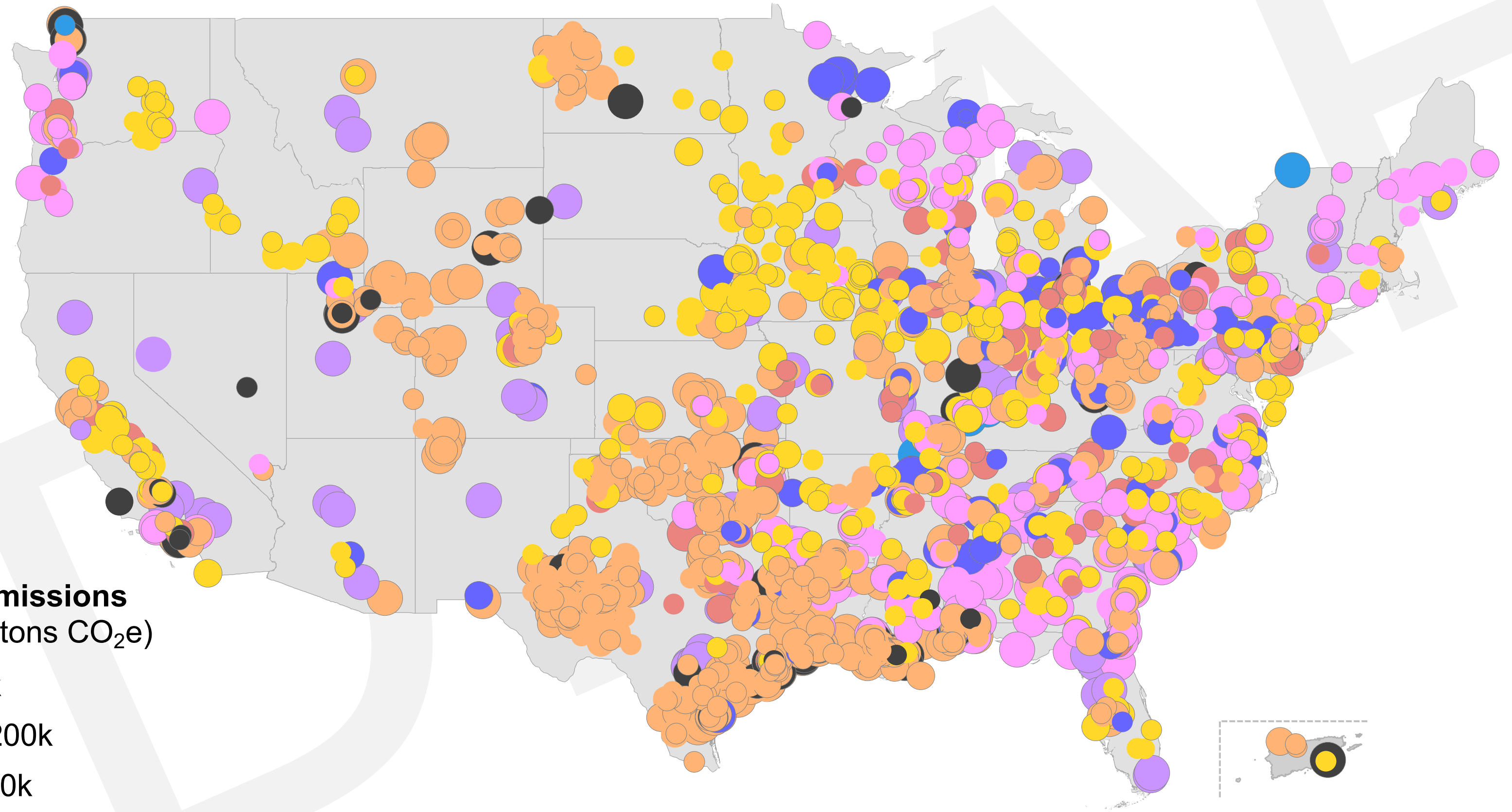
Geography: CO_2e emissions come from thousands of facilities, but 80% are concentrated in the South & Midwest[1]

ILLUSTRATIVE PRELIMINARY NOT EXHAUSTIVE

Map of select U.S. point source CO_2 emissions by sector, 2021[2]

Sectors

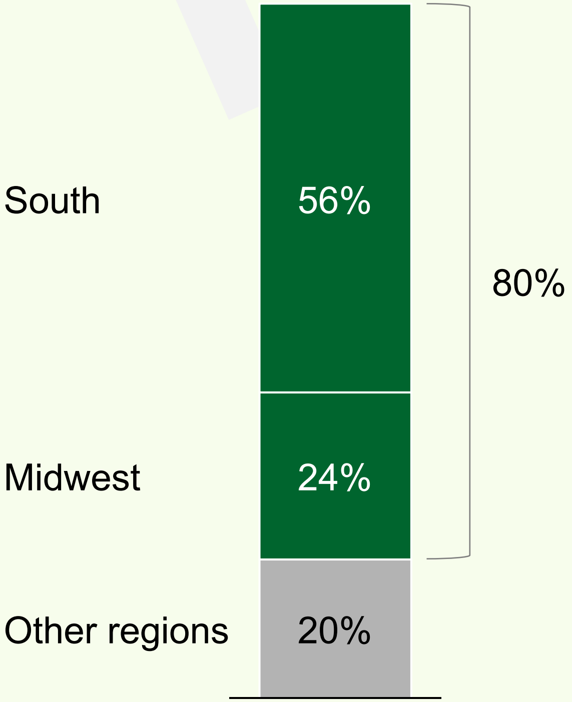
- Cement
- Pulp & Paper
- Aluminum
- Glass
- Chemicals
- Refining
- Iron & Steel
- Food & Beverage



GHG emissions
(metric tons CO_2e)

- <50k
- 50-200k
- >200k

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



South & Midwest regions represents ~80% of point source emissions

1. Regions are defined using U.S. Census guidance | 2. Includes natural gas processing, refineries, chemicals (various), food processing, cement production, glass production, lime manufacturing, aluminum production, iron & steel production, pulp and paper manufacturers, and other paper products. EPA flight only records GHG emissions from facilities with reported emissions or quantity of GHG > 25,000 metric tons CO2e

Source: EPA flight

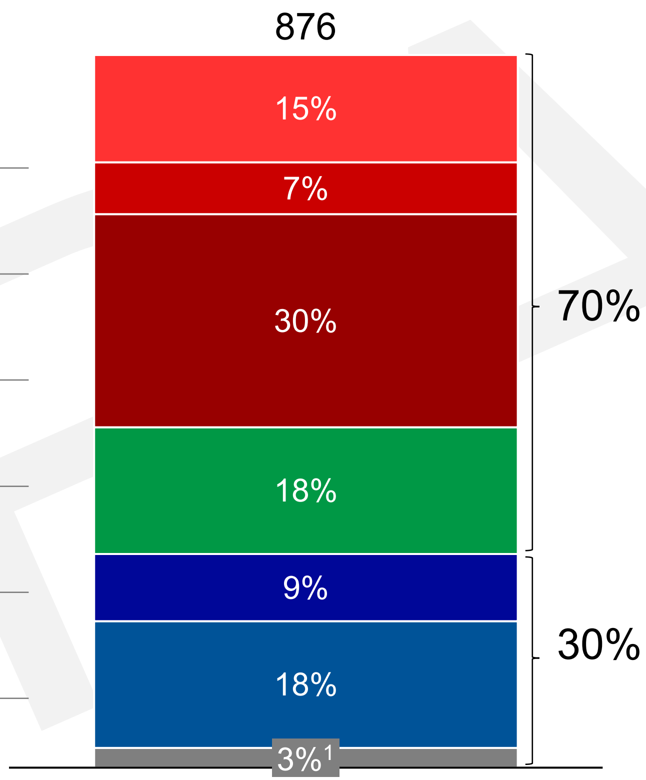
Emissions source: ~70% of CO2e emissions are heat- and process-related

PRELIMINARY – VALUES SUBJECT TO CHANGE

Emissions breakdown for industrial sectors of focus (2021), MT CO_2e

Emissions source		Definition
Heat	Low temp heat	Low heat (-30-200C) emissions, where heating is end use
	Mid temp heat	Medium heat (200-400C) emissions, where heating is end use
	High temp heat	High heat (400C+) 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



Industrials sector energy-related emissions

1. Includes quarry and logistics emissions (Cement)

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

Sector: Chemicals and Refining together represent 60%+ of CO_2e emissions, while other U.S. sectors contribute to larger global footprints

GWP100

Sector share of 2021 CO_2e emissions from eight industrial sectors of focus in IRA[1], %, 100% = 876 Million tonnes of U.S. 2021 CO_2e emissions		U.S. 2021 emissions MT CO_2e	Global 2021 emissions MT CO_2e
Chemicals[2]	36.0%	315	~1,000
Refining	27.7%	243	~1,400
Iron & Steel	10.2%	89	~3,200
Food & Beverage[3]	9.7%	85	~400
Cement[3]	7.9%	69	~3,500
Pulp & Paper[3]	5.5%	48	~200
Aluminum	1.8%	16	~1,100
Glass	1.3%	11	~100

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

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)

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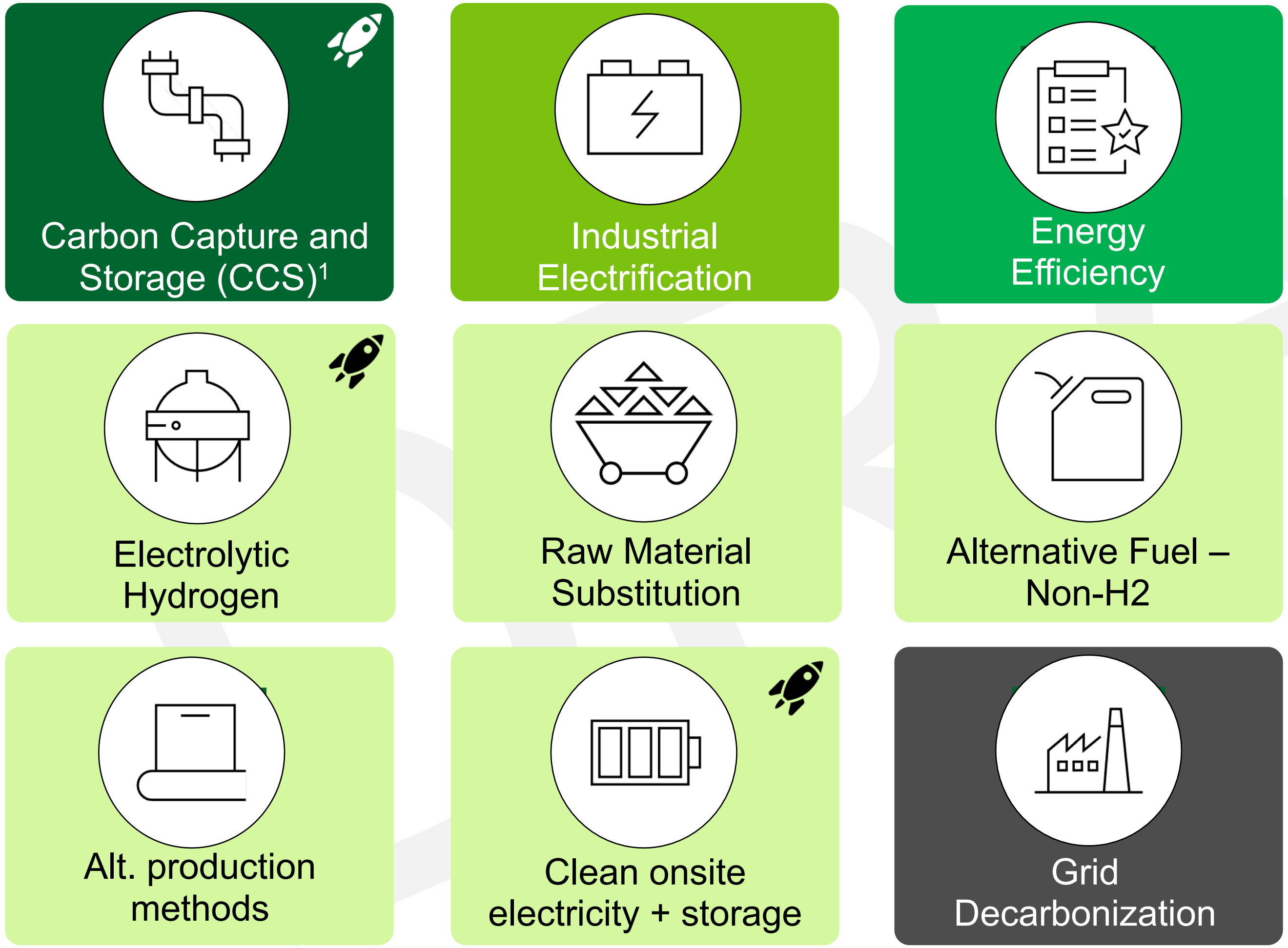
Recall: Based on DOE's Industrial Decarbonization Roadmap and prior Liftoff Reports, we identified nine decarbonization levers for focus

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



Notable assumptions

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

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

Technologies also discussed in prior Liftoff reports from DOE

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

On the path to net-zero, a set of decarbonization levers are estimated to be the least-cost including tax credits like 48C and 45V in 2030

PRELIMINARY – VALUES SUBJECT TO CHANGE

NOT EXHAUSTIVE BASED ON 2030 INTEGRATED MACC ANALYSIS[1]

REFLECTS IRA CREDITS (45Q & 45V)[7]

Emissions category	Industrial decarbonization lever[3]	Estimated abatement potential[1,6], MT CO_2	Share of abatement, %, 100% = 850 MT[10]
Heat and process	CCS (with H2 production)[5]	~210 + ~40[11]	~30%+
	Industrial electrification[8]	~85	~10%+
	Energy efficiency	~75	~9%+
	Electrolytic hydrogen[5]	~35	~4%+
	Raw material substitution	~25	~3%+
	Alternate fuel - Non hydrogen	~20	~2%+
	Alternative production methods[4]	*Economics TBD*	
Electricity	Clean onsite electricity + storage[2]	~120	~14%+
	Grid decarbonization		~17%

Reforming + CCS to produce H2

Despite high costs (shown on following page) CCS could abate emissions in 2030. However, **other decarbonization levers may address the same emissions as CCS with RD&D** in other levers and emerging technology.

Estimated capex needed: $700B-1.1[9]T

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

1. Based on 2021 emissions baseline | 2. Includes LDES / TES for storage of energy generated from renewables; subset of this abatement also includes electric boilers replacing natural gas boilers | 3. Unabated emissions account for ~30MT of CO_2, about ~4% share of total emissions. Additional external factors that reduce emissions by ~60 MT about ~8% of total emissions include mechanical recycling (Chemicals) and transport sector electrification (Refining) | 4. Includes alternative chemistries, production processes, and technologies | 5. Reforming + CCS H2 falls under the total abatement potential for CCS (~40 MT CO_2). IRA credits are used for all CCS levers and electrolytic hydrogen production levers | 6. Reflects total of current least cost abatement potentials for each sector | 7. IRA credits are indirectly reflected in calculation of least cost abatement levers for each industry | 8. Industrial electrification use cases include transition to EAF (Steel), switching NG boilers with electric boilers (cross multiple industries, and electrifying high-temp heat processes (Cross-sector) | 9. Reflects total of sector-level capex requirements. Details to follow in sector overviews | 10. Figure does not include unabated emissions or external factors (e.g., demand reduction) | 11. The split between electrolytic and reforming + CCS hydrogen was assumed based on currently announced projects; however, there is uncertainty around split in the long run. This analysis does not evaluate methane emissions trade-offs for chemicals and refining sectors. 75MT of CO2 abatement for H2 ties to ties to H2 roadmap estimates for H2 use in ammonia and refining by 2030.

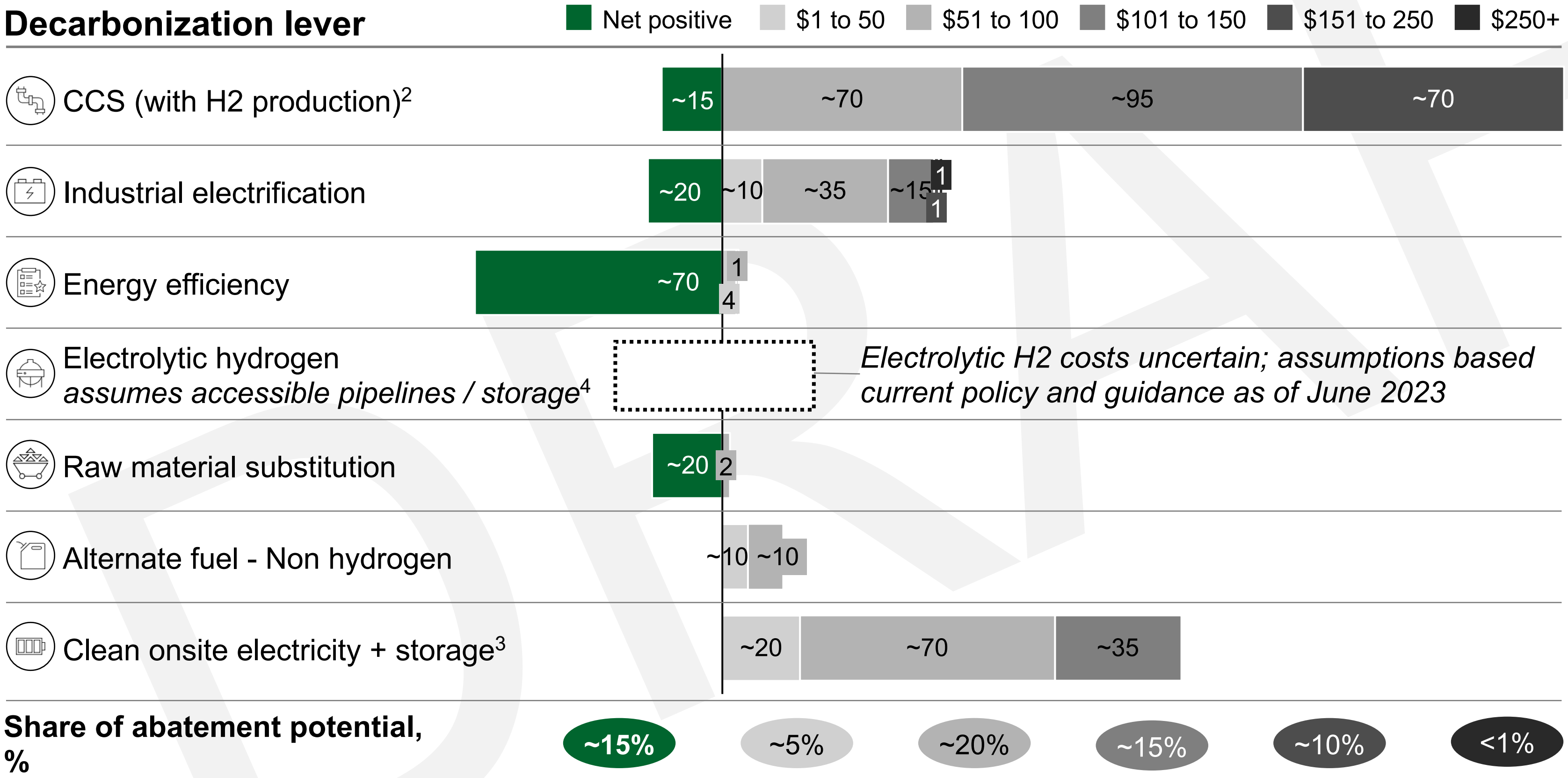
Source: Industrials sector integrated MACC, DOE Chemicals & Refining Decarbonization Pathway

Today, ~15% of emissions studied can be abated with net-positive levers, while other levers could abate emissions with additional cost

NOT EXHAUSTIVE

PRELIMINARY – VALUES SUBJECT TO CHANGE

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



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

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

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

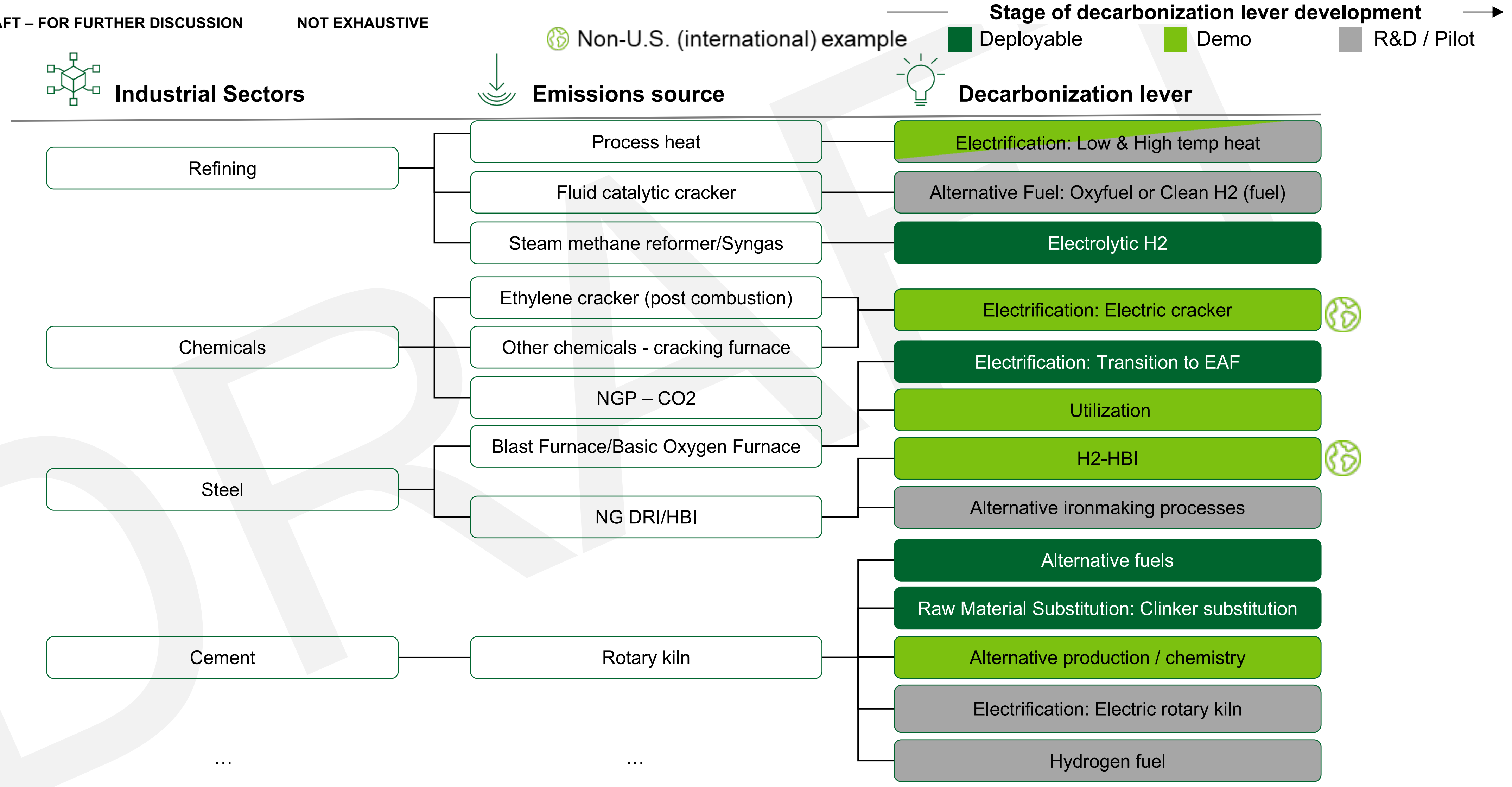
- **Long asset lifetime**, infrequent downtime
- **Higher cost** of other decarbonization levers
- **Absence and/or limitations** of commercially available alternative decarbonization technologies
- **Majority of CCS abatement potential in Chemicals and Refining** sectors

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

Note: Unabated emissions (~30 MT), external factors[5] (~200 MT) not shown

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

PRELIMINARY **DRAFT – FOR FURTHER DISCUSSION** **NOT EXHAUSTIVE**



Source: Press search, expert interviews

Industrial materials are often a small portion of the price of end-products, even after decarbonization costs

PRELIMINARY –SUBJECT TO CHANGE **ILLUSTRATIVE**

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Demand-side pull is building up…

2015 — **No significant pull** for low-carbon products

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

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

… and a small increase in end-product cost could enable industrial decarbonization today

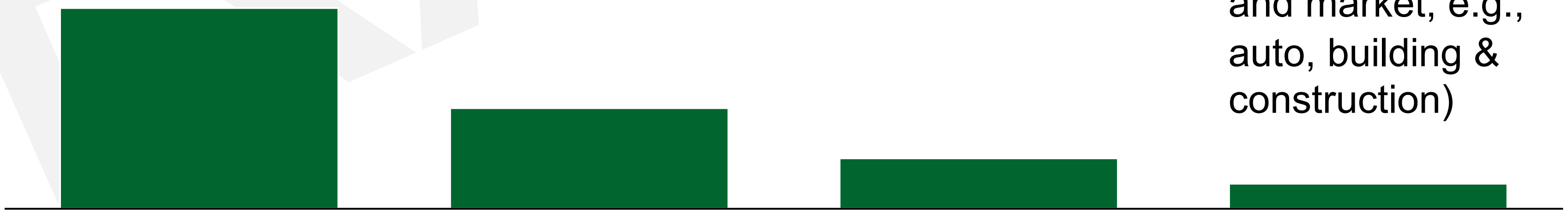
Upstream → *Downstream*

Material producer → **Component manufacturer** → **Goods manufacturer** → **End consumer**

Face higher cost of production to decarbonize operations and production methods

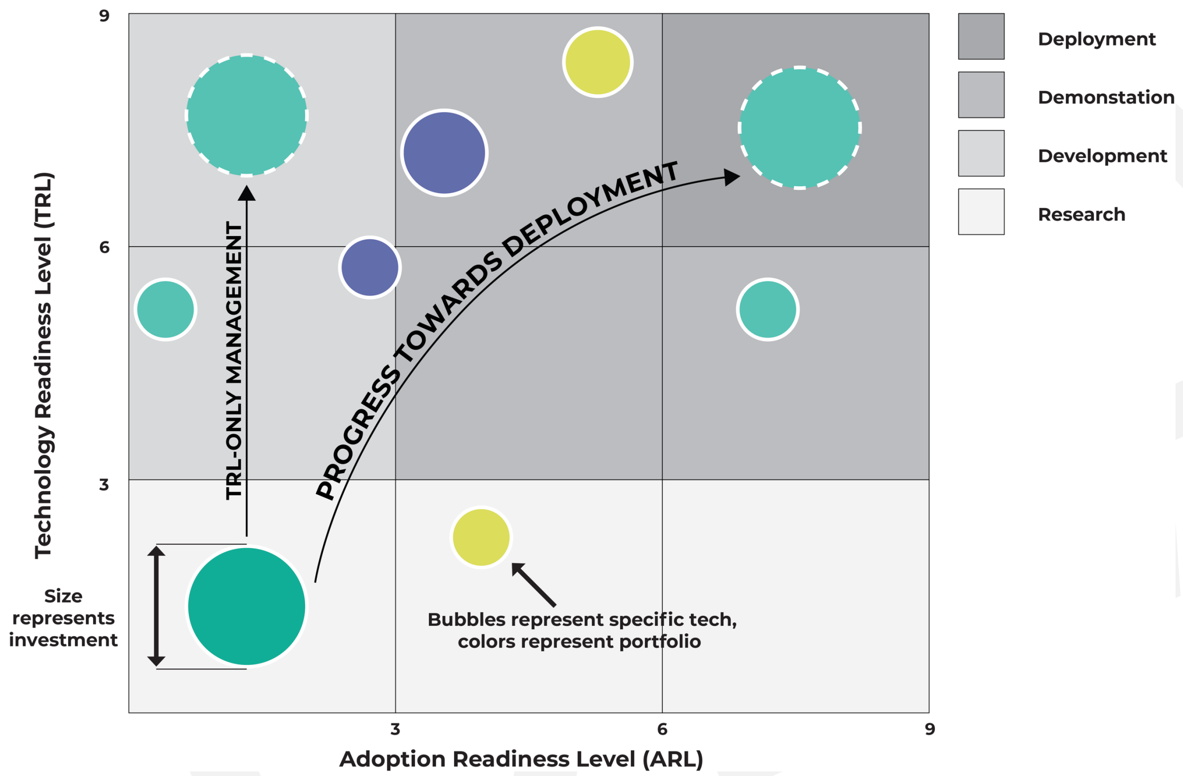
Dilute increase in bill of materials costs due to share of spend on other inputs and non-material costs

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



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

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



- **Technology Readiness Levels (TRL)** assess the maturity level of a particular technology (e.g., R&D vs. Commercial)
- **TRL does not capture essential tech commercialization risk factors**, such as product-market fit, demand pull, supply chain, workforce, siting & permitting, etc.
- DOE's new **"Adoption Readiness Level (ARL)" describes and assesses key adoption risks beyond technology risks** that impede commercialization

Source: https://www.energy.gov/technologytransitions/adoption-readiness-levels-arl-complement-trl

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

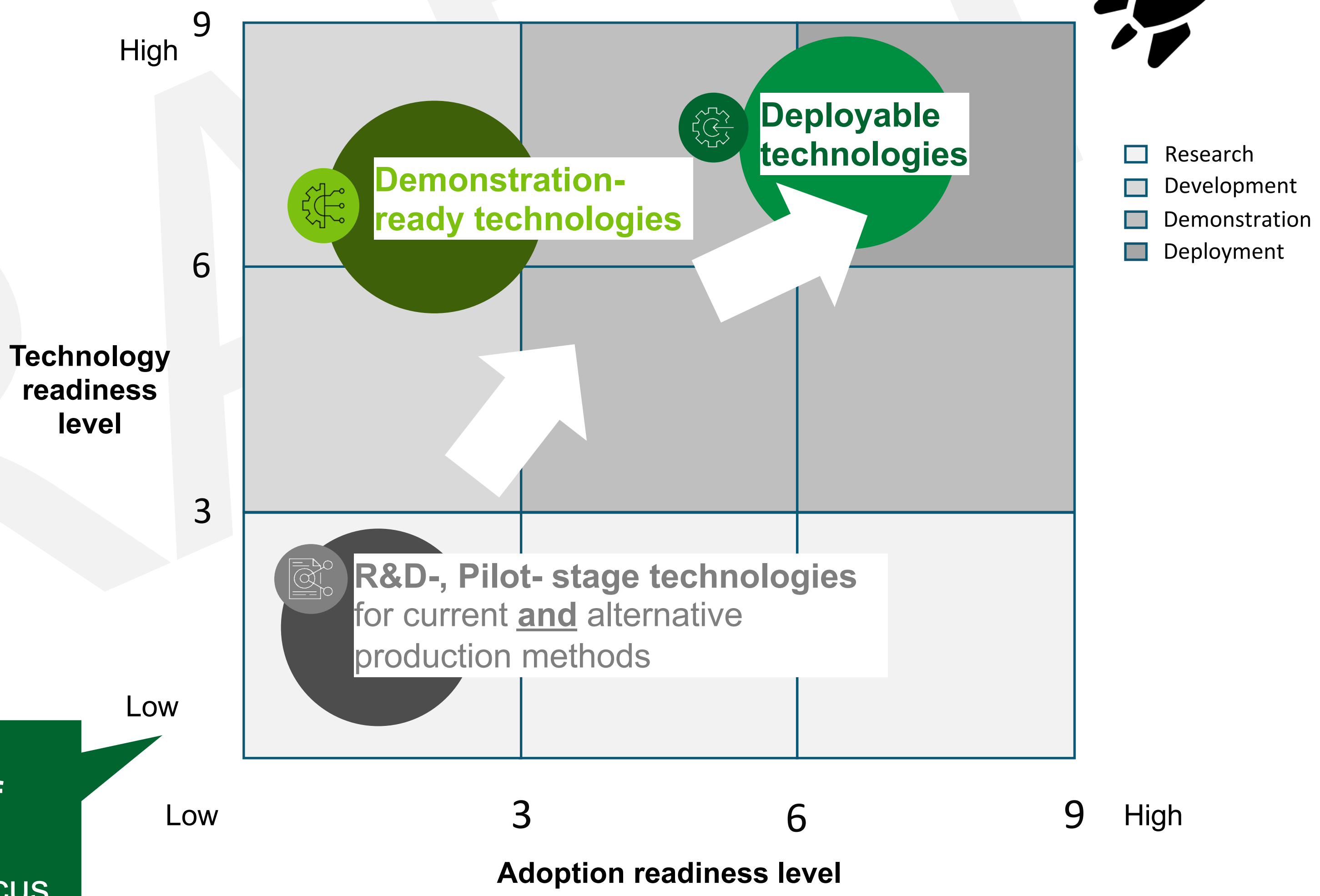
NOT EXHAUSTIVE ILLUSTRATIVE

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

Reaching net-zero will require:

Without development of new and existing technologies a portion of industrial emissions may remain unabated in the industrial sectors of focus

Stage of decarbonization technology lever development



Exact decarbonization levers and capital for net-zero varies by sector

U.S. stage of commercialization: Deployable | Demo | R&D / Pilot

Limited relevance for sector decarbonization

PRELIMINARY – VALUES SUBJECT TO CHANGE

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ILLUSTRATIVE

Industrial Sector Lens

Decarbonization Levers Lens

	Chemicals	Refining	Iron & Steel	Food & Beverage	Cement	Pulp & Paper	Aluminum	Glass
CCS (with 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	Bio-based feedstock	NG-DRI/HBI[5]		Clinker substitution	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	
Potential capex needed	$400-600B	$200-300B	$25-40B	$5-15B	$50-110B	$10-15B	$5-15B	$5-15B

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 | 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

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

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

- Across sectors, **goals of top U.S. industrial companies only represent only a ~15% reduction** of scope 1 and 2 U.S. industrial emissions by 2035
- Market players cite **common concerns driving reluctance to be a first mover**:

Value Proposition

Resource Maturity

Limited Technologies

Market Acceptance

Additional **sector-specific challenges**

…However, this narrative is changing including:

NOT EXHAUSTIVE

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

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

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

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

Challenges across the value chain must be addressed for industrial decarbonization to liftoff

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Suppliers

Consumers

Raw material development → **Processing & production** → **Fabrication & storage** → **Distribution** → **Customer**

- High delivered cost of technology
- High complexity to adopt
- Capital flow challenges
- Limited high-TRL[1] technologies
- Lack of enabling infrastructure
- Limited Demand Maturity

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

1. Technology Readiness Level

Targeted solutions can address challenges across the value chain

	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
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
Technology readiness	**Limited high-TRL[1] technologies**	Diversify decarbonization portfolios with **high-potential alternative technologies**	• Pilot projects • Sector-specific niches
Market Acceptance	**Limited demand maturity**	Activate **demand-side pull** through coalitions and individual procurement deals	• Offtake agreements with defined green premiums • Supplier assessments • Voluntary or statutory requirements

1. Technology Readiness Level

Agenda

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

Every sector has unique opportunities to lead industrial decarbonization

ILLUSTRATIVE PRELIMINARY NOT EXHAUSTIVE

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

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- **Sector-level insights**
  - Sector leadership opportunities
  - **Chemicals**
  - Refining
  - Iron & Steel
  - Food & Beverage
  - Cement
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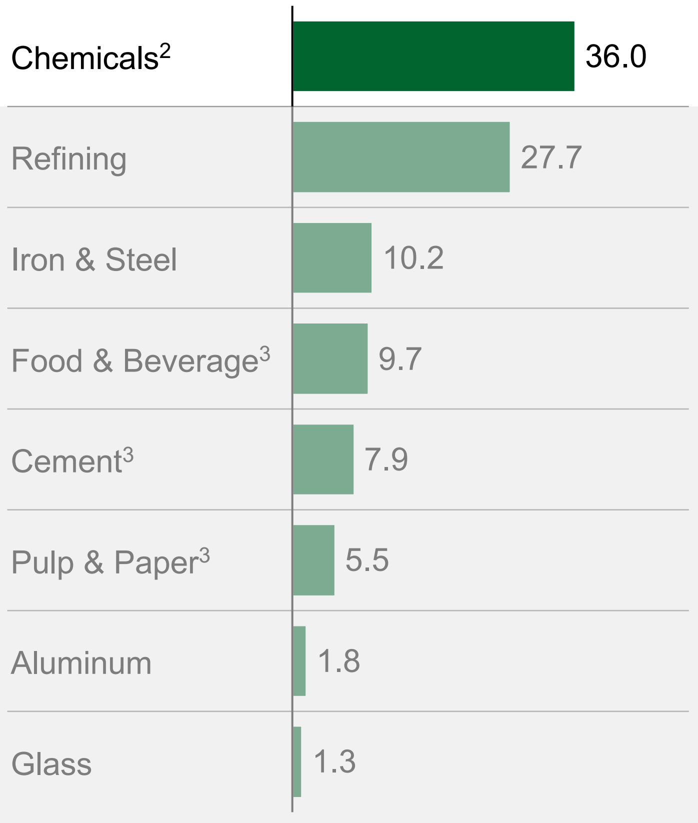
  - Aluminum
  - Glass

Chemicals: Industry Overview

Sector share of 2021 CO_2e emissions from eight industrial sectors of focus in IRA[1], %



Sub-sectors:

Ammonia, ethylene[5], Natural Gas Processing (NGP), and chlor-alkali

~315	MT CO_2e	2021 U.S. emissions
~1,000	MT CO_2e	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%

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

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

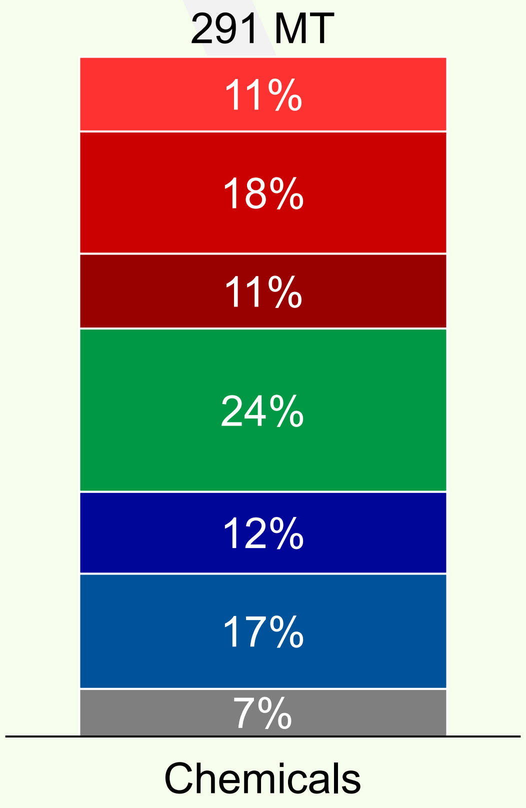
Chemicals: Emissions baseline

PRELIMINARY – VALUES SUBJECT TO CHANGE

Chemicals production has fragmented emission sources …

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], CO_2e



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

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, McKinsey Chemical Emissions Model

Chemicals: Decarbonization levers

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

% Share of sector abatement potential

PRELIMINARY – VALUES SUBJECT TO CHANGE   **ABATEMENT FIGURES ONLY REFLECT CO_2 (NO OTHER GHG)**

		Lever	Current lowest cost abatement, MT	Share of sector abatement potential (%)	Abatement cost, $/t$CO_2$
Heat	<200C	**Clean power [Other chem]:** Onsite RES[1] with LDES[1] and e-boiler with TES[1]	~50	~20%	~40-60
Heat	<200C	**Energy efficiency [Ethylene]:** Fuel use reduction	<5	<5%	~(100)-(80)[2]
Heat	<400	**Clean power [Chlor-alkali, Other chem]:** Onsite RES with LDES and e-boiler with TES	~35	~10%	~40-70
Heat	400C+	**CCS [Ethylene, Other chem]:** Steam cracking furnace	~35	~10%	~140-180
Heat	400C+	**CCS [Ammonia]:** Dilute flue gas from SMR	<5	<5%	~110-140
Process		**CCS [NGP[1]]:** Associated CO_2 emissions	~15	~5%	~(20)-10
Process		**CCS [Ammonia]:** Dilute flue gas from SMR	~15	~5%	~110-140
Process		**Electrolytic Hydrogen [Ammonia]:** Electrolyzer powered by RES	~15	~5%	*Costs uncertain; assumptions based current policy and guidance as of June 2023*
Power		**Electrification [NGP[1]]:** Compressor electrification with power generation by renewables	~20	~5%	~(50)-(30)
Power		**Clean power [Ammonia, Chlor-alkali, Ethylene, Other chem]:** Power generation with RES and LDES	~40	~15%	~30-70

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

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, McKinsey Chemical Emissions Model

Chemicals: Operational decarbonization momentum (varies by subsector)

PRELIMINARY **NOT EXHAUSTIVE** **ILLUSTRATIVE**

U.S. stage of decarbonization lever development →

Deployable | Demo | R&D / Pilot

Energy efficiency

CCS with H2 production[1] (Demo: Ethylene, Deployment: NGP, Ammonia, Chlor-Alkali)

Recycling[3]

Alternative production methods[5]

On-site low-carbon electricity

Electrification[2] (R&D: electric cracker, Demo: NGP Compressor)

Electrolytic Hydrogen[4]

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

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

Chemicals liftoff pathway: Demonstrate world class, low-carbon chemicals processing domestically in pursuit of competitive advantage internationally

PRELIMINARY – VALUES SUBJECT TO CHANGE

ILLUSTRATIVE NOT EXHAUSTIVE

	Technology examples	Net-zero pathway enablers	Sector abatement share[1], %
Deployable (Commercialize → Scale)	• Energy efficiency • Electrification [NGP] • Electrolytic H2 [Ammonia] • Clean electricity [Chlor-alkali] • CCS in concentrated streams [NGP] • Grid decarbonization	• Adopt **best available technology at large chemical plants** • Adopt **electric compressors** at 400+ NG processing plants • **Produce and use Electrolytic H2** in ammonia production, enabled by 45V • **Retrofit NG processing plants with CCS,** enabled by 45Q	40% (including grid decarb.)
Demo (Pilots/FOAK → Commercialize → Scale)	• Low temp. heat electrification • 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	40-55+%
R&D/Pilot (R&D → Scale)	• Electrification (e.g., Electric cracker, catalytic cracker [Ethylene]) • Alternative production methods (e.g., low-carbon feedstocks[2])	• **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	5-20+%

Timeline 2023 — 2030 — 2040 — 2050 (Net-zero)

Investment ← **$400 – 600[5]B** →

1. Current ranges consider how abatement potential might evolve if all CCS applications (e.g., dilute streams) do not reach full maturity/scale. Abatement share ranges are constrained and based on two alternative decarbonization pathways | 2. Includes bio-based or captured CO_2 | 3. Estimated as breakeven point on the MACC levelized cost of heat to reach $0/t$CO_2$e abatement cost for ethylene steam generation | 4. Estimated as breakeven point on the MACC levelized cost of heat to reach $0/tCO2e abatement cost for ethylene steam cracking furnace | 5. Refer to DOE Chemicals & Refining for further detail on capex methodology

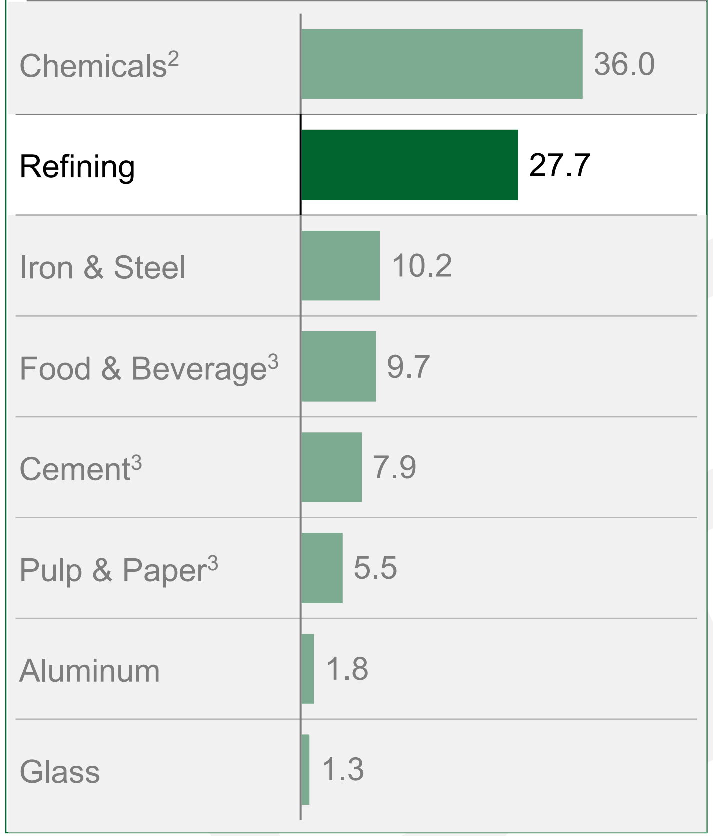
Source: EIA Natural Gas Processing Plants (Count of NGP plants)

Agenda

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

Refining: Industry Overview

Sector share of 2021 CO_2e emissions from eight industrial sectors of focus in IRA[1], %



~243	MT CO_2e	2021 U.S. Emissions
~1,400	MT CO_2e	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%

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

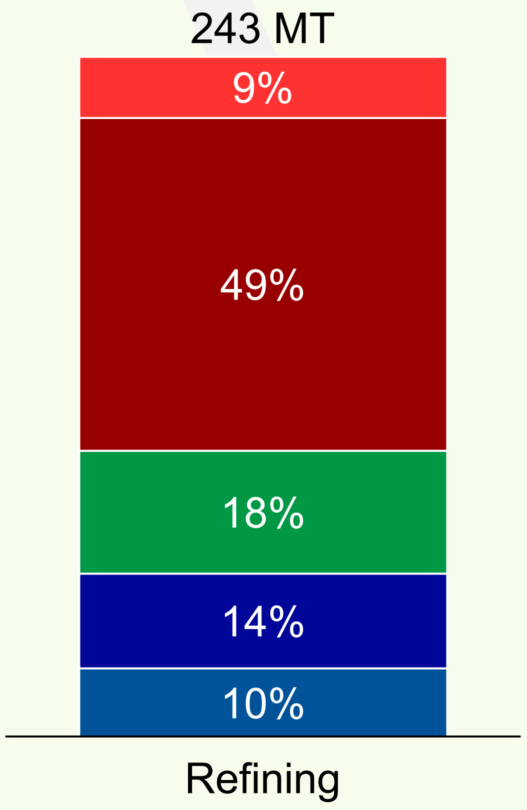
Refining: Emissions breakdown

PRELIMINARY – VALUES SUBJECT TO CHANGE

Almost half of refining emissions are from high-temp heating …

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], CO_2e



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

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: Decarbonization levers

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

PRELIMINARY – VALUES SUBJECT TO CHANGE **ABATEMENT FIGURES ONLY REFLECT CO_2 (NO OTHER GHG)**

% Share of sector abatement potential

Category	Temp.	Lever		Current lowest cost abatement[2], MT	Share of sector abatement potential	Abatement cost, $/tCO₂
Heat	<200C	**Finishing:** Treating products to achieve desired mix	Energy efficiency measures	~20	~10%	~(20)-30[3]
Heat	400C+	**Atmospheric distillation:** Boils and separates crude oil residuals **FCC[1]:** Cracks heavy products to generate lighter products in presence of catalyst **Hydrotreating:** Removes sulfur or nitrogen	CCS on process heat	~ 50	~20%	~100-130[4]
			CCS on FCC[1]	~25	~10%	~100-130[4]
Process		**Steam methane reforming:** Production of hydrogen for hydrotreating and hydrocracking	CCS on SMR[1]	~20	~10%	~80-100[4]
			Electrolytic H2	~15	~5%	*Costs uncertain; assumptions based current policy and guidance as of June 2023*
Power		**Power:** CHP for onsite power and steam generation	Onsite clean electricity and storage	~35	~15%	~110-130
		Grid decarbonization		~15	~5%	N/A

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

Source: 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

PRELIMINARY NOT EXHAUSTIVE ILLUSTRATIVE

U.S. stage of decarbonization lever development →

Deployable | Demo | R&D / Pilot

Energy efficiency

CCS with H2 production
(e.g., SMR[1])

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

Industrial electrification
(e.g., cracker)

Electrolytic Hydrogen[3]

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

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

Refining liftoff pathway: Make the U.S. a global leader in the production, usage and export of clean fuels, to preserve industrial base and retain social license to operate

PRELIMINARY – VALUES SUBJECT TO CHANGE ILLUSTRATIVE NOT EXHAUSTIVE

	Technology examples	Net-zero pathway enablers	Sector abatement share[1], %
Deployable (Commercialize → Scale)	• Energy efficiency • Electrolytic H2 • Grid decarbonization • Bio-based feedstocks with current production methods	• Adopt **best available technology at 130+ refineries** • **Produce and use Electrolytic H2,** enabled by 45V • **Scale production of sustainable fuels** (e.g., renewable diesel) with existing production methods	45% (including grid decarb. and demand reduction)
Demo (Pilots/FOAK → Commercialize → Scale)	• Low temp. heat electrification • CCS on dilute streams • CHP + modular nuclear reactor	• **Achieve <$30/MWh[2] 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** • **Mature** CHP + modular nuclear reactor through R&D and demonstrations to achieve **<$30/MWh cost to compete** with fossil-fuel-powered CHP	20-50+%
R&D/Pilot (R&D → Scale)	• Alternative production methods (e.g., sustainable fuels)	• Mature sustainable fuels (e.g., renewable diesel, sustainable aviation fuel) made with decarbonized production methods and capture emerging **green premium** for low-carbon fuels	5- 15+%

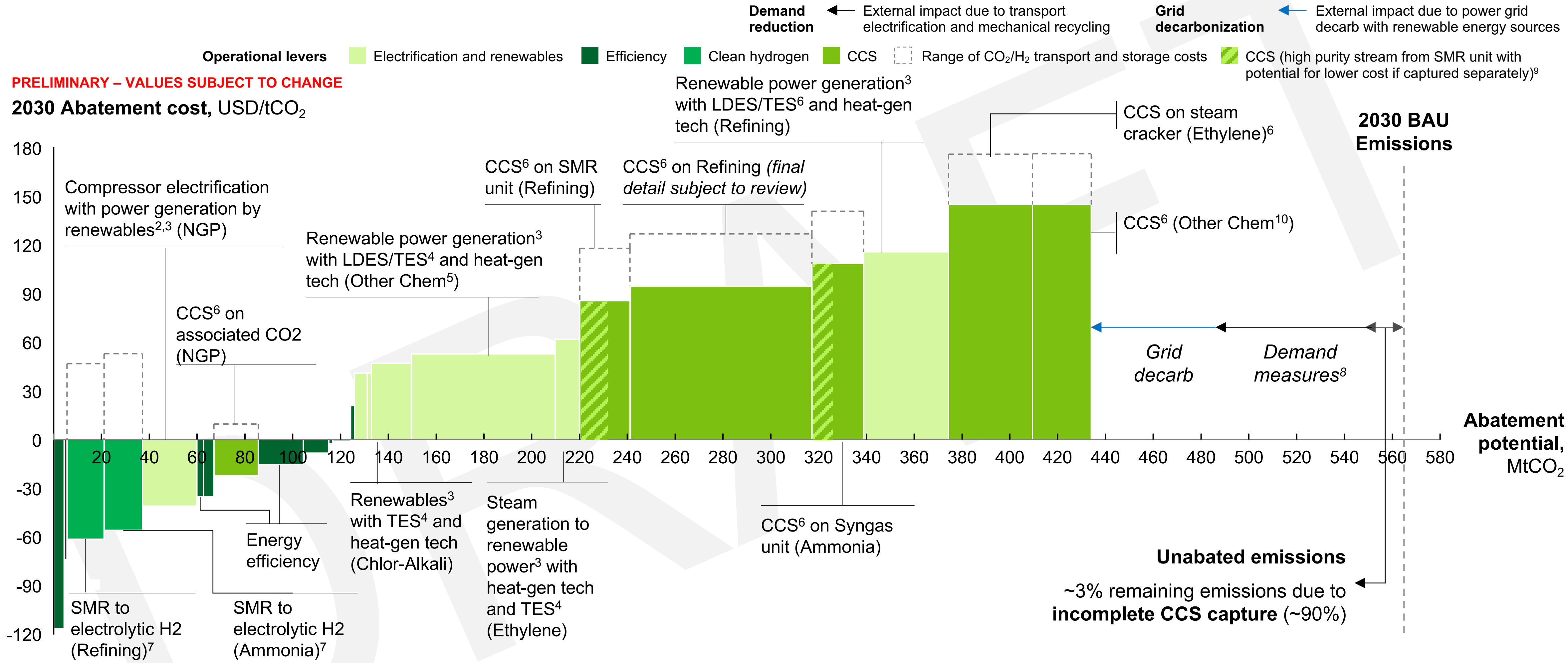
Timeline: 2023 – 2030 – 2040 – 2050 (Net-zero)

Investment: $200 – 300[3]B

1. Regardless of transport electrification goals, this breakdown of decarbonization technologies will be required to reach Net-zero refining in the U.S. at varying scales. Current ranges consider how abatement potential might evolve if all CCS applications (e.g., FCC, process heat) do not reach full maturity/scale. Abatement share ranges are constrained and based on two alternative decarbonization pathways | 2. Estimated as breakeven point on the MACC levelized cost of heat to reach $0/tCO_2e$ abatement cost for refining CHP | 3. Refer to DOE Chemicals & Refining for further detail on capex methodology

Chemicals & Refining: 2030 Marginal Abatement Cost Curve with IRA

PRELIMINARY – VALUES SUBJECT TO CHANGE



1. Electrification analysis includes IRA 48E incentive assuming the projects meet the prevailing wage and apprenticeship requirements and half of projects meet qualify for the domestic content adder. ITC incentives are included. Other policies are not considered in this analysis due to unclear economic impact (e.g., downstream impact of policies) and local impact (e.g., state and local policies). Asset and geography specific consideration of policies could significantly impact choice of technology and resulting abatement costs. | 2 Electrification of compressor results in significant efficiency improvements over steam turbines (95% vs. 35% efficiency) | 3. Renewable cost assumes Class 5 onshore wind production from NREL Annual Technology Baseline for 2030 and excludes the costs associated with transmission and delivery of electricity. IRA-inclusive scenarios includes investment tax credit of 35%, 30% from a base construction that meets the prevailing wage an apprenticeship requirements and an additional 5% due to an assumption that half of projects will claim the 10% domestic content adder. No adders included for low-income communities and energy communities. Net capex cost assumed is $621/kW and opex is $39/kW | 4. Heat generation technology assumes the costs associated with charging and TES as an archetypical setup; however, asset specific heat generation can be achieved with other technologies such as heat pumps and resistive heaters. Technology development and asset specific considerations could significantly impact the choice of heat generation technologies. | 5. Ethylene process assumptions used to model propylene and BTX processes (e.g., propane and naphtha cracking). | 6.Displayed CCS cost estimates based on EFI Foundation capture costs with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10-40/tonne (representing the lower and upper bounds of the displayed range) except where noted. All in 2022 dollars. All CCS figures represent retrofits, not new-build facilities. The inflation variance on each cost estimate represents the range of cost increases on a generic chemical processing facility due to inflation from 2018 using the Chemical Engineering Plant Cost Index (CEPCI) | 7. Hydrogen transport and storage costs are ranged from $0.30-1.30/kg H2 | 8. Demand reduction consists of primarily transport sector electrification as well as the impact of a mechanical recycling rate of 25% of all plastics | 9.Split of emissions streams assumed to be ~60% concentrated and ~40% dilute in SMR unit. Portion of SMR concentrated streams assumed to be smaller for ammonia due to captive usage of concentrated CO2 streams for urea production | 10. Assumes CCS implementation on other chemicals high temperature heat sources with costs based on ethylene steam cracker capture costs

Sources: GREET 2022, NREL, DOE Hydrogen Liftoff Report, EFI CCS Report – "Turning CCS projects in heavy industry & power into blue chip financial investments", Inflation Reduction Act, LDES Council, Expert interviews, Danish Energy Agency, Netherlands Enterprise Agency, GHG Protocol, White House Net-Zero targets, McKinsey Global Energy Perspective, EFI Foundation, "Turning CCS Projects in Heavy Industry & Power into Blue Chip Financial Investments"

Agenda

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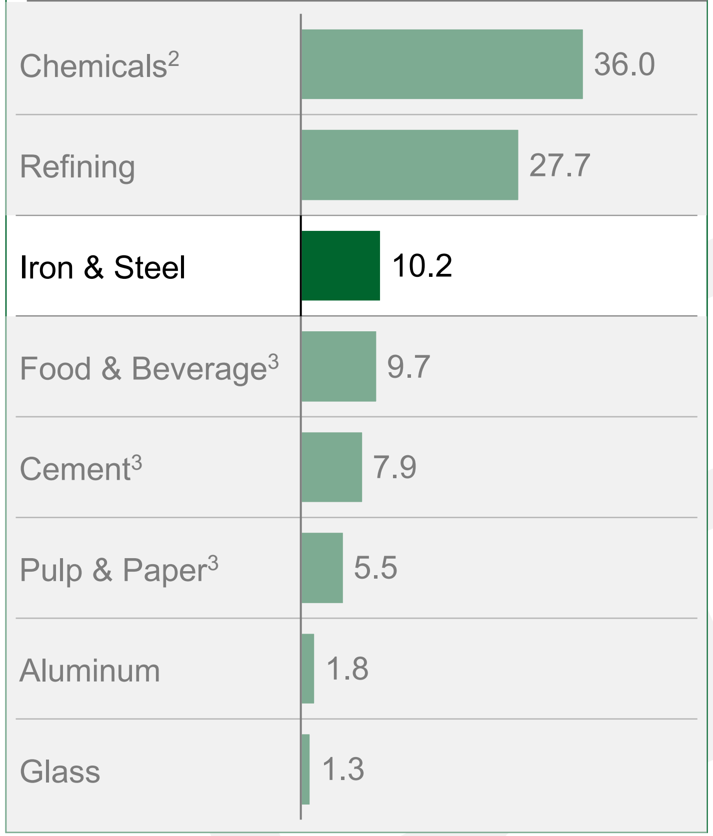
  - Refining
  - **Iron & Steel**
  - Food & Beverage
  - Cement
  - Pulp & Paper
  - Aluminum
  - Glass

Iron & Steel: Industry Overview

Sector share of 2021 CO_2e emissions from eight industrial sectors of focus in IRA[1], %



~89	MT CO_2e	2021 U.S. Emissions
~3,200	MT CO_2e	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%

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

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

PRELIMINARY – VALUES SUBJECT TO CHANGE

ASSUMING FULL GRID DECARBONIZATION , 90% CCS CAPTURE RATE, AND SUPPORTING H2 INFRASTRUCTURE

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

Opex breakdown, $/ton liquid steel[3]

	BF-BOF + CCS	Scrap + EAF	Scrap + NG-DRI/HBI – CCS + EAF	Scrap + H2-DRI/HBI + EAF	Scrap + AIU[12] – EAF
Emissions intensity,[2] kg CO2/ton steel	~0.3	<0.1	<0.1	<0.1	There are emerging production technologies for low-carbon iron units including: • Molten oxide electrolysis • Ammonia DRI • HIsmelt process • … 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 • CCS is cost additive	• Can only produce long steel products • Total production capacity limited by scrap availability	• 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 H2-DRI/HBI plants in the U.S. • Limited Electrolytic H2 infrastructure • Price of material & energy inputs (e.g., Electrolytic H2 price vs. NG6, DRI/HBI vs. pig iron)	• Technology still nascent, may take years to reach commercial scale

Detail on all BF-BOF decarb levers (beyond CCS) follows

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

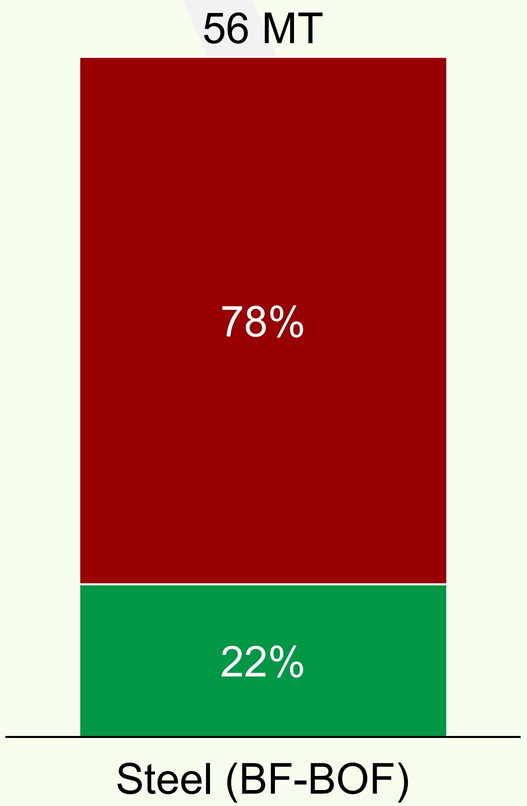
Iron & Steel: Emissions baseline

PRELIMINARY – VALUES SUBJECT TO CHANGE

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

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], CO_2e



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

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

Iron & Steel: Decarbonization Levers

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

PRELIMINARY – VALUES SUBJECT TO CHANGE

% Share of sector abatement potential

Heat | 400C+

Value chain step responsible for emissions	Lever	Current lowest cost abatement[5], MT	%	Abatement cost, $/tCO2
Coking Oven: Coal heated to produce coke	**Raw material substitution** (e.g., Add DRI/HBI to charge mix[4])	~5	~5%	~10-30
Blast Furnace: Iron ore pellets melted with coke & limestone	**CCS** on coking oven, BF heat, BOF, NG-DRI/HBI	~30	~50%	~40-290[5,6]
Basic Oxygen Furnace: Pig iron melted & refined	**Electrification** (e.g., EAF[1])	~20[2]	~35%[2]	~50-100[3]

1. As more U.S. steelmakers shift to DRI/HBI-EAF there could be constrains on scrap metal availability as a key material input in U.S. EAFs (~0.7t/t of steel). Abatement reflects decarbonized grid scenario | 2. Note that this reflects difference in furnace emissions and increased scrap consumption| 3. NG DRI-EAF is estimated to be ~$100-150/ton whereas H2 DRI-EAF is ~$150-250/t | 4. Can only make up ~10-15% of material input | 5. Varies by application. BF-BOF applications are expected to be $40-110/tCO2e with 45 Q and NG-DRI/HBI applications are expected to be $140-290/tCO2e.| 6. Displayed cost estimates based on EFI Foundation capture costs with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10-40/tonne, except where noted. All in 2022 dollars. All CCS figures represent retrofits, not new-build facilities. The lower bound costs represents a NOAK plant in a low cost retrofit scenario with low inflation. The higher bound costs represents a FOAK plant in a high cost retrofit scenario with high inflation.

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

Iron & Steel: Operational decarbonization momentum (varies by subsector)

PRELIMINARY NOT EXHAUSTIVE ILLUSTRATIVE

U.S. stage of decarbonization lever development

Deployable | Demo | R&D / Pilot

Energy efficiency

Industrial electrification
(e.g., EAF)

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

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

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

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

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

Source: World steel association, Steelmakers annual report, 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) ,

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

PRELIMINARY – VALUES SUBJECT TO CHANGE ILLUSTRATIVE NOT EXHAUSTIVE

	Technology examples	Net-zero pathway enablers	Sector abatement share[2], %
Deployable (Commercialize → Scale)	• Energy efficiency • Transition to EAF • Raw material substitution (scrap, H2 DRI/HBI) • Grid decarbonization	• Adopt **best available technology at 8 remaining U.S. BF-BOF** and increased use of DRI/HBI and **ferrous scrap** • **Continue migration of flat steel to EAF** steelmaking route • **Increase U.S. DRI/HBI production** enabled by stable supply of low-carbon DR pellets	30-45% (including grid decarb.)
Demo (Pilots/FOAK → Commercialize → Scale)	• BF-BOF + CCS • NG-DRI/HBI + CCS • Electrolytic H2-DRI/HBI	• **Reduce cost** of CCS on BF-BOF by **$75/tCO$_2$**[5] via **demonstrations**, **45Q incentives**, and buildout of **CCS infrastructure** • **Reduce CCS costs on NG-DRI/HBI, enabled by emerging green premium** of low-carbon DRI/HBI in U.S. and by stable supply of low-carbon DR pellets • **Build FOAK Electrolytic H2-DRI/HBI in the U.S.,** supported by 45V incentives, cost downs for on-site electrolyzers, and domestic Electrolytic H2 infrastructure	30-50+%
R&D/Pilot (R&D → Scale)	• Alternative production method (e.g., electrowinning, molten oxide electrolysis) • Increase EAF production	• **Scale alternative ironmaking processes** to reach $350-400[4]/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**[1]	20-40+%

Timeline: 2023 – 2030 – 2040 – 2050 (Net-zero)

Investment: $25 – 40[3] B

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

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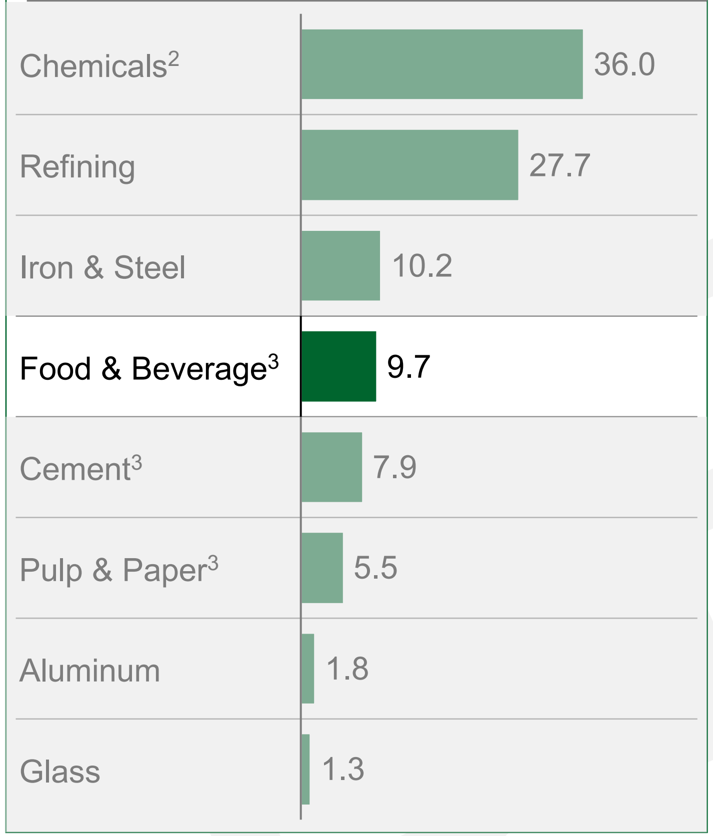
- Introduction
- Cross-sector insights
- **Sector-level insights**
  - Sector leadership opportunities
  - Chemicals
  - Refining
  - Iron & Steel
  - **Food & Beverage**
  - Cement
  - Pulp & Paper
  - Aluminum
  - Glass

Food & Beverage: Industry Overview

Sector share of 2021 CO_2e emissions from eight industrial sectors of focus in IRA[1], %



~85[4]	MT CO_2e	2021 U.S. Emissions
~400	MT CO_2e	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%

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

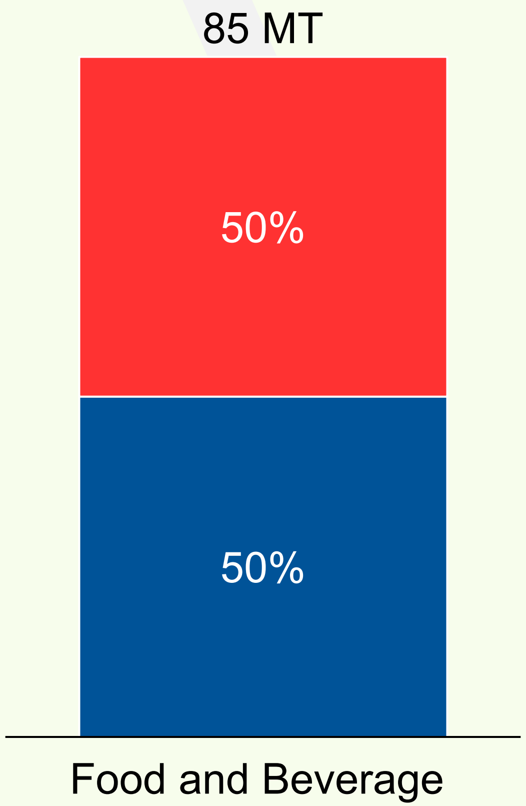
Food & Beverage: Emissions baseline

PRELIMINARY – VALUES SUBJECT TO CHANGE

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

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], CO_2e



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

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: Decarbonization levers

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

PRELIMINARY – VALUES SUBJECT TO CHANGE

(%) Share of sector abatement potential

		Value chain step responsible for emissions	Lever	Current lowest cost abatement, MT	%	Abatement cost,[1] $/$tCO_2$
Heat	<200C	**Steam generation:** Boilers and CHP	**Energy efficiency,** e.g., reduced steam losses	~5	~5%	Net positive
			Electrification, e.g., e-boiler + TES[3] with RES[3]	~20	~30%	~70-110[2]
		Process heating: Various equipment for different sub-sectors (e.g., ovens, fryers)	**Electrification,** e.g., electric oven, electric fryers	~10	~10%	TBD
			Alternative fuels, (e.g., biomass)	<1	<5%	TBD
Power		**Process cooling[5], conveyor belts, and other facility operations:** Electricity consumption	**Energy efficiency,** e.g., efficient process cooling/refrigeration	~2	<5%	Net positive
			Grid decarbonization	~40	~51%[4]	N/A

Reducing food loss is an indirect lever to reduce F&B processing emissions[6]

1. Wide range due to diverse products, processes, and facility sizes | 2. Figures for steam generation with electric boiler / TES and heat pumps / TES powered by on-site solar are $70-110 / tCO2e | 3. RES = Renewable energy sources; TES = Thermal energy storage| 4. Based on White House – Long-term strategy of the U.S. Pathways to Net-zero | 5. Process cooling is a significant portion of current F&B processing electrical load and there are a range of levers that could be used to reduce electricity consumption | 6. Manufacturing is the largest source of food waste/loss

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 (varies by subsector)

PRELIMINARY NOT EXHAUSTIVE ILLUSTRATIVE

U.S. stage of decarbonization lever development →

Deployable | Demo | R&D / Pilot

Efficiency
(e.g., waste energy recovery)

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

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

Alternative production methods[2]

Electrolytic Hydrogen[1]
(e.g., H2 boilers)

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

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

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

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

PRELIMINARY – VALUES SUBJECT TO CHANGE ILLUSTRATIVE NOT EXHAUSTIVE

Technology examples | **Net-zero pathway enablers** | **Sector abatement share**[1] (excluding biogenic from process heat), %

Deployable

Commercialize → Scale

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

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

70% (including grid decarb.)

Demo

Pilots/FOAK → Commercialize → Scale

- Alternative fuel for low temp heating equipment

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

5-10+%

R&D/Pilot

R&D → Scale

- Electrolytic H2 (e.g., boilers)
- Electrification (other equipment)
- Alternative production methods

- Make alternative **low-carbon, low temp. heat methods** such as H2 boilers **cost competitive** with incumbent methods
- Develop cost-effective electric alternatives to other process heating equipment (specific to product)
- **Make alternatives to conventional F&B processing equipment** (e.g., absorption chillers, ejector refrigeration, deep waste energy and water recovery, alternative protein manufacturing, etc.) **cost competitive** with incumbent methods

20-25+%

Timeline 2023 | 2030 | 2040 | 2050 (Net-zero)

Investment ← $5-15B[2] →

1. Abatement share ranges are constrained and based on alternative decarbonization pathways, varying on factors such as the evolution of Electrolytic H2 boilers | 2. Capex estimate for Food and Beverage processing was based on assuming a) fossil-fuel based boilers are replaced with electric boilers and b) given the wide range of alternative equipment needed across F&B facilities the boiler estimate would represent roughly half of the total investment needed to decarbonize the industry | 3. Estimated as breakeven point on the MACC levelized cost of heat to reach $0/tCO_2e abatement cost for ethylene steam generation (used as a proxy for low-temperature heat) | 4. Includes electrification or alternative fuel use

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  - Food & Beverage
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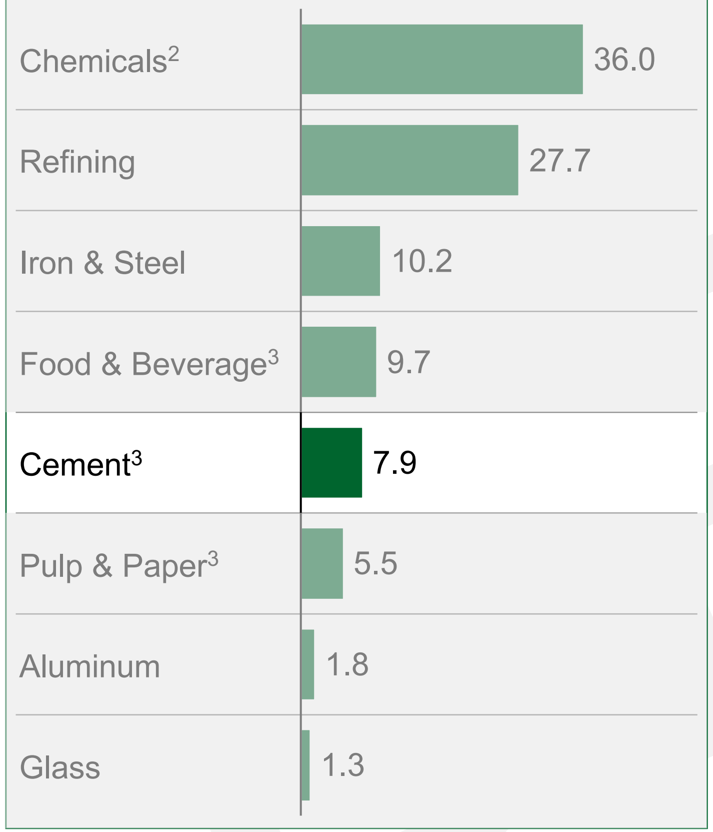
  - Pulp & Paper
  - Aluminum
  - Glass

Cement: Industry Overview

Sector share of 2021 CO_2e emissions from eight industrial sectors of focus in IRA[1], %



~69	MT CO_2e	2021 U.S. Emissions
~3,500	MT CO_2e	2021 Global Emissions[4]

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%

1. Includes other greenhouse gas emissions and non-industry sectors using GWP20 | 2. Split into natural gas processing (56 MT), ammonia (43 MT), ethylene steam cracking (39 MT), chlor-alkali (24 MT), other downstream chemical processes (112 MT) | 3. Does not reflect biogenic emissions of the sector | 4. Cement is the third largest CO_2 emitter globally | 5. Reflects range for major U.S. cement players by market share

Source: NLM, "Alternative Clinker Technologies for Reducing Carbon Emissions in Cement Industry: A Critical Review" (2021), IFC, "Increasing the Use of Alternative Fuels at Cement Plants (2017)

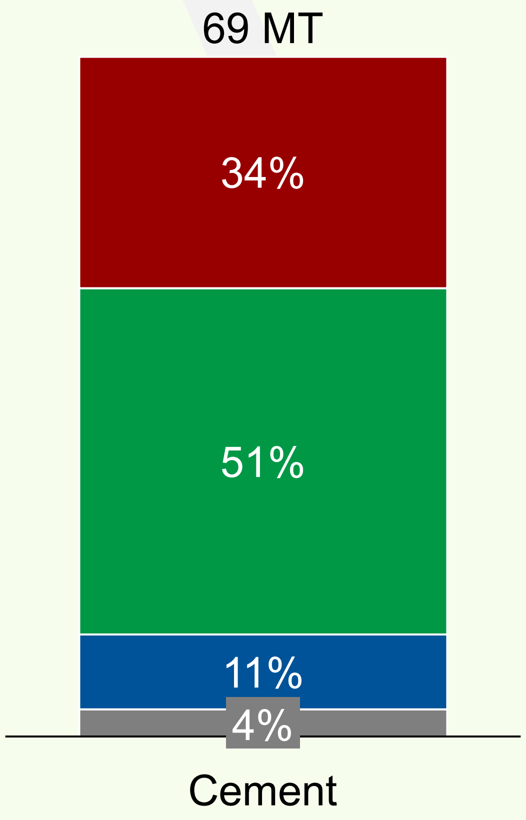
Cement: Emissions baseline

PRELIMINARY – VALUES SUBJECT TO CHANGE

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

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], CO_2e



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

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: Decarbonization levers

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

PRELIMINARY – VALUES SUBJECT TO CHANGE

Key: Heat | Process | Power

Lever	Current lowest cost abatement, MT	Abatement cost, $\$/tCO_2$
Energy efficiency	~10%	Net Positive
Clinker substitution – e.g., fly ash, calcined clay[3]	Up to 25%	Net Positive
Alternative fuel – waste, biomass[1]	Up to 34%	~0-100
Alternative fuel - hydrogen	Up to 34%	~50-80[2]
Heat electrification	Up to 34%	Emerging economics
CCS on combustion and remaining emissions[4]	Up to 80%	~25-90[6]
Alternative production methods	TBD	Emerging economics
Alternative chemistries	TBD	Emerging economics
Grid decarbonization	~10%	N/A

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

1. Average based on several different types of feedstocks | 2. Cost after applying levelized 45V tax credit | 3. Assuming 50% clinker to binder ratio with clinker substitution embodied emissions 50% lower | 4. Assuming 90% capture rate for all heat and production emissions | 6. Low figure based on low NETL estimate of $109 per ton including $10 T&S cost, assuming 30-year payback period; high figure based on NETL estimate of $132 per ton with $40 T&S cost and 15-year period.

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”

Note: Use of alternative fuels and clinker substitutes in the U.S. lags behind EU averages, resulting in opportunity to close gap. See Excel backup for further detail

Cement: Operational decarbonization momentum (varies by subsector)

PRELIMINARY NOT EXHAUSTIVE ILLUSTRATIVE

U.S. stage of decarbonization lever development →

Deployable Demo R&D / Pilot

Energy efficiency

Alternative fuel
(e.g., biomass, waste)

Raw material substitution
(e.g., clinker alternative)

CCS

Alternative production methods

Alternative chemistry

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

Alternate fuel – hydrogen

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: 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

PRELIMINARY – VALUES SUBJECT TO CHANGE

ILLUSTRATIVE NOT EXHAUSTIVE

	Technology examples	Pathway to commercial liftoff	Sector abatement share[1], %
Deployable	• Energy efficiency • Clinker substitutes (e.g., fly ash, steel slag, calcined clay) • Alternative fuels (waste, biomass)	Commercialize → Scale **Scale currently deployable measures rapidly,** enabled by accelerated testing & validation of clinker substitution and low-carbon procurement standards	~30-60% (including grid decarb)
Demo	• **CCS** retrofits of existing plants	Pilots/FOAK → Commercialize → Scale **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	~40-70+%
	• **Alternative production methods** – Noncarbonate feedstocks – Electrochemical production (Compatible with existing standards)	Pilots/FOAK → Commercialize → Scale **Build FOAK plants,** enabled by government support **Accelerate buildout of greenfield plants,** enabled by coordinated procurement to create investable demand signal	
R&D/ Pilot	• **Alternative chemistries** requiring updated standards	R&D → Scale 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	TBD

Timeline: 2023 – 2030 – 2040 – 2050 (Net-zero)

Investment: $50-110[2]B

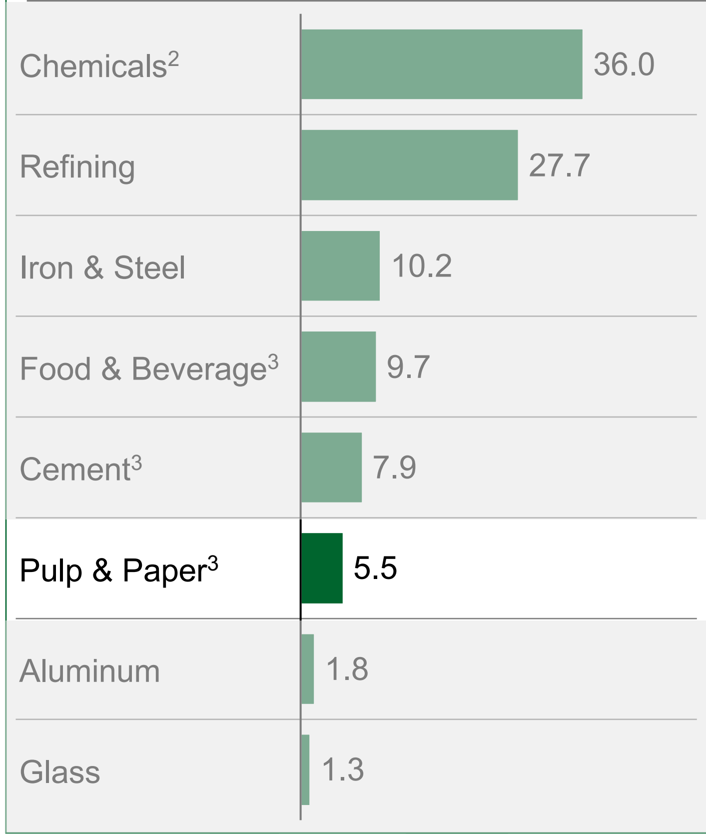
1. Abatement share ranges are constrained and based on alternative decarbonization pathways, varying on factors such as the emergence of alternative production methods and chemistries | 2. Capex figures based on expert syndication

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"

Agenda

Pulp & Paper: Industry Overview

Sector share of 2021 CO_2e emissions from eight industrial sectors of focus in IRA[1], %



~48	MT CO_2e	2021 U.S. Emissions[4]
~200	MT CO_2e	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%

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

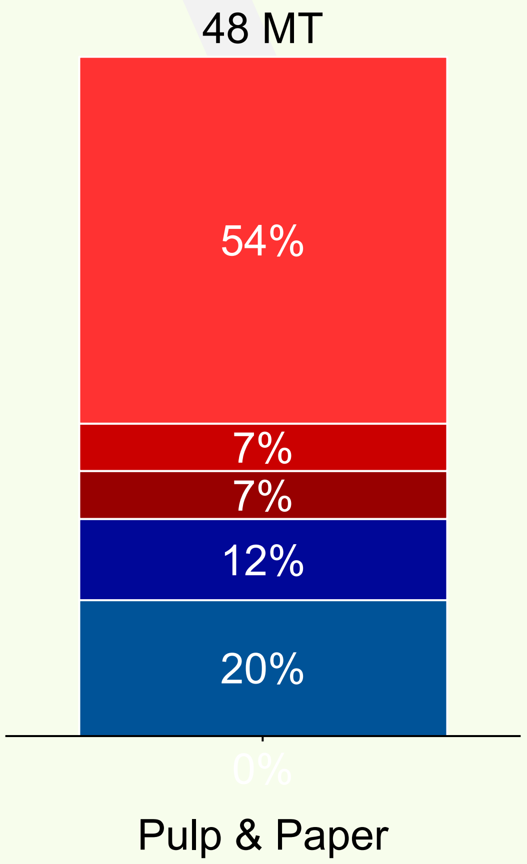
Pulp & Paper: Emissions baseline

PRELIMINARY – VALUES SUBJECT TO CHANGE

Most Pulp & Paper emissions are from low temp heat sources…

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]**,** CO_2e



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

Source: FisherSolve Next 4.0.23.0301, expert interviews

Pulp & Paper: Decarbonization levers

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

PRELIMINARY – VALUES SUBJECT TO CHANGE

% Share of sector abatement potential

	Value chain step responsible for emissions	Lever	Current lowest cost abatement, MT	%	Abatement Cost, $/t$CO_2$
Heat	**Drying:** Uses a multi-cylinder dryer, drying is the most energy-intensive phase within the papermaking process	**Energy efficiency**[1] e.g., real time energy management systems	~10	~20%	Net Positive
Heat		**Alternative fuels**[2] e.g., biomass	~10	~20%	~100 – 130
Heat	**Burners:** Supports drying process	**Electrification** e.g.,heat pumps, electric boiler, CHP	~10	~20%	~110 – 160
Heat	**Evaporators:** Evaporates and concentrates black liquor	**Electrolytic Hydrogen** e.g., hydrogen burners, hydrogen boilers	Emerging economics		
Heat	**Boilers:** Produces steam and electricity	**Alternative fuels** e.g., biomass gasification, pyrolysis	Emerging technology, economics unclear		
Power	**Onsite electricity:** burning fossil fuels on site to produce power	**Clean onsite electricity** e.g., biomass, onsite solar	~5	~15%	~50 – 100
Power	**Offsite electricity**	**Grid decarbonization**	~7.5	~15%	N/A

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

Source: FisherSolve Next 4.0.23.0301, DOE Chem and refining liftoff report, DOE hydrogen liftoff

Pulp & Paper: Operational decarbonization momentum

PRELIMINARY NOT EXHAUSTIVE ILLUSTRATIVE

U.S. stage of decarbonization lever development →

Deployable | Demo | R&D / Pilot

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

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

Raw material substitution
(e.g., recycling)

CCS
(e.g., black liquor boiler)

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

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

1. Real Time Energy Management

Pulp & Paper liftoff pathway: Achieve economic low-temperature heat decarbonization and reach carbon-negative operations with CCS retrofits

PRELIMINARY – VALUES SUBJECT TO CHANGE

ILLUSTRATIVE **NOT EXHAUSTIVE**

	Technology examples	Net-zero pathway enablers	Sector abatement share[2], % (excluding biogenic)
Deployable	• Energy efficiency • Clean electricity and alternative fuels (e.g., biomass) • Grid decarbonization	Commercialize → Scale • 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	~70-85% (including grid decarb)
Demo	• Low temp. heat electrification	Pilots/FOAK → Commercialize → Scale • **Reach ~$15/MWh[4] cost of low temp. heat electrification** to be competitive vs. fossil fuel boilers/burners, enabled by **demonstrations** and **cost downs**	~15-30+%
R&D/Pilot	• Alternative technology (e.g., gasification, pyrolysis)[1]	R&D → Scale • Commercialize biomass gasification and pyrolysis technology to create **new revenue streams from production of H2 and SAF fuels,** enabled by **stable long-term supply of biomass**	TBD

Timeline 2023 — 2030 — 2040 — 2050 (Net-zero)

Investment ← **$10 - 15[3]B** →

1. Biogenic emissions account for an additional 104MT CO_2e in 2020 (over 2x the sector's energy related emissions) | 2. Abatement share ranges are constrained and based on alternative decarbonization pathways, varying on factors such as the use of alternative fuels | 3. Based on assumption that fossil-fuel based boilers are replaced with electric boilers. Capex is scaled for adoption of other levers such as electrification and alternate fuels | 4. Estimated as breakeven point on the MACC levelized cost of heat to reach $0/tCO_2e abatement cost for ethylene steam generation (used as a proxy for low-temperature heat)

Source: FisherSolve Next 4.0.23.0301, expert interviews

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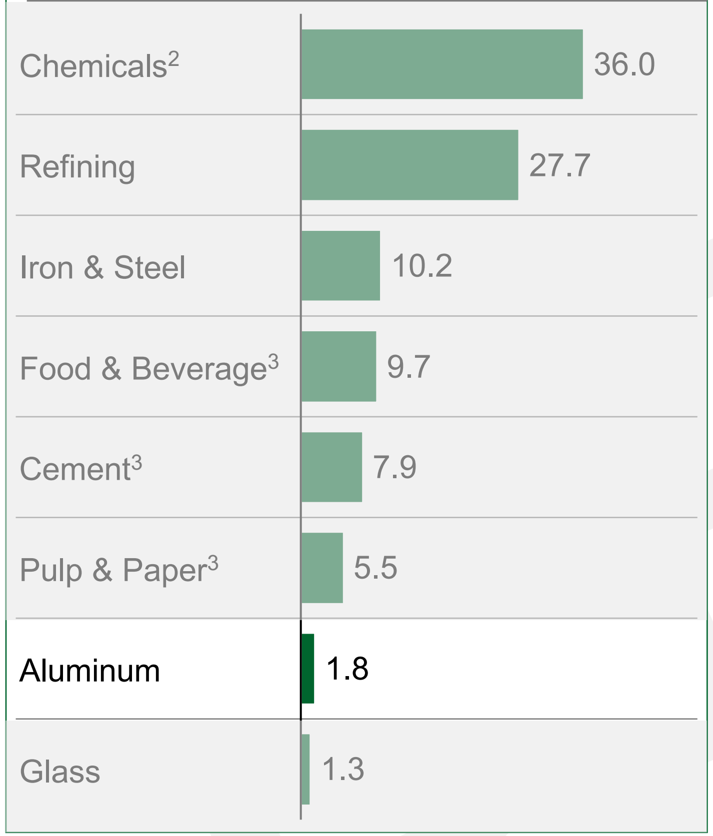
  - Cement
  - Pulp & Paper
  - **Aluminum**
  - Glass

Aluminum: Industry Overview

Sector share of 2021 CO_2e emissions from eight industrial sectors of focus in IRA[1], %



~16	MT CO_2e	2021 U.S. Emissions
~1,100	MT CO_2e	2021 Global Emissions

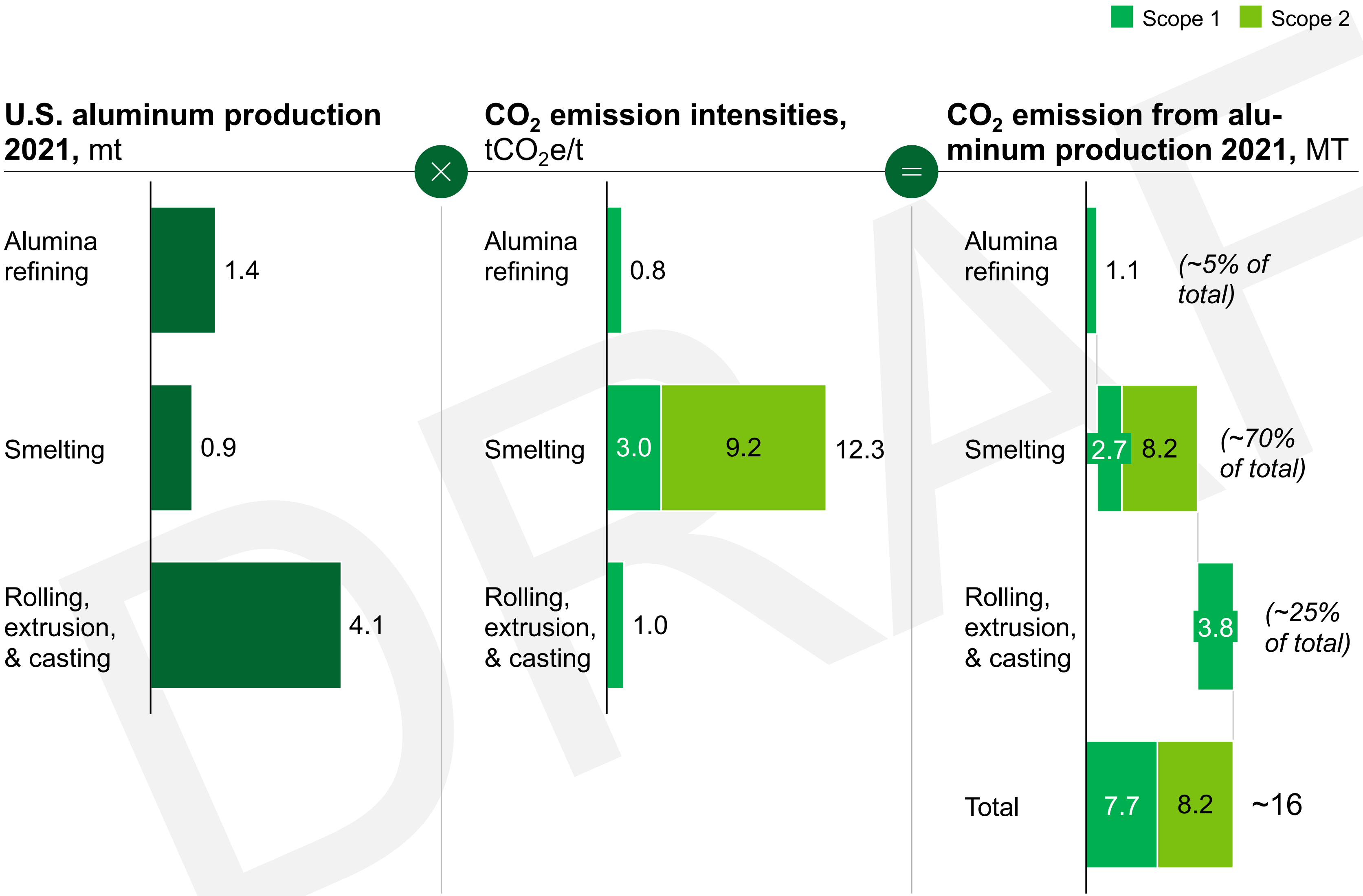
Industry Context

- 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%

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

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

Aluminum: Emissions baseline (1/2)



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

Smelting is significantly more energy intensive than refining and casting

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

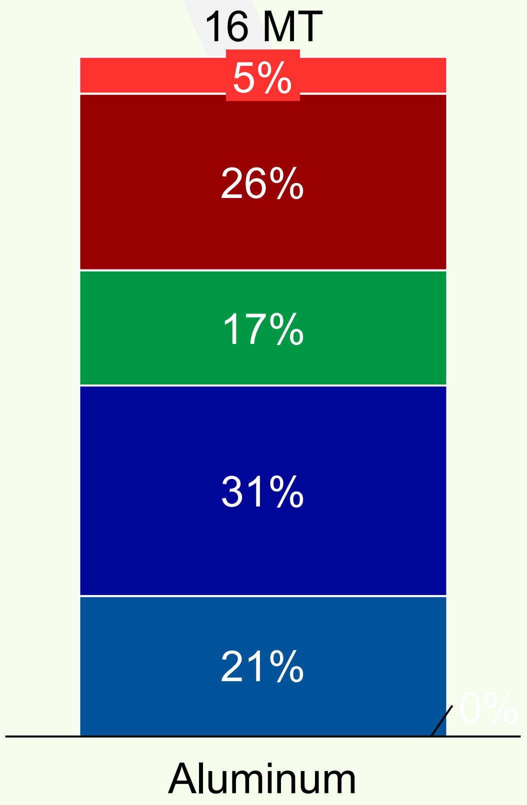
Aluminum: Emissions baseline (2/2)

PRELIMINARY – VALUES SUBJECT TO CHANGE

Most aluminum emissions come from electricity usage…

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]**,** CO_2e



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

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

Aluminum: Decarbonization levers

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

PRELIMINARY – VALUES SUBJECT TO CHANGE

Key: Heat | Process | Power

% Share of sector abatement potential

Production segment	Lever	Current lowest cost abatement, MT	Share of sector abatement potential	Abatement cost, $/tCO$_2$
Alumina refining: digestion and calcination	**Electrification** (e.g., electric boiler, e-calciner)	<1	<5%	~100-150
	Energy efficiency (e.g., waste heat recovery)	<1	<5%	~10-50
Smelting: carbon anode consumption and electricity	**Energy efficiency**[1]	~1	~10%	N/A
	Grid decarbonization	~5	~35%	N/A
	CCS on Hall-Heroult/Electrolysis	<2	~15%	~140-290
Rolling, extrusion, and casting	**Energy efficiency**	~2	~15%	~(100)-25[2]
	Electrification (e.g., e-reheater)	<1	~5%	~10-100
	Raw material substitution (recycling)[2]	<1	~5%	Net positive

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

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

Aluminum: Operational decarbonization momentum

PRELIMINARY NOT EXHAUSTIVE ILLUSTRATIVE

U.S. stage of decarbonization lever development →

- Deployable
- Demo
- R&D / Pilot

Energy efficiency
(e.g., heat recovery)

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

Alternative production methods
(R&D: Carbochlorination, Demo: Inert anode[1])

CCS
(e.g., smelting process[2])

Electrolytic Hydrogen
(e.g., H2 calciner)

Industrial electrification
(R&D: High temp heat[3], Deployable: Low temp heat)

1. Planned international deployment | 2. Select feasibility studies | 3. International pilots and deployments
Source International Aluminum Association, USGS, MPP – Net-zero aluminum, expert interviews, IEA

Aluminum liftoff pathway: Reach infinite recycling and build out cost-effective clean power to produce carbon-free aluminum and de-risk U.S. import reliance

PRELIMINARY – VALUES SUBJECT TO CHANGE

ILLUSTRATIVE NOT EXHAUSTIVE

	Technology examples	Net-zero pathway enablers	Sector abatement share[3], %
Deployable	• Energy efficiency • Raw material substitution: increase scrap usage • Grid decarbonization • Low temp heat electrification	Commercialize → 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[4] cost of low temp. heat electrification** to be competitive vs. fossil fuel boilers/burners, enabled by **demonstrations** and **cost downs**	70% (including grid decarb.)
Demo	• Raw material substitution: Increase Zorba processing • Alternative production methods: Inert anode	Pilots/FOAK → Commercialize → Scale • Increase domestic processing of scrap (e.g., Zorba) • **Mature inert anode** (smelting) to become cost competitive with Hall-Héroult smelting process	0-5+%
R&D/Pilot	• CCS on smelters • High heat electrification in rolling/extrusion/casting[2] • Electrification: E-calciner, • Electrolytic Hydrogen: H2-calciner • Alternative production methods: Carbochlorination	R&D → Scale • **Reduce cost** of CCS at smelters by **\$150-200/tCO_2[5] 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/ H2 calciner (refining)** to become cost competitive with Hall-Héroult smelting process and fossil-fuel calciner, respectively	25-30+%

Net-zero

Timeline 2023 — 2030 — 2040 — 2050

Investment ← \$5-15[1]B →

1. Reflects a) alumina refinery retrofit of fossil-fuel based boiler and calciner in digestion and calcination to electric boiler and electric/hydrogen calciner, b) retrofit of remaining 6 aluminum | 2. Electrical furnace – resistance, electrical furnace – induction, plasma furnace | 3. Abatement share ranges are constrained and based on alternative decarbonization pathways, varying on factors such as use of raw material substitution (e.g., Zorba processing) | 4. Estimated as breakeven point on the MACC levelized cost of heat to reach \$0/tCO_2e abatement cost for ethylene steam generation (used as a proxy for low-temperature heat) | 5. Cost estimates based on [EFI Foundation capture costs] with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~\$10-40/tonne

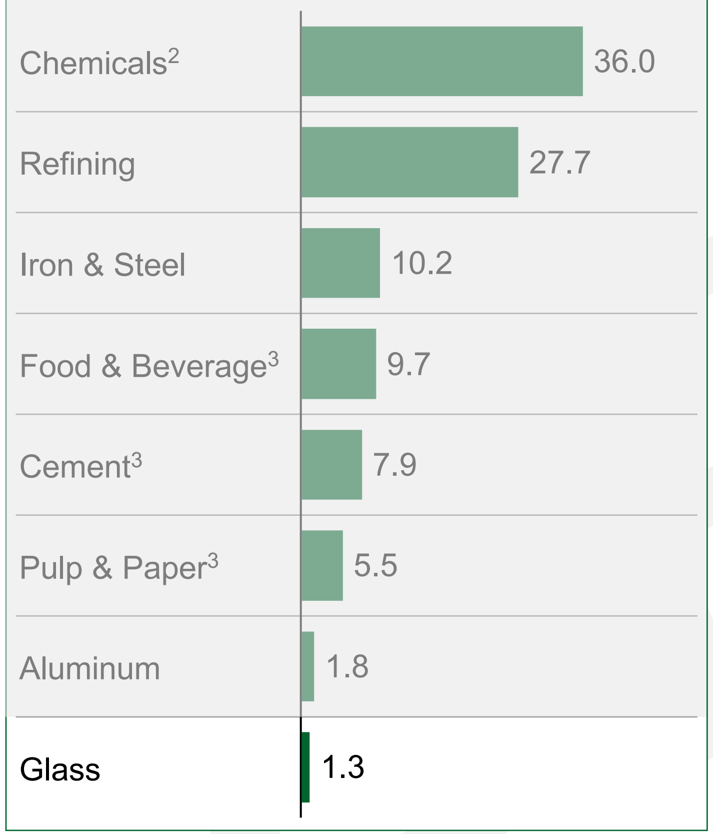
Source International Aluminum Association, USGS, MPP – Net-zero aluminum, expert interviews

Agenda

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

Glass: Industry Overview

Sector share of 2021 CO_2e emissions from eight industrial sectors of focus in IRA[1], %



~11	MT CO_2e	2021 U.S. Emissions
~100	MT CO_2e	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%

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

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), IEA, Trade Map

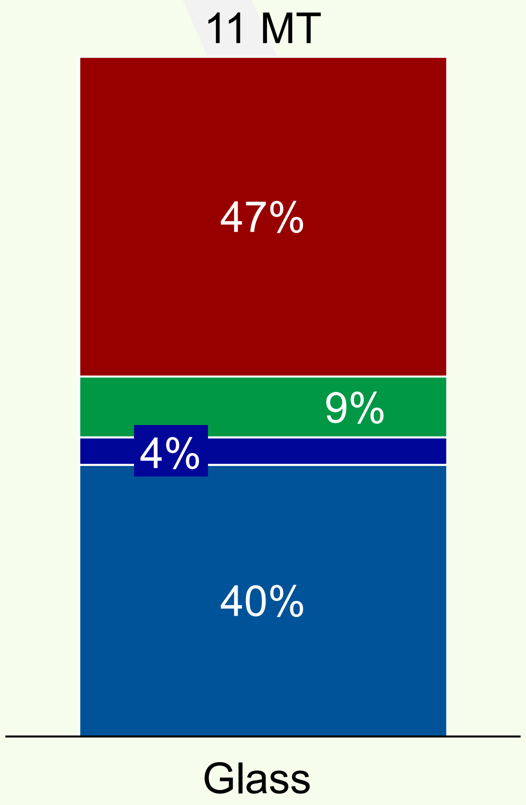
Glass: Emissions baseline

PRELIMINARY – VALUES SUBJECT TO CHANGE

Most Glass emissions are from heat…

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]**,** CO_2e



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

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: Decarbonization levers

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

PRELIMINARY – VALUES SUBJECT TO CHANGE

Key: Heat | Process | Power

xx% Share of sector abatement potential

Value chain step responsible for emissions	Lever	Potential abatement, $MTCO_2$	Share of sector abatement potential	Abatement Cost, $\$/tCO_2$
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[1]
	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
	Electrolytic Hydrogen – forming and post forming	<1	~5%	~190 - 550
	CCS – melting and forming	~1	~15%	~140 - 290
Batch and Mix: Weighing and mixing raw materials in specific proportions	**Raw material substitution and recycling**	~1	~10%	~30 - 50
Forming : Shaping molten glass according to the desired end-product	**Grid decarbonization**	~5	~40%	N/A

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

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

PRELIMINARY NOT EXHAUSTIVE ILLUSTRATIVE

U.S. stage of decarbonization lever development →

Deployable | Demo | R&D / Pilot

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

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

Industrial electrification
(e.g., electric melting)

CCS
(e.g., melting and forming)

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

Electrolytic Hydrogen
(e.g., H2 melting)

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

PRELIMINARY – VALUES SUBJECT TO CHANGE

ILLUSTRATIVE NOT EXHAUSTIVE

	Technology examples	Net-zero pathway enablers	Sector abatement share[5], %
Deployable	• Raw material substitution – cullet usage • Energy efficiency (e.g., Oxyfuel, waste heat recovery) • Grid decarbonization	Commercialize → Scale • 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	50% (including grid decarb.)
Demo	• CCS • Alternative fuel (biomass) • Electrification (preheating cullet) • Raw material substitution – cullet usage	Pilots/FOAK → Commercialize → Scale • **Reduce CCS cost** in glass plants (flat and container), enabled by 45Q tax credit incentives, emerging green premium for low-carbon glass and CCS infrastructure • **Increase cullet usage** at **flat glass plants,** enabled by building supply chain for PV recycling and support building demolition recycling	25-40+%
R&D/Pilot	• Electrolytic Hydrogen • Raw material substitution (e.g., silica alternatives) • Electrification (melter)	R&D → Scale • **Reach $35/MWh[3] cost of Electrolytic H2 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**	10-25+%

Timeline 2023 — 2030 — 2040 — 2050 (Net-zero)

Investment ← **$5-15[6]B** →

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

Note: Use of high strength glass (for use in glass containers) could reduce tonnage volumes produced as well as transportation-related emissions

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),