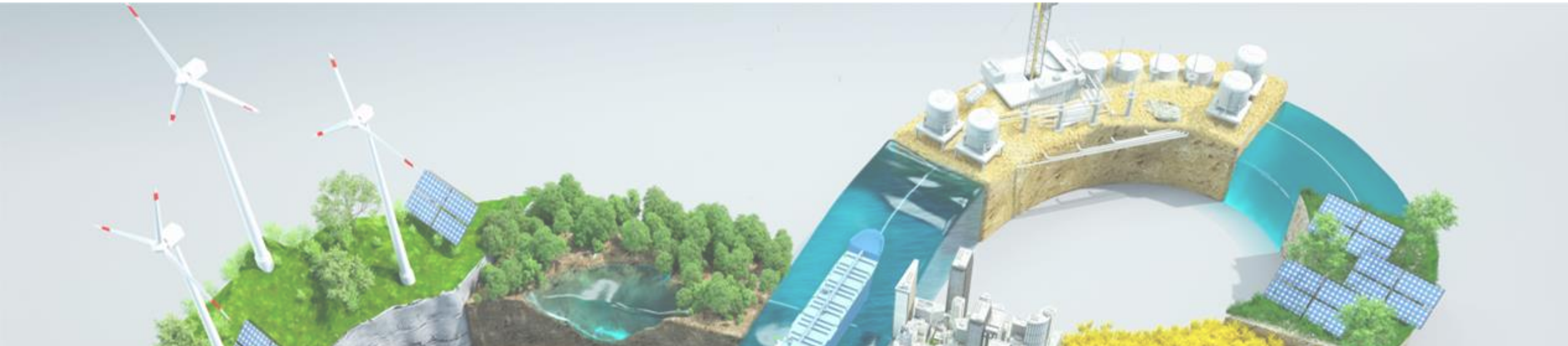




U.S. DEPARTMENT OF  
**ENERGY**



# Pathways to Commercial Liftoff: Industrial Decarbonization Family

ITIAC Meeting | March 21, 2024



# 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](https://liftoff.energy.gov)**

Feedback is eagerly welcomed via **[liftoff@hq.doe.gov](mailto:liftoff@hq.doe.gov)**

# Pathways to Liftoff Initiative: Waves 1 and 2

## Wave 1 topics:

Published in March/April 2023, to very positive reception and impact

Clean Hydrogen

Advanced Nuclear

Long-Duration  
Energy Storage

Carbon Management

## Wave 2 topics:

Reports were released in September 2023 at RE+ and Climate Week NYC.

Industrial Decarbonization preliminary learnings were also shared in a public webinar that occurred on June 28.

Focus for this briefing

Industrial Decarb:  
Cross-cutting view

Industrial Decarb.:  
Chemicals & Refining

Industrial Decarb.:  
Cement

Grid: VPPs

Industry and Ecosystem Engagement Ongoing across all Wave 1 and Wave 2 topics

# Agenda

- **Industrial Decarbonization (“Cross-Cut”) Overview**
- Low-Carbon Cement Overview

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

## Industrial Sector

### Simplified value chains<sup>2</sup>

In-scope

Out-of-scope

PRELIMINARY

ILLUSTRATIVE

TRANSPORTATION EMISSIONS NOT STUDIED

Raw material development

Processing &amp; production

Fabrication/Storage

Distribution

Chemicals<sup>1</sup>O&G  
upstreamOil & Gas  
midstream

Refining

Processing

Fabrication /  
conversion

Distribution

Refining

O&G  
upstreamOil & Gas  
midstream

Refining

Storage

Wholesale / retail

Iron &amp; Steel

Mining

Ironmaking

Steelmaking

Casting

Fabrication/  
conversion

Distribution

Food &amp; Beverage

Farming

Primary processing

Secondary / tertiary  
processing

Storage

Wholesale / retail

Cement

Mining

Clinker production

Cement production

Concrete  
production

Construction

Pulp &amp; Paper

Forestry

Pulp making

Paper making

Conversion

Distribution

Aluminum

Mining

Alumina  
refiningPrimary  
productionSecondary  
productionFabrication/  
conversion

Distribution

Glass

Mining

Melting

Forming

Fabrication /  
conversion

Distribution

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

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

NOT EXHAUSTIVE ILLUSTRATIVE

Highest stage of U.S. development\*

Deployable

Demo

R&amp;D / Pilot

Limited relevance for sector decarbonization

## Industrial Sector

Decarbonization Lever		Chemicals	Refining	Iron & Steel	Food & Beverage	Cement	Pulp & Paper	Aluminum	Glass
	CCUS (incl. H2 production)	Various	FCC <sup>2</sup> , process heat, SMR <sup>3</sup>	BF-BOF <sup>4</sup> , NG-DRI/HBI <sup>5</sup>		Rotary kiln	Black liquor boiler	Smelting	Melting, forming
	Industrial electrification	Low-high temp heat alternatives	Low-high temp heat alternatives	EAF <sup>6</sup> 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 <sup>9</sup>	H2-HBI	Boiler	Rotary kiln	Boilers, burners	Calciner	Melting
	Raw material substitutions	Recycling <sup>11</sup>	Bio-based feedstock	NG-DRI/HBI <sup>5</sup>		Clinker substitution <sup>10</sup>	Recycling	Recycling	Recycling, silica alternatives
	Alt. fuel (non-H2)				Boilers, various equipment	Rotary kiln	Boilers, burners		Melting
	Alt. production methods	Bio-based plastics <sup>1</sup>		Ironmaking processes	Various <sup>8</sup>	Electrochemical <sup>7</sup>		Carbochlorination, inert anode	

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



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

Emissions abatement potential by 2030 by decarbonization lever costs (incremental to IRA incentives)<sup>1</sup>

MT CO<sub>2</sub>

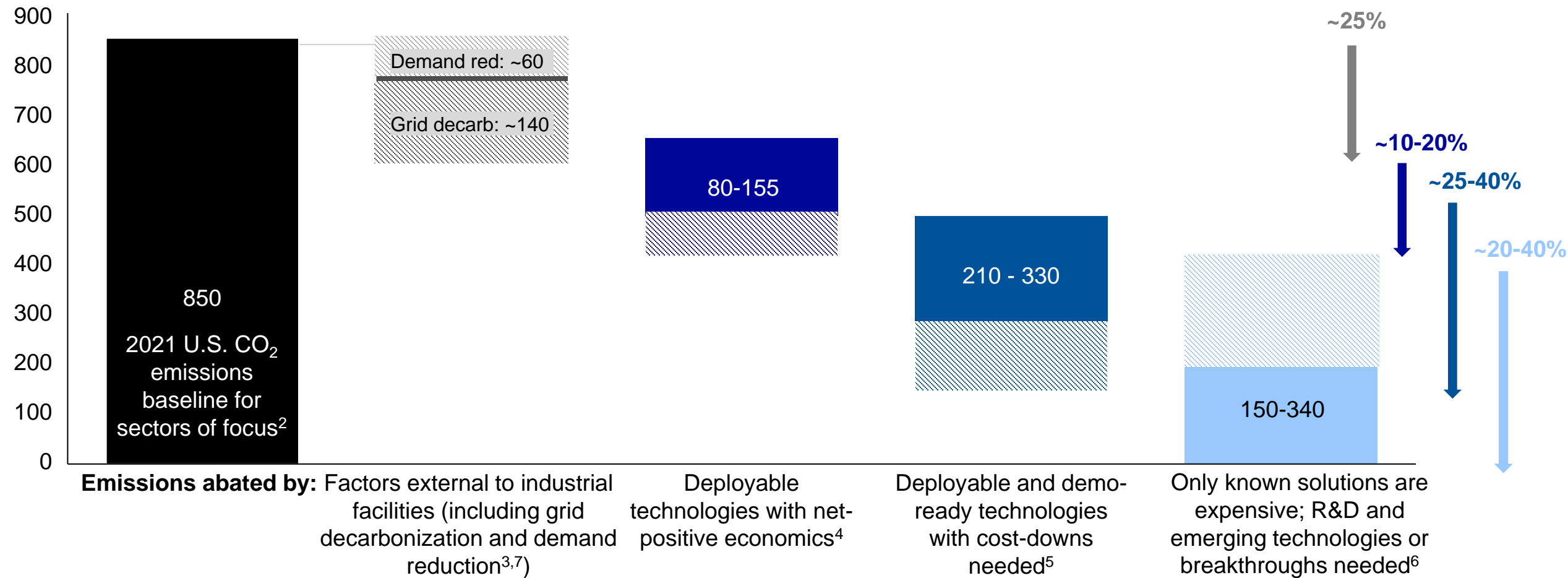
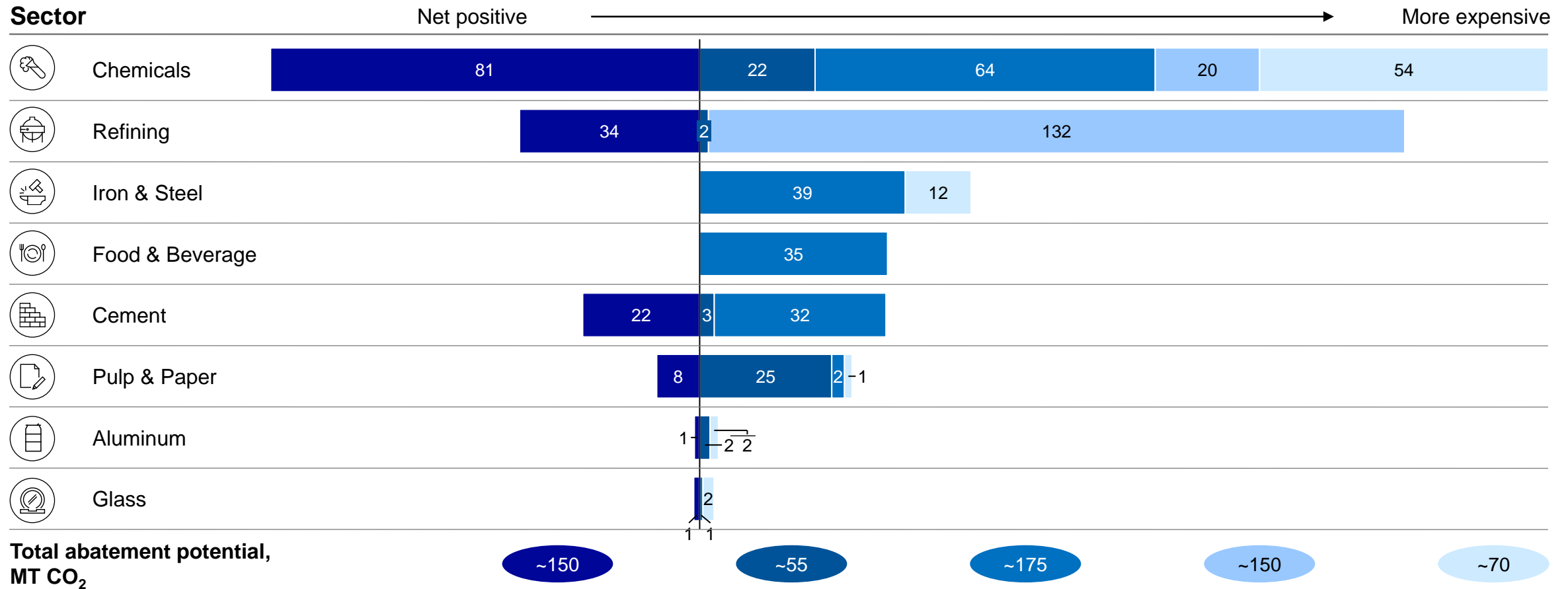


Figure 3.1: Industrial emissions abatement is split between external factors (i.e., grid decarbonization, transport sector electrification, and mechanical recycling), net-positive levers, and uneconomic levers (>\$0/t CO<sub>2</sub>e), with up to 40% of abatement achievable at- or below-cost | 1. Current ranges consider how abatement potential might evolve if abatement cost curve is higher or lower than anticipated. Abatement potential ranges are based on high and low scenarios for abatement cost. Ranges are not meant to represent a statistical accounting of confidence intervals but depict uncertainty in the range of cost estimates for decarbonization levers. | 2. Heat, electricity, and process emissions for industrial sectors included in IRA, excluding ceramics | 3. Emissions abated by external levers (e.g., grid decarbonization) | 4. Emissions abated by net-positive levers (< \$0/t) | 5. Emissions abated by levers approaching breakeven (\$0-\$100/t) | 6. Emissions abated by levers >\$100/t or that require further R&D | 7. Assumes Biden administration target of zero emissions from grid in 2035 and goals for transport decarbonization and EPA goals for recycling for this analytical exercise. Entire bar shaded to indicate uncertainty around factors external to industrial facilities  
Source: EIA data for energy-related emissions, EPA data for total U.S. emissions, IEDO Industrial Decarbonization Roadmap, Life Cycle Carbon Footprint Analysis of Pulp and Paper Grades in the United States using production-lined-based data and integration - Tomberlin et al (2020), White House Long-Term 2050 Roadmap

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

PRELIMINARY DRAFT

Estimated current abatement potential<sup>1</sup> grouped by economic impact (\$/tCO<sub>2</sub> including 45Q and 45V<sup>3</sup>), MT CO<sub>2</sub>



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

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

Note: Unabated emissions (~40 MT), external factors<sup>3</sup> (~200 MT), and abatement potential with costs \$250+ /tCO<sub>2</sub> (~5 MT) are not shown in this figure



# Agenda

- Industrial Decarbonization (“Cross-Cut”) Overview
- **Low-Carbon Cement Overview**

# 85% of emissions are from chemical process or industrial heat

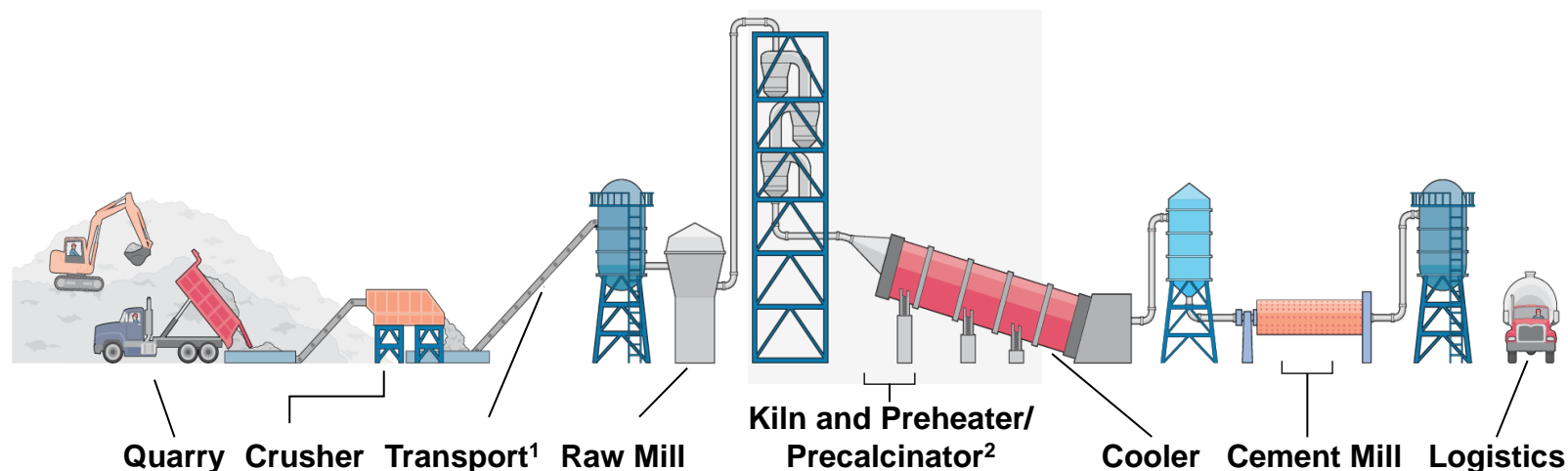
## Emissions in the cement production process

Industrial heat   Process   Electric power   Other

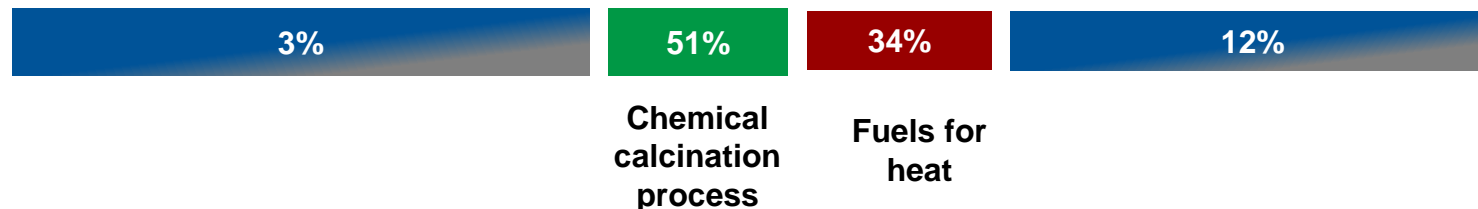
Raw materials, energy  
and resources

Clinker and cement manufacturing

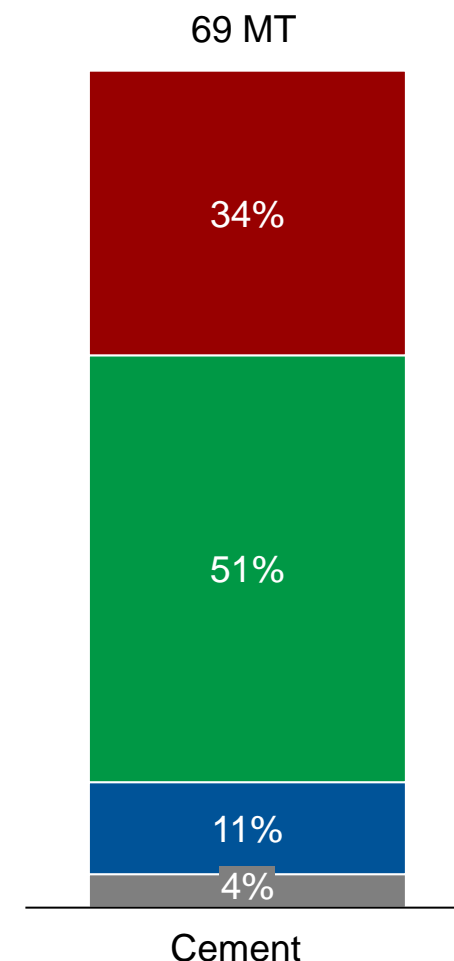
Transport and  
retail



CO<sub>2</sub>  
emissions,  
% of total



## Emissions breakdown<sup>6</sup>, CO<sub>2</sub>e



Notes: 1. U.S. EPA. (2021). Facility Level GHG Emissions Data from Large Facilities [Data set]. [https://ghgdata.epa.gov/ghgp/main.do?site\\_preference=normal](https://ghgdata.epa.gov/ghgp/main.do?site_preference=normal). Visual from Czigler, Thomas, et al. (2020, May). "Laying the foundation for zero-carbon cement." McKinsey & Company. [Laying the foundation for a zero-carbon cement industry | McKinsey](#).

# Range of technologies are emerging, but at different states of readiness

NON-EXHAUSTIVE // REPRESENTATIVE MIX OF TECHNOLOGIES // FIGURES INTENDED TO BE BROADLY REPRESENTATIVE, NOT REFLECTIVE OF ANY INDIVIDUAL COMPANY OR PROPRIETARY TECHNOLOGY

High costValue accretiveLowHigh

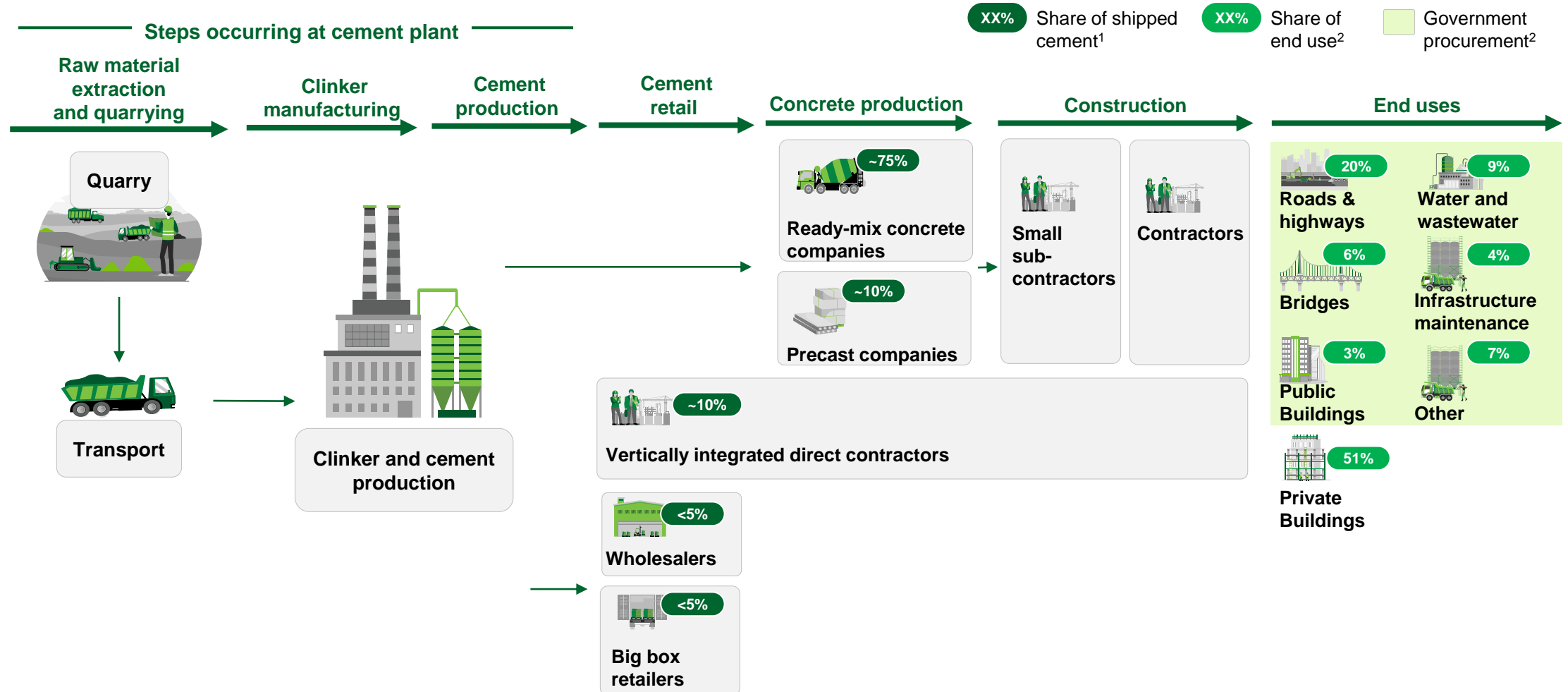
Emissions source	Representative approaches (not exhaustive)	Cost, \$/t CO2	Cost, \$/t cement	Unconstrained abatement potential, <sup>5</sup> (% to BAU)	ARL <sup>6</sup>	TRL <sup>6</sup>
Cross-cutting	Energy efficiency <sup>1</sup>	(35-40)	(0-5)	Up to 20%	5-9	9
	Portland limestone cement <sup>2</sup>	(75-80)	(5-10)	5-10%	7	7-9
	Fly ash blended cement <sup>2</sup>	(25-30)	(5-10)	30-50%	7	9
	Clinker substitution					
	Steel slag blended cement <sup>2</sup>	(15-20)	(5-10)	30-50%	7	9
	Natural pozzolans blended cement <sup>2</sup>	(70-75)	(15-20)	30-50%	2	7
	LC3 (Limestone Calcined Clay) blend <sup>2</sup>	(60-70)	(15-25)	30-50%	5	9
Heat	Alternative fuels					
	Biomass fuel <sup>3</sup>	30-35	0-5	1-8%	4	9
	Waste fuel <sup>3</sup>	(0-10)	(0-5)	1-4%	5	9
Process	Precalciner & kiln electrification	Emerging technologies		Up to 35%	1	5-6
	CCUS (with 45Q) <sup>4</sup>	35-75	25-55	85-99%	1	6-7.5
	Alternative production methods	Emerging technologies		25-100%	1	3-5
	Alternative binder chemistries			25-100%	1	3.5-9

**Note:** Approaches above are focused on primary production of cement. Additional approaches are available in downstream production of concrete (e.g., reduced cement consumption in concrete mixes, carbon curing of precast concrete products).

Notes: 1. A range of efficiency measures are available, but they are at different ARL and TRL today. Costs are estimated for measures that are deployable today, with more limited abatement potential. | 2. Clinker substitution economics estimated using blended cement composition ratios provided in Appendix A. | 3. Fuel abatement potential and economics estimated using fuel mixes and feedstock cost benchmarks provided in Appendix A. | 4. CCUS costs estimated using methodology discussed in Appendix B. Costs reported here are for CCS specifically and include \$85/tonne 45Q tax credit. | 5. Unconstrained abatement potential is for a given tonne of cement produced, not estimated for the entire cement sector. It is estimated for each approach in isolation (i.e., not tied to a specific decarbonization pathway or sequence of approaches). | 6. ARL and TRL figures are representative estimates based on DOE and expert input. They do not reflect an assessment of any specific individual company or proprietary technology and should not be interpreted as such.

# Government procurement drives ~50% of the market, but fragmented value chain attenuates demand signal

## Cement production in the construction value chain







1. The share of shipped cement is estimated based on data from the Portland Cement Association's Survey of Portland Cement Consumption by User Group (2022). | 2. End-use share is estimated based on an analysis of data from the Portland Cement Association's U.S. Cement Industry Annual Yearbook (2022) by Breakthrough Energy Ventures.

# Liftoff of technologies could follow four 'tracks'

## Technology 'track'

(examples illustrative, not exhaustive)

	Pathway to commercial liftoff	Capital formation required by 2050	Abatement potential by 2050
<b>A Currently deployable measures</b> <ul style="list-style-type: none"> <li>Clinker substitution</li> <li>Energy efficiency</li> <li>Alternative fuels</li> </ul>	 <p><b>Rapid deployment</b>, incentivized by demand signal from large buyers and enabled by accelerated validation of low-carbon blends</p>	~\$5-10B	~30-40%
<b>B CCUS</b> <ul style="list-style-type: none"> <li>CCUS retrofits and integration into new-build plants</li> </ul>	 <p><b>Initial ~3-5 demonstrations</b> enabled by 45Q and government support</p> <p><b>Accelerated buildout of CCS</b>, enabled by 45Q, cost reductions, and coordinated procurement to create investable demand signal</p>		
<b>C Alternative production methods</b> (compatible with existing standards) <ul style="list-style-type: none"> <li>Alternative feedstocks</li> <li>Alternatives to rotary kiln production</li> </ul>	 <p><b>Initial ~3-5 greenfield demonstration plants</b> enabled by government support</p> <p><b>Accelerated buildout of greenfield plants</b>, enabled by cost reductions and coordinated procurement to create investable demand signal</p>	~\$55-110B	~60-70%
<b>D Alternative binder chemistries</b> (need updated standards) <ul style="list-style-type: none"> <li>Alternative chemistries to traditional clinkers</li> </ul>	 <p><b>Initial market share</b> in non-structural niches</p> <p><b>Standards updated</b> and <b>consumers educated</b> to enable wider deployment</p> <p><b>Supply chain expands</b> to meet growing demand</p> <p><b>Liftoff achieved</b> in broader market</p> <p>Potential to <b>pull forward timeline</b> with expanded use of <b>performance-based standards</b></p>		
<b>Applied R&amp;D opportunities on emerging technologies</b> (not in focus for this report) <ul style="list-style-type: none"> <li>Earlier-stage novel SCMs and binders</li> <li>Higher-hydrogen fuel blends and electrification</li> <li>Alternative CCUS approaches</li> </ul>	<p><b>Ongoing R&amp;D investment to support rollout of key technologies</b> (e.g., novel carbon capture approaches on dilute streams, other novel materials for clinker substitution, improved plant efficiency measures)</p> <p><b>Long-term R&amp;D investment in 'next horizon' technologies</b> (e.g., electrification of kiln and precalciner, &gt;20% hydrogen fuel blends)</p>		

Timeline

2023

2030

2040

2050

*Emerging technologies, details less clear*

# Appendix



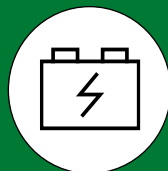
# Based on DOE's Industrial Decarbonization Roadmap and prior Liftoff Reports, we identified nine decarbonization levers for focus

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

Energy  
Efficiency



Industrial  
Electrification



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



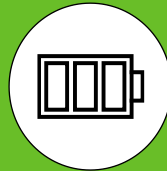
Electrolytic  
Hydrogen



Raw Material  
Substitution



Alternative  
Fuel – Non-H2

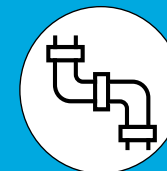


Clean onsite  
electricity +  
storage

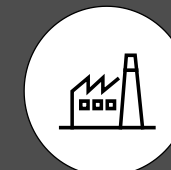


Alternative  
production  
methods

Carbon Capture, Utilization,  
and Storage (CCUS)



Grid Decarbonization and  
other external factors



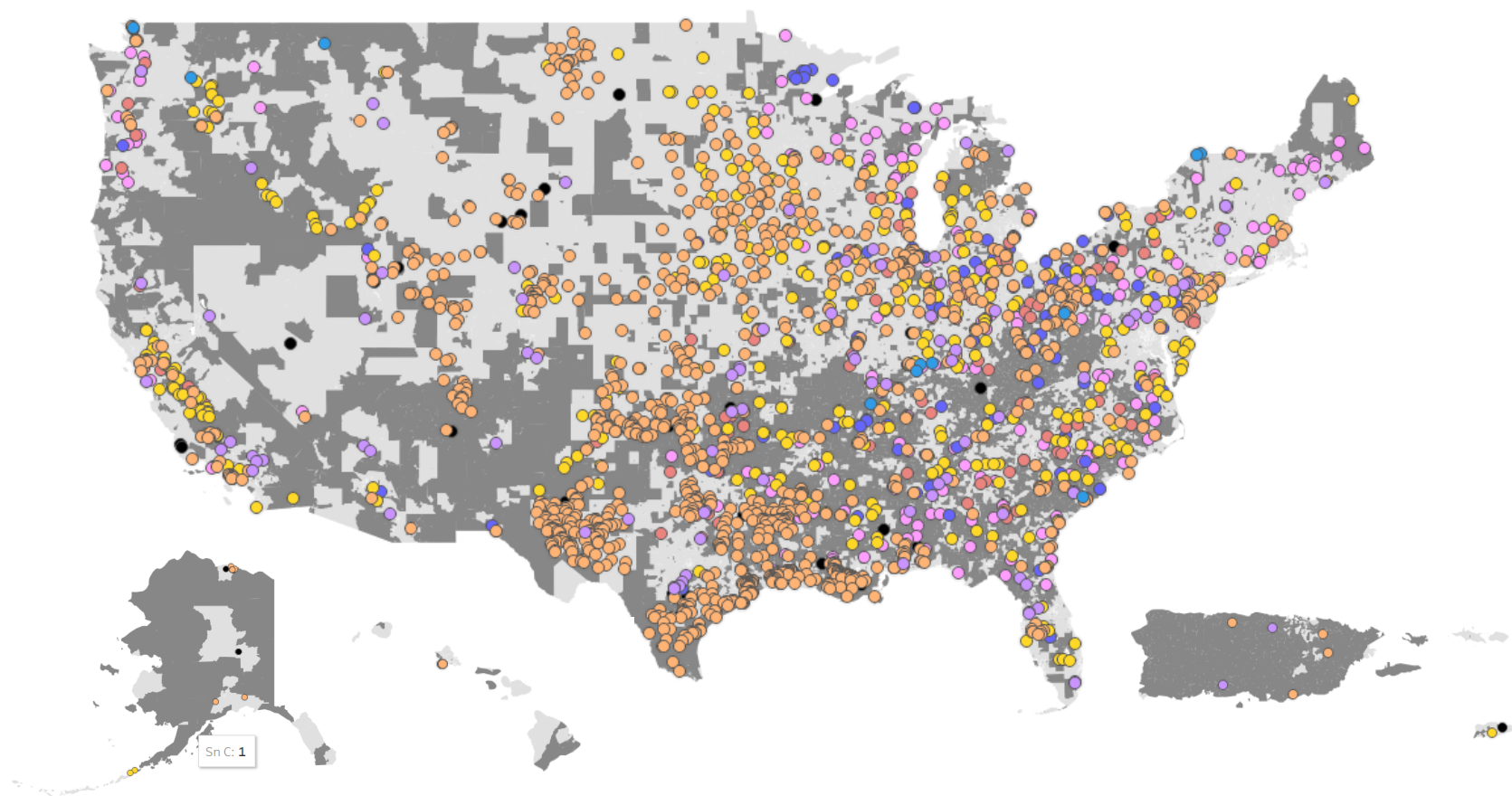
## Key



Technologies also discussed in  
prior Liftoff reports from DOE

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

Map of select U.S. point source CO<sub>2</sub> emissions and US Disadvantaged Communities, 2021<sup>1</sup>



## 2,500+

Industrial facilities  
in sectors of focus<sup>1</sup>

## 1,145+

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

Notes: 1. Includes natural gas processing, refineries, chemicals production (various), food processing, cement production, glass production, lime manufacturing, aluminum production, iron & steel production, pulp and paper manufacturers, and other paper products. EPA FLIGHT data only records GHG emissions from facilities with reported emissions or quantity of GHG emissions > 25,000 MT CO<sub>2</sub>e/year and does not include emissions from land use, land use change, or forestry

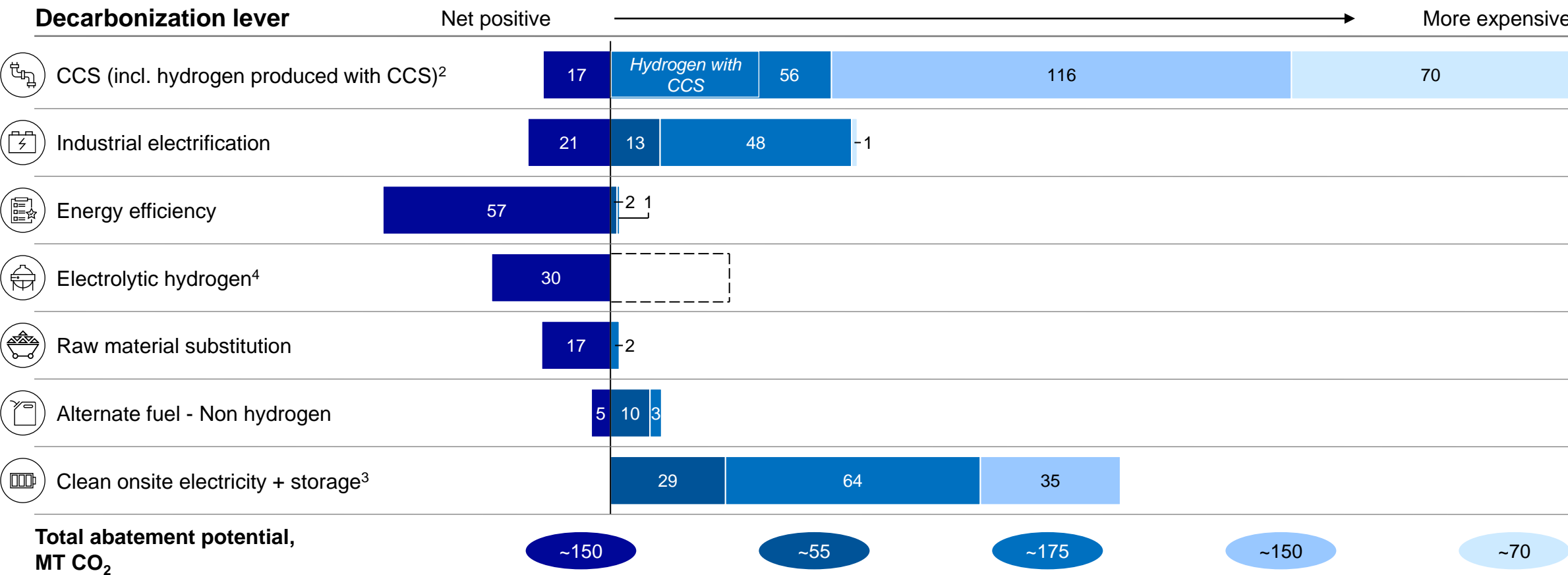
Source: EPA Flight, Climate and Economic Justice Screening Tool (CEJST)

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

PRELIMINARY DRAFT

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

Estimated current abatement potential<sup>1</sup> grouped by economic impact (\$/tCO<sub>2</sub> including 45Q and 45V<sup>6</sup>), MT CO<sub>2</sub>



Note: Unabated emissions (~40 MT), external factors<sup>5</sup> (~200 MT), and abatement potential with costs \$250+ /tCO<sub>2</sub> (~5 MT) are not shown in this figure

1. Based on 2021 emissions baseline for all industries except for Chemicals, Refining, and Cement where emissions were projected through 2050. All costs represented here took the midpoint of cost ranges | 2. Costs estimated after applying levelized 45Q tax incentive from the Inflation Reduction Act; includes 41MT of emissions abated with hydrogen produced with CCS (2030 Hydrogen with CCS costs range from x-X) | 3. Includes costs associated with heating equipment for steam generation | 4. Costs estimated after applying 45V tax incentives from the Inflation Reduction Act for hydrogen production via electrolysis. Cost estimates for 2030 range from \$2.02-3.02/kg H<sub>2</sub> including capital expenditure, operating expenditures and transport and storage costs. Overall electrolytic hydrogen costs are uncertain – assumptions based on current policy guidance and commercial cost estimates as of June 2023 and could change as more data emerges. Estimated abatement by clean hydrogen in line with Hydrogen Roadmap estimates for 2030 ammonia and refining use cases. | 5. Factors include grid decarbonization, transport sector electrification, and mechanical recycling | 6. Cost based on estimated 2030 prices for decarbonization levers. 45Q and 45V are not stacked in this analysis. Source: Industrials sector integrated MACC, DOE Chemicals & Refining Decarbonization Pathway

## 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.
-  **Industrial decarbonization affects 2,500+ communities** with coordination from the private sector, labor unions, and communities could be an opportunity for environmental justice.
-  **Up to 40% of studied emissions could be abated with existing net-positive decarbonization levers or external factors** (e.g., grid decarbonization) when IRA incentives are included.
-  **Facility planning for decarbonization** to leverage available downtime to rapidly implement net-positive levers, significantly expand enabling infrastructure, and achieve cost-downs through scale.
-  **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.
-  **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.
-  **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 could be required to decarbonize with additional funding for ongoing R&D/pilots.

# 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**



**Limited Technologies**



**Resource Maturity**



**Market Acceptance**



**License to Operate**



**Additional sector-specific challenges**

...However, this narrative is changing including:

NOT EXHAUSTIVE

## Public sector support in BIL<sup>1</sup>, IRA<sup>1</sup>, and more:

- OCED's ~\$6.3B for industrial decarbonization demonstration-to-deployment FOA
- 48C Advanced Manufacturing Tax Credit
- R&D and transformative solutions (e.g., Energy Earthshots)


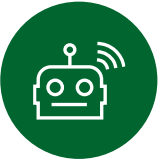



## Customers expect companies to address emissions:

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



# 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

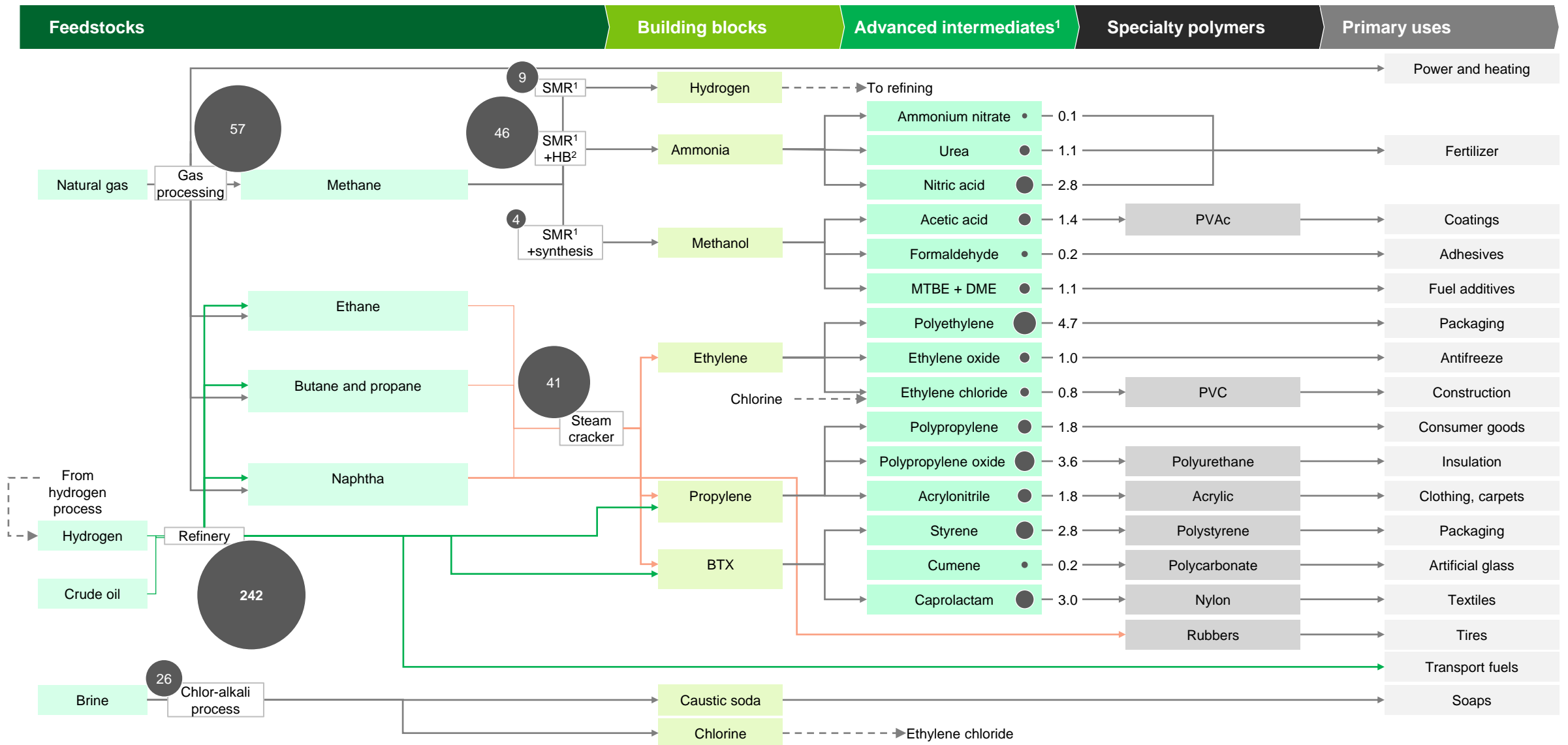
**Unlock decarbonized high-temperature heat** and **set a precedential roadmap** for other heat-intensive industrial processes



Product



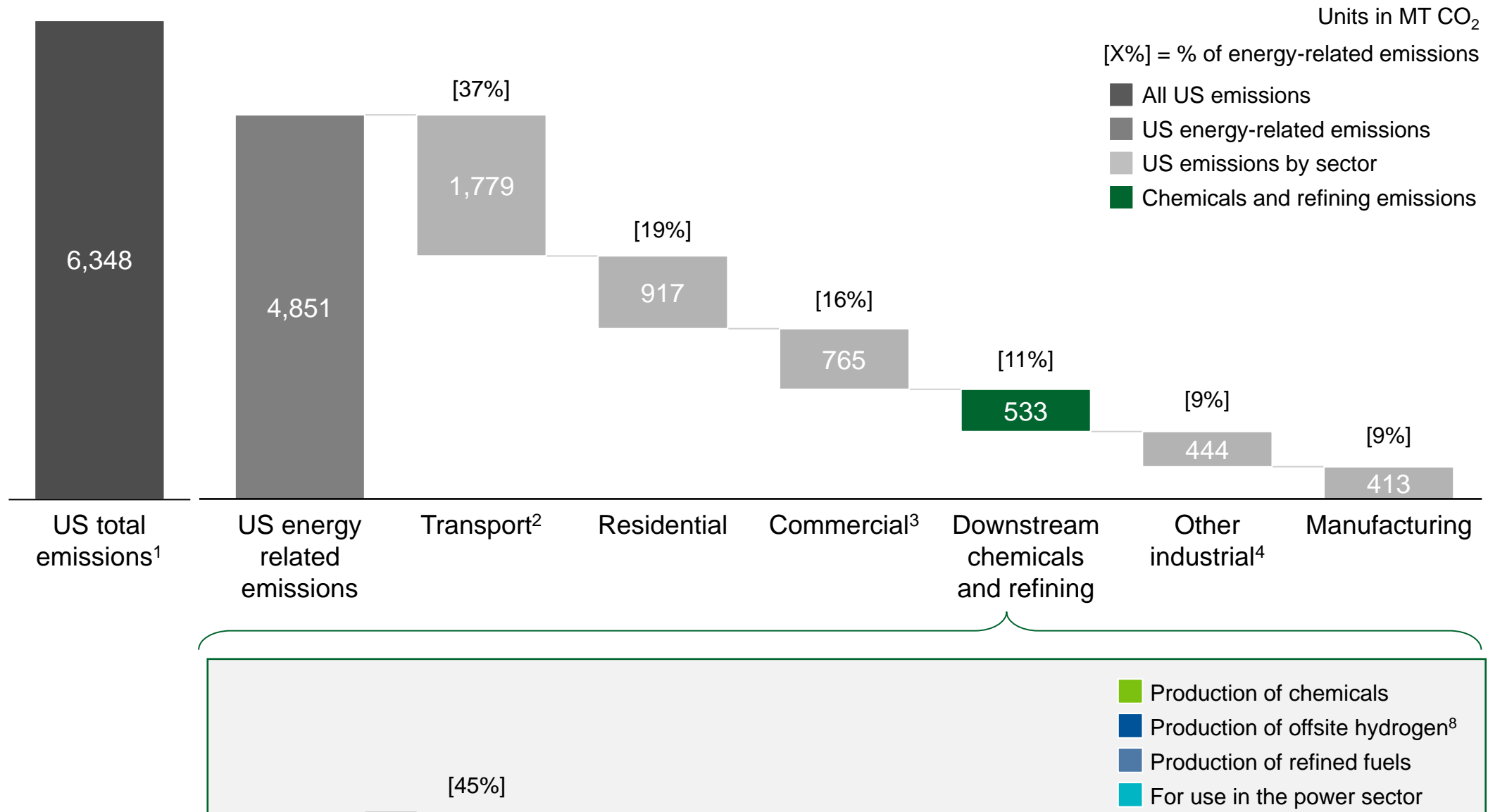
Process

US emissions, 2022, MTCO<sub>2</sub>e

Sources: S&P, Process Economics Program (2023), Opis a Dow Jones Company, Chemical Market Analytics (2023), Solomon, S., et al. "IPCC fourth assessment report (AR4)." *Climate change* 374 (2007), Hajny, Salmon et. Al, (2019), Observations of Methane Emissions from Natural Gas-Fired Power Plants, *Environmental Science & Technology* 2019 53 (15), 8976-8984, DOI: 10.1021/acs.est.9b01875

1. Emissions associated with advanced intermediates represents production process emissions and not material use emissions

# US total CO<sub>2</sub>e and energy-related CO<sub>2</sub> emissions by end-use sector in 2021, MT CO<sub>2</sub>



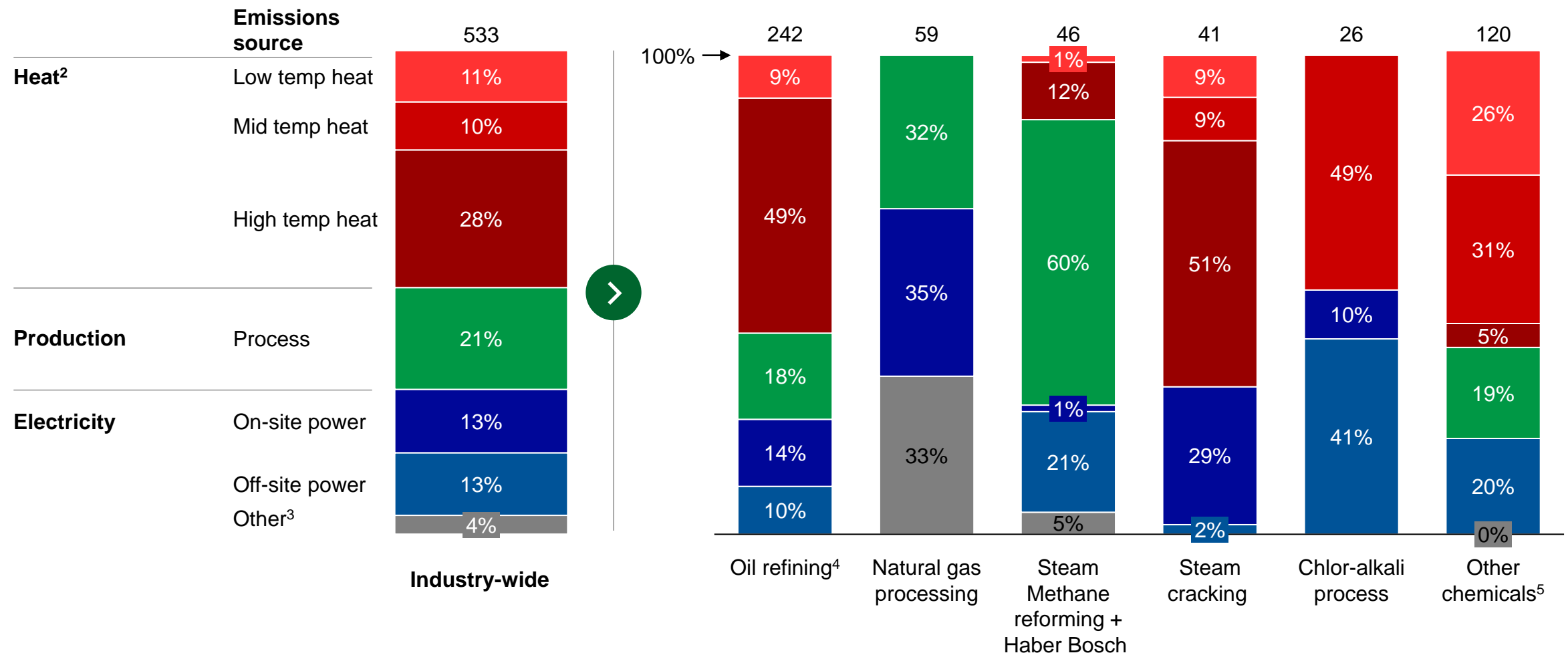
# Agenda

- Industrial Decarbonization (“Cross-Cut”) - Overview
- **Decarbonizing Chemicals & Refining - Overview**
- Low-Carbon Cement – Overview

## Key Messages for Decarbonizing Chemicals & Refining

- 1 Five major sub-sectors drive 80% of emissions in chemicals and refining.
- 2 Heat decarbonization and clean firm power are the “long poles in the tent.”
- 3 Most pathways to net zero for industrial sectors rely on external industries and technologies to significantly progress, including clean hydrogen and CCS.
- 4 Today through 2030, there is a ~\$90-120B investment opportunity in decarbonization levers with >10% IRR, and an additional investment of ~\$610-730B needed between 2030 to 2050.
- 5 Of the seven major challenges to decarbonize, a revenue gap leading to low IRRs for major measures is the most pervasive. Even by 2050, ~80% of measures making up the pathway to net zero add cost and either consumer willingness to pay or other support on the order of ~\$100/tCO<sub>2</sub> are needed.
- 6 Seven sets of solutions can help unlock industrial decarbonization. Solving the cost gap to attract capital will be the most challenging.

## Emissions breakdown from chemicals and refining industry in 2020,<sup>1</sup> MT CO<sub>2</sub>



1. Includes Scope 1 and Scope 2 for refiners and chemicals producers only

2. 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

3. Includes electrochemical processes, refrigeration, and cooling for ethylene / propylene; cooling, heat loss for ammonia, and fugitives or leakage emissions from NG processing

4. Based on EERE combustion breakdown for on-site / off-site power generation and process heat

5. E.g., production of urea, formaldehyde, polyethylene, polypropylene, styrene, ethylene dichloride

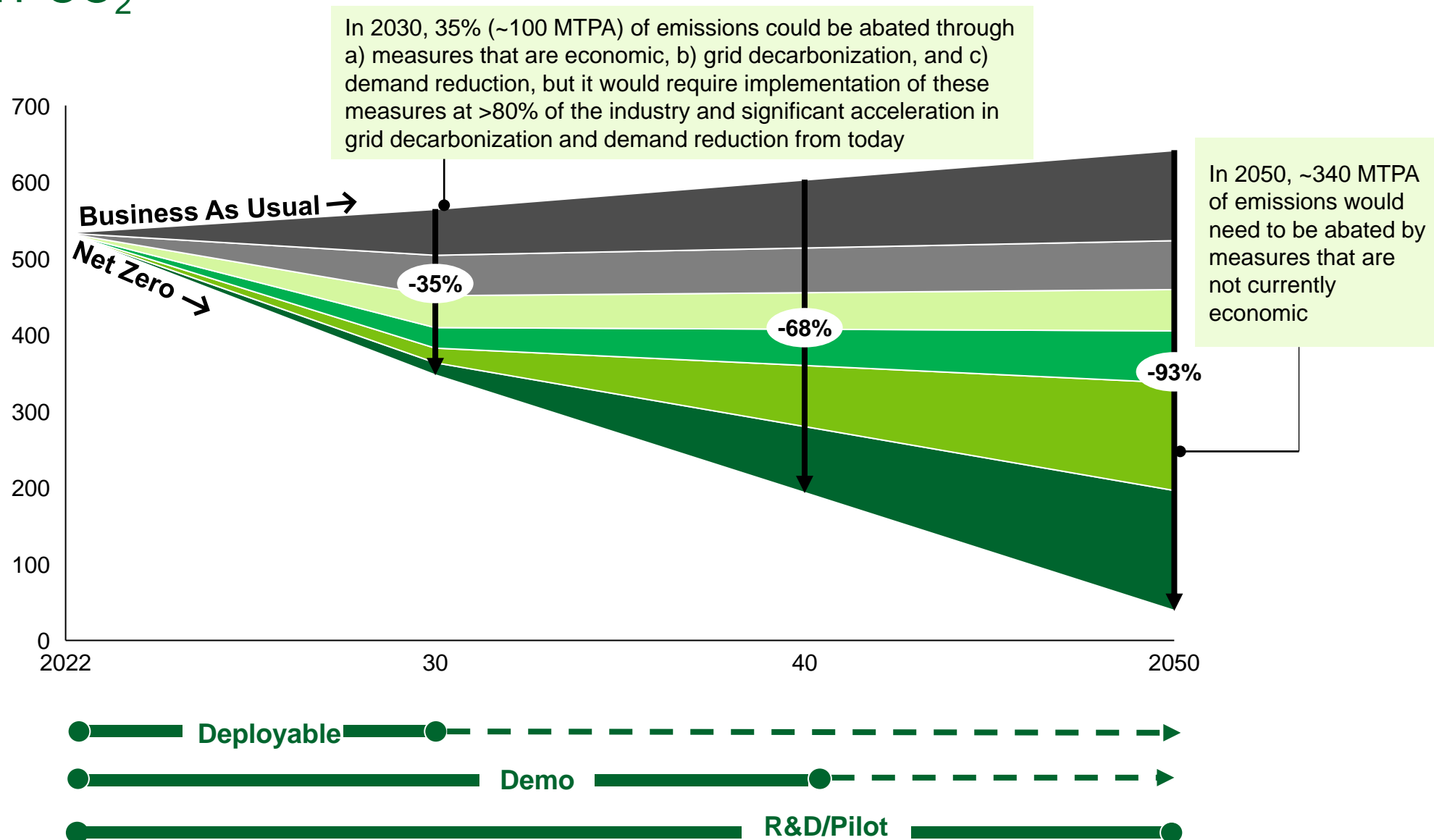
Source: 2018 EPA Flight, 2018 EERE Manufacturing Energy and Carbon Footprints report, 2022 IEDO Report, Energy Environ. Sci., 2020,13, 331-344, EIA, 2020 USGS, DOE Natural Gas Supply Chain report.



# Chemical and refining production emissions under BAU and net zero scenarios<sup>1</sup>, MT CO<sub>2</sub>

## Key decarbonization levers<sup>2</sup>

- Demand reduction
- Grid decarbonization
- Efficiency
- Clean hydrogen
- Electrification with clean High-capacity firm power
- CCS<sup>3</sup>



1. Deployable bio-processes that reduce lifecycle emissions of chemicals and refining products are not considered in the pathway to net zero | 2. Technologies considered in pathway are in the deployable and demo categories. Pathways may be updated with different developed technologies in future. | 3. Only CCS is considered in the net zero pathway, refer to Carbon Management Liftoff report for discussion of carbon utilization technologies

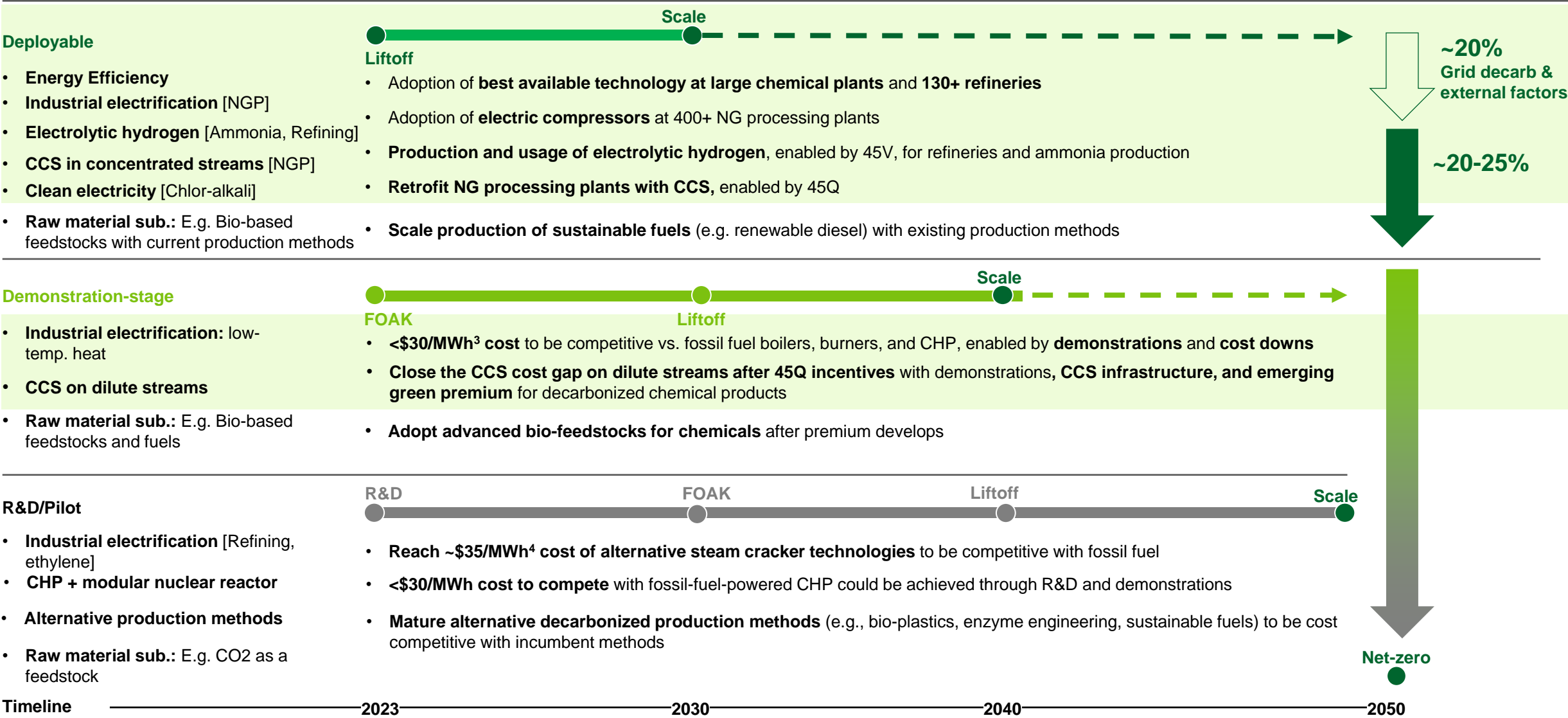
# Pathway to Commercial Liftoff: Chemicals & Refining

ILLUSTRATIVE NOT EXHAUSTIVE  
Technology examples

Pathway to commercial liftoff – Priority decarbonization actions<sup>2</sup>

Estimated emission abatement<sup>1</sup>

Technology included in least-cost net-zero pathway



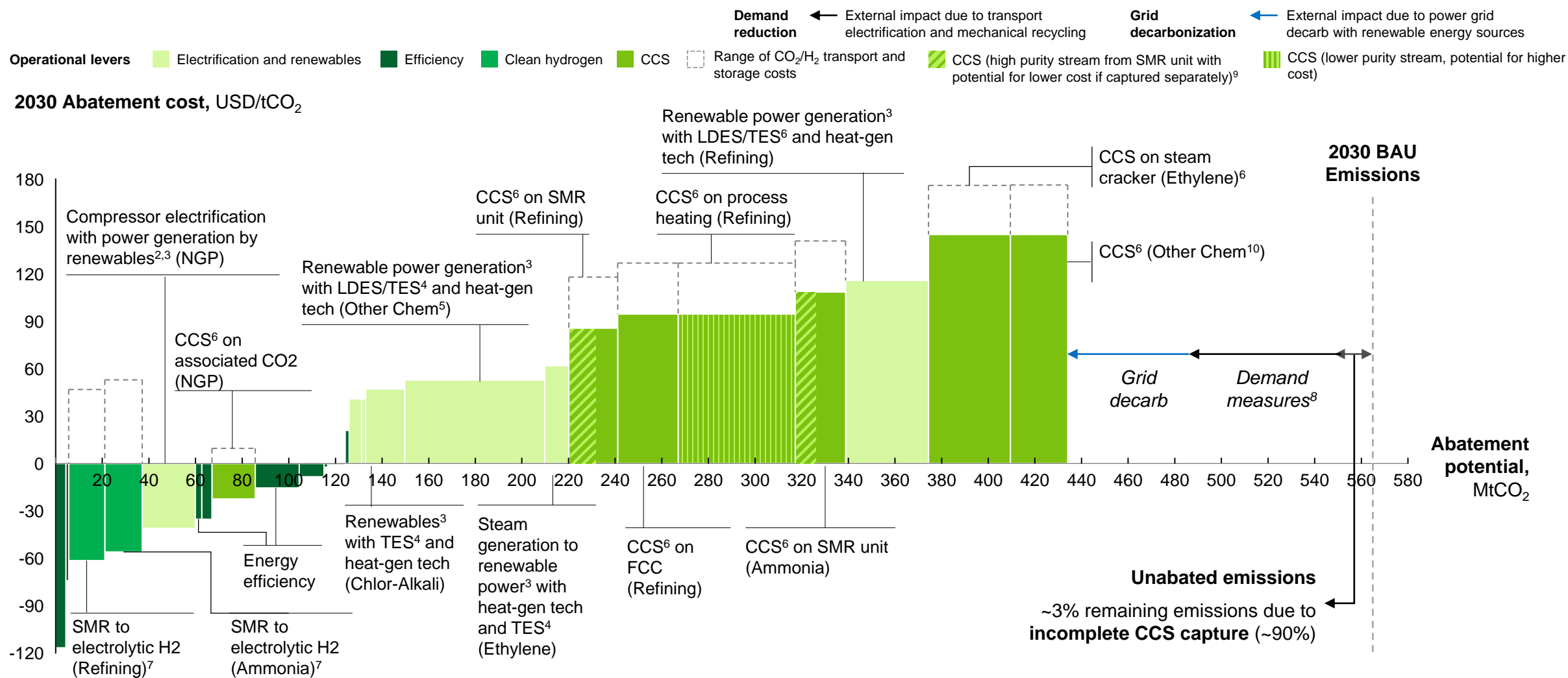
1. Abatement share ranges are constrained and based on alternative decarbonization pathways, varying on factors such as the emergence of alternative production methods and chemistries

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

3. Estimated as breakeven point on the MACC levelized cost of heat to reach \$0/tCO<sub>2</sub> abatement cost for refining CHP

4. Estimated as breakeven point on the MACC levelized cost of heat to reach \$0/tCO<sub>2</sub>e abatement cost for ethylene steam cracking furnace

## 2030 Marginal Abatement Cost Curve (MACC) for US Chemicals and Refining industry, with IRA<sup>1</sup>



- Heat 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.
- Electrification of compressor results in significant efficiency improvements over steam turbines (95% vs. 35% efficiency)
- 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

## Key messages of the Chemicals & Refining Report

- 1 Five major sub-sectors drive 80% of emissions in chemicals and refining.** Oil refining, natural gas processing, ammonia production, steam cracking for plastics and chemicals, and chlorine production drive emissions. A long tail of hundreds of other processes make up the remaining ~20% of emissions
- 2 Heat decarbonization and clean firm power are the “long poles in the tent.”** Together, heat to run chemical processes and power contribute ~75% of emissions
- 3 Most pathways to net zero for industrial sectors rely on external industries and technologies to significantly progress, including clean hydrogen and CCS.** The decarbonization of downstream chemicals and refining relies on these measures to achieve net zero by 2050, requiring that they abate ~225 MTPA of CO<sub>2</sub> by 2050 (~68 MTPA abated through clean hydrogen and ~157 MTPA abated through CCS), creating risks to the pathway if these solutions are not scaled quickly.
- 4 Today through 2030, there is a ~\$90-120B investment opportunity in decarbonization levers with >10% IRR,** and an additional investment of ~\$610-730B needed between 2030 to 2050. Clean H<sub>2</sub>, CCS on high-purity CO<sub>2</sub> streams, energy efficiency, and electrification of natural gas compressors could reduce chemicals and refining emissions by 35% when combined with grid and transport decarbonization, but full implementation is required
- 5 Of the seven major challenges to decarbonize, a revenue gap leading to low IRRs for major measures is the most pervasive.** Even by 2050, ~80% of measures making up the pathway to net zero add cost and either consumer willingness to pay or other support on the order of ~\$100/tCO<sub>2</sub> are needed
- 6 Seven sets of solutions can help unlock industrial decarbonization - Solving the cost gap to attract capital will be the most challenging.** This will require measures that improve willingness-to-pay on the demand side, low-cost renewable or nuclear power with transmission connecting to load centers, low-cost long duration heat storage, and potentially alternative technologies to make ‘synthetic’ fuels and chemicals to supply demand growth