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**

Feedback is eagerly welcomed via **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

Other Wave 2 topic:

- 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

In-scope | Out-of-scope

PRELIMINARY | ILLUSTRATIVE | TRANSPORTATION EMISSIONS NOT STUDIED

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

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&D / Pilot | Limited relevance for sector decarbonization (blank)

Industrial Sector

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

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

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

Emissions abatement potential by 2030 by decarbonization lever costs (incremental to IRA incentives)[1]
MT CO_2

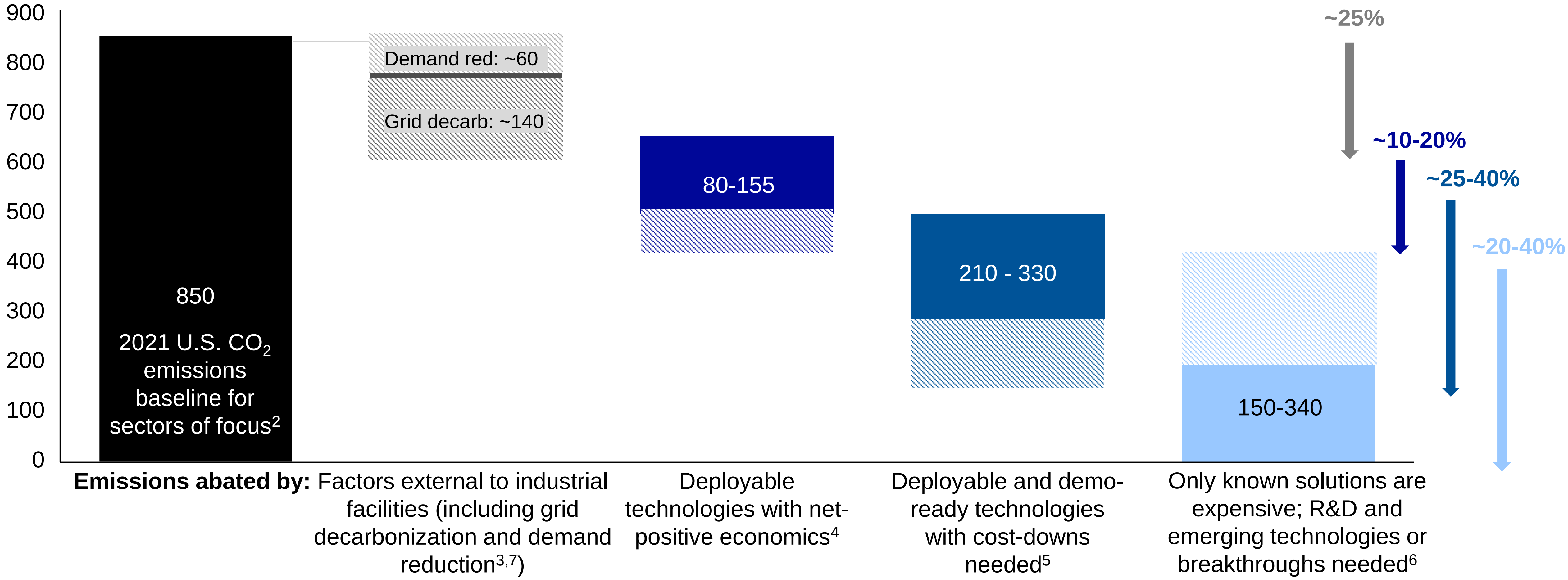


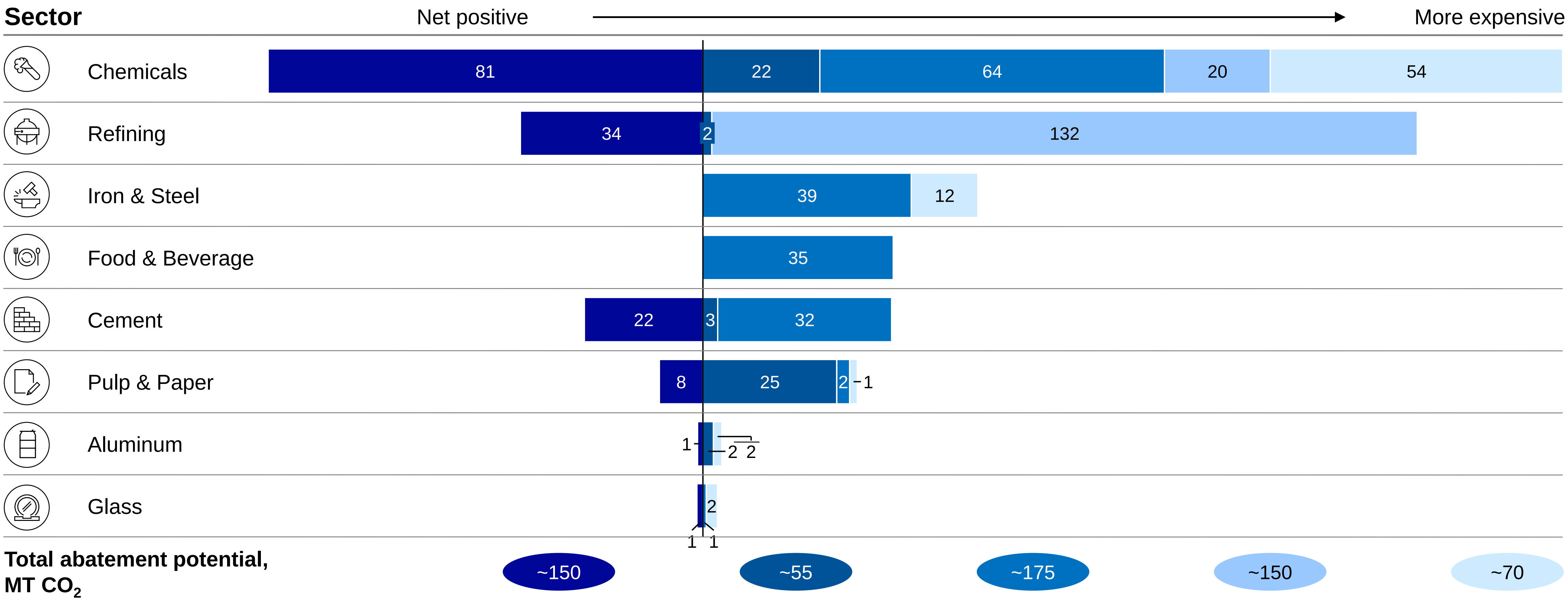
Figure 3.1: Industrial emissions abatement is split between external factors (i.e., grid decarbonization, transport sector electrification, and mechanical recycling), net-positive levers, and uneconomic levers (>$0/t CO2e), with up to 40% of abatement achievable at- or below-cost | 1. Current ranges consider how abatement potential might evolve if abatement cost curve is higher or lower than anticipated. Abatement potential ranges are based on high and low scenarios for abatement cost. Ranges are not meant to represent a statistical accounting of confidence intervals but depict uncertainty in the range of cost estimates for decarbonization levers. | 2. Heat, electricity, and process emissions for industrial sectors included in IRA, excluding ceramics | 3. Emissions abated by external levers (e.g., grid decarbonization) | 4. Emissions abated by net-positive levers (< $0/t) | 5. Emissions abated by levers approaching breakeven ($0-$100/t) | 6. Emissions abated by levers >$100/t or that require further R&D | 7. Assumes Biden administration target of zero emissions from grid in 2035 and goals for transport decarbonization and EPA goals for recycling for this analytical exercise. Entire bar shaded to indicate uncertainty around factors external to industrial facilities
Source: EIA data for energy-related emissions, EPA data for total U.S. emissions, IEDO Industrial Decarbonization Roadmap, Life Cycle Carbon Footprint Analysis of Pulp and Paper Grades in the United States using production-lined-based data and integration - Tomberlin et al (2020), White House Long-Term 2050 Roadmap

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

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

PRELIMINARY **DRAFT**

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



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

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

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

Agenda

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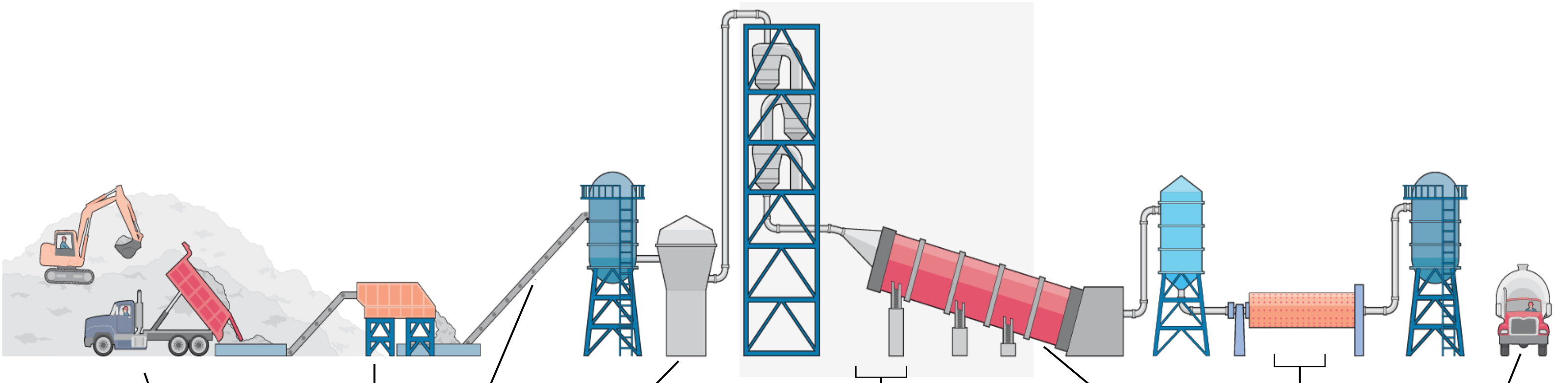
- **Low-Carbon Cement Overview**

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** →



Quarry | **Crusher** | **Transport[1]** | **Raw Mill** | **Kiln and Preheater/ Precalcinator[2]** | **Cooler** | **Cement Mill** | **Logistics**

CO2 emissions, % of total

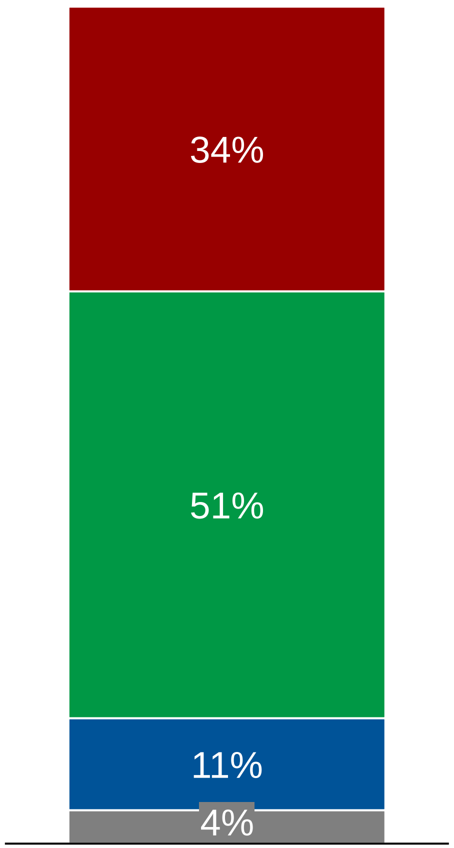
3% | **51%** | **34%** | **12%**

Chemical calcination process

Fuels for heat

Emissions breakdown[6], CO_2e

69 MT



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. 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 cost — Value accretive   Low — High

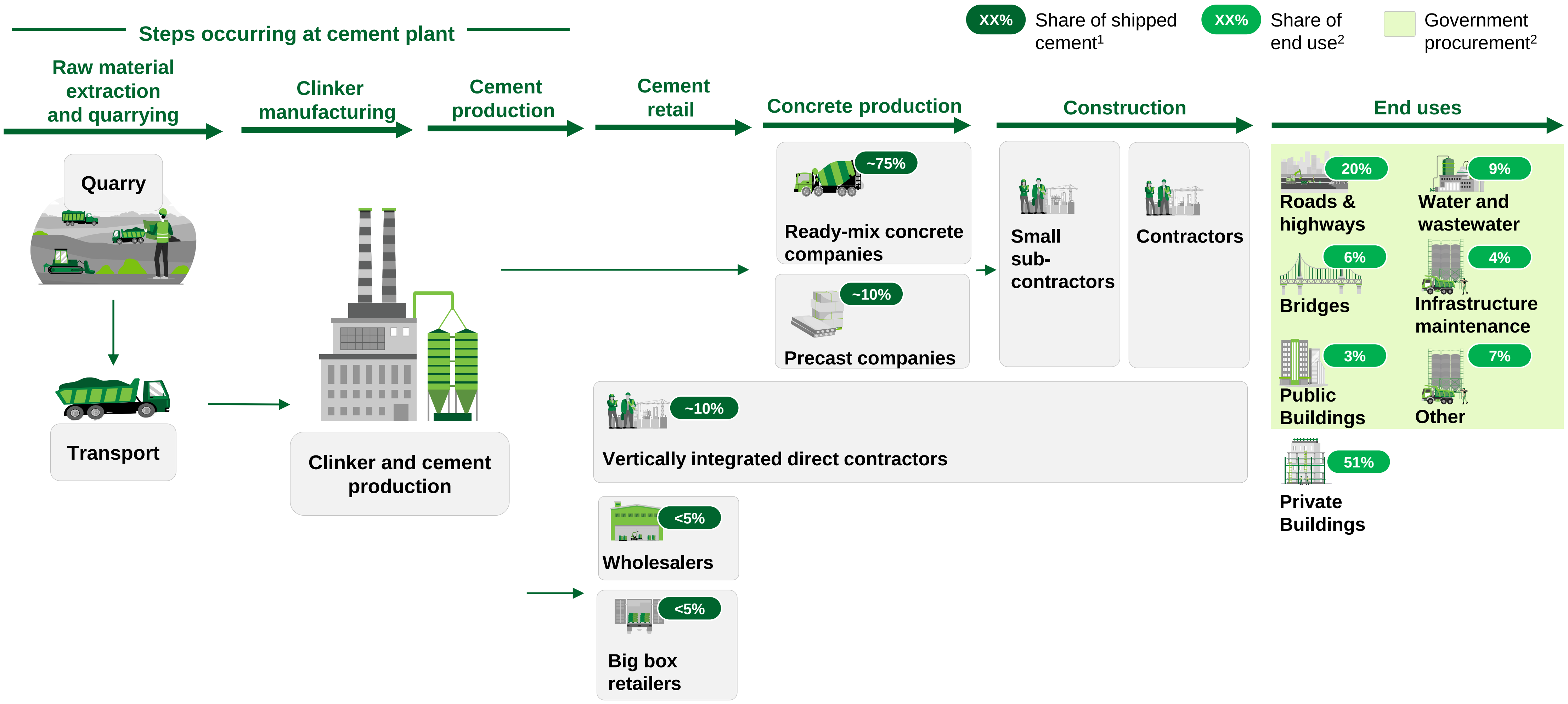
Emissions source	Representative approaches (not exhaustive)		Cost, $/t CO2	Cost, $/t cement	Unconstrained abatement potential,[5] (% to BAU)	ARL[6]	TRL[6]
Cross-cutting	Energy efficiency[1]		(35-40)	(0-5)	Up to 20%	5-9	9
Cross-cutting	Clinker substitution	Portland limestone cement[2]	(75-80)	(5-10)	5-10%	7	7-9
Cross-cutting	Clinker substitution	Fly ash blended cement[2]	(25-30)	(5-10)	30-50%	7	9
Cross-cutting	Clinker substitution	Steel slag blended cement[2]	(15-20)	(5-10)	30-50%	7	9
Cross-cutting	Clinker substitution	Natural pozzolans blended cement[2]	(70-75)	(15-20)	30-50%	2	7
Cross-cutting	Clinker substitution	LC3 (Limestone Calcined Clay) blend[2]	(60-70)	(15-25)	30-50%	5	9
Heat	Alternative fuels	Biomass fuel[3]	30-35	0-5	1-8%	4	9
Heat	Alternative fuels	Waste fuel[3]	(0-10)	(0-5)	1-4%	5	9
Heat	Precalciner & kiln electrification		*Emerging technologies*		Up to 35%	1	5-6
Process	CCUS (with 45Q)[4]		35-75	25-55	85-99%	1	6-7.5
Process	Alternative production methods		*Emerging technologies*		25-100%	1	3-5
Process	Alternative binder chemistries		*Emerging technologies*		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
A Currently deployable measures	• Clinker substitution • Energy efficiency • Alternative fuels	Liftoff **Rapid deployment,** incentivized by demand signal from large buyers and enabled by accelerated validation of low-carbon blends	~$5-10B	~30-40%
B CCUS	• CCUS retrofits and integration into new-build plants	**Initial ~3-5 demonstrations** enabled by 45Q and government support Liftoff **Accelerated buildout of CCS**, enabled by 45Q, cost reductions, and coordinated procurement to create investable demand signal	~$55-110B	~60-70%
C Alternative production methods (compatible with existing standards)	• Alternative feedstocks • Alternatives to rotary kiln production	**Initial ~3-5 greenfield demonstration plants** enabled by government support Liftoff **Accelerated buildout of greenfield plants,** enabled by cost reductions and coordinated procurement to create investable demand signal		
D Alternative binder chemistries (need updated standards)	• Alternative chemistries to traditional clinkers	**Initial market share** in non-structural niches **Standards updated** and **consumers educated** to enable wider deployment **Supply chain expands** to meet growing demand **Liftoff achieved** in broader market Liftoff Potential to **pull forward timeline** with expanded use of **performance-based standards**	*Emerging technologies, details less clear*	
Applied R&D opportunities on emerging technologies (not in focus for this report)	• Earlier-stage novel SCMs and binders • Higher-hydrogen fuel blends and electrification • Alternative CCUS approaches	**Ongoing R&D investment to support rollout of key technologies** (e.g., novel carbon capture approaches on dilute streams, other novel materials for clinker substitution, improved plant efficiency measures) **Long-term R&D investment in 'next horizon' technologies** (e.g., electrification of kiln and precalciner, >20% hydrogen fuel blends)		

Timeline

2023 — 2030 — 2040 — 2050

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)**

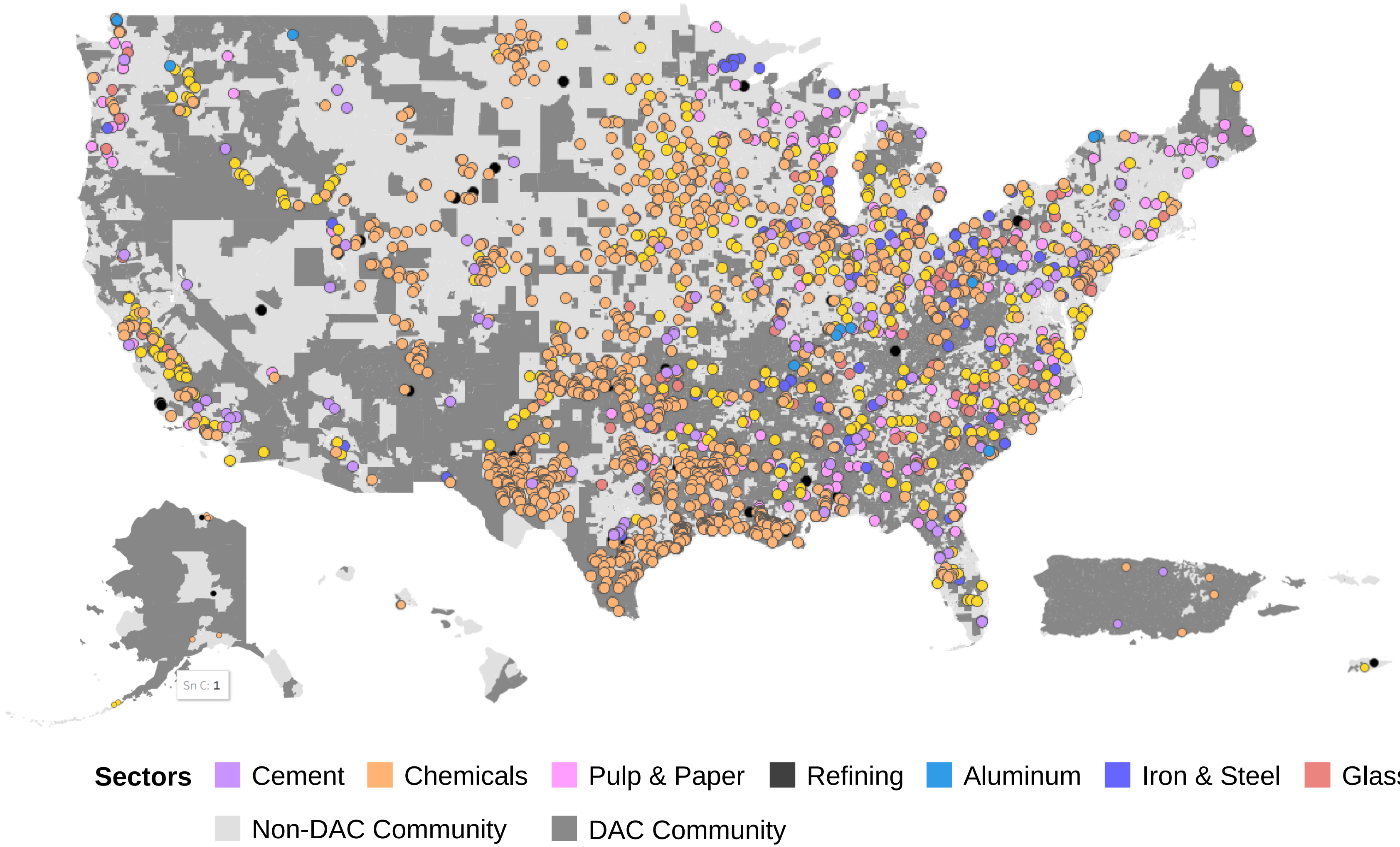
Grid Decarbonization and other external factors

Key
Technologies also discussed in prior Liftoff reports from DOE

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

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

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



2,500+

Industrial facilities in sectors of focus[1]

1,145+

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

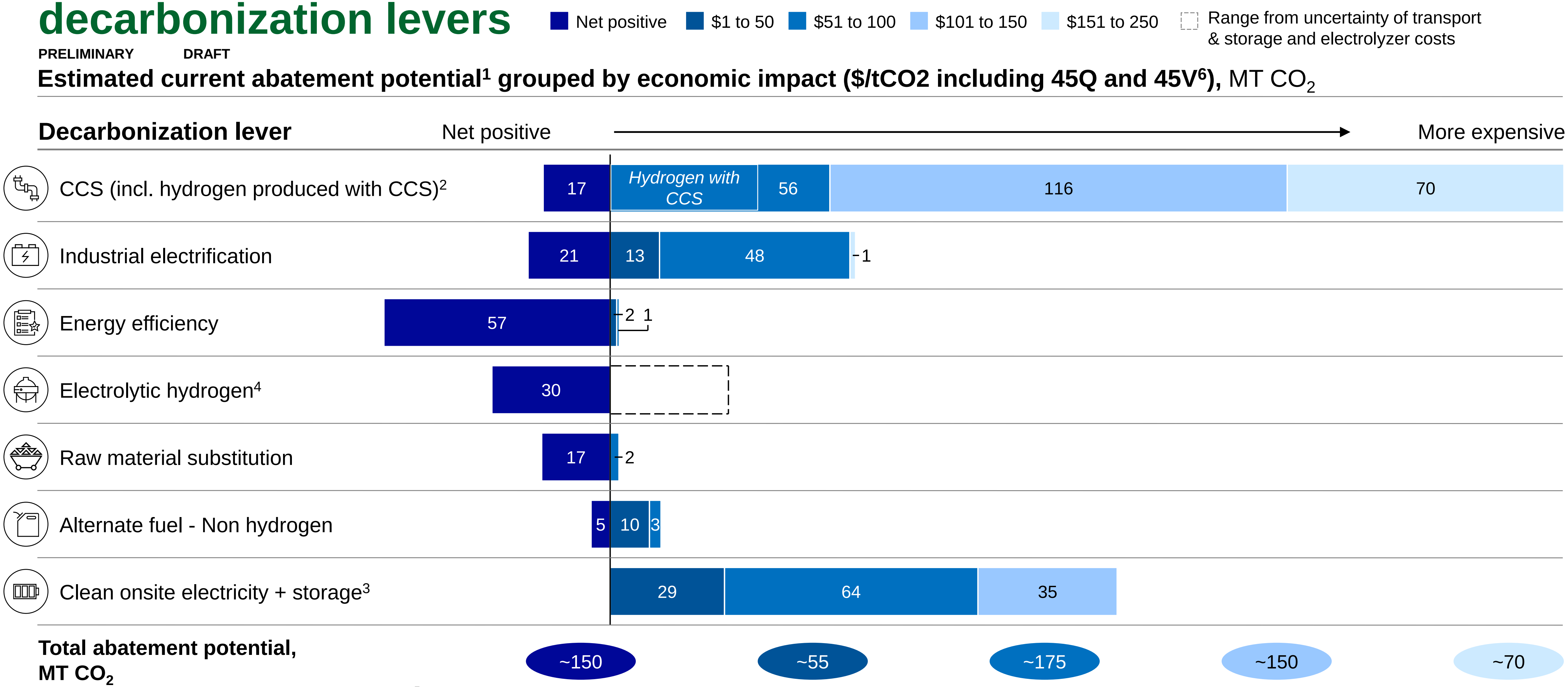
Notes: *1. Includes natural gas processing, refineries, chemicals production (various), food processing, cement production, glass production, lime manufacturing, aluminum production, iron & steel production, pulp and paper manufacturers, and other paper products. EPA FLIGHT data only records GHG emissions from facilities with reported emissions or quantity of GHG emissions > 25,000 MT CO_2e/year and does not include emissions from land use, land use change, or forestry*

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

~15% of CO_2 emissions studied could be abated with net-positive decarbonization levers

PRELIMINARY DRAFT

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



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

1. Based on 2021 emissions baseline for all industries except for Chemicals, Refining, and Cement where emissions were projected through 2050. All costs represented here took the midpoint of cost ranges | 2. Costs estimated after applying levelized 45Q tax incentive from the Inflation Reduction Act; includes 41MT of emissions abated with hydrogen produced with CCS (2030 Hydrogen with CCS costs range from x-X) | 3. Includes costs associated with heating equipment for steam generation | 4. Costs estimated after applying 45V tax incentives from the Inflation Reduction Act for hydrogen production via electrolysis. Cost estimates for 2030 range from $2.02-3.02/kg H2 including capital expenditure, operating expenditures and transport and storage costs. Overall electrolytic hydrogen costs are uncertain – assumptions based on current policy guidance and commercial cost estimates as of June 2023 and could change as more data emerges. Estimated abatement by clean hydrogen in line with Hydrogen Roadmap estimates for 2030 ammonia and refining use cases.| 5. Factors include grid decarbonization, transport sector electrification, and mechanical recycling | 6. Cost based on estimated 2030 prices for decarbonization levers. 45Q and 45V are not stacked in this analysis. Source: Industrials sector integrated MACC, DOE Chemicals & Refining Decarbonization Pathway

Key Messages for Industrial Decarbonization

Immediate actions for Liftoff

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[1], IRA[1], 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
Value Proposition	**High delivered cost of technology**	**Close cost gap** between incumbent and decarbonized technology for producers	Demonstration projects Create buy-side consortia R&D on technology costs
	High complexity to adopt	Integrate decarbonization strategy into **near- and long-term capital planning**	Opportunistic use of downtime Operational best practices R&D on manufacturing and system integration
Technology Readiness	**Limited high-TRL technologies**	Diversify industrial decarbonization portfolios with **high-potential alternative technologies**	Pilot projects Sector-specific niches
Resource Maturity	**Lack of enabling Infrastructure**	Build ecosystem to support **infrastructure** and assets	Expedited permitting Regional hubs Common carrier infrastructure
	Capital flow challenges	Improve access to **equity and debt financing** for low-carbon assets	Transition risk in business case development Offtake agreements
Market Acceptance	**Limited demand maturity**	Activate **demand-side pull** through coalitions and individual procurement deals	Offtake agreements with defined green premiums Supplier assessments
License to Operate	**Community perception**	**Engaging with communities** and addressing their reasons for concern	Community Benefits Agreements Mitigating Technologies

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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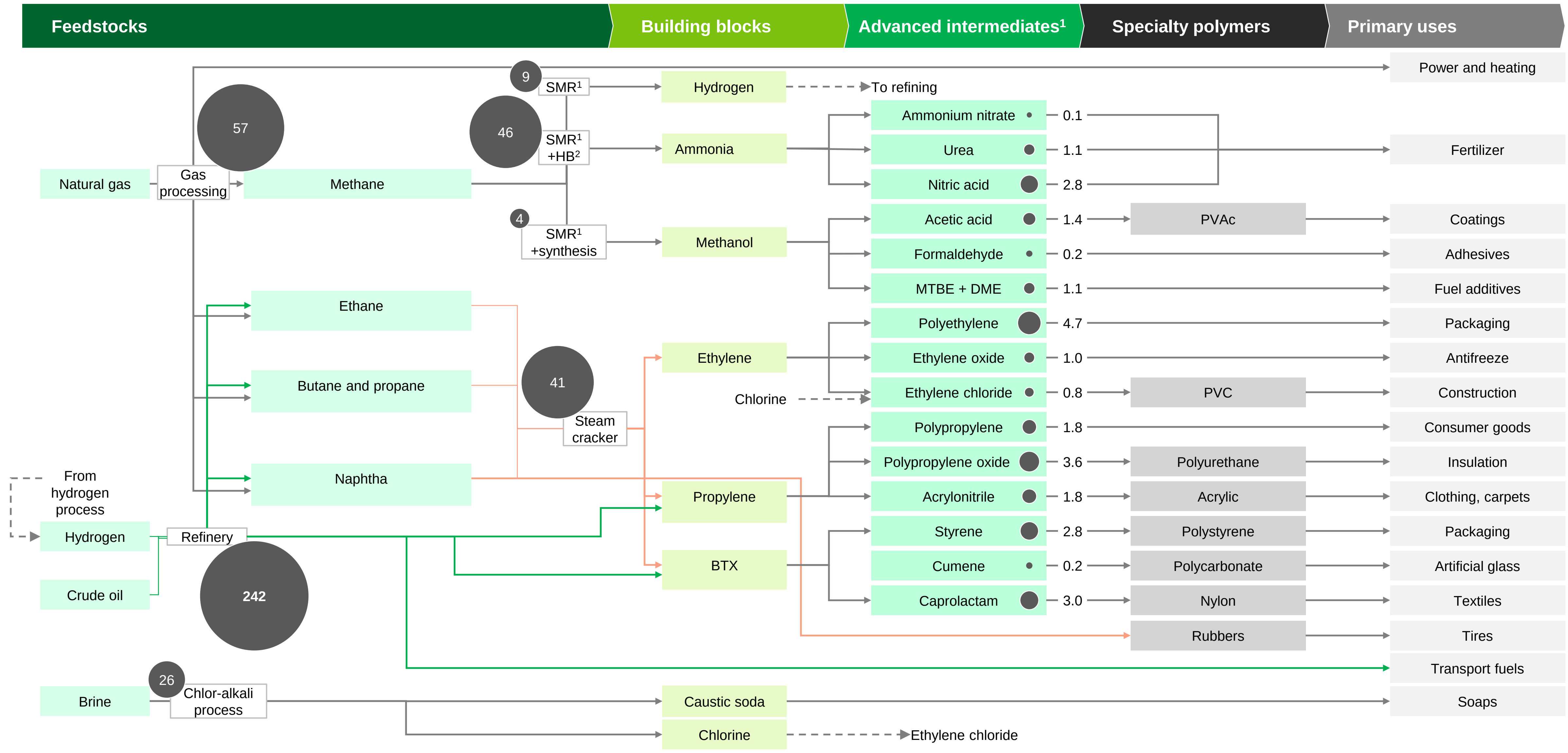
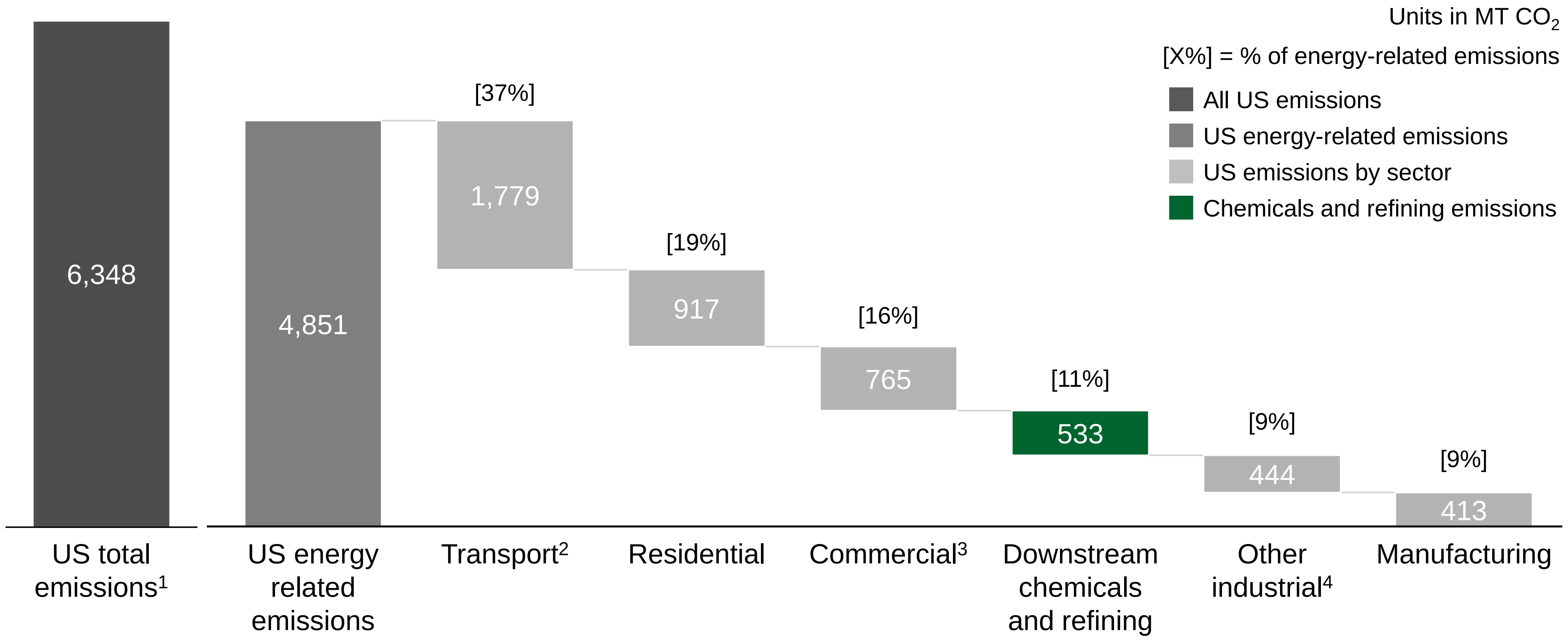
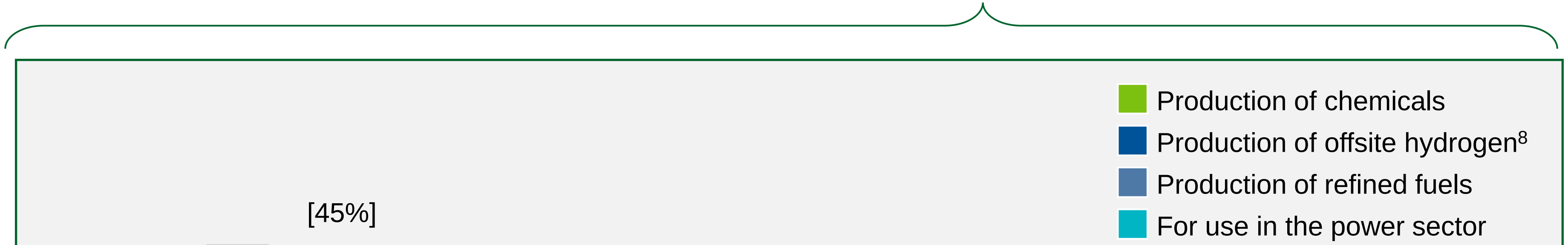


Sources: S&P, Process Economics Program (2023), Opis a Dow Jones Company, Chemical Market Analytics (2023), Solomon, S., et al. "IPCC fourth assessment report (AR4)." *Climate change* 374 (2007), Hajny, Salmon et. Al, (2019), Observations of Methane Emissions from Natural Gas-Fired Power Plants, *Environmental 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 CO2e and energy-related CO2 emissions by end-use sector in 2021, MT CO_2





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."**

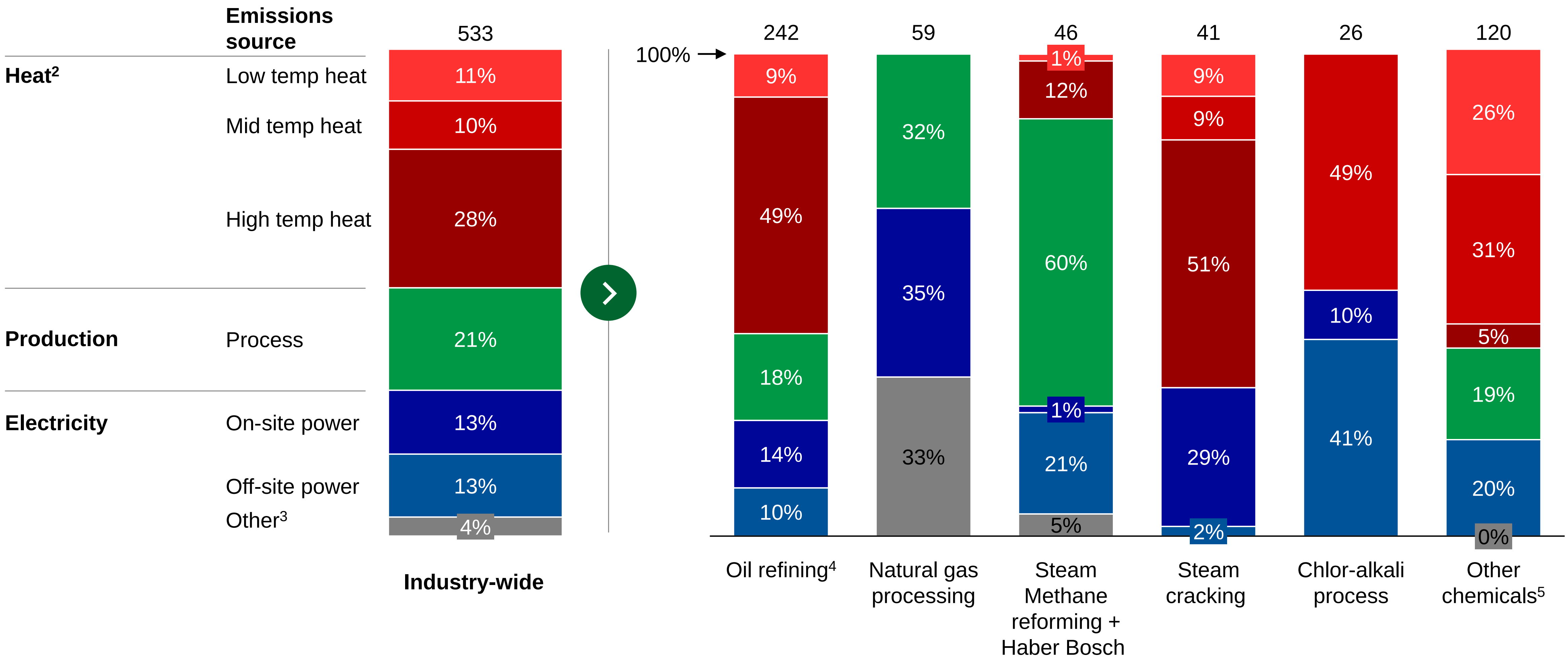
3. **Most pathways to net zero for industrial sectors rely on external industries and technologies to significantly progress, including clean hydrogen and CCS.**

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/tCO2 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,[1] MT CO_2



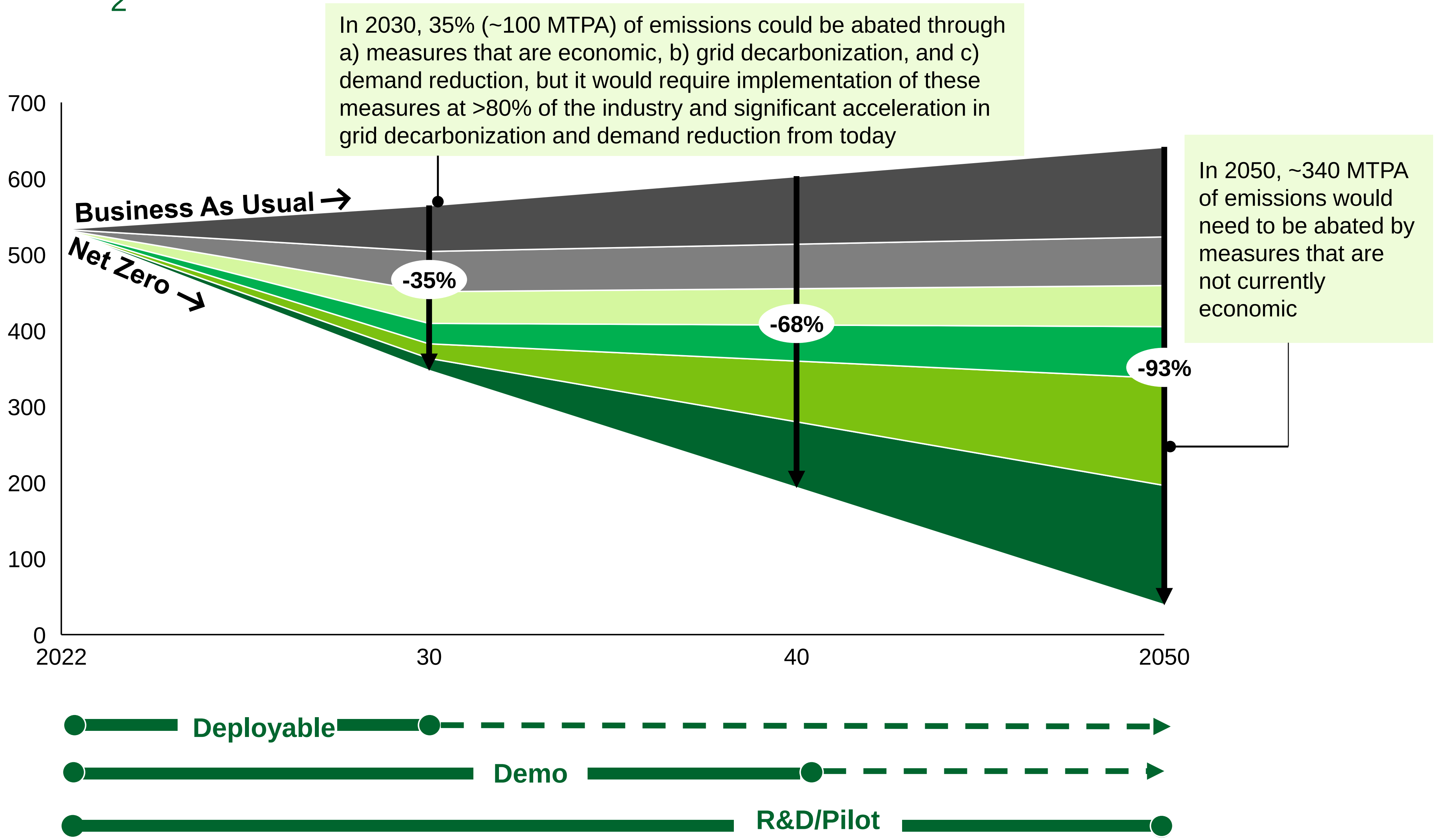
1.Includes Scope 1 and Scope 2 for refiners and chemicals producers only
2.Temperature ranges: low temperature heat is from -30 C to 200 C, medium heat is from 200 C to 400 C, and high heat is 400+ C
3.Includes electrochemical processes, refrigeration, and cooling for ethylene / propylene; cooling, heat 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[1], MT CO_2

Key decarbonization levers[2]

- Demand reduction
- Grid decarbonization
- Efficiency
- Clean hydrogen
- Electrification with clean High-capacity firm power
- CCS[3]



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

Technology included in least-cost net-zero pathway

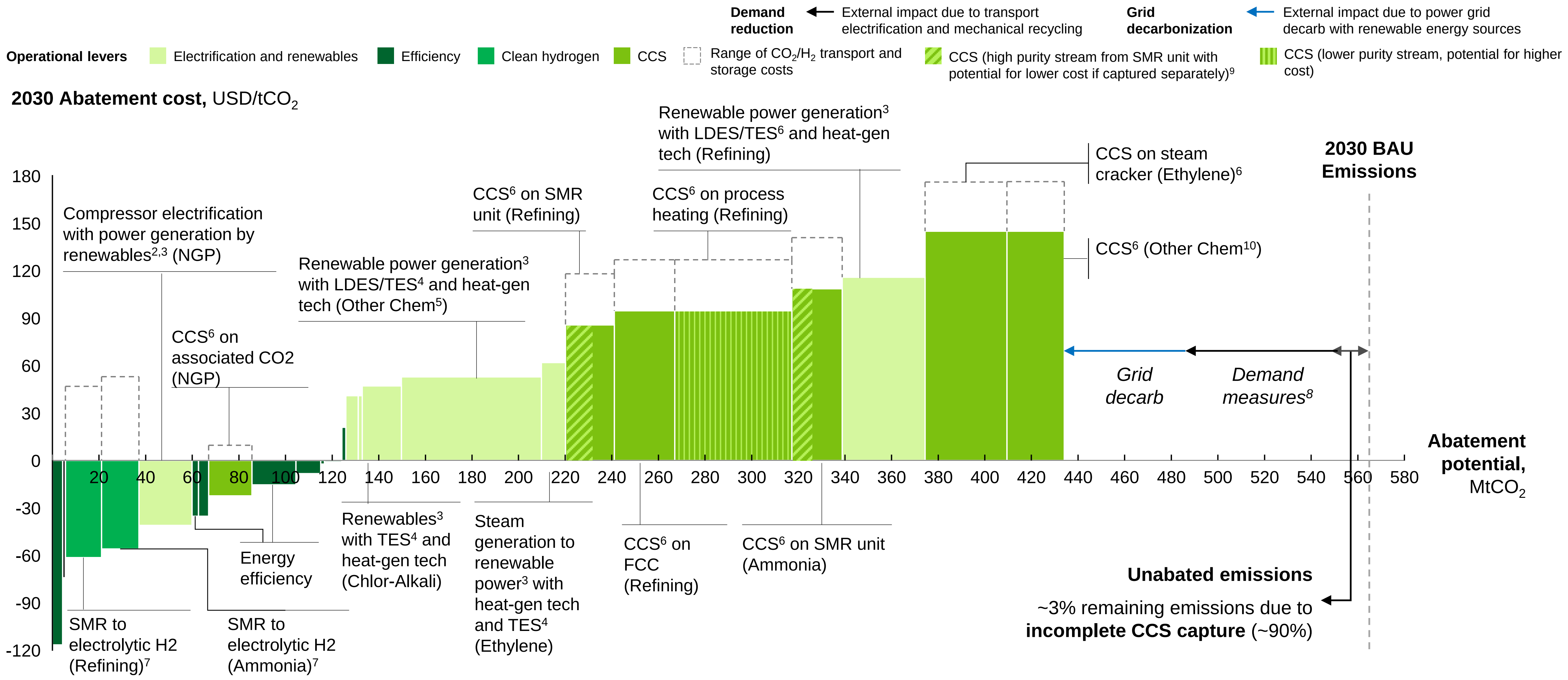
ILLUSTRATIVE NOT EXHAUSTIVE

Technology examples	Pathway to commercial liftoff – Priority decarbonization actions[2]	Estimated emission abatement[1]
Deployable • **Energy Efficiency** • **Industrial electrification** [NGP] • **Electrolytic hydrogen** [Ammonia, Refining] • **CCS in concentrated streams** [NGP] • **Clean electricity** [Chlor-alkali]	Liftoff → Scale • Adoption of **best available technology at large chemical plants** and **130+ refineries** • Adoption of **electric compressors** at 400+ NG processing plants • **Production and usage of electrolytic hydrogen**, enabled by 45V, for refineries and ammonia production • **Retrofit NG processing plants with CCS,** enabled by 45Q	~20% Grid decarb & external factors ~20-25%
• **Raw material sub.:** E.g. Bio-based feedstocks with current production methods	• **Scale production of sustainable fuels** (e.g. renewable diesel) with existing production methods	
Demonstration-stage • **Industrial electrification:** low-temp. heat • **CCS on dilute streams**	FOAK → Liftoff → Scale • **<$30/MWh[3] cost** to be competitive vs. fossil fuel boilers, burners, and CHP, 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	
• **Raw material sub.:** E.g. Bio-based feedstocks and fuels	• **Adopt advanced bio-feedstocks for chemicals** after premium develops	
R&D/Pilot • **Industrial electrification** [Refining, ethylene] • **CHP + modular nuclear reactor** • **Alternative production methods** • **Raw material sub.:** E.g. CO2 as a feedstock	R&D → FOAK → Liftoff → Scale • **Reach ~$35/MWh[4] cost of alternative steam cracker technologies** to be competitive with fossil fuel • **<$30/MWh cost to compete** with fossil-fuel-powered CHP could be achieved through R&D and demonstrations • **Mature alternative decarbonized production methods** (e.g., bio-plastics, enzyme engineering, sustainable fuels) to be cost competitive with incumbent methods	Net-zero

Timeline 2023 — 2030 — 2040 — 2050

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 $0/tCO_2$ abatement cost for refining CHP
4. Estimated as breakeven point on the MACC levelized cost of heat to reach $0/tCO_2e$ abatement cost for ethylene steam cracking furnace

2030 Marginal Abatement Cost Curve (MACC) for US Chemicals and Refining industry, with IRA[1]



1. 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.
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

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 CO2 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_2, CCS on high-purity CO_2 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/tCO2 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