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Pathways to Commercial Liftoff: Decarbonizing Chemicals & Refining

Clean Fuels and Products Shot™ Summit

Session 4: Technology Scaling and Demonstration

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U.S. Department of Energy

Agenda

- **Introduction and Stage Setting – 5 mins**
- Decarbonizing Chemicals & Refining Overview – 15 mins
- Q&A and Discussion

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**

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

In-scope | Out-of-scope

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

In-scope steps: Chemicals – Processing, Fabrication / conversion; Refining – Refining; Iron & Steel – Ironmaking, Steelmaking, Casting; Food & Beverage – Primary processing, Secondary / tertiary processing; Cement – Clinker production, Cement production; Pulp & Paper – Pulp making, Paper making; Aluminum – Alumina refining, Primary production, Secondary production; Glass – Melting, Forming. All other steps are out-of-scope.

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

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) 🚀

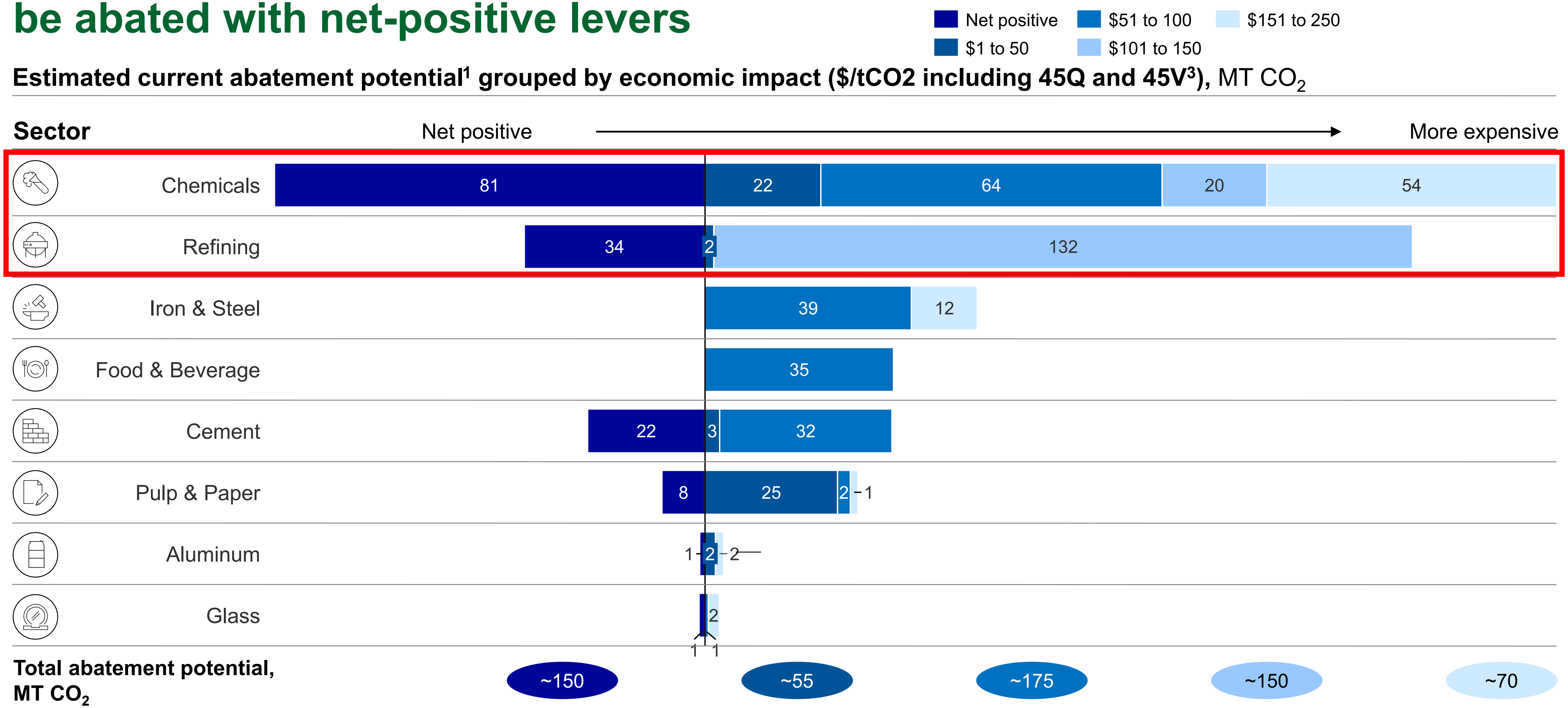
Grid Decarbonization and other external factors

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.

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

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



Note: Unabated emissions (~40 MT), external factors[3] (~200 MT), and abatement potential with costs $250+ /t$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. 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 Decarbonizati on Liftoff Report

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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."**

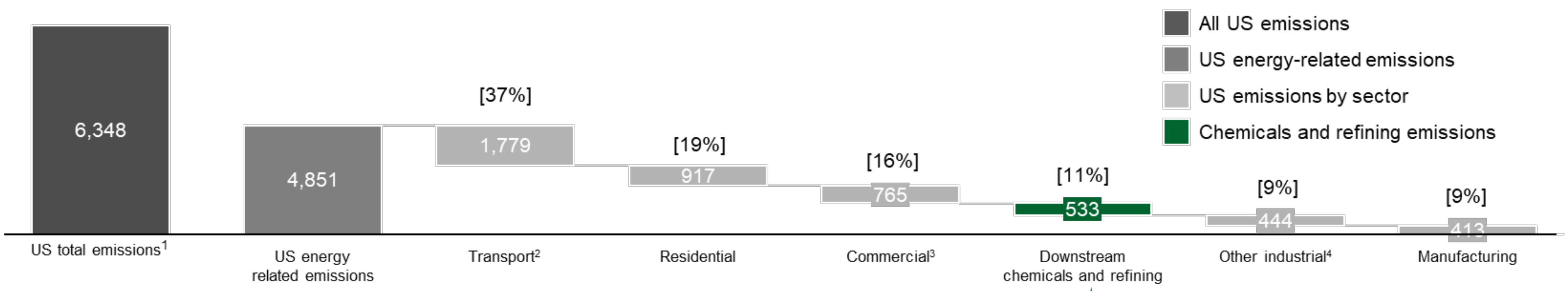
3. **Most pathways to net zero for industrial sectors rely on external industries and technologies to significantly progress, including clean hydrogen and CCS.**

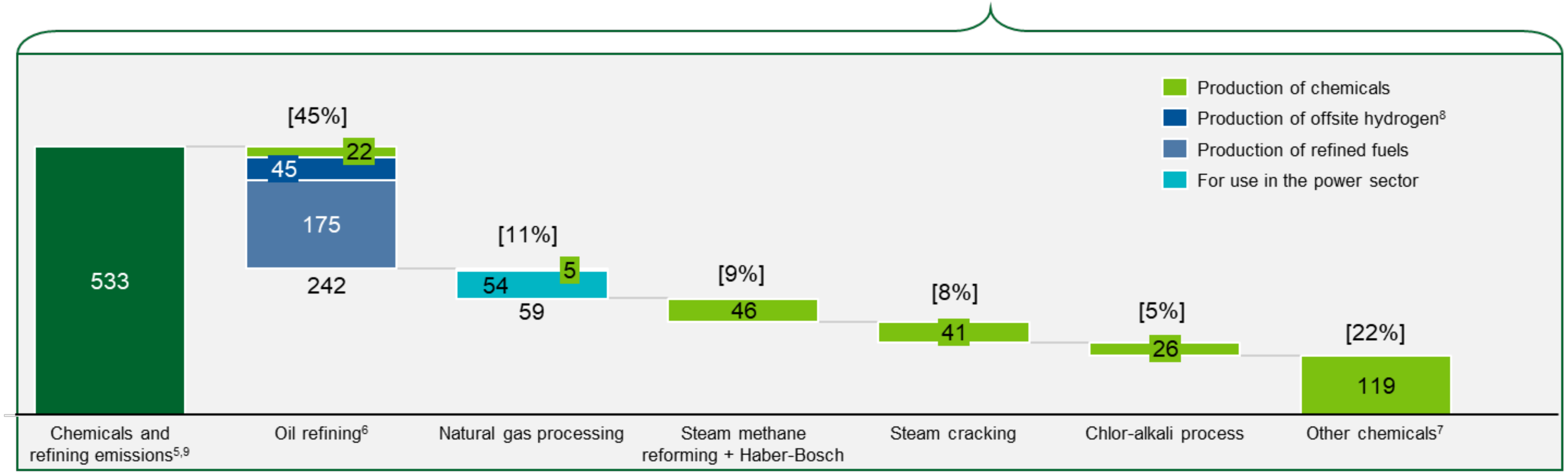
4. **Today through 2030, there is a ~$90-120B investment opportunity in decarbonization levers with >10% IRR,** and an additional investment of ~$610-730B needed between 2030 to 2050.

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.

US total CO2e and energy-related CO2 emissions by end-use sector in 2021, MT CO_2

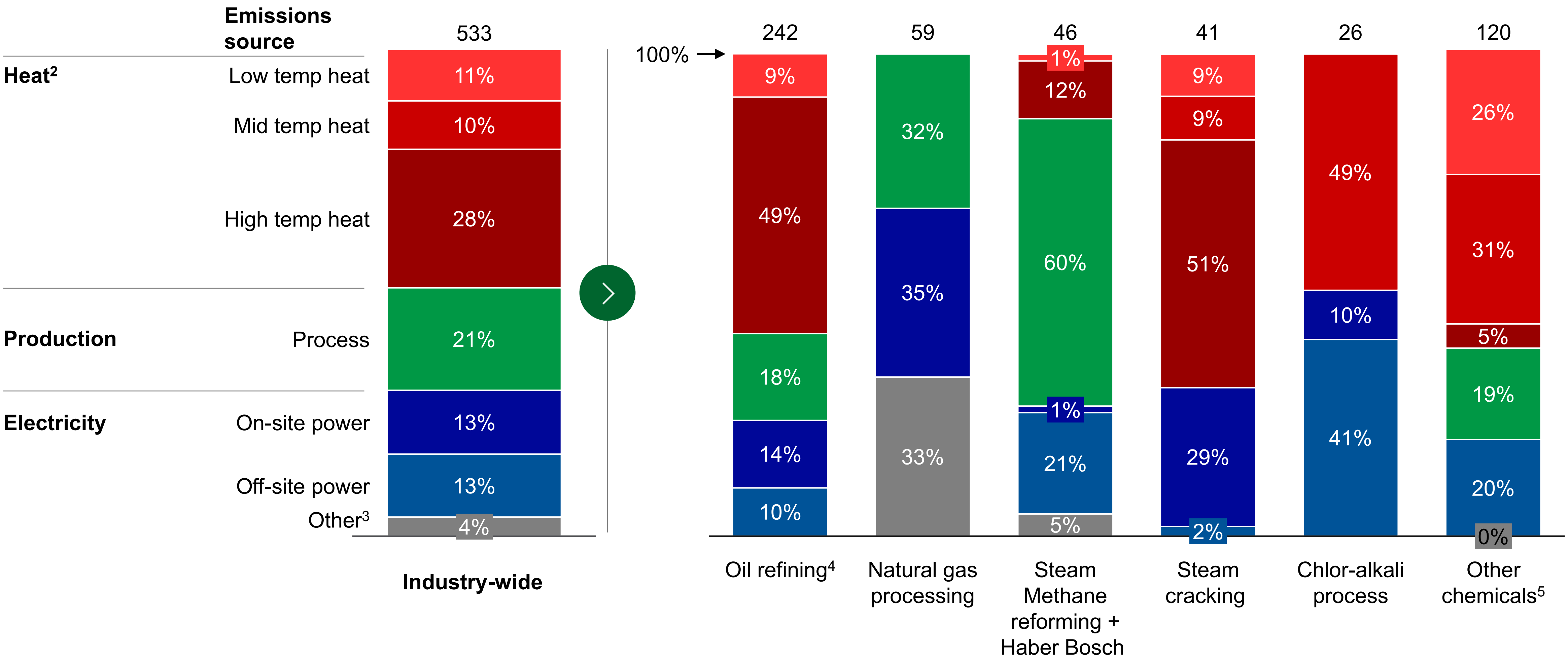




1. Includes all greenhouse gas emissions, including fluorinated gas, and nitrous oxide, and upstream methane emissions. Gross emissions excluding emissions and removals from land use, land-use change, and forestry | 2. An energy-consuming sector that consists of all vehicles whose primary purpose is transporting people and/or goods from one physical location to another. | 3. An energy-consuming sector that consists of service-providing facilities and equipment of businesses; Federal, State, and local governments; and other private and public organizations, such as religious, social, or fraternal groups. | 4. Including sectors like steel production, cement, and glass production | 5. Emissions are estimated due to lack of data availability. Total sector emissions of 533 MT CO2 and oil refining are from EIA and include energy-related CO2 emissions only (excluding process emissions and non-CO2 GHG emissions). Emissions from natural gas processing, stream methane reforming, steam cracking, and chlor-alkali process were modeled bottom-up account for process related emissions. Emissions in other chemicals were calculated from the delta between EIA's reported emissions from all chemicals and those modeled bottom-up. Therefore, total sector emissions and total emissions for other chemicals could increase if process-related emissions and non-CO2 GHG emissions were included. | 6. Assumes that nearly all merchant hydrogen production in the U.S. feeds into the oil refining process. Refinery production of chemicals (e.g., propylene and BTX) are considered in the oil refining sector | 7. Including production of multiple products derived from chemical building blocks, such as urea, formaldehyde, polyethylene, polypropylene, styrene, ethylene dichloride. All processes result in <5MT of emissions individually. Does not include process emissions, which could increase overall emissions in this segment | 8. Includes Scope 1 and Scope 2 for refiners and chemicals producers only | 9. 533 MT of CO2 emissions based on EIA energy-related CO2 emissions. Additional emissions come from process emissions and non-CO2 sources. 100% of emissions will contain non-CO_2 emissions in the chemicals and refining sector due to methane, N_2O, and other greenhouse gases

Sources: EIA data for energy-related emissions, EPA data for total US emissions, IEDO Industrial Decarbonization Roadmap, 2021 EPA Flight, EIA MECS, OPIS, IHS Markit, Argus, ITC, ICIS, McKinsey Chemical Insights, GREET GWP, Sci Rep 12 14490 (2022), FAO

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.

Many sustainability priorities for chemicals producers and refiners have benefits but may not directly reduce Scope 1 and 2 greenhouse gas emissions

High Low

	1. Recycled content	2. Bio-based & renewable materials	3. Bio-based & renewable fuels	4. Operational decarbonization
Description & Drivers	Increase use of recycled materials as feedstock for chemicals processes Driven by consumer pressure for waste reduction, recycled content targets from brand owners, and national goals	Increase substitution of fossil-based feedstocks with biodegradable bio-based feedstock or feedstocks derived from CO2 Driven by consumer demand for waste reduction and demand from brands	Increased production of fuels derived from renewable feedstock Driven by projected demand in hard-to-abate sectors with few decarbonization alternatives (e.g., aviation, marine) and incentives	Measures to decarbonize emissions from production (e.g., efficiency, CCS) Some interest driven by incentives (e.g., IRA), but limited industry momentum
Scope 1 & 2 emissions benefit	**Varies** Mechanical recycling can reduce emissions by~75% Chemical recycling can reduce emissions for certain materials[1]	**Varies** Reduction of production emissions varies significantly by product and production route	**Varies** Production emissions vary significantly by product and production route, but often higher than traditional fuel	**High** Levers all reduce emissions from production
Scope 3 emissions benefit	**Varies** Plastics recycling can offset 10-15% of US household waste[2], but impact varies greatly with choice of process	**High** Materials derived from bio-feedstocks or CO2 can act as long-duration carbon storage, reducing lifecycle emissions by up to 100%[3]	**High** Bio or CO2 sourced carbon may reduce lifecycle emissions for diesel and jet fuels by up to 100%, depending on feedstock source[4,5]	**n/a** Operational changes are captured by scope 1&2
Industry priority[6]				

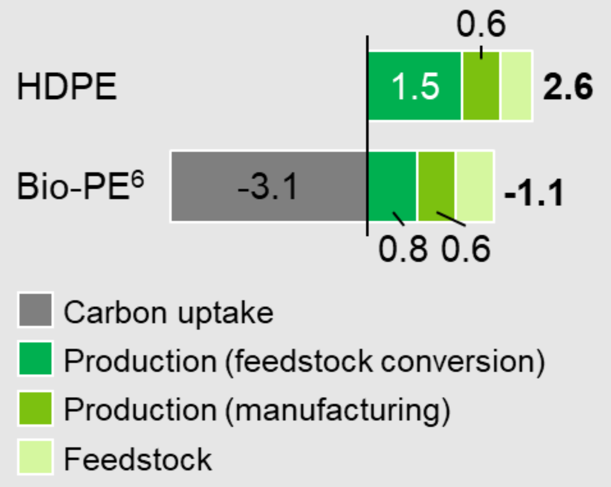
1. Uekert, Taylor, et al. "Technical, Economic, and Environmental Comparison of Closed-Loop Recycling Technologies for Common Plastics." *ACS Sustainable Chemistry & Engineering* (2023). | 2. Anshassi, M., Townsend, T.G. The hidden economic and environmental costs of eliminating kerb-side recycling. Nat Sustain (2023). https://doi.org/10.1038/s41893-023-01122-8 | 3. Liang, Chao, et al. "Life-Cycle Assessment of Biochemicals with Clear Near-Term Market Potential." ACS Sustainable Chemistry & Engineering 11.7 (2023): 2773-2783. | 4. Hannon, John R., et al. "Technoeconomic and life-cycle analysis of single-step catalytic conversion of wet ethanol into fungible fuel blend stocks." *Proceedings of the National Academy of Sciences* 117.23 (2020): 12576-12583. | 5. Prussi, Matteo, et al. "CORSIA: The first internationally adopted approach to calculate life-cycle GHG emissions for aviation fuels." *Renewable and Sustainable Energy Reviews* 150 (2021): 111398. | 6. Sourced from industry publications and press databases

Lifecycle emissions of platform petrochemicals for conventional and bio-based feedstock pathways, using current technologies

Lifecycle emissions: Conventional pathway | Bio pathway

Product	**Common uses**	**Lifecycle GHG emissions[1] of platform chemicals**, kg CO_2e[8]/kg product – Conventional pathway	Bio pathway
Polyethylene[2] *Deep dive below*	Packaging, consumer products	2.6	-1.1
Adipic acid[3]	Nylon precursor	9.5	0.8
1,4-butanediol[3]	Spandex precursor	4.0	0.7
Lactic acid[3]	Polyester manufacturing	8.0	0.4
Glycerol[4]	Sweetener, explosives ingredient	6.5	1.7
1,3-propanediol[4]	Adhesive and solvent precursor	9.5	4.5

Emissions from each stage of the polyethylene lifecycle, kg CO_2e[8]/kg product

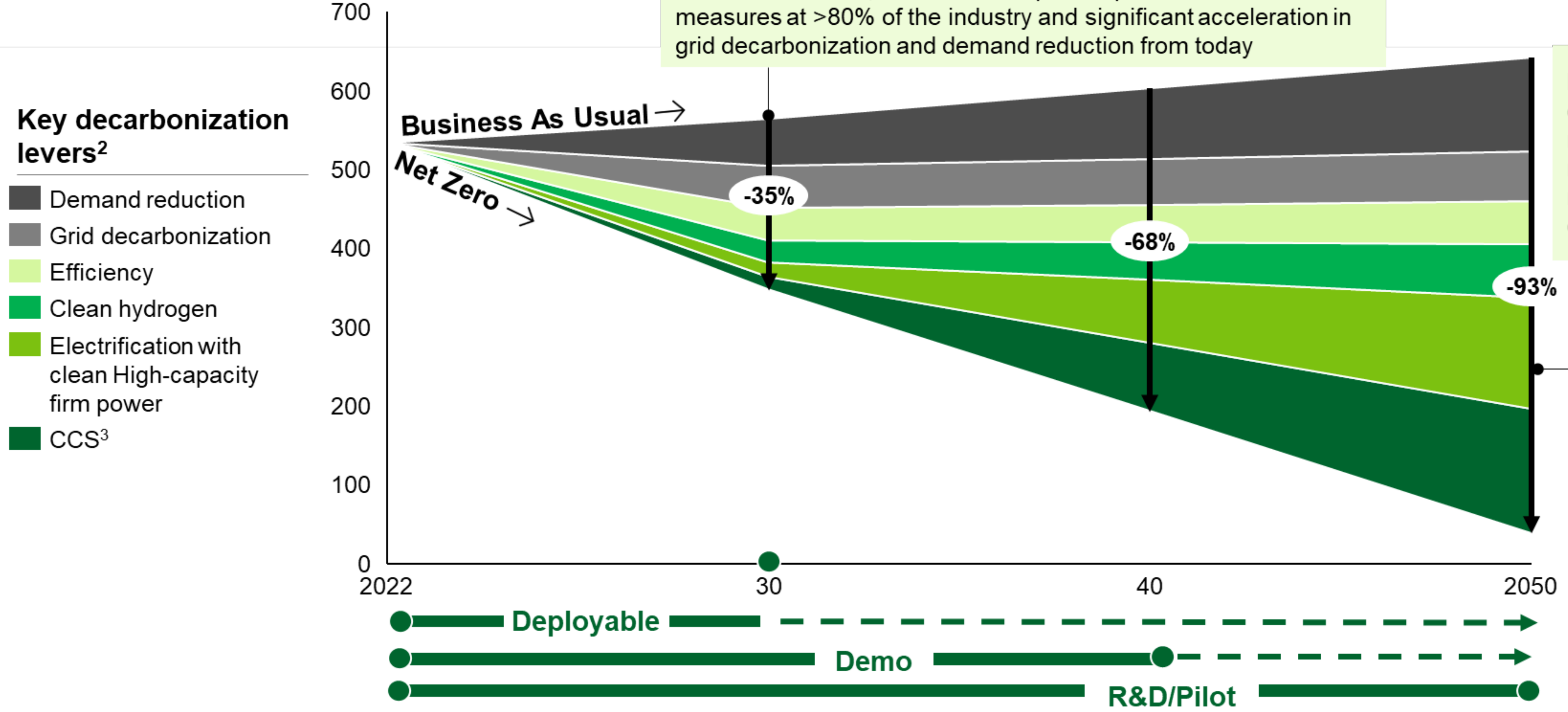


1. Lifecycle emissions including carbon uptake during plant growth, transport, production, and disposal. Negative lifecycle emissions are present for non-biodegradable materials where feedstock production leads to long-term removal of carbon from its natural cycle.
2. Comparison of HDPE and bio-PE. Source: Benavides, Pahola Thathiana, Uisung Lee, and Omid Zarè-Mehrjerdi. "Life cycle greenhouse gas emissions and energy use of polylactic acid, bio-derived polyethylene, and fossil-derived polyethylene." Journal of Cleaner Production 277 (2020): 124010.
3. Bio pathway uses corn stover feedstock. Source: Liang, Chao, et al. "Life-Cycle Assessment of Biochemicals with Clear Near-Term Market Potential." ACS Sustainable Chemistry & Engineering 11.7 (2023): 2773-2783.
4. Bio pathway uses algae feedstock. Source: Liang, Chao, et al. "Life-Cycle Assessment of Biochemicals with Clear Near-Term Market Potential." ACS Sustainable Chemistry & Engineering 11.7 (2023): 2773-2783.
5. Source: Benavides, Pahola Thathiana, Uisung Lee, and Omid Zarè-Mehrjerdi. "Life cycle greenhouse gas emissions and energy use of polylactic acid, bio-derived polyethylene, and fossil-derived
6. From corn stover feedstock. Material is assumed to be non biodegradable and carbon is effectively permanently removed from the carbon cycle.
7. With composting. Biodegradable carbon is released back into the atmosphere during decomposition
8. CO_2e, or CO_2-equivalent, is a measure used to compare the emissions of various greenhouse gases. 1kg CO_2e has the same warming impact as 1kg CO_2, but may be created by a mixture of gases

Chemical and refining production emissions under BAU and net zero scenarios[1], MT CO_2

In 2030, 35% (~100 MTPA) of emissions could be abated through a) measures that are economic, b) grid decarbonization, and c) demand reduction, but it would require implementation of these measures at >80% of the industry and significant acceleration in grid decarbonization and demand reduction from today

In 2050, ~340 MTPA of emissions would need to be abated by measures that are not currently economic



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

Source: EIA data for energy-related emissions, EPA national recycling strategy, White House – The Long-Term Strategy of the United States – Pathways to Net-Zero Greenhouse Gas Emissions by 2050

Pathway to Commercial Liftoff: Chemicals & Refining

ILLUSTRATIVE NOT EXHAUSTIVE

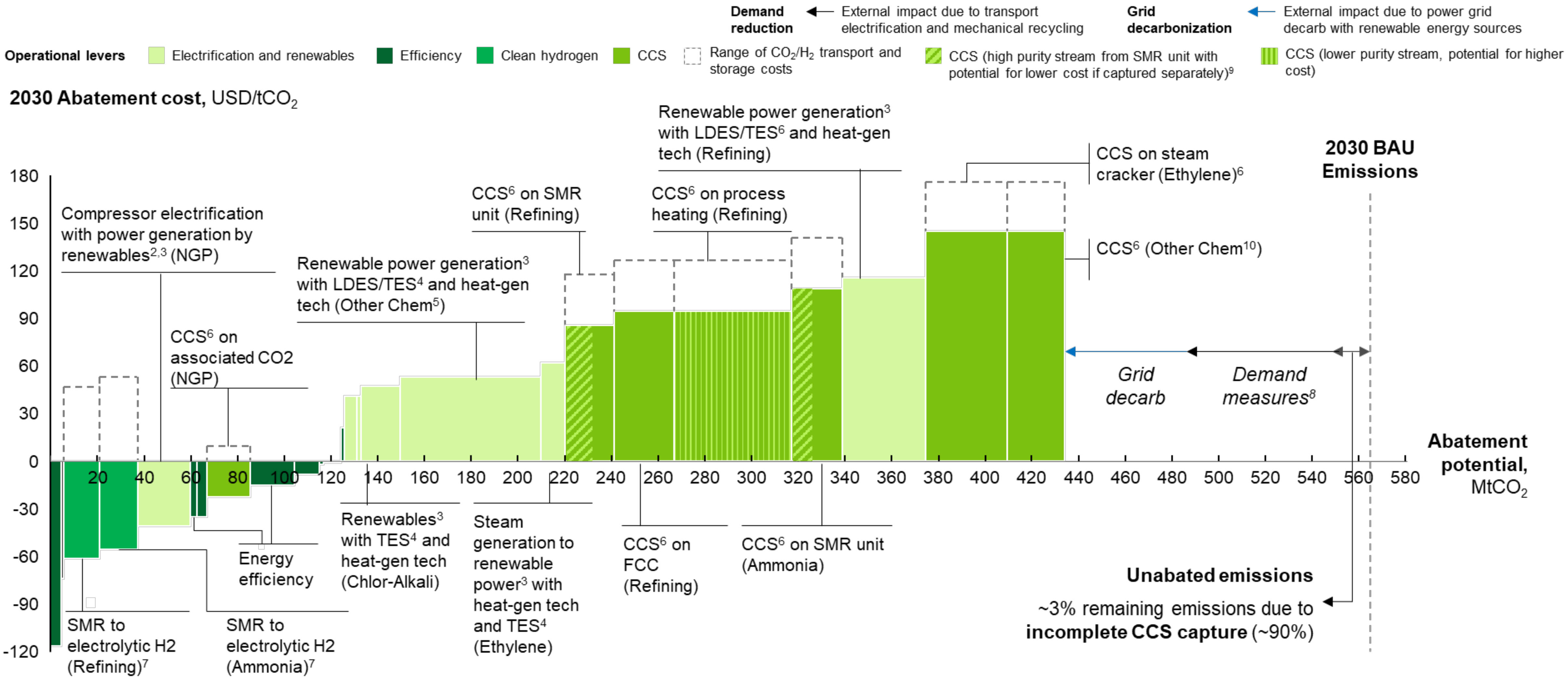
Technology included in least-cost net-zero pathway

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



Footnote detail on subsequent slide.

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

MACC Footnotes

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 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. The range of 2030 electrolytic hydrogen costs for Refining is estimated at $0.22-1.22/kg H2. The range of 2030 electrolytic hydrogen costs for Ammonia is estimated at $0.28-1.28/kg H2. All hydrogen cost assumptions for this modeled scenario are based on DOE’s Clean Hydrogen Liftoff report, which relied on the 2022 McKinsey Hydrogen Model. The impact of the 45V tax credit is modeled as a $1.80/kg H2 reduction in OpEx cost, based on assumptions of 10% WACC, 10 years of tax credit, and a 20-year project lifetime. It is important to note that the assumptions underlying this analysis are uncertain, and the Clean Hydrogen Liftoff report is continually being updated. DOE electrolyzer cost estimates have already increased since the values published in this report, due to variables such as supply chain constraints and inflation. Additionally, the impacts of tax incentives on cost will be subject to guidance from the U.S. Department of Treasury.
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

Seven key challenges to scaling the measures needed to decarbonization chemicals & refining

Level of impact on decarbonization measure: High | Medium | Low

Key challenges

Measures / ARL risks	1. Operational challenges *Ease of use*	2. Unattractive economics *Delivered costs, demand maturity / market openness*	3. Low technology readiness *Technology readiness level*	4. Capital formation challenges *Capital flow*	5. Nascent ecosystem of value chain partners *Manufacturing & supply chain, materials sourcing, workforce*	6. Lack of enabling infrastructure *Infrastructure, permitting & siting*	7. Social / pubic acceptance *Environmental safety, community perception*
i. Clean hydrogen	Low	Medium	Low	High	High	High	High
ii. Energy efficiency and waste reduction	High	Low	Low	Medium	Low	Low	Low
iii. Electrification with clean firm power	Low	High	Medium	High	Medium	Medium	Low
iv. CCS on high purity streams	Medium	Low	Low	High	High	High	High
v. CCS on dilute streams	Medium	High	Medium	High	High	High	High

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