U.S. DEPARTMENT OF ENERGY

Pathways to Commercial Liftoff: Industrial Decarbonization

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Comments

The Department of Energy welcomes input and feedback on the contents of this Pathway to Commercial Liftoff. Please direct all inquiries and input to liftoff@hq.doe.gov. Input and feedback should not include business sensitive information, trade secrets, proprietary, or otherwise confidential information. Please note that input and feedback provided is subject to the Freedom of Information Act.

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Purpose of this Report

These Pathway to Commercial Liftoff Reports aim to establish a common fact base and ongoing dialogue with the private sector around the path to commercial lift-off for critical clean energy technologies across core U.S. industries. Their goal is to catalyze more rapid and coordinated action across industries and the full technology value chain.

This Pathway to Commercial Liftoff report provides an overview of the pathways to decarbonize eight industrial sectors of focus: chemicals, refining, iron & steel, food & beverage, pulp & paper, cement, aluminum, and glass. It is one in a multi-part series focused on industrial decarbonization. The Industrial Decarbonization Liftoff series provides an overview of the pathways to decarbonization across eight industrial sectors of focus in the Inflation Reduction Act (IRA): chemicals, refining, iron and steel, food and beverage processing, pulp and paper, cement, aluminum, and glass. DOE has conducted deep analysis and developed reports in the Liftoff series focusing on chemicals and refining and cement. All other sectors, and cross-cutting perspectives, are covered in this report Pathway to Commercial Liftoff: Industrial Decarbonization.

Glossary

Term	Definition
Commercial Liftoff	**"Liftoff" represents the point where solutions become largely self-sustaining markets** that do not depend on significant levels of public capital and instead attract private capital with a wide range of risk
GWP 100	Global Warming Potential of greenhouse gasses (GHGs) over a 100-year time horizon
MT	Million Tonnes
Biogenic emissions	Emissions from the combustion, decomposition, or processing of biologically based materials
RDD&D	Research, development, demonstration, and deployment (RDD&D) continuum—defines the path to commercialization where a technology starts as an innovative idea in research, moves to development where the first prototype is created, proceeds to demonstration where the solution is tested in the real world and ending with commercial-scale deployment. Although RDD&D is a continuum, the pathways across stages are not always linear, and technologies may need to go back to earlier stages to be refined
R&D / Pilot stage	Technology in a stage of the RDD&D continuum where the objective is to discover and determine the technical feasibility of new technologies in a lab or in small pilots
Demonstration stage	Technology in a stage of the RDD&D continuum where the objective is to determine the technical and commercial feasibility of new technologies
Deployable stage	Technology in a stage of the RDD&D continuum where the objective is to develop commercial deployments
TRL[1]	Technology readiness level (1-9); Metric used for describing technology maturity. It is a measure used by many U.S. government agencies to assess the maturity of evolving technologies (materials, components, devices, etc.) before incorporating that technology into a system or subsystem
ARL[2]	Adoption readiness level (1-9); Represents important factors for private sector uptake beyond technology readiness, including value proposition, market acceptance, resource maturity, and license to operate
H2	Hydrogen
NG	Natural gas
CCUS	Carbon capture, utilization and storage.
CCS	Carbon capture and storage. This report focuses on Industrial CCS. It does not discuss use of CCS in the power sector
FOAK	First of a kind
NOAK	Nth of a kind
BAT	Best available technology
IRA	Inflation Reduction Act of 2022 (Pub. L. 117-169)
45Q	Tax incentive that encourages carbon capture, utilization, and storage (CCUS) projects

1 Technology Readiness Assessment Guide | Department of Energy

2 Adoption Readiness Levels (ARL): A Complement to TRL | Department of Energy

Term	Definition
45V	IRA tax incentive that encourages the production of clean hydrogen
48C	Tax incentive for a variety of different types of energy projects with a $10 billion limited allocation
48E/45Y	IRA tax incentive that is technology-neutral for clean energy generation projects placed in service after Dec. 31, 2024, based on emission measurements that require zero or net-negative carbon emissions
CBA	Community Benefits Agreement
PLA	Project Labor Agreement
IEDO	Industrial Efficiency and Decarbonization Office
Scope 1 emissions	Direct emissions from the company's owned or controlled sources, including refrigerants; emissions from combustion in owned or controlled boilers and furnaces; and emissions from fleet vehicles
Scope 2 emissions	Indirect greenhouse gas emissions from purchased or acquired energy, like electricity, steam, heat, or cooling, generated offsite and consumed by the reporting company
Scope 3 emissions	Indirect greenhouse gas emissions associated with a company's value chain activities both upstream and downstream, including emissions from sources not owned or controlled by the company, such as suppliers, customers, and product use

Executive summary

The U.S. industrial sector makes products and materials that Americans rely upon: products like steel and aluminum for automobiles and renewable energy generation, cement and concrete for buildings and infrastructure, pulp and paper for packaged goods, glass for windows and containers, and chemicals for fertilizers, pharmaceuticals, and plastics. Many of these industries export commodities, intermediate products, and final products, contributing to a strong U.S. presence in global industrial markets.[i] Many of these products are also essential materials for a clean-energy transition. At the same time, a decarbonized economy will require approaches that address the production emissions associated with industrial processes.

This Industrial Decarbonization Liftoff report provides an overview of the pathways to decarbonization across eight industrial sectors of focus: chemicals, refining, iron and steel, food and beverage processing, pulp and paper, cement, aluminum, and glass.[ii] This Pathway to Commercial Liftoff report is part of a series of reports on industrial decarbonization, including deep dives on chemicals and refining and cement. The goal of this family of pathway reports is to provide **a guide to a private sector-led, industry-wide decarbonization effort that is deeper and faster than it would otherwise be and that directly benefits fenceline communities** by emphasizing environmental justice and the creation of good jobs.

Broader U.S. industry progress toward deep decarbonization is at risk of lagging other countries and domestic net-zero targets, although the journey is nuanced by sector.[3] U.S. industrials are a significant contributor to emissions, accounting for 23% of U.S. CO2e emissions (GWP100) in 2021 total, as well as other health-harming emissions, including nitrogen oxides (NOx), sulfur oxides (SOx), and carbon monoxide (CO).[4,5,iii] **Within U.S. industrials, this report studies the energy and process-related emissions from the eight industrial sectors of focus, which accounted for 14% of domestic emissions totaling ~880 MT CO2e in 2021.** [6,iii,iv,v,vi] Chemicals and refining as a subsector has the largest share of these emissions, making up over 60% of emissions from industrial sectors of focus and 7% of total U.S. CO2e emissions.

Reasons often cited for slow progress on the decarbonization of industrial emissions include: the immaturity and high cost of many decarbonization levers; unidentified or uncertain customer demand for low-carbon products; and, in some but not all sectors, reluctance among companies to be a first mover. **If the U.S. transport and power sectors decarbonize in line with administration targets and limited abatement occurs in industrials, the share of emissions from all U.S. industrials could rise to 27% of total U.S. CO2e emissions by 2030.[vii]**

In many industrial sectors, the decarbonization narrative is changing. Technology deployment has received Congressional support from the Infrastructure Investment and Jobs Act[7] (IIJA), also referred to as the Bipartisan Infrastructure Law (BIL), and the Inflation Reduction Act[8] (IRA). **Customers and other stakeholders increasingly expect companies to address climate change**, **and some companies are making bold decarbonization moves**. Increased customer demand and willingness to pay for low-carbon products could create opportunities to build low-carbon businesses and exports and capture technology premia, especially as industrial material costs often make up a small portion of final product costs.[viii] At a

3 For example, the EU carbon tax has enabled 20+ DRI plants for steelmaking, CCS pilots in cement production, electric cracker pilot projects, and installation of electric boilers and heat pumps in pulp and paper mills.

4 GWP100 refers to Global Warming Potential with a period of 100 years.

5 The industrial sector includes manufacturing and non-manufacturing subsectors; those not studied in this report include agriculture, mining, construction, electronics, and transportation equipment, as well as upstream OandG emissions.

6 CO2e refers to carbon dioxide equivalent emissions; all references to MT refer to megatonnes (i.e., metric units) unless stated otherwise. For purposes of concision, references to industrial sectors are defined as the eight industrial sectors of focus (i.e., chemicals, refining, iron and steel, food and beverage, pulp and paper, cement, aluminum, and glass) unless otherwise noted. For purposes of concision, references to emissions associated with industrial sectors of focus are defined as energy- and process-related emissions.

7 Infrastructure Investment and Jobs Act, Pub. L. 117-58, 135 Stat. 429 (2021)

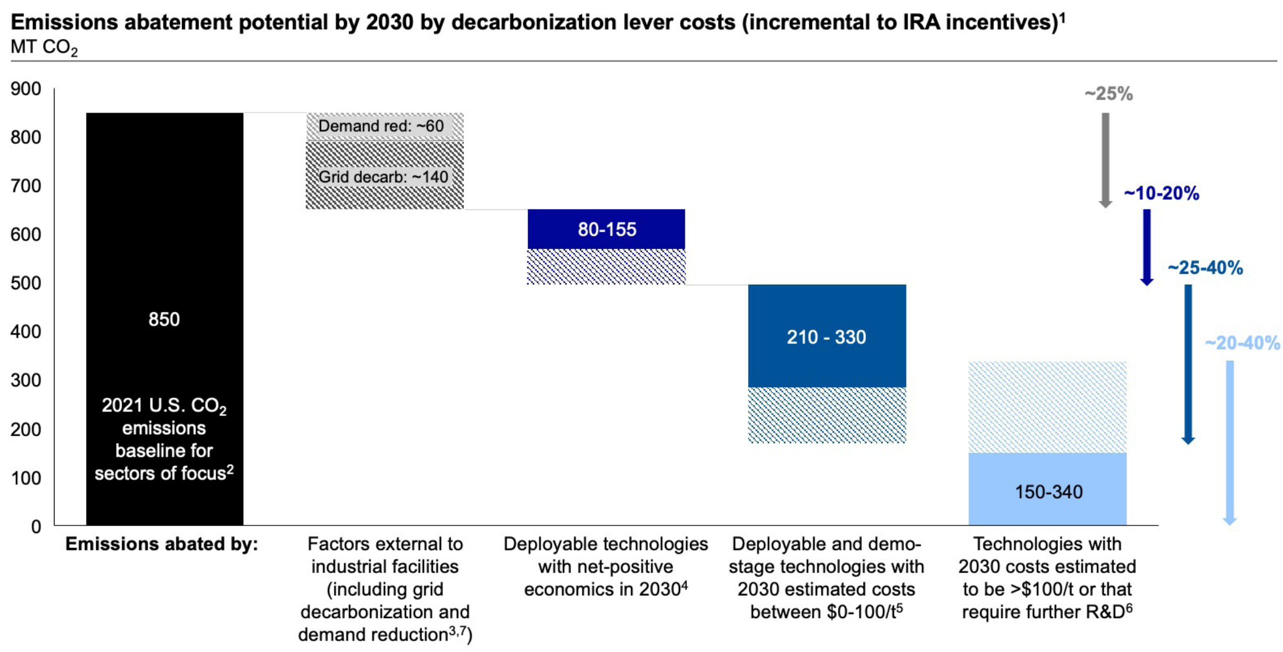
8 Inflation Reduction Act of 2022, Pub. L. 117–169, 136 Stat. 1818 (2022)

macro level, federal support enables the U.S. to modernize its industrial base, secure clean technology supply chains, and spur economic growth and good job creation through domestic manufacturing.[vii,ix] Progress towards these priorities – which are reflected in the U.S. long term strategy to achieve net zero – have been significantly accelerated by BIL and IRA.[x]

Willing U.S. industry participants could utilize the momentum of the present moment to accelerate the commercialization of decarbonization technologies, respond to rising global demand for clean industrial commodities, and establish the U.S. as a global leader in industrial decarbonization.

Across this report, **"Liftoff" represents the point where solutions become largely self-sustaining markets** that do not depend on significant levels of public capital and instead attract private capital with a wide range of risk. To analyze and articulate pathways towards achieving Liftoff for industrial emissions reductions, this report uses 1) a marginal abatement cost curve (MACC) analysis based on the best available information for 2021 emissions baselines, 2030 cost estimates and technical feasibility, and 2) deep private sector engagement on net-positive decarbonization levers for 2030, to underpin 3) both a consolidated Pathway to Liftoff and eight sector-specific Pathways to Liftoff. The emissions abatement potential and costs of nine major decarbonization levers are estimated in this report. The levers in focus build on the DOE's Industrial Decarbonization Roadmap pillars and include carbon capture and storage (CCS) at industrial facilities; clean onsite electricity and storage; industrial electrification; energy efficiency; electrolytic hydrogen; raw material substitution; alternative fuels and feedstocks; grid decarbonization and other external factors; and alternative production methods—each encompassing many sector-specific applications.[9]

First, the MACC analysis finds that by 2030, up to 40% of emissions[10] across these eight sectors could be abated through the implementation of industrial facility decarbonization levers that have net-positive economics (with IRA incentives included), alongside emissions reductions from external factors (Figure ES.1).[11] It is important to note that grid decarbonization makes up ~15% of total industrial emissions abatement potential in 2030, making it a critical dependency to decarbonizing U.S. industry.



9 Clean electricity includes electricity from renewable or nuclear energy sources that is procured from the grid or V/PPAs or generated onsite; industrial electrification is the replacement of fossil-fuel equipment with electric alternatives.

10 Emissions studied include energy and non-energy emissions.

11 IRA incentives reflected in the MACC analysis include 45V (i.e., hydrogen production tax credit), 45Q (i.e., CCS tax credit), and 48E (i.e., clean energy tax credit).

Figure ES.1: Net-positive levers and external factors could abate 30–40% of emissions by 2030. | 1. Current ranges consider how abatement potential might evolve if the 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 instead depict uncertainty in the cost estimates range for decarbonization levers. | 2. Heat, electricity, and process emissions for industrial sectors of focus (defined in text) | 3. Modeled emissions abatement in 2030 that is attributable to external factors, including grid decarbonization and changes in demand. | 4. Modeled emissions abatement associated with net-positive levers (< $0/t) | 5. Modeled emissions abatement associated with levers approaching breakeven ($0-$100/t) | 6. Modeled emissions abatement by levers with >$100/t or that require further R&D | 7. Assumes the Biden Administration's target of zero emissions from the grid in 2035 and applies goals for transport decarbonization and plastics recycling for this analytical exercise. The entire bar is shaded to indicate uncertainty around factors external to industrial facilities.

Using the MACC analysis as well as considerations informed by market dynamics, and societal considerations**,** the report summarizes a Pathway to Liftoff both across the industrial sectors of focus (Figure ES.2) and for sector-specific Pathways (Chapter 3b).

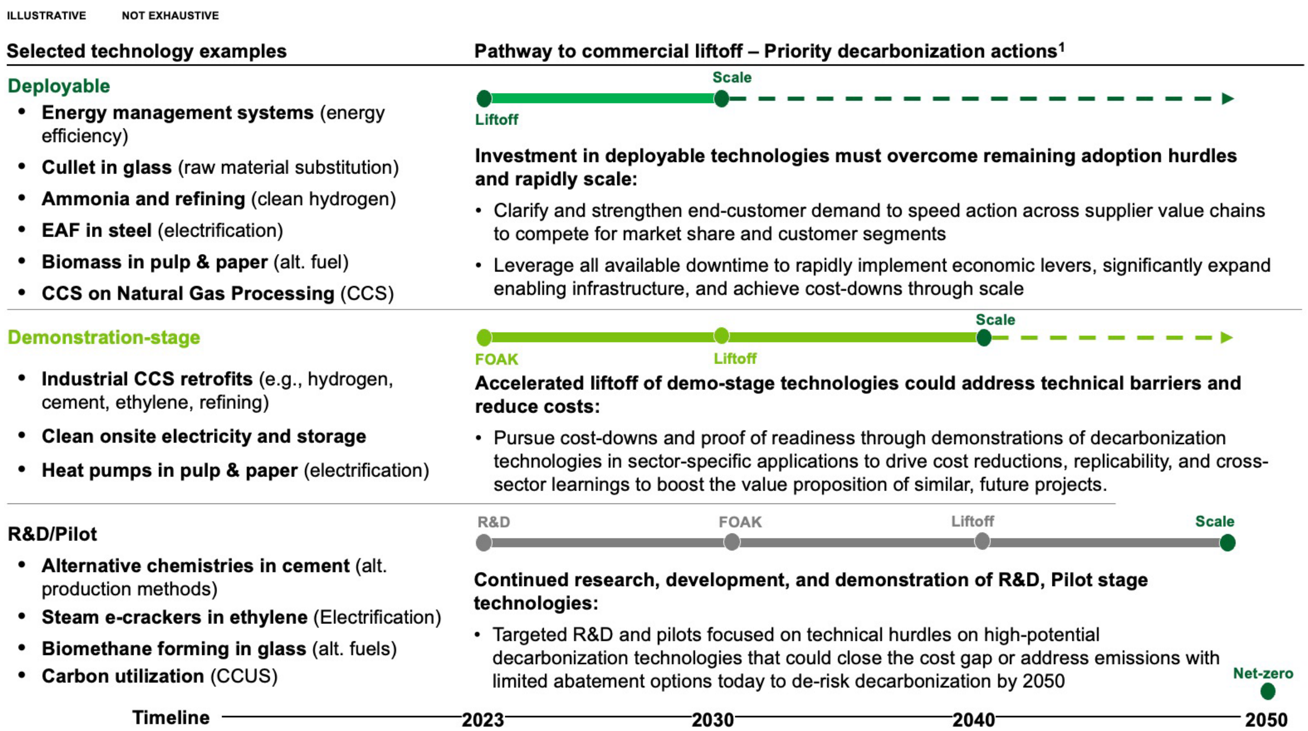


Figure ES.2: Liftoff pathway across industrial sectors is split across technologies with varying technology readiness levels (TRL) / adoption readiness levels (ARL) and can be enabled through policy, infrastructure, and supply chains | 1. Indicative timeline presented for R&D, FOAK, liftoff, and scale. Actual timelines will vary by technology based on technological maturity and barriers to adoption.

Figure ES.2 illustrates key actions along a potential Pathway to Liftoff scenario that relies upon three groups of technologies along the Research, Development, Demonstration, and Deployment (RDD&D) continuum – Deployable, Demonstration-stage, and R&D/Pilot. **Based on the MACC analysis cost estimates, this pathway to reach net zero by 2050 could require at least $700–1,100B of potential capital expenditure.**[12] However, this is just one illustrative scenario and other pathways may emerge as demonstration-stage and R&D technologies mature and achieve cost-reductions.

To achieve adoption at scale of deployable technology levers will require bold leadership, even for solutions

12 $700M to $1.1B represents the estimated potential capital investment required to decarbonize the eight industrial sectors of focus in the IRA, including chemicals, refining, iron and steel, food and beverage, cement, pulp and paper, aluminum, glass and reach net zero by 2050. This number was calculated by estimating the capital expenditure for scaling select deployable and demonstration-stage decarbonization levers (e.g., CCS, clean on-site power generation from renewables, energy efficiency measures) for each industry. The actual capital expenditure required to achieve net zero by 2050 may be higher given that this estimate does not include additional capital spending on R&D/pilots required for levers in that category. IRA incentives reflected in the MACC analysis include 45V (i.e., hydrogen production tax credit) and 48C (i.e., carbon capture and storage tax credit).

with net-positive economics. One factor is that, across the sectors of focus, many companies face pressure to plan towards and achieve near-term earnings targets. While the rise of Environmental, Social, and Governance (ESG) investing and "patient" capital has alleviated some of this short-term pressure, it can still affect decision-making on multi-year infrastructure investments. **Today, industry mostly focuses on a subset of deployable technologies requiring limited investment or process changes** such as energy efficiency, select electrification applications and alternative feedstocks.[13] However, full-scale adoption has not begun. Even if these technologies reached full adoption, they would only address ~10% of emissions in industrial sectors of focus compared to a 2021 baseline, underscoring the need for additional approaches and technologies.[14]

Expanding beyond near-term thinking and fully decarbonizing industry will be extremely challenging without cost reductions, education, breakthroughs, a complementary skilled workforce, and widespread public acceptance**. An accelerated pathway to commercial liftoff faces seven major commercial challenges across all decarbonization levers:**

1. Challenging economics with long payback periods and a subsequent lack of first-of-a-kind (FOAK) build-out for high-abatement levers with lower TRL and/or ARL (e.g., high-temperature heat electrification, alternative chemistries for cement production), even after IRA incentives.
2. Operational roadblocks delaying implementation of decarbonization retrofits, such as alignment of decarbonization investments to asset downtime windows.
3. Overreliance on a small portfolio of technologies with relatively low ARLs (e.g., dilute-stream CCS).
4. Nascent ecosystem of value chain partners and lack of enabling infrastructure (e.g., carbon dioxide and hydrogen pipelines).
5. Capital formation challenges due to relatively lower ROI, higher volume of capital needed, perceived risks of retrofits and lower-ARL, low-carbon assets resulting in higher cost of capital, and more favorable risk-adjusted return of sustaining existing assets.
6. Limited short-term decarbonization ambitions prompted, at least in part, by limited (to date) regulator actions and/or demand-side pull for low-carbon products.
7. Inconsistent public acceptance due to environmental and human health risks, environmental justice, and labor concerns.

Seven corresponding solutions could ensure the industrial sector keeps pace with national decarbonization goals and provides opportunities for early movers:

1. Close the persistent cost gap between incumbent and decarbonized technology for industrial producers by de-risking public and private sector investment and by achieving cost reductions through demonstrations.
2. Integrate decarbonization strategy into near- and long-term capital planning, facility retrofits, and equipment downtime (e.g., scheduled turnaround of specific process units in refining every five years; steel mill relining every 15–25 years).
3. Diversify decarbonization portfolios through R&D and pilot projects for high-potential alternative technologies or production methods (e.g., high-temp heat electrification, electric crackers, alternative cement chemistries) and cross-industry knowledge sharing.
4. Continue to build and expand existing infrastructure and supporting ecosystem by expediting permitting bottlenecks, building public acceptance, building or expanding regional hubs and

13 Select applications include compressor electrification in Natural Gas Processing; increased recycling in glass and aluminum; and clinker substitution in cement.

14 Includes efficiency, electrification, and alternative feedstocks levers where ~90% of abatement costs <$0/t CO_2e.

common-carrier infrastructure, and facilitating a shared learnings ecosystem.

5. Enable lowering the cost of capital investment by proving the business case for decarbonization measures and providing loans, cooperative agreements, or competitive tax credits.

6. Bolster demand-side pull and leverage industry coalitions to accelerate decarbonization ambition and potentially capture a technology premium from early-adopting consumers; this can be enabled through public sector programs (e.g., OCED's Industrial Demonstrations Program, Federal Buy Clean Initiative), regulatory actions, and private sector buy-in (e.g., Better Climate Challenge, World Economic Forum's First Movers Coalition, Frontier advance market commitment).[15]

7. Address public concerns through the development of Community Benefits Plans, market adoption of Community Benefits Agreements, Project Labor Agreements, and responsible business and labor practices.

In partnership with other federal agencies, the Department of Energy (DOE) has the mission, authority, and funding to begin to address these decarbonization challenges and help implement solutions in concert with the private sector. DOE recently launched a new crosscutting website to consolidate relevant Industrial Technology resources.[16] Example DOE efforts include funding opportunities such as Office of Clean Energy Demonstrations' (OCED) Industrial Demonstrations Program, Industrial Efficiency and Decarbonization Office's (IEDO)new Technologies for Industrial Emissions Reduction Development Program, the Department of the Treasury's Qualifying Advanced Energy Project Credit (48C) program supported by the Office of Manufacturing and Energy Supply Chain (MESC) in partnership with the IRS, the Loan Programs Office Title 17 authorities, the applied research offices and others. In addition to specific industrial programs, government procurement for low-carbon industrial materials could play an important role through initiatives like the Federal Buy Clean Initiative.

Finally, DOE is committed to working with communities, labor unions, and the private sector to build a 21st-century industrial base that meets the country's climate, economic, and environmental justice imperatives. Achieving a net-zero economy will have broad socioeconomic benefits, protect existing manufacturing employment, and create millions of good-paying jobs in construction and implementation[17], for a broad range of American workers, from now through 2050. Industrial decarbonization, if pursued with intention and attention to address legitimate public concerns and measurable harms, is a critical opportunity to: reinvigorate American industry, reduce hard-to-abate emissions, strengthen job security, enhance job creation, augment national economic security, and provide an avenue to abate health-harming pollutants from industrial operations that affect fenceline communities.[18]

Industrial decarbonization is a vital opportunity to transform industrial systems and focus on energy and environmental justice. While carbon-intensive industrial sectors are facing a critical inflection point and society is focused on accelerating deep decarbonization, this is a unique moment that neither American industry nor DOE can allow to pass. The DOE has been given unprecedented tools by the BIL and IRA to act on these challenges. **The time is now.**

15 Tactical examples of leveraging industry coalitions include knowledge sharing on emissions levels, tracking and verification systems for supply chains, and voluntary / statutory standards and requirements for low-CO2e materials.

16 DOE activities across the Industrial space are tracked at Industrial Technologies | Department of Energy.

17 Due to the nature of infrastructure projects with roles in construction, trades, engineering, and planning. These jobs may not be permanent but rather created in the implementation of industrial decarbonization.

18 Some studies have shown disproportionate burdening of BIPOC communities to industrial contaminates see: PM2.5 polluters disproportionately and systemically affect people of color in the United States | Science Advances, DOI: 10.1126/sciadv.abf4491. Life at the Fenceline Report: Life at the Fenceline - English - Public.pdf (ej4all.org) and Fumes at the Fenceline: catf-rpt-naacp-4.21.pdf

Chapter 1: Introduction and objectives

This Industrial Decarbonization Liftoff report provides an overview of the pathways to decarbonization across eight large industrial sectors highlighted in the Inflation Reduction Act (See IRA § 50161(g)(3), 42 U.S.C. § 17113b(g)(3) (2022)): Chemicals, refining, iron and steel, food and beverage, pulp and paper, cement, aluminum, and glass.[19] This Liftoff report focuses on the processing and production emissions from each sector's value chain (Figure 1.1). This report is the first in a multi-part series focused on industrial decarbonization and will include two deep-dive reports covering chemicals and refining and cement.

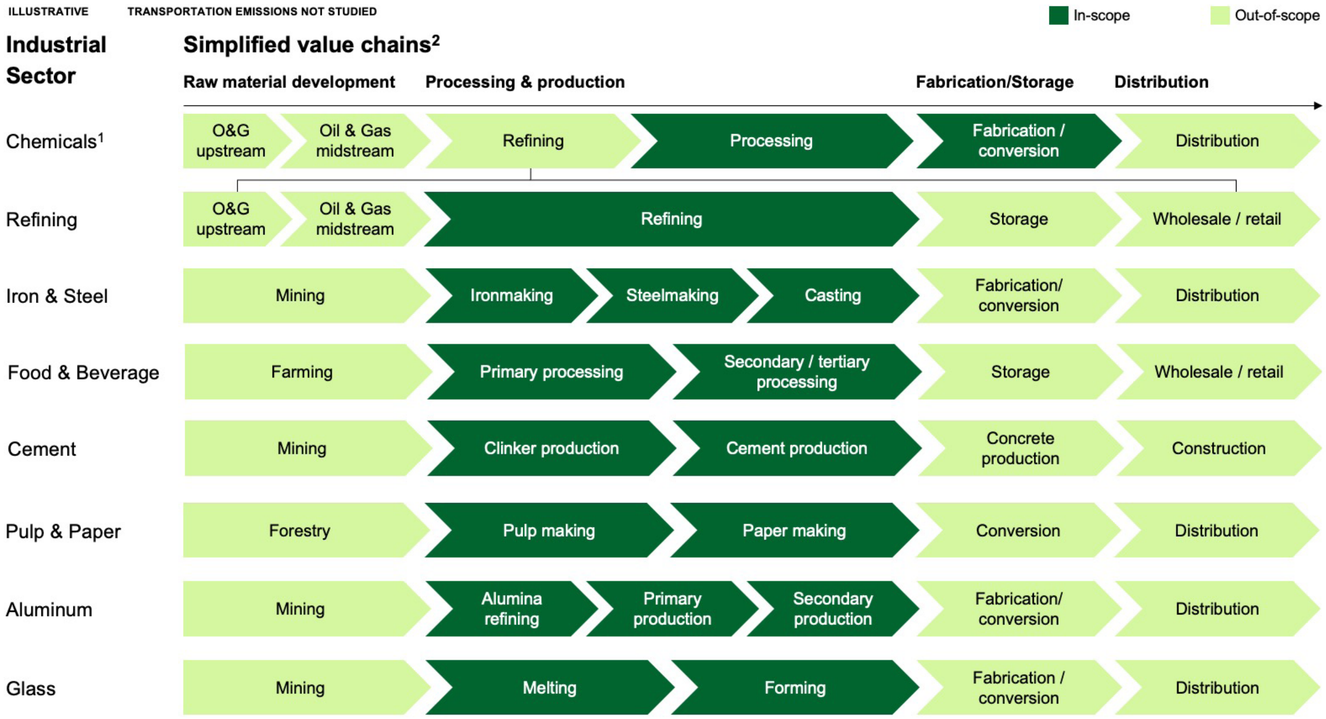


Figure 1.1: Value chain steps in scope of analysis 1. Given the share of U.S. emissions from Chemicals, further production stage emissions were included such as Natural Gas Processing due to its high emissions intensity. 2. "Well-to-gate" and "gate to grave" emissions are not discussed in this report.[20 xi xii xiii xiv]

U.S. industrial sectors could need ~$700B–1.1T21 in capital expenditures to deploy decarbonization technologies to reach net zero in 2050, with most project development and financing falling on the private sector. The analysis in this report provides a primer to investors and other parties interested in industrial decarbonization. It addresses the high-level near-term economics of decarbonization levers across industrial sectors, critical challenges to decarbonization, societal impacts and considerations, and potential solutions to those challenges.

19 Industrial sectors not studied include upstream agriculture and mining or downstream computers and electronics, transportation and electrical equipment, and other manufacturing processes with smaller emissions.

20 Note this scoping and focus on decarbonization at existing facilities while potentially addressing fenceline communities immediate EJ concerns around emissions, does not and cannot encompass their full range of EJ concerns associated with these industries supply chains and waste generation (Pellow 2017). This report also does not tackle the racialization of investment markets, only 50% of Americans own stock and only 37% of them own more than $5,000 dollars in stock. only 37 percent of households have total stock holdings over $5,000 (Palladino, L. 2019). Thirty-seven percent of Black families and 33 percent of Latino families have zero or negative wealth, compared to just 15.5 percent of white families (Hamilton et al. 2020). Shareholders are disproportionately White and high income, 92.1 percent of US corporate equity and mutual fund value is owned by white households; Black households own 1.5 percent while Hispanic households own 1.9 Percent (Palladino, L. M. (2023).

21 $700M to $1.1B represents the estimated potential capital investment required to decarbonize eight industrial sectors of focus in IRA, including chemicals, refining, iron and steel, food and beverage, cement, pulp and paper, aluminum, glass and reach net-zero by 2050.This number was calculated by estimating the capital expenditure for scaling select deployable and demonstration-stage decarbonization levers (e.g., CCS, clean on-site power generation from renewables, energy efficiency measures) for each industry. The actual capital expenditure required to achieve net-zero by 2050 may be higher given this estimate does not include additional capital spending on R&D/pilots required for levers in that category. IRA incentives reflected in the MACC analysis include 45V (hydrogen production tax credit) and 45Q (carbon capture and storage tax credit).

This report estimates the role of nine decarbonization levers based on a Marginal Abatement Cost Curve Analysis (MACC). The MACC identifies the lowest cost abatement solution for each ton of Scope 1 and Scope 2 CO2 emissions across the eight sectors. It uses high-level 2030 costs as a baseline. It is used to inform potential near-term paths to net zero in this report.[22] The MACC relies on assumptions informed by the best available public information at publication. Notable assumptions are below with full detail in Chapter 6: Modelling Appendix.

Emissions: Emissions baselines are included in terms of both 2021 CO2 (the focus of the MACC analysis) and CO2e (GWP 100), which is defined as carbon dioxide equivalent greenhouse gas (GHG) emissions and include carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), and fluorinated GHGs.[23] This analysis focused on four primary sources of energy and process-related emissions:[24]

- Low (below 200°C), medium (200–400°C), and high-temperature (400°C+) heat
- Process emissions
- Onsite generated electricity and grid power
- Other sources, such as fugitive emissions that could not reasonably pass through a stack, chimney, vent, or other functionally equivalent opening[xv]

Note: Due to the process emission scope of this report, life cycle emissions are not considered as part of the decarbonization pathway, so the approaches represented in the graphics and figures, including MACC analysis, do not represent all viable solutions for emissions reduction. In particular, the ability to reduce life cycle emissions via bio-based chemicals and bio-based fuels is not represented. However, bio-based solutions are referenced in Chapter 3b.i. and 3b.ii. There is greater detail on the role of bio-based feedstocks in Chapter 2 of the Pathway to Commercial Liftoff: Decarbonizing Chemicals and Refining report.

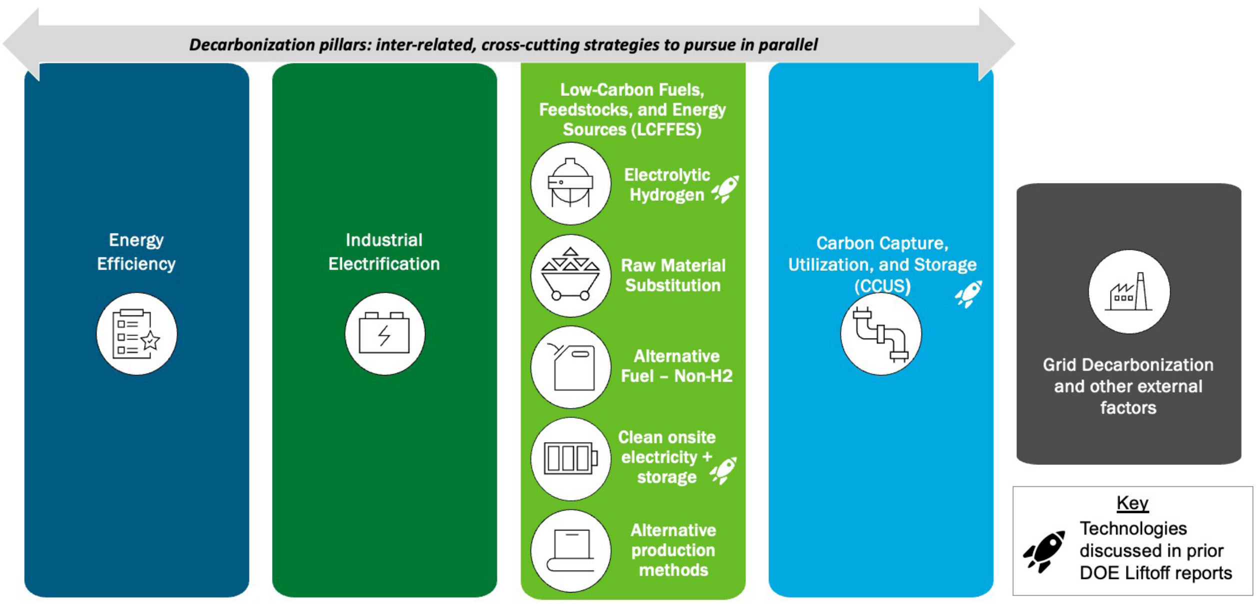


Figure 1.2: DOE Industrial Decarbonization Pillars and Liftoff levers. Decarbonization levers with a rocket ship icon have an existing Liftoff report.

22 For concision purposes, references to industrial sectors within this report are defined as the eight industrial sectors of focus (i.e., chemicals, refining, iron and steel, food and beverage, pulp and paper, cement, aluminum, and glass) unless otherwise noted.

23 N2O and fluorinated GHGs make up <10% of total CO2e emissions; CO2 and methane make up >90%; this report assumes Global Warming Potential (GWP) with a 100-year lifetime; biogenic CO2 emissions are not considered in this report, as EPA reporting states that these emissions are accounted for in Land Use, Land-Use Change, and Forestry (LULUCF) sector per IPCC and UNFCCC; however, biogenic non-CO2 emissions are accounted for in the Energy sector (e.g., incomplete combustion, waste treatment).

24 For concision purposes, references to emissions associated with the industrial sectors of focus are defined as energy- and process-related emissions, which align with IPCC's Energy and Industrial Process and Product Use sectors with the caveat that product use was not included.

Decarbonization Levers: This work started with the four pillars identified in DOE Industrial Decarbonization Roadmap. The roadmap pillars represent interrelated, cross-cutting strategies at the highest categorization of decarbonization approaches. Three decarbonization levers in this report mirror three of the pillars: CCUS, industrial electrification, and energy efficiency. For purposes of this Commercial Liftoff analysis, it was productive to disaggregate the low-carbon fuels, feedstocks, and energy sources (LCFFES) pillar into a second tier of granularity to evaluate the varying economics and implication considerations of five highly relevant technology categories: electrolytic hydrogen (the subject of the Hydrogen Liftoff report), raw material substitution, alternative fuels—non hydrogen, alternative production methods, and clean onsite power and storage. The final decarbonization lever evaluated was grid decarbonization and external factors to understand the importance of other efforts for industrial decarbonization. Therefore, nine decarbonization levers are included, and Figure 1.2 maps these levers to prior DOE reports. In future analysis, the three remaining pillars— economics and implications R&D, integration, and investments—could be similarly disaggregated as they emerge.

To conduct the MACC analysis, 2030 cost estimates are assumed for groups of technologies to abate emissions. Cost estimates use various sources depending on the decarbonization lever:

- **Carbon capture and storage** (CCS) includes the capture, transport, and storage of CO2 from industrial point sources as well as hydrogen production via natural gas reforming with CCS. While utilization is part of the DOE's Industrial Decarbonization Roadmap pillar (shown above), discussed in this report in cross-cutting abatement challenges (section 3.a.ii) and in specific sectors with emerging applications (e.g., steel), the expected 2030 market size for utilization is limited. Therefore, the MACC analysis results refer specifically to CCS and do not include utilization. This analysis assumes the use of the 45Q tax credit and cost estimates from the Carbon Management Liftoff Report, as well as cost estimates based on other industry sources where industries were not included in the Carbon Management Liftoff Report (see Appendix for further details).[25] Reformation-based hydrogen is included because these projects would likely claim the 45Q tax credit.
- **Industrial Electrification** of equipment assumes cost estimates for available sector-specific technologies.
- **Energy efficiency** assumes cost estimates for a suite of available sector-specific technologies.
- **Electrolytic hydrogen** (H2) includes hydrogen as a fuel or input to replace carbon-intensive hydrogen.[26] This analysis assumes the use of the 45V tax credit based on publicly available policy and guidance as of June 2023 and 2030 cost estimates for production, transport, and storage from the Hydrogen Liftoff Report.
- **Raw material substitution** includes recycling or alternative inputs (e.g., clinker substitution).
- **Alternative** (non-hydrogen) **fuels** and feedstocks include biomass and waste.
- **Alternative production methods** include nascent, lower-carbon alternatives to current production methods that vary by sector. This report does not estimate the costs for 2030 since economics are still emerging – these estimates could be updated in future reports. However, the potential role of alternative production methods in 2050 is assessed by sector.
    - *Note:* These technologies could meaningfully change decarbonization pathways in the future as

25 CCS figures represent incremental costs and revenues associated only with installing and operating carbon capture retrofits, not the overall facility economics. Costs for a specific carbon management project could vary even outside the ranges outlined in this report depending on facility-specific characteristics and energy prices that can significantly impact the ultimate deployment cost.

26 The MACC analysis in this report splits the category often called "Clean hydrogen" which includes hydrogen produced via electrolysis powered by clean energy sources (e.g., renewables or nuclear power) and reforming + CCS with carbon intensity <4 kg CO2e/kg H2 for life cycle (well-to-gate) emissions. (See the Clean Hydrogen Liftoff Report) This split was used based on whether projects were assumed to claim the 45V or 45Q tax credit. For more detail on assumptions, see Chapter 6: Modelling Appendix and the Clean Hydrogen Liftoff Report.

costs come down and availability increases (e.g., electric crackers, electric rotary kilns, alternative cement chemistries).

- **Clean onsite electricity and storage** assume cost estimates based on onsite solar with long duration energy storage (LDES) using costs from the LDES Liftoff report.
- **Grid decarbonization and external factors to industrial facilities** includes emissions abated by using cleaner power from the grid and expected demand reductions from other market trends. Decarbonization from these levers depends on action outside of industrial players' immediate control. Thus, this analysis uses assumptions to highlight the dependence of industrial decarbonization on these actions; but it does not conduct a scenario analysis. This analysis estimates the potential based on the linear progress of the Administration's 100% clean power by the 2035 goal.
- **Technology readiness and applicability:** Decarbonization levers are at different stages of development and maturity within each sector. This analysis uses available public information to assess technically feasible decarbonization technologies for each emissions source and sector.

This work is in support of the Department of Energy's broader industrial decarbonization activities[27] like the DOE Industrial Technologies Joint Strategy, the Office of Clean Energy Demonstrations' Industrial Demonstration Program, the Office of Manufacturing and Energy Supply Chains programs, the Industrial Efficiency and Decarbonization Office's programs including the new Technologies for Industrial Emissions Reduction Development (TIEReD) Program, and Energy Earthshots Initiative™.

27 DOE activities across the Industrial space are tracked at Industrial Technologies | Department of Energy.

Chapter 2: Current state – Technologies and markets

Key takeaways

- **The U.S. industrial sectors of focus significantly contribute to U.S. emissions, accounting for ~14% of 2021 U.S. CO2e emissions (GWP100) and other health-harming pollutants.** These emissions can be understood through three lenses:
  - *Emissions source*, which constrains the technology that can be used.
  - *Facility-specific factors* (e.g., physical location, layout, maintenance schedule) constrain what, when, and how implementations can happen (i.e., the operational plan).
  - *Sector*, which constrains the commercialization plan for scaling technologies.
- **The technology landscape of industrial decarbonization can be understood by comparing a specific technology's technology readiness level (TRL) and adoption readiness level (ARL).**
  - Throughout this report, the ARL and TRL classify technologies in one of three stages of development along the research, development, demonstration, and deployment (RDD&D) continuum: Deployable, Demonstration, and R&D/Pilot.
- **Industry momentum around the deployment of decarbonization levers varies but is concentrated around high technology readiness level (TRL) levers with attractive economics.**
  - Yet, customers and other stakeholders increasingly expect companies to address climate change, and some companies are making bolder decarbonization moves (e.g., First Mover Coalition, Frontier).
  - Increased customer demand and willingness to pay for low-carbon products will create opportunities to build low-carbon businesses and exports that capture technology premiums.

Section 2a: Emission baseline and scope

- **The industrial sector accounted for ~23% of 2021 U.S. CO2e emissions.**[28] **The energy and process-related emissions from the eight sectors of focus in the IRA account for ~14% of emissions, totaling ~876 MT CO2 equivalent or ~850 MT CO2 in 2021.**[ii] As noted above, these emissions can be examined through three lenses: *emissions source*, *facility*, and *sector*.

- **Emissions source (i.e., heat, process, electricity) determines the applicable decarbonization levers.** Emissions sources are highly variable, both within and across these eight industrial sectors, due to industry differences, including production processes. The emissions source is the most important factor in determining what decarbonization lever can abate emissions.

  There are four sources of industrial emissions: those from heat generation (~52%), process emissions associated with chemical reactions (~18%), electricity consumption (~27%), and other (3%) (Figure 2.1).[iii, iv, v, vi, vii, viii]

28 Based on 2021 data calculated using GWP100 (Global Warming Potential). The percentage represents the share of total US CO2e GHG emissions from these sources in the eight industries of focus and the emissions from the other industries (e.g., machinery, computers and electronics, transportation equipment, wood products, agriculture, mining), which were sourced from the EIA Annual Energy Outlook 2021 and EPA Greenhouse Gas Reporting Program.

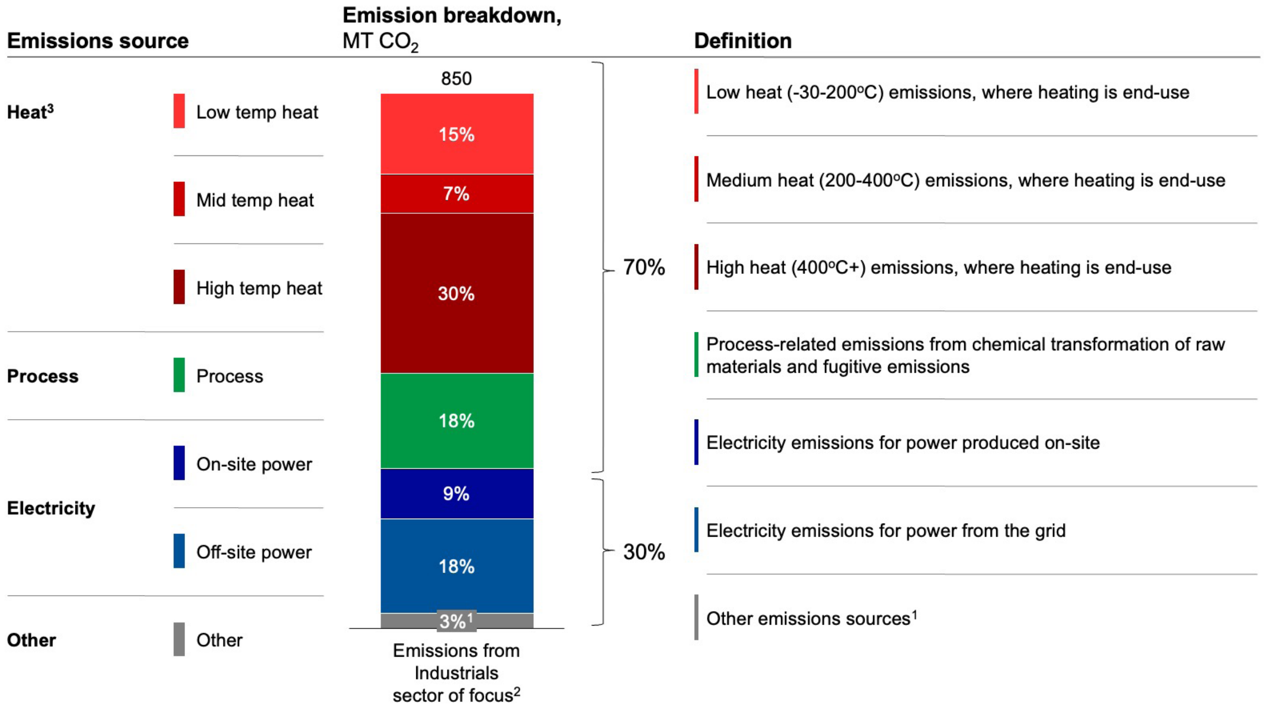


Figure 2a.1: Most industrial emissions in the eight sectors of focus come from heat and chemical processes | 1. Includes electrochemical processes, refrigeration, and cooling for ethylene / propylene; cooling and heat loss for ammonia; fugitives or leakage emissions from NG processing; and quarry and logistics emissions (e.g., cement) | 2. Estimate based on available data | 3. Temperature ranges: low temperatures heat is from -30oC to 200oC, medium heat is from 200oC to 400oC, and high heat is 400+oC
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

Different production processes across sectors mean that emissions sources can vary significantly (Figure 2a.2). While production processes vary significantly across sectors, decarbonization solutions for heat, process, and power emissions may offer cross-cutting solutions for other sectors (e.g., pulp and paper and food and beverage sharing learnings for decarbonizing low-temperature heat).

Heat generation is fundamental to various industrial processes. Examples include boilers that produce steam for pasteurization processes (food and beverage), cracking furnaces used for ethylene production (chemicals), and blast furnaces used to heat limestone and melt iron ore pellets (cement and iron and steel), respectively.[29, xvi] Heat generation can be further categorized into low- (below 200°C), mid- (200°C to 400°C), and high-temperature (> 400°C) heat, and the type of low-carbon solutions will vary depending on the temperature change needed across process temperatures.

Process emissions result from the chemical transformation of raw materials Examples include: CO2 released from the calcination process during clinker manufacturing in cement production (i.e.,) and CO2 released due to the chemical reaction between carbon anode and alumina in the smelting process (i.e., 2 Al2O3 (alumina)+ 3 C (carbon anodes)→ 4 Al (molten aluminum)+ 3 CO2).

29 Only ~15% of emissions from cracking furnaces are associated with mid-temperature heat; ~80% is associated with high-temperature heat and ~5% with electricity.

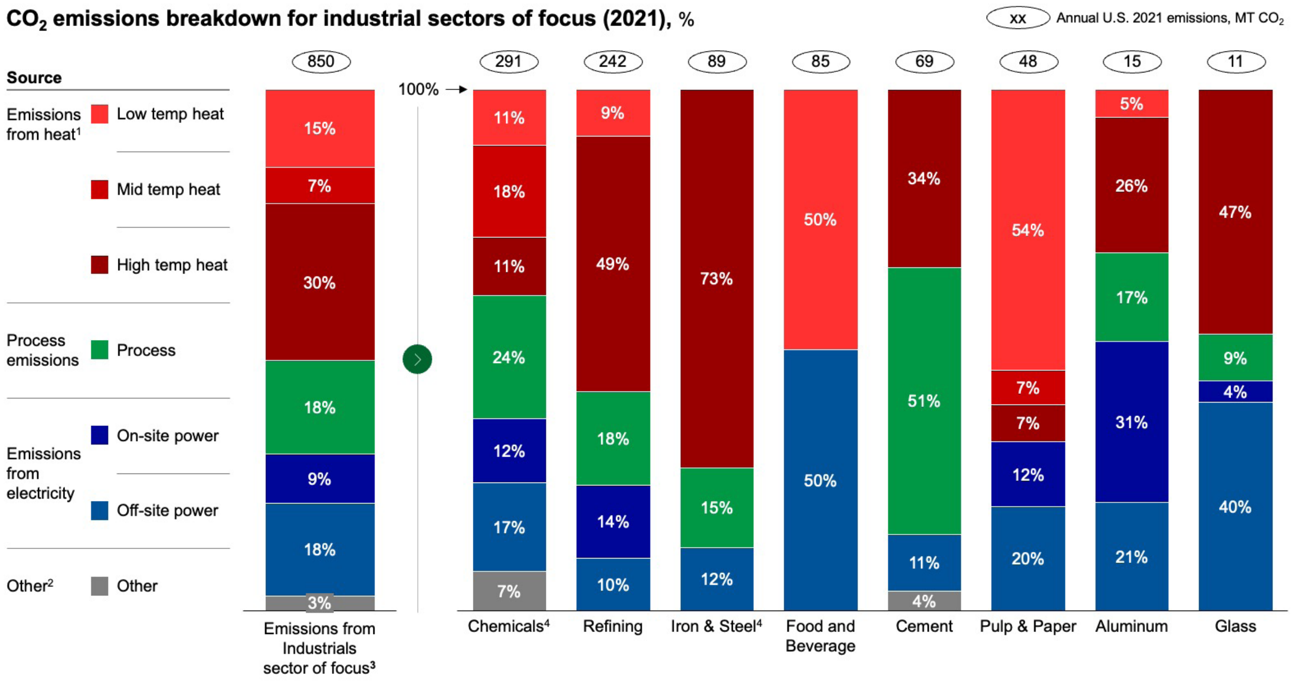


Figure 2a.2: Emissions sources across the sectors of focus are highly variable | 1. Temperature ranges: low-temperature heat is from -30ºC to 200ºC, medium-temperature heat is from 200ºC to 400ºC, and high-temperature heat is 400+ºC | 2. Includes electrochemical processes, refrigeration, and cooling for ethylene / propylene; cooling, heat loss for ammonia; fugitives or leakage emissions from NG processing; and quarry and logistics emissions | 3. Includes Scope 1 and 2 emissions for U.S. industry only; estimate based on available data | 4. Weighted average of in-scope subsegments
Source: 2018 EPA Flight, 2018 EERE Manufacturing Energy and Carbon Footprints report, 2022 IEDO Report, Energy Environ. Sci., 2020,13, 331-344, EIA, 2020 USGS, DOE Natural Gas Supply Chain report

Finally, electricity consumption contributes to emissions from both onsite and purchased power. Onsite electricity refers to generating electrical power within an industrial facility for consumption. For example, refineries use onsite turbines powered by natural gas or refinery fuel gas to generate power (refining), and some aluminum smelters have onsite generation due to high electricity usage (aluminum).[30] Grid-connected facilities across all eight sectors also use electric power purchased from the grid—which can vary in carbon intensity depending on region, time of consumption, and clean energy procurement mechanisms.

Other emissions include electrochemical processes, refrigeration, and cooling for ethylene/propylene; cooling, heat loss for ammonia; fugitives or leakage emissions from NG processing; and quarry and logistics emissions.

- **Facility-specific factors and available infrastructure determine an operational plan's feasibility.** Facility maintenance cycles can mean downtime is slated in 10+ year increments, and industrial companies often want to time decarbonization projects with downtime. Physical layouts and space on site can dictate whether certain levers are viable. A facility's geographic location determines the availability of infrastructure and its associated costs (e.g., CO2 transport and storage in North Dakota or the Gulf Coast will cost less than on the East Coast because of geology). In the U.S., CO2e emissions come from thousands of facilities, with the South and Midwest representing 80% of the emissions (Figure 2a.3).

30 In the U.S., the source of onsite power for aluminum smelters varies by geography

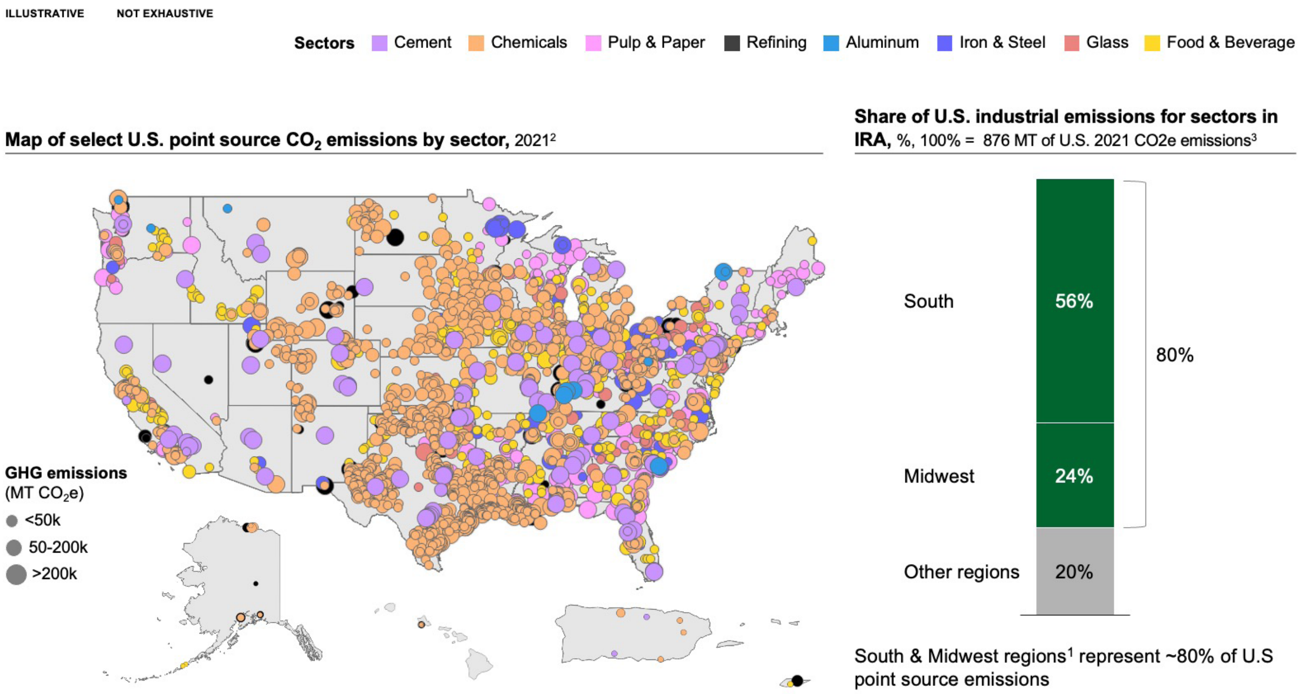


Figure 2a.3: Emissions are dispersed across 2,500+ facilities across the U.S. | 1. Regions are defined using U.S. Census guidance | 2. Includes natural gas processing, refineries, chemicals production (various), food processing, cement production, glass production, aluminum production, iron and steel 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 CO2e/year and does not include emissions from land use, land use change, or forestry | 3. Includes 850 MT CO2 emissions in addition to other non-CO2 GHG emissions.
Source: EPA flight.

Biogenic emissions in sector (not included in share)[3]

Sector share of 2021 CO_2e emissions from eight industrial sectors of focus,[1] %, 100% = ~876 MT of U.S. 2021 CO_2e emissions (14% of total U.S. CO_2e emissions)

Sector	Share	U.S. 2021 emissions MT CO_2e	U.S. 2021 emissions MT CO_2[4]	Global 2021 emissions MT CO_2
Chemicals	35.5%	315	291[2]	~1,000
Refining	27.4%	243	242	~1,400
Iron & Steel	11.3%	89	89	~3,100
Food & Beverage[3]	9.6%	85	85	~400
Cement[3]	7.8%	69	69	~2,500
Pulp & Paper[3]	5.4%	48	48	~200
Aluminum	1.8%	16	15	~1,100
Glass	1.2%	11	11	~100
Total		876	850	~9,800

Figure 2a.4: The eight industrial sectors of focus represent 14% of US CO2e emissions | 1. Includes other greenhouse gas emissions and non-industry sectors using GWP100 | 2. CO2 split into natural gas processing (59 MT), steam methane reforming + Haber-Bosch (46 MT), steam cracking (41 MT), Chlor-alkali process (26 MT), Other (119 MT). | 3. Does not reflect the biogenic emissions of the sector. Paper has estimated biogenic emissions of ~104 MT. Cement biogenic emissions resulting from the use of alternative fuels. | 4. For all decarbonization assessments in the remainder of this report, the analysis considers CO2 rather than CO2e. 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).

- **Sector determines the commercialization environment for decarbonization. For example,** in the U.S., chemicals and refining represent 60%+ of CO_2e emissions (Figure 2a.4). [iii, iv, v, vi]. These emissions are also concentrated in a handful of large industrial players. The pathway to decarbonization will depend on the ability of these players to invest and deploy decarbonization technologies to offer low-carbon products. In other sectors, the U.S. footprint is small compared to the sector abroad; domestically, the work to decarbonize could be impactful in a global mission to reduce emissions. As an example, although cement only represents ~1% of overall emissions in the U.S., globally, it represents 7–8%. The sector dynamics are critical to understand, including industry context, applicable technologies, and decarbonization momentum (e.g., ambition, existing demonstrations). To successfully reach net zero and utilize commercial tailwinds, sector-specific Pathways to Commercial Liftoff must be determined. Chapter 3.b details these dynamics and offers sector-specific decarbonization leadership opportunities and "Pathways to Liftoff."

Section 2b: Technology landscape

The technology landscape of industrial decarbonization can be understood by comparing a specific technology's TRL and ARL, which vary across decarbonization levers, sectors, and development stages.

Technology readiness levels[31] (TRL) assesses the maturity of technology elements across a lab, pilot, demonstration, or commercial scale. Adoption readiness levels[32] (ARL) focuses on commercialization risk factors like value proposition, product-market fit, demand-pull, supply chain availability, etc. These dimensions come together to highlight the overall readiness of technologies across our decarbonization levers and sectors. **Throughout this report, we classify specific technologies in one of three stages of development along the research, development, demonstration, and deployment (RDD&D) continuum based on both their technology readiness and adoption readiness**: deployable, demonstration-stage, and R&D or pilot-stage (Figure 2b.5).

- **Deployable** technologies have high TRL and relatively high ARL but may not be fully commercialized today. The lack of widespread adoption typically results from barriers in one area of adoption readiness (e.g., net-positive energy efficiency improvements deprioritized for other higher return uses of capital). Investments in this stage are important to de-risk remaining ARL barriers such as ease of implementation, demand maturity, or infrastructure availability.

- **Demonstration-stage** technologies have high TRL but low ARL. Investments in this stage could address technical barriers to increase TRL and improve the ARL of the technology by focusing on functional performance and delivered cost.

- **R&D- and pilot-stage** technologies are lower TRL and low ARL. Typically, technologies do not have clear economics at this stage, but development could change the path to net zero. Investments in this stage typically focus on overcoming technical barriers and do not focus on improving ARL, but anticipated barriers like materials sourcing could guide research consideration.

31 The full definition of Technology Readiness Levels can be found at the Department of Energy's Office of Management, Directives Program website.

32 A brief definition is available in this report's glossary. The full definition of Adoption Readiness Levels can be found at the Department of Energy's Office of Technology Transition website.

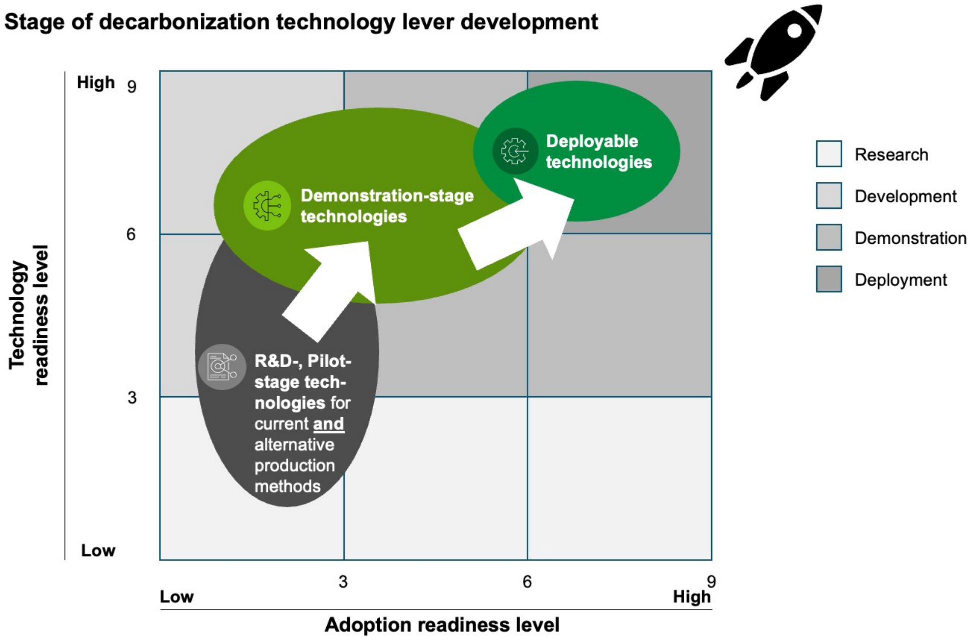


Figure 2b.5: Stages of decarbonization lever development by technology readiness level and adoption readiness level

Each decarbonization lever represents a group of technologies used to abate emissions from different sources—each has sector-specific nuances for commercialization. The stage of development of the same lever can vary across sectors. For example, the stage of industrial electrification in a sector depends on the specific process; while the technology to electrify steelmaking—electric arc furnaces—is deployable, technology for electrifying food and beverage processes like fryers is in the R&D stage. Figure 2.6 highlights opportunities across sectors in various stages of development; technologies are evaluated across seven decarbonization levers studied and eight sectors. This figure is non-exhaustive but rather highlights near-term opportunities in every industry and every lever. The rest of this section examines the decarbonization levers and some examples of existing commercialization activity. The two decarbonization levers (clean onsite electricity and storage and grid decarbonization) not shown in Figure 2.6 are discussed at a cross-sector level.

In addition, social acceptance or opposition to these levers varies generally and locally, reflecting public concerns about health, employment, and environmental impacts. This can impact the viability of certain levers in certain locations. Please see Chapter 3, section C, other Liftoff reports, and the societal considerations and impact wrapper for further discussion.

ILLUSTRATIVE

U.S. stage of development: Deployable | Demo | R&D / Pilot | Limited relevance for sector decarbonization

NEAR-TERM OPPORTUNITIES EXIST IN EVERY INDUSTRY AND IN EVERY LEVER - NOT EXHAUSTIVE

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

Industrial Sector

Figure 2b.6: Opportunities to implement deployable levers exist across all sectors | 1. Ethanol dehydration | 2. Fluid Catalytic Cracker (FCC) | 3. Steam Methane Reformer (SMR) | 4. Blast Furnace – Basic Oxygen Furnace (BF-BOF) | 5. Natural Gas – Direct Reduced Iron / Hot Briquetted Iron (NG-DRI/HBI); Refers to the substitution of natural gas as a reductant in place of coal | 6. Electric Arc Furnace (EAF) | 7. Geopolymers | 8. E.g., absorption chillers, ejector refrigeration, deep waste energy and water recovery, alternative protein manufacturing | 9. Refers to electrolytic hydrogen 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 and Renewable Energy. (n.d.). Industrial Efficiency and Decarbonization Office (IEDO) FY23 Multi-Topic FOA. B.) Novel cements. Cembureau. (2018, September 28). | 11. Mechanical recycling is widely deployed, while chemical/advanced recycling is more nascent. Additional details can be found in the Chemicals and Refining Liftoff report.

Investments are urgently needed in both deployable decarbonization technologies and those in the Demonstration and R&D stage. The industry is reasonably concerned about becoming locked into a high-capital decarbonization technology when a lower-cost alternative could be developed. However, the urgency and scale of the abatement needed to reach net zero requires an 'all of the above' approach to investment. Deployable decarbonization technologies can be implemented on existing assets, while investment in R&D could enable new technologies for low-carbon greenfield development in the future.

- **Carbon capture, utilization, and storage (CCUS)** refers to technologies that can be applied to the concentrated and dilute flue gas streams generated from industrial heat generation and processes, which capture emissions for utilization or storage. This report focuses on CCS unless CCUS is used due to the nascency of utilization today. **These technologies can be added to existing facilities as retrofits in regions with access to CCS wells, facilities, and suitable geological formations.** CCS retrofits can enable decarbonization in industrial applications that have exhausted other decarbonization technologies and strategies, have limited ability to transition to lower-carbon production methods, or where capital costs for low-carbon greenfield facilities can be prohibitive. Greenfield facilities can also be designed for easier/less expensive CCS from the start (e.g., new ATRs or crackers engineered to accommodate capture equipment). CCS applications vary from concentrated flue gas streams (e.g., natural gas processing, process emissions from steam methane reforming SMR) to dilute streams (e.g., combustion for fluid catalytic cracking in refining, process emissions in aluminum smelters).[33] This lever also includes hydrogen created via reforming with CCS with carbon intensity <4 kg CO2e/kg H2 well-to-gate emissions, which would use the 45Q tax credit. Please reference the Carbon Management and Clean Hydrogen Liftoff Report for further details.

33 SMR units have concentrated flue gas streams associated with chemical process emissions and dilute flue gas streams associated with the combustion of natural gas.

Carbon management is commercially mature and already deployed in some sectors that feature concentrated flue gas streams. CCS in the power sector is typically viewed as a higher TRL and ARL technology than CCS in the industrial sector due to previous R&D investments. In the industrial sector, several dozen commercial-scale carbon management projects are in operation today, primarily in the U.S. and Canada, for natural gas processing or ethanol to enhanced oil recovery (EOR), where capture costs are low, and projects have sufficient returns from policy supports and EOR revenues to make them attractive. With expanded 45Q in the US, and increased policy supports in Europe, Canada, and elsewhere, over a hundred CCS projects are in various stages of development. These projects are also largely in natural gas processing and ethanol, as the 45Q expansion has made more projects appear economically viable. However large projects have also been announced around ammonia/hydrogen and direct- reduced- iron production. Estimated project economics for CCS retrofits on higher-cost-to-capture applications (e.g., cement, iron and steel) require cost or revenue improvements or additional policy for widespread CCS deployment. [34, 35] Implementation of these technologies is also affected by the current or potential future availability of CCS infrastructure, or where facility- level siting and geology would enable onsite storage.

- **Industrial electrification** refers to electrifying fossil-fuel-powered equipment or replacing fossil-fuel-driven industrial processes. Examples of the former include resistive heaters or thermal energy storage to replace natural gas-powered steam generation and electric kilns for cement, and examples of the latter include iron electrolysis or other electrochemical approaches. Industrial electrification presents a major opportunity to reduce emissions in industrial sectors.

  The commercial readiness of industrial electrification technologies varies across sectors and emissions sources. Some electrification options are relatively mature and ready for deployment (e.g., electric compressors in Natural Gas Processing (NGP), electric arc furnace (EAF) in iron and steel). Low-temperature heat decarbonization has existing technologies (e.g., industrial heat pumps, electric boilers), but requires cost improvements to scale. Other technologies require research, development, and demonstration (RDandD) investment or other economic support to achieve commercialization and scale (e.g., electric crackers, high-temperature heat electrification). Electrification of heat will be further discussed in Chapter 3.

  While electrification often represents a major process shift and requires a large investment (e.g., onsite facility infrastructure upgrades, interconnection process with grid), this equipment relies on reliable, low-cost, clean electricity onsite or from the grid to reach full decarbonization potential. These two decarbonization levers are discussed at the end of this section.

- **Energy efficiency** improves current processes to reduce demands for inputs like fuels, electricity, and other utilities or raw materials. Across the eight industrial sectors analyzed in this report, energy efficiency solutions represent the "low-hanging fruit" to reduce emissions in cost-effective and/or net-positive ways that optimize fuel or power consumption. Specific technologies vary by sector, but examples include real-time energy management systems, waste heat recovery, upgrades to best-available technologies, and material pre-heating.

  Most efficiency solutions are mature and economic, passing a 10% hurdle rate. Many players across sectors have been implementing best-practice solutions for years, but implementation is a continuous process the pace of adoption can be accelerated across industrials.

- **Electrolytic hydrogen** uses clean energy to power an electrolyzer, which passes an electric current through water, splitting it into hydrogen and oxygen (an example of process electrification).

34 Project economics for CCS applications are impacted by tax incentives, which provide up to $85/t CO2e stored from carbon capture on industrial and power generation facilities (45Q)

35 In general, the cost of CO2 capture is inversely proportional to the CO2 purity of the emission stream. But even within the same industry, several factors meaningfully impact the cost of capture, including facility design, the separation technology used in the capture process, local energy prices, emissions volumes, flue gas temperature and pressure, and the presence of emissions stream contaminants.

Clean hydrogen can also be produced by reforming fossil fuels and CCS, which uses hydrocarbons to create hydrogen and then captures the resulting carbon emissions. Reformation-based hydrogen with CCS is considered under the CCS lever in this analysis. Several industrial sectors use hydrogen as a process input (e.g., chemical, refining), and clean hydrogen could be a replacement to reduce process emissions.

The stage of commercialization for electrolytic hydrogen varies across sectors. Some industries have process streams where clean hydrogen is deployable (e.g., hydrotreating in refineries). These are focused on the drop-in-replacement of clean hydrogen for existing hydrogen applications. Others are demonstration-stage (e.g., clean ammonia production, hydrogen-based direct-reduced ironmaking). These require some equipment or process modification or testing. Clean hydrogen integration and use in other industries require R&D to understand design challenges and reduce costs (e.g., hydrogen for decarbonized heat). For example, food and beverage (FandB) processing, pulp and paper, and aluminum largely use natural gas boilers which could be supplemented or replaced with clean hydrogen. R&D and pilot-level work are needed to address fuel switching challenges (e.g., flashback, mitigating pollutants like nitric oxides, and different heat transfer profiles), and production and distribution networks will need to reach commercial scale and become cost competitive with existing fuels. Looking ahead, capital costs-reductions are forecasted between ~60–80% across electrolyzer types through 2030. [36, xvii] Please reference the Clean Hydrogen Liftoff Report for further details.

- **Raw material substitution** uses lower-carbon inputs to reduce emissions. Seven out of eight sectors have distinct opportunities to lower operational emissions by using alternative and recycled materials as process inputs.

  The use of raw material substitutes is relatively mature. For example, recycled materials are already used in sectors like ethylene, pulp and paper, glass, iron and steel, and aluminum. Other industries feature substitutes that are deployable today with room for further adoption, e.g., decreasing the average clinker-to-cement ratios (currently 89% in the U.S. and 76% in the EU) with clinker substitutes such as pozzolan, fly ash, and calcined clay, or increasing cullet use in glass production.[xviii]

- **Alternative fuel (non-hydrogen):** Several industrial sectors can reduce emissions through alternative, lower-carbon fuels, e.g., biomass, waste, etc. Due to the scope of the analysis pursued in this report being focused on production emissions, detailed discussion low-carbon fuels and feedstocks are currently not included, but were explored further in the Chemicals and Refining Liftoff Report Section 2e.The stage of commercialization varies by sector with some deployable use cases (e.g., rotary kilns in cement, boilers in pulp and paper), while other applications are in the demonstration phase (e.g., boilers in FandB) or R&D (e.g., melting furnaces in glass). [37, 38]

- **Alternative production methods:** Industries are researching and developing new production pathways to create the same or similar products with lower emissions that could also have other operational or product quality benefits. These alternative methods are typically nascent and inherently sector specific. DOE's Industrial Decarbonization Roadmap includes a discussion of emerging alternative methods in some sectors. These new production pathways will be covered in further detail in the individual industry Liftoff reports. For example, please see the Cement Liftoff report for a discussion on the emerging production pathways and chemistries for producing low-carbon cement.

The remaining two decarbonization levers are discussed at a cross-sector level, given the similarities of technologies across industries. Additional detail on commercializing clean power technologies can be found in existing and future liftoff reports (e.g., Long Duration Energy Storage and Advanced Nuclear).

36 Project economics for clean hydrogen applications are impacted by 45V IRA tax incentives, which provide up to $3/kg of hydrogen produced with low carbon intensity (<0.45 kg CO_2e / kg H_2).

37 Substitute fuels include waste tires and combustible industrial byproducts.

38 Melting furnaces can employ oxyfuel technology, which uses pure oxygen instead of air as an oxidizing agent, resulting in improved efficiency and reduced emissions.

- **Clean onsite electricity and storage** includes industrial facilities that need reliable heat and power from dedicated onsite power generation or combined heat and power (CHP) systems. Both situations offer opportunities for reductions in the emissions associated with power production. Some applications could replace current onsite fossil-powered CHP generation with solutions like electrified steam-generating equipment or advanced nuclear reactors.

  Many clean electricity technologies are commercially mature and used in U.S. power markets (e.g., solar, wind, and nuclear), and some sectors have already deployed onsite generation. However, applications face challenges to adoption due to reliability concerns for variable renewables, the capital required for buildouts, and space limitations within a facility. Nuclear and renewables with storage can provide clean, firm power, which is especially important for operations that require 24/7 reliability.

  In the Industrial sectors of focus, many onsite systems are used for combined heat and power (CHP). Advanced nuclear designs, such as high temperature gas reactors, can fully replace CHP systems to provide electricity and high-quality steam, but will require demonstration in an industrial environment to prove their ability to meet cost and schedule requirements. Energy storage technologies and process flexibility can address variability concerns but vary in technological maturity. To gain competitiveness with existing technologies, these solutions must improve their economics through cost reductions driven by RDandD. Options for CHP like Thermal Energy Storage will be discussed in Chapter 3a.ii, and more detail is available on clean, firm power in the LDES and Nuclear Liftoff Report.[xix]

- **Grid decarbonization** focuses on the ~20% of industrial emissions attributed to fossil fuels that generate grid electricity. This source is external to the sustainability efforts of the facilities themselves. Addressing this portion of emissions relies on utilities reaching administration goals of 100% grid decarbonization by 2035. [xii]

  In addition to decarbonizing existing generation, U.S. electricity demand could grow substantially from 2020–2035 due to increased end-use electrification and growing hydrogen production. [xx] Industrial players may seek to secure access to decarbonized electricity through various energy attribute credits, power purchase agreements (PPAs), and virtual PPAs.

Section 2c: Industry momentum

On the public side, there are now incentives to catalyze industrial decarbonization in the near-term following passage of the Inflation Reduction Act (IRA) and Bipartisan Infrastructure Law (BIL). Several examples include:

- **BIL:** The BIL provides funding to decarbonize industrial processes. This funding includes allocations for high-potential projects across industrial decarbonization, including funding for demonstration and pilot projects. Some selected examples are: $8B for Regional Clean Hydrogen Hubs, which will generate and use clean hydrogen in close proximity with connective infrastructure;[39] approx. $800M for Carbon Capture Demonstration Projects at industrial facilities;[40] $750M for Advanced Energy Manufacturing and Recycling Grants[41] that can be used to reduce GHG emissions in facilities; and $400M for Industrial Research and Assessment Center Implementation Grants[42] to fund small- and medium-sized manufacturers.

- **BIL / IRA - OCED's Industrial Demonstration Program (IDP):** This program released an approximately $6B Funding Opportunity Announcement (DE-FOA-0002936) that aims to support projects that can effectively showcase the feasibility and scalability of technologies or practices contributing to industrial decarbonization and emission reduction goals while generating benefits and mitigating harms to surrounding communities.

39 IIJA § 40314, 42 U.S.C. § 16161a (2021).
40 IIJA § 41004, 42 U.S.C. § 16292 (2021).
41 IIJA § 40209, 42 U.S.C. 18742 (2021).
42 IIJA § 40521, 42 U.S.C. § 17116 (2021).

- **IRA – Section 48C Tax Credit:** IRS reestablished the advanced energy property credit program, which will provide a credit of up to 30% for various types of energy projects. Qualifying entities must apply to secure a portion of a limited $10B allocation.[43]

- **IRA – Section 45Q Tax Credit:** As amended by the IRA, the 45Q credit pays up to $85 per ton of CO2 stored; requires that qualified projects commence construction by the end of 2032; and allows the taxpayer to claim the credit for 12 years once a project is placed in service.[44] Please reference DOE's Carbon Management Liftoff Report for further detail.

- **IRA – Section 45V Tax Credit:** The IRA established the 45V Hydrogen Production Tax Credit, which provides up to $3 per kg[45] of hydrogen produced to qualified facilities with a well-to-gate greenhouse gas emissions intensity of less than 0.45 kilograms per kilogram of hydrogen (kg CO2e/kg H2) for 10 years once a project is placed in service.[46] Please reference and DOE's Hydrogen Liftoff Report for further detail.

- **IRA – Section 45Y Tax Credit**: The IRA introduces a technology-neutral tax credit for clean energy production from projects placed in service after Dec. 31, 2024. Distinct from the technology-specific tax credits under the existing PTC regime, under section 45Y, taxpayers with qualifying facilities will be able to claim an inflation adjusted incentive of $0.03-0.015 per KWh of electricity produced with zero or negative GHG emissions.[47]

- **IRA – Section 48E Tax Credit:** The IRA introduces a technology-neutral tax credit for clean electricity generation and storage projects placed in service after Dec. 31, 2024. Distinct from the technology-specific tax credits under the existing ITC regime, under Section 48E, taxpayers can claim a 30% credit based on emission measurements, which requires zero or net-negative carbon emissions.[48]

- **IRA / Buy Clean:** Initiative in the United States aimed at incorporating environmental criteria into federal procurement decisions for construction materials. It encourages the selection of materials with lower carbon emissions, promoting sustainability and reducing the environmental impact of federal infrastructure projects. By prioritizing low-carbon building materials, the program aims to drive the adoption of cleaner manufacturing practices in the construction industry. IRA Section 60503 provides the U.S. General Services Administration (GSA) with $2.15 billion for acquisition and installation of construction materials and products with substantially lower levels of embodied greenhouse gas emissions as compared to estimated industry averages, as determined by the Administrator of the U.S. Environmental Protection Agency (EPA).[49]

- **LPO Title 17 authorities:** LPO offers senior debt to support major industrial decarbonization and supply chain projects. These loans are intended to enable and accelerate the bankability of emerging industrial decarbonization technologies and the decarbonization of existing energy infrastructure while creating good jobs and supporting local communities.

Other policies could add to the momentum. For example, carbon border adjustment mechanism (CBAM) policies establish a price on carbon for imported goods. In October 2023, the European Union will begin the first phase of its CBAM, requiring importers to report emissions associated with their imports. In January 2026, the EU will set a price on carbon for imports, including U.S. steel, cement, fertilizers, and hydrogen. Such a policy could accelerate the clean energy transition domestically and abroad while also strengthening American economic competitiveness.

43 IRA § 13501, 26 U.S.C. § 48C (2022).

44 IRA § 13104, 26 U.S.C. § 45Q (2022).

45 Assuming the qualified facility satisfies the prevailing wage and apprenticeship requirements, which allow for a 5X multiplier. 26 U.S.C.§45V(e).

46 IRA § 13204, 26 U.S.C. § 45V (2022).

47 IRA § 13701, 26 U.S.C. § 45Y (2022).

48 IRA § 13702, 26 U.S.C. § 48E (2022).

49 IRA § 60503.

In addition, there has been demand-side traction across industrial sub-sectors. Demand for low-carbon products has emerged over the last eight years, with early movers like Apple committing to buy low-carbon products and industry consortia like First Movers Coalition (FMC) and Frontier strengthening demand. FMC is organizing companies to use their combined purchasing power to create positive market signals for upfront investment in clean technologies.[xxi] For many end uses of industrial goods, additional costs for decarbonized inputs, e.g., clean steel or cement, is diluted along the value chain and represents a small share of finished good costs.[xxii] Meeting these demand signals requires traceability for the carbon intensity of products. In addition, traceability requirements could offer an opportunity to highlight environmental, social, and governance (ESG) metrics for these products. A key challenge for catalyzing action for demand signals is connecting industrial goods suppliers with buyers, as the end customer's willingness to pay and connectivity to suppliers varies widely by product and market. However, there are encouraging examples in markets like the auto industry, where clean premiums are emerging for some steel products, and large car makers are making public statements about their need for low-carbon steel and traceability through the value chain.

The government can play a key role in enabling demand for industrial end use products. As a significant buyer of cement and steel, the government is using the Federal Buy Clean Initiative to create firm demand for low carbon goods. States could also play a role. Bills were considered in both California[50] and New York[51] focused on low-carbon materials in public projects.[xxiii] In July, the DOE announced plans to invest up to $1B in a demand-side initiative to support the Regional Clean Hydrogen Hubs by providing market certainty with the goal to unlock follow-on private investment. The funding will help form the foundation of a national clean hydrogen network aimed at reducing emissions from energy-intensive sectors.[xxiv]

Today, industry ambition and momentum around deployment varies, but is concentrated around economic levers with high TRL. Overall, most large players in the eight industrial sectors of focus have Scope 1 and 2 emissions reduction ambitions of between 10–50% by 2035, however, this varies by sector.[52, 53] Approximately 70–90% of top players in cement, FandB, caustic soda/chlorine (chemicals), ethylene (chemicals), iron and steel, and pulp and paper have set public 2035 Scope 1 and 2 targets, while only ~40–60% of top players in refining, aluminum, glass, and ammonia (chemicals) have public 2035 targets. If successful, **these targets represent only a ~10% reduction of Scope 1 and 2 U.S. industrial emissions by 2035** from the 2021 baseline.

However, first movers across sectors are taking action on demonstration stage technologies. Ammonia (chemicals) and iron and steel producers have already announced or implemented critical decarbonization technologies in U.S. facilities. Ten of the world's active CCS projects are at chemical plants, stripping the CO2 naturally contained in natural gas processing. [xxv] Ammonia producers and steelmakers have also announced more brown-to-green retrofits (i.e., decarbonizing new production capacity and retrofitting existing capacity). Market leaders in glass, steel, and cement production are already deploying raw material substitution technologies. Three natural gas DRI/HBI steel plants operate in the US today, and first-movers in cement are introducing clinker substitutions into their processes. [xxvi, xxvii] Leaders in the glass industry are using cullet, improving U.S. container glass recycled content compared to Europe. [xxviii] Across industrial sectors, private-sector participants lead decarbonization. Additional detail on sector-specific stages of commercialization can be found in Chapter 3 within sector overviews.

Despite progress made by a few sectors, most have not yet implemented decarbonization levers with a large abatement potential. For example, CCS has not yet been implemented at scale in the U.S. apart from natural gas processing. Challenges affecting the implementation and scale-up of these decarbonization levers—and potential solutions—are discussed in Chapter 4.

Finally, along with decarbonizing direct emissions from operations, some industrial sectors must balance competing sustainability priorities. For example, both chemicals and pulp and paper see demand for

50 SB-778 Buy Clean California Act

51 A08617 (2019)

52 Range excludes outlier targets with N<2

53 Top players are defined as the 10 largest companies by U.S. market share in each sector.

increasing the recycled content of products. Recycling reduces waste, however, the impacts on lifecycle emissions are under active study and vary depending on the type of recycling used, e.g., mechanical vs. chemical.[xxix,xxviii] Another example is present in food and beverage, where emission reductions are often eclipsed by efforts to reduce the even larger "on-the-farm" emissions.

Chapter 3: Pathways to commercial scale

Key takeaways

- **By 2030, up to 40% of emissions could be abated with external factors to facilities or existing net-positive (10% estimated internal rate of return) decarbonization levers when IRA incentives are included.**
  - ~15% of total industrial emissions abatement potential in 2030 depends on grid decarbonization, making it a critical dependency to decarbonizing U.S. industry.
  - Net-positive decarbonization measures in 2030 (costing <$0/t CO2e), such as energy efficiency, electrification, and alternative feedstocks, could total ~10–15% of the required industrial-sector abatement.
- **Decarbonizing industry emissions is a complex problem requiring sector-specific deployment of the relevant abatement levers.**
  - Heat decarbonization is a critical cross-sector abatement challenge (over 50% of studied emissions are from heat), but many solutions have high operational costs that far exceed low natural gas prices in 2023.
  - CCS retrofits can enable decarbonization in industrial applications that have exhausted other decarbonization technologies and strategies, but other solutions could mature to eliminate CO2 and lower costs in the long term.
- **Based on today's technology, the pathway to net zero by 2050 across industrial sectors could entail a total capital requirement of $700–1,100B.**[54]
  - For each sector, specific leadership opportunities offer a possible vision for decarbonization leadership domestically and globally.
  - While levers are similar across sectors, their timing, deployment, and enablers will vary by facility, incentive structures, emissions source, and societal context.
- **Achieving net zero could have broad socioeconomic impacts, protecting existing employment and creating up to millions of good-paying jobs in contruction and implementation** across industries through direct and indirect jobs in the investment phase through 2050.
- **Industrial decarbonization presents an opportunity to abate health-harming pollutants from industrial operations that impact frontline communities and workers (e.g., use of scrubbers to both reduce pollutants and enable CCS).**[55]
  - Each industry and decarbonization lever has unique environmental attributes, and not all decarbonization projects are environmentally improving.
  - Communities, workers, and unions must be continually engaged and consulted in decisions affecting their cumulative burden.

54 $700M to $1.1B represents the estimated potential capital investment required to decarbonize eight industrial sectors of focus in IRA, including chemicals, refining, iron and steel, food and beverage, cement, pulp and paper, aluminum, glass and reach net-zero by 2050.This number was calculated by estimating the capital expenditure for scaling select deployable and demonstration-stage decarbonization levers (e.g., CCS, clean on-site power generation from renewables, energy efficiency measures) for each industry. The actual capital expenditure required to achieve net-zero by 2050 may be higher given this estimate does not include additional capital spending on R&D/pilots required for levers in that category. IRA incentives reflected in the MACC analysis include 45V (hydrogen production tax credit) and 45Q (carbon capture and storage tax credit).

55 Carbon-capture-and-air-quality-factsheet.pdf (betterenergy.org)

Section 3a.i: Marginal abatement cost curve (MACC) results

From a commercial point of view, the cost of a decarbonization lever is critical to achieving liftoff. This section focuses on the estimated 2030 costs across decarbonization levers to assess this critical dimension of adoption readiness.

By 2030, up to 40% of emissions could be abated with external factors to industrial facilities or existing net-positive decarbonization levers when tax credits are included (Figure 3a.i.1).[56] It is important to note that grid decarbonization makes up ~15% of the total industrial emissions abatement potential in 2030, making it a critical dependency to decarbonizing U.S. industry. Another ~25–40% could be addressed with levers approaching breakeven with estimated abatement costs between $0–100/t CO2e in 2030. The remaining ~20–40% of emissions could be abated with levers costing >$100/t CO2e or require further R&D to address.

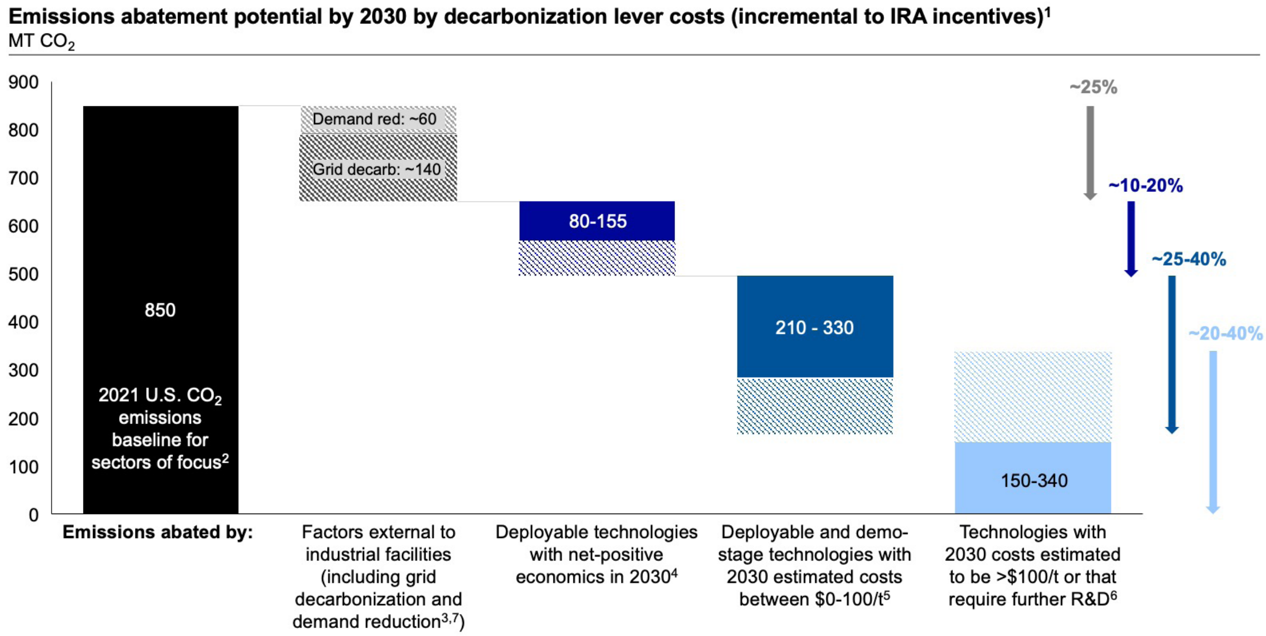


Figure 3a.i.1: Industrial emissions abatement is split between external factors (i.e., grid decarbonization, transport sector electrification, and mechanical recycling), net-positive levers, and uneconomic levers (>$0/t CO2e), with up to 40% of abatement achievable at- or below-cost | 1. Current ranges consider how abatement potential might evolve if the 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 instead depict uncertainty in the cost estimates range for decarbonization levers. | 2. Heat, electricity, and process emissions for industrial sectors of focus (defined in text) | 3. Modeled emissions abatement in 2030 that is attributable to external factors, including grid decarbonization and changes in demand. | 4. Modeled emissions abatement associated with net-positive levers (< $0/t) | 5. Modeled emissions abatement associated with levers approaching breakeven ($0-$100/t) | 6. Modeled emissions abatement by levers with >$100/t or that require further R&D | 7. Assumes the Biden Administration's target of zero emissions from the grid in 2035 and applies goals for transport decarbonization and plastics recycling for this analytical exercise. The entire bar is 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

The MACC analysis conducted for this report was used to highlight a current least-cost decarbonization pathway based on the economic cost of abatement and the potential scale of emissions reduction for a range of levers across industries. Net-positive is defined using a 10% weighted average cost of capital (WACC; refer to Chapter 6: Modeling Appendix for further detail). **This analysis determined that net-positive decarbonization measures in 2030 (costing <$0/t CO2e), such as energy efficiency, electrification, and alternative feedstocks, could compose ~10–15% of required industrial sector abatement.**

56 IRA incentives reflected in the MACC analysis include 45V (i.e., hydrogen production tax credit), 45Q (i.e., CCS tax credit), and 48E (i.e., clean energy tax credit)

The decarbonization levers that could address the remaining emissions, net of external factors, are not projected to clear a 10% WACC by 2030. However, a significant share (~25–40%) of emissions could be addressed by levers approaching the breakeven point (costing between $0–$100/t CO2e). Industrial players who position their low-carbon investments as early movers could capture technology premia for some products likely to cover $100/t CO2e costs as the demand for low-carbon products increases. For levers below the ~$100/t CO2e threshold, it is expected that cost decreases from technology demonstrations and scaling could close a significant portion of the gap to breakeven, while additional revenue streams such as technology premiums could also contribute.[57] Several carbon-pricing schemes—including in Canada and the EU and UK ETS—have prices in this range. Additionally, costs for CCS point source retrofits in higher cost-of-capture applications could drop by ~45% between FOAK (first-of-a-kind) and NOAK (Nth-of-a-kind) deployments by 2040.[58]

Another 20–40% of emissions could be abated by levers costing above ~$100/t CO2e or levers that require additional R&D and have uncertain costs. Technical factors, including complexity (e.g., multiple emissions streams in a refinery), feedstock supply (e.g., limited biomass supply), and lever limitations (e.g., maximum temperature ranges for certain high-temperature heat decarbonization technologies) result in higher abatement costs. Note that uncertainty also increases for lower-TRL technologies due to higher variability in cost estimates and abatement potential. These technologies typically have higher costs, and this relationship is reflected through the error bars for the last two categories.

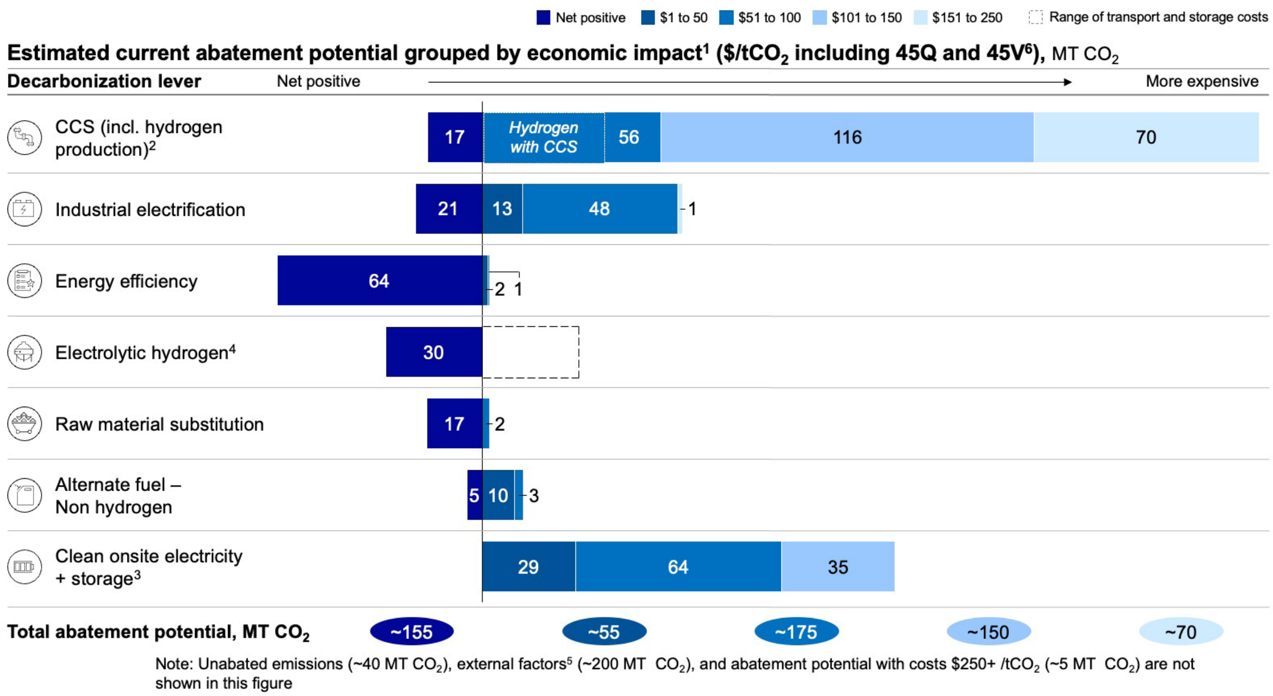


Figure 3a.i.2: Abatement cost analysis shows levers with the largest abatement potential (i.e., CCS, clean onsite electricity and storage, industrial electrification) are also the most expensive. | 1. Based on 2021 emissions baseline for all industries except for chemicals, refining, and cement where 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 $86-140/ton) | 3. Includes costs associated with heating equipment for steam generation | 4. Hydrogen cost estimates for 2030 range from $2.02-3.08/kg H2. These cost assumptions for this modeled scenario are based on DOE's Clean Hydrogen Liftoff report, which relied on the 2022 McKinsey Hydrogen Model. It is important to note that the assumptions underlying this analysis of hydrogen cost are uncertain, and the Clean Hydrogen Liftoff report is continually being updated. DOE electrolyzer cost estimates have already increased since the values published in the report, due to variables such as supply chain constraints and inflation. . 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.

57 Per the Hydrogen and Carbon Management Liftoff Reports, technology demonstrations and scaling could result in a ~50% decline in water electrolysis levelized production costs through 2030 and a ~45% reduction in CCS point source retrofit costs in higher cost-of-capture applications between FOAK and NOAK deployments by 2040.

58 Industrial applications from EFI Foundation, "Turning CCS Projects in Heavy Industry and Power into Blue Chip Financial Investments" – cost reduction represents FOAK with a high retrofit factor (i.e., high cost) to NOAK with a low-retrofit factor (i.e., low cost). Transport (GCCSI, 2019) and storage (BNEF, 2022) range from $10–40/tonne.

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

Three decarbonization levers could play a large role in abatement for 2030 based on the current least-cost decarbonization pathway: CCS, clean onsite electricity and storage, and industrial electrification. These solutions could abate ~470 MTPA of CO2, comprising ~55% of emissions in these industrial sectors (Figure 3.2).[xxx, xxxi, xxxii, xxxiii, xxxiv, xxxv, xxxvi, xxxvii, xxxviii, xxxix, xl, xli, xlii, xliii, xliv] Further details on assumptions, constraints, and limitations of the modeling approach can be found in Chapter 6. Other decarbonization measures (e.g., energy efficiency, clean hydrogen, alternative fuels, feedstocks) could compose ~20% of abatement options.

Across multiple levers—including CCS, industrial electrification, and electrolytic hydrogen—access to low-cost, clean electricity will be a critical enabler to reaching maximum abatement potential; this results in a significant increase in industrial demand for clean electricity. Clean electricity operational costs and constraints are also discussed in Chapter 3.a.ii concerning heat decarbonization. Power requirements for CCS applications vary by the amount of CO2 captured and CO2 purity based on concentration. For example, CCS on a smaller-scale, high-purity source such as an ammonia plant could be ~6 MW per plant, or ~13W per tonne CO2, whereas CCS on a larger-scale, more-dilute source such as a coke oven/blast furnace in steel might require almost ~63 MW per plant or ~16W per tonne CO2.[59, xlv]

Potential decarbonization pathways for chemicals, refining, and iron and steel have a larger share of higher-cost-to-abate levers, while pathways for cement, pulp and paper, and aluminum may have a larger share of the lower-cost-to-abate levers (Figure 3.3).[60]

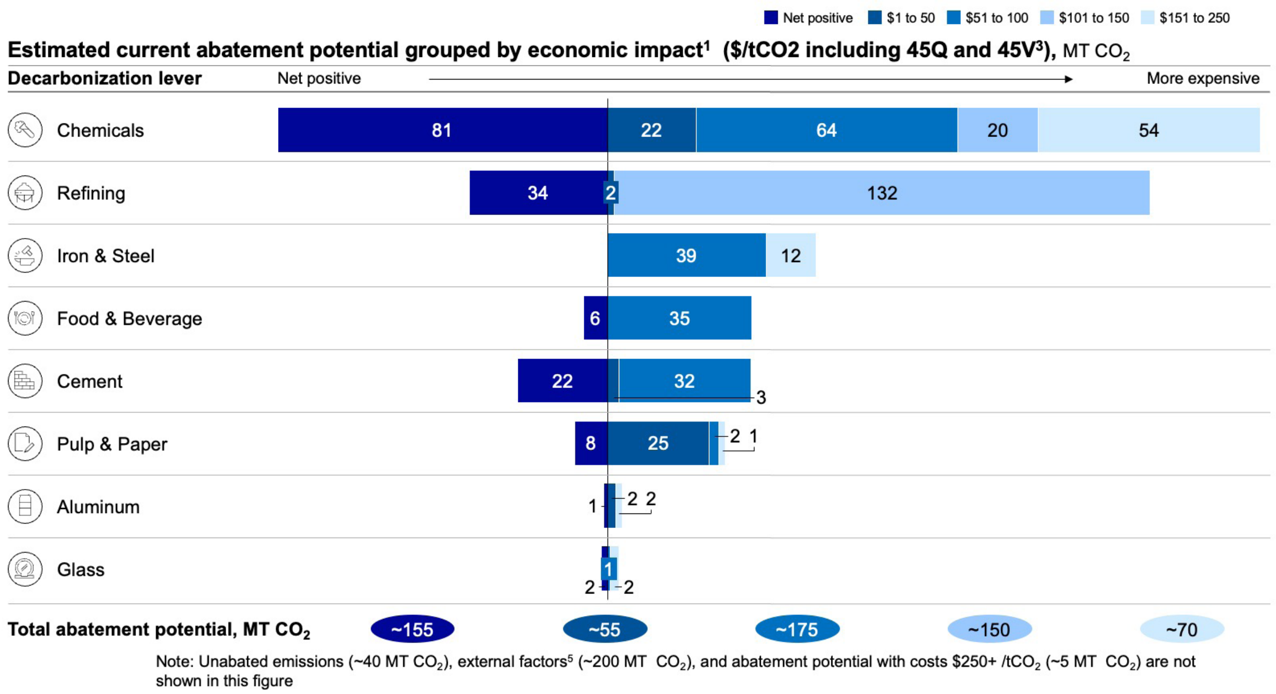


Figure 3.3: Abatement cost analysis shows that chemicals, refining, and iron and steel sectors have the most expensive decarbonization pathways | 1. Based on the 2021 emissions baseline for all industries except for chemicals, refining, and cement where emissions were projected through 2050. All costs 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.
Source: Industrials sector integrated MACC, DOE Chemicals and Refining Decarbonization Pathway

59 Assumes the representative ammonia plant has a production rate of 653,000 tonnes/year, is powered by natural gas, has 0.46 MTPA CO2 available for capture after urea production, and utilizes a reciprocating compression system to capture CO2. The representative steel mill has a production capacity of 2.54 MTPA, emits 3.91 MTPA CO2 and considers two separate capture systems, one for a coke oven and one for a blast furnace, both of which require separation, compression, and cooling.

60 High-cost-to-abate levers are those >$50/t CO2e in 2030 after accounting for IRA tax incentives; lower cost-to-abate are those <$50/t CO2e.

Sector-specific decarbonization opportunities are discussed in Chapter 3.b, which details specific nuances across technology applications, industry momentum, and other relevant context.

Section 3a.ii: Cross-sector abatement challenges

In the Pathway to Liftoff, emissions abated with Carbon Capture and Storage and emissions from heat are two critical abatement challenges across the sectors of focus**.** This section will investigate the full suite of decarbonization options—not just the lowest cost—to address the emissions driving these challenges.

Emissions abated with Carbon Capture and Storage (CCS):

CCS retrofits can enable decarbonization in industrial applications for certain emissions sources. CCS retrofits could be considered for emissions that have exhausted other decarbonization technologies and strategies, have limited ability to transition to lower-carbon production methods, or where capital costs for low-carbon greenfield facilities can be prohibitive. However, in the long term, greenfield facilities can be designed for easier/less expensive CCS from the start (e.g., new ATRs or crackers engineered to accommodate capture equipment).

The MACC results are a decarbonization pathway considering levers' abatement potential and least-cost position for 2030; however, there are three critical risks for CCS. First, as the Carbon Management report highlights, while utilization models may develop, they are nascent and currently uneconomic relative to incumbent products. As such, CCS is an additional cost to current production, even as costs are reduced with demonstration projects; without regulatory constraints, cost could be a persistent adoption barrier. Second, portfolio risk is associated with relying on any one lever. Figure 3.2 shows that up to ~30% of emissions in 2030 could require CCS above $50/tonne to abate. Third, CCS faces public acceptance challenges, which are further discussed in Chapter 3c.ii and in the Energy and Environmental Justice section of the Carbon Management Liftoff Report. It is important to note that costs associated with a carbon management project vary based on the type of facility CCS is applied to, as well as several regional and facility-specific factors that can drive variation in the cost associated with capturing, transporting, and storing or using a tonne of CO2. Costs for a specific carbon management project could vary outside the ranges outlined in this report.

Three factors drive the least-cost position of CCS in 2030:

1. Long asset lifetimes and infrequent downtimes in the industrial space, where CCS retrofits can be added to existing facilities in regions where access to CCS wells, facilities, and suitable geological formations are available and remove the need for expensive greenfield projects in the near term.

2. Although most abatement with CCS cost (i.e., costs above $50 per ton), other available levers to abate the same emissions are estimated to be more expensive indicating a need for more development to drive competition along with increased decarbonization policies and demand for clean products.

3. For some emissions, existing commercially viable alternative technologies are absent or limited.

Due to the challenge of decarbonizing these industrial sectors and the adoption barriers for identified solutions, a larger portfolio of decarbonization levers will be required, including levers at earlier technology readiness stages. Many early-stage technologies or alternative production methods could dramatically reshape the sector's overall emissions and energy profile, reducing reliance on the largest existing levers like CCS. **Figure 3a.ii.4 summarizes decarbonization levers that would eliminate the same emissions CCS seeks to abate, including electrification, electrolytic hydrogen, and utilization opportunities.**

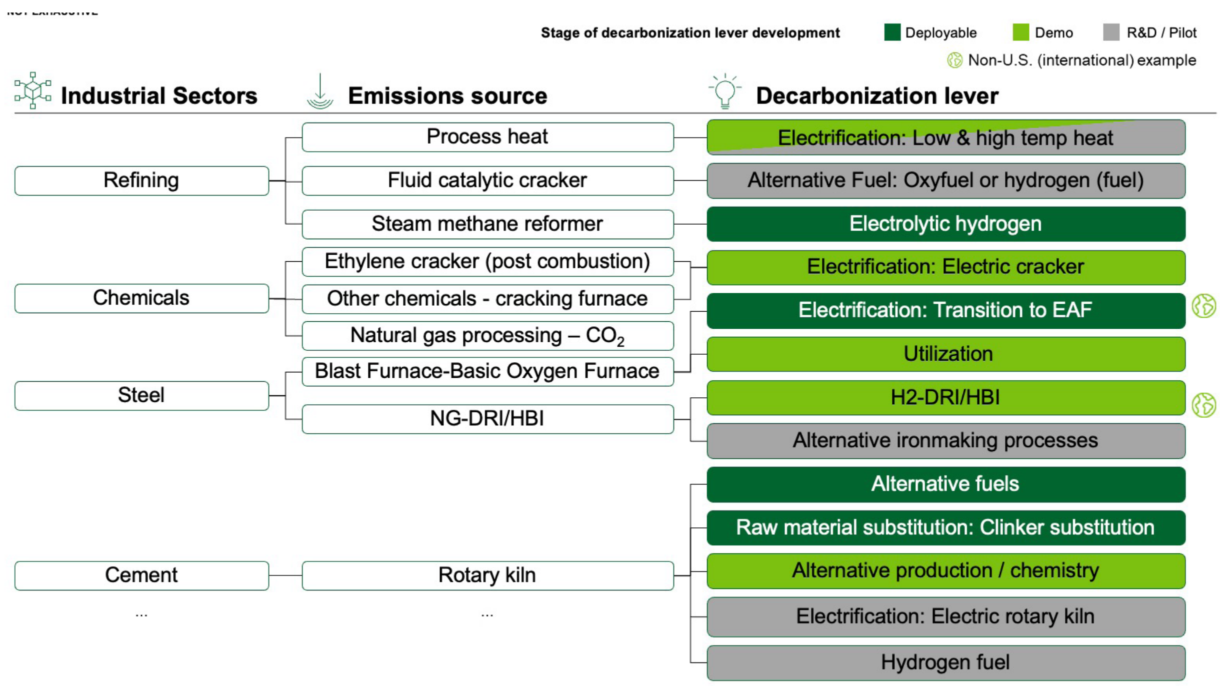


Figure 3a.ii.4: The left and middle columns outline the sources of emissions abated via CCS in this report's MACC results. The right column identifies potential alternative technologies to CCS and their associated stages of deployment.
Source: Press search, expert interviews

While the technologies on the right-hand side of Figure 3a.ii.4 are estimated to have higher costs or face limitations in addressing the same emissions as CCS, as economics and technology improve, there could be multiple levers to address these emissions. Many of the technologies listed are part of the continued development of decarbonization levers, which can leverage continued R&D and focused scale-up to drive down costs. For example, if electric crackers were to reach commercial scale (depending on economics and technology maturity), ~50MT of abatement potential could be addressed via electrification rather than CCS. Other examples include alternative fuels, alternative raw materials, or alternative chemistries (cement) (Figure 3a.ii.4).[61]

Heat Emissions:

Decarbonizing heat is a critical challenge across sectors, with commercial and R&D challenges to achieving net zero. Across all sectors, emissions from heat account for ~50% of overall emissions. High-temperature heat above 400°C accounts for ~30% of overall emissions (Figure 2.1).

Like overall industrial emissions, heat emissions are heterogeneous; decarbonization of heat emissions has diverging and cross-cutting challenges across sectors. The share of emissions driven by heat varies across sectors (Figure 2a.2) since different industries and facilities use heat in different ways—from relatively low-temperature drying processes below 200°C in food manufacturing to high-temperature operations (400°C+), like glassmaking. The specific sector and facility using heat will dictate final operational challenges and commercial feasibility. To illustrate this point, Figure 3.5 summarizes the specific options and critical considerations across sectors for high-temperature heat decarbonization, often considered the most difficult to decarbonize. These sector-specific challenges are further investigated in sector overviews and are a focus of DOE's Industrial Heat Shot™, which is discussed at the end of this section.

61 Stage of decarbonization-lever development was informed through press articles and sustainability reports.

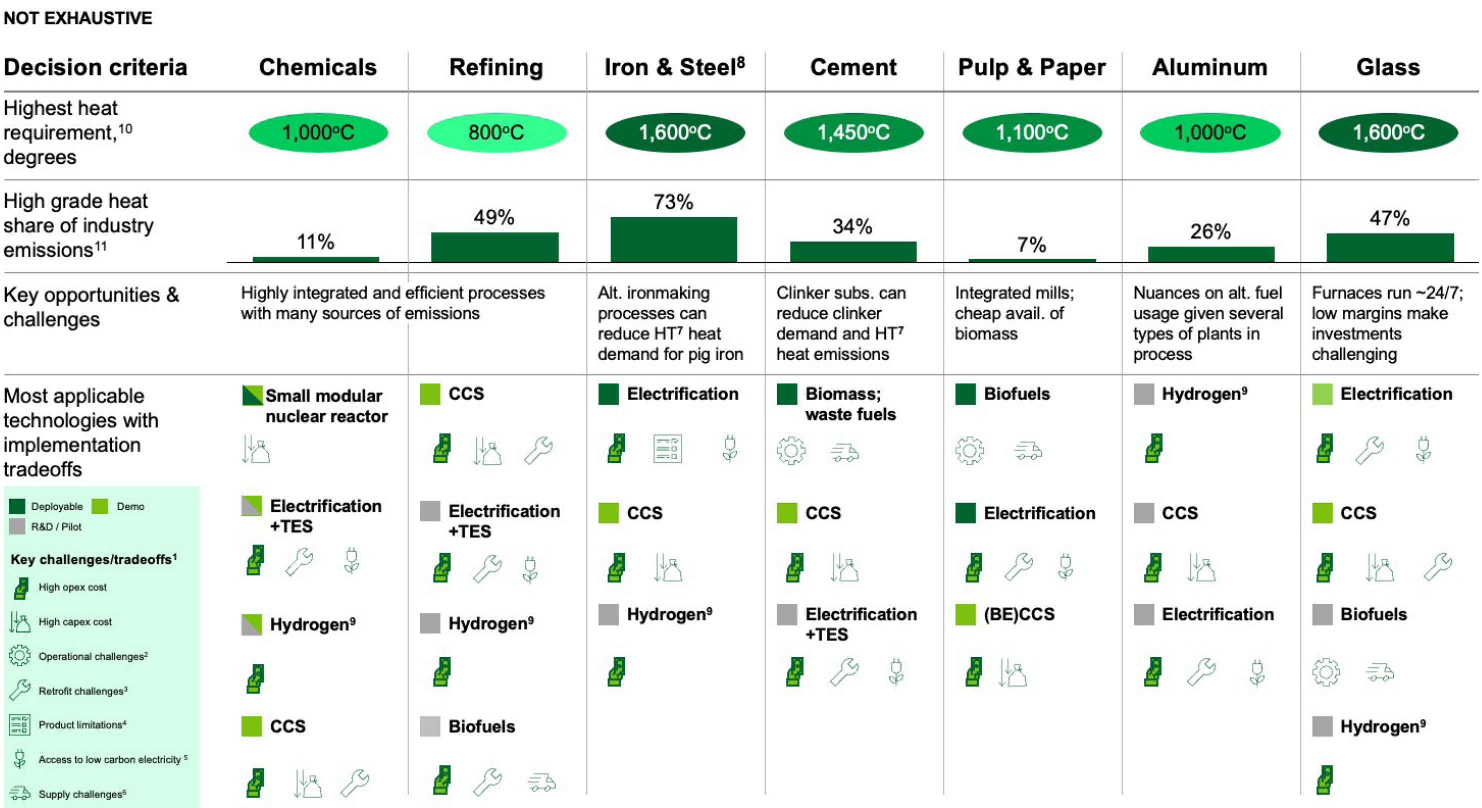


Figure 3a.ii.5: A case study on High-Temperature Heat Decarbonization Considerations | 1. The highest priority challenges/tradeoffs for each technology in each sector are listed. Other challenges could apply but may not be as critical a decision factor for the industry | 2. Operational challenges refer to difficulty meeting the process's heat or other technical requirements with the decarbonization technology. For example, using biomass in cement presents operational challenges as it has a lower heat value than fossil fuels and, therefore, cannot replace 100% of the fuel and reach sufficient temperatures | 3. Retrofit challenges are difficult in implementing decarbonization technologies. For example, the quantity of emissions sources in refining and chemicals is a retrofit challenge for CCS as emissions sources could need to be rerouted to combine multiple streams to be captured within the facility | 4. Product quality challenges refer to when the decarbonization technology impacts the product's quality. For example, EAF produces steel that does not meet technical requirements for some end-uses (e.g., automotive). | 5. Refers to challenges accessing sufficient low-carbon electricity from the grid or onsite | 6. Supply challenges arise when decarbonization technology relies on an input with a limited or localized supply chain. For example, access to biomethane for use in melting glass will depend on the location of the glass production and the availability of sufficient biomethane within range | 7. High temperature (HT) | 8. A weighted average of in-scope subsegments | 9. Assumes purchase of electrolytic hydrogen. Production of electrolytic hydrogen has challenges (e.g., access to low-carbon electricity for electrolytic hydrogen) | 10. The general maximum heat requirement for current processes; excludes consideration of new processes | 11. High-temperature heat emissions data is estimated from this combination of sources.

Sources: Columbia Center on Global Energy Policy, EPA, DOE IEDO, DOE EERE, industry publications (e.g., individual company publications, industry associations, such as Eurofer)

Across sectors, high operational expenditures compared to fossil fuels challenge economic heat decarbonization. All heat decarbonization levers must provide energy at costs competitive with energy-dense cheap fossil options, especially Natural Gas in the United States.[62] To illustrate this point, Figure 3.6 includes a case study comparing the cost of industrial heat electrification coupled with thermal energy storage (TES) for reliability to a comparable system using natural-gas-fired options. This does not include one-time operational and infrastructure costs to adopt electrified options.

62 Natural Gas in the United States receives regulatory exemptions which can artificially advantage its production over other more regulated energy generation (e.g., nuclear).

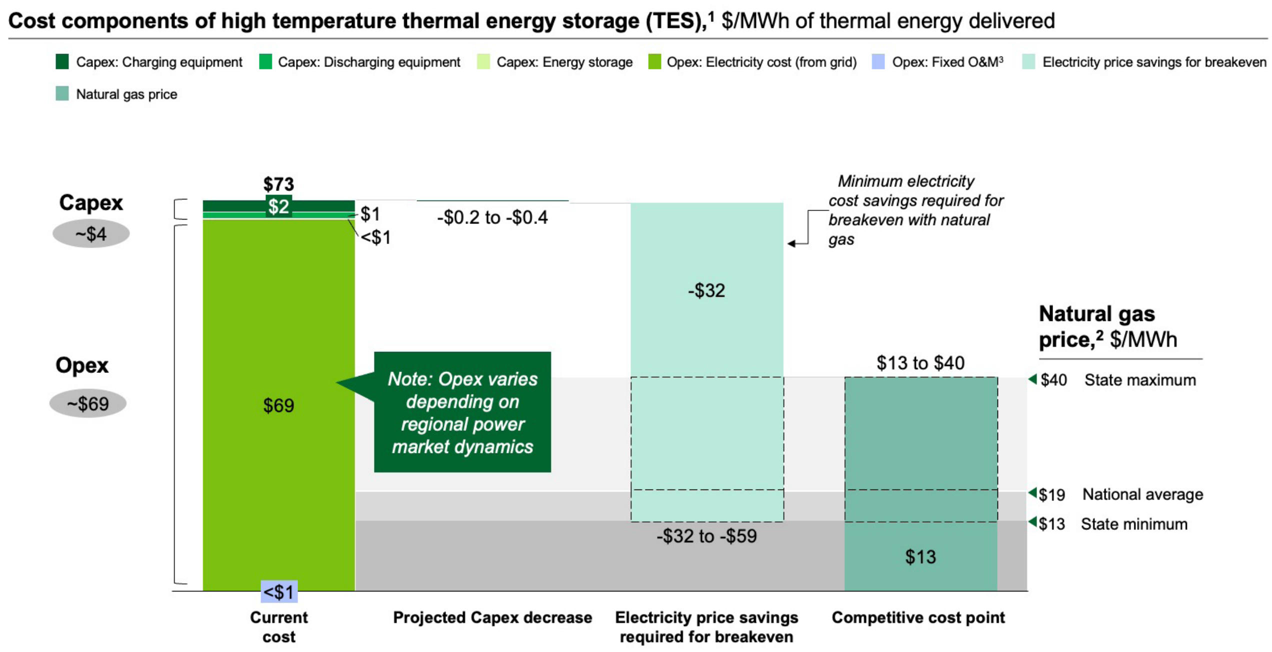


Figure 3a.ii.6: Electricity price compared to fossil fuel is the largest determinant of TES's economic viability | 1. Capex figures are based on anonymized industry data from LDES council members; technology agnostic, assumes 16-hour storage, 8-hour charging, 365 cycles per year, an 8% WACC, a 30-year lifetime, and 5,840 MWh heat discharge per year. Opex costs based on EIA average electricity price to industrial customers. | 2. EIA annual Natural Gas Prices: Industrial (2021); minimum represents the lowest (West Virginia) and highest (Delaware) annual natural gas price by state; note that the natural gas price doesn't include a small efficiency loss from combustion. | 3. Assumes that fixed OandM cost is 2% of capex, in line with similar energy technologies; no data from the LDES council is available. Source: LDES Council, EIA Monthly Electric Power Industry Report

Figure 3a.ii.6 demonstrates that capital expenditures for electrification and thermal energy storage systems are relatively small. However, the operational expenditures of the new system are substantially higher due to the cost of grid electricity for energy instead of the cost of energy from natural gas. Significant electricity price savings or regulation, green premiums, or other incentives are required for electrification with TES to be cost-competitive with today's fossil options. There are a few opportunities for electricity price savings today:

- Grid arbitrage to ensure the purchase of grid electricity when prices are low.
- Low-carbon energy PPAs, which tend to be cheaper than baseload grid electricity prices.
- Operating in a region with low electricity prices relative to fossil fuel prices

Beyond electricity prices, in scenarios with low-cost natural gas, there are enablers to improve the competitiveness of any decarbonized approach:

- Low-cost energy available as electricity either from onsite generation, through the grid (combined with storage), alternative clean fuels, or other heat technologies (e.g., small modular nuclear reactors, geothermal, or concentrated solar)
- Accelerated build-out of necessary infrastructure, either renewable generation and grid capacity or fuel transport and storage pipelines
- Continued demonstration of TES that can store and discharge the highest temperatures (e.g., ~1,500°C)

- Incentives for TES or other decarbonization options (e.g., clean hydrogen) to enable competitive access to low-cost electricity
- Premium for low-carbon materials and products to improve economics relative to fossil fuels
- Innovation in production processes to reduce energy demand by incorporating novel heating technologies (e.g., electrification or novel combustion)

Today, momentum is building for solutions. Industrial coalitions like the Renewable Thermal Collective are focused on the need for decarbonized heat and cooling among members. Early industrial adopters are exploring the implementation of technologies at different stages of development such as thermal energy storage, concentrated solar, geothermal and advanced nuclear.[xlvi] In addition, industrial heat pumps have already benefited from the increasing deployment of lower-temperature heat pumps for building applications, but with R&D could have more applications at higher temperatures. To focus on these R&D and integration challenges, the DOE established the Industrial Heat Shot™ to develop cost-competitive industrial heat decarbonization technologies with at least 85% lower greenhouse gas emissions by 2035.

Section 3a.iii: Consolidated Pathway to Liftoff

The overall considerations are outlined in a **consolidated Industrial Decarbonization Pathway to Liftoff.** This pathway and the sector-specific figures that follow offer a high-level discussion of technologies across stages of development and enable actions for each sector to achieve net zero by 2050. On the path to 2050, the uncertainty of costs and technology development increases, meaning the report offers signposts rather than estimates where information is unavailable, especially for lower TRL technologies. For 2050, the simultaneous pursuit of cost-reductions via demonstrations and R&D will enable the lowest risk and cost pathway to net zero.

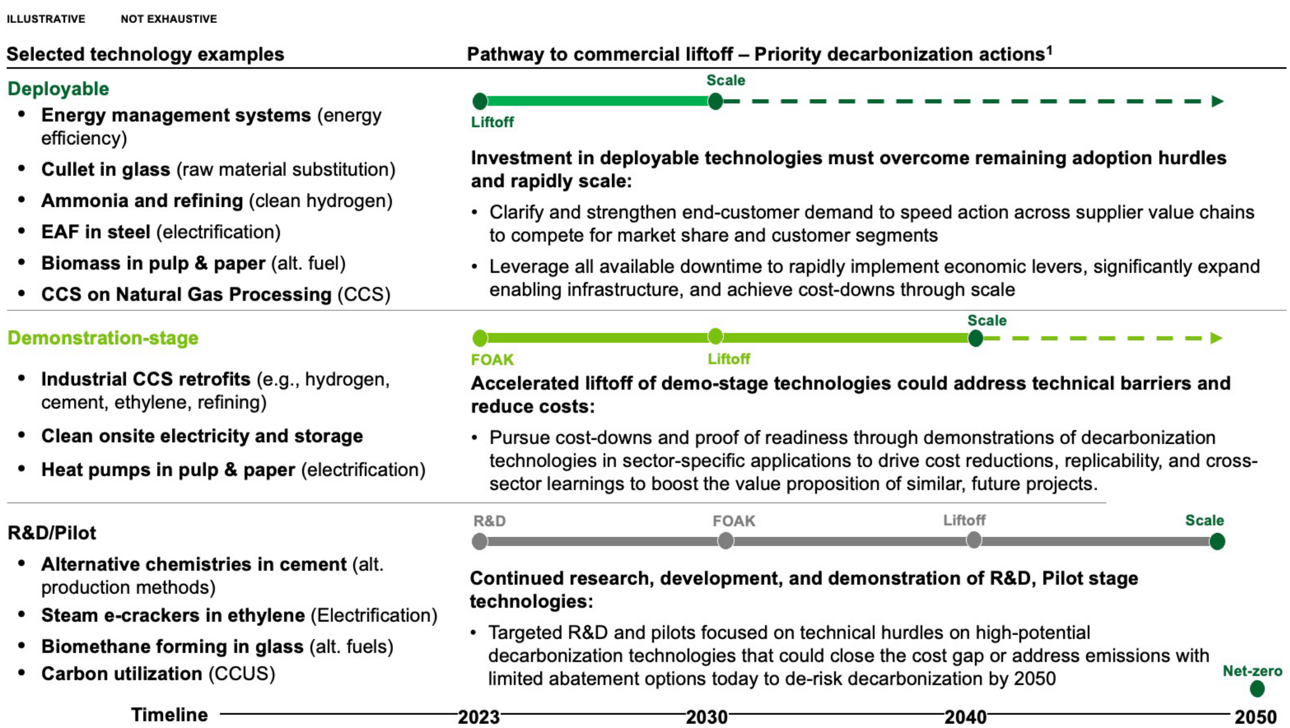


Figure 3a.iii.7: The U.S. industrials pathway to commercial liftoff consists of a series of industry actions across deployable, demonstration-stage, and R&D / pilot-stage technologies. | 1. Indicative timeline presented for R&D, FOAK, liftoff, and scale. Actual timelines will vary by technology based on technological maturity and barriers to adoption.

The U.S. industrial sector pathway to net zero by 2050 is expected to evolve across three groups of technologies and entail a potential capital requirement of $700B-1.1T.[63] For industry players, this transformation would likely begin with rapidly scaling deployable technologies available in the short term through 2030, making up ~30–40% of the required abatement across industrial sectors. These short-term opportunities can be further supplemented by the progressive decarbonization of U.S. power and transportation sectors, providing an estimated ~25% reduction in industrial emissions. In parallel, investment is required in demonstration-stage and R&D/pilot stage technologies to address technical barriers, achieve cost reductions, and ultimately close the gap to net zero.

Substantial capital formation across sectors requires significant progress through FOAK and NOAK projects, spanning multiple technologies and business models to mitigate execution risks and unlock larger pools of lower-cost capital. Government funding and corporate investments from industry players could catalyze and de-risk the market for early-stage projects. As a result, such projects would become more attractive for traditional debt or equity financing from private equity, institutional investors, and banks. For example, the first generation of carbon management projects relied on government funding and investment from large industry players. In 2022, more than $1B in equity funding was raised to develop large-scale CO2 pipelines, capture equipment, and FOAK direct air capture (DAC) projects. While levers and enablers are similar across sectors, their timing, deployment, and enablers will vary by facility, incentive structures, emissions source, and community context. The sector-specific opportunities in industrial decarbonization are summarized in Section 3.b.

Section 3b: Sector Pathways to Liftoff

Each industrial sector's "Pathway to Liftoff" for scaling decarbonization technologies requires a set of existing and emerging technologies that must be developed, commercialized, and adopted at scale.[64] Section 3.b includes eight sector-specific overviews. Each overview briefly characterizes the sector's market dynamics, momentum toward decarbonization, and emissions outlook. These pieces are brought together in a sector-specific "Pathways to Liftoff." These sections include the estimated capital needed, key enablers, and abatement potential for decarbonization technologies in a sector. In addition to the commercial considerations, this report examines the social impacts and environmental justice considerations for decarbonization (see Section 3.c.ii). These considerations will vary by technology and sector and should be included alongside the factors presented in this section.

The "Pathways to Liftoff" support sector-specific leadership opportunities as part of a possible vision for decarbonization leadership as part of an equitable energy transition (Figure 3b.8). These unique opportunities could inspire action to attain leadership both domestically and globally. While the leadership opportunities represent a vision, the synthesized Pathways to Liftoff highlight the potential activities that would be timely to support this decarbonization liftoff.

63 $700M to $1.1B represents the estimated potential capital investment required to decarbonize eight industrial sectors of focus in IRA, including chemicals, refining, iron and steel, food and beverage, cement, pulp and paper, aluminum, glass and reach net-zero by 2050.This number was calculated by estimating the capital expenditure for scaling select deployable and demonstration-stage decarbonization levers (e.g., CCS, clean on-site power generation from renewables, energy efficiency measures) for each industry. The actual capital expenditure required to achieve net-zero by 2050 may be higher given this estimate does not include additional capital spending on R&D/pilots required for levers in that category. IRA incentives reflected in the MACC analysis include 45V (hydrogen production tax credit) and 45Q (carbon capture and storage tax credit).

64 "Industrial sectors" herein are defined as the eight sectors of focus: chemicals, refining, iron and steel, food and beverage, cement, pulp and paper, aluminum, and glass; unless otherwise stated (e.g., "all industrial sectors").

ILLUSTRATIVE 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

Figure 3b.8: Sector-specific leadership opportunities based on a sector's industrial context, current momentum, and available technologies. Activities outlined in each sector's Pathway to Liftoff could support achieving these leadership opportunities.

Section 3b.i: Chemicals

Sub-sectors: Ammonia, ethylene/propylene/BTX, natural gas processing, chlor-alkali processes

~291	MT CO_2	2021 U.S. missions
~315	MT CO_2e	2021 U.S. Emissions
~1,000	MT CO_2	2021 Global Emissions

The U.S. downstream commodity chemicals sector provides essential inputs to widely used products, including plastics, fertilizer, and pharmaceuticals within the U.S. and worldwide. The United States is the world's second-largest chemicals producer, with ~$517B of products produced annually at over 10,000 chemical facilities nationwide.[xlvii] While there are thousands of chemicals facilities, domestic production of bulk petrochemicals is concentrated in five primary producers that make up ~50% share of the U.S. market.[xlviii, xlix, l] Inorganic and specialty chemicals production is even more concentrated. **Chemicals is the largest U.S. export sector, making up 14% of the global chemical market.**[li, lii] The industry accounted for ~3% of U.S. CO2e emissions in 2021, or 315 MT CO2e (~35% of emissions in sectors of focus).[65]

The full chemicals value chain is complex, and production processes vary widely across products. However, roughly 60% of emissions are attributed to four subsectors: **natural gas processing**, **ammonia production, steam cracking, and chlor-alkali processes. Approximately 80% of these operational emissions originate from onsite point sources.** Certain subsectors, such as chlor-alkali and ammonia, release significant emissions from a few primary sources within the facility. However, for other production processes, like steam cracking, there are many emission sources, often from disparate flue streams in a facility. Additionally, the space within the fence line of chemicals processing facilities can make any decarbonization intervention logistically challenging as there is often not available physical space to add power capacity.

65 The chemicals and refining deep-dive report focuses on CO2 emissions specifically—broader analysis has been expanded to include CO2-equivalent emissions; MACC analysis is based on CO2 emissions (not CO2e)

Chemicals sector emissions come from three primary sources: heat generation (~40%), electricity (~29%), and process emissions (~24%). The remaining ~7% comes from various other sources, such as fugitive emissions (Figure 3b.1.1).[iii, iv, v, vii, viii, ix] There are opportunities to leverage specific technologies that address the largest cluster of chemicals emissions. For example, technologies that can decarbonize high-temperature heat could have applications across many sectors (e.g., steam methane reforming, steam cracking), but these technologies could also help reduce the costs of technologies that could decarbonize mid- and low-temperature heat. **Significant decarbonization levers include CCS and equipment electrification powered by clean electricity.** Yet, these levers are expensive, with costs ranging from ~$110–140/t CO2e for CCS on dilute flue gas streams and ~($50)–60/t CO2e for electrification of equipment after IRA incentives (Figure 3.1.1).[66, 67]

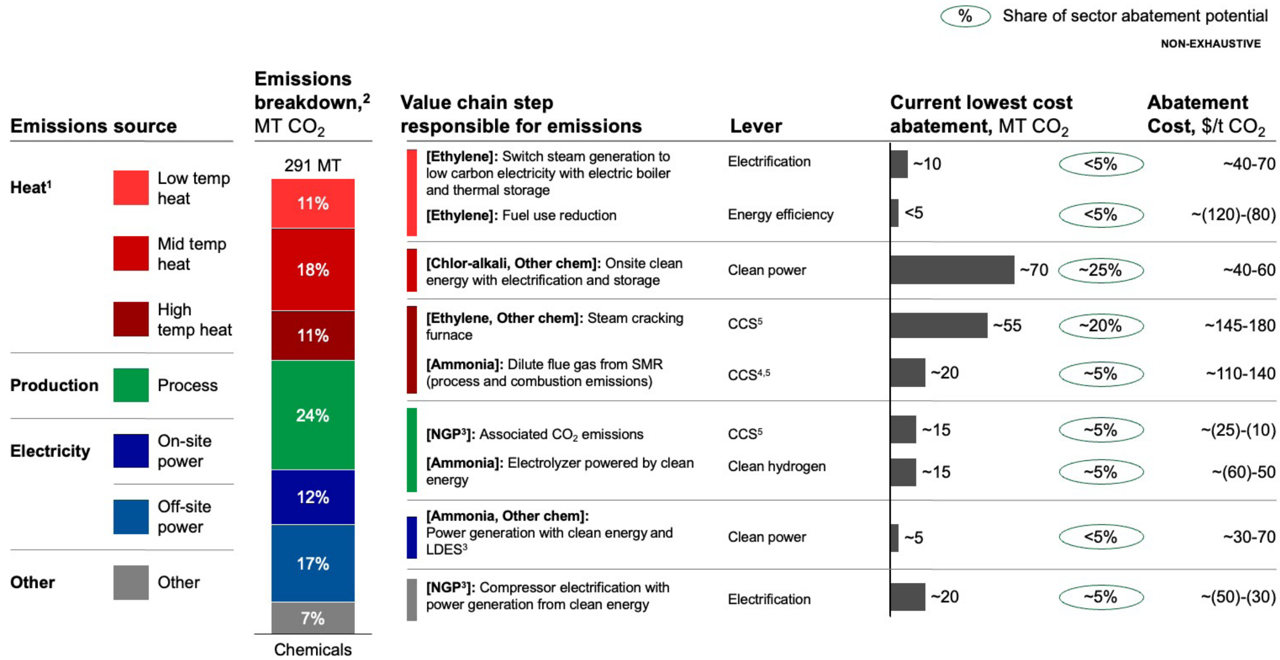


Figure 3b.1.1: Chemicals production has fragmented emissions sources that can be abated using various levers | 1. Temperature ranges are defined as low-temperature heat (-30°C to 200°C), medium-temperature heat (200°C to 400°C), and high-temperature heat (400°C+). | 2. A breakdown of 2021 chemicals production emissions | 3. Natural gas processing (NGP); long duration energy storage (LDES) | 4. The blended cost of applying CCS to an SMR unit (concentrated and dilute flue gas streams) 5. The displayed cost estimates are based on the capture costs from various sources (see the appendix for details) with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10–40/t; all figures are in 2022 dollars. All CCS figures represent retrofits, not new-build facilities. The lower-bound costs represent a NOAK plant in a low-cost retrofit scenario with low inflation. The higher-bound costs represent a FOAK plant in a high-cost retrofit scenario with high inflation.
Source: 2018 EPA Flight, 2018 EERE Manufacturing Energy and Carbon Footprints report, 2022 IEDO Report, DOE Natural Gas Supply Chain report, Energy Environ. Sci., 2020,13, 331-344, 2020 USGS, IHS Markit data

This report focuses on methods to reduce process Scope 1 and 2 emissions of various industrial sectors and does not focus in detail on solutions that address the attributional life cycle emissions of these products.[68] However, in some cases, technologies with higher production emissions may be useful levers for decarbonization if they have lower process-based life cycle emissions. They may also have greater community benefits and lesser negative impacts on communities. Attributional life-cycle greenhouse gas

66 The lower bound of costs represents compressor electrification in natural gas processing. The remainder of electrification / clean electricity levers is expected to have costs >$80/t CO2e; tax incentives provide up to $85/t CO2e stored in saline geologic formations from carbon capture on industrial and power generation facilities (45Q), up to $3/kg of H2 produced with low carbon intensity (<0.45 kg CO2e / kg H2) (45V), and up to 30% credit for applicable clean electricity projects (48E). For this analysis, only IRA tax incentives for CO2 sequestration in saline geologic formations were considered; use in enhanced oil recovery was not considered.

67 Costs for a specific carbon management project could vary even outside of the ranges outlined in this report depending on facility-specific characteristics and energy prices that can significantly impact the ultimate cost of deployment.

68 Life cycle emissions throughout this report refer to "attributional" or "process-based" life cycle analysis emissions, which are defined as "environmentally relevant physical flows to and from a life cycle and its subsystems." Additional information can be found through the National Academies of Sciences, Engineering and Medicine [Current Methods for Life cycle Analyses of Low-Carbon Transportation Fuels in the United States | The National Academies Press]

(GHG) accounting evaluates and reports the full life cycle GHG emissions associated with the raw materials extraction, manufacturing or processing, transportation, use, and end-of-life management of a good or service. Many biochemicals pathways require complex processing of a bio-based feedstock but have lower process-based life cycle emissions as carbon is absorbed during the growth of feedstock crops. The Biden Administration has set ambitious goals related to the role of biotechnologies and materials to harness innovation and further societal goals to transform industries, including bold goals on bio-based chemicals.[liii]

In a business-as-usual (BAU) pathway, chemical production due to increased end-product demand—and associated emissions—are expected to grow by ~35% by 2050.[liv] Operational decarbonization of chemicals production—and its associated end products—remains limited. Without the widespread implementation of decarbonization levers for new and legacy infrastructure, it will be challenging for the sector to meet the Administration's economy-wide net-zero targets. As of April 2023, 10 of the largest 15 chemicals companies across sub-sectors have made decarbonization commitments for Scope 1 and 2 emissions reductions ranging from 15–50% by 2035.[69] Most companies have prioritized implementing energy-efficiency solutions and increased use of recycled materials for feedstocks. A handful are making exploratory investments in projects to decarbonize production. Figure 3.1.2 shows the development stages of levers across U.S. chemicals.

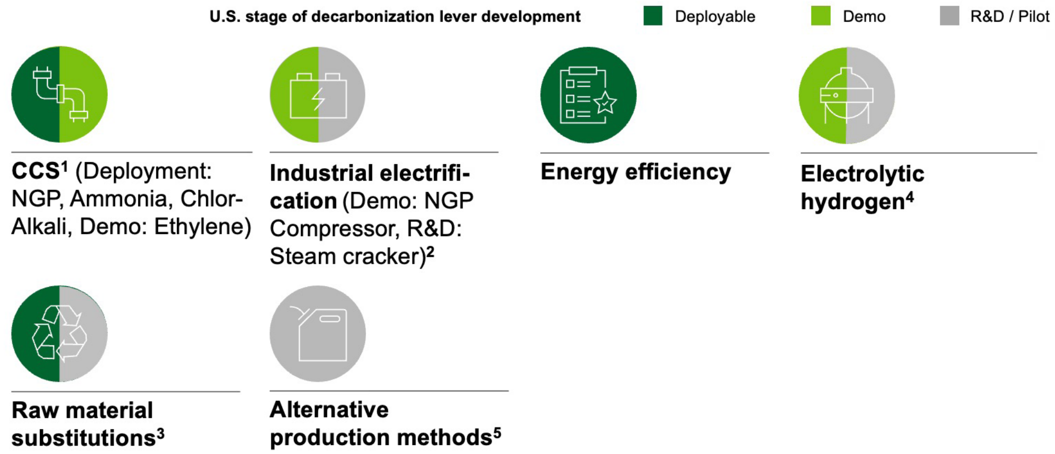


Figure 3.1.2: Stage of lever deployment within the chemicals sector | 1. Deployed for natural gas processing and ammonia, pilot/demo for ethylene, limited deployment for chloralkali | 2. Not exhaustive | 3. Not applicable for natural gas processing and ammonia; mechanical recycling is widely deployed, while chemical/advanced recycling is more nascent. Additional details can be found in the Chemicals and Refining Liftoff report | 4. Limited deployment only (e.g., ammonia) | 5. Such as biobased plastics (ethanol dehydration)
Source: EIA, EPA, IEDO Industrial Decarbonization Roadmap, IEA, press search, company sustainability reports, expert interviews

Today through the mid-2030s, a suite of deployable pathway enablers can kickstart the chemicals sector's reduction of production emissions. These enablers include: (i) **accelerating energy and operational efficiency** measures at most facilities, (ii) adopting **select electrification measures** with a strong business case today (i.e., natural gas processing), (iii) transitioning steam methane reformers used in sectors like ammonia production to **clean hydrogen**, accelerated with 45V and 45Q incentives, and (iv) **installing CCS on high-purity streams** (i.e, natural gas processing with streams of >90% CO2 concentration), accelerated with 45Q incentives.

Building on the success of the prior decade, chemical processes will ideally be able to utilize the scaled infrastructure for clean hydrogen and CCS developed in the 2020s and early 2030s. This means adding abatement options through (v) **adopting CCS on dilute streams** and (vi) **rapidly electrifying low- and medium- temperature heat sources**. Additional GHG emissions reductions could be driven by (vii) expanded use of **biofuels and low-carbon alternative feedstocks**, which displace fossil carbon and have been shown to have lower life cycle GHG emissions compared to fossil fuels.

69 Chemical companies analyzed are largest by U.S. market share and include Oxy, Westlake, Olin, Shintech, and Formosa Plastics for chloralkali; ExxonMobil, Dow, Marathon, LyondellBasell, and Shell for ethylene/propylene/BTX; and Koch, OCI, Dyno Nobel, CF Industries, and Nutrien for Ammonia. Analysis based on public reports and press search

Achieving net zero for downstream chemicals production and refining by 2050 would require near universal adoption of the previously mentioned decarbonization measures (i) through (vii), plus additional levers, including **increased amounts of clean electricity to meet demand**, and **full adoption for clean hydrogen** in ammonia production. Achieving net zero across the sector would improve environmental justice concerns. **The U.S. chemicals decarbonization "Pathway to Liftoff" could require $400–600B in capital investment through 2050 to scale decarbonization technologies** (Figure 3.1.3).

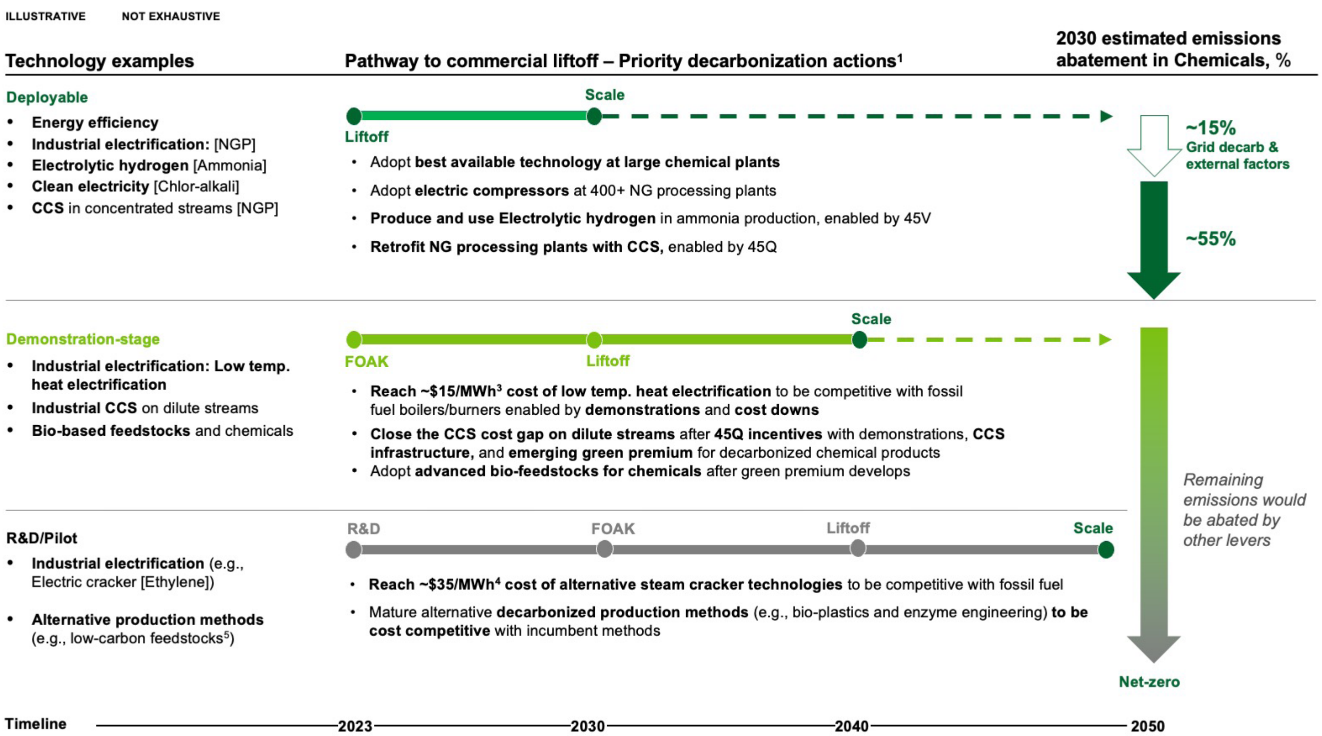


Figure 3.1.3: Liftoff pathway for decarbonization technologies within the chemicals sector | 1. Indicative timeline presented for R&D, FOAK, liftoff, and scale. Actual timelines will vary by technology based on technological maturity and barriers to adoption. | 3. Estimated as the breakeven point on the MACC-levelized-cost-of-heat to reach $0/tCO2 abatement cost for ethylene steam generation. | 4. Estimated as the breakeven point on the MACC-levelized-cost-of-heat to reach $0/tCO2 abatement cost for ethylene steam cracking furnace. | 5. Includes bio-based or captured CO2
Source: EIA Natural Gas Processing Plants (Count of NGP plants)

Section 3b.ii: Refining

~242	MT CO_2	2021 U.S. Emissions
~243	MT CO_2e	2021 U.S. Emissions
~1,400	MT CO_2	2021 Global Emissions

Crude oil refining has been a critical component of U.S. energy security. **In 2022, the U.S. produced 20% of global refined oil and was the world's top producer of refined oil products (e.g., gasoline, diesel, jet fuel, biofuels) on a volume basis.**[70, lv] **Production emissions from refining accounted for ~2% of U.S. CO2e emissions in 2021, or ~242 MT CO2e (approximately 27% of emissions from sectors of focus).**[71] Similar to the chemicals industry, refining production is concentrated. Refining production is spread across ~130 refineries nationwide, with >40% of capacity concentrated in the top five players. Domestic refineries produce two product groups: transport fuels (e.g., gasoline, diesel, jet fuel), accounting for >90% of U.S. refined products in 2022**,** and other products, composing only ~5% of the market.[lvi] This product mix is unique to the

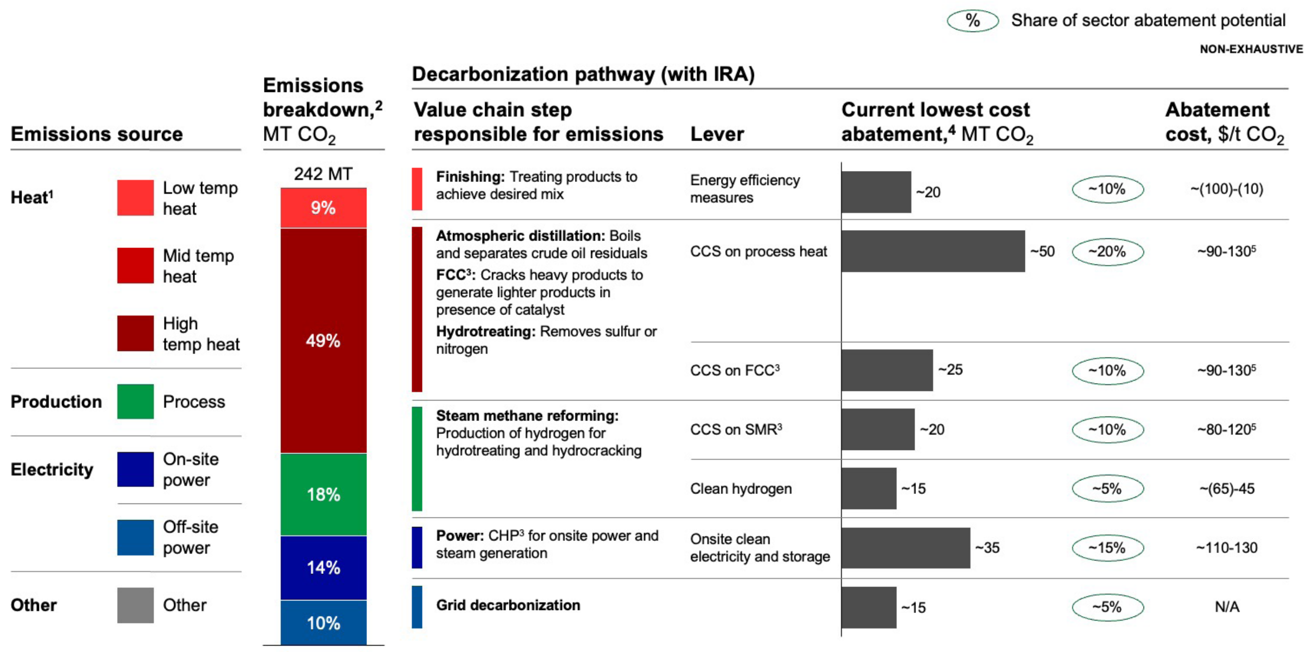
70 Refined oil products include gasoline, diesel, jet fuel, biofuels, and other products.

71 The chemicals and refining deep-dive report focuses on CO2 emissions specifically–broader analysis has been expanded to include CO2-equivalent emissions; MACC analysis is based on CO2 emissions (not CO2e); upstream refining emissions are not included in this figure.

U.S. given the country's large natural gas reserves. However, the share of these "other products" as a total of refining end products may increase as domestic demand for transport fuels declines due to the electrification of the transport sector.[72]

The typical refining process consists of three primary steps: (1) separating crude oil into different compounds, (2) converting lower-value components into higher-value ones through molecular rearrangement, and (3) finishing to improve quality through blending products to get an optimal mix and treating (e.g., to remove impurities).[73] **Refining sector emissions come from three primary sources: heat generation (~58%), electricity (~24%), and process emissions (~18%)** (Figure 3.2.1). **Approximately 90% of the above-mentioned operational emissions originate from onsite point sources.**

The fuel mix combusted in refineries is optimized to include a higher share (>60%) of byproduct refinery fuels and influences the viability of different decarbonization levers. **Decarbonization levers with high abatement potential include hydrogen, CCS, and industrial electrification supported by clean electricity sources.** However, refineries produce multiple sources of CO2e with varying concentrations, making CCS complex to implement. On top of the complexity, these solutions are expensive, and as each refinery operates for a customized set of products, space is typically very limited, given co-location with ports and other industrial hubs. CCS costs range from ~$80/tCO2e on the low end for CCS on concentrated flue streams, such as on steam methane reformers, to $130/tCO2e on the high end for dilute streams like those associated with fluid catalytic converters (or FCCs).[74] It could cost between ~$110–130/tCO2e for onsite clean electricity and storage after factoring in tax incentives, including 45Q, 45V, and 48E. Generally, CCS will be more cost attractive for higher-CO2-concentration facilities, with hydrogen more attractive for lower-concentration facilities.[75]



72 Other products include asphalt, petroleum coke, and petrochemical feedstocks such as naphtha and liquefied petroleum gas (LPG)

73 One of the key post-production steps between refineries and end customers is the transport of final products, particularly fuels, via pipeline; this is out-of-scope for this report, as seen in Figure 1.1 on value chain steps in-scope

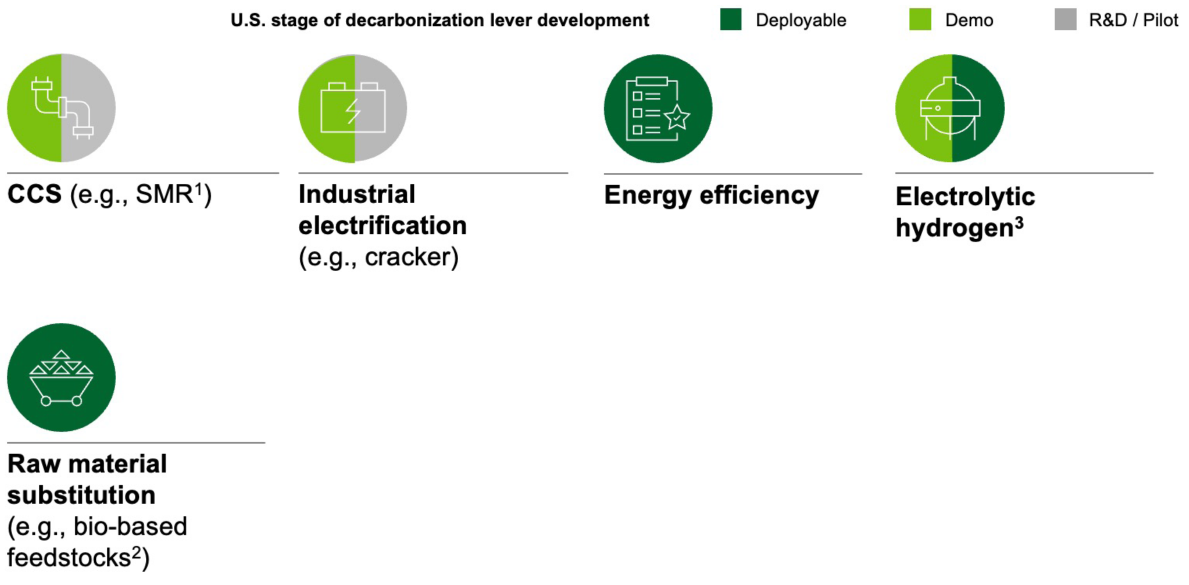
74 Lower bound of CCS costs is represented by CCS on steam methane reformers (SMRs), which are a concentrated source of flue gases. CCS on fluid catalytic converters (FCCs) and on sources of process heat represent the higher bound of CCS costs. IRA tax incentives provide up to $85/t CO2e stored in saline geologic formations from carbon capture on industrial and power generation facilities (45Q), up to $3/kg of H2 produced with low carbon intensity (<0.45 kg CO2e / kg H2) (45V), and up to 30% credit for applicable clean electricity projects (48E)

75 In general, the cost of CO2 capture is inversely proportional to the CO2 purity of the emission stream. But even within the same industry, several factors meaningfully impact the cost of capture, including facility design, separation technology used in the capture process, local energy prices, emissions volumes, flue gas temperature and pressure, and the presence of emissions stream contaminants.

Figure 3.2.1: Almost half of refining emissions come from high-temperature heat and can be addressed with CCS on process heating and fluid catalytic crackers (FCCs) | 1. Temperature ranges are defined as low-temperature heat (-30°C to 200°C), medium-temperature heat (200°C to 400°C), and high-temperature heat (400+°C). | 2. Breakdown of 2021 refining emissions | 3. Steam methane reformer (SMR); Fluidized catalytic cracking (FCC); combined heat and power (CHP); long duration energy storage (LDES) | 4. An additional 9% of abatement potential can be gained from energy-efficiency measures, including reducing fuel consumption and repurposing flare gas. | 5. The displayed costs are based on the capture costs from various sources (see the appendix for details) with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10–40/t; all figures are in 2022 dollars. All CCS figures represent retrofits, not new-build facilities. The lower-bound costs represent a NOAK plant in a low-cost retrofit scenario with low inflation. The higher-bound costs represent a FOAK plant in a high-cost retrofit scenario with high inflation.
Source: 2018 EPA Flight, 2018 EERE Manufacturing Energy and Carbon Footprints report, 2022 IEDO Report, White House – Long-term strategy of the U.S. Pathways to Net-zero, refining MACC

Similar to the chemicals sector, albeit not within the scope of this report, refining has an opportunity to leverage bio-based feedstocks to lower life cycle emissions. **Petroleum-derived products are often minimally processed from crude oil and have very low production emissions from refining compared to total life cycle emissions.** With demand for fuel products changing as the transportation sector decarbonizes, current refinery configurations and optimization can be reconsidered. Bio-based and waste feedstocks can be incorporated into existing or new facilities to produce drop-in or new fuel products.

Decarbonizing the transportation sector could lead to a meaningful reduction in demand. However, without widespread implementation of decarbonization levers, refining will likely continue to be a major contributor to U.S. emissions given the challenge of decarbonizing disparate emission sources and general sector sentiment. Refining emissions could grow ~5–10% by 2050 in a business-as-usual (BAU) scenario [76] if the transportation sector does not transition.[77] Of the nine largest refining companies by market share, six have made decarbonization commitments that range from 30–50% reduction in Scope 1 and 2 emissions by 2035. [78, lvii] Most companies are implementing energy efficiency solutions, but this may only address ~10% of the required abatement for the sector to achieve net zero. Some companies are making exploratory investments in projects to decarbonize production. For example, certain players have initiated demos of CCS on steam methane reformers (SMRs) to produce hydrogen from natural gas, incentivized by 45Q. Figure 3.2.2 shows the development stages of levers across U.S. refining.



76 The BAU scenario assumes that the crude oil inputs and a slate of product outputs in the Energy Information Administration's Annual Energy Outlook reference case projections (2022) are refined at the same energy intensity (GJ/barrel of oil) and carbon intensity (MT CO2/GJ) of U.S. refineries in 2015. For more information, see the Department of Energy's Industrial Decarbonization Roadmap.

77 The BAU scenario assumes that the crude oil inputs and slate of product outputs in the Energy Information Administration's Annual Energy Outlook reference case projections (2022) are refined at the same energy intensity (GJ/barrel of oil) and carbon intensity (MT CO2/GJ) of U.S. refineries in 2015. For more information, see the Department of Energy's Industrial Decarbonization Roadmap.

78 Refining companies analyzed are the largest by market share and include Marathon Petroleum, Valero Energy, Philips 66, ExxonMobil, Chevron, BP, Shell, Citgo, and PBF Energy. Analysis is based on public reports and press search.

Figure 3.2.2: Stage of lever deployment within the refining sector | 1. SMR = Steam methane reformers | 2. Such as bio-based feedstocks for fuel production and sustainable aviation fuels with decarbonized production facilities | 3. Refers to hydrogen use in traditional processes as a feedstock
Source: EIA, EPA, IEDO Industrial Decarbonization Roadmap, IEA, press search, company sustainability reports, expert interviews

U.S. refineries can set the standard for decarbonization over the near term by adopting the best-available technologies at more than 130 locations, producing and using clean hydrogen, and scaling the production of sustainable fuels.[79, lviii, lix] By 2040, they will need to achieve a <$30/MWh cost of electrifying low-temperature heat units to be competitive with fossil-fuel-powered processes, close the CCS cost gap on dilute streams, such as FCCs and process heat, and mature modular nuclear reactor technologies to achieve cost competitiveness with fossil-fuel-powered processes. To abate the remaining emissions by 2050, the refining sector must mature sustainable fuels made with decarbonized production methods and capture emerging green premiums for low-carbon fuels. This pathway could allow refineries to scale and develop new products (e.g., bio-based fuels), preserve the industrial base, retain the social license needed to operate, and become a global leader in clean fuel production. **The U.S. refining decarbonization "Pathway to Liftoff" could require $200–300B in capital investment through 2050 to scale decarbonization technologies** (Figure 3.2.3).

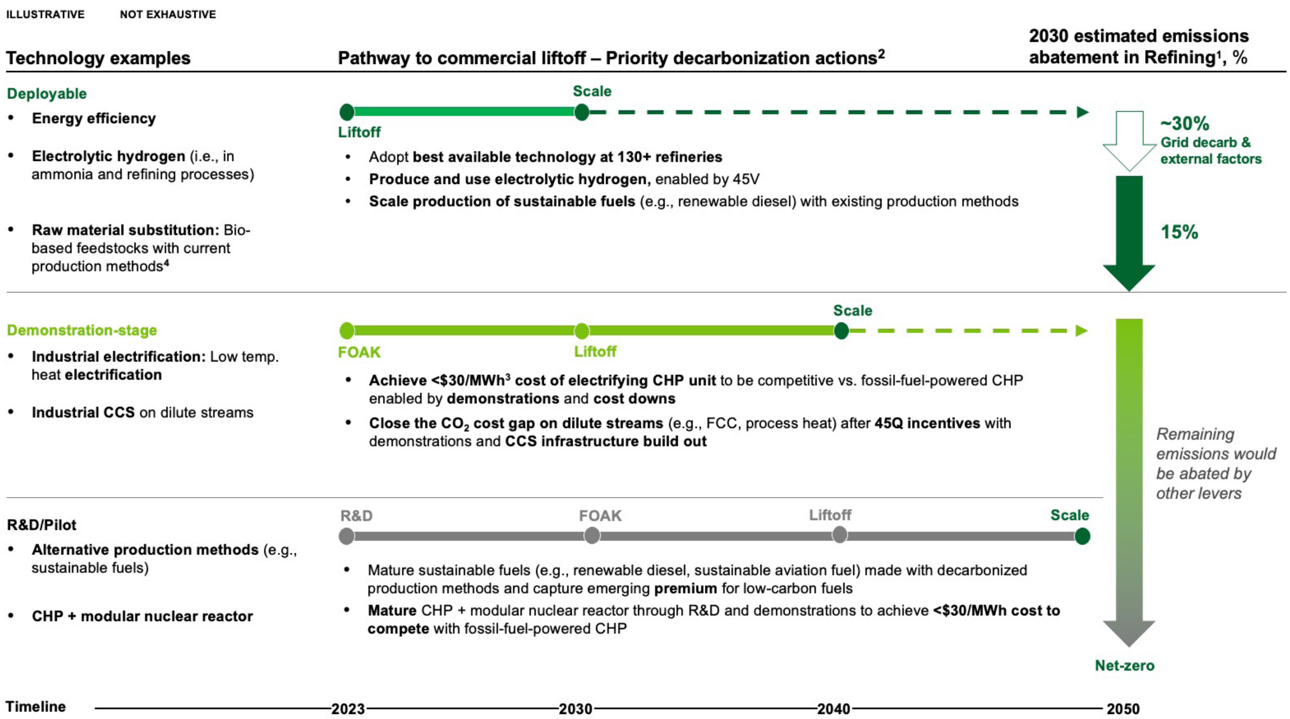


Figure 3.2.3: Liftoff pathway for decarbonization technologies within the refining sector | 1. Regardless of transport electrification goals, this breakdown of decarbonization technologies will be required to reach net-zero refining in the U.S. at varying scales. | 2. Indicative timeline presented for R&D, FOAK, liftoff, and scale. Actual timelines will vary by technology based on technological maturity and barriers to adoption | 3. Estimated as the breakeven point on the MACC-levelized-cost-of-heat to reach $0/tCO2 abatement cost for refining combined heat and power | 4. Bio-based feedstocks are not included in estimated emissions abatement due to the focus on process and production emissions vs. life cycle emissions. See the Chemicals and Refining Liftoff Report for more details.

79 The balance of onsite production of hydrogen and purchased merchant hydrogen varies based on region but is increasingly shifting towards merchant hydrogen; all merchant hydrogen production is included under the emissions baseline for refining as refineries are the largest offtakers

Section 3b.iii: Iron and steel

The U.S. iron and steel sector provides essential inputs to critical sectors of the economy, including automotive, building and construction, and energy.

~89	MT CO_2	2021 U.S. Emissions
~3,100	MT CO_2	2021 Global Emissions

Iron and steel accounted for 89 MT CO2e, or ~1% of total U.S. CO2e emissions in 2021. U.S. crude steel production is projected to grow 2% annually through 2030, driven by demand from building and construction, automotive, and energy sectors. [xliii] The U.S. has two main steel production routes: integrated Blast Furnace–Basic Oxygen Furnaces (BF-BOF) [80] and Electric Arc Furnaces (EAF), also known as mini-mills. [81] Both use a mix of three iron inputs to make molten steel: pig iron from blast furnaces produced from iron ore and coking coal; direct reduced iron (DRI) / hot briquetted iron (HBI) produced from higher-quality iron ore using natural gas or hydrogen as a reducing agent (reductant); and varying qualities of scrap, depending on the finished steel's performance requirements.[82]

As the birthplace of and world leader in mini-mills, the U.S. has seen production shift from BF-BOFs to EAFs, which now account for ~70% of domestic steel. [xxxviii] EAFs are less carbon-intensive (~0.3-0.7 tCO2e/t liquid steels. ~2–2.5 tCO2e/t liquid steel from BF-BOFs) but will face increased resource constraints (e.g., limited domestic prime scrap availability requiring further use of higher-carbon pig iron or DRI/HBI).[83] As a result of EAF leadership, the US is a world leader in low-carbon steel production. The remaining BF-BOFs are ~30% of production but represent 65% of sector CO2e emissions. All US BF-BOFs are owned and operated by two large, integrated steelmakers, Cleveland Cliffs and US Steel, where a large share of the workforce is represented by labor unions.[84]

There are two categories of steel products: flat (e.g., coil and plate) and long (e.g., wire rod, rebar, pipes, beams, bar). Flat steel production in 2021 was ~50% BF-BOF and ~50% EAF. Long steel in the U.S. is produced entirely through the EAF route. A few grades of steel demanded by the auto and defense industries, notably high-strength galvanized/peritectic steel, still require BF-BOFs for production. EAFs have continuously marched up the quality curve and are expected to be able to produce all key grades by ~2030.

80 In a BF, coke and iron ore sinter or pellets are combined to produce pig iron. The pig iron is then transferred to a BOF, which blows air currents to turn iron ore, mixed with coal and smelting agents such as limestone, into molten metal.

81 Most flat steel coil-producing EAFs in the U.S. use DRI/HBI in combination with pig iron. In a DRI/HBI furnace, iron ore pellets are directly reduced to purer iron using natural gas. These iron units are then transferred to an EAF, where electricity is passed through graphite electrodes to create the high heat necessary to produce steel.

82 BF-BOF charge mix creates pig iron in its first production stage, whereas EAF charge mix depends on pig iron and DRI / HBI to substitute high-quality prime scrap. BF-BOF can also use a limited percentage of scrap or DRI (maximum ~20% scrap, ~10% DRI/HBI).

83 Emissions intensity reflects iron production and steel production; the total emissions intensity of EAF depends on the type of steel product produced as certain long products can be made with 100% scrap input which nearly eliminates process emissions from iron and steelmaking.

84 There are additional BF-BOF proximate to the US border in both Canada and Mexico

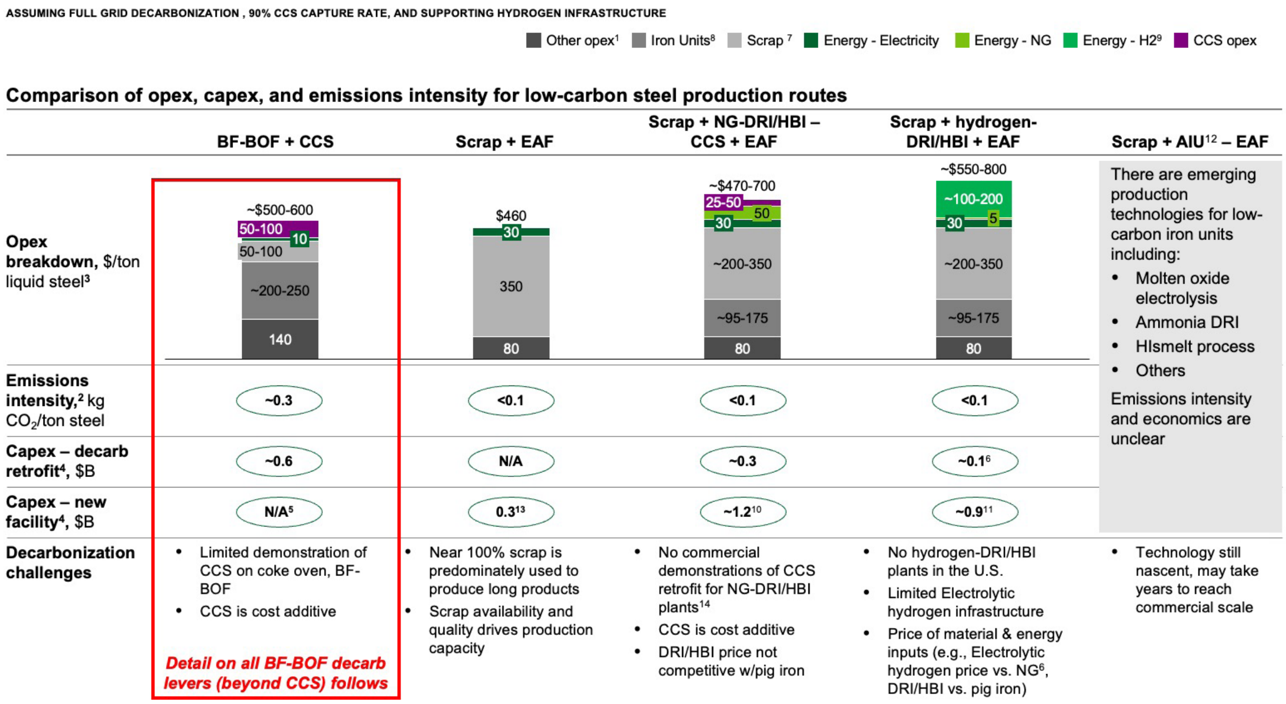


Figure 3.3.1: Costs above represent the perspective of steel producers | 1. Largely labor and mill maintenance | 2. Emissions intensity per ton of liquid steel assumes that grid decarbonization reaches 100% and is contingent on a carbon capture rate of 90% | 3. Assumes a scrap ratio of 60%, combined with iron units in EAF and a scrap ratio of 20% in BF-BOF | 4. Reflects costs for a 1.2 MT steel facility. Retrofit reflects the cost of CCS or hydrogen installation on an existing facility | 5. There are no domestic plans to build additional BF-BOF mills. | 6. Cost of retrofitting NG-DRI/HBI to hydrogen | 7. Scrap use is highly variable; many steelmakers will fluctuate the use of iron ore and scrap as the costs of these inputs change due to external conditions. | 8. The assumed range uses the cost difference between merchant and integrated DRI/HBI production. | 9. The range assumes an electrolytic hydrogen price of $2–$4/kg. | 10. Includes new NG-DRI/HBI built with CCS | 11. Includes electrolyzer | 12. Alternative iron units | 13. Cost to build a new EAF | 14. Recent deployment announcement by Nucor

Figure 3.3.1 highlights the preliminary cost data for deep-decarbonized steel in the medium term, inclusive of 45V and 45Q tax credits. While BF-BOFs have some efficiency opportunities, retrofitting integrated facilities with CCS can have the largest impact on their emissions.

All deep decarbonized EAF routes (scrap, scrap + NG DRI w/CCS, and scrap + H2 DRI) will likely have lower emissions intensities than retrofitting BF-BOFs with CCS. Pure prime scrap + EAF is the lowest emissions path currently available, however, both the need for primary iron for high performance products and the tightening of the market for prime scrap in the U.S. mean that the industry will need to supplement scrap with alternative iron units like low-carbon DRI/HBI to meet the demand for clean steel.

Low-carbon DRI/HBI can come from direct reduction with natural gas with CCS or using hydrogen as a reductant. There are opportunities for both routes in the U.S., with decisions impacted by local geology (i.e., storage availability), availability of clean hydrogen, and facilities' underlying technology. The two-leading gas-DRI-technology providers engineer plants with different flue streams. One provider's facilities produce a flue stream with a concentration of ~60% carbon dioxide, while another produces a 15% stream. CCS will be more cost attractive for higher-CO2-concentration facilities, with hydrogen more attractive for lower-CO2-concentration facilities.

In the long term, a range of technologies, like molten oxide electrolysis, offer alternative options for decarbonized steel, but these are currently in the Pilot/R&D stage.

BF-BOF emissions are responsible for 70% of U.S. iron and steel emissions, ~80% of which are heat-related, stemming from coking coal combustion. [lx, lxi] Significant decarbonization levers include CCS and potential transition toward EAFs.

Ninety percent of BF-BOF emissions can be technically addressed with CCS retrofits or by shifting steelmaking production to EAF and reducing reliance on high-carbon inputs (e.g., pig iron).[85] These solutions are cost additive, ranging from ~$40–290/t CO2 for CCS on flue streams on BF-BOF and NG-DRI/HBI after IRA incentives to transitioning to EAF, which adds ~$50–100/t CO2 abated due to the need for more expensive raw material and energy inputs (Figure 3.3.2). [86]

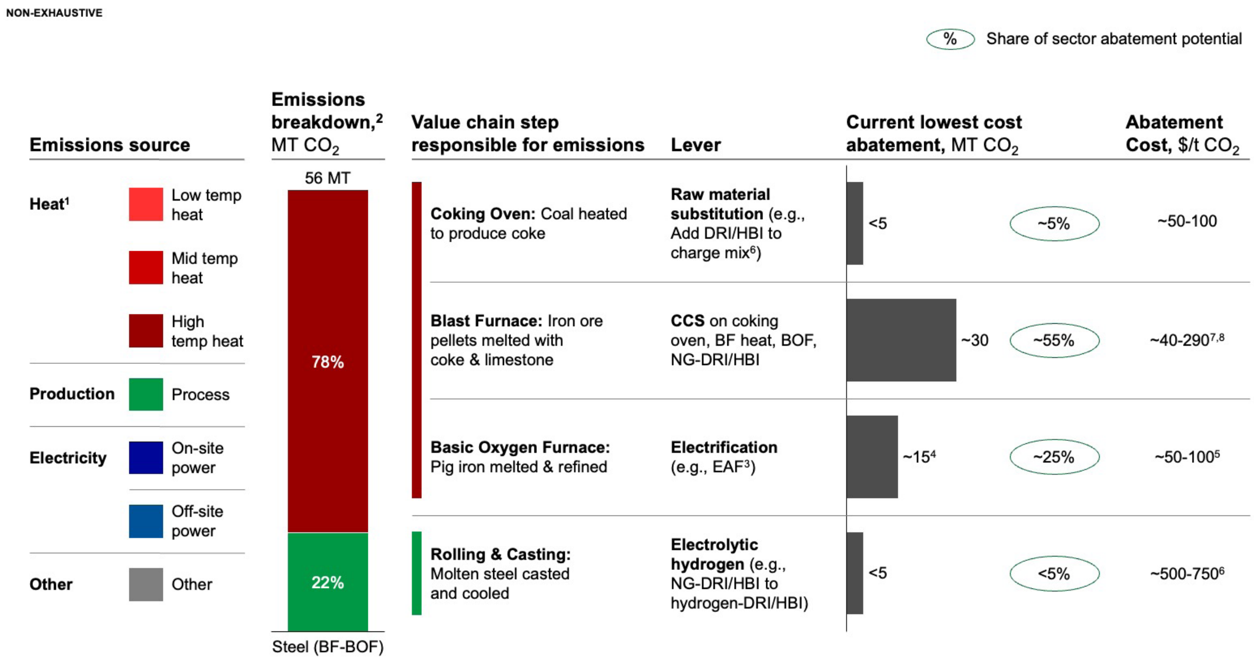


Figure 3.3.2: BF-BOF steel production has two primary emissions sources that can be abated using various levers (e.g., CCS, raw material substitution, electrification) | 1. Temperature ranges are defined as low-temperature heat (-30°C to 200°C), medium-temperature heat (200°C to 400°C), and high-temperature heat (400+°C). | 2. Breakdown of 2021 BF-BOF steel emissions | 3. As more U.S. steelmakers shift to DRI/HBI-EAF, constraints could form on scrap metal availability, a key material input in U.S. EAFs (~0.7t/t of steel). Abatement reflects a decarbonized grid scenario. | 4. Note that this reflects a difference in furnace emissions and increased scrap consumption | 5. NG DRI-EAF is estimated to be ~$100–150/t, whereas hydrogen DRI-EAF is ~$150–250/t | 6. Can only comprise ~10-15% of material input | 7. Varies by application. BF-BOF applications are expected to be $40–110/tCO2 with 45Q, and NG-DRI/HBI applications are expected to be $140–290/tCO2. | 8. Displayed cost estimates are based on capture costs from various sources (see the appendix for details) with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10–40/t, which are in 2022 dollars. All CCS figures represent retrofits, not new-build facilities. The lower-bound costs represent a NOAK plant in a low-cost retrofit scenario with low inflation. The higher-bound costs represent a FOAK plant in a high-cost retrofit scenario with high inflation.
Source: McKinsey, Mission Possible Partnership Net Zero Steel, "Decarbonizing the iron and steel industry: A systematic review of sociotechnical systems, technological innovations, and policy options" (Kim et al., July 2022), World steel association, Steelmakers annual report

The EAF pathway emissions (including some DRI production) come from two primary sources: offsite electricity (~55%) and high-temperature heat (~30%). [lxii] **Significant decarbonization levers include grid decarbonization, CCS, and clean hydrogen. Clean onsite electricity and storage could be an important lever if additional onsite power is built.**

Most DRI-EAF pathway heat emissions come from producing direct-reduced iron/hot briquetted iron (DRI/HBI). U.S. production of DRI/HBI is 100% natural gas today, but majority of emissions can be abated with clean hydrogen (~$100-250/tCO2 after IRA incentives) or CCS.

There is ongoing momentum for clean steel in the U.S. Recent examples include blast furnaces implementing waste heat recovery, continuing transition toward EAFs with 20 MTPA new capacity announced, additional

85 Transitioning to EAF lowers ironmaking emissions for several reasons: 1) EAFs can use a greater share of scrap, as most U.S. EAFs use at least 60% scrap vs. a maximum of 20% for BF-BOF. 2) EAFs in the U.S. generally use DRI/HBI instead of pig iron in addition to scrap, which is a lower carbon iron unit.

86 Merchant DRI/HBI and scrap are more expensive than merchant pig iron, although select integrated players have DRI/HBI production capacity and/or own scrapyards, which can adjust the economics of the steel mill on a case-by-case basis. EAF mills use significantly more electricity, and production of DRI/HBI requires natural gas or clean hydrogen inputs, which add additional energy opex costs to the steel production route.

plans for DRI/HBI facilities, announcements for natural gas DRI with CCS, and global activity around hydrogen DRI.[87] Six of the nine large iron and steel players have made decarbonization commitments, with 2035 goals ranging from 20–50% reductions in Scope 1 and 2 emissions.[88]

However, the transition in iron and steel will take time and investment. There are economic constraints to transition production from BF-BOF to EAF (using mixes of virgin iron and scrap) because iron and steel production is integrated into most BF-BOF mills. Retrofitting facilities requires large shutdown costs, and new EAF and DRI/HBI mills require high capex. Further, EAF production will face supply challenges as prime / prompt scrap in the U.S. is expected to be limited vs. demand in the coming years, and lower grades of scrap require dealing with tramp elements. While some virgin pig iron or DRI/HI is required to make many grades of steel in EAF's, EAF steelmakers may become more reliant on virgin iron to scrap supply constraints.[89] The next decade will be critical. Key off-takers, like the auto industry, can spur demand for clean investment, and public and private investment can accelerate the process.

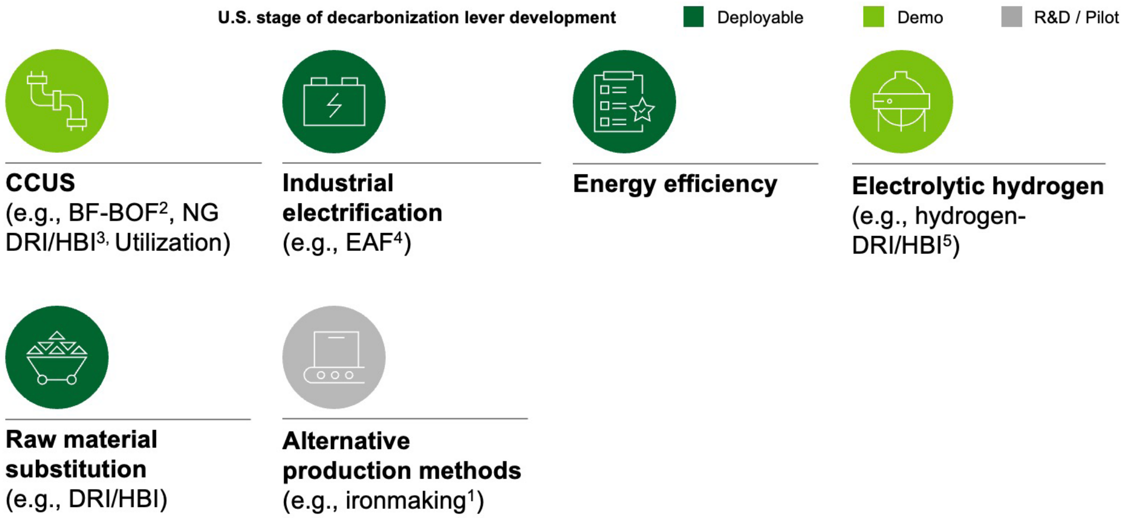


Figure 3.3.3: Stage of lever deployment within the iron and steel sector | 1. Includes direct reduced iron and molten oxide electrolysis from companies such as Boston Metal | 2. Blast furnace-basic oxygen furnace (BF-BOF) | 3. Natural gas direct reduced iron / hot briquetted iron (NG DRI/HBI) | 4. Electric arc furnace (EAF) | 5. Direct reduced iron / hot briquetted iron (DRI/HBI)

U.S. iron and steel decarbonization "Pathway to Liftoff" could require \$25–40B in capital investment through 2050 to scale decarbonization technologies (Figure 3.3.4).[90]

The U.S. can solidify its position as a global leader of low-carbon iron and steel. In the near term, the U.S. can drive the adoption of the best technology at the remaining BF/BOF facilities, increase low-carbon DRI/HBI production and scrap, and continue to migrate production toward EAF routes. Each of these options have potentially significant effects on the existing workforce, workers, and the unions who represent them. These groups should be part of the planning process to ensure job quality is maintained or improved.

CCS is a high cost decarbonization lever in steel. However, barring rapid advancement of early-stage, low-cost decarbonization technologies, some CCS, alongside clean hydrogen, is likely needed to decarbonize the sector. Demonstrations and tax credits like 45V and 45Q can lower costs of CCS on BF/BOF, natural gas DRI + CCS, and H2 DRI while growing CCS and hydrogen transport and storage infrastructure. Working with leading off-takers like the auto industry can foster technology premia for decarbonized steel (e.g., First Movers

87 This 20MT is expected to produce flat steel products, and capacity will come fully online by 2025.

88 Largest companies were selected based on market share; "short-term" refers to targets for 2035; companies considered include Steel EAF: Nucor, Steel Dynamics, Gerdau, CMC, Timken, and Charter steel; Steel BF-BOF: Cleveland Cliffs, US Steel, and ArcelorMittal

89 Scrap limitations not considered in MACC analysis.

90 This total investment was estimated using several decarbonization scenarios considering the cost of CCS retrofits on BF-BOF, NG-DRI/HBI, and EAF, as well as additional build-out of domestic DRI/HBI production and FOAK U.S. clean H2 DRI/HBI – EAF.

Coalition steel commitments). There are R&D opportunities to scale alternative ironmaking processes like iron electrolysis and support EAF technology development to produce all grades of steel.

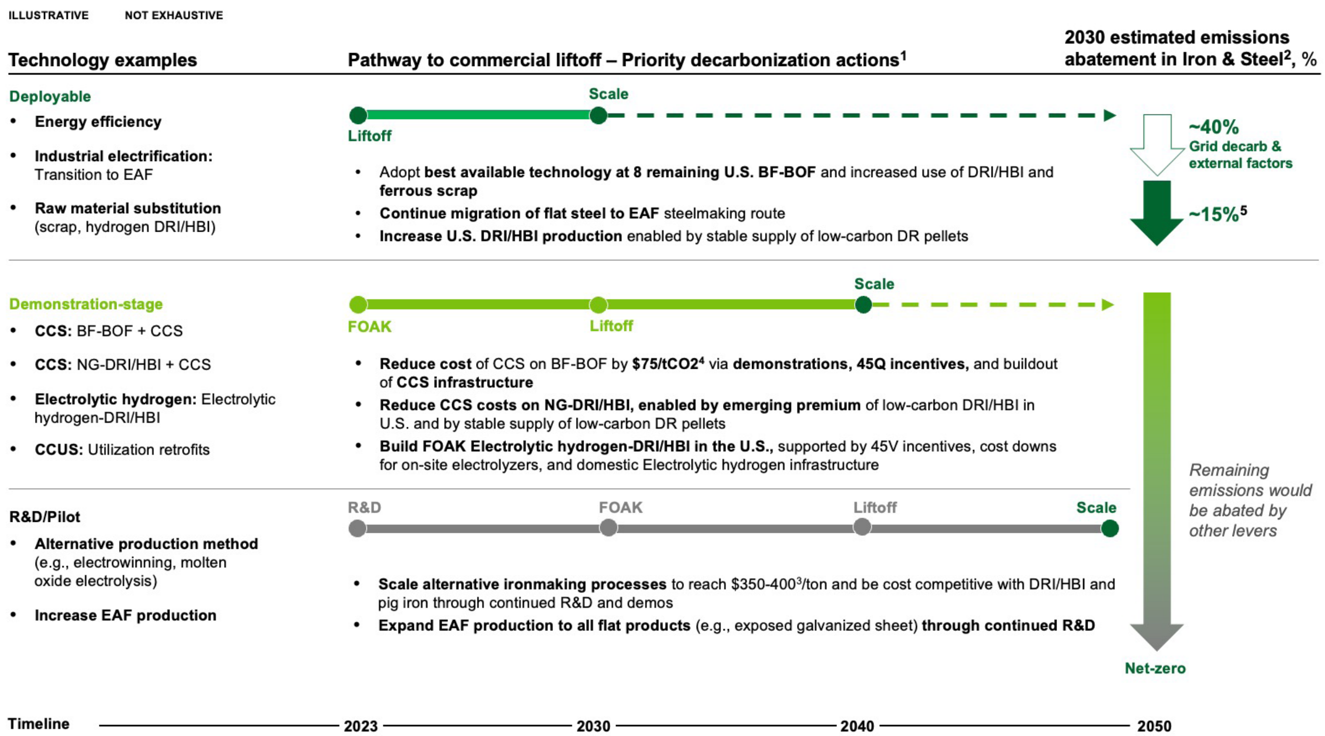


Figure 3.3.4: Liftoff pathway for decarbonization technology within the iron and steel sector 2. Abatement share ranges are constrained and based on alternative decarbonization pathways, varying on factors such as the number of BF-BOF mills that transition to EAF and the evolution of CCS on BF-BOF and NG-DRIHBI | 3. Reflects multiple decarbonization scenarios considering the cost of CCS retrofits on 2-8 remaining BF-BOF, potential environmental clean-up shutdown costs for 2-6 BF-BOF, building additional domestic 2.5 to 10MT NG based DRI/HBI, CCS to 5-15MT NG-based DRI/HBI, and FOAK U.S. clean H2 DRI/HBI-EAF | 4. Based on the estimated merchant cost of pig iron, DRI/HBI | 5. Reflects cost gap for BF-BOF CCS as published in the carbon management report

Section 3b.iv: Food and beverage

~85	MT CO_2	2021 U.S. Emissions
~400	MT CO_2	2021 Global Emissions

Food and beverage (FandB) processing in the U.S. involves a wide range of activities to transform raw agricultural materials into consumable food and drink products. There are thousands of FandB products across 10 major groups, including meats, dairy, beverages, fruits and vegetables, grains and oilseeds, bakery, animal food, sugar and confectionary, seafood, and others. While many sectors covered in this report have complex value chains, FandB is among the most diverse. FandB products are produced in over 35,000 U.S. facilities, creating unique challenges for full industry decarbonization.

FandB processing accounted for ~1% of U.S. CO2e emissions in 2021, or ~85 MT CO2e (~10% of emissions from the sectors of focus). Processing generally represents less than 10% of the total value chain emissions across major FandB products. The seven most energy-intensive subsectors of FandB processing are wet corn milling, soybean oil, cane sugar, beet sugar, fluid milk, red meat product processing, and beer production.[91] On-the-farm/agricultural activities, transportation, packaging, retail, and post-consumer activities are all out of this analysis' scope, but major opportunities for decarbonization in these areas could warrant further investigation.

FandB processing sector emissions come from two primary sources: electricity (~50%) and heat generation

91 These sectors combined represent ~1/3 of all energy use in FandB, highlighting how disparate energy use and emissions sources are within the industry.

(~50%) (Figure 3.4.1.[92, lxiii] **Decarbonization levers with high abatement potential for the sector include grid decarbonization, energy efficiency, and electrification of heating equipment, including boilers, ovens, fryers, etc.**[93] Energy efficiency solutions can be applied across several segments of FandB processing (e.g., steam generation, process cooling) and are relatively inexpensive, with the potential for operational cost savings due to more efficient processes. The other levers with high abatement potential, such as electrification and alternative-fuel equipment, are more expensive, with costs ranging from ~$70–110/t CO2e for electric boilers or heat pumps (Figure 3.4.1).

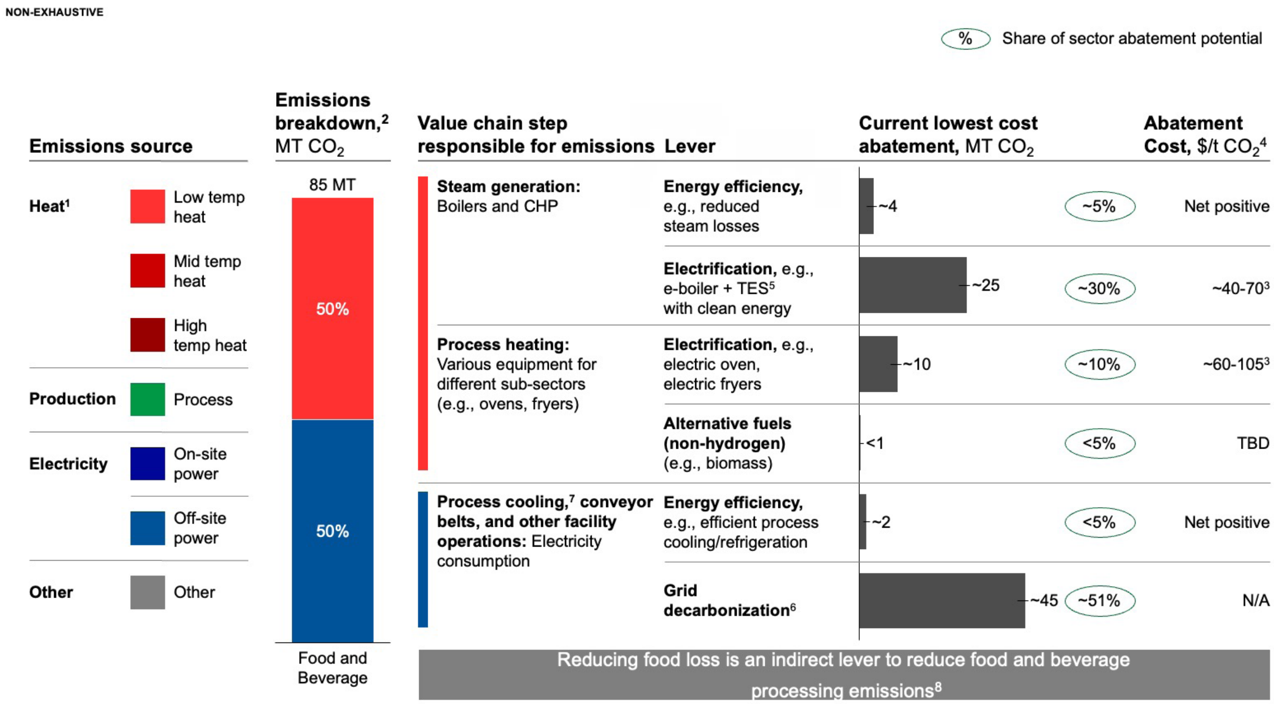


Figure 3.4.1: Food and beverage emissions come from low-temperature heating and electricity and can largely be addressed through grid decarbonization, electrification, and alternative fuels. | 1. Temperature ranges are defined as low-temperature heat (-30°C to 200°C), medium-temperature heat (200°C to 400°C), and high-temperature heat (400+°C). | 2. Breakdown of 2021 food and beverage processing emissions | 3. Assumed to be 1.5x the cost of electrified steam generation | 4. Wide range due to diverse products, processes, and facility sizes | 5. Thermal energy storage (TES) | 6. Biden Administration goal of reaching 100% clean electrical grid by 2035 | 7. Process cooling is a significant portion of current food and beverage processing's electrical load, and a range of levers could be used to reduce electricity consumption. | 8. Manufacturing is the largest source of food waste/loss.
Source: 2018 EPA Flight, 2018 EERE Manufacturing Energy and Carbon Footprints report, 2022 IEDO Report, McKinsey Global Energy Perspective, Communications, Earth and Environment (2022)

There is potential to decarbonize FandB processing by scaling deployable technologies such as electric boilers. However, the sustainability efforts of major FandB players are generally focused on agricultural activities, given that most emissions originate "on the farm" rather than during processing. Almost 90% of large FandB players have decarbonization commitments that span all facilities, in many cases including farms. Within the sub-sectors covered: grain, dairy, and meat processing, short-term targets across the sector range from a 10–40% reduction in Scope 1 and 2 emissions by 2035; however, other FandB companies have higher targets (i.e., 75% by 2030).[94] To date, there has been little momentum in deploying significant decarbonization levers, with most processing efforts focused on efficiency solutions; Figure 3.4.2 shows the development stages of levers across the FandB sector**. While the technology solutions to decarbonize FandB may be comparatively simple, there is a challenging case for**

92 Heat generation for FandB processing is almost entirely low-temperature heat (i.e., <200°C).

93 Energy efficiency measures could include increasing CHP (onsite generation) to reduce reliance on purchased fuels.

94 FandB companies analyzed were selected by largest market share and included JBS Foods, Tyson Foods, Cargill, Dairy Farmers of America, Land O' Lakes, California Dairies, Bunge

investment, given the industry's low margins. Sector decarbonization will likely rely on cost-effective, low-carbon, low-temperature heating via either electrification or alternative fuels. The low margins of FandB players are often a limiting factor to upfront capex investment, even if there is potential for long-term economic benefits.

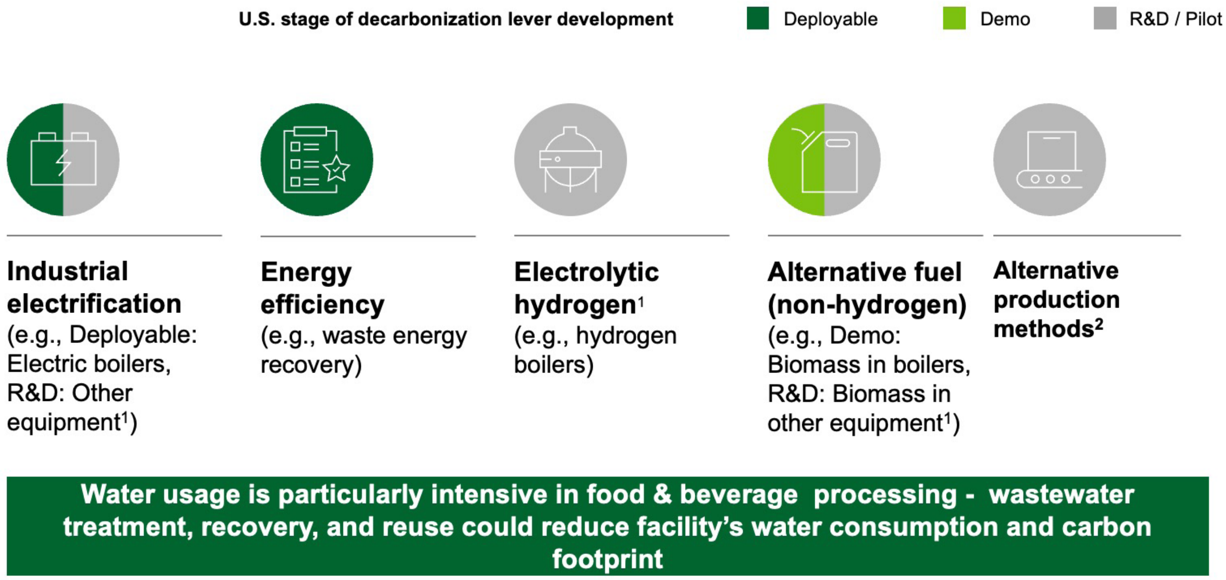


Figure 3.4.2: Stage of lever deployment within the food and beverage sector | 1. Equipment varies by subsegment, product, and facility, with some applications in different stages. | 2. E.g., absorption chillers, ejector refrigeration, deep waste energy and water recovery, alternative protein manufacturing
Source: 2018 EPA Flight, 2018 EERE Manufacturing Energy and Carbon Footprints report, 2022 IEDO Report, McKinsey Global Energy Perspective, Communications, Earth and Environment (2022)

The U.S. FandB processing decarbonization "Pathway to Liftoff" could require $5–15B in capital investment through 2050 to scale decarbonization technologies (Figure 3.4.3).[95, lxiii]

The sector is well positioned to activate consumer-side pull and grow business by educating consumers on the decarbonization benefits of implemented solutions. Further, FandB processing could unlock economic low-temperature heat decarbonization by **maximizing alternative fuel usage, driving down electrification costs to support broader industrial decarbonization efforts and low-carbon demand signals, which** can also support broader U.S. food system decarbonization.

95 Investment required was estimated considering the capex requirements to replace all industrial boiler capacity in FandB with electric boilers but does not yet include other heating equipment or alternative production methods.

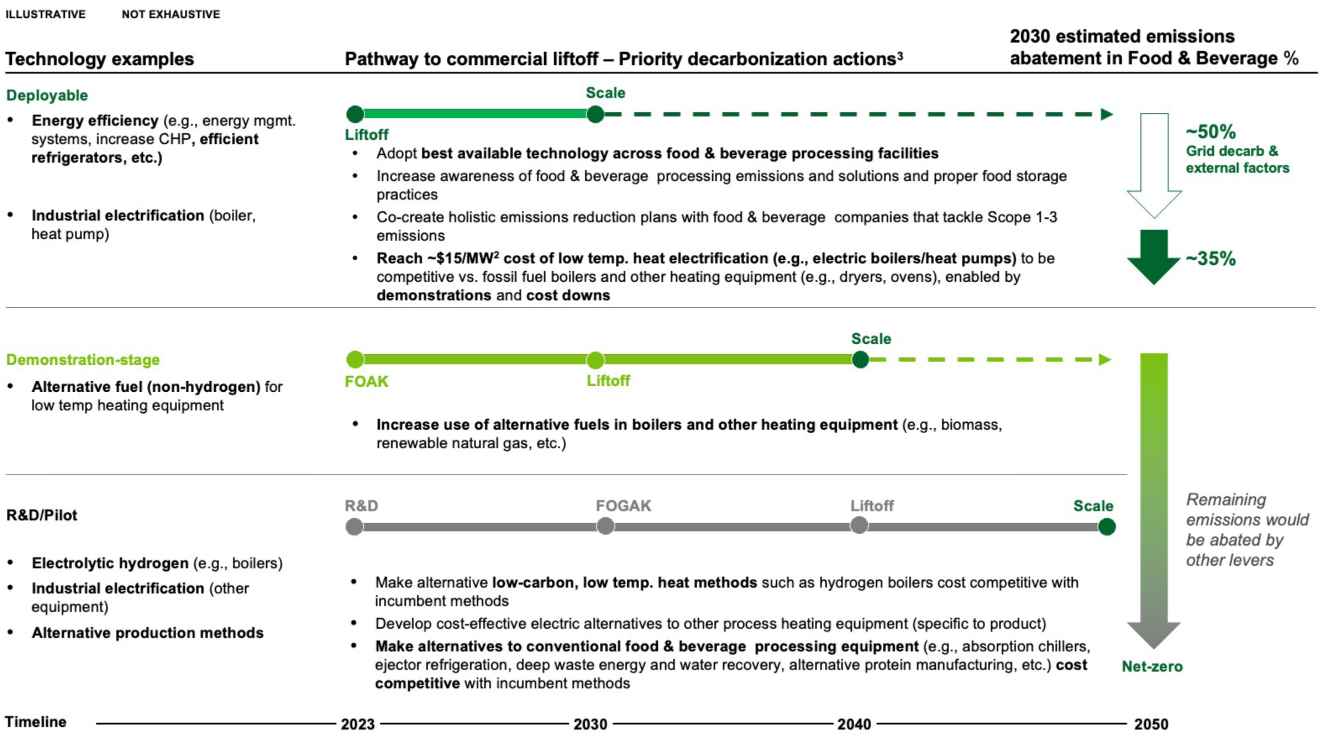


Figure 3.4.3: Liftoff pathway for decarbonization technology within the food and beverage processing sector | 1. Abatement share ranges are constrained and based on alternative decarbonization pathways, varying on factors such as the evolution of clean hydrogen boilers | 2. Estimated as the breakeven point on the MACC levelized cost of heat to reach $0/tCO2e abatement cost for ethylene steam generation (used as a proxy for low-temperature heat) | 3. Indicative timeline presented for R&D, FOAK, liftoff, and scale. Actual timelines will vary by technology based on technological maturity and barriers to adoption.

Section 3b.v: Cement

Cement is the primary component of concrete, the most widely consumed manufactured material on earth. Cement is and will remain a critical input for the nation's infrastructure, housing, and other essential construction projects. [lxiv, lxv, lxvi]

~69	MT CO_2	2021 U.S. Emissions
~2,500	MT CO_2	2021 Global Emissions

U.S. cement production accounted for 69 MT CO2e emissions in 2021 (~1% of U.S. CO2e emissions and ~8% of emissions from the sectors in focus in this report) and **~2,500 MT CO2e emissions from cement worldwide (~7–8% of all global carbon emissions)**. Decarbonizing the sector domestically will be necessary to achieve net zero goals, and establishing the U.S. as a center for low-carbon cement will also provide an opportunity to lead internationally by exporting American-made technologies worldwide.[96]

Though there may be some small variation across plants, cement production largely follows the same process: limestone and other raw materials are quarried, crushed, and milled, preheated in a multistage pre-calciner, then fed into a rotary kiln that is heated to ~1,400–1,450°C. Under high heat in the kiln, raw materials are converted into a new substance, clinker, that is ground and mixed with limestone, gypsum, and other additives to create a final cement mix for sale. This cement is then mixed with water and aggregates to produce concrete for use in construction.

Approximately 85% of emissions from this process come from difficult-to-abate sources—34% come from fuels and feedstocks used to generate the high heat at the kiln, and 51% come from the process of calcination itself, by which calcium oxide is extracted from limestone to create clinker. The remaining 15% comes from electricity consumption and other sources. (Figure 3.5.1).

Decarbonization levers with substantial abatement potential include clinker substitution and other material-use efficiency measures in the shorter term and a combination of CCS, alternative production methods for traditional cement products, and potentially alternative binder chemistries in the longer term. Alternative fuels and efficiency measures could play an important role. Measures that are technologically proven and have a strong economic value proposition, particularly clinker substitution, could abate ~30% of emissions if deployed aggressively by 2030. Abating the remaining ~70% of emissions will likely require scale-up of CCS, alternative production methods, and novel binder chemistries, all at earlier stages of technological maturity and/or have challenging economics and require additional support to achieve liftoff. Figure 3.5.1 includes only a least-cost abatement-constrained scenario. See the Cement Liftoff Report for detailed information on cement decarbonization pathways and lever abatement.

96 Cement is the third largest CO2 emitter globally.

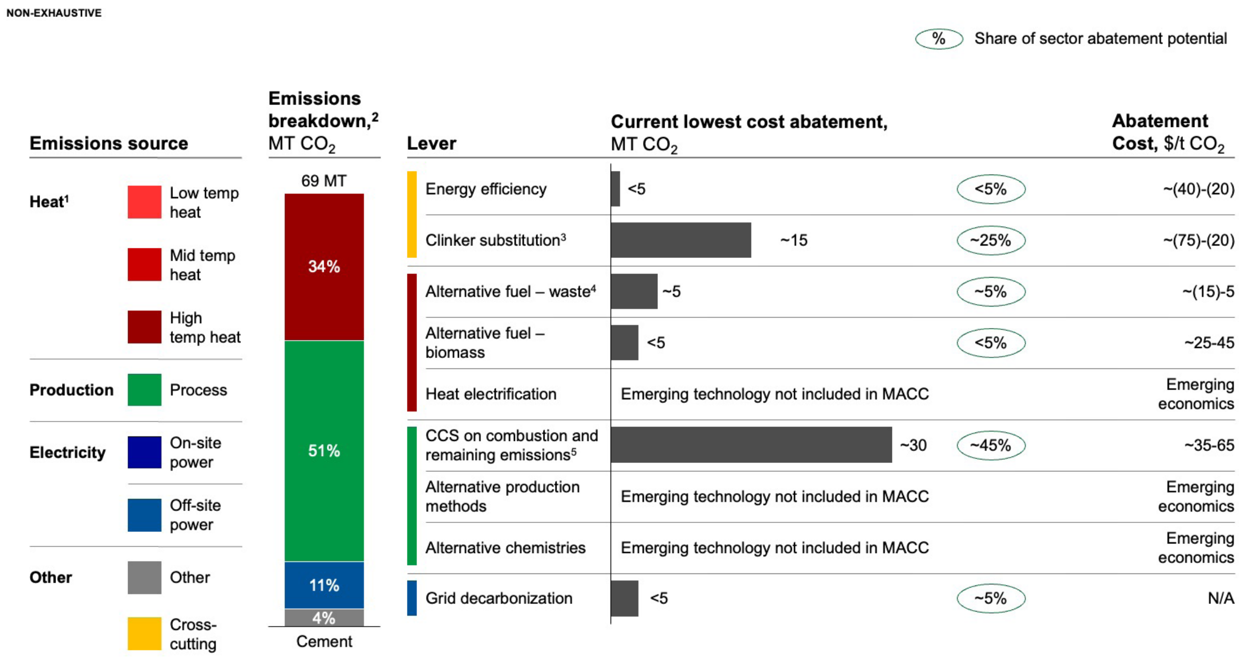


Figure 3.5.1: Cement emissions can be abated using various levers (e.g., CCS, clinker substitutes, alternate fuel) | 1. Temperature ranges are defined as low-temperature heat (-30°C to 200°C), medium-temperature heat (200°C to 400°C), and high-temperature heat (400+°C). | 2. Breakdown of 2021 cement emissions | 3. Assuming 65% clinker ratio | 4. Average based on several different types of waste feedstocks | 5. The displayed cost estimates are based on the capture costs from various sources (see the appendix for details) with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10–40/t; all figures are in 2022 dollars. All CCS figures represent retrofits, not new-build facilities. The lower-bound costs represent a NOAK plant in a low-cost retrofit scenario with low inflation. The higher-bound costs represent a FOAK plant in a high-cost retrofit scenario with high inflation.

Source: McKinsey –"Laying the foundation for zero-carbon cement", Portland Cement Association, DOE Carbon Management Liftoff Report, GCCA, Cement, IFC, GNR, IEA "Low-Carbon Transition in the Cement Industry"

Momentum is building in industry, but progress must accelerate significantly to keep pace with net-zero goals. The largest U.S. cement companies have pledged to reduce emissions by 10–60% by 2035. Incumbents have begun implementing efficiency measures and clinker substitution, but adoption has been slow and must be scaled up significantly and rapidly to realize their full abatement potential. A robust start-up ecosystem has developed to bring many novel production methods and alternative chemistries to market. CCS and alternative production methods are rapidly approaching their first deployments and could see initial commercial-scale demonstrations in the mid-to-late 2020s.

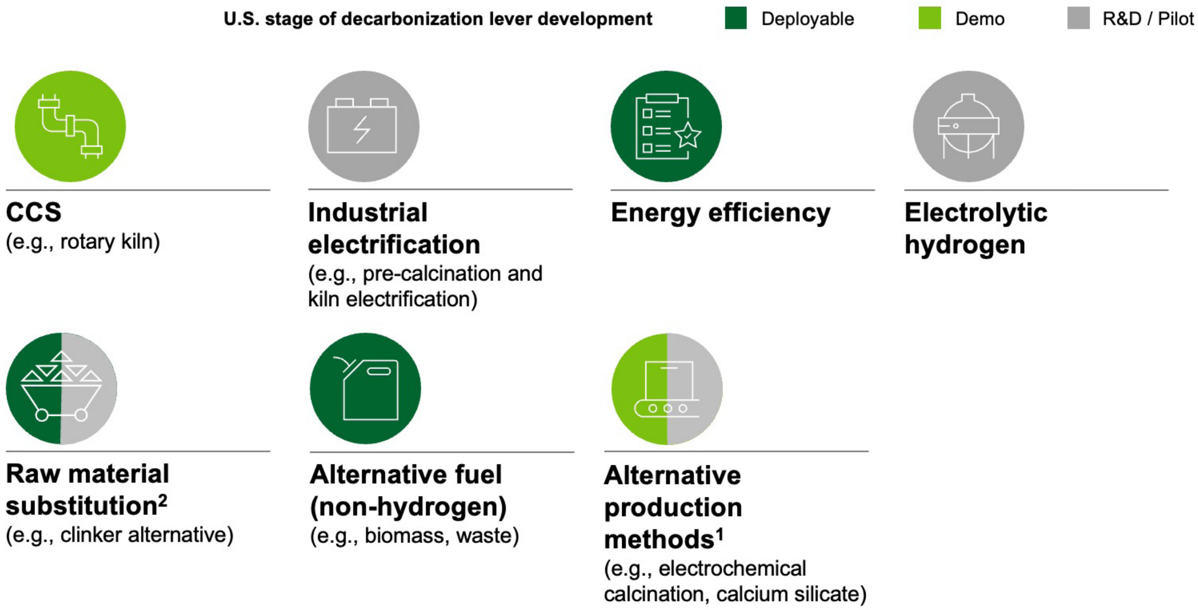


Figure 3.5.2: Stage of lever deployment within the cement sector | 1. Geopolymers | 2. While substitution of limestone and fly ash are deployed today, other clinker substitutes are more nascent. See the following sources for additional detail: a.) U.S. Department of Energy – Office of Energy Efficiency and Renewable Energy. (n.d.). Industrial Efficiency and Decarbonization Office (IEDO) FY23 Multi-Topic FOA. Novel cements. Cembureau. (2018, September 28.)
Source: McKinsey – "Laying the foundation for zero-carbon cement", Portland Cement Association, DOE Carbon Management Liftoff Report, GCCA, Cemnet, IFC, GNR, IEA "Low-Carbon Transition in the Cement Industry"

Structural features of the cement market offer unique opportunities and constraints on deployment. Government procurement accounts for ~50% of U.S. cement consumption (e.g., roads, highways, bridges, public buildings, and other infrastructure projects), giving federal and state governments an outsized role in creating the demand signal for low-carbon cement. Challengingly, cement producers sit at the far end of a value chain with multiple layers of intermediaries—ready-mix concrete companies, subcontractors, and contractors—and substantial fragmentation, making it difficult to pass a demand signal from end consumers to cement plants. The market also has a slow adoption cycle for new cement and concrete products and approaches, which must be accelerated substantially to meet decarbonization goals.

The Pathway to Liftoff for low-carbon cement could require $5–20B in capital investment by 2030 and $50–110B cumulatively through 2050 to scale decarbonization technologies. The critical first step to any liftoff pathway will be creating a strong demand signal of coordinated low-carbon procurement, combining the ~50% of the market from government agencies with the buying power of the largest private customers. Demand-pull from coordinated procurement can accelerate industry adoption of clinker substitution, efficiency measures, and economically viable alternative fuels (chiefly wastes and biomass) by 2030, then unlock capital-intensive deep decarbonization measures, CCS retrofits, and greenfield deployments of novel production methods in the 2030s and beyond. Other technologies (e.g., alternative binder chemistries, alternative heat sources like hydrogen and kiln electrification) could achieve liftoff on a longer timeframe (potentially in the 2040s) after overcoming tough economics and more substantial barriers to market adoption.

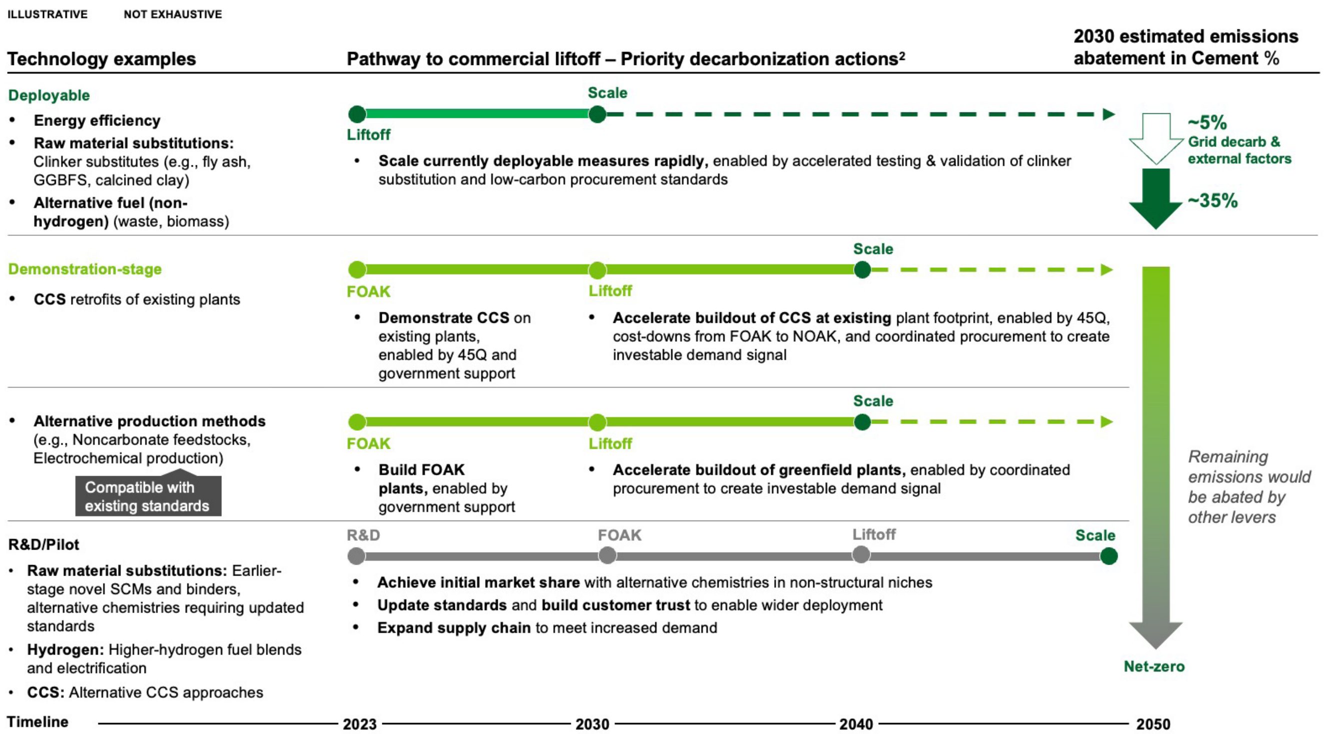


Figure 3.5.3: Liftoff pathway for decarbonization technology within the cement sector. | 1. Abatement share ranges are constrained and based on alternative decarbonization pathways, varying on factors such as the emergence of alternative production methods and chemistries | 2. Indicative timeline presented for R&D, FOAK, liftoff, and scale. Actual timelines will vary by technology based on technological maturity and barriers to adoption.

Decarbonization is a significant opportunity for the country, cement companies, established players, and start-ups. By aggressively scaling just the measures that are economic today, particularly clinker substitution, the industry could capture $1B+ of incremental value per year by 2030, and companies that lead on decarbonization will position themselves to capitalize on billions of dollars in low-carbon procurement from government and private buyers. Longer-term, innovative technologies could transform the market, confer durable competitive advantages, and position fast adopters to lead globally. [97, 98, lxvii]

More detail on the Pathway to Liftoff and more market dynamic detail is provided in the Liftoff report on Low-Carbon Cement.

Section 3b.vi: Pulp and paper

~48	MT CO_2	2021 U.S. Emissions
~200	MT CO_2	2021 Global Emissions

The U.S. pulp and paper sector provides various end products, including containerboard, tissue and towel, printing and writing, pulp, and carton board. The industry accounted for <1% of U.S. CO2e emissions in 2021, or ~50MT CO2e (~5% of emissions from sectors of focus).[lx, lxii, lxi] It also contributes ~100MTPA of related biogenic emissions that are out-of-scope for this analysis.[99, lxi, lxii]

Over 400 paper mills across the U.S. produce different end products, with containerboard production being the largest share.[lxviii] The production of paper products consists of three main steps: (1) pulping, which

97 Supply side: IRA 50161 Advanced Industrial Facilities Deployment Program; Demand side: IRA 60505 Low Carbon Transportation Materials Program

98 The Federal Government is the largest purchaser in the world, with an annual purchasing power of over $650 billion. To harness that procurement power to support low-carbon, made-in-America materials, President Biden charged his Administration through his December 2021 Federal Sustainability Plan and Executive Order 14057 to launch a Buy Clean Task Force and initiative to promote the use of low-carbon, made-in-America construction materials

99 EIA's calculation of carbon intensities uses the convention that emissions from biomass combustion do not count as net energy-related CO2 emissions because biogenic fuels are produced as part of a natural cycle that absorbs carbon dioxide from the atmosphere during the growth phase.

includes debarking/chipping followed by digesting/ bleaching and drying; (2) papermaking, which includes feeding the pulp into various paper machines; and (3) converting to corrugator, sheets, box plants or tissues. Approximately ~60% of CO2e (non-biogenic) comes from the pulping process (e.g., dryers, burners, boilers, evaporators). It should be noted that not all paper mills have pulping operations. In the past five years, the U.S. has seen increased recycled fiber capacity, with 25+ new recycled paper mills announced since 2018. This capacity increase has partially helped the U.S. reach a ~68% paper recycling rate—in line with the EU average. [lxix, lxx, lxxi] Paper circularity and diverting paper products from landfill is important and could potentially reduce methane emissions. However, increased recycled fiber capacity might increase fossil-fuel energy demand due to reduced black liquor production from virgin fibers, further creating the need to electrify and move away from fossil fuels.[lxxii]

Pulp and paper sector emissions come from two primary sources: heat generation (~70%) and electricity (~30%) (Figure 3.6.1)**.** [xxii, xxiv, lx] **Significant decarbonization levers include energy efficiency, alternate fuels (e.g., biomass), and electrification**. Decarbonization levers include energy efficiency, such as improved separation technology, leveraging alternate fuels (e.g., residual biomass), and electrification. These levers have a wide range of abatement costs in a capital-intensive sector.

Most energy-efficiency levers (e.g., real-time energy management systems, air dryers) are net positive. However, they do not always clear the industry's high hurdle rates, which can be ~25%. Alternative fuels (e.g., biomass) and electrification levers range from ~$100–160/t CO2e (Figure 3.6.1).[100] Hydrogen burners, boilers, and other alternative fuels (e.g., biomass gasification, pyrolysis) are in the R&D stage with emerging economics.

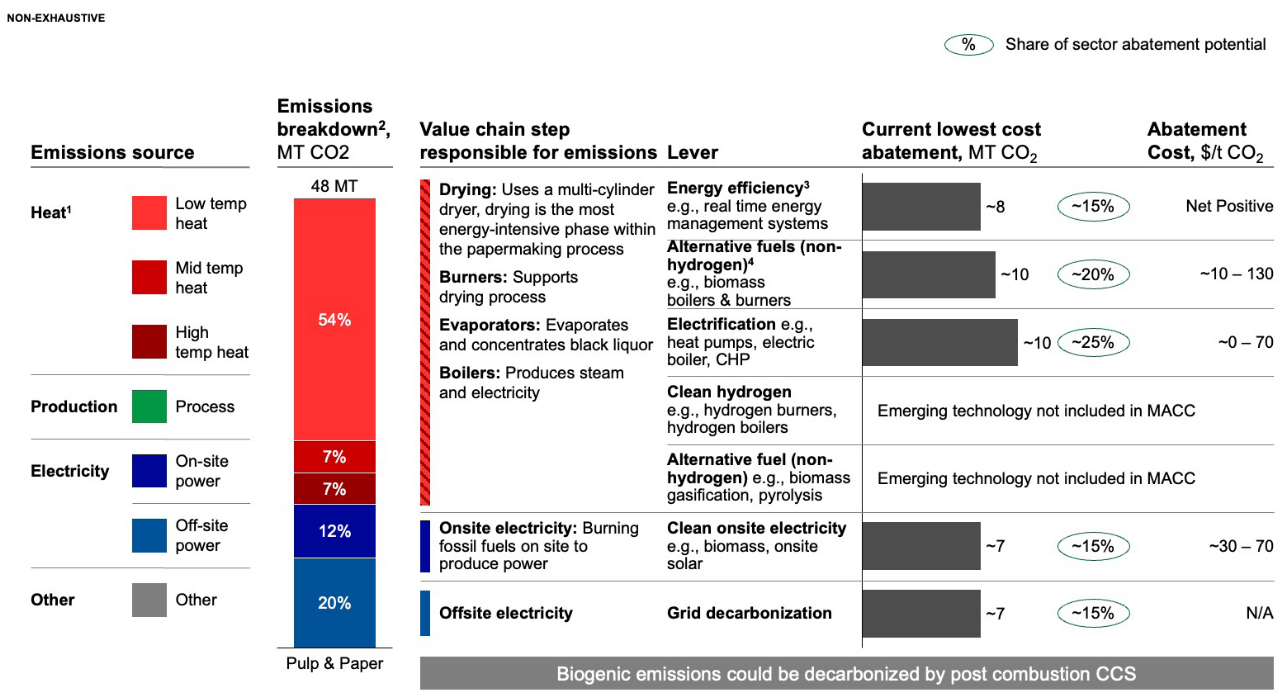


Figure 3.6.1: Pulp and paper production emissions can be abated with energy efficiency measures, alternative fuels, and electrification. | 1. Temperature ranges are defined as low-temperature heat (-30°C to 200°C), medium-temperature heat (200°C to 400°C), and high-temperature heat (400+°C). | 2. Breakdown of 2021 pulp and paper production emissions | 3. Energy-efficiency levers could include real-time energy management systems, air dryers, variable speed drivers, turbo blower pumps, new-technology pulper, radial blowers, mechanical vapor recompression, stationary siphon and drying bar | 4. Includes biomethane boilers (brownfield), biomass burner, RDF boiler, biomass boiler, and biomethane burner (brownfield).
Source: FisherSolve Next 4.0.23.0301, expert interviews

100 EIA's calculation of carbon intensities uses the convention that emissions from biomass combustion do not count as net energy-related CO2 emissions because biogenic fuels are produced as part of a natural cycle that absorbs carbon dioxide from the atmosphere during the growth phase.

Without widespread decarbonization measures, pulp and paper will continue to significantly contribute to U.S. emissions. Five out of eight large players have made short-term (Scope 1 and 2) decarbonization commitments.[101, 102] While the industry supplies >60% of its fuel needs from biomass,[lxxiv] some paper mills are focusing on transitioning from coal-fired boilers to natural gas and biomass boilers.[lxxi, lxxiii, xlv] While many decarbonization levers exist commercially, there's room to accelerate the adoption of best practices, including advanced membranes for separation, combusting residual biomass, increasing recycling, and electrifying heat. Pulp and paper could incorporate CCS onto black liquor boilers, thereby driving negative emissions via Biogenic Emission Capture and Storage. U.S. paper producers are largely not implementing decarbonization levers beyond energy efficiency, renewable energy, and recycling; Figure 3.6.2 shows the development stages of levers across pulp and paper.

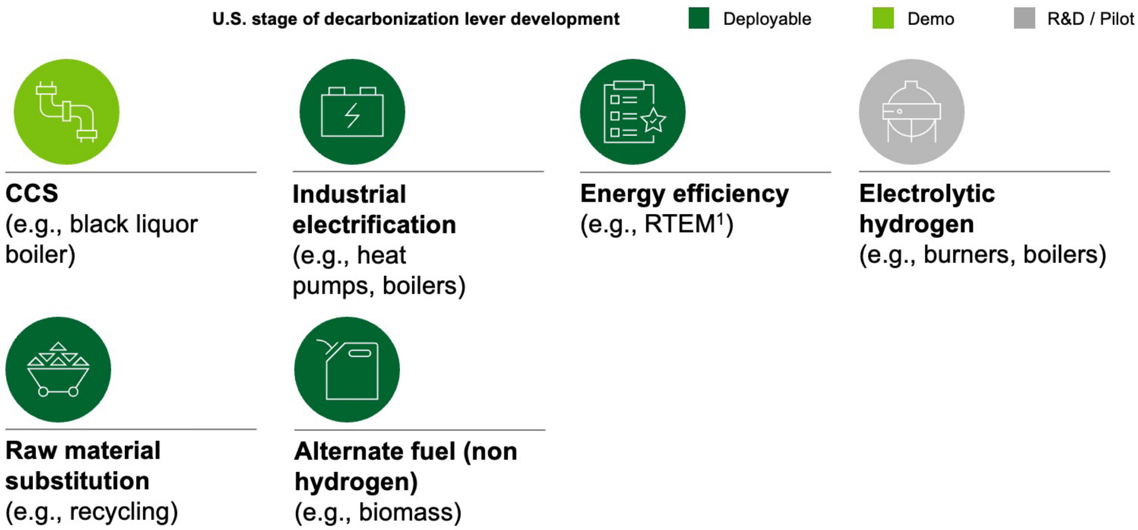


Figure 3.6.2: Stage of lever deployment within the pulp and paper sector | 1. Real-Time Energy Management

The U.S. pulp and paper decarbonization "Pathway to Liftoff" could require $10–15B in capital investment through 2050 (Figure 3.6.3). In the near term, there is an opportunity to support commercialized energy-efficiency technologies and the combustion of waste biomass for heat and power. Low-temperature electrified heat—like heat industrial heat pumps—and better separations membranes are key on the demonstrations front while supporting efforts to adopt CCS for biogenic emissions.

101 Largest companies were selected based on market share

102 The pulp and paper companies analyzed are the largest by market share and include West Rock, International Paper, Cascades, Pappel Packaging, Clearwater Paper, Graphic Packaging, Greif, Georgia Pacific, and Sonoco. Analysis is based on public reports and press search.

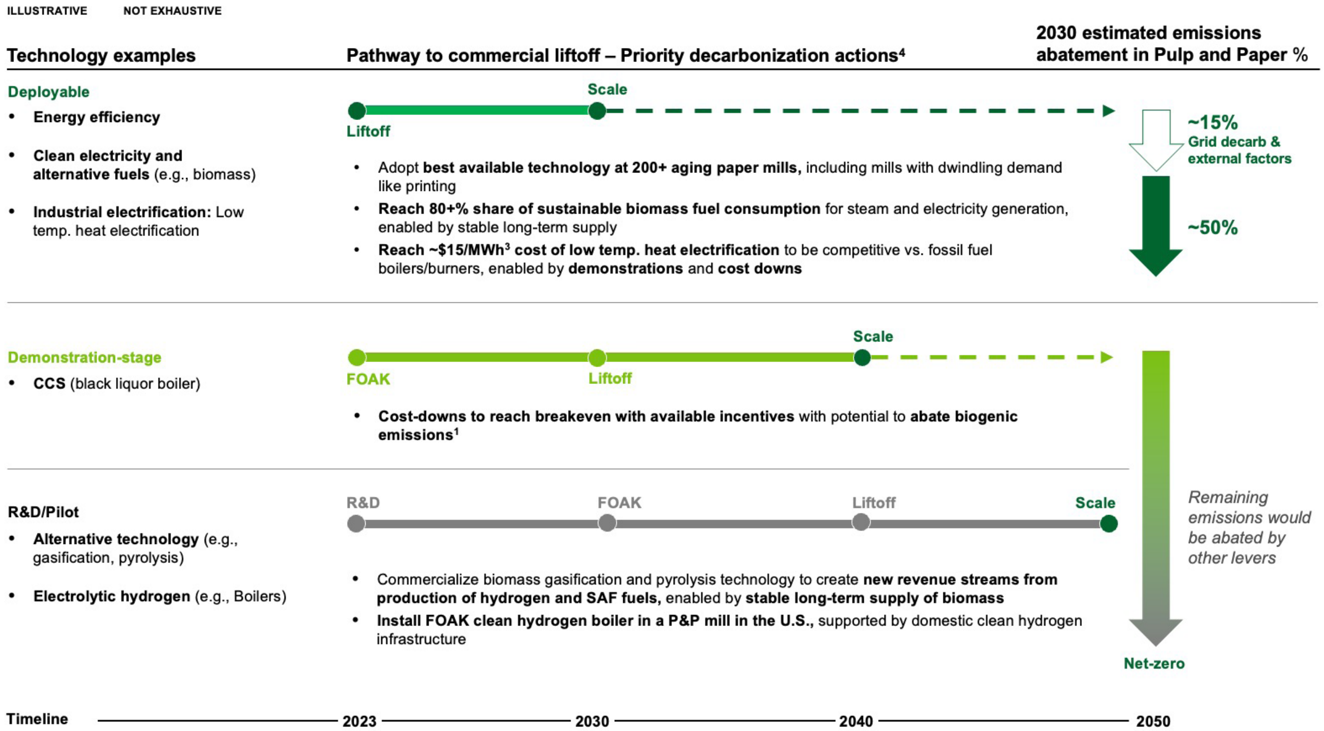


Figure 3.6.3: Liftoff pathway for decarbonization technology within the pulp and paper sector | 1. Biogenic emissions account for an additional 104MT CO2e in 2020 (over 2x the sector's energy-related emissions) | 2. Abatement share ranges are constrained and based on alternative decarbonization pathways, varying on factors such as the use of alternative fuels | 3. Based on the assumption that fossil-fuel-based boilers are replaced with electric boilers. Capex is scaled for the adoption of other levers such as electrification and alternate fuels | 4. Indicative timeline presented for R&D, FOAK, liftoff, and scale. Actual timelines will vary by technology based on technological maturity and barriers to adoption.

Section 3b.vii: Aluminum

~15	MT CO_2	2021 U.S. Emissions
~16	MT CO_2e	2021 U.S. Emissions
~1,100	MT CO_2	2021 Global Emissions

U.S. primary and secondary aluminum products are used by the automotive, packaging, and energy sectors, with U.S. demand expected to rise due to energy-transition technologies (e.g., solar PV frames / inverters and batteries) **and increased EV uptake.** The U.S. was the global leader in primary aluminum production through 2000, but by 2021 was the ninth largest producer (<1MTPA), driven by high energy prices. [lxxiv] The U.S. relies significantly on imports of primary aluminum (mostly from Canada), as domestic production has declined significantly in the last 25 years**.** As of 2021, 65% of aluminum production in the U.S. was secondary production.

The industry accounted for <1% of U.S. CO2e emissions in 2021, or ~16 MT CO2e (<2% of emissions from the sectors of focus). Sector emissions are incredibly concentrated by process and industry players. Smelting accounts for 70% of aluminum-industry emissions, and there are only six remaining smelters in the U.S., which are owned and operated by three players. One of the three aluminum smelters has a short term decarbonization target. Looking across the aluminum value chain, six out of 10 major aluminum players have made decarbonization commitments with 2035 goals ranging from a 20–50% reduction in Scope 1 and 2 emissions. [103, lxxv] The U.S. aluminum industry has also been increasing its use of recycled content in secondary aluminum production and building new recycling capacity.

The typical aluminum production process consists of three main steps: (1) alumina refining, which

103 The aluminum companies analyzed are the largest by market share and include Atalco, Alcoa, Century Aluminum, Magnitude 7, Norks Hydro, Kaizer, Bonnel, Novelis, Arconic, and Constellium.

consists of refining alumina from bauxite oxide; (2) aluminum smelting, which consists of converting alumina into primary aluminum metal through electrolysis; and (3) secondary aluminum production, which consists of combining primary aluminum metals with aluminum scrap through casting, rolling, extruding, and other surface treatments to create the final aluminum products.

Aluminum sector emissions come from three primary sources: electricity (~52%), heat generation (~31%), and process emissions (~17%) (Figure 3.7.1).**Decarbonization levers with high abatement potential include grid decarbonization, energy efficiency, and CCS on smelting (specifically on the Hall-Héroult electrolysis process).** The energy efficiency solutions in alumina refining, aluminum smelting, and secondary aluminum processing are relatively inexpensive and can potentially save operational costs due to more efficient processes. However, the remaining levers, including CCS on Hall-Héroult Electrolysis, are significantly more expensive due to low CO2e concentrations with costs of ~$140–290/t CO2e after IRA incentives (Figure 3.7.1).[104] Alternative production methods (e.g., inert anode) could be an alternative to CCS by capturing aluminum smelting process emissions.

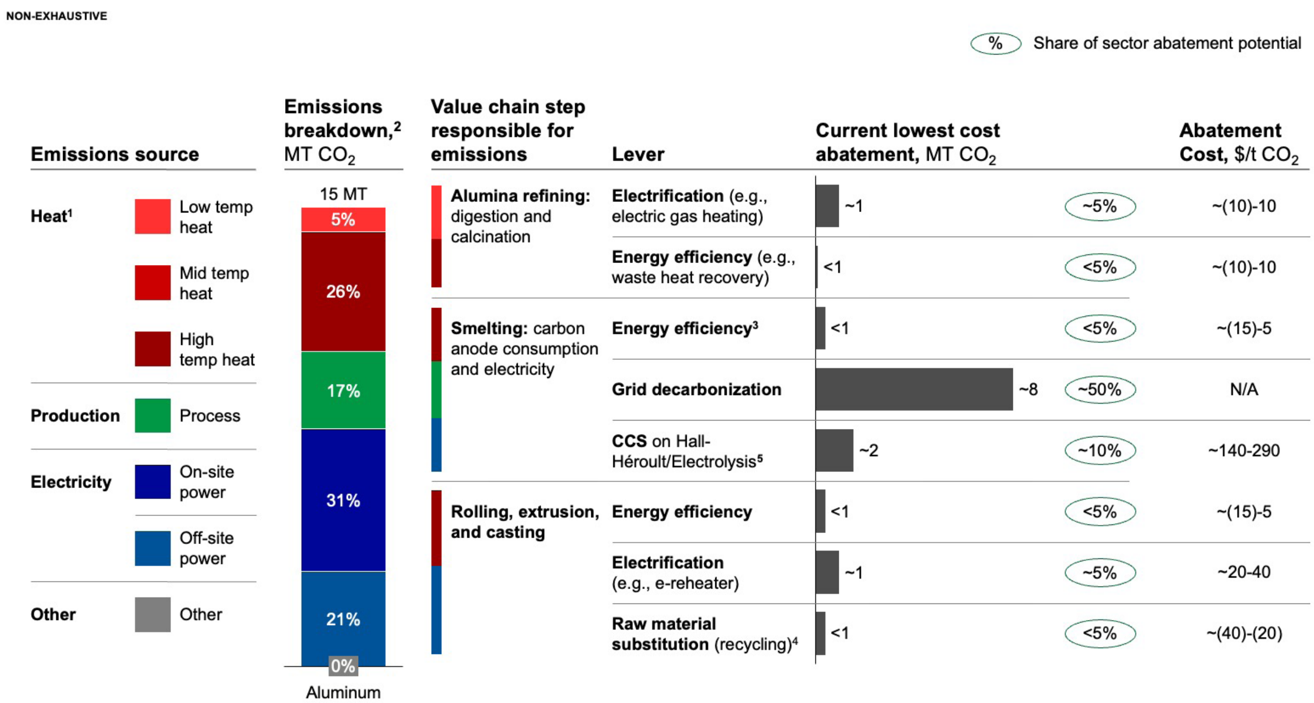


Figure 3.7.1: Sector emissions can largely be addressed through grid decarbonization and CCS | 1. Temperature ranges are defined as low-temperature heat (-30°C to 200°C), medium-temperature heat (200°C to 400°C), and high-temperature heat (400+°C). | 2. Breakdown of 2021 aluminum production emissions | 3. U.S. aluminum smelters are largely very old, resulting in residual emissions of perfluorocarbons which are highly potent greenhouse gases from equipment leaks and disrepair | 4. Despite relatively small abatement potential, recycling has other ancillary benefits, including de-risking U.S. aluminum exposure | 5. The displayed cost estimates are based on the capture costs from various sources (see the appendix for details) with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10–40/t; all figures are in 2022 dollars. All CCS figures represent retrofits, not new-build facilities. The lower-bound cost represents a NOAK plant in a low-cost retrofit scenario with low inflation. The higher-bound costs represent a FOAK plant in a high-cost retrofit scenario with high inflation.
Source: International Aluminium Association, USGS, MPP – Net zero aluminium, IEA

104 Costs for a specific carbon management project could vary even outside the ranges outlined in this report depending on facility-specific characteristics and energy prices that can significantly impact the ultimate cost of deployment.

There is significant potential to decarbonize the aluminum industry by scaling deployable efficiency technologies, such as increasing waste-heat recovery and preheat and using scrap in secondary production. (Figure 3.7.2) Further decarbonization will likely rely on cost-effective low-carbon electricity and continued RDandD to address emissions from key point sources (e.g., CCS in the smelting process or alternative production methods).[105]

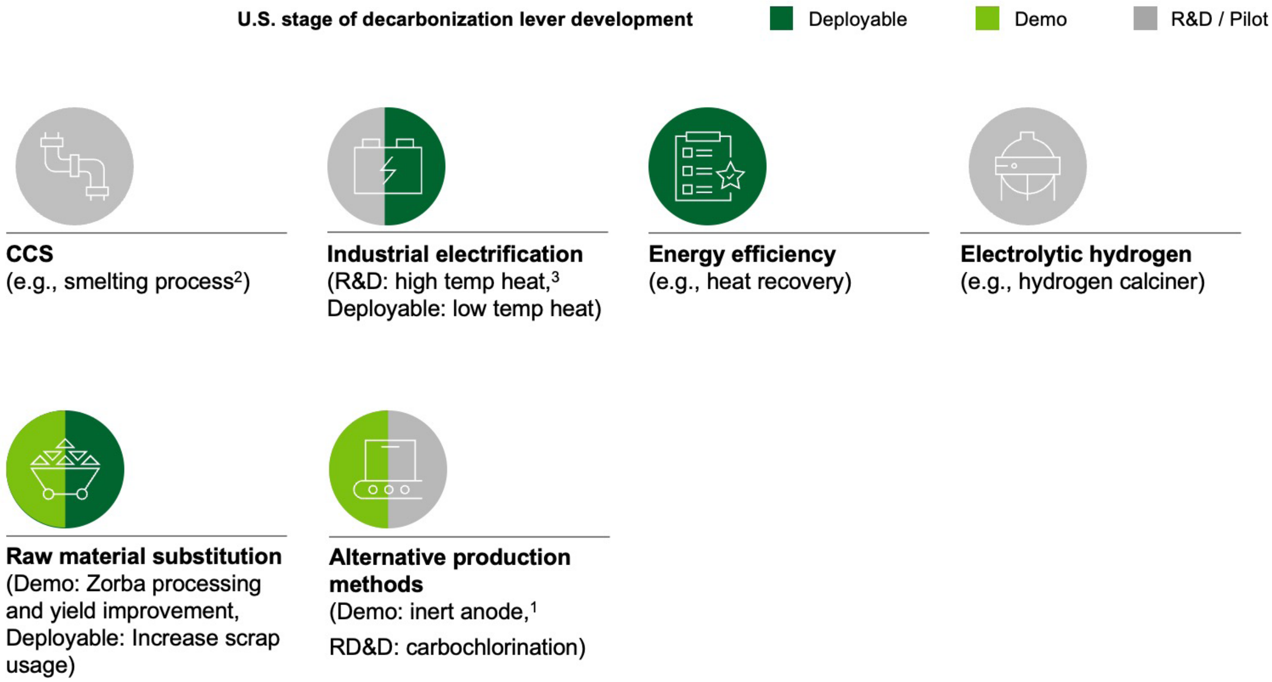


Figure 3.7.2: Stage of lever deployment within the aluminum sector | 1. Planned international deployment | 2. Select feasibility studies | 3. International pilots and deployments

The U.S. aluminum decarbonization "Pathway to Liftoff" could require $10–15B in capital investment through 2050 to scale decarbonization technologies (Figure 3.7.3).[106, lxxvi] The sector has a unique opportunity to reach infinite recycling as materials can be reused without losing quality if the supporting recycling supply chain can be developed.[107] Near term, it will be important to **achieve grid decarbonization** and de-risk domestic aluminum supply by **building out cost-effective clean power** and **unlocking economic high-temperature heat decarbonization.** The sector can further decarbonize by building out a **recycling supply chain** (e.g., diverting scrap from landfill, increasing yield), **developing alternative production methods** (e.g., inert anode materials), and **strengthening low-carbon demand signals**. To achieve net zero, the aluminum sector must **reduce the cost of CCS on smelters** and **achieve cost parity for clean high-temperature heat, smelting, and refining processes compared to fossil-fueled technologies.**[108]

105 One example is an inert anode: Traditional anodes used in this process are made of carbon, which reacts with oxygen to produce carbon dioxide during electrolysis. However, the carbon anodes contribute to CO2-process emissions as they are consumed, which can potentially be addressed with an inert anode made from materials that do not react with oxygen, such as ceramics or certain metal oxides.

106 Capex estimate for aluminum was based on assuming a) alumina refinery retrofit of fossil-fuel based boiler and calciner in digestion and calcination to electric boiler and electric/hydrogen calciner, b) retrofit of remaining six aluminum smelters in the U.S. with either CCS or inert anode and c) retrofit of hundreds of U.S. rolling mills, extrusions plants and cast houses with BAT, oxyfuel burners, induction furnaces, electric heaters, resistive heaters, and other decarbonized sources of heat

107 This includes diverting scrap from landfill and increased domestic processing of Zorba, mixed non-ferrous metal scrap material typically obtained from the shredding and sorting processes of end-of-life consumer products or industrial waste. The composition of Zorba can vary but often includes aluminum, copper, brass, and zinc, which must be processed to reuse.

108 In general, capture costs are the most expensive component in the CCS value chain, but economies of scale, learning by doing, modularization and standardization, and novel capture technologies could all yield significant cost improvements.

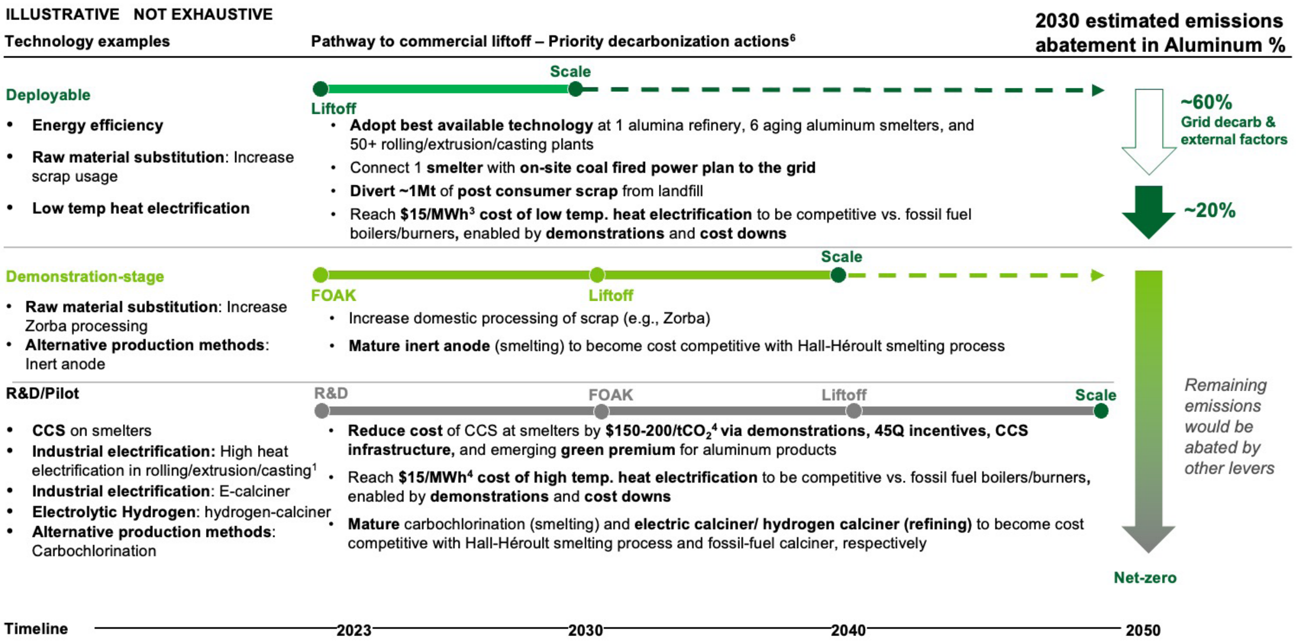


Figure 3.7.3: Liftoff pathway for decarbonization technology within the aluminum sector | 1. Electrical furnace – resistance, electrical furnace – induction, plasma furnace | 2. Abatement share ranges are constrained and based on alternative decarbonization pathways, varying on factors such as raw material substitution (e.g., Zorba processing). | 3. Estimated as breakeven point on the MACC levelized cost of heat to reach $0/tCO2 abatement cost for ethylene steam generation (used as a proxy for low-temperature heat) | 4. The displayed cost estimates are based on the capture costs from various sources (see the appendix for details) with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10–40/t; all figures are in 2022 dollars. All CCS figures represent retrofits, not new-build facilities. The lower-bound costs represent a NOAK plant in a low-cost retrofit scenario with low inflation. The higher-bound costs represent a FOAK plant in a high-cost retrofit scenario with high inflation. | 5. Estimated as breakeven point on the MACC levelized cost of heat to reach $0/tCO2 abatement cost for ethylene steam generation (used as a proxy for low-temperature heat) | 6. Indicative timeline presented R&D, FOAK, liftoff, and scale. Actual timelines will vary by technology based on technological maturity and barriers to adoption.
Source International Aluminum Association, USGS, MPP – Net-zero aluminum, expert interviews

Section 3b.viii: Glass

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

While the U.S. is a leading importer of glass worldwide, importing $8B+ of glass products in 2018, the domestic glass industry accounted for 11MT of CO2e emissions in 2021, which is <2% of the emissions from the sectors of focus in this report and <1% of overall emissions in the U.S.[lxxvii, lxxviii, lxxix, lxxx] There are four main types of glass, including container glass, flat glass, specialty glass, and fiberglass, and all have different end-use applications, such as solar PV modules, building windows, electronics, packaging, etc.

Flat glass and container glass are the largest glass segments in the U.S. by volume, followed by specialty glass and fiberglass. The growth in demand for solar panel and construction glass is driving growth in flat glass usage in the U.S. It's also changing consumer preferences toward sustainability, and the premium perception of glass containers is driving growth in container glass usage.

The typical glass-making process consists of the following steps: (1) batch preparation: mixing the main raw materials of glass are silica (found in sand), soda ash (sodium carbonate), and limestone**, (2) melting and fining:** heating a mixture of materials in a furnace (around 1,700°C) until it melts and forms molten glass, followed by removing bubbles and impurities**, (3) forming:** shaping molten glass by various methods, according to the desired end product, and **(4) post-forming and finishing:** inspecting finished glass product for defects and undergoing any necessary finishing processes.

Glass sector emissions come from heat generation (~47%), electricity (~44%), and process emissions (~9%) (Figure 3.8.1). Approximately 50% to 85% of the energy required for glass production, and the associated emissions, are attributed to the melting process, which requires very high-temperature heat.lxxxi To address emissions from high-temperature heat in glass production, decarbonization levers include switching fuel to biomethane or hydrogen, electrification coupled with grid decarbonization, energy efficiency in the form of waste heat recovery or oxyfuel furnaces, and CCS. Oxyfuel furnace abatement cost ranges from ~$10–140/t CO2e (Figure 3.8.1). [lxxxii, lxxxiii] To address process emissions, raw material substitution and recycling is the main decarbonization lever and has relatively low abatement costs at roughly $30–50/t CO2e. Because glass is 100% recyclable and can be recycled endlessly without decreases in quality or purity, recycled glass (cullet) can theoretically be used to substitute for 95% of raw materials (e.g., silica sand and soda ash, in container manufacturing) (Figure 3.8.1).[lxxxiv] The main lever to address electricity emissions is grid decarbonization because the glass industry's electricity emissions are predominantly from off-site generation (Figure 3.8.1).[lxxxv]

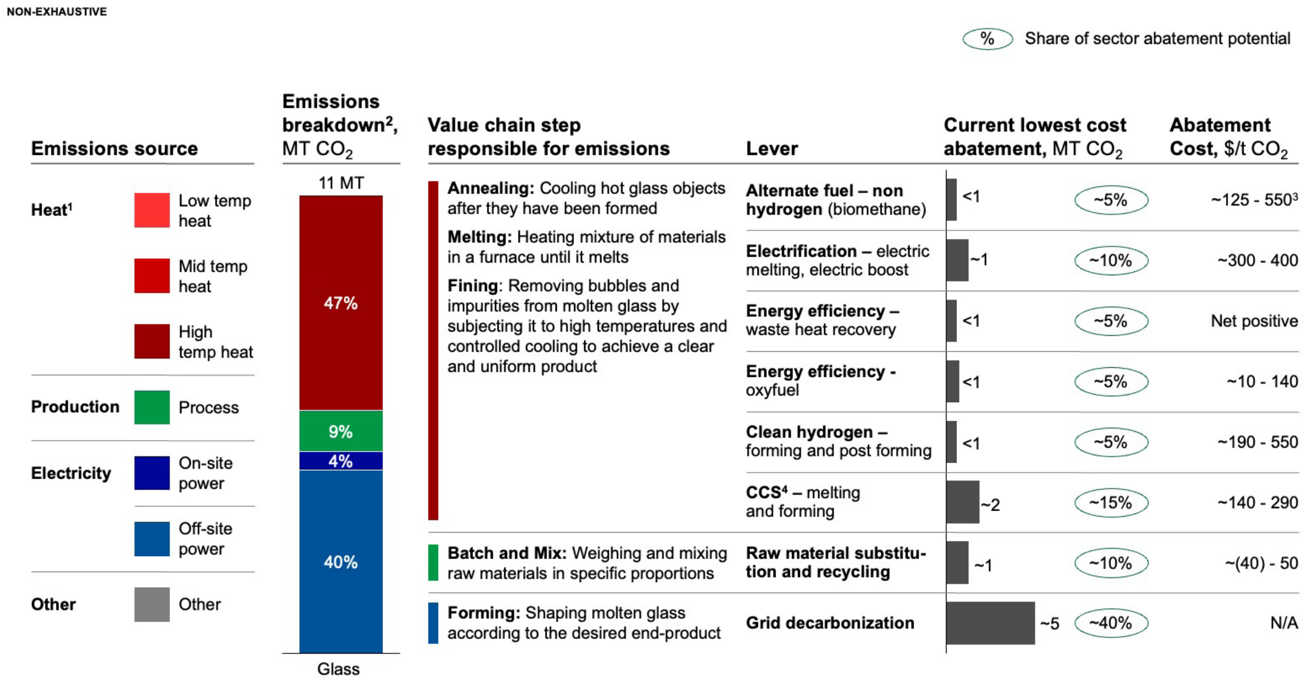


Figure 3.8.1: Glass production that can be abated using various levers (e.g., CCS, energy efficiency, electrification) | 1. Temperature ranges are defined as low-temperature heat (-30°C to 200°C), medium-temperature heat (200°C to 400°C), and high-temperature heat (400+°C). | 2. Breakdown of 2021 glass production emissions | 3. The lower bound represents estimates for biomethane forming in container glass, and the higher bound represents estimates for biomethane melting in container glass. | 4. The displayed cost estimates are based on the capture costs from various sources (see the appendix for details) with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10–40/t; all figures are in 2022 dollars. All CCS figures represent retrofits, not new-build facilities. The lower-bound costs represent a NOAK plant in a low-cost retrofit scenario with low inflation. The higher-bound costs represent a FOAK plant in a high-cost retrofit scenario with high inflation.
Source: Manufacturing Energy and Carbon Footprint: Glass and Glass Production U.S. DOE, Glass International 'Could carbon capture work in the glass manufacturing sector?', Zier 2021 A review of decarbonization options for the glass industry, technical analysis – Glass sector (NACEC23.1)

Two-thirds of large glass companies have made decarbonization commitments, with Scope 1 and 2 commitments for 2035 averaging 25%.[109] To achieve decarbonization commitments, the glass industry is focused on adopting oxyfuel furnaces, a mature and deployable technology, and increasing cullet usage. However, increasing cullet usage is challenged by low U.S. recycling rates—U.S. container-glass recycled content is 30%, whereas stricter environmental regulations and developed recycling collection systems have pushed it to 60% in Europe.

Other technologies for decarbonizing high-temperature heat include electrification, CCS, alternative fuels, and hydrogen, which are currently in the demonstration, pilot, or R&D stages (Figure 3.8.2). Additional technologies, like thermal energy storage, may provide network benefits that accelerate the deployment of technologies to decarbonize high-temperature heat by improving their business case, providing flexibility, and balancing energy demand and supply.

109 Glass companies analyzed are the largest by market share and include ArdaghGroup, OI, and Dlubak Strategic Materials. Analysis based on search of public reports and press

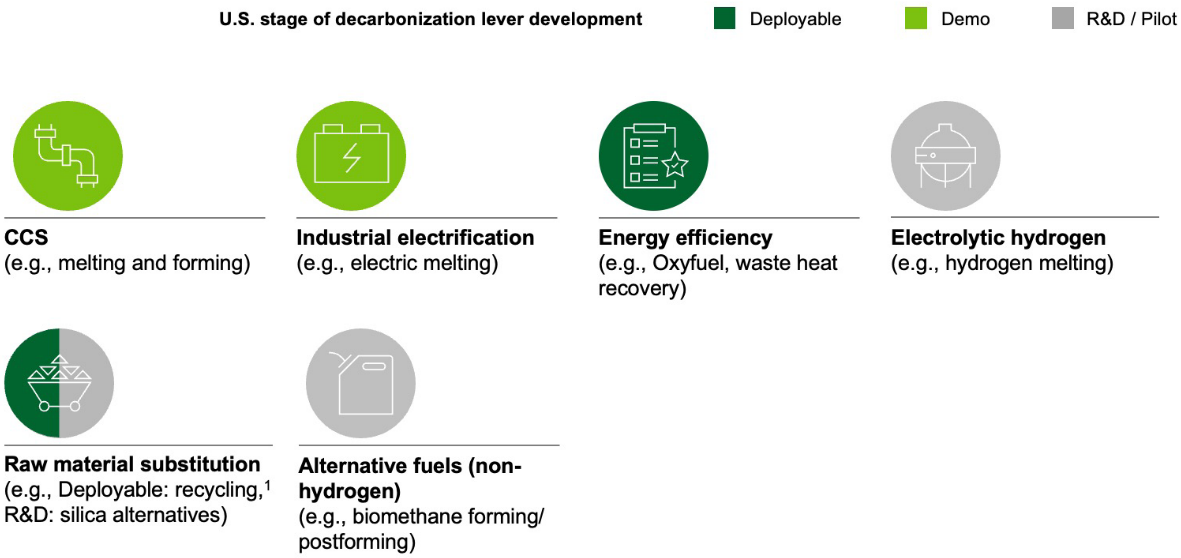


Figure 3.8.2: Stage of lever deployment within the Glass sector | 1. Increase cullet usage
Source: Manufacturing Energy and Carbon Footprint: Glass and Glass Production U.S. DOE, Glass International 'Could carbon capture work in the glass manufacturing sector?', Zier 2021 A review of decarbonization options for the glass industry, Technical analysis – Glass sector (NACEC23.1),

The U.S. Glass decarbonization "Pathway to Liftoff" could require $5–15B in capital investment through 2050 to scale decarbonization technologies (Figure 3.8.3). Overall, the glass industry could increase the production of low-carbon domestic glass and reduce U.S. dependency on low-cost glass imports by building out the recycling supply chain (e.g., diverting scrap from landfill), unlocking high-temperature heat decarbonization, and strengthening low-carbon demand signals (e.g., Buy Clean for flat glass).

In the near term to 2035, 50% of emissions can be abated through deployable technologies (e.g., raw material substitution, energy efficiency via oxyfuel, and waste heat recovery) and grid decarbonization. In the medium term to 2040, 25–40% of emissions can be abated through deploying technologies that are in the demonstration phase, such as CCS, alternative fuel, and electrification, as well as more advanced cullet usage. Building out the recycling supply chain will be a large component of this effort. In the longer term (i.e., to 2050), deploying technologies in the R&D and pilot stage could abate the remaining 10–25% of emissions in this industry or more cost-effectively abate emissions, enabled by process and equipment substitutions proven out in the coming decades.

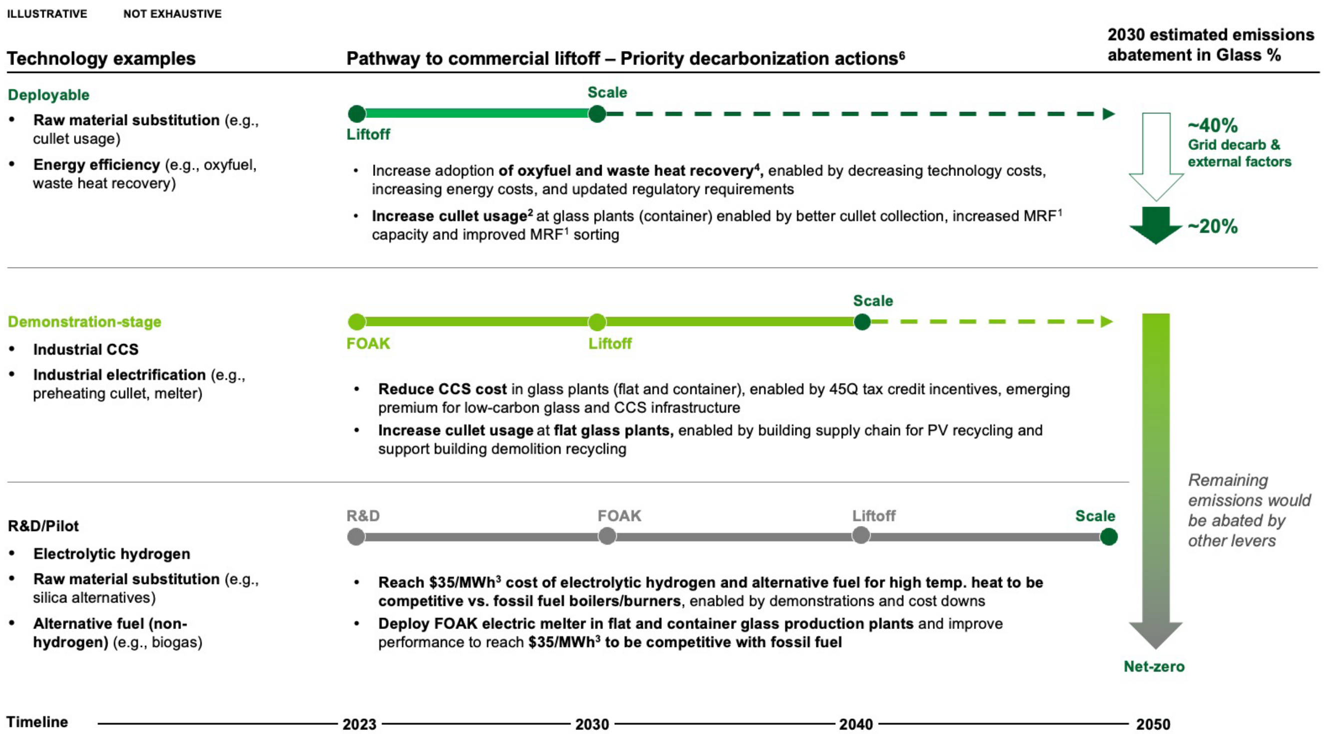


Figure 3.8.3: Liftoff pathway for decarbonization technology within the glass sector | 1. Material recovery facility (MRF) | 2. EU's average cullet usage is 60% compared to the U.S. average of 30% | 3. Estimated as breakeven point on the MACC levelized cost of heat to reach $0/tCO2e abatement cost for ethylene steam cracking furnace (used as a proxy for low-temperature heat) | 4. The use of oxyfuel will diminish the potential for waste-heat recovery due to much lower flue gas volumes. | 5. Abatement share ranges are constrained and based on alternative decarbonization pathways, varying on factors such as the evolution of CCS | 6. The indicative timeline presented R&D, FOAK, liftoff, and scale. Actual timelines will vary by technology based on technological maturity and barriers to adoption.

Section 3c: Workforce and Energy and Environmental Justice (EEJ)

The U.S. industrial sector will play an essential role in a successful clean energy transition, both by producing the materials needed to generate clean energy and by decarbonizing a major source of U.S. emissions. With proactive and concerted effort, industrial decarbonization can also play a role in addressing long-standing environmental injustices, preserving and creating good jobs, and ensuring the energy transition is just and equitable. Clean energy relies on U.S. iron and steel, aluminum, cement, and chemical production for the manufacturing of technologies such as electric vehicles, wind turbines, and photovoltaic cells. The eight sectors discussed in this report account for nearly 60% of U.S. industrial greenhouse gas emissions. Reaching a net-zero economy requires a wide variety of technological levers and project-specific approaches, as each sector and each facility has unique features that could dictate the range of feasible decarbonization approaches. Some levers that may be key options for decarbonization, such as carbon capture in cement production, are the subject of public concern, and feasibility may depend on social acceptance gained by adequately addressing these concerns.

To meet the country's climate, economic, and environmental justice imperatives, it is critical that industrial decarbonization occurs in a way that ensures the development of quality jobs and respects the concerns of fenceline communities. This report takes a broad look at workforce and environmental justice concerns to highlight the key opportunities that can arise from industrial decarbonization, as well as the risks that must be mitigated to protect communities from additional harms beyond what they have already suffered.

While this report offers a quantitative analysis of GHG baselines and CO2 emissions abatement and an initial qualitative analysis on workforce and EEJ topics in the eight U.S. industrial sectors and nine decarbonization levers studied, **it does not include a comprehensive analysis of non-GHG emissions from industrial processes, specific industry workforce considerations, or technical solutions for EEJ concerns. It also**

does not address considerations or concerns specific to tribes, which include considerations of tribal sovereignty and treaty rights. This qualitative analysis offers a high-level introduction to what must be a robust and quantitative discussion on how to implement a societally just decarbonization strategy, and it should complement quantitative, sector- and technology-specific assessments and deep dives. Additional work from many stakeholders is needed to outline tactical solutions toward a shared goal of a prosperous, just, net-zero economy.

Section 3c.i: Workforce

Achieving net zero would have broad socioeconomic and employment impacts, and there are many potential benefits, particularly if existing employment is sustained and labor standards and community benefits plans are implemented to ensure good quality[110] jobs are created across industries through direct and indirect jobs spurred in the investment phase through 2050. In 2023, employment in industrial sectors of focus is over 4M jobs.[111] For example, U.S. employment in chemicals and plastics manufacturing is ~1.7M employees, petroleum manufacturing is ~110k employees, iron and steel is ~80k employees, cement is ~210k employees, food and beverage manufacturing is ~2M employees, aluminum manufacturing is ~120k employees, glass manufacturing is ~80k employees, and pulp and paper manufacturing is ~350k employees. This section will focus on cross-cutting workforce considerations. Sections on workforce implications within sectors are available in the Chemicals and Refining and Cement Liftoff Reports and in the Liftoff societal considerations and impacts wrapper.

Ensuring a just energy transition requires engaging workers throughout the implementation process. Jobs in the industrial sector have long provided middle class incomes and benefits for workers. The introduction of decarbonization technologies that impact the number and types of jobs available must include concerted planning and direct engagement with workers to ensure that there are pathways to retirement, reemployment, or retraining, including on-the-job training to staff new occupations, and that jobs are good jobs. Consideration should be taken to retain skilled workers within industries. Collaboration with labor and management groups across the industrial sector can lead to just outcomes for workers and help employers hire, train, and retain skilled workers. For example, the Battery Workforce Initiative aligns stakeholders (employers and unions) on critical skills for the industry, and the electrical training ALLIANCE offer models for apprentice and training programs.

The build out of industrial decarbonization will also require millions of hours of work. Across industries, staffing could be challenging as other decarbonization technologies come online simultaneously. This challenge could be particularly acute in the skilled trades (e.g., electrical, plumbing, mechanical trades). Like other sectors, high paying jobs with strong labor protections, training, and placement opportunities such as registered apprenticeships, and pathways for long-term career growth, can attract and retain a skilled workforce. Project Labor Agreements (PLAs) – described below – can be useful tools for attracting and training a skilled workforce for the infrastructure build out, and other collective bargaining agreements can support operations and maintenance workforce needs. PLAs and collective bargaining agreements can be part of community workforce agreements and community benefits plans that also address community and environmental justice concerns. The Pathways to Commercial Liftoff: Introduction provides an in-depth discussion of the significance of these quality jobs and how they can be achieved.

110 See Administration announcements for more information on high quality job goals: FACT SHEET: The American Jobs Plan | The White House. Also see Pathway to Commercial Liftoff: Societal Impacts and Considerations for further discussion.

111 Based on BLS Current Employment Statistics - CES (National) as of May 2023. Industries referenced are chemicals and plastics manufacturing (chemicals manufacturing plus plastics and rubber products manufacturing); petroleum and coal products manufacturing; iron and steel mills and ferroalloy manufacturing; cement and concrete product manufacturing; food and beverage manufacturing (food manufacturing plus beverage manufacturing); alumina, aluminum, and other nonferrous metal production and processing; glass and glass product manufacturing; and paper manufacturing.

Project Labor Agreements (PLAs)

- A PLA is a collective bargaining agreement negotiated between construction unions and employers. The agreement, unique to the construction industry, establishes terms and conditions for specific projects.
- PLAs generally specify wages and benefits for project workers, require contractors to hire union represented workers, and have no strike and no lockout clauses to ensure timely project completion.
- Since construction projects often interface with multiple trade unions, PLAs can streamline the process of coordinating labor contracts under one agreement.
- PLAs also often contain provisions on worker safety and can have additional clauses relating to employing local workers, environmental equity, engaging with underserved communities, and small businesses.
- **Commercial Liftoff:** Overview of Societal Considerations and Impacts offers additional information and guidance on cross-cutting issues related to EEJ, community and labor engagement, workforce development and quality jobs, and diversity, equity, inclusion, and accessibility.

If jobs are high-paying and offer the free and fair choice to join a union, strong labor standards, competitive wages and benefits (e.g., retirement, health insurance), and training/placement opportunities such as registered apprenticeships, they will likely attract the skilled workers required and draw new workers to the field and to the locations where they are needed. Roughly half of non-union employers in the energy sector found it "very difficult" to find and hire new workers in 2022 compared to only 29% of union employers.[lxxxvi]

Section 3c.ii: Energy and Environmental Justice

Decarbonizing industrial facilities provides a critical opportunity to remediate the social, economic, and health burdens experienced by fenceline communities disproportionately harmed by industrial sector emissions. In addition to emitting large quantities of GHGs, industrial facilities emit other pollutants, waste streams, and by-products that may harm human and environmental health. Decarbonization efforts can include measures to address these impacts (e.g., reduction of particulate matter, metals, and sulfur oxides with the addition of CCS and a scrubber[112]).

112 Better Energy Carbon Capture and Air Quality Factsheet

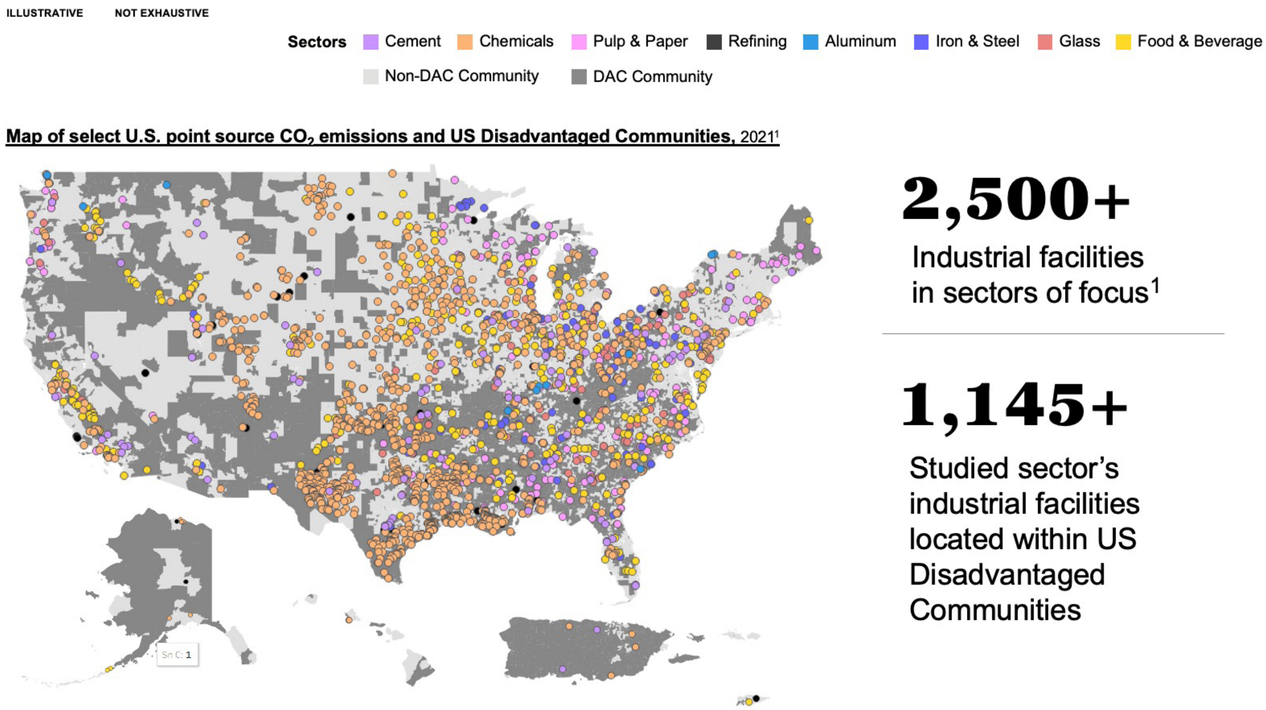


Figure 3.9 Map of Industrial facilities and disadvantaged communities (DAC) as defined by the Climate and Economic Justice Screening Tool. Emissions are dispersed across 25,000+ facilities across the U.S. | 1. Includes natural gas processing, refineries, chemicals production (various), food processing, cement production, glass production, aluminum production, iron and 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 CO2e/year and does not include emissions from land use, land use change, or forestry
Source: EPA flight, Climate and Economic Justice Screening Tool (CEJST)

Figure 3.9 highlights the locations of industrial facilities in the United States. Based on the EPA FLIGHT database, there are over 2,500 industrial facilities in the eight sectors of focus with more than 25,000 MT CO2e/year in the United States. Each of these facilities will have neighboring communities, referred to as fenceline throughout this report. The following section highlights common concerns for fenceline communities.

Approximately 1,145 industrial facilities studied are located in disadvantaged communities (DACs), using the Council on Environmental Quality's definition of DACs outlined in the Climate and Economic Justice Screening Tool (CEJST).[113] DACs are defined as census tracts with low income and burdens (above a threshold) in one or more of these eight categories: climate change, energy, health, housing, legacy pollution, transportation, water and wastewater, and workforce development. All federally recognized Tribal lands are classified as DACs. These are communities that are disadvantaged because they are overburdened and underserved. DACs are also disproportionately burdened by industrial facilities: only 36% of census tracts are classified as DACs; however, they contain 45.7% of these industrial sectors facilities.

Communities with multiple industrial facilities could experience additional burden. Overall, there are 383 census tracts with multiple industrial facilities throughout the United States. These tracts are home to 3 facilities on average, but a handful of census tracks on the Gulf Coast contain 10 or more. Not only are DACs more likely to have one industrial facility, but they are also more likely to have multiple industrial facilities compared to non-DACs. Industrial facilities in DACs should pay additional attention to burdens from hosting their facility, given there are likely multiple environmental justice concerns in these areas.

While this analysis begins to explore the connection between these industrial facilities and disadvantaged

113 https://screeningtool.geoplatform.gov/en/#3/33.47/-97.5

communities, the scope of this analysis was limited. This does not consider census tracts that are adjacent to industrial facilities. It also does not examine regional variation, differences across industrial sectors or DACs' degree of disadvantage. Additional analysis is required to understand the intricacies of these relationships.

Industrial fenceline communities are exposed to a mix of contaminants, particulate matter (PM), and carcinogens through air, water, and soil pollution that results from facility construction and operation. These exposures are linked to higher rates of premature death, cancer, and chronic respiratory conditions, including asthma; increased risk of diabetes, hypertension, cardiovascular disease, and acute respiratory viral infection; and greater frequency of poor mental health days. Industrial facilities also generate local noise and light pollution that impact the quality of life.[lxxxvii] These emissions are a risk to human and environmental health, and proximity to industrial plants can lead to declines in nearby home values.[lxxxviii] In addition to the impacts of normal operation, communities face risks from accidents or emissions events, a reality that can contribute to chronic stress and stress-related health issues.

Beyond fenceline communities, the burdens of the U.S. industrial sector are disproportionately borne by communities of color and low-income communities.[lxxxix, xc, xci] Members of these groups are disproportionately exposed to elevated levels of air pollution—both from industrial and other sources—and consequently experience higher rates of adverse health impacts than the general population.[xcii] In all but four states, race, not poverty, is the most direct link to particle pollution exposure. Compared to white populations, Black populations were exposed to 1.54x more small pollution particles ($PM_{2.5}$) from anthropogenic sources (burning fossil fuels, cigarettes, or biomass), and this exposure is linked to lung and heart disease.

Ensuring that industrial decarbonization supports energy and environmental justice (EEJ) is critical as a moral and lift-off imperative. Effectively implementing decarbonization projects also depends on the engaging with and garnering the support of surrounding communities, who have effectively challenged many industrial projects based on environmental justice and environmental health concerns. The EEJ impacts on any decarbonization levers detailed in this report depend on the benefits and harms, who experiences them, and how the impacts alleviate or compound existing burdens**. Across nearly all decarbonization levers, how technologies are deployed can combat or exacerbate existing inequalities, especially if technology is installed in communities already overburdened by existing infrastructure and underserved by government programs.** The magnitude and nature of local concerns—and the scale of potential impacts or benefits—vary by project type, technology, and local context, requiring that community impact and perceptions are assessed on a project-by-project basis. The lived experiences of frontline communities inform **concerns around safety, accountability, transparency, and the continued operation's potential environmental and health impacts.**

The "Pathways to Commercial Liftoff: Overview of Societal Considerations and Impacts" offers specific considerations and actions related to the distribution of impacts (i.e., who experiences benefits and who experiences burdens) and process (i.e., enabling impacted individuals/groups to make decisions about projects that affect them). To proactively account for societal considerations and impacts, project developers should meaningfully engage with impacted communities, tribes, and labor unions early and often to support real accountability and transparency; assess and address EEJ concerns and opportunities; create quality jobs and invest in career-track workforce development; and support diversity, equity, inclusion, and accessibility.

Cross-cutting EEJ concerns and opportunities

Under the Clean Air Act, the Environmental Protection Agency (EPA) regulates many of the key pollutants released from industrial assets, such as criteria air pollutants including sulfur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM). These pollutants adversely impact health—contributing to chronic and acute respiratory issues, asthma, heart disease, and heart attacks—and the environment, causing acid rain, smog, damage to plant growth, and nutrient pollution.[114] The Clean Water Act, also overseen by the EPA, limits the discharge of harmful pollutants based on the performance of well-designed and well-operated

114 CAA, 42 U.S.C. ch. 85 (2022).

control and treatment technologies.[115] However, because federal regulations focus on the health impacts of isolated pollutants rather than their potential cumulative impacts, the limitations set by the Clean Air and Clean Water Acts may not accurately reflect the emissions levels needed to mitigate health risks.[xciii] Even when facilities operate within regulatory limits, fenceline communities have been found to have increased cancer risks.[xciv] Additionally, enforcement discretion lies with state regulatory bodies. There are instances in which sources may not operate within their regulatory limits.

EPA inspections of facilities that make, use, and store extremely hazardous substances regulated under the Clean Air Act via EPA's Risk Management Program, have revealed "significant noncompliance" with federal regulations. In 2021, EPA estimates about 150 catastrophic accidents, which can result in fatalities, serious injuries, evacuations, and other harm to human and environmental health, occur at such facilities every year in the U.S.[xcv] Excess emissions are not always the result of catastrophic accidents. Grist Magazine's analysis of the Texas Commission on Environmental Quality's (TCEQ) database of industry-reported pollution shows that industrial facilities emitted 1.1 billion pounds of pollution beyond permit levels between 2002 and 2021, with excess emissions increasing over time.

Reducing the frequency of these accidents and emissions events—and securing proper monitoring, reporting, and emergency alert systems—are key concerns for EEJ advocates and local communities. Accurate and publicly available emissions reporting—and timely and effective emergency alert systems—are critical so communities can take necessary steps to protect their health, including sheltering in place, turning off air conditioners, and reducing exposure to the outside air. Alert systems also help companies, workers, and regulatory agencies respond more quickly and appropriately to emissions events.[xcvi] **Efforts to decarbonize may present new safety risks that must come with appropriate monitoring, reporting, and emergency response. These facility upgrades also present an opportunity to improve or build strong safety and alert systems.**

While some advocates and local groups are familiar with the safety, health, and environmental impacts of decarbonization technologies, other communities may lack the necessary information to make informed decisions about their priorities and concerns. A lack of information about project impacts, timelines, and decision-making can generate local opposition, especially in areas with low levels of trust in government and industry.[xcvii] In some cases, a facility may be able to pursue multiple decarbonization options; the concerns and priorities of impacted communities, informed by transparent and complete information about technology impacts, should inform which approaches are pursued. Community Benefits Plans and Agreements are a way for developers to work with local communities to obtain public support for their projects in return for providing some form of tangible benefit to the community hosting it.[xcviii]

115 CWA, 33 U.S.C. § 1251 et seq .

Community Benefit Agreements (CBAs)

- A Community Benefits Agreement is an agreement made between a developer of a project and a coalition of local community stakeholders wherein return for public support of a project, the developer will provide a number of benefits for the community hosting the project.
- Coalitions that sign CBAs on behalf of the community can include neighborhood associations, union, environmental groups, faith based organizations, non profits, and other local stakeholders.
- CBAs are flexible in that the developer and community can work together to negotiate a CBA which suits both parties. Benefits CBAs can provide include local hiring and job training commitments, PLAs, agreements on wages and benefits, funding for local infrastructure, support for local businesses, and more.
- Strong CBAs center on promoting inclusiveness, enforceability, transparency, coalition building, and efficiency.
- **Commercial Liftoff:** Overview of Societal Considerations and Impacts offers additional information and guidance on cross-cutting issues related to EEJ, community and labor engagement, workforce development and quality jobs, and diversity, equity, inclusion, and accessibility.

For many first-of-a-kind technologies, there is also concern that companies may pass the costs of commercial-scale demonstrations and early implementation of new technologies onto consumers. In many cases, the 45Q credit, other tax incentives, and BIL / IRA programs will help to defray costs and insulate ratepayers from the costs of such projects, but facility operators should consider how costs are managed to limit consumer burden.

Selected technology specific EEJ concerns and opportunities

Industrial electrification and clean onsite electricity and storage

Key Sectors

Chemicals | **Iron & Steel** | **Aluminum**
Refining | **Pulp & Paper** | **Food & Beverage**

- Replacing carbon-based feedstocks with clean electricity may lower direct pollutants and decrease associated health risks, including respiratory and cancer risks.[xcix]
- Fully electrifying industry could double national electricity demands, generating concerns about competition for renewable energy resources between communities and industry. Facilities may need to build additional renewable capacity, rather than drawing from the local grid, to avoid competing with communities for clean energy. Expanding clean energy generation can increase land use change.[c] Facilities developing additional generation capacity should consider the environmental and cultural impacts of land use change and limit negative impacts (e.g., by building on brownfield sites).
- Replacing carbon-based feedstocks with clean electricity may lower direct pollutants and decrease associated health risks, including respiratory and cancer risks.[ci]
- Without proper on-site storage, some clean electricity feedstocks may be at risk of intermittency. Installing certain types of battery storage (e.g., Li-ion) may increase fire or explosion risk, requiring

proper fire safety measures to protect communities.[cii] Battery disposal and decommissioning can also lead to increased air, water, and soil pollution (see DOE's Pathways to Commercial Liftoff: Long Duration Energy Storage for more on EEJ considerations.[ciii]

- Industrial electrification technologies, such as industrial heat pumps, can generate significant noise pollution that can impact the health of workers and surrounding communities, requiring noise mitigation measures.[civ, cv]
- Additional high voltage equipment may introduce risks associated with shocks, burns, and fires for electrical workers. Workers need electrical safety initiatives to keep them safe among increased electrical infrastructure.[cvi]
- Critical minerals for electrification include copper, nickel, manganese, cobalt, and others. Mining for these will increase negative environmental impacts, including increased pollution and land use change, especially in developing countries without increased policies and sustainable operations.[cvii]
- Without proper on-site storage, some clean electricity feedstocks may be at risk of intermittency. Installing certain types of battery storage may increase fire or explosion risk, requiring proper fire safety measures to protect communities. Battery disposal and decommissioning can also lead to increased air, water, and soil pollution (see DOE's Pathways to Commercial Liftoff: Long Duration Energy Storage for more on EEJ considerations).

Energy efficiency

Key Sectors

Refining **Aluminum**

Pulp & Paper **Food & Beverage**

- Increased efficiency reduces fuel needs, reducing emissions of greenhouse gases and health-harming pollutants like NO_x, SO_x, metal HAPs (e.g., mercury, nickel), and acid gas HAPs (HCl), in addition to driving down energy costs.[cviii] Energy-efficiency measures may be taken with other decarbonization measures to increase the benefits for communities.
- Certain waste-heat recovery techniques have large footprints; companies should consider the environmental and cultural impacts of land use change and take steps to limit negative impacts.[cix]

Raw material substitution

Key Sectors

Chemicals **Cement**

Refining

- Recycling materials can limit impacts caused by material disposal, such as plastic pollution.[cx] It can reduce hazardous substance use and waste, reducing water and soil contamination.[cxi]
- Experts estimate that plasma gasification of plastic waste to produce syngas emits less CO, SO2, HCl, and dioxins than incinerating the waste, a typical disposal method.
- Recycling process heat and water decreases overall energy and water use, reducing demand on the electricity grid[cxii] and limiting industrial contributions to water scarcity.[cxiii, cxiv]
- For sector-specific concerns, please see Chemicals and Refining and Cement Liftoff Reports.

Alternative fuel (non-hydrogen)

Key Sectors Cement Pulp & Paper

- Waste as fuel can reduce pollution and contamination from landfills, decreasing landfill size.[cxv] However, it can also introduce and concentrate potentially toxic air pollution at a new point source that must be permitted, treated, and monitored carefully. Different wastes and uses or conversions will have varying environmental impacts and pollution, depending, for instance, if the waste stream includes toxic elements.[cxvi]
- Criteria air pollutants from biomass burning, including volatile organic compounds, NOx, SOx, CO, and PM, can lead to public health issues. The danger of individual carbonaceous aerosols, the primary chemicals composing $PM_{2.5}$, to human health is not well known, but diesel particulate matter, primarily black carbon, is a commopollutant in AirToxScreen. [cxvii] Additional steps should be taken to mitigate and monitor emissions.
- Biomass as an alternative fuel has significant land and water use implications. Some studies argue that dedicated (i.e., non-residue) biomass can displace food crops.[cxviii]
- Proper worker training and emergency response systems are needed to minimize the risks from changes in plant operations using or producing alternative fuels.[cxix]

Carbon capture and sequestration and reformation-based hydrogen

Key Sectors Chemicals Iron & Steel Aluminum Refining Cement

The discussion below presents a high-level overview of the EEJ considerations related to CCS and reformation-based hydrogen described in the Pathways to Commercial Liftoff reports on carbon management and clean hydrogen.[cxx, cxxi]

- In certain applications, especially with scrubbers, point-source carbon capture can reduce emissions of criteria air pollutants, such as SOx, NOx, particulate matter, and hazardous air pollutants, such as mercury and hydrogen chloride, relative to non-CCS operations.[cxxii]
- The energy needed to operate the capture unit can introduce additional energy demand and, depending on the energy source, associated pollutants at the capture point and over the feedstock supply chain. Pollution control equipment could mitigate these risks.
- Some compounds associated with the capture unit (e.g., aerosols such as nitrosamines from solvent-based capture systems) can add new pollutants to a site. Pollution monitoring and control mechanisms for these pollutants are currently standard operating procedure for CCUS facilities employing these capture technologies.[cxxiii]
- Some EEJ advocates are concerned that CCS and reformation-based hydrogen projects extend the life of fossil-fuel-burning industrial facilities beyond when they would have otherwise shut down, thereby continuing to harm nearby communities and providing financial support to companies who have harmed and disadvantaged communities.[cxxiv]
- Supporting CCS and reformation-based hydrogen as a decarbonization solution may provide continued financial support to fossil fuel companies despite their role in causing the climate crisis and delaying climate action.

Clean Hydrogen

Key Sectors Refining Iron & Steel Chemicals

The discussion below presents a high-level overview of the EEJ considerations related to hydrogen described in the Pathways to Commercial Liftoff report on clean hydrogen.[cxxv]

- Because of the multiple pathways to produce, distribute, and use hydrogen, the type and magnitude of benefits and harms – and who experiences them – varies significantly by project, making it critical to assess impacts on a project-by-project basis.
- Hydrogen combustion emits NO_x, which can impair lung growth in children, harm cardiovascular function, and lead to higher rates of emergency room visits and premature death.[cxxvi] Reducing NO_x emissions requires improving pollution control technology and/or lowering flame temperatures. Lower flame temperatures require either lower volumes of hydrogen (and more fossil fuels) in the combustion or de-rating the engine, causing efficiency losses and power decreases.[cxxvii] In hydrogen fuel cells, the only byproducts are electricity, water, and heat. Therefore, fuel cells used to generate onsite power would eliminate air pollutants relative to fossil-based processes (e.g., internal combustion engines, natural gas peaker plants without CCS).

Chapter 4: Commercialization challenges and potential solutions

Key takeaways

Solutions to tackle cross-cutting industrial decarbonization challenges require coordinated action (Figure 4.1)

	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	Expediated 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

Figure 4.1 Industrial decarbonization is challenging, but a range of solutions are available

Industrial decarbonization in the U.S. is at risk of lagging behind other countries.[116] Across the sectors of focus, companies, especially publicly traded, face pressure to report near-term earnings and return on investment. Companies point to the immaturity and high cost of deep decarbonization levers, unidentified or uncertain customer demand for low-carbon products, and a reluctance to be a first mover in certain sectors. In some sectors, hurdle rates can be as high as 25%, reducing the appetite for large-scale investments that can be perceived as riskier without clear carbon costs.

In many sectors, however, this narrative is changing. Technology deployment has received Congressional support from the BIL and IRA. Customers and other stakeholders are pressuring companies to decarbonize. Several companies are taking bold action. These public sector supports can enable the U.S. to modernize its industrial base, secure clean-technology supply chains, and grow the economy through domestic manufacturing.[vii,ix,viii] Public-sector supports reduce capital exposure to new technology investments, helping make cutting-edge deep decarbonization investments less risky. Increased customer demand and willingness to pay for low-carbon products can create opportunities to build low-carbon businesses, increase exports, and capture premia. These conditions enable industrials to accelerate the deployment of decarbonization technologies and position the U.S. as a global leader.

116 For example, the EU carbon tax is a powerful catalyst for accelerated industrial decarbonization across the Atlantic, with 20+ DRI plants for steel, CCS pilots in cement production, electric cracker pilot projects, and installation of electric boilers and heat pumps in pulp and paper mills

U.S. industrial players cite common challenges that make them reluctant to be a first mover. [117] **Several cross-cutting solutions can accelerate decarbonization Figure 4.1.** Major challenges and potential solutions include:

Value proposition

Challenge 1: High delivered cost of decarbonization technology. Economics can be challenging for deep decarbonization levers. FOAK demonstrations can be challenging to shepherd through, even after IRA incentives (see Chapter 3 for more detail on the economics of decarbonization levers).

Potential solution 1: Close the cost gap between incumbent and decarbonized technologies by developing bankable revenue streams and lowering costs. Industrial producers could develop bankable revenue streams by working with public and private buyers to create firm demand for low-carbon products with price premia *(see Potential Solution 4 for details on tracking embodied carbon)*. For example, private sector action could convene a low-carbon buyers' club for consumer-packaged goods and pharmaceutical companies to secure commitments to pay premia for low-carbon chemicals.

Public-private partnerships can lower the cost of future projects through FOAK demonstrations, proving out new technologies and lowering the costs of financing. For example, Congress has provided the DOE with over $6 billion in funding through the Bipartisan Infrastructure Law (BIL) and the Inflation Reduction Act (IRA) to accelerate industrial decarbonization demonstrations. Published cost and performance information from FOAKs can further de-risk future projects.

Challenge 2: High complexity to adopt. Companies may need to time retrofits during rare scheduled maintenance windows and physically fit retrofits into existing facilities. These windows can be decades apart, and physical space can be limited or require re-engineering. Figure 4.2 details the frequency and duration of equipment downtime across sectors.

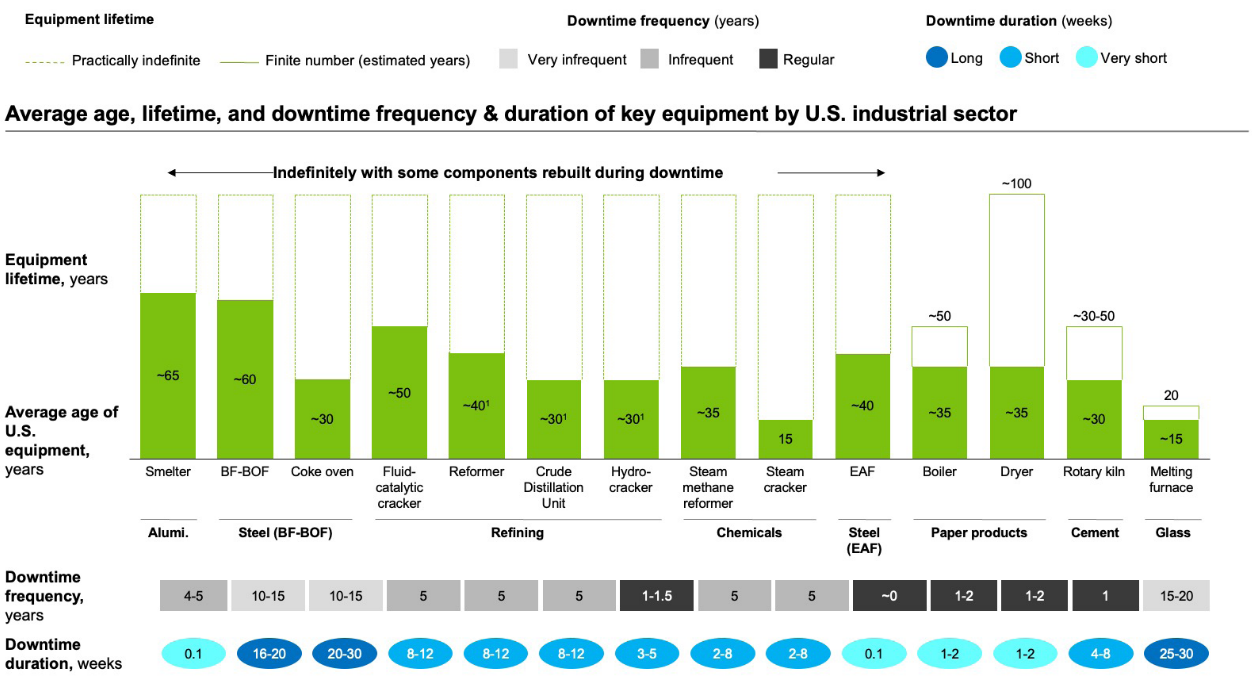


Figure 4.2: Average age of U.S. industrial assets
Source: Press search, Annual reports, Expert interviews, International Aluminum Association, World Steel Association, IHS, Fertecon

117 "Industrial sectors" herein are defined as the eight sectors of focus: chemicals, refining, iron and steel, food and beverage, cement, pulp and paper, aluminum, and glass; unless otherwise stated (e.g., "all industrial sectors")

Potential solution 2: Integrate a decarbonization strategy into near- and long-term capital planning at the asset level. Public sector and industrial players could prioritize investing in and developing retrofits that can be executed quickly during planned equipment downtime. Retrofits that require minimal changes could improve adoption. Examples include drop-in replacements for natural gas and biofuels and/or waste material inputs for aluminum, steel, and glass production.

Industrial players could integrate retrofit planning with "Industry 4.0" upgrades to improve industrial production efficiency, e.g., retrofitting existing equipment with cyber-physical systems to monitor energy use and predict production interruptions. [118, cxxviii, cxxix] In sectors with frequent, highly choreographed downtime (e.g., refining), it is more critical to plan CCS retrofits and other significant decarbonization investments well in advance, particularly for levers where preparation and installation could synergize with downtime.

Technology readiness

Challenge 3: Overreliance on a small portfolio of developing technologies with low TRL and/or ARL (see Chapter 3 for more detail). While the most considerable decarbonization levers by abatement potential—CCS, clean onsite electricity and storage, and industrial electrification—have relatively high TRLs, their ARLs are low. The challenges in this chapter—high delivered costs, capital formation challenges, and a lack of enabling infrastructure—are stark. [119] For example, for CCS on dilute streams, investments in RDandD, scale-up, and operational efficiencies are needed to lower costs and provide certainty (see Carbon Management Liftoff Report for more detail at liftoff.energy.gov).

Based on the least-cost modeling of currently available technologies, these three levers account for ~55% of emissions abatement in the industrial sectors of focus, which can be broken down into ~30% abatement through CCS, ~15% through clean onsite electricity and storage, and ~10% through industrial electrification.

Potential solution 3: Industrial players can diversify decarbonization portfolios through RDandD and pilots for high-potential alternative technologies with lower TRLs. Information sharing from pilots can drive faster learnings across the industrial ecosystem (e.g., high-temperature heat electrification, electric crackers, electric rotary kilns, electrolysis)—*see Chapter 3 for an example of different technologies to address the same emissions as CCS*.

There are several ways that large industrial players could pursue RDandD and FOAK build-out for high-potential alternative technologies, including individual demonstrations, joint ventures, and coalitions. Some structures may be deemed more suitable depending on financial resource availability, risk sharing, technological complexity, IP considerations, and the competitive landscape. There is already growing private sector collaboration on pre-competitive R&D.

RDandD into breakthrough technologies could also be catalyzed by industry-leading startups, cutting-edge academic research (e.g., alternative cement chemistries, heat electrification), and relevant parts of the DOE, including IEDO and ARPA-E. Non-profits could also play a role by highlighting the importance of industrial decarbonization research and fostering collaborative partnerships between research institutions, industry experts, and government agencies. At various stages, capital providers are crucial to RDandD *(see Potential Solution 5 for more information)*.

Resource maturity

Challenge 4: Nascent ecosystem and lack of enabling infrastructure. Electrification, grid decarbonization, CCS, and electrolytic hydrogen are large levers for industrial decarbonization, but enabling infrastructure is not yet available at the scale needed. Cost uncertainty, demand uncertainty, lack of commercial standardization, lead times in permitting transport and storage infrastructure, and public acceptance

118 According to the International Society of Automation, cyber-physical systems (CPS) are smart systems that include engineered interacting networks of physical and computational components

119 TRL for these technologies range from 6-8

must be addressed. While the exact nature of the challenge is described below, across all these solutions, infrastructure availability is necessary for full scale adoption. See Chapter 4 of the Carbon Management and Hydrogen Liftoff Reports for more details on challenges to CCS and clean hydrogen deployment.

Electrification and grid decarbonization will require significant growth in generation, transmission, and distribution infrastructure. On generation, Energy Innovation, an energy and environment-focused think tank, found that electrifying low-temperature industrial heat using heat pumps could require ~1,000 TWh of electricity in 2030 and ~1,400 TWh in 2050. [cxxx] While grid infrastructure buildout is a mature industry, today, lengthy interconnection queues (wait times to connect to the grid) could hamper deployment. In 2022, there were ~2,000 GW of renewables capacity in interconnection queues, nearly double current total grid capacity. [cxxxi] These queues are often 5+ years. The DOE's draft National Transmission Needs study found that transmission deployment is needed as soon as 2030 in the Plains, Midwest, and Texas regions. [cxxxii] Without appropriate generation and transmission infrastructure, electrification, and grid decarbonization could be constrained.

CCS and clean hydrogen also require enabling infrastructure to reach their full potential. Class VI wells (storage sites) must be permitted at an accelerating rate and are the subject of ongoing discussions[cxxxiii].. Clean hydrogen can also require large hydrogen buffer storage. While in some regions both CO2 and hydrogen pipelines and storage already exist, other regions would require additional transport infrastructure (e.g., new pipelines). Permitting challenges for both CCS and Hydrogen are further discussed in each technology's respective Liftoff Report.

Potential solution 4: Support infrastructure build-out by expediting permitting bottlenecks (as detailed in Fiscal Responsibility Act 2023 (Public Law No. 118-5), addressing public acceptance, building regional hubs, creating shared/open access infrastructure (e.g., H2Hubs, cross-sector shared CCS infrastructure), developing policies and regulations supporting CCS demand in other sectors, and sharing learnings across the ecosystem. Examples include the public sector coordinating to ensure investments account for future demand. Examples of lever-specific solutions include:

- **Electrification / Grid Decarbonization**: Support the development of new transmission and clean generation to support increased power demand. Develop clean power micro-grids supporting electricity-intensive industrial areas, particularly in regions where long regional grid connection delays are expected and could limit available capacity.
- **CCS / H2**: Oversize limiting infrastructure like initial carbon capture and hydrogen pipelines and storage sites to provide capacity for future projects. Push for open access infrastructure to allow for transparent and competitive pricing.

Over time, successful projects and scaled infrastructure across sectors (e.g., new transmission lines or H2 pipelines for non-industrial uses) could compound to support cost-competitive deployment of decarbonization technologies for industrial uses.

Nascent value chain and infrastructure challenges—and potential solutions—are discussed at length in Chapter 4 of the Carbon Management Liftoff Report and in Chapter 4 of the Clean Hydrogen Liftoff Report. Refer to the Long Duration Energy Storage Liftoff Report for a discussion of barriers to grid transmission upgrades. Each report can be accessed at liftoff.energy.gov

Challenge 5: Capital formation challenges. Many deep decarbonization projects have relatively low ROIs, often under 10%, and are capital intensive (i.e., energy efficiency projects with low annual return rates). Deep decarbonization projects often face higher-cost financing because solutions have not been demonstrated at scale and are perceived as riskier investments. And some projects can be more expensive on an opex basis because they are optimized for emissions reductions instead of a purely cost- or production-efficiency basis.

Many industrials operate capital-constrained businesses and cannot finance off-balance sheet. They operate in commoditized markets without steep growth trajectories. Many perceive extending the life of an existing asset to be a better investment than investing in decarbonization. Though the sustainable/green debt market is growing, it faces challenges with inadequate green contractual protection for investors, quality and transparency of reporting metrics, issuer confusion and fatigue, greenwashing, and pricing. [cxxxiv]

Potential solution 5: Improve access to low-cost debt and equity for deep decarbonization projects. Below we focus on financing-specific measures; other solutions in this chapter can also lower capital cost (*Potential Solutions 1 and 6 include details on demand-pull, which can securitize offtake, reducing investment risks and financing costs, and see Potential Solution 2 for cost reductions and FOAK build-out).*

Industrial players can access public and private financing across the capital stack in ways that correspond to the RDandD stages of decarbonization levers:

- Direct risk mitigation for R&D and pilot stage projects by public sector interventions. Examples include first-loss guarantees, public procurement policies like the Federal Buy Clean Initiative and the New Jersey Low Embodied Carbon Concrete Leadership Act[120], and funding and tax credits from the IRA and the BIL.
- Demonstration technologies close to commercialization can benefit from collaboration between private and/or infrastructure equity providers and asset owners and public-private partnerships (PPPs) like cooperative agreements such as OCED's Industrial Decarbonization Program.
- Joint venture structures between large industry players have the potential to lower the cost of borrowing, share technological learnings, and scale successful solutions from lab and bench scale work for earlier TRL paths.
- Industrial producers with deployable technology solutions could tap into sustainable/ green debt flows, such as sustainability-linked loans (SLLs) and green bonds, that can reward the achievement of KPIs related to decarbonization. [cxxxv] These financing vehicles can be strengthened by clear contractual protection for investors, transparent and third-party validated reporting metrics, and transition-risk-adjusted pricing. They can also leverage low-interest public loans and loan guarantees from the LPO.

In addition to returns, investors evaluating business cases can consider how investments in decarbonization can pre-empt and reduce transition risk factors (e.g., policy and legal, technological, market-based, reputational). [cxxxvi] Investors in alliances to reduce their financed emissions (e.g., the UN-convened Net-Zero Banking Alliance) can progress toward these commitments by investing in industrial decarbonization.

Technology readiness

Challenge 5: Overreliance on a small portfolio of developing technologies with low TRL and/or ARL (see Chapter 3 for more detail). While the most considerable decarbonization levers by abatement potential—CCS, clean onsite electricity and storage, and industrial electrification—have relatively high TRLs, their ARLs are low. The challenges in this chapter—high delivered costs, capital formation challenges, and a lack of enabling infrastructure—are stark. For example, for CCS on dilute streams, investments in RDandD, scale-up, and operational efficiencies are needed to lower costs and provide certainty (see Carbon Management Liftoff Report for more detail at liftoff.energy.gov).

Based on the least-cost modeling of currently available technologies, these three levers account for ~55% of emissions abatement in the industrial sectors of focus, which can be broken down into ~30% abatement through CCS, ~15% through clean onsite electricity and storage, and ~10% through industrial electrification.

Potential solution 5: Industrial players can diversify decarbonization portfolios through RDandD and

120 New Jersey P.L.2023, c.4, NJ

pilots for high-potential alternative technologies with lower TRLs. Information sharing from pilots can drive faster learnings across the industrial ecosystem (e.g., high-temperature heat electrification, electric crackers, electric rotary kilns, electrolysis)—*see Chapter 3 for an example of different technologies to address the same emissions as CCS.*

There are several ways that large industrial players could pursue RDandD and FOAK build-out for high-potential alternative technologies, including individual demonstrations, joint ventures, and coalitions. Some structures may be deemed more suitable depending on financial resource availability, risk sharing, technological complexity, IP considerations, and the competitive landscape. There is already growing private sector collaboration on pre-competitive R&D.

RDandD into breakthrough technologies could also be catalyzed by industry-leading startups, cutting-edge academic research (e.g., alternative cement chemistries, heat electrification), and relevant parts of the DOE, including IEDO and ARPA-E. Non-profits could also play a role by highlighting the importance of industrial decarbonization research and fostering collaborative partnerships between research institutions, industry experts, and government agencies. At various stages, capital providers are crucial to RDandD *(see Potential Solution 4 for more information).*

Market acceptance

Challenge 6: Industrials do not perceive a meaningful market or willingness to pay for low-carbon goods in the U.S., hindering decarbonization ambitions. The top U.S. industrial players by market share have limited short-term decarbonization ambitions, and global industry emissions are not on track.[cxxxv, xxxvii, xliii, lxxviii, lxxx] Scope 1 and 2 decarbonization targets across the sectors of focus range from 10-100% by 2035, with the average target of less than 30%.[121]

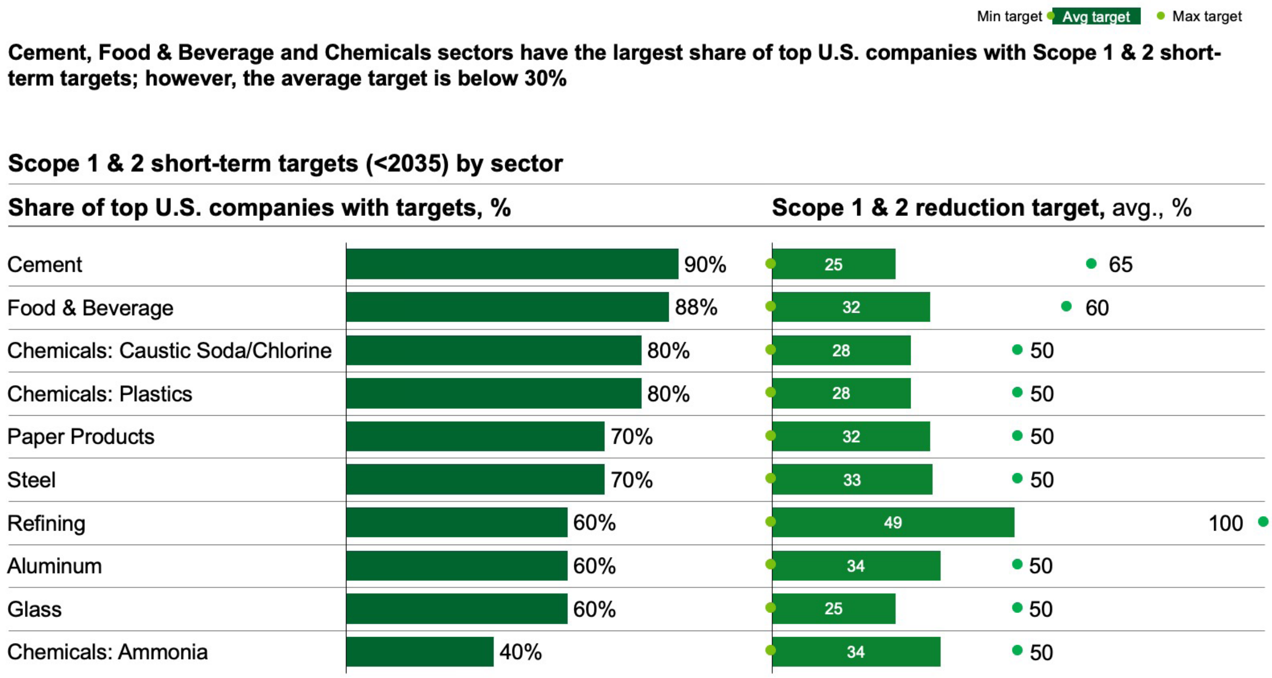


Figure 4.3: Share to top U.S. Industrial companies with decarbonization targets. Average Industry targets by sector. | Aluminum companies included: Atalco, Alcoa, Century Aluminum, Magnitude 7, Norsk Hydro, Kaiser, Bonnell, Novelis, Arconic and Constellium | Cement companies included: LafargeHolcim, Heidelberg, Cemex, CRH, Buzzi, Martin Marietta Materials, Vulcan Materials, Argos, Eagle Materials and CalPortland | Food and beverage companies included: JBS Foods, Tyson Foods, Cargill, Dairy Farmers of America, Land O' Lakes, California Dairies, Bunge, ADM | Glass companies included: Ardagh, Owens Corning, Anchor glass, Gentex, NSG, Jeld Wen, Knauf Insulation, Certain Teed, Saint Gobain Glass and Strategic Materials, Owens Illinois | Paper product companies included: International Paper, Weyerhaeuser, West Fraser, WestRock, Graphic packaging, Kimberly Clark, PCA, Pratt, Georgia Pacific, Sonoco Products and

121 All targets above 50% are N<2

Greif | Steel companies included: Cleveland Cliffs, US Steel, ArcelorMittal, Nucor, Steel Dynamics, Gerdau, CMC, Timken, Charter | Ammonia companies included: CF Industries Inc., Koch Industries Inc., Iowa Fertilizer Co., Dyno Nobel Inc., Nutrien | Caustic Soda/ Chlorine companies included: Westlake Chemical, Formosa Plastics, Shintech, Oxy, Olin | Ethylene, Propylene, BTX companies included: ExxonMobil, Dow, LyondellBasell, Marathon Petroleum, Shell | Refining companies included: Marathon Petroleum, Valero, Phillips 66, ExxonMobil, Chevron, PBF Energy, Koch, BP, Citgo, Shell,

Potential solution 6: Bolster demand-side pull by understanding the cost difference between low-carbon vs. business-as-usual goods. Build coalitions of early adopters and policies that will pay for decarbonized products

Demand-side mechanisms can include guaranteed long-term offtake (e.g., procurement programs such as the Federal Buy Clean Initiative and advance market commitments such as the WEF First Movers Coalition and Frontier). End customers can drive down costs while rewarding companies for maximizing their abatement potential. The public sector can bridge gaps between customer willingness-to-pay and the cost of production. For example, the DOE has a notice of intent for a demand-side support initiative to bolster hydrogen offtake[122].

Other policies could add to the momentum. For example, carbon border adjustment mechanism (CBAM) policies establish a price on carbon for imported goods. In October 2023, the European Union will begin the first phase of its CBAM, requiring importers to report emissions associated with their imports. In January 2026, the EU will set a price on carbon for imports, including U.S. steel, cement, fertilizers, and hydrogen. Such a policy could accelerate the clean energy transition domestically and abroad while also strengthening American economic competitiveness.

Developing knowledge-sharing and tracking initiatives can close the knowledge gap around embodied emissions and ESG (Environmental, Social, Governance) concerns, and help end consumers make informed purchasing decisions. Producers can identify offtake markets and address structural undersupply of low-CO2 products (e.g., commodity goods). [cxxxvii, cxxxviii] Markets could be identified where there is value chain pressure for lower-carbon production paths for existing low-CO2 and high social responsibility products such as consumer white goods, EVs, renewable power, etc. Price premia could differ between off-takers of the same product, and higher costs for some offtakes, e.g., green steel for EVs has little price impact on the final cost born by the consumer.[xcix] As decarbonization technologies undergo continued RDandD and eventually benefit from economies of scale, the size of premiums would decrease. [cxxxix.]

Industrial producers could leverage coalitions to strengthen collective action and ensure consistent progress. Examples include:

- The Together for Sustainability (TFS) network (chemicals) collaborates on sustainable procurement from a global network of audited suppliers, decreasing costs and protecting companies from future potential legal action and reputational damage.
- The Global Cement and Concrete Association (GCCA) has created a shared 2050 Net Zero Roadmap, which aligns members to advocate for shared policies and priorities.
- The Oil and Gas Climate Initiative (OGCI) reports climate performance data from its members, including carbon and methane emissions and a CO2 storage catalog.
- Department of Energy's Fossil Energy and Carbon Management Office is in the process of accepting public comments on a sector wide strategy to support best practices in Carbon Management. This Responsible Carbon Management Initiative123 is developing shared principles for safely and

122 Biden-Harris Administration to Jumpstart Clean Hydrogen Economy with New Initiative to Provide Market Certainty And Unlock Private Investment | Department of Energy

123 Federal Register: Notice of Intent and Request for Information Regarding Launching a Responsible Carbon Management Initiative

transparently implementing carbon management to proactively address emerging public concerns.

License to Operate

Challenge 7: Inconsistent public acceptance and community perception due to environmental and human health risks, environmental justice and labor concerns. Local communities often have concerns regarding pollution that make them wary of any industrial developments located within proximity of their homes. Community opposition can result in increased costs to developers due to both lost productivity and time spent engaging with the community to solve the conflict, possibly a result of developers conducting limited community engagement prior to the start of a project.[cxl] Lack of community buy-in to a project can also stymie projects to the point that they are no longer feasible to develop. Work stoppages, strikes, or other delays or labor opposition can further delay projects. Public push back to industrial decarbonization projects is more prominent with CCS and hydrogen levers, as communities are more likely to oppose projects which could require large amounts of new infrastructure, are perceived to allow the continued use of fossil fuels and could possibly introduce increased amounts of new pollutants unique to decarbonization levers.

Potential solution 7: Implement robust community benefits plans and agreements which respond to labor and community concerns and mitigate potential harms. Community benefits agreements (CBA) are signed between developers and community groups that negotiate community support for a project in return for benefits from the developer.[cxli] CBA negotiations are avenues for developers to engage with communities to understand how their project can meet with their goals, while ensuring that community needs are met. These CBAs can incorporate mechanisms designed to mitigate the impacts from project development that the community is concerned about. Selected examples include requiring the usage of state-of-the-art SOx scrubbers for hydrogen burning facilities, investments in local infrastructure, labor standards including utilization of apprentices, pay and benefit standards, and local hiring requirements, implementation of GHG reduction programs. To prompt projects to consider the community impact of their work and engage with stakeholders, DOE requires applicants to most BIL/IRA funding opportunities to submit "Community Benefit Plans." These plans, generally weighted at 20% of the technical merit points for a project, prompt applicants to develop actionable plans for formal engagement with their communities on Justice40, DEIA, Good Jobs, and workforce and community agreements. More information is available here: https://www.energy.gov/infrastructure/about-community-benefits-plans

Chapter 5: Metrics and milestones

The DOE will track two types of key performance indicators to understand the progress needed for successfully decarbonizing the U.S. industrial sector.

- **Leading indicators** are signs to evaluate the present status of decarbonization levers across technology readiness, market adoption readiness, and penetration of key technologies.
- **Lagging indicators** are the retroactive verification of successful or unsuccessful scaling and adopting decarbonizing levers (e.g., evaluations of progress toward net-zero targets).

These indicators can track industry milestones and evaluate decarbonization progression across sectors between 2030 and 2050. These leading and lagging indicators—quantified on sector-, corporation-, and facility-bases—allow tracking in an integrated way. These metrics are progress indicators rather than requirements and can create confidence across an ecosystem.

	Possible Leading Indicators	Possible Lagging Indicators
Cross-cutting (i.e., applies to all industrial sectors of focus)		
	• Number of top industrial companies with short-term (pre-2035) Scope 1 and 2 emissions-reduction and net-zero targets[124] • Average short-term Scope 1 and 2 emissions-reduction targets • Cost and price of decarbonized products relative to existing products (e.g., the existence of technology price premiums) • Volume of low-carbon commodities traded on commodity exchanges and dedicated low-carbon trading metrics • Market growth for low-carbon products in each sector • Number and size of announced purchase commitments for low-carbon products • Number of FOAK and NOAK projects announced • Decarbonization-focused R&D spending	• Cost of decarbonization levers per tCO_2e abated • Total capital mobilized • Amount of capital raised for decarbonization-focused private equity and infrastructure funds • Electrified equipment capacity relative to fossil-fuel-powered equipment • Assets converting to best-available technologies
Sector-specific		
Chemicals	• Announced CCS retrofits on chemicals assets (e.g., steam-cracking furnaces, SMRs, NGP) • Electrolyzer capacity • Increase in recycling rate for consumer plastics	• MT of reduction in CO_2e emissions • Low-carbon chemicals production capacity
Refining	• Demand reduction via electrification of transport capacity and production reduction • Electrolyzer capacity • Announced CCS retrofits on Refining process units (e.g., FCC, SMR)	• MT of reduction in CO_2 emissions

124 Top industrial companies are defined as the top 10 by market share in each sector

Iron and steel	• Flat steel charge mix (AIU vs. scrap) [125] • Announced conversions of existing DRI/HBI-to-hydrogen reduction and greenfield H2-DRI/HBI with resulting capacity • Announced CCS retrofits in ironmaking and steelmaking (e.g., BF-BOFs and NG-DRI/HBI) • Production capacity of alternative ironmaking processes	• MT of reduction in CO2 emissions • Production capacity of EAFs
Food and beverage	• Production capacity of alternative production methods (e.g., electrified low-temperature heat)	• MT of reduction in CO2 emissions • Percentage of fuel mix supplied by alternative fuels (e.g., biofuels)
Pulp and paper	• Announced CCS retrofits in pulp and paper mills • Low-temperature heat demand met through decarbonized sources	• MT of reduction in CO2 emissions • Percentage of fuel mix supplied by alternative fuels (e.g., biomass)
Cement	• Announced CCS retrofits in cement plants (e.g., rotary kilns) • Production capacity of alternative production methods • Production capacity of alternative chemistries	• MT of reduction in CO2 emissions • Clinker-to-binder ratio • Percentage of fuel mix supplied by alternative fuels (e.g., waste, biomass material, hydrogen)
Aluminum	• Collected and recycled volume domestically vs. exported volume vs. landfilled volume • Imports of primary aluminum • Announced CCS retrofits on aluminum production processes (e.g., Hall-Héroult) • Production capacity of inert anode systems	• MT of reduction in CO2e emissions
Glass	• Announced CCS retrofits in glass plants (e.g., melting furnaces) • Collected and recycled cullet domestically vs. exported vs. landfilled • Production capacity of oxyfuel furnaces • Production capacity of furnaces supplied by alternative fuels (e.g., H2, biomethane)	• MT of reduction in CO2 emissions
Lever-specific		
Clean electricity	• Announced clean electricity capacity (GW) • Total clean electricity capacity connected to the grid • Average grid interconnection queue time for clean electricity projects • Capex targets for inter-day and multi-day/week LDES technologies • *Storage: Refer to Chapter 5 and Appendix 7 of the Long Duration Energy Storage Liftoff Report. The report can be accessed at liftoff.energy.gov*	• Total clean-electricity capacity and share of grid electricity • Total deployed LDES capacity target • *Storage: Refer to Chapter 5 and Appendix 7 of the Long Duration Energy Storage Liftoff Report. The report can be accessed at liftoff.energy.gov*

125 AIU refers to Alternative Iron Units (e.g., pig iron, direct reduced iron DRI/hot briquetted iron HBI)

CCS	• Announced CO2 pipeline capacity • Commercial storage capacity • Creation of standardized agreements and contract structures between technology providers, shared infrastructure for transport, and end-use storage providers • *Refer to Chapter 5 of the Carbon Management Liftoff Report. The report can be accessed at liftoff.energy.gov*	• Total CO2 pipeline capacity • Capacity of operational CCS projects • *Refer to Chapter 5 of the Carbon Management Liftoff Report. The report can be accessed at liftoff.energy.gov*
Clean hydrogen	• Announced hydrogen pipeline capacity • Electrolytic hydrogen produced annually • *Refer to Chapter 5 of the Clean Hydrogen Liftoff Report. The report can be accessed at liftoff.energy.gov*	• Total hydrogen pipeline capacity • *Refer to Chapter 5 of the Clean Hydrogen Liftoff Report. The report can be accessed at liftoff.energy.gov*

Chapter 6: Modeling appendix

Appendix A: Modeling methodologies and assumptions

Methodology 1: Sources of emissions by sector

Analysis objective: Produce a representative emissions breakdown—sub-divided into emission types (e.g., heat, process, power)—across the eight industries of focus based on a 2021 emissions baseline.

Description of analysis

Seven categories of emissions sources were analyzed across the industrial sectors considered for this report: low-temperature heat (-30–200°C), mid-temperature heat (200–400°C), high-temperature heat (400+°C), process emissions, onsite power emissions, off-site power emissions, and other emissions. The analysis and assumptions varied by industry and emissions source, as no centralized data source exists. The emission baseline for each sector includes 2021 CO2e emissions using GWP100 (AR4), aligned with the EPA's GHG Reporting Program (GHGRP) and the DOE's Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (GWP table used). [cxlii] Non-CO2 greenhouse gases include methane (CH4), nitrous oxide (N2O), and fluorinated GHGs. [126] Total 2021 sector CO2e emissions were drawn from various sources, and the share of emissions by source was determined as a percentage of the sector total (see details for each sector below).

A summary of each sector's approach is as follows:

- **Chemicals:** Sector emissions sources were calculated for sub-sectors, including natural gas processing, steam methane reforming + Haber-Bosch (for ammonia production), steam cracking, chloralkali process, and other downstream chemicals. *See the Chemicals and Refining Liftoff Report modeling appendix for the emissions-source approach for each sub-sector.*

- **Refining:** Expert input on refinery emissions sources across refinery was considered for the breakdown of major sources of emissions, including fluid catalytic cracking, naphtha upgrading, distillation, hydrotreating, hydrocracking, and other conversion and supporting units. A hydrogen-production emissions breakdown was determined from an academic source (see assumptions, Smith et al.) for a steam methane reformer. DOE Manufacturing Energy and Carbon Footprints were used to determine the proportion of onsite and off-site power generation.

- **Iron and steel:** Sector emissions were based on iron and steelmaking emissions intensity data from the World Steel Association in the U.S. and cross-referenced with reported 2021 emissions from U.S. steel players and EPA FLIGHT data. Expert input, reports on net-zero steel by Mission Possible Partnership, and net-zero heat by the LDES Council were used to calculate the share of steelmaking emissions attributable to heating processes. The emissions intensity for BF-BOF is assumed to be a weighted average of 2.5 tCO2/t liquid steel. Emissions intensity for EAF flat and long steelmaking is assumed to be a weighted average of 0.7 tCO2/t liquid steel and 0.3 tCO2/t liquid steel, respectively.

- **Food and beverage:** Sector emissions were drawn from the EIA Annual Energy Outlook 2022, using 2021 as the baseline emissions. The sector emissions breakdown was based on the DOE Manufacturing Energy and Carbon report (2018), scaled for consistency with 2021 emissions numbers, and further refined with expert input on food and beverage emissions sources across the value chain. Expert input was used to complement the above-mentioned sources.

126 N2O and fluorinated GHGs make up <10% of total CO2e emissions; CO2 and methane make up >90%; this report assumed Global Warming Potential (GWP) with a 100-year lifetime; biogenic CO2 emissions are not considered in this report as EPA reporting states these emissions are accounted for in Land Use, Land-Use Change, and the Forestry sector per IPCC and UNFCCC; however, biogenic non-CO2 emissions are accounted for in the Energy sector (e.g., incomplete combustion, waste treatment)

- **Cement:** Total industry emissions were drawn from the EIA Annual Energy Outlook 2022 using 2021 as the baseline emissions and syndicated with DOE JST to separate cement emissions from lime. Expert input on cement emission sources across the value chain was considered. Calcination-process emissions were included as process emissions, and fossil fuel emissions used in the kiln were identified as high-temperature heat emissions. Crusher, raw mill, cooler, and cement mill emissions were included as offsite electricity emissions.

- **Pulp and paper:** Expert input on pulp and paper emissions sources across the value chain was considered. The weighted-average paper-making emissions intensity across different paper grades (including tissue, cartonboard, containerboard, pulp, newsprint, non-paper, packaging paper, printing and writing, and specialty paper) is calculated based on expert assumptions and data from FisherSolve. Fuel emissions for combined heat and power (CHP) systems are assumed to be equally split between steam generation and onsite electricity.

- **Aluminum:** Total industry emissions were drawn from the EIA Annual Energy Outlook 2022. Aluminum for Climate by Mission Possible Partnership, the International Aluminum Institute database, and private companies' sustainability reports were considered to calculate the breakdown of emissions by value-chain step and source. These figures were further validated with expert input.

- **Glass:** Total industry emissions were drawn from the EIA Annual Energy Outlook 2022. The sector emissions breakdown was based on the DOE Manufacturing Energy and Carbon report (2018), scaled for consistency with 2021 emissions and further refined with expert input.

Considerations and limitations of the approach:

- The breakdown of emissions at any individual industrial source will differ by facility specifications, technology, and production unit—individual facilities were not considered in this approach. Rather, a facility archetype was used by sector.

- Publicly available data on emissions is limited across the analyzed industrial value chains. The breakdown of emissions should be understood to show the relative magnitude of each emissions source per industrial sector rather than as a precise description of emissions from any individual facility/product.

Key inputs:

- Chemicals and refining:
  - DOE Chemicals and Refining Liftoff Report
  - Smith et al.—Current and future role of Haber–Bosch ammonia in a carbon-free energy landscape, 2019[cxliii]
  - Bradbury et al.—Greenhouse Gas Emissions and Fuel Use within the Natural Gas Supply Chain—Sankey Diagram Methodology, 2015[cxliv]
  - Tau Ren et al. [cxlv]
- Iron and steel:
  - Net-zero heat—Long Duration Energy Storage by the LDES Council[cxlvi]
  - Mission Possible Partnership—Net Zero Steel Initiative (reports, open-source model, Expert input [lx]
- DOE and National Lab expertise
- Food and beverage:
  - U.S. Energy Information Administration, Annual Energy Outlook 2022[cxlvii]

  - DOE Manufacturing Energy and Carbon Footprint sector analysis (2018)[cxlviii]
  - U.S. EPA—Inventory of U.S. Greenhouse Gas Emissions and Sinks[cxlix]
  - DOE and National Lab expertise
- Cement
  - McKinsey and Co.—Laying the foundation for zero-carbon cement[cl]
  - DOE and National Lab expertise
- Pulp and paper
  - FisherSolve Next 2022[lxviii]
  - U.S. EPA—Inventory of U.S. Greenhouse Gas Emissions and Sinks[cxlix]
  - DOE and National Lab expertise
- Aluminum
  - Mission Possible Partnership—Aluminum for Climate initiative (reports, open-source model)[cli]
  - U.S. Energy Information Administration, Annual Energy Outlook 2022[cxlvii]
  - DOE and National Lab expertise
- Glass
  - U.S. Energy Information Administration, Annual Energy Outlook 2022[cxlvii]
  - DOE and National Lab expertise
- Cross-cutting
  - FisherSolve Next 2022[lxviii]
  - U.S. Energy Information Administration, Annual Energy Outlook 2022 [cxlvii]
  - U.S. Environmental Protection Agency – Inventory of U.S. Greenhouse Gas Emissions and Sinks[cxlix]
  - DOE and National Lab expertise

Methodology 2: Integrated marginal abatement cost curve (MACC) analysis

Analysis objective

This analysis aims to create an integrated MACC across the eight industrial sectors of focus detailing the economic considerations for implementing key decarbonization levers.

The analysis highlights the Inflation Reduction Act's (IRA) significant impact on incentivizing investment into solutions (e.g., CCS, clean electricity, and clean hydrogen) while visually displaying the need for public and private investment into sector decarbonization.

This analysis details the least-cost decarbonization levers to abate each major emissions source in 2030. It does not imply industry will implement all of these measures by 2030. Instead, this analysis details the economics of abating each source of emissions through the least-cost lever available today. Through this analysis, an assessment of the investment required and the relative economics of abating each source of emissions can be determined. This analysis also illustrates the need for additional R&D to develop other decarbonization technologies that de-risk and could improve the economics of decarbonization.

Description of analysis

A MACC analysis evaluates decarbonization technologies based on the economic cost of abatement and the potential scale of emissions reduction. Abatement costs are calculated as the difference between the net present values of the incumbent (reference) case and the decarbonization case, divided by displaced emissions. In this analysis, an integrated MACC was built across the eight industries of focus using the 2021 U.S. emissions baseline and 2030 abatement cost estimates. Key emissions sources considered include heat generation (split between low-, medium-, and high-heat requirements), process emissions, onsite and off-site power generation, and other emissions.

Potential decarbonization technologies were considered for each industry against each emissions source. For example, in the Glass sector, a large portion of emissions (i.e., >50%) are from heat generation for the melting process. These emissions could be decarbonized with several technologies, including CCS on the melting furnace, electric melting, alternate fuel, and oxyfuel. In the MACC analysis, the current least-cost decarbonization measure to address each emissions source—after accounting for IRA incentives—was selected within each industry. Some emissions cannot be abated with current technologies, and these are left as unabated. This analysis represents a least-cost assessment of decarbonizing each major emissions source in 2030, however, the adoption of decarbonization levers may vary as technologies mature and develop.

The technologies considered in this report fall under nine decarbonization levers:

1. CCS,
2. Clean onsite electricity and storage,
3. Industrial electrification,
4. Energy efficiency,
5. Clean hydrogen,
6. Alternative raw materials,
7. Alternative fuel (non-hydrogen),
8. Grid decarbonization, and
9. Alternative production methods.

Considerations and limitations of the approach: Simplifying assumptions regarding clean energy solutions, energy efficiency levers, and emissions reduction impact were made.

- On renewable energy, the MACC reflects the assumption that current onsite power / combined heat and power (CHP) facilities are replaced with onsite solar power generation and long duration energy storage (LDES) with electrified heat generation alongside thermal energy storage (TES) where required, which does not account for the utilization of PPAs and grid power. Assumptions on LDES are consistent with the DOE's LDES Liftoff Report.
- On energy efficiency, the analysis includes an assumption that several energy-efficiency optimization levers can be combined to achieve ~5–10% fuel consumption efficiency gains across sectors. In practice, after consulting several industry players, it is acknowledged that energy efficiency opportunities are unique to each asset and facility and must be considered at that level by operators. The level of detail for energy-efficiency levers varies across sectors based on the breadth of measures and publicly available information. A simplifying assumption was made for several chemicals sub-sectors (i.e., ethylene, chloralkali processes, and ammonia) and for refining, cement, and food and beverage. However, pulp and paper, aluminum, glass, and natural gas processing (a sub-sector of chemicals) all included more detailed lists. Please see the detailed MACC table below for further information.
- On the impact of external emissions reductions, nationwide grid decarbonization, transport sector electrification, and mechanical recycling were considered.
  - The White House has set a target of 100% grid decarbonization by 2035, reflected on a linear scale for the 2030 MACC as an external-emissions reduction factor instead of a direct decarbonization measure.

- Transport sector emissions reduction goals of ~25% by 2030 are based on the White House—Pathways to Net Zero report. Similar to grid decarbonization, it is assumed these goals are met and reduce transport sector demand for refining products.
- Recycling goal of a 50% recycling rate in 2030 is based on the EPA's National Recycling Strategy. It is assumed that 50% of this recycling target is addressed through mechanical recycling, which reduces the overall demand for virgin plastic. The other 50% could be met through advanced recycling processes. However, due to the relatively high emissions footprint of advanced recycling today, they were not considered as a demand reduction.

The MACC provides useful information for decarbonization levers that are well-established and reported. However, the MACC does not include nascent technologies due to a lack of publicly available information and the following assumptions.

- The MACC considers a limited number of abatement measures:
  - Some technologies do not have widely available abatement cost data that can be used to compare with existing alternatives.
  - Some levers, such as those currently in earlier stages of R&D, may provide a lower-cost pathway to decarbonization, but a lack of deployment has prevented their inclusion in the MACC analysis.
- The MACC considers the costs and technological advancements as of information that is publicly available today; any future technology advancements that can affect the cost-effectiveness of abatement measures might not be fully captured.
  - The MACC represents a snapshot in time and may not accurately reflect long-term cost-reduction trends and the potential for innovation.
  - The MACC and supporting datasets are constantly evolving with the best available information. Updated costs, abatement potential, and details can be used to continually improve the MACC outputs.
  - The MACC includes publicly available cost reduction projections published by DOE in the Carbon Management and Hydrogen Liftoff Reports.
- The MACC has simplified cost assumptions—including limiting the number of tax incentives reflected—to inform the abatement potential. Other incentives and potential funding opportunities are outlined in *Chapter 3*.
  - This analysis also does not account for the economic impact of additional facility infrastructure upgrades that may be required to enable the industrial electrification of processes. Infrastructure costs are assumed for CCS and Hydrogen per the respective liftoff report analyses.

Key inputs and assumptions:

Lever	Sector	Key assumption	Value	Unit	Source
CCS	Cross sector	Capture rate	90	%	Carbon management liftoff report
CCS	Cross sector	Levelized 45Q CCS tax credit	$48.26	$/t CO2 sequestered	45Q IRA incentive [127]
CCS	Cross sector	Transport and storage costs	~$10–40	$/t CO2 sequestered	Carbon management liftoff report GCCSI, 2019, BNEF, 2022

127 IRA tax incentives provide up to $85/t CO2e stored in saline geologic formations from carbon capture on industrial and power generation facilities for up to 12 years; this analysis used a levelized tax credit using a 10% WACC over the 12-year period starting in 2030, matching the methodology used in DOE's Hydrogen Liftoff Report for calculating the levelized hydrogen production tax credit (PTC) from 45V

CCS	Chemicals	Capture cost for NGP	~$(20) –10[128]	$/t CO2 sequestered	CandR liftoff report
CCS	Chemicals	Capture cost for ammonia	~$110–140	$/t CO2 sequestered	CandR liftoff report
CCS	Refining	SMR	~$85–116	$/t CO2 sequestered	CandR liftoff report
CCS	Refining	Process heating	~$95–126	$/t CO2 sequestered	CandR liftoff report
CCS	Refining	FCC	~$95–126	$/t CO2 sequestered	CandR liftoff report
CCS	Steel	BF-BOF	~$85–159	$/t CO2 sequestered	Carbon management report—includes carbon capture, transport, and storage
CCS	Steel	BF-BOF	~$37–111	$/t CO2 sequestered	Carbon management report with 45Q
CCS	Steel	NG DRI/HBI	~$175–300	$/t CO2 sequestered	MPP—Net-Zero Steel, Global CCS Institute—technology readiness and costs of CCS
CCS	Steel	NG DRI/HBI	~$140–300	$/t CO2 sequestered	Includes carbon capture, transport and storage (Carbon management report) + 45Q
CCS	Aluminum	Hall-Heroult	~$175–300	$/t CO2 sequestered	Calculation based on MPP - Net zero aluminum, Global CCS institute - technology readiness and costs of CCS, Verdox
CCS	Aluminum	Hall-Heroult	~$140–300	$/t CO2 sequestered	Includes carbon capture, transport and storage (Carbon management report) + 45Q
CCS	Glass	Melting furnace	~$175–300	$/t CO2 sequestered	Calculation based on Global CCS institute—technology readiness and costs of CCS, "A review of decarbonization options for the glass industry" (Zier M. et al., 2021), "Decarbonization options for Dutch container and tableware glass" (Papadogeorgos et al., 2019) + 45Q
CCS	Glass	Melting furnace	~$140–300	$/t CO2 sequestered	Includes carbon capture, transport and storage (Carbon management report) + 45Q
CCS	Cross sector	Assumptions on CCS are consistent with the DOE's Carbon Management Liftoff Report. Note that assumptions on CCS retrofits in aluminum, NG-DRI/HBI, and glass melting furnaces, where CCS cost estimates beyond the Carbon Management report methodology were required, are based on Global CCS Institute and adjusted to be consistent with the Carbon Management Liftoff Report's transport and storage cost estimates.			
Grid Decarbonization	Cross sector	The extent of grid decarbonization by 2030	81	%	Chemicals and Refining Liftoff Report

128 Note that parentheses () depict negative values in this modeling appendix.

Clean onsite electricity and storage	Cross sector	MACC reflects the assumption that current onsite power / combined heat and power (CHP) facilities are replaced with onsite solar power generation and long duration energy storage (LDES). • This shift will likely unfold with a combination of onsite clean energy sources based on geographic constraints (e.g., on- and off-shore wind, nuclear), PPAs, and grid power. • Assumptions on LDES are consistent with the DOE's LDES Liftoff Report.			
Alternative raw material	Cement	Clinker substitution: Assume the U.S. evolves to a clinker-to-binder ratio of 50%	50	%	Consistent with upper bound for clinker substitution under ASTM standards (e.g., for ternary blends with fly ash and steel slag, calcined clay blended cements)
Clean Hydrogen		Assumptions on Hydrogen are consistent with DOE's Hydrogen Liftoff Report.			
Clean Hydrogen	Cross sector	Levelized cost of 45V tax credit	1.80	$/kg H2	Inflation Reduction Action – assumes 10% WACC, 10 years of tax credit, and a 20-year project lifetime
Clean Hydrogen	Cross sector	Transport and storage costs are estimated to range between $0.4-1.4/kg hydrogen, H2 consistent with the DOE Hydrogen Liftoff report.			
Alternative fuel (non-hydrogen)	Cement	The U.S. uses ~16% alternative fuels compared to the EU average of 50%.	30	%	DOE expert input, Portland Cement Association - selected 30% informed by the higher EU average usage
Alternative fuel (non-hydrogen)	Cross sector	Biomethane price	12.5–15	$/GJ	Expert input, FisherSolve Zier, M., Stenzel, P., Kotzur, L., and Stolten, D. (2021). A review of decarbonization options for the glass industry. Energy Conversion and Management: X, 10, 100083. https://doi.org/10.1016/j.ecmx.2021.100083
NG-DRI/HBI to H2-HBI/DRI	Steel	% of NG-DRI/HBI that will retrofit to hydrogen instead of CCS to decarbonize	20	%	DOE expert input
NG-DRI/HBI + CCS	Steel	% of NG-DRI/HBI that will use CCS retrofits to decarbonize	80	%	DOE expert input
Electrification (transition to EAF)	Steel	Existing BF-BOF capacity that will transition to EAF production route	15	MT	DOE expert input

Raw material substitution	Steel	% of BF-BOF charge mix that can be replaced by DRI/HBI	10	%	Expert input, Hatch (2022, August). Addition of DRI, HBI, and Scrap to the Blast Furnace: A Means to Reduce Greenhouse Gas Emissions. https://www.hatch.com/About-Us/Publications/Technical-Papers/2022/08/Addition-of-DRI-HBI-and-scrap-to-the-blast-furnace-A-means-to-reduce-greenhouse-gas-emissions#:~:text=Direct%20reduced%20iron%20(DRI)%20and,and%20increase%20productivity%20%5B1%5D

- For chemicals and refining, the MACC was developed as part of the DOE's *Chemicals and Refining Liftoff Report*, which can be referenced for more detailed considerations and limitations.
- For aluminum, opex numbers were estimated based on the Mission Possible Partnership Net-Zero Aluminum Open-Access model.

Methodology 3: Capex investment required

Analysis Objective: This analysis aims to calculate the capital expenditure investment required in each sector to reach net zero. The key inputs and assumptions table detail cost estimates for each retrofit/decarbonization lever. Publicly available sources and sector expert input were used to determine capex costs for implementing these technologies. This methodology ties to each sector's estimated capex required range, totaling $700B–1.1T through 2050.

Description of analysis:

- **Iron and steel**: The range of capex investment required for iron and steel decarbonization was estimated using several decarbonization scenarios considering the cost of CCS retrofits on 2–8 remaining BF-BOF facilities, the potential environmental clean-up shutdown costs for 2–6 BF-BOF facilities, domestically building additional 2.5–10MT NG based DRI/HBI facilities, CCS retrofits on 5–15MT NG based DRI/HBI plants, and a FOAK U.S. clean hydrogen DRI/HBI-EAF plant.
- **Food and beverage**: The capex estimate investment required for food and beverage processing decarbonization was based on assuming a) that fossil-fuel-based boilers are replaced with electric boilers and b) the boiler estimate would represent roughly half the total investment needed to decarbonize the industry given the wide range of alternative equipment needed across food and beverage facilities.
- **Pulp and paper**: The capex required for decarbonizing pulp and paper assumes fossil-fuel-based boilers are replaced with electric boilers. Further, the capex is scaled for the adoption of other levers, such as electrification and alternative fuels.
- **Glass**: The capex estimate is based on oxyfuel, CCS, and hydrogen technology deployment for flat and container glass. Per-ton capex values were multiplied by total glass production.
- **Aluminum:** Estimated capex investment required for aluminum decarbonization was based on assuming a) alumina refinery retrofit of fossil-fuel based boiler and calciner in digestion and calcination-to-electric boiler and electric/hydrogen calciner, b) retrofit of remaining six aluminum smelters with either CCS or inert anode, and c) retrofit fossil-fuel burners/pre-heaters/furnaces in secondary aluminum production.
- **Cement:** Capex estimate for cement assumes deployment of a) currently deployable measures (e.g.,

clinker substitution, efficiency measures, alternative fuels) at all 93 existing cement plants (excludes five that are grinding-only) and new-build plants required to keep pace with demand by 2030 and 2050; (b) either a CCS retrofit or greenfield plant (roughly equivalent capex requirement) at all 93 existing plant sites plus new-build plants by 2030 and 2050.

Considerations and limitations of the approach:

- The total investment required assumes that the selection of decarbonization levers for the integrated MACC analysis is adopted and implemented.
  - The capex calculations are not done facility-by-facility and may not accurately reflect the total investment required to decarbonize a sector.
- The analysis is based on publicly available data, which is limited for most decarbonization technologies in this analysis.
  - This analysis does not consider geographic variation in energy or material inputs across the U.S.
- The analysis includes a non-exhaustive list of decarbonization technologies; as nascent technologies continue to develop economics; capex requirements might change.
- This model does not account for larger macroeconomic effects, including inflation.

Key inputs and assumptions:

Sector	Category	Variable	Units	Value	Source
Iron and steel	BF-BOF	2021 number of facilities	Number	8	DOE expert input World Steel Association Mission Possible Partnership
Iron and steel	NG-DRI/HBI	2021 number of facilities	Number	3	DOE expert input World Steel Association Mission Possible Partnership
Iron and steel	H2 HBI plant	2021 number of facilities	Number	0	DOE expert input World Steel Association Mission Possible Partnership
Iron and steel	BF-BOF	2021 number of furnaces	Number	12	DOE expert input World Steel Association Mission Possible Partnership
Iron and steel	EAF	2021 number of furnaces	Number	90	DOE expert input World Steel Association Mission Possible Partnership
Iron and steel	BF-BOF	2021 production capacity	MT	26	DOE expert input World Steel Association Mission Possible Partnership
Iron and steel	EAF	2021 production capacity	MT	60	DOE expert input World Steel Association Mission Possible Partnership
Iron and steel	NG-DRO/HBI	2021 production capacity	MT	5	DOE expert input World Steel Association Mission Possible Partnership

Iron and steel	H2 HBI plant	2021 production capacity	MT		DOE expert input World Steel Association Mission Possible Partnership
Iron and steel	U.S. capex assumption	Mill/plant capacity (t)		1.2M	DOE expert input World Steel Association Mission Possible Partnership
Iron and steel	U.S. capex assumption	Utilization		0.85	DOE expert input World Steel Association Mission Possible Partnership
Iron and steel	U.S. capex assumption	Electrolyzer	USD/Kg	0.40	Hydrogen liftoff report
Iron and steel	U.S. capex assumption	H2 DRI/HBI (t of H2)	Tons of H2	96k	DOE expert input World Steel Association Mission Possible Partnership
Iron and steel	BF-BOF	Capex	USD	$1,627,683,368	DOE expert input World Steel Association Mission Possible Partnership
Iron and steel	EAF	Capex	USD	$300M	DOE expert input World Steel Association Mission Possible Partnership
Iron and steel	H2 DRI/HBI+EAF	Capex	USD	$1,156,067,226	DOE expert input World Steel Association Mission Possible Partnership
Iron and steel	BF-BOF+CCS	Capex	USD	$2,188,881,549	DOE expert input World Steel Association Mission Possible Partnership
Iron and steel	CSP (Castor and Water Treatment)	Capex	USD	$150M	DOE expert input World Steel Association Mission Possible Partnership
Iron and steel	Hot mill	Capex	USD	$350M	DOE expert input World Steel Association Mission Possible Partnership
Iron and steel	Cold mill	Capex	USD	$230M	DOE expert input World Steel Association Mission Possible Partnership
Iron and steel	Galvanized system	Capex	USD	$400M	DOE expert input World Steel Association Mission Possible Partnership
Iron and steel	BF-BOF shutdown	Capex	USD	$3.5B	Placeholder assumption, which will require further validation from future studies
Iron and steel	CCS on NG-DRI/HBI	Capex	USD	$259,865,168	Mission Possible Partnership
Iron and steel	Retrofit NG-DRI/HBI to H2	Capex	USD	$100M	Expert interview, Mission Possible Partnership

Food and beverage	U.S. FandB boiler capacity	Food and beverage asset base	MMBtu/hr	250k	NREL—Electrification potential of U.S. Industrial Boilers and assessment of GHG impact https://www.nrel.gov/docs/fy22osti/81721.pdf
Food and beverage	U.S. FandB boiler electrification potential	Food and beverage asset base	MWh	110k	NREL—Electrification potential of U.S. Industrial Boilers and assessment of GHG impact https://www.nrel.gov/docs/fy22osti/81721.pdf
Food and beverage	# of industrial boilers in FandB	Food and beverage asset base	Number of boilers	7,500	NREL—Electrification potential of U.S. Industrial Boilers and assessment of GHG impact https://www.nrel.gov/docs/fy22osti/81721.pdf
Food and beverage	Capex assumptions	2030 E-boiler + RES LCOHt	$/MWh	34	Integrated MACC, McKinsey Global Energy Perspective, Danish Energy Agency
Food and beverage	Capex assumptions	2030 electric steam boiler capex	$/MW	77k	Integrated MACC, McKinsey Global Energy Perspective, Danish Energy Agency
Food and beverage	Capex assumptions	2030 electric steam boiler efficiency	%	99	Integrated MACC, McKinsey Global Energy Perspective, Danish Energy Agency
Food and beverage	FandB Capex Assumptions	2030 Electric steam boiler fixed opex	$/MW/year	1,122	Integrated MACC, McKinsey Global Energy Perspective, Danish Energy Agency
Food and beverage	Capex Assumptions	2030 Electric steam boiler variable opex	$/MWh	0.55	Integrated MACC, McKinsey Global Energy Perspective, Danish Energy Agency
Food and beverage	Capex Assumptions	MMBTU/hr conversion	MW	0.29	Integrated MACC, McKinsey Global Energy Perspective, Danish Energy Agency
Pulp and paper	Asset base	Wood and paper capacity	MMBtu/hr	480k	NREL – Electrification potential of U.S. Industrial Boilers and assessment of GHG impact https://www.nrel.gov/docs/fy22osti/81721.pdf
Pulp and paper	Asset base	Wood and paper boiler	Number of boilers	6k	NREL – Electrification potential of U.S. Industrial Boilers and assessment of GHG impact NREL – Electrification potential of U.S. Industrial Boilers and assessment of GHG impact https://www.nrel.gov/docs/fy22osti/81721.pdf
Pulp and paper	Capex assumptions	2030 e-boiler + RES LCOHt	$/MWh	34	Integrated MACC, McKinsey Global Energy Perspective, Danish Energy Agency
Pulp and paper	Capex assumptions	2030 electric steam boiler capex	$/MW	77k	Integrated MACC, McKinsey Global Energy Perspective, Danish Energy Agency
Pulp and paper	Capex assumptions	2030 electric steam boiler efficiency	%	99	Integrated MACC, McKinsey Global Energy Perspective, Danish Energy Agency
Pulp and paper	Capex assumptions	2030 electric steam boiler fixed opex	$/MW/year	1,122	Integrated MACC, McKinsey Global Energy Perspective, Danish Energy Agency

Pulp and paper	Pulp and paper Capex Assumptions	2030 electric steam boiler variable opex	$/MWh	0.55	Integrated MACC, McKinsey Global Energy Perspective, Danish Energy Agency
Glass	Total capex	Emission intensity	USD/ (t glass/y)	223–742	Expert input Zier, M., Stenzel, P., Kotzur, L., and Stolten, D. (2021). A review of decarbonization options for the glass industry. Energy Conversion and Management: X, 10, 100083. https://doi.org/10.1016/j.ecmx.2021.100083
Glass	Total volume of glass	Volume (tons produced)	t glass/y	17M	Global Market Insights

For aluminum, capex numbers were estimated based on Mission Possible Partnership Net-Zero Aluminum Open-Access model.

Appendix B: Detailed Marginal Abatement Cost Curve Results

This table provides additional details on the high-level MACC analysis based on the 2021 U.S. emissions baseline across the eight sectors of focus in the IRA: chemicals, refining, iron and steel, food and beverage processing, cement, pulp and paper, aluminum, and glass, highlighting the current least-cost pathway for decarbonization. This table does not include all assumptions used in the analysis but describes the key assumptions. Sources for all MACC analyses are found in the sources table.

Analysis output

Sector	Emission source	Category of decarbon-ization lever	Estimated least-cost decarbon-ization initiative	Estimated abatement potential for the decar-bonization initiative, MT CO2	Estimated abatement cost range for decar-bonization initiative, $/t CO2	Additional details (if applicable)
CHEMICALS						
Chemicals, ethylene	Low- tem-perature heat	Energy efficiency	Efficiency, fuel consumption	4	-120 to -80	Efficiency initiatives vary by process and sector, impacting the abatement cost. Assumes average ~10% reduction in fuel usage (not maximum potential) based on DOE industry stakeholder interviews
Chemicals, ammonia	High-tem-perature heat / Process	Electrolytic hydrogen	Electrolytic hydrogen production	15	-56 to 53	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 electrolyz-er 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.
Chemicals, chlor-alkali	Mid- tem-perature heat	Energy efficiency	Efficiency, fuel consumption	3	-100 to -30	Efficiency initiatives vary by process and sector, impacting the abate-ment cost. Assumes an average ~10% reduction in fuel usage (not maximum potential) based on DOE industry stakeholder interviews
Chemicals, ammonia	Low- tem-perature heat	Energy efficiency	Efficiency, fuel consumption	4	-100 to -30	Efficiency initiatives vary by process and sector, impacting the abatement cost. Assumes average ~10% reduction in fuel usage (not maximum potential) based on DOE industry stakeholder interviews
Chemicals, NGP	On-site power	Industrial electrification	Compressor electrification with low car-bon electricity and LDES	21	-50 to -30	Electrification of compressors results in significant efficiency im-provements 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 the transmission and delivery of electricity. IRA-inclusive scenarios include an investment tax credit of 35%, 30% from a base construction that meets the prevailing apprenticeship wage requirements and an additional 5% due to an assumption that half of projects will claim the 10% domestic content adder. No adders were included for low-income communities and energy communities. Net capex cost assumed is $621/kW and opex is $39/kW.

Chemicals, NGP	Process	CCS	Install CCS on associated CO2	17	-23 to 10	Displayed CCS cost estimates are 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 figures are 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)
Chemicals, NGP	Other	Energy efficiency	Instrument air systems	10	-10 to 10	Efficiency initiatives vary by process and sector, impacting abatement cost. Assumes total capex costs across the industry as $56M and ($9)/ton CO2 in opex cost (savings)
Chemicals, NGP	Other	Energy efficiency	Compressor rod packing replacement	1	-10 to 10	Efficiency initiatives vary by process and sector, impacting the abatement cost. Assumes $0 in capex costs and ($2)/ton CO2 in opex cost (savings)
Chemicals, NGP	Other	Energy efficiency	Annual LDAR	7	-10 to 10	Efficiency initiatives vary by process and sector, impacting the abatement cost. Assumes $0 in capex costs and ($1)/ton CO2 in opex cost (savings)
Chemicals, Other	On-site power	Clean onsite electricity and storage	Switch power generation to low-carbon electricity with LDES	5	40 to 60	Energy required differs by process and sector, impacting costs. Clean energy cost assumes Class 5 onshore wind production from NREL Annual Technology Baseline for 2030 and excludes the costs associated with the transmission and delivery of electricity. IRA-inclusive scenarios include an investment tax credit (48E) of 35%, 30% from a base construction that meets the prevailing apprenticeship wage requirements and an additional 5% due to an assumption that half of projects will claim the 10% domestic content adder. No adders were included for low-income communities and energy communities. The net capex cost assumed is $621/kW and opex is $39/kW
Chemicals, ammonia	On-site power	Clean onsite electricity and storage	Switch power generation to low-carbon electricity with LDES	2	30 to 70	Energy required differs by process and sector, impacting costs. Clean energy assumes Class 5 onshore wind production from NREL Annual Technology Baseline for 2030 and excludes the costs associated with the transmission and delivery of electricity. IRA-inclusive scenarios include an investment tax credit (48E) of 35%, 30% from a base construction that meets the prevailing apprenticeship wage requirements and an additional 5% due to an assumption that half of projects will claim the 10% domestic content adder. No adders were included for low-income communities and energy communities. The net capex cost assumed is $621/kW and opex is $39/kW
Chemicals, chlor-alkali	On-site power / mid-temperature heat	Clean onsite electricity and storage	Switch power generation to low-carbon electricity with LDES and electric boiler with storage	15	40 to 60	Energy required differs by process and sector, impacting costs. Clean energy assumes Class 5 onshore wind production from NREL Annual Technology Baseline for 2030 and excludes the costs associated with the transmission and delivery of electricity. IRA-inclusive scenarios include an investment tax credit of 35% (48E), 30% from a base construction that meets the prevailing apprenticeship wage requirements and an additional 5% due to an assumption that half of projects will claim the 10% domestic content adder. No adders were included for low-income communities and energy communities. The net capex cost assumed is $621/kW and opex is $39/kW; 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

Chemicals, other	On-site power / mid-temperature heat	Clean onsite electricity and storage	Switch power generation to low-carbon electricity with LDES and electric boiler with storage	55	40 to 60	Energy required differs by process and sector, impacting costs. Clean energy assumes Class 5 onshore wind production from NREL Annual Technology Baseline for 2030 and excludes the costs associated with the transmission and delivery of electricity. IRA-inclusive scenarios include an investment tax credit (48E) of 35%, 30% from a base construction that meets the prevailing apprenticeship wage requirements and an additional 5% due to an assumption that half of projects will claim the 10% domestic content adder. No adders were included for low-income communities and energy communities. The net capex cost assumed is $621/kW and opex is $39/kW; 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
Chemicals, ethylene	Low- / mid-temperature heat	Clean onsite electricity and storage	Switch steam generation to low-carbon electricity with an electric boiler and thermal storage	9	40 to 70	Energy required differs by process and sector, impacting costs. Clean energy cost assumes Class 5 onshore wind production from NREL Annual Technology Baseline for 2030 and excludes the costs associated with the transmission and delivery of electricity. IRA-inclusive scenarios include an investment tax credit (48E) of 35%, 30% from a base construction that meets the prevailing apprenticeship wage requirements and an additional 5% due to an assumption that half of projects will claim the 10% domestic content adder. No adders were included for low-income communities and energy communities. The net capex cost assumed is $621/kW and opex is $39/kW; 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
Chemicals, ammonia	High-temperature heat	CCS (including hydrogen production)	SMR unit with post-combustion CCS	20	108 to 140	In general, the cost of CO2 capture is inversely proportional to the CO2 purity of the emission stream, which differs by process and industry. Displayed CCS cost estimates are 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 figures are 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).
Chemicals, ethylene	High-temperature heat	CCS	Cracking furnace with post-combustion CCS	32	145 to 177	In general, the cost of CO2 capture is inversely proportional to the CO2 purity of the emission stream, which differs by process and industry. Displayed CCS cost estimates are 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 figures are 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).

Chemicals, other	High-temperature heat	CCS	Cracking furnace with post-combustion CCS	22	145 to 177	In general, the cost of CO2 capture is inversely proportional to the CO2 purity of the emission stream, which differs by process and industry. Assumes CCS implementation on other-chemicals high-temperature heat sources with costs based on ethylene steam-cracker capture costs; Displayed CCS cost estimates are 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 figures are 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).
Chemicals, ethylene	External	External	External demand reduction (mechanical recycling)	4	External	Based on the EPA target of 50% recycling and assuming mechanical recycling for half of plastics recycled for a 25% total plastic recycling rate
Chemicals	Off-site power	Grid decarbonization	Grid decarbonization	34	External	Based on the Biden Administration's goal of reaching a 100% clean electrical grid by 2035
Chemicals	Unabated	Unabated emissions	Unabated emissions	11	Unabated	
			REFINING			
Refining	High temp heat / Process	Electrolytic hydrogen	Electrolytic hydrogen production	15	-62 to 47	The range of 2030 electrolytic hydrogen costs for Refining is estimated at $0.22-1.22/kg H2. TAll 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.
Refining	Low temp heat	Energy efficiency	Efficiency - Fuel consumption	19	-100 to -10	Efficiency initiatives vary by process and sector, impacting the abatement cost. Assumes an average ~10% reduction in fuel usage (not maximum potential) based on DOE industry stakeholder interviews
Refining	Low temp heat	Energy efficiency	Repurpose flaring gas	2	11 to 22	Efficiency initiatives vary by process and sector, impacting the abatement cost. Assumes capex costs across the industry as $478M and ($11)/t CO2 of opex costs (savings)
Refining	High temp heat / Process	CCS (incl. hydrogen production)	SMR with CCS	21	86 to 118	In general, the cost of CO2 capture is inversely proportional to the CO2 purity of the emission stream, which differs by process and industry. Displayed CCS cost estimates are 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 figures are in 2022 dollars. All CCS figures represent retrofits, not new-build facilities.
Refining	High temp heat	CCS	Install CCS on process heating	50	95 to 127	In general, the cost of CO2 capture is inversely proportional to the CO2 purity of the emission stream, which differs by process and industry. Cost estimate uses FCC CCS cost as a proxy; 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.

Refining	High temp heat	CCS	Install CCS on FCC	26	95 to 127	In general, the cost of CO2 capture is inversely proportional to the CO2 purity of the emission stream, which differs by process and industry. Displayed CCS cost estimates are 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 figures are in 2022 dollars. All CCS figures represent retrofits, not new-build facilities.
Refining	On-site power	Clean onsite electricity and storage	Switch to power generation to low carbon electricity with LDES and electric boiler with storage	35	110 to 130	Energy required differs by process and sector, impacting costs. Clean energy cost assumes Class 5 onshore wind production from the NREL Annual Technology Baseline for 2030 and excludes the costs associated with the transmission and delivery of electricity. IRA-inclusive scenarios include an investment tax credit (48E) of 35%, 30% from a base construction that meets the prevailing apprenticeship wage requirements and an additional 5% due to an assumption that half of projects will claim the 10% domestic content adder. No adders were included for low-income communities and energy communities. Net capex cost assumed is $621/kW and opex is $39/kW
Refining	External	External	External demand reduction (transport electrification)	55	External	Based on the White House Long-term Strategy (~75% transport sector electrification by 2050)
Refining	Off-site power	Grid decarbonization	Grid decarbonization	15	External	Based on the Biden Administration's goal of reaching a 100% clean electrical grid by 2035
Refining	Unabated	Unabated emissions	Unabated emissions	5	Unabated	
			STEEL			
Steel (EAF)	High temp heat	Electrolytic hydrogen	NG-DRI/HBI to H2-DRI/HBI	2	500-750	Assumes $2–3/kg cost of purchased electrolytic hydrogen for DRI process feeding into existing EAFs; Range reflects $0.40–1.40/kg in transport and storage costs due to variations in location in relation to the supply of hydrogen; IRA-inclusive scenarios include 45V
Steel (EAF)	Off-site power	Grid decarbonization	Grid decarbonization	21	External	Based on the Biden Administration's goal of reaching a 100% clean electrical grid by 2035
Steel (EAF)	High temp heat	CCS	CCS on NG-DRI/HBI	7	140 to 290	In general, the cost of CO2 capture is inversely proportional to the CO2 purity of the emission stream, which differs by process and industry. Calculation based on Mission Possible Partnership–Net-zero Steel and Global CCS Institute, adjusted to be consistent with the CM Liftoff Report with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10–40/tonne
Steel (EAF)	Unabated	Unabated emissions	Unabated emissions	4	Unabated	
Steel (BF-BOF)	High temp heat	Industrial electrification	Transition to EAF	13	50 to 110	The continued transition of the remaining BF-BOF to EAF will depend on the lifetimes of existing BF-BOFs (e.g., last relining date) and economics for integrated players sourcing the raw materials needed for EAF.
Steel (BF-BOF)	High temp heat	Raw material substitution	10% charge mix Pig iron to NG-DRI/HBI	2	55 to 75	Increased use of DRI/HBI in BF can reduce emissions, but this lever is limited as it can only make up ~10% of the charge mix and is impacted by DRI/HBI availability
Steel (BF-BOF)	High temp heat	CCS	CCS on NG-DRI/HBI	3	140 to 290	In general, the cost of CO2 capture is inversely proportional to the CO2 purity of the emission stream, which differs by process and industry. Calculation based on Mission Possible Partnership–Net-zero Steel and Global CCS Institute, adjusted to be consistent with the CM Liftoff Report with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10–40/tonne

Steel (BF-BOF)	High temp heat	CCS	CCS on remaining BF and BOF	23	40 to 110	In general, the cost of CO2 capture is inversely proportional to the CO2 purity of the emission stream, which differs by process and industry. Displayed CCS cost estimates are 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 figures are in 2022 dollars. All CCS figures represent retrofits, not new-build facilities
Steel (BF-BOF)	Off-site power	Grid decarbonization	Grid decarbonization	6	External	Based on the Biden Administration's goal of reaching a 100% clean electrical grid by 2035
Steel (BF-BOF)	High temp heat	Electrolytic hydrogen	NG-DRI/HBI to H2-DRI/HBI	1	500 to 750	Range reflects $0.40–1.40/kg in transport and storage costs due to variations in location in relation to the supply of hydrogen; IRA-inclusive scenarios include 45V
Steel (BF-BOF)	High temp heat	CCS	CCS on NG-DRI/HBI	3	140 to 290	In general, the cost of CO2 capture is inversely proportional to the CO2 purity of the emission stream, which differs by process and industry. Calculation based on Mission Possible Partnership–Net-zero Steel and Global CCS Institute, adjusted to be consistent with the CM Liftoff Report with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10–40/tonne
Steel (BF-BOF)	Unabated	Unabated emissions	Unabated emissions	4	Unabated	
			FOOD AND BEVERAGE			
Food and beverage	Low temp heat	Energy efficiency	Energy efficiency measures for steam generation (e.g., reduced steam leakage)	4	Less than 0	Efficiency initiatives vary by process and sector, impacting the abatement cost. Assumes an average ~5–10% reduction in fuel usage (not maximum potential) based on industry stakeholder interviews
Food and beverage	Low temp heat	Industrial electrification	Boiler electrification (e.g., eboiler + TES w RES)	25	40 to 70	Energy required differs by process and sector, impacting costs. Cost estimate based on ethylene electric boiler decarbonization initiative; Clean energy cost assumes Class 5 onshore wind production from the NREL Annual Technology Baseline for 2030 and excludes the costs associated with the transmission and delivery of electricity. IRA-inclusive scenarios include an investment tax credit (48E) of 35%, 30% from a base construction that meets the prevailing apprenticeship wage requirements and an additional 5% due to an assumption that half of projects will claim the 10% domestic content adder. No adders were included for low-income communities and energy communities. Net capex cost assumed is $621/kW and opex is $39/kW; 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
Food and beverage	Low temp heat	Industrial electrification	Electrification of various process heating equipment	10	60 to 105	Certain food and beverage end products require a flame to cook, requiring more specialized heating equipment (<6% of total); the exact equipment needed varies by use case, and the cost is based on a multiplier on top of the electric boiler cost estimates
Food and beverage	Low temp heat	Alternate fuel - Non hydrogen	Alternative fuels for various process heating equipment	1	88 to 108	Many food and beverage processing facilities already use readily available waste products (e.g., grain dust) in boilers when possible, so increasing the share of alternative fuels would require purchasing alternative fuels (e.g., renewable natural gas)

Food and beverage	Off-site power	Energy efficiency	Energy efficiency measures for machine drive, refrigeration, and facility electricity consumption	2	Less than 0	Efficiency initiatives vary by process and sector, impacting the abatement cost. Assumes an average ~5–10% reduction in fuel usage (not maximum potential) based on DOE industry stakeholder interviews
Food and beverage	Off-site power	Grid decarbonization	Grid decarbonization	44	External	Based on the Biden Administration's goal of reaching a 100% clean electrical grid by 2035
PULP AND PAPER						
Pulp and paper	Low temp heat	Energy efficiency	Board: Real-time energy management system	1	-100 to -50	Assumes installation of real-time energy management system that could reduce energy consumption by <5%
Pulp and paper	Low temp heat	Energy efficiency	Air dryers	1	-100 to -50	These systems leverage both hot air and infrared emitters for paper drying. When combined, these two technologies lead to higher efficiency. These systems are mostly relevant for coated paper grades
Pulp and paper	Low temp heat	Energy efficiency	Energy efficiency for frequency inverters	<1	-100 to -50	Assumed opportunity for energy savings with variable speed drives. Additional cost of the drive installation is typically justified by energy savings in practice
Pulp and paper	Low temp heat	Energy efficiency	High-efficiency refiner	<1	-100 to -50	Assumes installation of state-of-the-art refiners in pulp will reduce energy consumption by <5% and have not been installed in all pulp mills
Pulp and paper	Low temp heat	Energy efficiency	Stock Prep. Upgrade for OCC line	<1	-100 to -50	References high-efficiency OCC stock preparation systems, such as Voith's BlueLine OCC process that integrates new-tech refiners, deflakers, and cleaners to achieve optimal properties in the secondary raw material (e.g., post-use recovered corrugated cardboard)
Pulp and paper	Low temp heat	Energy efficiency	Turbo blower pump	<1	-100 to -50	These are energy-efficient vacuum systems for paper, board and tissue manufacturing. In pulp and paper, achieving vacuum is a complex, energy-intensive process; however, this new technology has significant heat recovery potential/energy optimization that is achievable based on variable-speed and variable-capacity features
Pulp and paper	Low temp heat	Energy efficiency	Energy efficiency measures	1	-100 to -50	Efficiency initiatives vary by process and sector, impacting the abatement cost. Assumes an average ~5–10% reduction in fuel usage (not maximum potential) based on DOE industry stakeholder interviews
Pulp and paper	Low temp heat	Energy efficiency	Shoe press	1	-100 to -50	Calculation assumes that shoe-press technology is not already installed for all grades of paper (especially tissue and writing/print paper). Assumes that 50% of old machines and 75% of new linerboard machines already have installed shoe press technology
Pulp and paper	Low temp heat	Energy efficiency	New technology pulper	<1	-100 to -50	Assumes that the latest pulpers would reduce energy consumption by <2.5% and have not been installed in all pulp and paper mills
Pulp and paper	Low temp heat	Energy efficiency	Paper machine drying hood	<1	-100 to -50	Assumes that state-of-the-art paper machine drying hoods would reduce energy consumption by <2.5% and have not been installed in all pulp and paper mills
Pulp and paper	Low temp heat	Energy efficiency	Radial blowers	<1	-100 to -50	Assumes that more efficient radial blowers would reduce energy consumption by <2.5% and have not been installed in all pulp and paper mills
Pulp and paper	Low temp heat	Energy efficiency	Mechanical vapor recompression	1	-100 to -50	Assumes that mechanical vapor recompression will reduce natural gas consumption by <5%
Pulp and paper	Low temp heat	Energy efficiency	Stationary siphon and drying bar	1	-100 to -50	Assumes that stationary siphon and spoiler bars are not installed in all pulp and paper facilities

Pulp and paper	Low temp heat	Industrial electrification	Heat pumps for low-temperature heat	11	1 to 21	Calculation assumes Danish Energy Agency 2030 cost estimates: capex cost for the industrial heat pump as $1,028,016/MW, efficiency as 200%, fixed opex as $957/MW/yr, and variable opex as $1.87/MWh
Pulp and paper	Off-site power	Grid decarbonization	Grid decarbonization	7	External	Based on the Biden Administration's goal of reaching a 100% clean electrical grid by 2035
Pulp and paper	High / mid temp heat	Industrial electrification	Electric burners	1	110 to 160	Assumes $0.08/kWh for clean electricity purchased in the U.S.
Pulp and paper	High / mid temp heat	Alternate fuel – Non-Hydrogen	Biomethane boilers (brownfield)	2	100 to 130	Assumes $0.05/kWh for biomethane purchased in the U.S.
Pulp and paper	High / mid temp heat	Alternate fuel – Non-Hydrogen	Biomass burner	2	7 to 27	Assumes $0.03/kWh for biomass purchased in the U.S.
Pulp and paper	High / mid temp heat	Alternate fuel – Non-Hydrogen	RDF Boiler	2	18 to 38	Assumes $0.04/kWh for RDF purchased in the U.S.
Pulp and paper	High / mid temp heat	Alternate fuel – Non-hydrogen	Biomass boiler	2	-6 to 16	Assumes $0.03/kWh for biomass purchased in the U.S.
Pulp and paper	Unabated	Unabated emissions	Unabated emissions	4	Unabated	
Pulp and paper	On-site power	Clean onsite electricity and storage	Onsite low-carbon electricity	7	30 to 70	Energy required differs by process and sector, impacting costs. Clean energy cost assumes Class 5 onshore wind production from the NREL Annual Technology Baseline for 2030 and excludes the costs associated with the transmission and delivery of electricity. IRA-inclusive scenarios include an investment tax credit (48E) of 35%, 30% from a base construction that meets the prevailing apprenticeship wage requirements and an additional 5% due to an assumption that half of projects will claim the 10% domestic content adder. No adders were included for low-income communities and energy communities. Net capex cost assumed is $621/kW and opex is $39/kW.
CEMENT						
Cement	Crosscut across the value chain	Raw material substitution	Traditional clinker (e.g., fly ash) and non-traditional clinker (e.g., LC3) substitution	16	-70 to -50	Analysis assumes clinker substitution from present 89% clinker, 4% limestone, 5% gypsum, 0.5% fly ash, 0.3% natural pozzolans, 0.5% GGBFS, and 0.7% other (GNR 2020 report) to 65% clinker, 15% limestone, ~9% calcined clay, 5% gypsum, 3% fly ash, ~2% natural pozzolans, 0.5% GGBFS, and 0.7% other. PCA 2021 US roadmap (p. 35) documents a planned decrease to 0.75 clinker-to-cement ratio by 2050 with a 0.85 target for 2030. Have assumed a 0.65 target for 2030 could be met by using calcined clay and shifts of fly ash from concrete to cement production step. Assumed high replacement of clinker with calcined clay given the abundance of material and favorable economics. 15% limestone based on the high-end of the ASTM C595 range. Assumed a small increase in the share of pozzolans used given low emissions intensity, though generally not used in the U.S. (Concrete Innovations–NRMCA). The ASTM C595 range is used for fly ash. Key capex modeled is the cost of installing a new kiln in the plant, a separate cement silo, and storage for raw materials to support the calcination of clay
Cement	Crosscut across the value chain	Energy efficiency	Energy efficiency measures for cement production	1	-40 to -20	Assumed a 5% energy efficiency improvement via modernizations, upgrades, machine learning, and artificial intelligence. PCA 2021 US roadmap (p. 30) documents a potential efficiency gain of 5–7% by 2030. Estimated average capex costs through select energy-efficiency measures (e.g., efficient transport systems, energy management, process control) listed at Mokhtar, Nasooti (2020), Energy Strategy Reviews

Cement	High / mid temp heat	Alternate fuel - Non hydrogen	Alternative fuels - biomass	3	25 to 45	Analysis assumes the share of fuel mix for biomass-based alternative fuels increases from 3% (GNR 2020) to 15% in 2030. PCA 2021 US roadmap (p. 29) documents an aspiration to use biomass-based alternative fuels for ~5% of the fuel mix in 2030. Assumed a 10% higher scenario for modeling. Assumed wood chips as the main component of biomass-based alternative fuels for cost modeling. Calculated net emissions and assumed zero emissions for using biomass-based fuels. The key capex expenditure modeled includes the cost of adding a kiln bypass; assumes the presence of a multi-fuel burner in reference U.S. cement plant. Analysis accounts for a 5% energy efficiency improvement from the energy efficiency lever.
Cement	High / mid temp heat	Alternate fuel - Non hydrogen	Alternative fuels - waste	5	-15 to 5	Analysis assumes the share of fuel mix for waste-based alternative fuels increases from 12% (GNR 2020) to 35% in 2030. PCA 2021 US roadmap (p. 29) documents an aspiration to use waste-based alternative fuels for ~25% of the fuel mix in 2030. Assumed a 10% higher share in the scenario given the cost-effectiveness of waste-based alternative fuels. Assumed tires, waste plastics, and other waste streams as components of waste-based alternative fuels for cost modeling. Calculated net emissions and assumed zero emissions for using waste-based fuels. The key capex expenditure modeled includes adding kiln bypass and co-processing costs; assumes the presence of a multi-fuel burner in reference U.S. cement plant. Analysis accounts for a 5% energy-efficiency improvement from energy-efficiency lever.
Cement	Process	CCS	Post-combustion CCS for cement production emissions	32	35 to 75	From Low-Carbon Cement Liftoff report. Based on NETL 2023 modeling, with modified capital cost assumptions from Energy Futures Initiative.
Cement	Off-site power	Grid decarbonization	Grid decarbonization	3	External	Based on the Biden Administration's goal of reaching a 100% clean electrical grid by 2035
Cement	Unabated	Unabated emissions	Unabated emissions	10	Unabated	
ALUMINUM						
Aluminum	High temp heat	Energy efficiency	Energy efficiency measures	<1	-14 to 6	Efficiency initiatives vary by process and sector, impacting the abatement cost. Assumes an average ~10% reduction in fuel usage (not maximum potential) based on stakeholder interviews and the age of aluminum rolling mills, extrusion, and casting plants
Aluminum	High temp heat	Energy efficiency	Oxyfuel technology	<1	109 to 129	Assumes capex cost of ~$700/t Al and 15% efficiency gains
Aluminum	High temp heat	Industrial electrification	Electrical gas heating	~1	21 to 41	Assumes capex cost of ~$800/t Al and 2 years construction duration
Aluminum	High temp heat	Raw material substitution	Increase recycling	<1	-37 to -17	Assumes a 30% opex reduction
Aluminum	Off-site power	Grid decarbonization	Grid decarbonization	~1	External	Based on the Biden Administration's goal of reaching a 100% clean electrical grid by 2035
Aluminum	Unabated	Unabated emissions	Unabated emissions	~1	Unabated	Assumes current alternatives to NG in melting are not yet commercially available, particularly plasma torches and hydrogen burners
Aluminum	High temp heat	Energy efficiency	Smelting: Energy efficiency	<1	-13 to 7	Efficiency initiatives vary by process and sector, impacting the abatement cost. Assumes an average ~10% reduction in electricity usage (not maximum potential) based on stakeholder interviews and the age of U.S. smelters
Aluminum	Process	CCS	Smelting: CCS on aluminum process emissions	2	137 to 292	In general, the cost of CO2 capture is inversely proportional to the CO2 purity of the emission stream, which differs by process and industry. Calculation based on Mission Possible Partnership–Aluminum for Climate and Global CCS Institute, adjusted to be consistent with the CM Liftoff Report with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10–40/tonne

Aluminum	Off-site power	Grid decar-bonization	Smelting: Grid decarboniza-tion	8	External	Assuming the remaining captive coal-fired power smelter connects to the grid
Aluminum	Unabated	Unabated emissions	Smelting: Unabated emissions	<1	Unabated	Remaining emissions post-retrofit of pots with CCUS with a 90% capture rate
Aluminum	Process	Energy efficiency	Refinery: En-ergy efficiency digestion	<1	-11 to 9	Efficiency initiatives vary by process and sector, impacting the abatement cost. Assumes an average ~10% reduction in fuel usage (not maximum potential) based on stakeholder interviews and the age of the refinery (>60 years old)
Aluminum	Low temp heat	Industrial electrification	Refinery: electric boiler	~1	-6 to 14	Calculation based on Mission Possible Partnership–Aluminum for Climate refinery decarbonization model
Aluminum	Low temp heat	Energy efficiency	Refinery: En-ergy efficiency calcination	<1	-9 to 11	Efficiency initiatives vary by process and sector, impacting the abatement cost. Assumes an average ~10% reduction in fuel usage (not maximum potential) based on stakeholder interviews and the age of the refinery (>60 years old)
Aluminum	Unabated	Unabated emissions	Refinery: Unabated emissions	<1	Unabated	Assumes calcined emissions cannot be abated since current decar-bonization technologies (e.g., H2-calciner, electric calciner or MVR are in the R&D/pilot phase)
GLASS						
Glass	Process	Raw material substitution	Recycling	1	-40 to -20	Assumes every 10% of cullet will reduce energy consumption by 3%
Glass	High temp heat	Industrial electrification	Electrified melting	1	300 to 400	Energy required differs by process and sector, impacting costs. Clean energy cost assumes Class 5 onshore wind production from the NREL Annual Technology Baseline for 2030 and excludes the costs associ-ated with the transmission and delivery of electricity. IRA-inclusive scenarios include an investment tax credit (48E) of 35%, 30% from a base construction that meets the prevailing apprenticeship wage requirements and an additional 5% due to an assumption that half of projects will claim the 10% domestic content adder. No adders were included for low-income communities and energy communities. Net capex cost assumed is $621/kW and opex is $39/kW
Glass	Off-site power	Grid decar-bonization	Grid decar-bonization	4	External	Based on the Biden Administration's goal of reaching a 100% clean electrical grid by 2035
Glass	High temp heat	Energy efficiency	Oxyfuel for glass melting furnace	1	10 to 140	Assumes CAPEX cost of ~$700/t glass and lifetime of oxyfuel furnace as 15 years
Glass	High temp heat	Alternate fuel - Non hydrogen	Biomethane forming	<1	125 to 550	Assumes biomethane cost of $15/GJ
Glass	High temp heat	Alternate fuel - Non hydrogen	Biomethane melting	<1	125 to 550	Assumes biomethane cost of $15/GJ
Glass	High temp heat	Electrolytic hydrogen	Hydrogen forming	<1	190 to 550	Assumes purchased electrolytic hydrogen cost of $2–3/kg; Range reflects $0.40–1.40/kg in transport and storage costs due to varia-tions in location in relation to the supply of hydrogen; IRA-inclusive scenarios include 45V
Glass	High temp heat	Electrolytic hydrogen	Hydrogen melting	<1	190 to 550	Assumes purchased electrolytic hydrogen cost of $2–3/kg; Range reflects $0.40–1.40/kg in transport and storage costs due to varia-tions in location in relation to the supply of hydrogen; IRA-inclusive scenarios include 45V

Glass	High temp heat	CCS	CCS on glass melting furnace	2	140 to 290	In general, the cost of CO2 capture is inversely proportional to the CO2 purity of the emission stream, which differs by process and industry. Cost estimate is based on Global CCS Institute and scientific literature, adjusted to be consistent with the CM Liftoff Report with transport (GCCSI, 2019) and storage (BNEF, 2022) costs of ~$10–40/tonne.
Glass	High temp heat	Energy efficiency	Waste heat recovery	1	Less than 0	Efficiency initiatives vary by process and sector, impacting the abatement cost. Assumes waste heat recovery allows for a reduction in natural gas consumption
Glass	Unabated	Unabated emissions	Unabated emissions	<1	Unabated	

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