Title

Transformative Pathways for U.S. Industry: Unlocking American Innovation

Author
Karki, Unique

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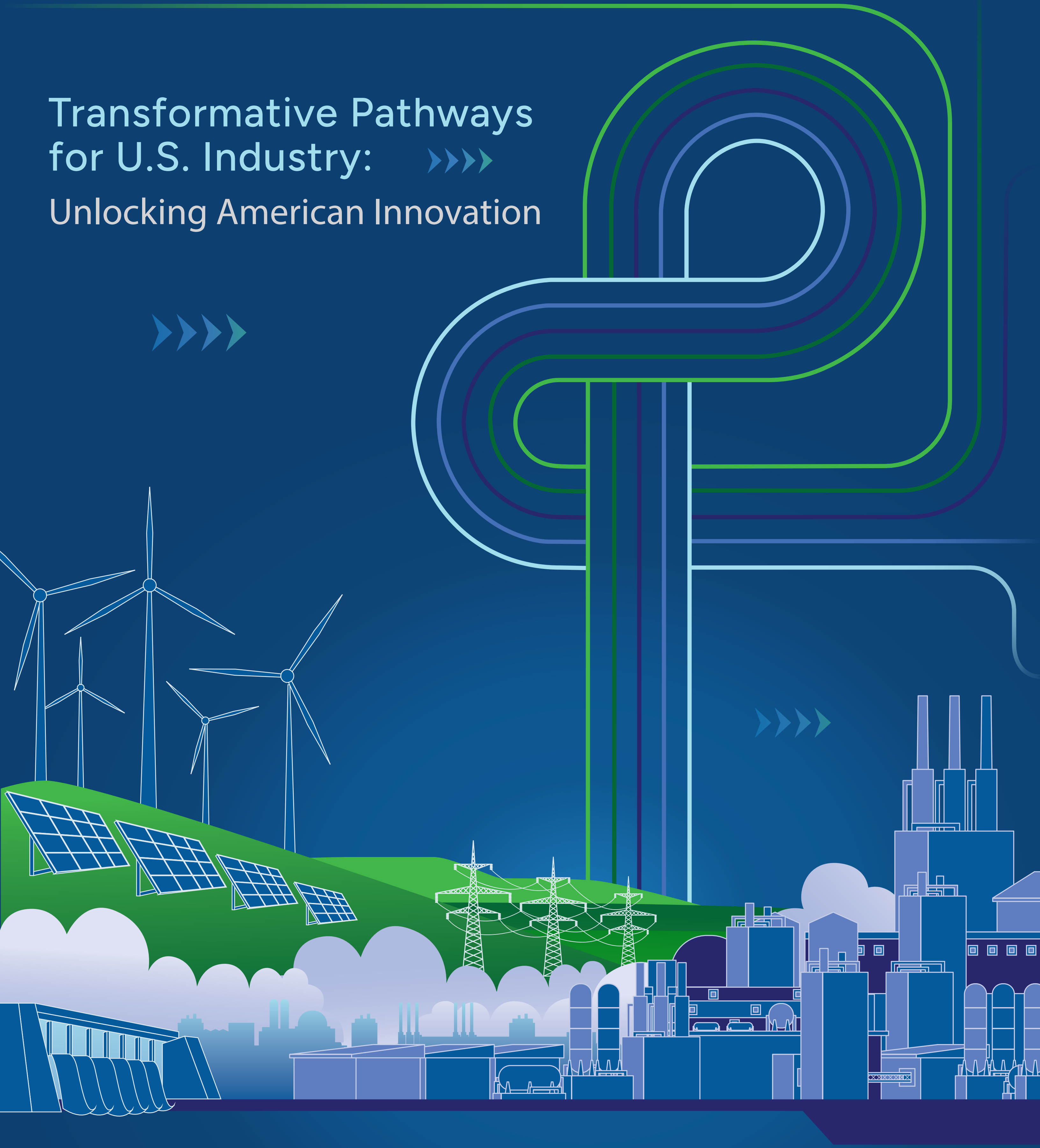

U.S. Department of ENERGY

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EXECUTIVE SUMMARY

The United States (U.S.) is undergoing an energy transformation[1] that will depend on continued U.S. innovation. Although U.S. industry has been foundational to the nation's economic growth and prosperity, it has also given rise to decades' worth of industrial pollutants in our air and water, which acutely impact the most vulnerable communities, as well as greenhouse gas (GHG) emissions contributing to climate risk. At the same time, U.S. industry is facing growing competitive pressures. Global investors and financial regulations are increasingly focusing on emissions footprints, governments are developing emissions-based trade adjustments and procurement specifications, and downstream demand for low-carbon products is emerging.

Developing cost-competitive solutions to meet these needs provides an opportunity to fundamentally transform U.S. industry and sharpen its competitive edge, while reducing the GHG emissions and adverse environmental and health impacts (see Figure ES-1). Innovation is central to this transformation. *Pathways to Commercial Liftoff: Industrial Decarbonization*, which provides a descriptive fact base on what is needed to reach commercial scale in the marketplace, estimates that over 60% of emissions reduction for the industrial sector will need to come from technologies that are still nascent today.[2] This report, *Transformative Pathways for U.S. Industry*,[3] focuses on the pathways that rely on the nascent and innovative technologies that were too early for consideration in the *Pathways to Commercial Liftoff* report. Targeted and sustained public and private investment in research, development, demonstration, and deployment is required to catalyze innovation and meet this moment.

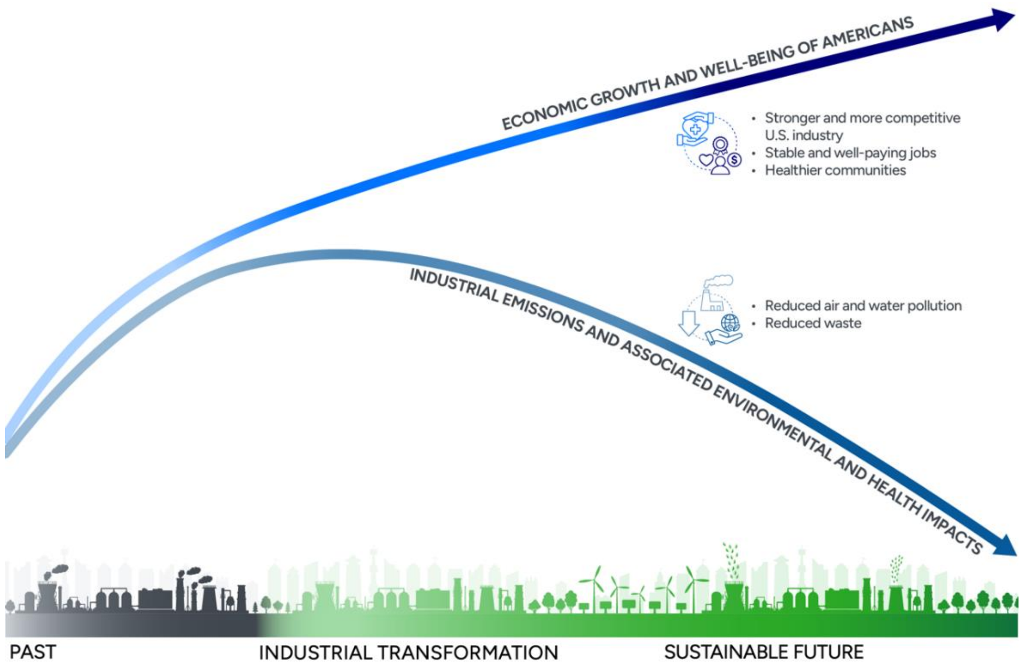


Figure ES-1. Transformation of industry from resource-intensive to a sustainable[4] future is an opportunity to continue economic growth and well-being while reducing emissions and associated environmental and health impacts

For other perspectives on energy transitions and transformations, see United Nations Environment Programme Global Resources Outlook 2024.[5]

[1] In the *Global Resources Outlook 2024,* the United Nations Environment Programme defines transformation as an "overall change or outcome of large-scale shifts in technological, economic and social systems". See: United Nations Environment Programme, *Global Resources Outlook 2024* (Nairobi, 2024), www.resourcepanel.org/reports/global-resources-outlook-2024.
[2] U.S. Department of Energy, *Pathways to Commercial Liftoff: Industrial Decarbonization* (2023), liftoff.energy.gov/industrial-decarbonization/overview/.
[3] Throughout this report, the title, *Transformative Pathways for U.S. Industry: Unlocking American Innovation*, is short-handed to *Transformative Pathways*.
[4] For perspectives on sustainability and sustainable manufacturing, see U.S. Department of Energy, *Sustainable Manufacturing and the Circular Economy*, by Kristina Armstrong et al., DOE/EE-2696 (January 2023), www.osti.gov/biblio/1963668.
[5] United Nations Environment Programme, *Global Resources Outlook 2024* (Nairobi, 2024), www.resourcepanel.org/reports/global-resources-outlook-2024.

As shown in Figure ES-2, the industrial sector accounted for approximately 38% of total U.S. economy emissions (both energy-related and non-energy-related scope 1 and scope 2).[6] Under business as usual (BAU) operations, the U.S. industrial sector's energy consumption and energy-related carbon dioxide (CO_2) emissions are projected to increase by 2050.[7] This report's findings reinforce that fundamental changes to industrial processes and materials are needed to reach the nation's goal[8] of net zero GHG emissions by 2050.

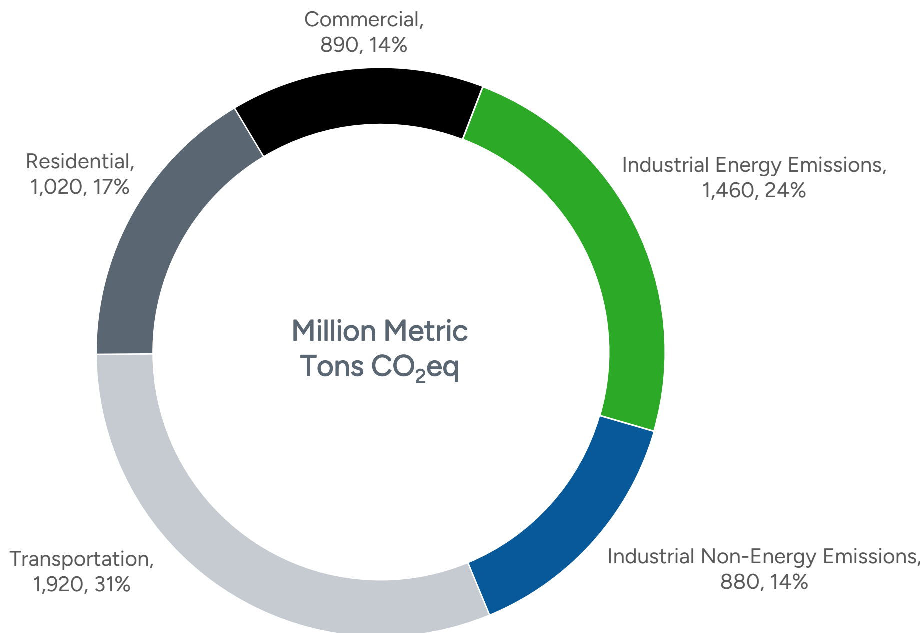


Figure ES-2. Total U.S. GHG emissions in 2018 by economic sector in million metric tons carbon-dioxide equivalent (MMT CO_2e)

2018 is the latest data year available for inclusion of detailed industrial subsectors energy-related and non-energy related emissions. Compiled from multiple sources; see Figure 4 for full details.

The Industrial Ecosystem

The transformative, systemic challenge of industrial decarbonization will require a holistic industrial ecosystem viewpoint. The industrial ecosystem includes industrial processes, production systems, interconnected industrial partners, and their surrounding communities. Building strategies within this complex ecosystem requires identifying the specific, potential pathways toward decarbonization. However, there are many challenges to industrial decarbonization as well as broader technology, market, and infrastructure barriers. These barriers include the complexity and interconnectedness of the industrial ecosystem, cost uncertainty, and lack of infrastructure.

Addressing these barriers will achieve better societal outcomes, develop cost competitive technologies, improve efficiency, and decarbonize industry, all of which will benefit the American people.

Transformative Pathways to Overcoming Challenges and Barriers

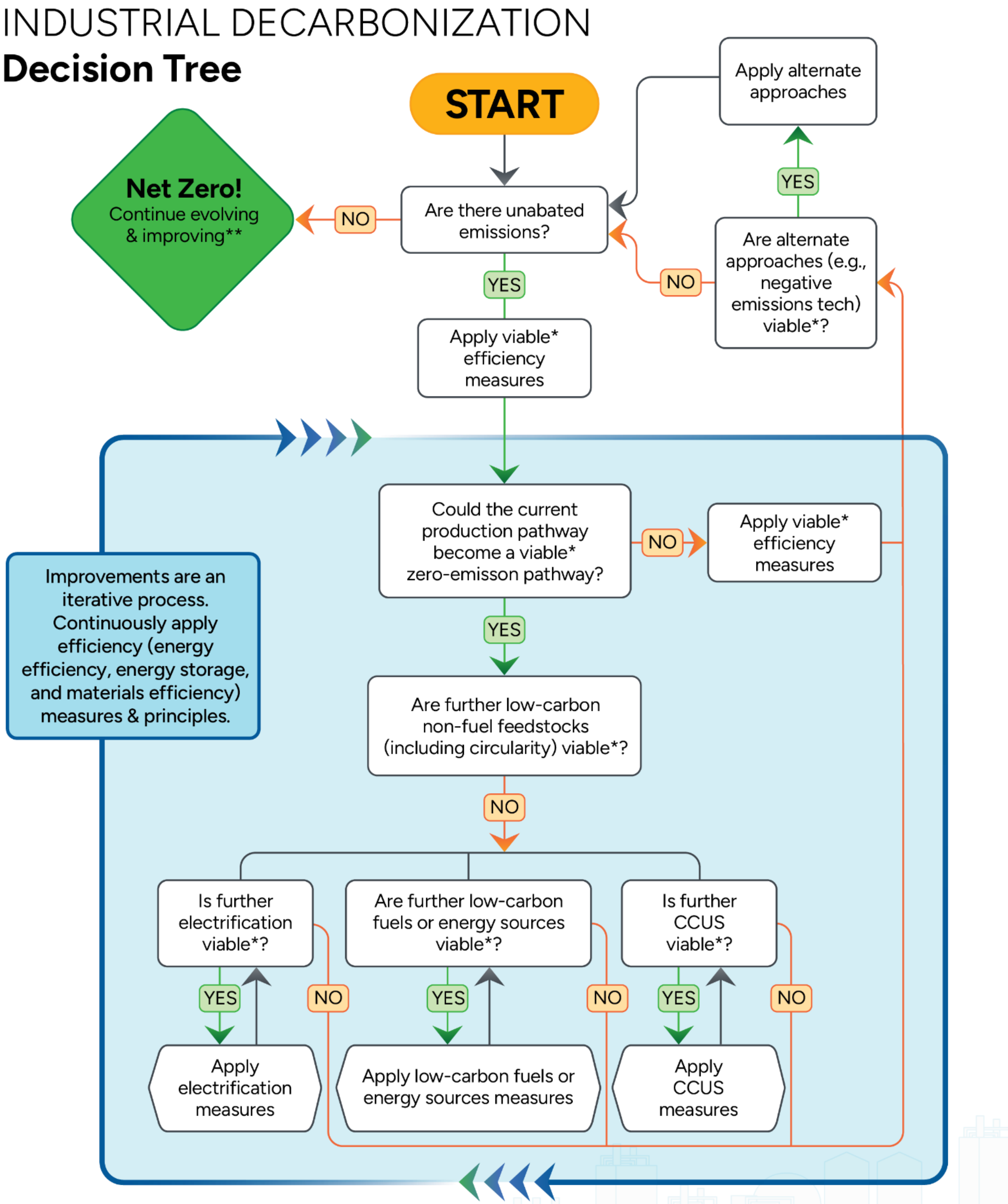
A pathway[9] is not a single decision, but rather a series of decisions over time. Decarbonization pathways require decision-making and investment under uncertainty. All pathways require investments to achieve net zero or near

[6] Data compiled from multiple sources, see Figure 4.
[7] U.S. Energy Information Administration, "Annual Energy Outlook 2023," 2023, www.eia.gov/outlooks/aeo/.
[8] U.S. Department of State and the U.S. Executive Office of the President, *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050* (Washington, DC: 2021), www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf.
[9] Within the context of this report's industrial modeling framework, a decarbonization pathway is characterized as a sequence of technology deployments and retirements over time that allow U.S. industrial subsectors to arrive at an established level of GHG emissions (such as net zero or near zero) in an established timeframe.

zero[10] GHG emissions by 2050. Due to the long lifetimes of industrial facilities and related infrastructure, timing is challenging for any pathway. Pathways for the future can be mapped with the knowledge of existing barriers, but additional challenges will likely emerge as industry transforms and the future unfolds.

Figure ES-3 presents a decision tree approach describing the decisions within the industrial decarbonization pathway opportunity space. Technology decisions for a particular industry or facility may deviate from the general version shown. Many decarbonization technologies in the opportunity space covered by this decision tree are currently commercially viable, while others are expected to be commercialized in the coming decades. Further, some decarbonization measures will likely rely on decarbonization of energy supply systems and/or development or expansion of energy and industrial infrastructure. Such interdependencies require careful consideration of technology choice phasing, whether at a facility or industry-wide scale, to avoid emission "lock-ins," potential stranded assets, or "dead-ends" in the future.

[10] Net zero refers to achieving a balance of net zero GHG emissions while near zero refers to very low emissions intensity. While some U.S. industrial subsectors could possibly achieve net zero or negative emissions, others will likely achieve only near zero GHG emissions by 2050; any remaining emissions would need to be balanced with other economic sectors to reach net zero industry-wide.



*Viable implies currently available, cost-effective, and that the measures are deemed effective through social and environmental criteria and necessary

** Morrow, William III et al. 2017. "U.S. Industrial Sector Energy Productivity Improvement Pathways." U.S. Industrial Sector Energy Productivity Improvement Pathways (aceee.org)

Figure ES-3. Example industrial decarbonization decision tree

Sequencing and specific decarbonization strategies may vary. This figure is provided to facilitate discussion, to identify the barriers and opportunities in decarbonization pathways, and to better understand decision-making under uncertainty.

Evaluating and Modeling Pathways to U.S. Industrial Decarbonization

Impacts and Evaluation Criteria

Industrial transformation will involve changes not only within the industrial sector, but across the entire U.S. economy—and it must not result in net-negative adverse outcomes. Comprehensive and robust evaluation criteria are needed to better understand the technological, economic, environmental and health, and societal risks and impacts the adoption of certain decarbonization pathways may have on the communities and environment surrounding an industrial facility as well as its technical and business operations. Together, these criteria may ultimately determine the viability of a pathway's adoption.

Transformative Pathways Modeling

The *Transformative Pathways* modeling considers technology options across four cross-cutting decarbonization pillars, first introduced in the *Industrial Decarbonization Roadmap*: energy efficiency; industrial electrification; low-carbon fuels, feedstocks, and energy sources (LCFFES); and carbon capture, utilization, and storage (CCUS).[11] Boundaries between pillars can be indistinct because crosscutting actions, approaches, and infrastructure investments can accelerate progress and improvements across multiple pillars.

Sensitivity analysis was conducted to better understand future uncertainties and their impacts on the emissions trajectory for certain decarbonization interventions. Eight potential sources of uncertainy were considered: (1) energy efficiency improvements, (2) electric grid decarbonization, (3) clean hydrogen, (4) CCUS, (5) alternative energy sources, (6) market share of low-maturity technologies, (7) changes in modeled demand, and (8) feedstock availability and quality.

Industrial Subsector Pathways to Decarbonization

Decarbonizing U.S. industry will be challenging, given its complexity (diversity of material inputs, industrial processes, and manufactured products) and the range of timing, resources, and boundary conditions around industrial decarbonization. Industrial emissions come from a range of sources, including onsite combustion of fuels, electricity generation (both onsite and offsite), non-energy-related process emissions (from chemical transformations), and from supply chains.

This report presents multiple possible transformative pathways to decarbonize six of the most energy- and emissions-intensive industrial subsectors—cement and concrete, chemicals, food and beverage, iron and steel, petroleum refining, and pulp and paper. These U.S. subsectors accounted for 38% of total industrial CO_2e emissions and 15% of total economy CO_2e emissions in 2018 (including both energy- and non-energy-related emissions).[12]

This *Transformative Pathways* report expands upon the *Industrial Decarbonization Roadmap*[13] analysis and more thoroughly assesses specific technology options for energy- and emissions-intensive industrial operations and production routes. It utilizes the best current understanding of decarbonization technologies and approaches and their technical potential, adoption readiness, subsector applicability, and emissions reduction potentials. The pathways in this study highlight the importance and impact of both commercially available and emerging technologies toward deep industrial decarbonization. Table ES-1 summarizes the representative near zero pathways and high-level takeaways for the six modeled subsectors. Each subsector is also detailed below the table, and full information can be found in the report and appendices. The near zero pathways shown throughout the report represent a selection of possibilities for each subsector. These pathways represent the highest emissions reductions potential by 2050 based on the U.S. Department of Energy's best current understanding of

[11] U.S. Department of Energy, *Industrial Decarbonization Roadmap*, DOE/EE-2635 (2022), www.energy.gov/industrial-technologies/doe-industrial-decarbonization-roadmap.
[12] See Figure 4 note for references.
[13] U.S. Department of Energy, *Industrial Decarbonization Roadmap*, DOE/EE-2635 (2022), www.energy.gov/industrial-technologies/doe-industrial-decarbonization-roadmap.

decarbonization technologies and approaches and their technical potential, adoption readiness, subsector applicability, and emissions reduction potentials.

Table ES-1. Industrial Subsector Near Zero Pathways Presented in the *Transformative Pathways* Report

SUBSECTOR	MODELED PATHWAYS TO NEAR ZERO GHG EMISSIONS AND THEIR DEFINING CHARACTERISTICS
Cement and concrete	**High Clean Clinker Production, Moderate SCM Pathway** • Phase out of conventional clinker production and complete transition toward carbon capture and storage (CCS)-enabled clinker production and nascent, alternative clinker production routes • Moderate supplementary cementitious material (SCM) adoption (clinker-to-cement ratio of 0.6) • Fuel switching from coal and petroleum coke to natural gas and biomass **Moderate Clean Clinker Production, High SCM Pathway** • Modest use of conventional clinker production and high adoption of CCS-enabled clinker production and nascent, alternative clinker production routes • High adoption of low carbon intensity SCM (clinker-to-cement ratio 0.4) • Fuel switching from coal and petroleum coke to natural gas and biomass.
Chemicals	**Best Available and Emerging Technologies Pathway** • Adoption of energy efficiency and best available technologies for existing production routes • Fuel switching to biofuels, where appropriate • Increased recycling and material efficiency to reduce demand for virgin chemicals • Adoption of alternative clean production routes, including CCS and nascent production technologies
Food and beverage	**Higher Uptake of Electrification Pathway** • High adoption of heat pumps and energy efficiency measures • Lower adoption of low-carbon fuels and advanced electrification technologies **Higher Uptake of Low-Carbon Fuels Pathway** • High adoption of low-carbon fuels and energy efficiency • Modest adoption of heat pumps to account for assumed low-carbon fuel availability limits
Iron and steel	**Integrated Mill with High CCS Pathway** • Transition to clean ironmaking, primarily CCS at blast furnace integrated mills and natural gas direct reduced iron (DRI) integrated mills • Adopt clean electric arc furnace (EAF) and clean finishing **Hydrogen Direct Reduced Iron (H_2-DRI) Pathway** • Transition to clean ironmaking, primarily clean hydrogen-DRI and electrolysis processes • Adopt clean EAF and clean finishing • Maximize use of clean H_2 as a fuel
Petroleum refining	**Demand Reduction Pathway** • Aggressive adoption of decarbonization measures: energy efficiency, clean hydrogen, CCS • Deployment of available alternative crude oil substitutes: fats, oils, greases and biomass • Demand reduction for refining products to meet near zero conditions
Pulp and paper	**Increased Use of Biomass for Fuel Pathway** • High adoption of solid biomass-based fuels and energy efficiency for core unit processes • Modest electrification of steam generation and drying processes

Cement and Concrete

Two near zero pathways for U.S. cement and concrete manufacturing were identified with the potential to reduce annual GHG emissions by approximately 85% from 68 MMT CO_2e in 2018 to 10 MMT CO_2e in 2050. Key characteristics within and across these pathways are summarized in Table ES-2.

Table ES-2. Cement and Concrete Near Zero Pathways Summary

PATHWAY	KEY CHARACTERISTICS OF THIS MODELED PATHWAY BY 2050
High Clean Clinker Production, Moderate SCM (Figure ES-4)	• Phase out of conventional clinker production and complete transition toward CCS-enabled clinker production and nascent, alternative clinker production routes • Moderate adoption of low carbon intensity SCMs (clinker-to-cement ratio of 0.6)
Moderate Clean Clinker Production, High SCM (Figure ES-5)	• Modest use of conventional clinker production and high adoption of CCS-enabled clinker production and nascent, alternative clinker production routes • High adoption of lower carbon intensity SCMs (clinker-to-cement ratio of 0.4)
Characteristics applicable to both pathways	• Fuel switching from coal and petroleum coke to natural gas and biomass • Reduced use of incumbent clinker technologies, increased use of dry kilns with CCS with 95% of CO_2 captured and stored

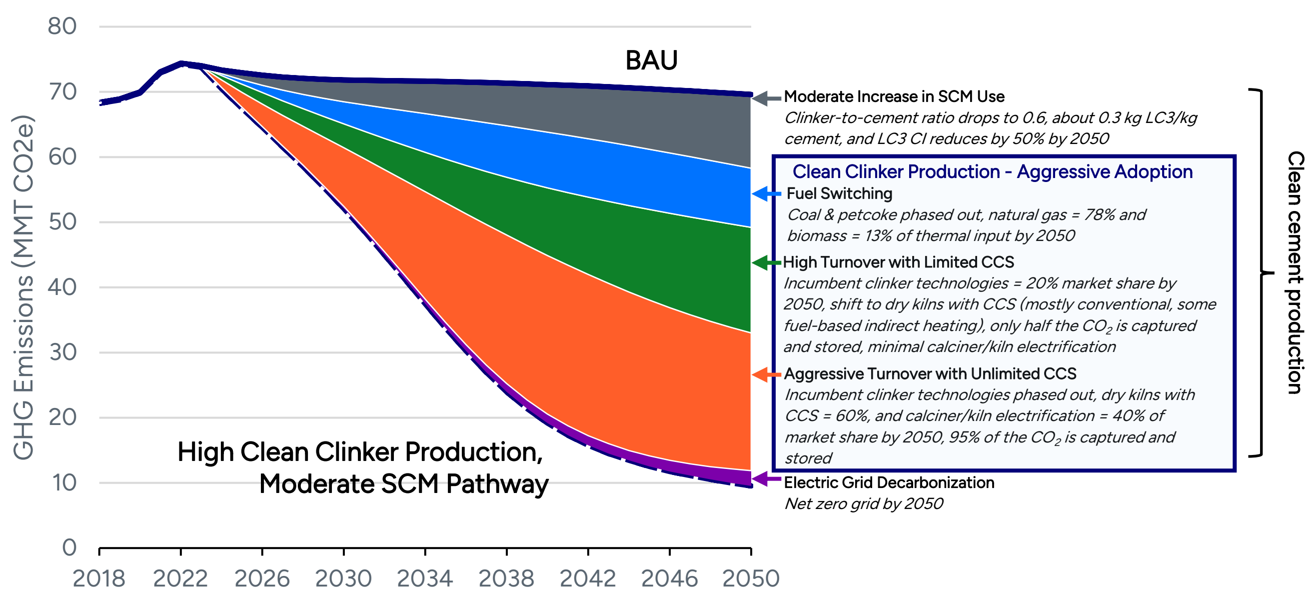


Figure ES-4. Annual GHG emissions reductions, U.S. cement and concrete manufacturing–High Clean Clinker Production, Moderate SCM pathway (MMT CO_2e/year), 2018–2050

The emissions impact of the interventions (for the year 2050) in the box on the right can be functionally equivalent to nascent clean clinker production routes that were not explicitly considered in the model. The emissions impact of the interventions (for 2050) within the bracket can be functionally equivalent to nascent clean cement production routes. In both instances, a change in the interventions would change the shape of the wedges. Details on assumptions, parameters, and timing of transformative technology application can be found in Section 4.1 and Appendix C. Source: Transformative Pathways modeling.

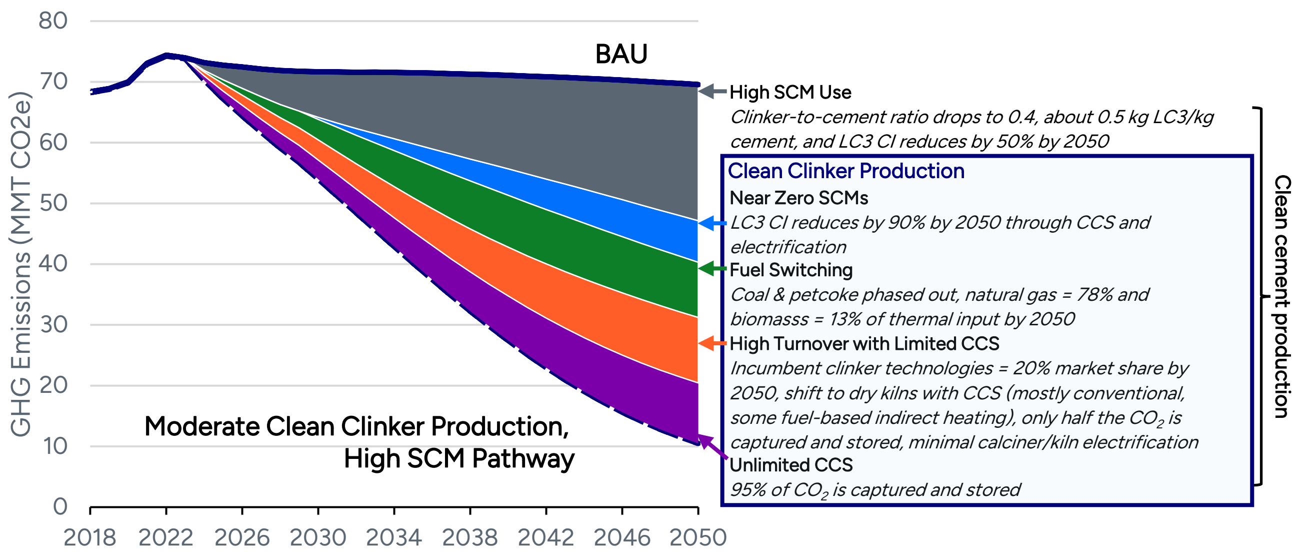


Figure ES-5. Annual GHG emissions reductions, U.S. cement and concrete manufacturing–Moderate Clean Clinker Production, High SCM pathway (MMT CO_2e/year), 2018–2050

The emissions impact of the interventions (for the year 2050) in the box on the right can be functionally equivalent to nascent clean clinker production routes that were not explicitly considered in the model. The emissions impact of the interventions (for 2050) within the bracket can be functionally equivalent to nascent clean cement production routes. In both instances, a change in the interventions would change the shape of the wedges. Details on assumptions, parameters, and timing of transformative technology application can be found in Section 4.1 and Appendix C. Source: Transformative Pathways modeling.

Key takeaways for cement and concrete include:

- The two pathways are not fully distinct, as they both utilize the same interventions but to differing degrees.
- Realizing these pathways will require clean cement production. This could be met through a combination of SCMs, clean clinker production (CCS-integrated or nascent production routes), alternative binders, and other approaches.
- SCMs can be a near-term decarbonization intervention, but the extent of their benefits will depend in part on their embodied emissions, especially as clinker production becomes cleaner.
- For novel clinker production routes to have any appreciable market share by 2050, they must be commercially viable against conventional clinker pyroprocessing with CCS before 2035.
- In addition to clean clinker production and SCMs, the analysis also identified fuel-switching from coal and petroleum coke to natural gas and biomass as a decarbonization opportunity. Although fuel-switching will likely generate smaller GHG emissions reductions, it is still necessary to achieve near zero GHG emission by 2050.

Chemicals

One near zero pathway for the production of nine modeled chemicals was identified with the potential to reduce annual GHG emissions by 84% from 92 MMT CO_2e in 2018 to 15 MMT CO_2e in 2050. The Transformative Pathways modeling included deep dives on nine key basic chemicals which account for 40% of 2018 subsector emissions–ethylene, propylene, butadiene, benzene-toluene-xylene (BTX) aromatics, chlor-alkali (co-production of chlorine and sodium hydroxide), soda ash, ethanol, methanol, and ammonia–and estimated the impact of crosscutting decarbonization measures for the remaining chemicals in the subsector. The near zero pathway shown in this figure covers eight chemicals–ethylene, propylene, butadiene, BTX, chlor-alkali, soda ash, methanol, and ammonia.

Key characteristics within and across this pathway are summarized in Table ES-3.

Table ES-3. Chemicals Near Zero Pathway Summary

PATHWAY	KEY CHARACTERISTICS OF THIS MODELED PATHWAY BY 2050
High Uptake of Best Available and Emerging Technologies (Figure ES-6)	• Adoption of energy efficiency and best available technologies for existing production routes • Fuel switching to biofuels, where appropriate • Increased recycling and material efficiency to reduce demand for virgin chemicals • Adoption of alternative clean production routes, including CCS and nascent production technologies

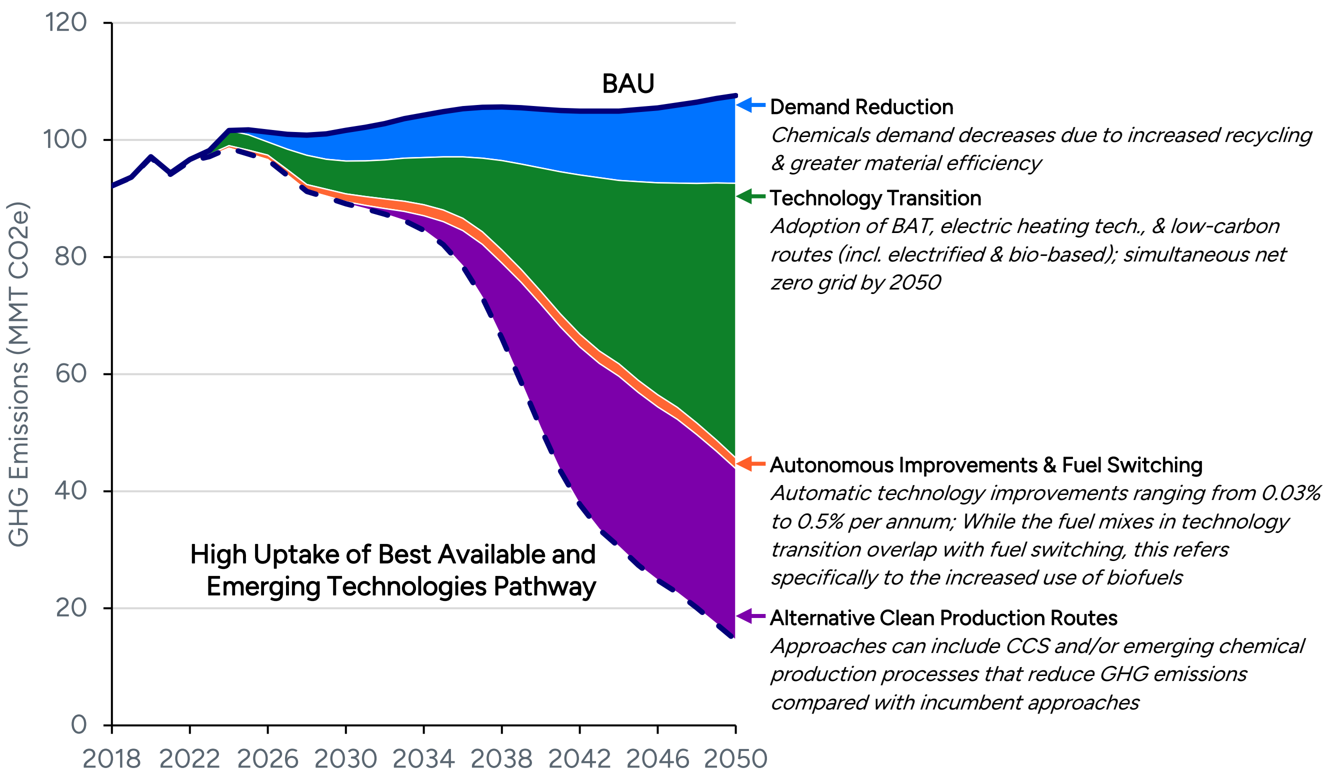


Figure ES-6. Annual GHG emissions reductions, U.S. chemicals manufacturing*—High Uptake of Best Available and Emerging Technologies pathway (MMT CO_2e/year), 2018–2050

* Figure includes results for eight of the modeled chemicals (methanol, ethylene, propylene, butadiene, BTX aromatics, chlorine, soda ash, and ammonia). See Section 4.2.3.9 for details on Ethanol. Details on assumptions, parameters, and timing of transformative technology application can be found in Section 4.2 and Appendix C. Source: Transformative Pathways modeling.

Key takeaways for chemicals include:

- Decarbonizing chemicals is especially challenging due to the diversity of products, processes, and feedstocks.
- While the specific technologies and their implementation will be unique to each chemical, broad interventions identified here are applicable across chemicals.
- Although these interventions provide substantial decarbonization potential, innovative clean chemicals production technologies are needed to reach near zero emissions.

Food and Beverage

Multiple feasible near zero pathways for U.S. food and beverage manufacturing[14] were identified with the potential to reduce the annual GHG emissions by approximately 99% from 76 MMT CO_2e in 2018 to 0.3 MMT CO_2e in 2050. Key characteristics within and across two of these pathways are summarized in Table ES-4.

Table ES-4. Food and Beverage Near Zero Pathways Summary

PATHWAY	KEY CHARACTERISTICS OF THIS PATHWAY BY 2050
Higher Uptake of Electrification (Figure ES-7)	• High adoption of steam-generating and hot water heat pumps • Lower adoption of low-carbon fuels and advanced electrification technologies
Higher Uptake of Low-Carbon Fuels (Figure ES-8)	• High adoption of low-carbon fuels, where applicable • Modest adoption of steam-generating and hot water heat pumps to account for assumed low-carbon fuel availability limits
Characteristics applicable to both pathways	• High adoption of energy efficiency measures (e.g., boilers, machine drive) • Investments in demonstration and deployment, especially given that there are commercially available or mature technology options (e.g., heat pumps)

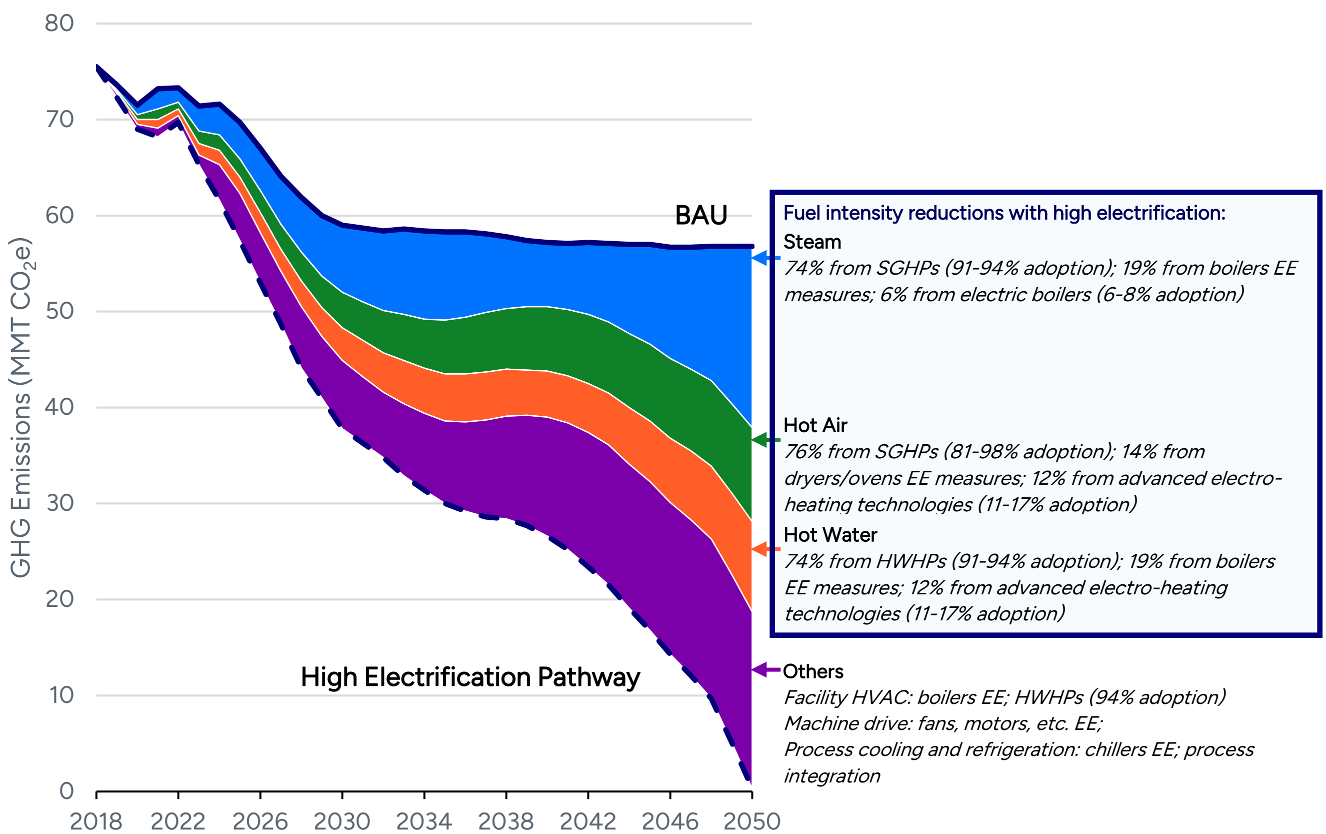


Figure ES-7. Annual GHG emissions reductions, U.S. food and beverage manufacturing*—Higher Uptake of Electrification pathway (MMT CO_2e/year), 2018–2050

* Figure includes results for six modeled food and beverage manufacturing subsectors (grain and oilseed milling; sugar; fruit and vegetable preserving and specialty food; dairy products; animal slaughtering and processing; and beverages). These subsectors accounted for 78% of emissions for food and beverage manufacturing in 2018 (see Table 10). "Others" in the figure includes machine drive, process cooling and refrigeration, facility HVAC, other process uses, and other nonprocess uses. Acronyms/abbreviations: BAU (business as usual); CO_2e (carbon dioxide equivalent); EE (energy efficiency); GHG

[14] The *Transformative Pathways* modeling included six food and beverage manufacturing subsectors–grain and oilseed milling; sugar; fruit and vegetable preserving and specialty food; dairy products; animal slaughtering and processing; and beverages–which accounted for 78% of emissions for food and beverage manufacturing in 2018. See Section 4.3 for more details.

(greenhouse gas); HVAC (heating, ventilation, and air conditioning); HWHP (hot water heat pump); MMT (million metric tons); SGHP (steam-generating heat pump). Details on assumptions, parameters, and timing of transformative technology application can be found in Section 4.3 and Appendix C. Source: Transformative Pathways modeling.

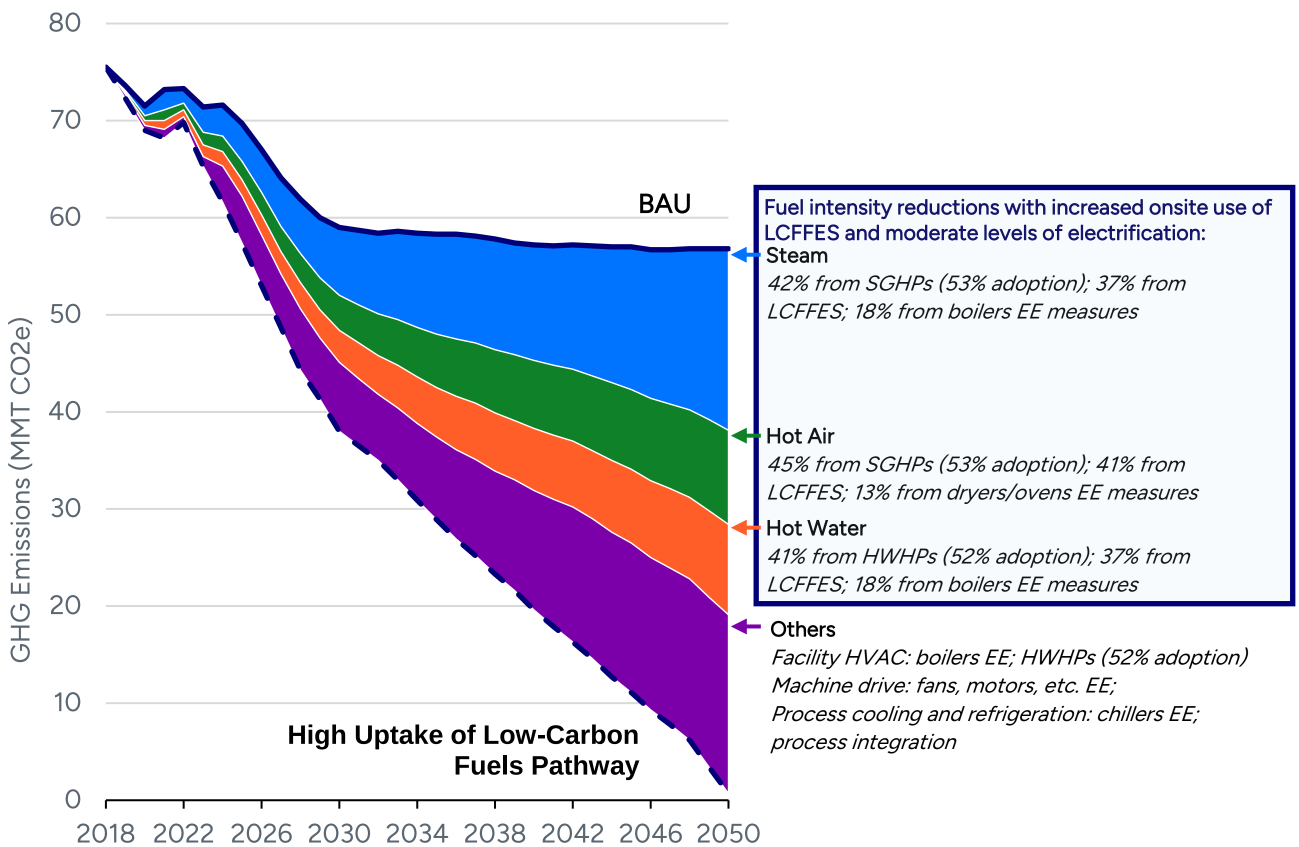


Figure ES-8. Annual GHG emissions reductions, U.S. food and beverage manufacturing*—Higher Uptake of Low-Carbon Fuels pathway (MMT CO_2e/year), 2018–2050

* Figure includes results for six modeled food and beverage manufacturing subsectors (grain and oilseed milling; sugar; fruit and vegetable preserving and specialty food; dairy products; animal slaughtering and processing; and beverages). These subsectors accounted for 78% of emissions for food and beverage manufacturing in 2018 (see Table 10). "Others" in the figure includes machine drive, process cooling and refrigeration, facility HVAC, other process uses, and other nonprocess uses. Acronyms/abbreviations: BAU (business as usual); CO_2e (carbon dioxide equivalent); EE (energy efficiency); GHG (greenhouse gas); HVAC (heating, ventilation, and air conditioning); HWHP (hot water heat pump); MMT (million metric tons); SGHP (steam-generating heat pump). Details on assumptions, parameters, and timing of transformative technology application can be found in Section 4.3 and Appendix C. Source: Transformative Pathways modeling.

Key takeaways for food and beverage include:

- Multiple feasible near zero pathways exist for this subsector, driven largely by decarbonizing hot water, hot air, and steam production, mostly for low- to medium-temperature ranges.
- While specific pathways shared in this report lean heavily into the impact of one individual pillar, electrification, energy efficiency, and LCFFES will all be needed to reach near zero emissions.
- Changes in consumer demand, including preferences for certain products, food loss and waste reduction across the supply chain, and food safety regulations can affect the choices industrial entities make in decarbonizing their operations.
- Investments in demonstration and deployment is a "no regrets" strategy because the subsector can greatly benefit from commercially available or mature technologies, such as heat pumps and electric boilers.

Iron and Steel

Two near zero pathways for U.S. iron and steel manufacturing were identified that have the potential to reduce annual GHG emissions by over 90% from 95 MMT CO_2e in 2018 to 10 MMT CO_2e in 2050. Key characteristics within and across these pathways are summarized in Table ES-5.

Table ES-5. Iron and Steel Near Zero Pathways Summary

PATHWAY	KEY CHARACTERISTICS OF THIS MODELED PATHWAY BY 2050
Integrated Mills with High CCS (Figure ES-9)	• Transition to clean ironmaking, primarily CCS at blast furnace integrated mills and natural gas DRI integrated mills • Address remaining emissions at integrated mills, primarily at steelmaking and finishing stages
Hydrogen-Direct Reduced Iron (Figure ES-10)	• Transition to clean ironmaking, primarily DRI with hydrogen as a reductant • Maximized use of hydrogen as a fuel
Characteristics applicable to both pathways	• Adoption of clean EAF technology including bio-based carbon inputs and electrified preheating • Adoption of clean finishing with electrified or low-carbon fueled process heat

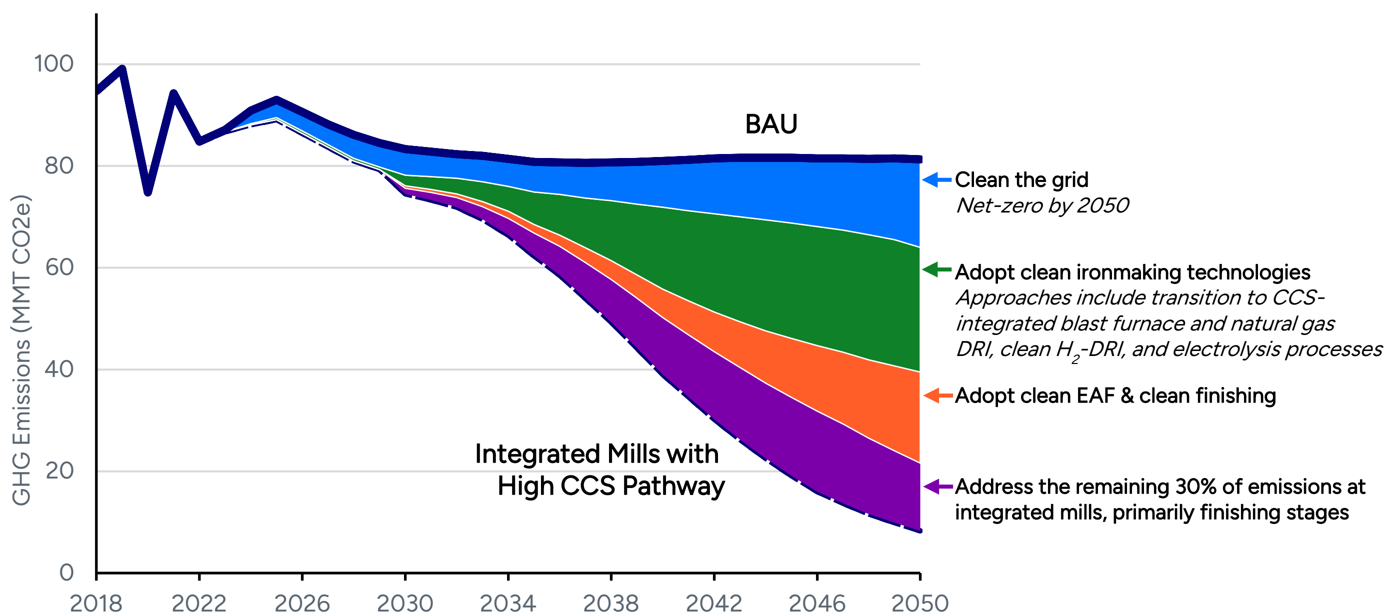


Figure ES-9. Annual GHG emissions reductions, U.S. iron and steel manufacturing–Integrated Mills with High CCS pathway (MMT CO_2e/year), 2018–2050

Details on assumptions, parameters, and timing of transformative technology application can be found in Section 4.4 and Appendix C. Source: Transformative Pathways modeling.

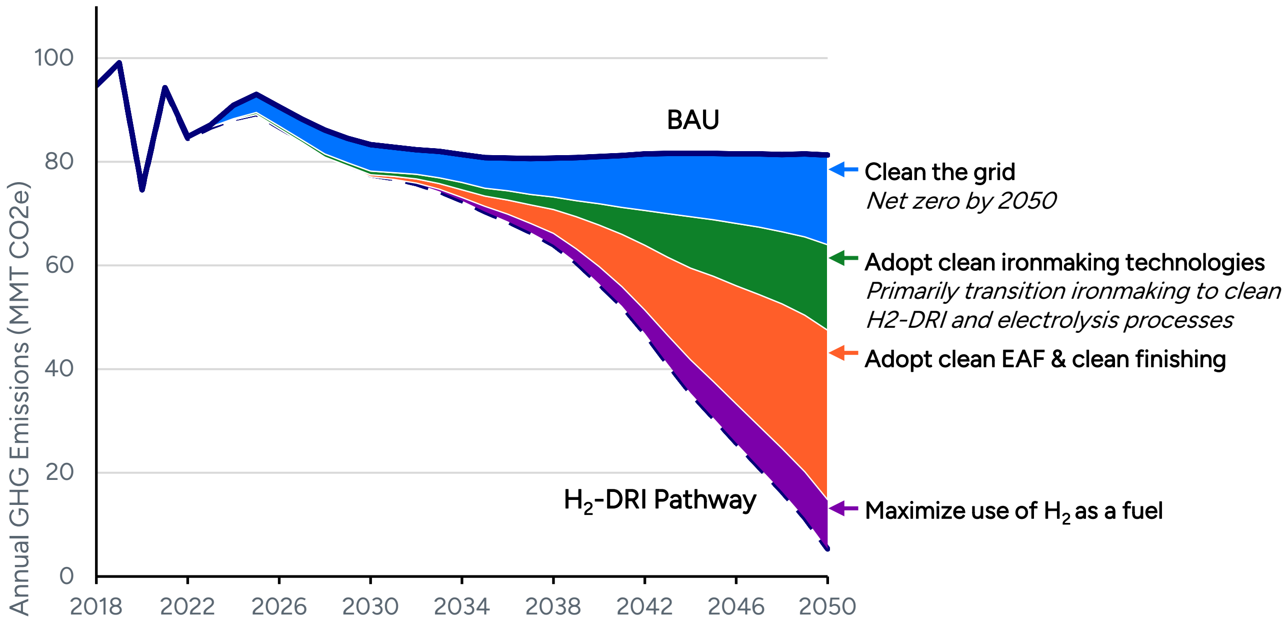


Figure ES-10. Annual GHG emissions reductions, U.S. iron and steel manufacturing–Hydrogen-Direct Reduced Iron pathway (MMT CO_2e/year), 2018–2050

Details on assumptions, parameters, and timing of transformative technology application can be found in Section 4.4 and Appendix C. Source: Transformative Pathways modeling.

Key takeaways for iron and steel include:

- Both pathways rely on clean ironmaking. This can be accomplished through CCS-integrated blast furnace and natural gas DRI, clean hydrogen DRI, electrolytic routes, or other emerging approaches.
- Each ironmaking approach will require different capacity build-out, supporting infrastructure, and broader decarbonization measures; hence near-term (3–5 years) decisions on which pathway to pursue are required.
- Regardless of ironmaking approach, clean EAF steelmaking, clean finishing processes, and high scrap utilization are also needed.

Petroleum Refining

One near zero pathway for U.S. petroleum refining was identified that has the potential to reduce annual GHG emissions by 97% from 243 MMT CO_2e in 2018 to 7 MMT CO_2e in 2050. Key characteristics for this pathway are summarized in Table ES-6.

Table ES-6. Petroleum Refining Near Zero Pathway Summary

PATHWAY	KEY CHARACTERISTICS OF THIS MODELED PATHWAY BY 2050
Demand Reduction (Figure ES-11)	• Aggressive adoption of decarbonization measures: energy efficiency, clean hydrogen, CCS • Deployment of available alternative crude oil substitutes: fats, oils, greases and biomass • Demand reduction for refining products to meet near zero conditions

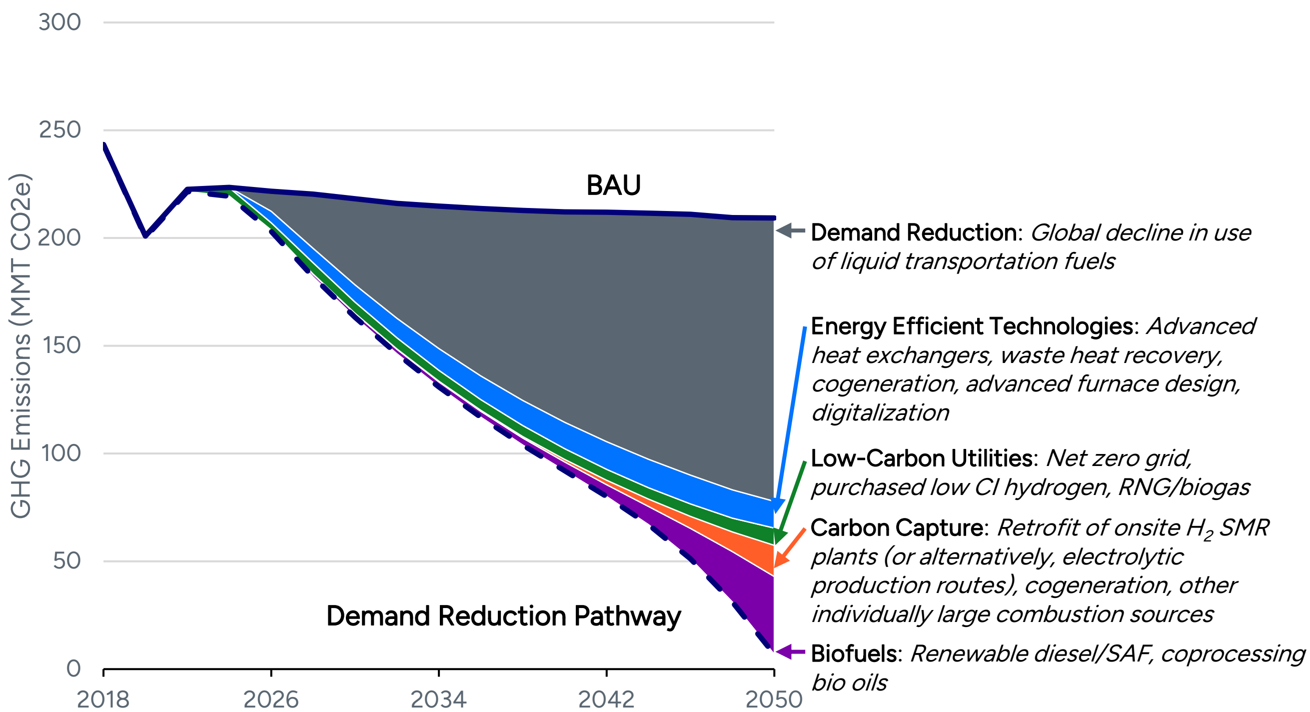


Figure ES-11. Annual GHG emissions reductions, U.S. petroleum refining–Demand Reduction pathway (MMT CO_2e/year), 2018–2050

Details on assumptions, parameters, and timing of transformative technology application can be found in Section 4.5 and Appendix C. Source: Transformative Pathways modeling.

Key takeaways for petroleum refining include:

- Energy efficiency provides immediate and consistent emissions reduction potential.
- Significant infrastructure will be needed to realize emissions reduction potential of carbon capture and clean hydrogen.
- Development of supply chains and conversion technologies of alternative feedstocks are needed to enable adoption of biofuels.
- Reducing demand is necessary for reaching near zero emissions in refining because the maximum adoption of other decarbonization intervention achieves less than half of the emissions reduction from 2018.

Pulp and Paper

One near zero pathway for U.S. pulp and paper manufacturing was identified that has the potential to reduce annual GHG emissions by 95% from 113 MMT CO_2e in 2018 to 6 MMT CO_2e in 2050. Key characteristics for this pathway are summarized in Table ES-7.

Table ES-7. Pulp and Paper Near Zero Pathway Summary

PATHWAY	KEY CHARACTERISTICS OF THIS MODELED PATHWAY BY 2050
Increased Use of Biomass for Fuel (Figure ES-12)	• Higher adoption of solid biomass-based fuels and energy efficiency for core unit processes • Modest electrification of steam generation and drying processes

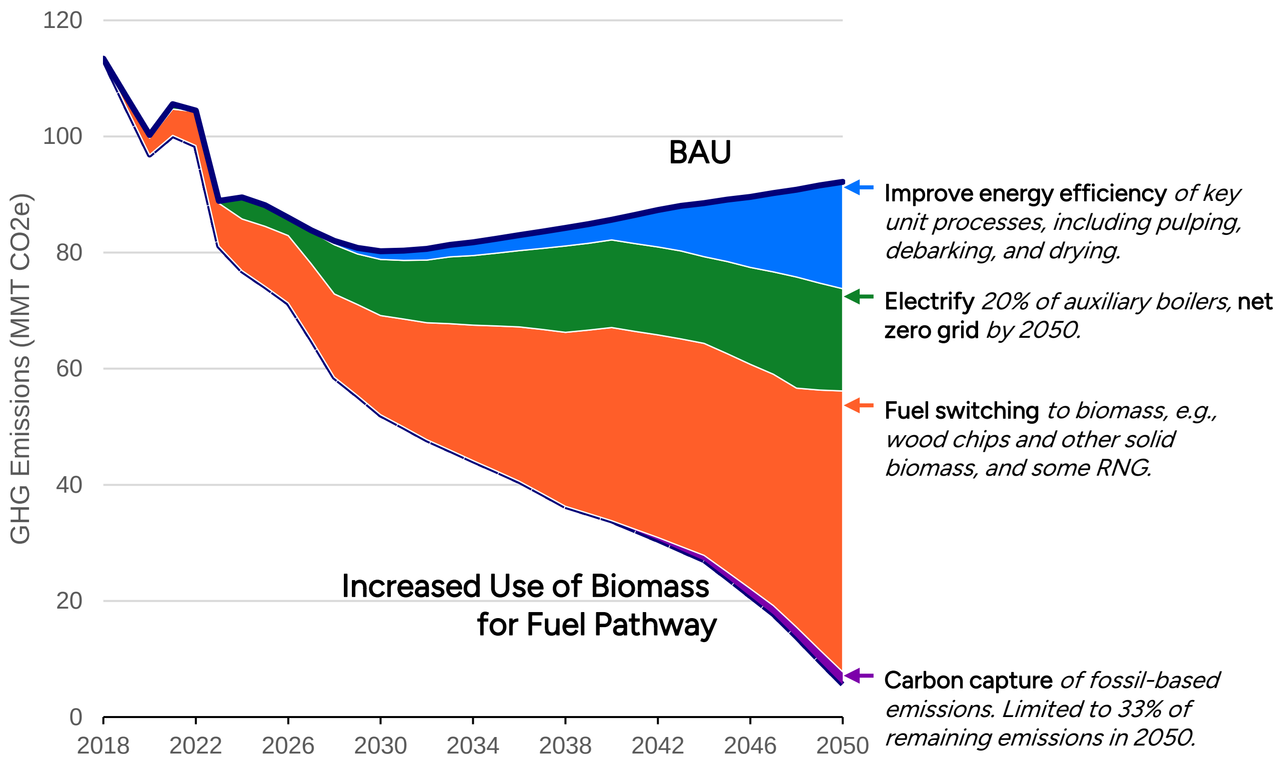


Figure ES-12. Annual GHG emissions reductions, U.S. pulp and paper manufacturing–Increased Use of Biomass for Fuel pathway (MMT CO_2e/year), 2018–2050

Details on assumptions, parameters, and timing of transformative technology application can be found in Section 4.6 and Appendix C. Source: Transformative Pathways modeling.

Key takeaways for pulp and paper include:

- Decarbonizing the pulp and paper subsector is largely driven by increasing biomass use and improving energy efficiency of existing core unit processes.
- The technology adoption assumed in the near zero pathway constrains the decarbonization potential of other interventions. Higher rates of electrification, recycling, and pulp imports had minimal effect on emissions trajectory. Similarly, reducing demand had minor effect.
- While the estimated reductions reach near zero GHG emissions, biogenic emissions should be considered, especially due to increased biomass consumption as the primary decarbonization intervention.

Other Industrial Subsectors

The "rest of industry" is large and diverse, representing nearly half of the industrial sector's energy-related emissions in 2018. Decarbonizing the long tail of industrial sector emissions is challenging given the scale and variability across the remaining subsectors. Although not explicitly modeled in this study, the fundamental decarbonization pillars and approaches described in this report can be applied when considering other industrial subsector decarbonization pathways. For example, adoption of energy efficiency measures can be a near-term strategy, while hybridization and electrification key unit processes can be a mid-term strategy. Additional information is needed to better understand and develop decarbonization pathways for the rest of industry to help the overall industrial sector reach net zero emissions by 2050. More information on these subsectors can be found in Section 4.7.

Emissions Reductions Across Supply Chains and the Industrial Ecosystem

Industrial decarbonization will not only require targeted efforts within industrial subsectors but must also consider the supply chains associated with these industries to fully assess emissions and other impacts. The industrial ecosystem is interconnected, as subsectors buy from and sell materials or services to one another. A life cycle perspective is required to address upstream and downstream scope 3 emissions, considering the entire value chain from raw material extraction to production, distribution, product use, and eventual disposal or reuse. For example, the food and beverage subsector has significant upstream supply chain emissions from agriculture, which includes crop and livestock production. On the other hand, petroleum refining has significant downstream supply chain emissions from the combustion of petroleum crude-derived fuels in the transportation sector. Although the *Transformative Pathways* modeling focused on scope 1 and scope 2 emissions, this study expanded the bounds for food and beverage, pulp and paper, and petroleum refining and considered a broader systems perspective for specific scenarios or factors.

Considerations for U.S. Industrial Transformation

An industrial transformation will be challenging. It will require ambitious action from many actors in the industrial ecosystem, including individual facilities and organizations, technology providers, research organizations, public and private capital allocators, and local, state, and federal policymakers. These actions may have far-reaching impacts across domestic and international supply chains and markets. The following topics will require careful consideration.

- **Innovations are needed to catalyze industrial transformation**: Investments in industrial decarbonization technologies and infrastructure to date are impactful but insufficient to reach a net zero emissions industrial sector by 2050.[15] Continued strong investment will be needed to accelerate the innovation required to drive down emissions, help communities, improve well-being, and increase U.S industry's competitiveness.
- **An industrial transformation must include efficient utilization of energy, resources, and materials across the industrial ecosystem:** Critical to success are the transformations that occur beyond the boundaries of any individual facility, including promoting the most efficient use of natural resources, driving circular manufacturing concepts, and decarbonizing the entire industrial supply chain.
- **A transformation of the industrial sector will require actionable measures**: The United States must transform the marketplace through continued investment in research, development, and demonstration, expand public-private partnerships, develop enabling policies and incentives, support industrial facilities transition through technical assistance, and deploy technologies.
- **People, communities, and the environment are a central part of an industrial transformation**: Investing in the next generation of American workers and engaging communities can facilitate the industrial transformation. A robust, clean industrial sector can be an economic engine for communities, regions, and the nation.

Beyond the work that informed this report, the *Transformative Pathways* models will further evolve and expand to better characterize industrial subsectors and inform decision making, including the addition of more nascent production routes and technologies. Although work will continue, the core message remains the same: Transformation provides the opportunity to maintain America's status as a global industrial leader, strengthen the American workforce and communities, and reduce environmental and health impacts. To do so, we must catalyze innovation and embrace the next generation of industrial technologies; the pathways identified in this report demonstrate tangible ways to achieve this vision.

[15] U.S. Energy Information Administration, "Issues in Focus: Inflation Reduction Act Cases in the AEO 2023," 2023, www.eia.gov/outlooks/aeo/IIF_IRA/.

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The *Transformative Pathways* report was executed by a core team responsible for all aspects of production, including writing the report, engaging stakeholders, and managing the peer review process:

Joe Cresko, DOE

Caroline Dollinger, Energetics

Brian Ray, Energetics

Kenta Shimizu, Energetics

Leonardo Marchetti, DOE

Samuel Gage, Energetics

Matherly Gainer, DOE

Camille Kirkbride, Akoya

With input and contributions from the full *Transformative Pathways* team:

Kristina Armstrong, ORNL

Swaroop Atnoorkar, NREL

Greg Avery, NREL

Aline Banboukian, ORNL

Bob Brasier, Energetics

Larrie Brown, Energetics

Alberta Carpenter, NREL

Hernan Delgado, ANL

Jasey Diaz, Energetics

David Forrest, Nexight

Heidi Fuchs, LBNL

Diane Graziano, ANL

Logan Guy, Energetics (now Deloitte)

Ali Hasanbeigi, Global Efficiency Intelligence

Chukwunwike Iloeje, ANL

Dipti Kamath, ORNL

Unique Karki, LBNL

Heather Liddell, Energetics (now Purdue University)

Tae Lim, LBNL

Seungwook Ma, Energetics

Prashant Nagapurkar, ORNL

Sachin Nimbalkar, ORNL

Ikenna Okeke, ORNL

Jessica Papa, BCS Allegiant

Peng Peng, LBNL

Kristin Powell, Energetics

Lindsay Price, Energetics

Thomas Price, Energetics

Prakash Rao, LBNL

Samantha Reese, NREL

Isabelle Sgro Rojas, Energetics

Naushita Sharma, ORNL

Arman Shehabi, LBNL

Udayan Singh, ANL

Michael Sortwell, Energetics (now Office of Clean Energy Demonstrations)

Cecilia Springer, Global Efficiency Intelligence

Shravan Sreekumar, Nexight

Darlene Steward, NREL

Daniel Stewart, Energetics (now FM Insurance)

Sarang Supekar, ANL

David Thaller, Energetics

Kiran Thirumaran, ORNL

David Turpin, Nexight

Taylor Uekert, NREL

Shubhankar Upasani, NREL

Julien Walzberg, NREL

Hope Wikoff, NREL

Li Yu, ANL

Yongxian Zhu, ANL

Jibran Zuberi, LBNL

Report topic leads are provided below:

Cement and Concrete

Sarang Supekar, ANL

Ikenna Okeke, ORNL

Chemicals

Jibran Zuberi, LBNL

Food and Beverage

Caroline Dollinger, Energetics

Unique Karki and Prakash Rao, LBNL

Iron and Steel

Brian Ray, Energetics

Sachin Nimbalkar, ORNL

Yongxian Zhu, ANL

Petroleum Refining

Samuel Gage, Energetics

Pulp and Paper

Dipti Kamath, ORNL

Other Industrial Subsectors

Harper Alerion, Kristian Kiuru, Seungwook Ma, and Lindsay Price, Energetics

Leonardo Marchetti, DOE

Samantha Reese, Isabella Roszell, and Hope Wikoff NREL

Sachin Nimbalkar and Naushita Sharma, ORNL

GHG Emissions Reductions Across the Industrial Ecosystem

Joe Cresko, DOE

Alberta Carpenter, Samantha Reese, and Hope Wikoff, NREL

Lindsay Price and Brian Ray, Energetics

Prakash Rao, LBNL

CCUS

Sarang Supekar and Hernan Delgado, ANL

Electric Grid

Brian Ray, Energetics

Hydrogen

Peng Peng, LBNL

Model Development

Brian Ray, Seungwook Ma, and Kristin Powell, Energetics

Sarang Supekar, ANL

Additional key contributors

Hope Wikoff, NREL

Eryn Kim, Lindsay Price, Harper Alerion, Phoebe Brown, Kristian Kiuru, Jasey Diaz, Mahia Qureshi, Jesse Geiger, Tommy Finamore, Energetics

Reviewers

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DOE Integrated Strategies Office–Ashna Aggarwal, Colin Cunliff, William Dean, Anna Hagstrom, Sue Hamm, Shrayas Jatkar, Natalie Lefton, Terrence Mosley, Samantha Sekar

DOE Office of Clean Energy Demonstrations–Andrew Dawson, Melissa Klembara, Kate Scott

DOE Office of Energy Justice and Equity–Lauren Ross, Monika Roy

DOE Office of Fossil Energy and Carbon Management–Raj Gaikwad, Mani Gavvalapalli, Jonah Williams

DOE Office of International Affairs–Zoe Brouns, Calli Obern, Aaron Ng, Aaron Stone

DOE Office of Manufacturing and Energy Supply Chains–Andrew Alcorta, Laura Graham, Hutch Hutchinson, Emmeline Kao, Mustafa Mahmoud, David Simms, Kelly Visconti

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DOE Office of Policy–Eric Masanet, Brandon McMurtry, Nicole Ryan

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DOE Office of Technology Transitions–Felipe Barcia, Stephen Hendrickson, Mary McManmon

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[16] U.S. Department of Energy, "U.S. Department of Energy Workshop: Transforming Industry—Strategies for Industrial Decarbonization," accessed October 2024, www.energy.gov/eere/iedo/events/us-department-energy-workshop-transforming-industry-strategies-decarbonization.

[17] U.S. Department of Energy, "Pathways to U.S. Industrial Transformations Workshop to Inform Impacts on Energy, Equity, and Workforce," accessed October 2024, www.energy.gov/eere/iedo/events/pathways-us-industrial-transformations-workshop-inform-impacts-energy-equity-and.

[18] Federal Register, "Industrial Technology Innovation Advisory Committee," August 5, 2024, www.federalregister.gov/documents/2024/08/05/2024-17241/industrial-technology-innovation-advisory-committee.

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LIST OF ACRONYMS AND ABBREVIATIONS

AEO	Annual Energy Outlook
AGO	atmospheric gas oil
ANL	Argonne National Laboratory
APS	Announced Pledges Scenario (IEA)
AqE	aqueous electrolysis
ATR	autothermal reforming
BAT	best available technologies
BAU	business as usual
BF	blast furnace
Bio-aromatics	biomass-to-aromatics
BOF	basic oxygen furnace
Btu	British thermal unit(s)
BTX	benzene-toluene-xylene
C	Celsius
CAPEX	capital expenditures
CCS	carbon capture and storage
CCUS	carbon capture, utilization, and storage
CH_4	methane
CHP	combined heat and power
CI	carbon intensity
CNZ	Core Near Zero
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalent
COP	coefficient of performance
CS	Core Scenario
DOE	U.S. Department of Energy
DRI	direct reduced iron
EAF	electric arc furnace
EE	energy efficiency
EEJ	energy and environmental justice
EIA	U.S. Energy Information Administration
EOR	enhanced oil recovery
EPA	U.S. Environmental Protection Agency
eSMR	electrified steam methane reforming

F	Fahrenheit
FCC	fluid catalytic cracking
FLW	food loss and waste
FOG	fats, oils, and greases
GHG	greenhouse gas(es)
GJ	gigajoule(s)
Gt	gigaton(s)
GWP	global warming potential
H_2	hydrogen
HGL	hydrocarbon gas liquid(s)
HTHP	high-temperature heat pump(s)
HVAC	heating, ventilation, and air conditioning
HWHP	hot water heat pump(s)
IEA	International Energy Agency
iEAF	integrated electric arc furnace
IEDO	Industrial Efficiency and Decarbonization Office
kg	kilogram
LBNL	Lawrence Berkeley National Laboratory
LC3	limestone calcined clay cement
LCA	life cycle analysis or assessment
LCFFES	low-carbon fuels, feedstocks, and energy sources
m^3	cubic meters
MECS	Manufacturing Energy Consumption Survey
MMBtu	million British thermal units
MMT	million metric ton(s)
MOE	molten oxide electrolysis
MTA	methanol-to-aromatic(s)
MTO	methanol-to-olefin(s)
N_2O	nitrous oxide
NAICS	North American Industry Classification System
NG	natural gas
NGL	natural gas liquid(s)
NMP	n-methylpyrrolidone
NOx	nitrogen oxide(s)
NREL	National Renewable Energy Laboratory
OCM	oxidative coupling of methane

ODC	oxygen depolarized cathode
OPEX	operational expenses
ORNL	Oak Ridge National Laboratory
p.a.	per annum
PDH	propane dehydrogenation
PET	polyethylene terephthalate
PM	particulate matter
$PM_{2.5}/PM_{10}$	fine particulate matter
R&D	research and development
RDD&D	research, development, demonstration, and deployment
RFI	request for information
RNG	renewable natural gas
SAF	sustainable aviation fuel
SCM	supplementary cementitious material
sEAF	standalone electric arc furnace
SGHP	steam-generating heat pump(s)
SMR	steam methane reforming
STEPS	Stated Policies Scenario (IEA)
TBtu	trillion British thermal units
TEA	techno-economic analysis or assessment
TFEC	total final energy consumption
TWh	terawatt-hour(s)
UN	United Nations
UNEP	United Nations Environment Programme
U.S.	United States
USDA	U.S. Department of Agriculture
UV-C	germicidal ultraviolet
VFD	variable frequency drive
WEO	World Energy Outlook
WHR	waste heat recovery
WWTP	wastewater treatment plant
W/WW	water and wastewater

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1 FRAMING INDUSTRIAL TRANSFORMATION

The United States is undergoing an energy transformation[19] that will depend on continued U.S. innovation. Since the first industrial revolution, U.S. industry has been foundational to the nation's economic growth and prosperity.[20] The industrial sector creates more than 21 million stable, well-paying American jobs, and it is a critical driver of national productivity, contributing $4.8 trillion to the U.S. economy.[21,22]

However, these economic engines have also given rise to decades' worth of industrial pollutants in our air and water. As global greenhouse gas (GHG) emissions increase, areas across the nation and the world are experiencing environmental degradation and its associated costs.[23] In addition, today's communities are facing adverse health impacts, such as cancer and asthma, from long-term exposure to pollution.

At the same time, the goalposts for winning in the global marketplace are rapidly shifting. Global investors and financial regulations are increasingly focusing on emissions footprints, governments are developing emissions-based trade adjustments and procurement specifications, and downstream demand for low-carbon products is emerging. Additionally, U.S. national security is becoming increasingly tied to the independence and resilience of domestic industrial supply chains.

This landscape provides an opportunity to grow the U.S. industrial sector and sharpen our competitive edge and national security globally, while bending the sector's upward emissions trend (see Figure 1). This is a decisive moment to accelerate the industrial sector's growth and the benefits it brings to our economy and communities, while minimizing or eliminating negative impacts.

Leveraging the opportunity before us will require a full-scale industrial transformation[24]—fundamentally reimagining a sector that has been optimized throughout hundreds of years. We will need to quickly move state-of-the-art emissions reduction technologies to today's factory floors while continuously innovating to develop the next wave of breakthrough ideas.

The United States can pursue many pathways in parallel across each individual subsector to bring about an industrial transformation. This vision study identifies and explores representative pathways and how they can be pursued together to chart a course to an industrial transformation. Innovation has historically moved the United States forward since the industrial revolution—and it will do so again today and in the future. This vision study provides a framework to help industry meet the next defining moment for American innovation.

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[19] In the *Global Resources Outlook 2024,* the United Nations Environment Programme defines "transformation" as an "overall change or outcome of large-scale shifts in technological, economic and social systems." See: United Nations Environment Programme, *Global Resources Outlook 2024* (Nairobi, 2024). www.resourcepanel.org/reports/global-resources-outlook-2024.

[20] Manufacturing has one of the largest sectoral impacts on the U.S. economy: Every $1 spent in manufacturing has a total impact of $2.69 on the overall economy. See: National Association of Manufacturers, "Facts About Manufacturing" (2024), accessed November 2024, nam.org/manufacturing-in-the-united-states/facts-about-manufacturing-expanded/.

[21] U.S. Bureau of Labor Statistics, "Industries at a Glance: Goods-Producing Industries," accessed November 2024, www.bls.gov/iag/tgs/iag06.htm.

[22] U.S. Bureau of Economic Analysis, "Interactive Data Application: Interactive Access to Industry Economic Accounts Data," accessed November 2024, apps.bea.gov/iTable/?reqid=150&step=2&isuri=1&categories=gdpxind.

[23] Emma Charlton, "This is what the climate crisis is costing economies around the world," World Economic Forum, November 29, 2023, www.weforum.org/stories/2023/11/climate-crisis-cost-global-economies/.

[24] An industrial transformation from a resource-intensive production paradigm to a sustainable one will require a decoupling of well-being and economic activity from resource use and environmental impacts.

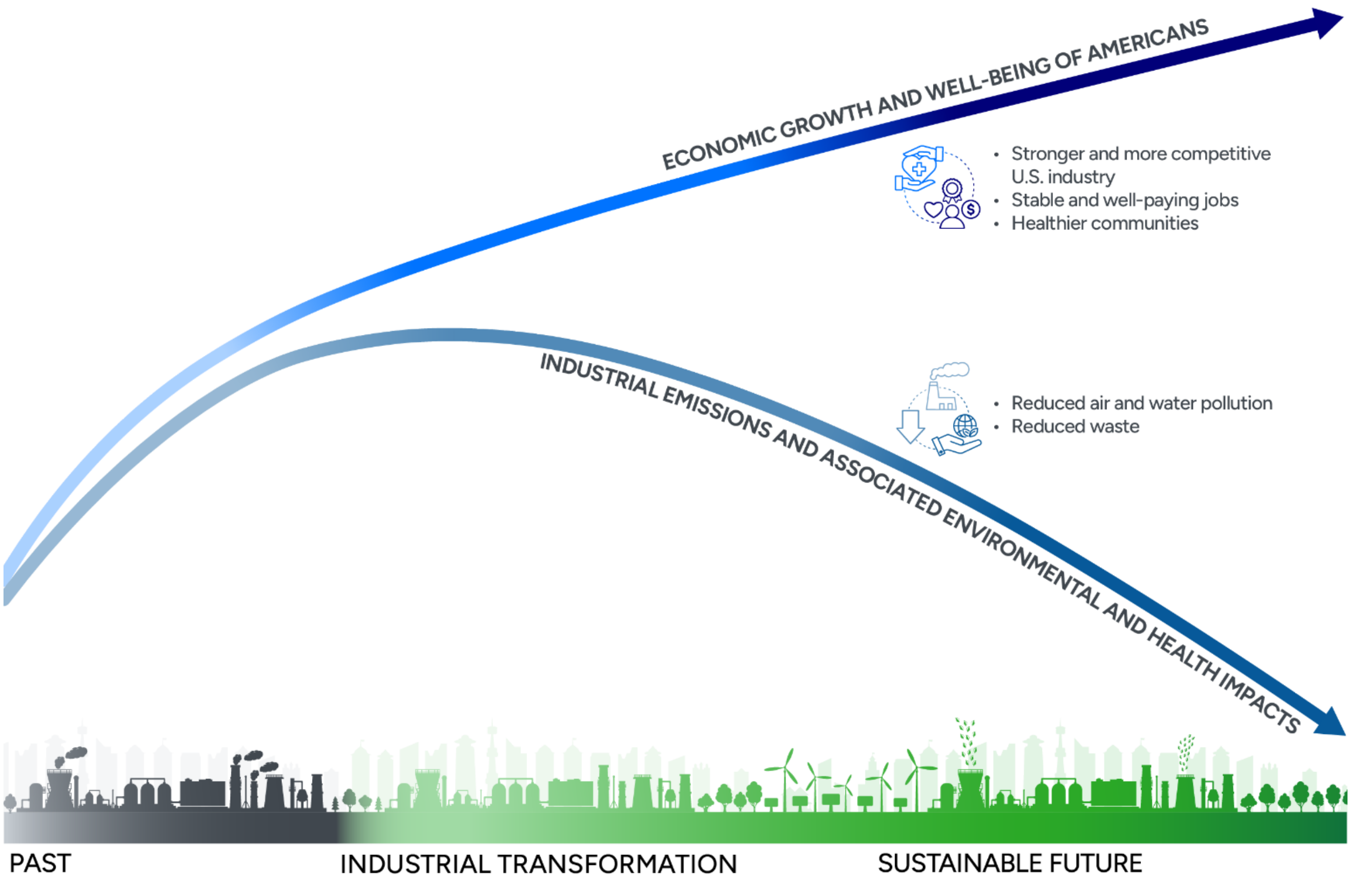

Figure 1. Transformation of industry from resource-intensive to a sustainable[25] future is an opportunity to continue economic growth and well-being while reducing emissions and associated environmental and health impacts

For other perspectives on energy transitions and transformations, see United Nations Environment Programme Global Resources Outlook 2024.[26]

> *Industrial transformation will require enabling conditions such as innovation, de-risking, investment, clean energy, education, and demand for clean products, resulting in improved use of resources, materials, and energy across the economy.*

In this report, Section 1 establishes and frames the opportunity, scope, and context around an industrial transformation. Section 2 introduces the industrial ecosystem framework to consider the primary challenges and barriers industry faces in decarbonizing, with the goal of a net zero economy. Section 3 details the impact and evaluation criteria necessary to enable data-informed decision making as well as decarbonization pillars and sensitivities used to model industrial decarbonization pathways. Section 4 includes a discussion of and modeled results for industrial subsector-specific pathways. Finally, Section 5 lays out conclusions and considerations for a U.S. industrial transformation based on the qualitative and quantitative information presented throughout this report.

1.1 The Opportunity for U.S. Industrial Transformation

As established in *The Long-Term Strategy of the United States*,[27] achieving net zero emissions across the entire U.S. economy by 2050 is vital. Decarbonizing the industrial sector is critical to achieving this goal. The U.S. industrial sector creates approximately 38% of the total U.S. economy emissions (both energy-related and non-

[25] For perspectives on sustainability and sustainable manufacturing, see U.S. Department of Energy, *Sustainable Manufacturing and the Circular Economy*, by Kristina Armstrong et al., DOE/EE-2696 (January 2023), www.osti.gov/biblio/1963668.
[26] United Nations Environment Programme, *Global Resources Outlook 2024* (Nairobi, 2024), www.resourcepanel.org/reports/global-resources-outlook-2024.
[27] U.S. Department of State and the U.S. Executive Office of the President, *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050* (Washington, DC: 2021), www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf.

energy-related scope 1 and scope 2).[28] Under business as usual (BAU) operations, the U.S. industrial sector's energy consumption and energy-related carbon dioxide (CO_2) emissions are projected to increase by 2050.[29] Facing increased demand from consumers for low-carbon products, the private sector is increasingly motivated to decarbonize its supply chains and compete in low-carbon markets.

Due to the diversity and complexity of energy inputs, processes, and operations, the industrial sector is considered one of the most difficult to decarbonize. Although there has been progress in energy efficiency, clean energy use, and other decarbonization strategies, industry—both nationally and globally—is not on track to meet the 2050 decarbonization goals.[31] To articulate our goals toward achieving them, having clear definitions for what constitutes industrial decarbonization, net zero, near zero, and pathways is necessary.

Achieving net zero industrial GHG emissions will require an accelerated, multidimensional, and system-wide approach. It is essential to holistically evaluate decarbonization potential and the use of critical and limited resources by considering all industrial subsectors, their interconnections, and their supply chains and value chains. Innovations are required within unit operations, facilities, feedstocks, and beyond the plant bounds. Formulating an appropriate approach will require that we re-envision how the sector uses energy and materials.

As we revolutionize the processes and technologies that power the industrial sector, we have an opportunity to transform its impact beyond the facilities—within and across U.S. communities as well as nationally and globally. This transformation must keep American communities at the forefront and ensure that our decarbonization efforts increase American jobs and U.S. competitiveness abroad.

In this transformation, which heavily impacts American communities, ensuring that these communities have a voice in charting our course to the future is vital. The U.S. Department of Energy (DOE) has engaged with a diverse group of stakeholders—from communities, researchers, and industry to other government agencies and international organizations—to inform this study, envisioning an industrial transformation and how we will achieve it together.

Industrial Decarbonization: Industrial decarbonization refers to minimizing atmospheric GHG emissions attributable to the industrial sector. The most important gases contributing to the global GHG effect are CO2, methane (CH4), nitrous oxide (N2O), and fluorinated gases. The modeling in this report focuses on both scope 1 and scope 2 energy-related and non-energy-related CO2 equivalent (CO2e) U.S. industrial sector emissions. More than 80% of U.S. manufacturing CO2e GHG emissions are represented by direct CO2 emissions.

Net zero and Near zero: In this report, the use of the term, "net zero" refers to achieving an overall balance of zero GHG emissions; that is, a "net zero economy" which removes or averts as much GHG as it produces.[30] Near zero refers to very low emissions intensity. Although some U.S. industrial subsectors could achieve net zero or negative emissions, others will likely achieve only near zero GHG emissions. The remainder of the subsector GHG emissions will need to be balanced with other economic sectors to reach net zero emissions industry-wide.

1.1.1 Energy and Environmental Justice

Ensuring just and equitable outcomes for all Americans is central to achieving a sustainable economy with net zero GHG emissions. An industrial transformation provides an opportunity to realize broad socioeconomic benefits and to address the country's climate, economic, and environmental justice imperatives beyond GHG emissions reduction impacts. The industrial transition to a clean energy economy and net zero GHG emissions considers energy and environmental justice (EEJ) at the forefront of all decarbonization activities.

Ensuring that the benefits of industrial decarbonization efforts are equitably distributed among all communities, particularly those that have been historically underserved and overburdened by pollution, is challenging but

[28] Data compiled from multiple sources, see Figure 4.
[29] U.S. Energy Information Administration, "Annual Energy Outlook 2023," 2023, www.eia.gov/outlooks/aeo/.
[30] U.S. Department of Energy, "Net-Zero Economy," accessed January 2025, www.energy.gov/topics/net-zero-economy.
[31] International Energy Agency, "Industry: Tracking Clean Energy Progress," accessed October 2024, www.iea.org/energy-system/industry#tracking.

necessary. Industrial facilities are often located in disadvantaged communities.[32] These facilities produce significant amounts of energy- and non-energy-related GHG emissions, pollution from waste or by-product streams, and air pollutants—such as nitrogen oxides (NOx), carbon monoxide, and particulate matter (PM)—that have harmful impacts on respiratory and cardiovascular health.[33]

American communities—comprising workers, consumers, and regulators—form the foundation of industrial success; therefore, local engagement is a critical step in successful industrial transformations. Decisions around large infrastructure and energy projects are largely influenced by powerful individuals, sowing mistrust and opposition in the communities where these projects will take place. Planned industrial transformations are much more likely to be successful when organizations integrate the community in decision making and project implementation. Engaging communities through existing networks at the outset provides opportunities to support local objectives and build trust by addressing local concerns, leading to outcomes that benefit all.[34]

1.1.2 U.S. Leadership, Competitiveness, and Innovation

An industrial transformation provides a critical opportunity to advance U.S. manufacturing competitiveness. Technological innovations will position the United States as a leader in the clean production of manufactured goods. The use of clean energy and sustainable manufacturing approaches can minimize the environmental impacts of the production, use, and disposal of manufactured goods, which range from fundamental commodities such as metals and chemicals to sophisticated final-use products such as automobiles and wind turbine blades.[35] U.S. manufacturing can shift to using sustainable practices and principles to minimize negative environmental impacts and address climate change. To do so while growing the economy, the United States needs to develop and implement advanced manufacturing technologies like smart manufacturing, grow the advanced manufacturing workforce, and build resilient supply chains.[36,37]

Industrial modernization must give rise to a multifaceted vision: a national industry that remains domestically and globally competitive, catalyzes innovation to create advanced and environmentally-just[38] technologies, maintains and grows a skilled and diverse workforce, encourages continued onshoring, and leverages appropriate trade actions and relationships to level the global playing field. Manufacturing drives both U.S. knowledge production and innovation,[39] areas that will be key to keeping industry competitive in the development and deployment of decarbonization technologies. DOE's vision is of a vibrant and productive net zero U.S. industry, supplying products, technologies, and strategies to enable global decarbonization.

The shift toward net zero GHG emissions by 2050 will require substantial investment from industry, alongside crucial government support. Decarbonizing industrial processes requires advanced technologies and sustainable practices, and their adoption entails significant upfront costs. At the same time, materials and products with high (or low) embodied carbon are imported and exported across borders. This can lead to industrial emissions shifting between countries, allowing global emissions contributions to appear artificially high or low (i.e., "onshoring" or "offshoring" industrial emissions). Any decarbonization strategy must disincentivize GHG emissions throughout the supply chains, but not disadvantage U.S. industry and ensure that it is globally and

[32] Grace Linczer and Jeanette Pablo, *Understanding Disenfranchised and Underserved Communities in the U.S.* (Clean Air Task Force, 2023), www.catf.us/resource/understanding-disenfranchised-underserved-communities-us/.
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[38] U.S. Environmental Protection Agency, "Environmental Justice," accessed October 2024, www.epa.gov/environmentaljustice.
[39] President's Council of Advisors on Science and Technology, *Report to the President on Ensuring American Leadership in Advanced Manufacturing* (2014), obamawhitehouse.archives.gov/sites/default/files/microsites/ostp/pcast-advanced-manufacturing-june2011.pdf.

domestically competitive. Markets for low-carbon products are emerging both domestically and abroad. Public-private initiatives in North America are committing to steadily decarbonizing their supply chains through advance market commitments while European governments have considerably expanded low-carbon markets through green public procurements. With growing market demand for lower embodied carbon products, American industrial companies seeking to create real value from decarbonization will have to enter these emerging marketplaces with definitive technological advantages.

1.2 Pathways to Net Zero GHG Emissions

The use of the term "pathways" is at the heart of this new vision study. Within the context of this industrial modeling framework, a decarbonization pathway is characterized as a sequence of technology deployments and retirements over time that allow U.S. industry to arrive at an established level of GHG emissions (such as net zero or near zero) within an established time frame. These pathways can be mapped ahead with the knowledge of existing challenges and barriers, but there is also the chance that additional pathways will emerge as the industrial

No single pathway exists for the industrial sector overall or for any individual subsector, as steps can and will change as the future unfolds. Competition across different possible pathways will be essential to success. Not every technology choice or pathway is equivalent, as some will be more challenging than others or might not be as economically viable. Environmental, human health, and societal outcomes for each pathway must also be carefully evaluated. Considering a range of potential pathway futures will be useful to help inform industry now and guide corporate, government, and societal decision making. Additionally, pathways to net zero GHG emissions will (when necessary) take a more holistic approach and consider both upstream and downstream emissions.

Decarbonization over time will require a series of key decisions and investments under uncertainty. All pathways require parallel investments to achieve net zero GHG emissions by 2050. Additionally, RDD&D to advance new technologies and improve cost-competitiveness is needed to help achieve these pathways and reduce emissions. Due to the long lifetimes of industrial facilities and related infrastructure, timing is challenging for any pathway. As part of this study, frameworks and data-informed decision tools have been developed to help map and inform such decisions. To help visualize the optionality to achieve near zero GHG emissions within industrial subsectors, we introduce a decision tree framework (see Section 2.4). These frameworks can help us evaluate and understand potential pathways.

1.2.1 Building On Previous Work

This *Transformative Pathways* report builds on significant prior research and stakeholder engagement. The 2022 *Industrial*

Definition of pathway

- Pathways as defined for this report: Within the context of this industrial modeling framework, a decarbonization pathway is characterized as a sequence of technology deployments and retirements over time that allow U.S. industry to arrive at an established level of GHG emissions (such as low-carbon to near zero) within an established timeframe.
- Pathways as defined in the *Industrial Decarbonization Roadmap*[1]: Pathways are the specific actions needed to achieve progress within and across the four decarbonization pillars: (1) energy efficiency; (2) industrial electrification;[1] (3) low-carbon fuels, feedstocks, and energy sources (LCFFES); and (4) carbon capture, utilization, and storage (CCUS). These actions are informed and supplemented by research, development, demonstration, and deployment (RDD&D) to advance viable solutions (i.e., technologies, practices, approaches, and behaviors) that will need to be adopted at scale in the marketplace.
- The use of the term "pathway" can be subject to the specific use case. This report considers decarbonization pathways as broadly encompassing the U.S. industrial sector and subsectors, and decarbonization pathways are aggregated to assess GHG emissions reduction potential at the national scale. Pathways related to any individual company or facility can use the same or similar actions, and this definition can be adapted or tailored if the context changes (e.g., defining pathways specifically for a region, company, or facility).

Decarbonization Roadmap[40] provides the framework for DOE's industrial decarbonization strategy and outlines technology opportunities and potential challenges for five major manufacturing subsectors: (1) cement, (2) chemicals, (3) food and beverage, (4) iron and steel, and (5) petroleum refining. The *Industrial Decarbonization Roadmap* characterizes technology opportunities within the context of four industrial decarbonization pillars, shown in Figure 2, which highlight the need for both crosscutting technologies and system solutions. This *Transformative Pathways* report extends and expands upon the *Industrial Decarbonization Roadmap* analysis and more thoroughly assesses specific technology options for energy- and emissions-intensive industrial operations and production routes.

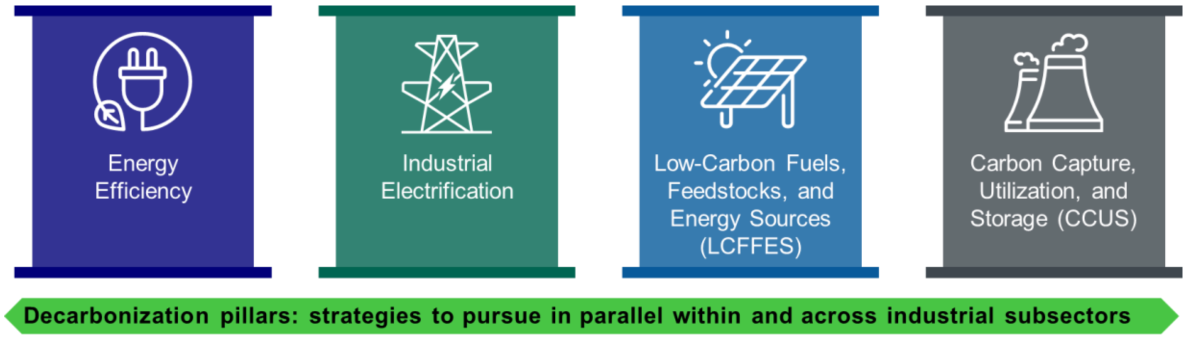

Figure 2. Pillars of industrial decarbonization from the *Industrial Decarbonization Roadmap*[41]

> As outlined in the *Industrial Decarbonization Roadmap*, there are four foundational pillars to industrial decarbonization. Underlying these pillars are existing and emerging foundational materials and manufacturing technologies.

Beyond the four main pillars, material efficiency (including material substitution, resource conservation, and circular economy strategies) is an important crosscutting decarbonization lever that can reduce the embodied energy[42] and emissions[43] of materials and products. Because these strategies can be difficult to quantify and can have impacts outside the bounds of an industrial facility, material efficiency is not explicitly assessed in the modeled pathways (which are limited to the manufacturing subsector), but it is considered in certain technology choices. Material efficiency strategies need further exploration and analysis, including defensible life cycle assessments (LCAs) and techno-economic assessments (TEAs).

DOE's *Pathways to Commercial Liftoff* reports[44] focus on commercial considerations for near-term technology adoption (through 2030), whereas the *Industrial Decarbonization Roadmap* and this *Transformative Pathways* modeling focus on innovation across the industrial ecosystem (through 2050). The *Pathways to Commercial Liftoff* reports utilized extensive stakeholder engagement and the best available cost estimates to provide a fact base to public- and private-sector capital allocators. These reports offer a perspective on how and when various technologies could reach full-scale commercial adoption through 2030, including specific reports focused on industrial decarbonization, chemicals and refining, cement, clean hydrogen, and carbon management, among others. In concert, these reports are meant to identify the opportunity space for technologies to reduce industrial sector emissions, while clarifying technology pathways that are complementary, partially complementary, or inconsistent with a full industrial transformation. Figure 3 illustrates the focus of *Pathways to Commercial Liftoff: Industrial Decarbonization* and *Transformative Pathways* and how they interact across the RDD&D continuum.

[40] U.S. Department of Energy, *Industrial Decarbonization Roadmap*, DOE/EE-2635 (2022), www.energy.gov/industrial-technologies/doe-industrial-decarbonization-roadmap.

[41] Ibid.

[42] Colin McMillan, *Material and Energy Efficiency: A Framework for Broader Analysis of Energy Use in the U.S. Economy,* NREL/TP-6A20-70609 (Golden, CO: National Renewable Energy Laboratory, 2018), www.nrel.gov/docs/fy18osti/70609.pdf.

[43] International Energy Agency, *Material Efficiency in Clean Energy Transitions* (2023), www.iea.org/reports/material-efficiency-in-clean-energy-transitions.

[44] U.S. Department of Energy, "Liftoff Reports," accessed October 2024, liftoff.energy.gov/

Figure 3. The focus of Pathways to Commercial Lift: Industrial Decarbonization and Transformative Pathways and a mapping across the RDD&D continuum and Adoption Readiness Level (ARL) scale. Darker shades indicate a stronger focus.

1.2.2 Report Development

The development of this report and the associated modeling and analysis incorporates not only *Industrial Decarbonization Roadmap* groundwork but also input from multiple internal DOE and external stakeholder channels obtained since the *Industrial Decarbonization Roadmap*'s publication in 2022. Stakeholder engagement undertaken to directly inform this work included a May 2024 in-person workshop on "Transforming Industry: Strategies for Decarbonization" and a request for information, as well as an August 2024 virtual workshop on "Impacts of Energy Equity and Environmental Justice on Decarbonizing the Industrial Sector."[45,46] DOE's Office of Energy Efficiency and Renewable Energy Industrial Efficiency and Decarbonization Office (IEDO) sought input from a diverse group of stakeholders (both within and outside of industry) who will be integral to U.S. industrial transformation. These stakeholders represented companies, academia, communities impacted by industrial activities, utilities, low-carbon fuels suppliers, technology developers, engineering consultants, firms designing new facilities, local and regional governments, and more. In addition, IEDO leveraged information and knowledge gathered from other DOE offices and reports and external stakeholder events, including workshops and roundtables.

Transformative Pathways Modeling

The modeling behind this report focuses on six manufacturing subsectors: (1) cement and concrete, (2) chemicals, (3) food and beverage, (4) iron and steel, (5) petroleum refining, and (6) pulp and paper. These energy- and emissions-intensive subsectors create a range of commodities, intermediaries, and products and are key to both the U.S. industrial sector and economy overall. Excel-based models were created to capture the nuance of each individual subsector; to capture the specific pillar- and technology-level detail; to harmonize key inputs, outputs, and carbon accounting across subsector models; to allow exploration of different pathways; and to be adaptable for future iterations and analyses. Other industrial subsectors have not yet been modeled, but this report includes a discussion on example decarbonization pathways and opportunities (Section 4.7). Future work will be undertaken to better understand decarbonization opportunity impacts for additional subsectors in a consistent format comparable to the existing *Transformative Pathways* modeling.

The *Transformative Pathways* models estimate energy- and process-related emissions for select industrial processes based on assumed inputs, manufacturing technologies, energy intensities, and energy sources tailored for each subsector. Each model defines subsector-specific baseline technologies and processes and characterizes commercially available and emerging decarbonization technology options. Aggregate subsector energy and emissions impacts are calculated based on assumptions (such as adoption rates or energy sources) within the context of other included technologies. The modeling results present numerous candidate decarbonization opportunities—or pathways—highlighting important emergent technologies that can lead to deep decarbonization of the industrial sector. Details on the models and assumptions can be found in Section 4 and the appendices.

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[45] U.S. Department of Energy, "U.S. Department of Energy Workshop on Transforming Industry: Strategies for Decarbonization," accessed December 2024, www.energy.gov/eere/iedo/events/us-department-energy-workshop-transforming-industry-strategies-decarbonization.
[46] U.S. Department of Energy, "Pathways for U.S. Industrial Transformations: Workshop to Inform Impacts of Energy, Equity, and Environmental Justice on Decarbonizing the Industrial Sector," accessed December 2024, www.energy.gov/eere/iedo/events/pathways-us-industrial-transformations-workshop-inform-impacts-energy-equity-and.

The results presented in this report reflect what is known about today's industrial sector and emerging technologies in 2024. Pathways in the near term (by 2030), midterm (2031–2040), and long term (2041–2050 and beyond) will likely change. The models behind these results have been designed for DOE use in future pathways analysis, given expected changes in industry and research and development (R&D), and for a deeper look at pathways for other industrial subsectors beyond the six detailed in Section 4. The models are adaptable to allow updates of key baseline subsector or technology data as well as additions to technology options or new data as they become available. As technology characteristics evolve over time, these models can easily run new scenarios. IEDO expects to make copies of these models publicly available on its website soon. These models will be continually improved and updated, and they will be expanded to include other parts of industry beyond the six subsectors highlighted in this report. Continued stakeholder engagement is also needed to ensure that DOE is as well-informed as possible.

1.3 Industrial Sector Scope and Emissions

This report looks beyond the energy-related emissions covered by the *Industrial Decarbonization Roadmap* and includes non-energy-related (e.g., process) emissions and product demand considerations for the subsectors studied. In this report, the industrial sector is defined as the manufacturing subsector (including the energy- and emissions-intensive cement and concrete, chemicals, food and beverage, iron and steel, pulp and paper, and petroleum refining subsectors, among others), the non-manufacturing subsectors (agriculture and forestry; mining, oil and gas; and construction), and the industry-adjacent subsectors of data centers and water and wastewater treatment. More information on industrial subsectors can be found in Section 4.

Approximately 38% of the total U.S. economy emissions (both energy-related and non-energy-related scope 1 and scope 2) are attributable to the U.S. industrial sector, as shown in Figure 4. The U.S. Energy Information Administration (EIA) projects that if the U.S. industrial sector continues with BAU operations, energy consumption and energy-related CO_2 emissions would increase, primarily driven by export demands of energy-intensive manufacturing products and growth in non-manufacturing industrial subsectors.[47] This study's findings reinforce EIA's projection that incremental improvements in industrial energy and emissions intensity are inadequate to reach the goal of net zero GHG emissions by 2050.

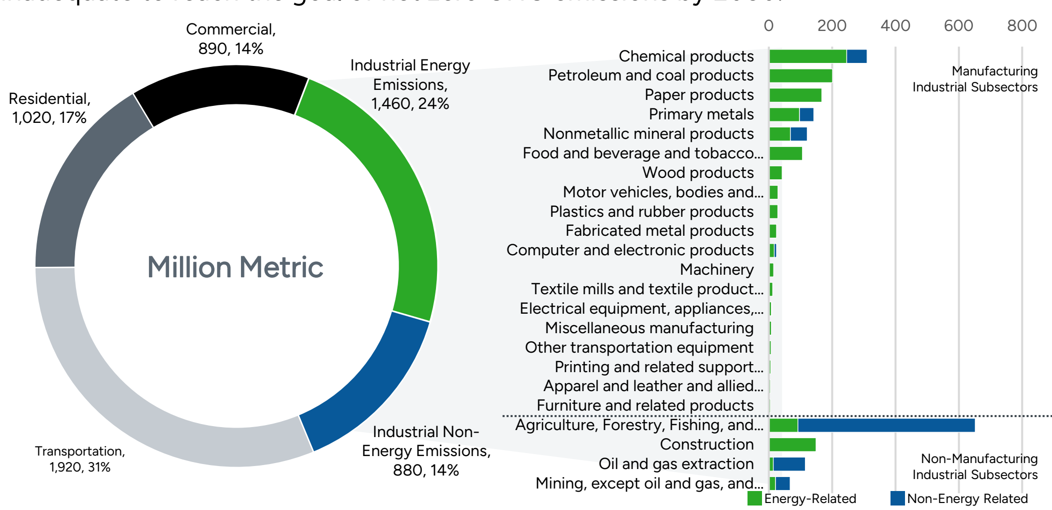

Figure 4. U.S. GHG emissions in 2018 by economic sector (left pie chart) and a breakout by industrial subsector (right bar chart)

This figure shows the carbon dioxide equivalent emissions in million metric tons (MMT CO_2e) are shown, as well as the percentage contribution of that sector to the whole economy. Both scope 1 (from onsite combustion and process-generated non-energy) and scope 2 (from the consumption of offsite-generated electricity) emissions are included. All modeled Transformative Pathways subsectors are reflected in this figure. "Nonmetallic mineral products" include cement and concrete; "primary metals" include iron and steel and aluminum; and "paper products" include pulp and paper. Data compiled from

[47] U.S. Energy Information Administration, "Annual Energy Outlook 2021: Projections Tables for Side Cases," accessed October 2024, www.eia.gov/outlooks/aeo/tables_side.php.

multiple U.S. Energy Information Administration (EIA) and U.S. Environmental Protection Agency (EPA) sources: EIA Monthly Energy Review,[48] EIA Manufacturing Energy Consumption Survey,[49] EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks,[50] DOE IEDO Environmentally Extended Input-Output for Industrial Decarbonization Analysis (EEIO-IDA Tool).[51] Note that the large amount of non-energy emissions in the Agriculture, Foresty, Fishing, and Hunting subsector is due to multiple factors, including from the application of fertilizers, livestock, and manure.[52] The year 2018 is the latest data year available for the inclusion of detailed industrial subsector energy-related and non-energy related emissions.

> *The industrial sector accounts for 38% of the total U.S. economy emissions (both energy-related and non-energy-related scope 1 and scope 2) and comprises many different subsectors across manufacturing and non-manufacturing (agriculture; mining, oil, and gas; and construction).*

1.3.1 Scope and Emissions Modeled in This Study

U.S. industry is challenging to model given its complexity (diversity of material inputs, industrial processes, and manufactured products) and the range of timing, resources, and scopes around industrial decarbonization. Six of the most energy- and emissions-intensive manufacturing subsectors—cement and concrete, chemicals, food and beverage, iron and steel, pulp and paper, and petroleum refining—are the focus of this report. These subsectors had a combined emissions of approximately 900 million metric tons (MMT) of CO_2e in 2018, accounting for 38% of industrial CO_2e emissions and 15% of the total U.S. economy CO_2e emissions.[53] Although most industrial sector emissions are energy-related, 38% are non-energy-related (or process emissions) due to the chemical transformations inherent in certain industrial processes.

Table 1 provides an overview of the different types of industrial emissions relevant to this report and the accompanying modeling and analysis.

Table 1. Types of Industrial Sector Emissions

Emission Type	Description
Fuel-related emissions	Emissions associated with the combustion and use of fuels (from fossil or non-fossil sources) at industrial facilities for needs other than electricity (e.g., for process heat).
Electricity generation emissions	Emissions attributed to the generation of electricity used at industrial facilities, whether that electricity is generated onsite or offsite.
Industrial process emissions	Non-energy-related process emissions from industrial activities (e.g., direct CO2 emissions from chemical transformations in materials being processed).
Supply chain emissions*	Emissions generated from cradle-to-grave (or cradle-to-cradle), including emissions generated both upstream of the manufacturing processes (supply chain) and downstream (during product use and end-of-life). These emissions are not included in the modeled results in this report, but they are important to properly account for and reduce to reach overall net zero economy-wide emissions. Section 4.8 includes a high-level discussion on the impact of industrial supply chain emissions.

* Clear carbon accounting is an important and emerging area for demand-side initiatives and emerging trade methodologies/programs that account for carbon in traded goods. Knowing and properly accounting for supply chain emissions is an important lever for reducing overall emissions.

1.3.2 Treatment of Economics in the Transformative Pathways Models

This *Transformative Pathways* modeling focuses on industrial energy consumption and emissions and does not directly model cost estimates; however, economics, a key evaluation criterion for industrial decarbonization technologies, can change as a technology matures, and it varies according to use case. Examples of economic criteria include the cost to abate carbon, the cost to produce a carbon-abated product, the levelized cost of

[48] U.S. Energy Information Administration, "September 2024 Monthly Energy Review," accessed October 2024, www.eia.gov/totalenergy/data/monthly/index.php. See Tables 11.1-11.5.
[49] U.S. Energy Information Administration, "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data," 2021, www.eia.gov/consumption/manufacturing/data/2018/.
[50] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022*, EPA 430-R-24-004 (2024), www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.
[51] U.S. Department of Energy, "Environmentally Extended Input-Output for Industrial Decarbonization Analysis (EEIO-IDA) Tool," accessed October 2024, www.energy.gov/eere/iedo/articles/environmentally-extended-input-output-industrial-decarbonization-analysis-eeio.
[52] U.S. Environmental Protection Agency, *Sources of Greenhouse Gas Emissions: Agriculture Sector Emissions*, accessed October 2024, www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions#agriculture.
[53] See Figure 4 note for references.

heat (or clean energy), the broader levelized cost of material transformation, and others. Many types of costs and factors influence the development and deployment of any technology, including the initial design and analysis, permitting, regulatory compliance, training, downtime, capital, operating costs, demand incentives, potential future regulatory or market drivers, competitiveness, and resilience (e.g., from supply chain disruptions, natural disasters).

Economics are especially challenging to estimate for early-stage technologies, which are important to industrial decarbonization, as discussed later in this report. DOE estimates that more than 60% of the heavy industry GHG emissions reductions that are needed to achieve net zero by 2050 will come from technologies that are still in the innovation pipeline and/or are not currently market-ready.[54] TEA is a key tool for estimating the economic viability of individual technologies. More information on shorter-term (by 2030) cost estimates for commercially available technologies is provided in the 2023 *Pathways to Commercial Liftoff* reports (including deep dives on chemicals, refining, and cement).[55] Although costs are not included in the modeling in this report, the results are meant to be directionally informative. Over time, as more information on emerging technologies becomes available, this study's models can be updated, and the estimates can be improved based on technology uptake in the marketplace and other factors that will affect deployment.

Although this study modeled only industrial subsectors, industrial decarbonization pathways will also be affected by non-industrial economic sectors (residential, commercial, and transportation). For example, in today's economy, the transportation sector and mining, oil and gas, and petroleum refining subsectors are interdependent because refinery products produce emissions through the supply chain from extraction to use; however, this work does not explicitly consider the impacts on the industrial sector from the decarbonization of other economic sectors. Reaching net zero economy-wide GHG emissions will require a variety of decarbonization strategies from the four pillars as well as alternate approaches, such as negative-emissions technologies.

[54] U.S. Department of Energy, "Liftoff Reports," accessed October 2024. liftoff.energy.gov/.
[55] Ibid.

2 THE INDUSTRIAL ECOSYSTEM: PRIMARY DECARBONIZATION CHALLENGES AND BARRIERS

A transformation of the industrial sector must concurrently decrease GHG emissions, reduce the detrimental environmental and societal impacts associated with resource use, increase well-being, and drive economic growth. Reaching these objectives can enable a decarbonized U.S. economy that is both equitable and competitive. To achieve the systemic goal of net zero GHG emissions, our approach considers the interconnectedness of industry with economic, technical, environmental, and societal considerations. Through this lens of an industrial ecosystem, the full suite of challenges and barriers can be considered.

2.1 The Industrial Ecosystem

The transformative, systemic challenge of industrial decarbonization will require a holistic, broader industrial ecosystem viewpoint. Although there are a range of different definitions for an industrial ecosystem, all of them fundamentally include industrial processes, production systems, and interconnected industrial partners.56 The industrial ecosystem includes actors across the value chain, including small start-up companies, large multinational organizations, academia, service providers, distributors, waste management providers, end users, and the physical infrastructure connecting them all.[57] Each segment of the value chain interacts with its surrounding environment and community and requires resources. The aggregated environment, community, and accompanying resource demands define the industrial ecosystem.

Building strategies within this complex ecosystem requires identifying the specific, most likely potential pathways toward decarbonization. The industrial ecosystem of an individual product is the cumulative web of environmental, economic, societal, and technological impacts surrounding and attributable to each step in the product life cycle, from extraction to manufacturing to use to end-of-life; therefore, this scope—broader than the fence lines of industry—requires consideration of financial and technological costs in conjunction with environmental and societal criteria.

There are many flows within the industrial ecosystem that connect the full value chain, interact with many societal, environmental, financial, and technological aspects, and transcend industry. These flows can be loosely organized into several categories that must be addressed from a life cycle perspective to ensure that changes associated with an industrial transformation provide net benefits:

Industrial Ecosystem: The industrial ecosystem encompasses all actors and resources (e.g., natural, material, human) in an industrial value chain and their surrounding communities. The industrial ecosystem comprises an integrated single market with all research, design, production, distribution, consumption, and disposal activities spread across participating entities. The system is inclusive of small start-ups, large companies, academia, service providers, suppliers, distributors, waste management providers, end users and the physical infrastructure connecting them all, as well as the complex sets of interactions among subsectors and firms spreading across countries. The industrial ecosystem considers specificities of business models, resource demands, vulnerable stakeholders, and interdependencies among actors.

- *Energy and carbon flows*: Primary energy flows, energy transport and storage infrastructure, and the associated decarbonization infrastructure (e.g., building out the clean electric grid, fuel pipelines and transport networks, CO_2 pipelines, carbon use and sequestration markets, emerging renewable and clean sources of energy and fuels).
- *Material and natural resource flows:* The feedstocks and resources (including water) that industry uses and transforms into products and waste streams, including increased use of end-of-life materials.

[56] Thommie Burström et al., "Industrial ecosystems: A systematic review, framework and research agenda," *Technological Forecasting and Social Change* 208, 123656 (November 2024), doi.org/10.1016/j.techfore.2024.123656.
[57] This is an example of one contemporary description of an industrial ecosystem that is being used by the European Union. See: European Cluster Collaboration Platform, "Industrial Ecosystems: Definition," accessed October 2024, www.clustercollaboration.eu/in-focus/industrial-ecosystems/definition.

- *Information flows*: Effective information flows across actors in the industrial ecosystem can have wide-ranging benefits, such as improving the efficiency of material and energy use, providing a better understanding of supply and demand, and enabling transparency and broader participation of stakeholders in decision-making processes.

A transformation of the U.S. industrial sector will, by default, require changes in the sources, types, and flows of energy, carbon, materials, natural resources, and information. The interconnections of these flows through value chains are complex, creating a need for sophisticated analytical frameworks and data-driven approaches to assess the net impacts of technological changes.[58] Addressing individual parts of the product life cycle in isolation might generate much smaller impacts (and perhaps ultimately unviable or net damaging impacts) than an industrial ecosystem approach[59]; however, the scale and complexity of the industrial ecosystem create many challenges to industrial decarbonization, as detailed in the next section.

2.2 Key Industrial Decarbonization Challenges

Industry faces key challenges that can prevent the fruition of industrial decarbonization and transformation goals. Though difficult, overcoming these challenges will achieve greater societal outcomes, develop cost competitive technologies, and improve efficiency, all of which will ultimately bring value to consumers. This section provides an overview of key challenges that must be considered and addressed in parallel:

- The industrial ecosystem is complex and interconnected, and decarbonizing it requires a systems approach from the outset.
- An industrial transformation cannot occur without an equitable transition. Although the average standard of living attributed to industrial activity has increased over time, benefits and burdens have not been equitably distributed across communities.
- Thermal systems emissions are ubiquitous and heterogeneous in industry, and they are the largest contributor to sector GHG emissions. These systems operate over a broad temperature range, and cost-effective zero-emissions technologies do not yet exist for much of that range.
- Decarbonizing only energy-related emissions does not solve the process emissions problem. These process emissions arise from material transformations of some feedstocks, which are intrinsic to current industrial production of commodities that are vital to the U.S. economy.
- Many needed decarbonization technologies are nascent. Approximately two-thirds of emissions reductions will need to come from technologies that have not yet been invented or are not yet commercially viable.

The following sections describe these challenges, though they are not ranked in any order and should be seen as equally important to address.

2.2.1 Industrial Ecosystem Complexity and Interconnectedness

Deep decarbonization of the industrial sector requires both low-carbon energy supply and a significant expansion of clean manufacturing infrastructure. Such interdependencies necessitate a careful consideration of technology choices, whether at a facility level or an industry-wide scale, to avoid emissions "lock-ins" and the potential for stranded assets or negative impacts on other parts of the supply chain.[60] As noted earlier, the industrial ecosystem is complex, with a range of environmental, economic, societal, and technological impacts.

[58] A range of materials flow analysis, LCA, and TEA techniques can be used; DOE has training, tools, and methodologies available that can be applied based on need. For examples, see: U.S. Department of Energy, "Life Cycle Assessment and Techno-Economic Analysis Training," www.energy.gov/eere/iedo/life-cycle-assessment-and-techno-economic-analysis-training; National Energy Technology Laboratory, "Life Cycle Analysis (LCA) of Energy Technology and Pathways," www.netl.doe.gov/LCA; U.S. Department of Energy, "GREET," www.energy.gov/eere/greet; National Renewable Energy Laboratory, "Materials Flows through Industry (MFI)," mfitool.nrel.gov/about.
[59] United Nations Environment Programme, *Global Resources Outlook 2024* (Nairobi, 2024), www.resourcepanel.org/reports/global-resources-outlook-2024.
[60] For discussions of carbon lock-in, see: Ichiro Sato, Beth Elliott, and Clea Schumer, "What Is Carbon Lock-in and How Can We Avoid It?" World Resources Institute, May 2021, www.wri.org/insights/carbon-lock-in-definition; and Karen C. Seto et al., "Carbon Lock-In: Types, Causes, and Policy Implications," *Annual Review of Environment and Resources* 41 (September 2016): 425-452, doi.org/10.1146/annurev-environ-110615-085934.

This complexity is depicted in Figure 5, which shows some of the multiple systems, stakeholders, and levels of interest that are involved in industrial decarbonization.

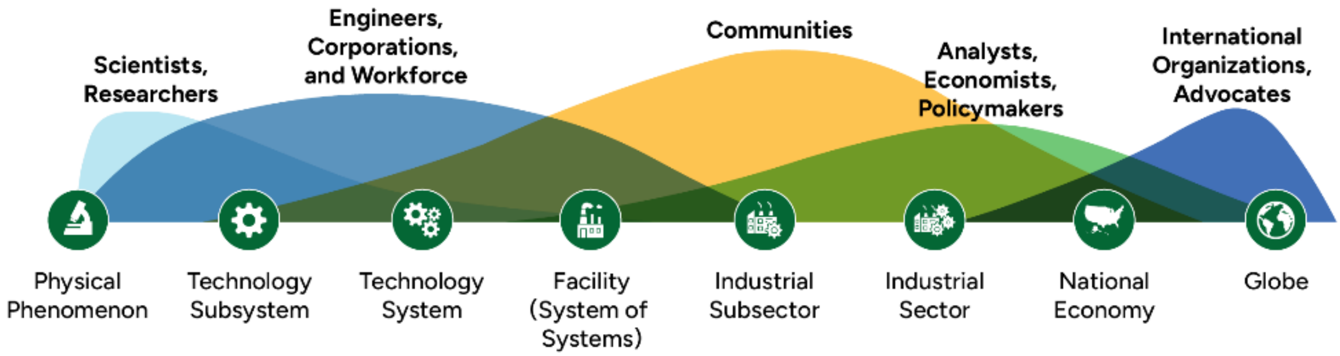

Figure 5. The range of systems involved in the industrial ecosystem across stakeholders and relative levels of interest

Decarbonization efforts require a whole-of-economy approach, using new and emerging technologies to support existing and new industries, to train and employ a skilled and diverse workforce, and to build new or retrofit old manufacturing facilities. Solutions must be able to simultaneously capture and address all these aspects of the transition. Understanding the widespread impacts of emerging decarbonization technologies, though difficult, provides an opportunity to have positive impacts on multiple economic areas with each decarbonization choice.

To understand the complexity of the decarbonization challenge and the range of sustainability (or environmental, economic, and societal) impacts, a complex systems analysis approach is needed, and technologies should be evaluated as part of the entire value chain. Simply decarbonizing a facility using any chosen technology is not sufficient; the technology must be environmentally friendly upstream and through its end-of-life. For example, materials that are used to create a technology should be acquired sustainably, and they should be easy to break down for recycling or reuse. Without capturing this complexity in modeling scenarios, the impacts of some decarbonization pathways might be missed, potentially resulting in some communities or stakeholders being negatively affected or not receiving the benefits of the transition.

Impacts on workforce can be overlooked in a complex system, in which the interplay between economy-wide success and household-level economic success are heavily influenced by labor market opportunities; however, the interdependencies between these two factors are often undervalued. Other technical challenges are difficult for industry to quantify, e.g., the risks of changing an industrial process to include decarbonized process steps as opposed to building a novel decarbonized process solution from the ground-up. The nature of the risks of novel technology, including long technology maturation and validation cycles, encourages status quo biases in industry.[61] Further, determining how new technologies might be integrated into existing manufacturing facilities and processes without compromising the material and process compatibility, such as concerns related to catalyst deactivation or product quality, is difficult.

Achieving a net zero economy will impact all parts of life; thus, pathways to industrial decarbonization also present opportunities to further other goals beyond emissions reduction, such as EEJ, where a technology could address multiple challenges.

2.2.2 Equitable Transition

In the United States, many industrial facilities are located in disadvantaged communities, which are disproportionately affected by industrial activity, resulting in societal, economic, and health burdens beyond those of the general population.[62] Historically, the burdens of industrial expansion have been carried by low-

[61] National Academies of Sciences, Engineering, and Medicine, *Developing and Assessing Ideas for Social and Behavioral Research to Speed Efficient and Equitable Industrial Decarbonization* (Washington, DC: The National Academies Press, 2024), nap.nationalacademies.org/catalog/27815.
[62] Debra J. Salazar et al., "Race, Income, and Environmental Inequality in the U.S. States, 1990–2014," *Sociological Quarterly* 100, 3 (February 2019): 592-603, doi.org/10.1111/ssqu.12608.

income communities and communities of color.[63] The impacts of climate change compound these inequalities. Moreover, "energy insecure" communities, or those unable to adequately meet household energy needs,[64] will experience even higher economic stress as temperatures rise.[65] These communities continue to bear the brunt of the industrial pollution burden, and they stand to benefit the most from the economic revitalization and reduced pollution that a just transition to clean manufacturing can provide.

An example of disproportional impacts includes the distribution of fine particulate matter ($PM_{2.5}$), a well-documented environmental burden indicator of air pollution, which largely stems from the combustion of fossil fuels, including those from industrial processes. $PM_{2.5}$ exposure is linked to 63% of deaths from environmental causes and 3% of all deaths in the United States.[66] Although the total $PM_{2.5}$ pollution has decreased, racial, ethnic, and socioeconomic disparity in exposure remains. The industrial sector is the largest source of absolute $PM_{2.5}$ exposure disparity for people of color compared to the national average.[67] Moreover, the low spatial resolution of the limited data that are currently available remains a key challenge to the further exploration of local and dynamic impacts caused by $PM_{2.5}$ as well as those related to other environmental burden indicators.

The link between industry and disadvantaged communities highlights the opportunity to integrate EEJ concepts into the energy transition, maximizing the benefits of economic stimulus and reduced environmental impacts in disadvantaged communities. Although federal actions have started integrating EEJ considerations into the clean energy transition[68,69], more is needed, particularly as industry is asked to address challenges beyond emissions.

The constant element of an equitable transition is that the societal changes propagated by industrial decarbonization are spatial. Disadvantaged communities are not uniformly spread throughout the United States, they do not all face the same types of issues, and they can have different priorities. EEJ strategies must be developed and applicable to the specific industrial context of a given disadvantaged community.

Community engagement is central to ethical industrial practices and must begin well before a project is underway, with attention given to the impacts of a particular industrial subsector and the needs of the community impacted. Understanding the unique aspects of each project will support productive community engagement and feedback. Without focused attention on developing relationships and community trust in the project development process, community engagement challenges may arise, such as a lack of availability among community members to provide feedback, a lack of understanding of the issues at hand, and a lack of buy-in of the overall project. Supporting strong community engagement relationships may look different depending on the project and community but may include providing compensation for time spent in meetings, offering a meal during meetings, and/or making childcare and transportation services available.

2.2.3 Thermal Systems Emissions

Emissions from thermal systems (e.g., process heat, combined heat and power) represent approximately half of all energy-related manufacturing emissions, with more than 90% due to fossil fuel combustion.[70] Thermal systems operate over broad temperature ranges, and some heating applications lack commercialized zero-

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[63] Jill Johnston and Lara Cushing, "Chemical Exposures, Health, and Environmental Justice in Communities Living on the Fenceline of Industry," *Current Environmental Health Report* 7 (2020): 48–57, doi.org/10.1007/s40572-020-00263-8.
64 Diana Hernández, Qëndresa Krasniqi, and Alexandra Peek, "Energy Insecurity in the United States," (Columbia University Center on Global Energy Policy, 2023), www.energypolicy.columbia.edu/publications/energy-insecurity-in-the-united-states.
[65] Ciaran L. Gallagher and Tracey Holloway, "U.S. decarbonization impacts on air quality and environmental justice," *Environmental Research Letters* 17, 11 (October 2022), doi.org/10.1088/1748-9326/ac99ef.
[66] Christopher W. Tessum et al., "Inequity in Consumption of Goods and Services Adds to Racial–Ethnic Disparities in Air Pollution Exposure," *Proceedings of the National Academy of Sciences* 116, 13 (March 2019): 6001–6006, doi.org/10.1073/pnas.1818859116.
[67] Christopher W. Tessum et al., "$PM_{2.5}$ Polluters Disproportionately and Systemically Affect People of Color in the United States," *Science Advances* 7, 18 (April 2021), doi.org/10.1126/sciadv.abf4491.
[68] Joseph R. Biden, "Tackling the Climate Crisis at Home and Abroad," *Federal Register* 86, no. 19 (February 1, 2021): 7619–7623, www.federalregister.gov/d/2021-02177.
[69] Joseph R. Biden, "Revitalizing Our Nation's Commitment to Environmental Justice for All," *Federal Register* 88, no. 80 (April 26, 2023): 25251–25257, www.federalregister.gov/d/2023-08955.
[70] U.S. Department of Energy, "Manufacturing Energy and Carbon Footprints (MECS 2018)," accessed November 2024, www.energy.gov/eere/iedo/manufacturing-energy-and-carbon-footprints-2018-mecs.

emissions technologies.[71] Figure 6 shows the estimated carbon intensity and emissions of process heating in manufacturing subsectors by amount and energy source in 2018, highlighting the emissions baseline that must be overcome.

Figure 6. Process heat carbon emissions and emissions intensity for U.S. manufacturing subsectors, 2018

Acroynms/abbreviations: carbon dioxide (CO_2), kilogram (kg), million British thermal units (MMBtu), million metric tons (MMT). Note: The apparel and leather & allied products subsectors consume neglible amounts of electricity and fuel (<0.1 trillion Btu) for process heat and are not shown. Data sources: U.S. Department of Energy, "Manufacturing Energy and Carbon Footprints (MECS 2018)," accessed November 2024, www.energy.gov/eere/iedo/manufacturing-energy-and-carbon-footprints-2018-mecs; U.S. Energy Information Administration, "Manufacturing Energy Consumption Survey (MECS)," accessed October 2024, www.eia.gov/consumption/manufacturing/.

Traditionally, many process heat needs have been met through the combustion of fossil fuels, which have historically been available in high quantities and at low costs. Cheap and plentiful fossil fuels have allowed industry to benefit from low product costs and high productivity, making it challenging to replace what has been the primary energy source for many manufacturers. Hydrocarbon availability and onsite combustion have further allowed for the coproduction of electricity and heat at high efficiencies. Highly optimized process parameters based on fossil fuel use will need to be modified when implementing alternative heating strategies that are more consistent with decarbonization efforts, such as fuel swapping (e.g., using clean hydrogen[72]), electric heating using clean electricity, or low-thermal budget and non-thermal solutions.

In addition, process heating requires tailored solutions for individual subsectors and products. Beyond heating needs, decarbonized solutions for existing facilities or processes must also consider existing space and other constraints, such as the limited temperature range of a technology, which complicates and limits the number of solutions with the right technical capabilities. Concerns over the availability of both clean fuels and electricity for proposed heating solutions, and the associated infrastructure requirements, must also be considered. Infrastructure to meet demand must be built to support the production, transportation, and use of alternative fuels or additional clean electricity. These factors cause additional risks compared to hydrocarbons, which have had established and standardized methods for all process stages for decades (e.g., rail cars for coal transportation or hundreds of miles of pipelines for oil and gas delivery).

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[71] Joe Cresko et al., *Thermal Process Intensification: Transforming the Way Industry Uses Thermal Process Energy* (U.S. Department of Energy, 2022), www.osti.gov/biblio/1871912.

[72] DOE's Hydrogen Shot™ aims to reduce the cost of clean hydrogen produced using diverse domestic resources (including electrolysis powered by clean electricity and natural gas reforming with carbon capture and storage, among others) to $1/kg H_2 to achieve better cost parity with incumbent fuels. See: U.S. Department of Energy, "Hydrogen Shot," accessed October 2024, www.energy.gov/eere/fuelcells/hydrogen-shot.

Transitioning to an alternative fuel or moving to another energy source or carrier might require an infrastructure overhaul to facilitate the industrial transition and maintain a resilient supply. On the other hand, diversifying the sources of energy for process heat provides an opportunity to build resilience by reducing the reliance on potentially volatile fossil fuel markets. Electrification is particularly beneficial in this regard. Onsite generation, including through clean sources, onsite energy storage, and purchased electricity can diversify an industrial facility's sources of energy. Even if the grid is not fully decarbonized, concentrating the emissions to a centralized power generation facility, as opposed to emissions from distributed thermal processes, can enable further reduction of the overall environmental impacts.[73]

2.2.4 Process Emissions

Even if grid electricity, process heating, and other energy consuming end uses are fully decarbonized, some processes will still have remaining non-energy-related process emissions. Generated from material transformations, process emissions are intrinsic to the current production of vital commodities and can be difficult to decarbonize. Though limited to specific subsectors, as shown in Figure 7, process emissions make up approximately 15% of total manufacturing emissions.[74]

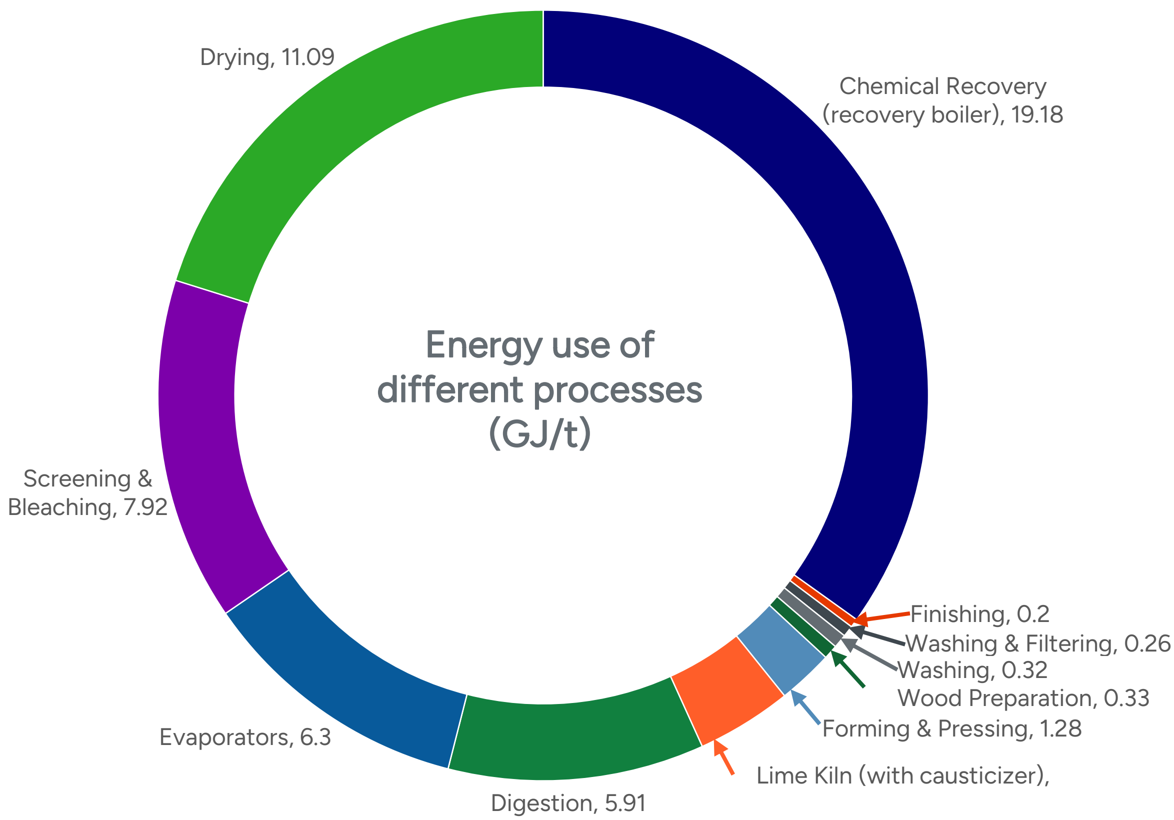

Figure 7. U.S. manufacturing process emissions in 2018

Data sources: U.S. Department of Energy, "Manufacturing Energy and Carbon Footprints (MECS 2018)," accessed November 2024, www.energy.gov/eere/iedo/manufacturing-energy-and-carbon-footprints-2018-mecs; U.S. Environmental Protection Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022, EPA 430-R-24-004 (2024), www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.

Chapter 4 of the U.S. Environmental Protection Agency's (EPA's) Inventory of U.S. Greenhouse Gas Emissions and Sinks[75] provides a detailed breakdown of industrial process emissions and tracks trends of these emissions

[73] Deason et al., "Electrification of buildings and industry in the United States: Drivers, barriers, prospects, and policy approaches," Lawrence Berkeley National Laboratory Energy Analysis and Environmental Impacts Division (March 2018), www.osti.gov/biblio/1430688.
[74] U.S. Department of Energy, "Manufacturing Energy and Carbon Footprints (MECS 2018)," accessed November 2024, www.energy.gov/eere/iedo/manufacturing-energy-and-carbon-footprints-2018-mecs.
[75] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022*, EPA 430-R-24-004 (2024), www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.

by manufacturing source. An example of non-energy-related process emissions occurs in the conversion of limestone (calcium carbonate) to lime, which releases a molecule of CO_2 for every molecule of lime, and it is essential in the production of cement clinker, glass, and steel. According to the latest version of the *Inventory of U.S. Greenhouse Gas Emissions and Sinks*, the EPA notes that metal production process emissions have significantly declined since 1990 in the United States, as their production has been shifted to other countries or, in the case of iron and steel production, has moved to a less emissions-intensive process (from blast furnace–basic oxygen furnace, which releases CO_2 and CH_4 process emissions, to electric arc furnace, which involves an increased use of steel scrap).[76]

Compared with energy-related emissions, addressing process emissions will require more substantial changes to the process or facility and will bring added risks and challenges. Although CCUS can be implemented, infrastructure constraints and additional energy burdens must be considered. In addition, changing production processes or input materials might introduce uncertainty in final product quality, process economics, and regulatory compliance.

2.2.5 Emerging Decarbonization Technologies

As decarbonization efforts progress, approximately 60% of the heavy industry GHG emissions reductions is expected to come from technologies that are not yet commercialized or developed—or perhaps even conceptualized.[77] This projection suggests that, though investments are needed to implement existing decarbonization technologies, realizing a fully decarbonized economy will also require significant R&D, particularly because identified theoretical methodologies for providing process heat require support technologies and process knowledge that have not yet reached commercialization. Emerging technologies must address new process parameters of concern, such as material degradation or corrosion as well as increasing resilience and application in real-world scenarios. Non-equilibrium process parameters, such as startup and shutdown of processes, and control parameters will also need to be considered and adjusted by these emerging solutions.

The scale-up of existing bench-scale demonstrations will also be a focus of these continued R&D efforts. New technologies must be demonstrated in real-world design conditions and variability that occurs at the commercial scale to facilitate industrial confidence. Many industrial subsectors that operate at large production scales also require large pilot testing as a proof of concept to consider an emerging technology viable, particularly when process parameters convert a process from continuous to batch operation and as it operates on a clean grid.

Typically, modeling, simulation, or other virtual tools are used to facilitate the investigation of process alternatives; however, further clarification is needed to understand how these tools can accelerate adoption or de-risk technology transfer. Modeling can miss large-scale processing concerns, indicating that additional guidance for performing these analyses might be required. Difficulties with modeling emphasize the value of actual data from large-scale pilot systems.

Most of these decarbonization challenges are underscored by the concern of the potential unavailability of the generation, transmission, and distribution of low-cost clean electricity. This supply risk will also require further innovation. Concerns about grid stability, reliability, and infrastructure limit industrial adoption of new and emerging technologies. Infrastructure such as pipelines—both for delivering fuels like hydrogen or transporting captured CO_2—might be required to realize cross-cutting strategies.

2.3 Common Barriers Across the Industrial Ecosystem

A variety of technology, market, and infrastructure barriers currently exist, which can hinder decarbonization efforts by slowing or ultimately preventing industrial decarbonization if left unaddressed. Although many of these barriers exist within an industrial entity, others exist more broadly across the industrial ecosystem, and they can be exacerbated by the implementation of new processes and emerging technologies. Such barriers

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[76] Ibid

[77] U.S. Department of Energy, *Pathways to Commercial Liftoff: Industrial Decarbonization* (2023), liftoff.energy.gov/industrial-decarbonization/overview/.

include, but are not limited to, underrepresented societal criteria, costs and value, decarbonization infrastructure, inefficient information flows, and other constraints within and around industrial entities.

2.3.1 Underrepresented Societal Criteria

Protecting the human element, including the workforce and associated communities that interact with industry, is a priority during the clean energy transition; however, lack of data and societal metrics to measure workforce and community impacts can impede both the energy transition and societal and environmental justice objectives. Including metrics in technology decision-making can allow consistent and comparable societal impact analysis to enable equitable outcomes.

Some analytical frameworks, indices, and databases have been created to assist in developing strategic objectives for disadvantaged communities. These tools include the Equitable Deep Decarbonization framework,[78] the Climate and Economic Justice Screening Tool of the White House Council on Environmental Quality,[79] and DOE's Energy Justice Dashboard,[80] among others. However, these tools rely on quantifiable metrics, and the "metrification" of EEJ may not fully capture the spirit and complexity of the issues disadvantaged communities face. For example, though physical territory or toxic chemical levels can be quantified, the cultural and spiritual significance of land cannot.[81] Thus, new approaches, metrics, and/or criteria might be needed to fully capture EEJ issues associated with the clean energy transition.

Similarly, additional research, methodologies, and criteria can help to assess the impacts of industrial decarbonization on the workforce. A more holistic approach, one that extends beyond the focus on jobs and skills and considers workers as individuals and community members, is needed to ensure a successful labor transition.[82] Although traditional labor metrics exist, such as labor supply and productivity, new criteria might be needed to supplement our understanding of workforce impacts within the context of industrial decarbonization.

Additionally, data availability for many societal criteria remains insufficient. For example, although data related to air quality are highly available in the United States from the EPA, data for other criteria (e.g., soil contamination) are much less comprehensive, which is also the case for qualitative data such as narratives and storytelling that help provide a more holistic assessment of societal impacts. The lack of data limits the ability of researchers, developers, and industrial entities to evaluate technologies and projects, and of decision makers to further protect communities from environmental injustices and support the workforce through this transition.

2.3.2 Costs and Value

The cost of decarbonization and decarbonized products is a barrier that extends beyond a specific industrial subsector and applies to both manufacturers and consumers. Typically, the first barrier to the implementation of decarbonized solutions is cost uncertainty. There are many aspects of costs and value that can create barriers to industry, a few of which are described here.

As with any new production method or process parameter, capital investments might be required to ensure a successful product. Capital expenses and potential new operating costs are significant barriers to industrial adoption of decarbonized processes.

Further, unforeseen costs for decarbonized technologies also play a role in the hesitancy to adopt decarbonized processes. These costs include the fluctuation of energy prices and supply chain constraints that will arise as

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[78] C. Anna Spurlock, Salma Elmallah, and Tony G. Reames, "Equitable deep decarbonization: A framework to facilitate energy justice-based multidisciplinary modeling," *Energy Research & Social Science* 92, (October 2022), doi.org/10.1016/j.erss.2022.102808.
[79] U.S. Environmental Protection Agency, "Climate and Economic Justice Screening Tool," accessed October 2024, screeningtool.geoplatform.gov/en/.
[80] U.S. Department of Energy, "Energy Justice Dashboard," accessed October 2024, www.energy.gov/justice/energy-justice-dashboard-beta.
[81] Jennifer Hirsch et al., "The Crucial Role of Just Process for Equitable Industrial Decarbonization: An Action Research Agenda for Carbon Management and Other Emerging Technologies," (National Academies of Sciences, Engineering, and Medicine, 2024), www.nationalacademies.org/event/docs/DF5F159E0D15E4C4589386276C5F167ADB63713FA639.
[82] National Academies of Sciences, Engineering, and Medicine, *Developing and Assessing Ideas for Social and Behavioral Research to Speed Efficient and Equitable Industrial Decarbonization* (Washington, DC: National Academies Press, 2024), nap.nationalacademies.org/catalog/27815.

new materials and technologies begin competing with historical supplies. For example, as organizations consider electrifying their processes, they are concerned about the availability and affordability of clean electricity sources. Electricity prices have already been increasing faster than other sources of energy in some parts of the United States,[83] and the lack of accurate modeling impacts the projected costs and benefits of emerging electrified decarbonized processes. In addition to the uncertainty in forecasting trends in electricity prices, there is also electricity price volatility, which can significantly affect a project's operating expenses. All energy markets have some volatility, although changes in electricity prices have different temporal frequencies than other markets. Electricity prices are affected by the cost pass-through of volatility in the fuels market, primarily with natural gas generation, as well as supply-side or demand-side driven volatility, e.g., outages or weather-induced peak loads.[84]

Despite cost uncertainty, decarbonization presents opportunities to generate value for both industrial entities and consumers. Investments in new processes and equipment can increase energy and material efficiency, directly improving an industry's bottom line while offering an opportunity to improve product quality, benefiting consumers. Although decarbonization strategies might not prove profitable in the near term, learning curve trends and experience curve effects (such as Wright's Law[85]) indicate that capital and operational costs will generally decrease over time, extending further value to future decarbonization investments.

Above all, data for the cost and operation of decarbonized technologies are lacking and more work is needed to fill this gap. High-quality, objective data are rare, rendering difficulties to their use for plant or industry planning. This data deficiency further complicates the estimation of potential costs for industry to pursue decarbonization, and the existing incentives for implementing decarbonized processes or reducing supply chain emissions intensity often do not outweigh the risks of elevated costs.

2.3.3 Availability of Decarbonization Infrastructure

All decarbonization pathways will require the expansion of decarbonization infrastructure, such as transmission lines for the clean electric grid; pipelines for the transport of CO_2, clean hydrogen, and biofuels; and transport networks for CCUS. Each action faces technological, geographic, and temporal limitations. The same decarbonization infrastructure that will serve manufacturing subsectors is also facing growing demand from the transportation and commercial buildings sectors. Moreover, access to decarbonization infrastructure will vary regionally, requiring a diversity of solutions to meet local decarbonization targets.

Existing limitations for decarbonization infrastructure include a current reliance on fossil fuels, inadequate integration capacity for clean energy sources, and limited regional hydrogen and carbon capture transportation networks. Addressing the grid integration of clean energy sources, including nuclear and renewable energy sources, will diminish the reliance on fossil fuels.[86] The current U.S. electric grid has been designed to complement unidirectional energy transfers from a plant to consumers.[87] Because clean energy production can be intermittent, it requires grids that can both distribute and store energy at larger capacities.[88] For example, wind and solar energy are intermittent resources, which necessitate extensive networks of energy storage facilities. When considering a clean grid, noting the likeliness of price fluctuation in parallel with energy availability is important. Technical solutions to these limitations exist or are under development (e.g., new energy

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[83] U.S. Energy Information Administration, "Electricity," updated October 2024, www.eia.gov/electricity/data.php.
[84] Alessio Saretto, Anastasia Shcherbakova, and Jeremy Lin, "What Fuels the Volatility of Electricity Prices?" (Federal Reserve Bank of Dallas, 2024), doi.org/10.24149/wp2408.
[85] Béla Nagy et al., "Statistical Basis for Predicting Technological Progress," *PLoS One* 8, 2 (February 2013), doi.org/10.1371/journal.pone.0052669.
[86] One example that can address limitations to industrial infrastructure with potential co-benefits for demand response is the uptake and adoption of flexible combined heat and power systems. For more information, see U.S. Department of Energy, *Flexible Combined Heat and Power (CHP) Systems,* DOE/EE-1631, (2018), www.energy.gov/eere/amo/articles/flexible-combined-heat-and-power-chp-systems-fact-sheet-2018 and Dal Jesai et al., *Potential Impact of Flexible CHP on the Future Electric Grid in California,* ORNL/TM-2019/1259 (Oak Ridge National Laboratory, 2020), doi.org/10.2172/1649545doi.org/10.2172/1649545.
[87] Benjamin K. Sovacool et al., "Beyond the factory: Ten interdisciplinary lessons for industrial decarbonisation practice and policy," *Energy Reports* 11 (June 2024): 5935-5946, doi.org/10.1016/j.egyr.2024.05.048.
[88] Jaquelin Cochran et al., *Grid Integration and the Carrying Capacity of the U.S. Grid to Incorporate Variable Renewable Energy,* NREL/TP-6A20-62607 (National Renewable Energy Laboratory, 2015), www.osti.gov/biblio/1215010.

storage, demand response),[89] but their adoption is primarily limited by the underestimation of certain factors, such as local benefits, air quality improvements, and the added value of diverse energy sources.[90]

CCUS and clean hydrogen are both primary pathways to industrial decarbonization with limited existing infrastructure.[91] Carbon capture is an essential tool for reducing non-energy emissions and abating emissions not addressed by other decarbonization pillars. Regional transport infrastructure for further utilization or storage is necessary to realize the potential of carbon capture.[92]

Similarly, the transportation of hydrogen is essential to enabling its use in industrial facilities. Hydrogen is transported via pipeline, on cryogenic liquid tanker trucks, or on gaseous tube trailers.[93] Pipelines are feasible only in areas expected to sustain high demand over the course of decades.[94] Due to the current high costs of different hydrogen transport options, there is an emphasis on regional hydrogen networks that can help minimize transport distances.[95] DOE has identified nine high-potential areas for the development of regional hydrogen networks. The largest of these investments is $7 billion toward Regional Clean Hydrogen Hubs, an initiative dedicated to solving issues around hydrogen transportation and storage to make hydrogen a viable clean energy carrier.[96, 97]

Industrial decarbonization will require the integration of novel technologies in a manner that ensures equitable, efficient distribution and the use of clean feedstocks. Unoptimized infrastructure will hinder decarbonization efforts, requiring further analysis and infrastructure investment to achieve success at the industrial operation scale. Overcoming this barrier could involve strategies such as repurposing or reusing existing infrastructure at brownfield and greenfield sites, co-locating industrial facilities to reduce investment costs, and repurposing fossil fuel pipelines for the transport of hydrogen or biofuels, particularly for rapid, near-term efforts.

2.3.4 Inefficient Information Flows

Another barrier to industrial decarbonization involves the inefficient flow of information across the industrial ecosystem. Data privacy concerns and the lack of information-sharing mechanisms and incentives can affect the scale and speed of industrial decarbonization efforts, particularly with ever-evolving cybersecurity needs. These challenges are particularly salient for intellectual property, as its protection is key to retaining a competitive edge for industrial companies, and uncertainties about what might lead to intellectual property can limit industry's ability to share information across manufacturers and subsectors that can aid in decarbonization.

Hoarding information limits the production of data and the publication of case studies (as discussed in Section 2.3.1 around societal criteria and in Section 2.3.2 around cost), and it ultimately represents a barrier to decarbonization efforts. Improved information exchange within industry and between stakeholders would allow for more optimal resource allocation. Sharing information to develop case studies could encourage early technology adoption; allow companies to benchmark against their peers; inform analyses; assess targets; enlighten decision-makers, operators, and partners across industry; and enable an equitable transition with all stakeholders' input.

Information sharing would be facilitated through shared universal structures. Standardizing metrics and frameworks for assessing technology performance in societal, environmental, and economic categories within the context of industrial decarbonization would be beneficial to multiple stakeholders and enable third-party

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[89] June Kim, "Heat-storing batteries are scaling up to solve one of climate's dirtiest problems," MIT Technology Review, October 24, 2023, www.technologyreview.com/2023/10/24/1082217/heat-battery-manufacturing-facility/.
[90] Ibid.
[91] U.S. Department of Energy, "Clean Hydrogen Production Standard Guidance," accessed October 2024, www.hydrogen.energy.gov/library/policies-acts/clean-hydrogen-production-standard.
[92] Elizabeth Abramson, Dane McFarlane, and Jeff Brown, *Transport Infrastructure for Carbon Capture and Storage: White Paper on Regional Infrastructure for Midcentury Decarbonization* (Great Plains Institute, 2020), www.betterenergy.org/wp-content/uploads/2020/06/GPI_RegionalCO2Whitepaper.pdf.
[93] U.S. Department of Energy, "Hydrogen Delivery," accessed October 2024, www.energy.gov/eere/fuelcells/hydrogen-delivery.
[94] Ibid.
[95] Ibid.
[96] U.S. Department of Energy, *U.S. National Clean Hydrogen Strategy and Roadmap* (2023), www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap.
[97] U.S. Department of Energy, "Regional Clean Hydrogen Hubs," accessed October 2024, www.energy.gov/oced/regional-clean-hydrogen-hubs-0.

organizations to verify their claims. Creating well-defined, standardized terms and concepts would reduce confusion. Together, these types of standardizations can speed up project planning, reduce risk for industrial subsectors, and remove burdens on the federal government to verify these claims.

2.3.5 Other Constraints Within and Around Industrial Entities

Current industrial entities' operations and structures can limit zero-emissions technology adoption and material and energy efficiency improvements in existing processes. Beyond cost factors such as capital and operating budget limitations, barriers include (but are not limited to) a low risk tolerance, the prioritization of technology reliability and uptime, a limited workforce trained in decarbonized technologies and processes, and challenges surrounding the emergence and the use of artificial intelligence. These barriers are only a few examples of additional constraints related to decarbonization within and around industrial entities. Factors that play into these barriers within industrial entities include a lack of genuine leadership buy-in to reach emissions reduction or energy-reduction goals, company culture, institutional inertia, and a resistance to change.

Historically, large-scale subsectors have low risk tolerances, which limits the speed of industrial decarbonization because of the risks inherent in adopting emerging technologies (as discussed in previous sections). Risks exist in understanding and complying with new, zero-emissions technologies and standards, permitting, and other emerging regulations. Delays in permitting can also increase technological risks. Infrastructure and energy projects must often undergo a complex and lengthy permitting process. These projects require approval from local, state, and federal authorities, across a range of categories, such as land use and zoning ordinances, air and water protection, and grid interconnection agreements. The types and number of permits that are necessary will depend on the project's intended purpose and its size, location, and jurisdiction.[98,99] These factors often result in significant delays, create uncertainty in project timelines, and can limit the adoption of decarbonization technologies.

Regulation is an additional source of uncertainty for industrial decarbonization efforts. Regulatory frameworks to promote the adoption of emerging technologies can come in many forms, such as feed-in tariffs and premium schemes, net metering, renewable portfolio standards and trading certificate systems, investment subsidies, and/or tax credits.[100] The combination of these frameworks can create a complex system of local, county, state, and federal incentives that can affect the adoption of pathways viewed as viable by industrial partners. Further incentives for industry to improve resource and material efficiencies could accelerate adoption.

Additionally, the sensitivity of most industrial subsectors to any disruptions or uncertainties in their processes cannot be understated. Retrofitting or adopting new technologies can cause downtime in facilities, which is especially challenging to companies whose operating processes are inherently sensitive to disruption (e.g., batch processes) or to companies operating on slim profit margins and unable to accommodate production stoppages or slows. Some companies or facilities also might not want to be early adopters of technologies that have not been commercially proven and that might be perceived as unreliable.

Challenges with the workforce also exist across industrial subsectors and products. Concerns around skilled labor shortages are expected to increase—and potentially become exacerbated—as workforce requirements for future technologies in a decarbonized economy will increasingly include additional, novel skill sets. To achieve successful industrial decarbonization, the existing workforce must first be adequately prepared for the industrial transformation. Concerns about job security, skill requirements, reluctance to change, and the uncertain reliability of new technologies can be overcome by expanding education and training programs to help new and existing workers acquire in-demand skills and knowledge and by investing in workers' human capital through competitive compensation and pathways for career advancement.

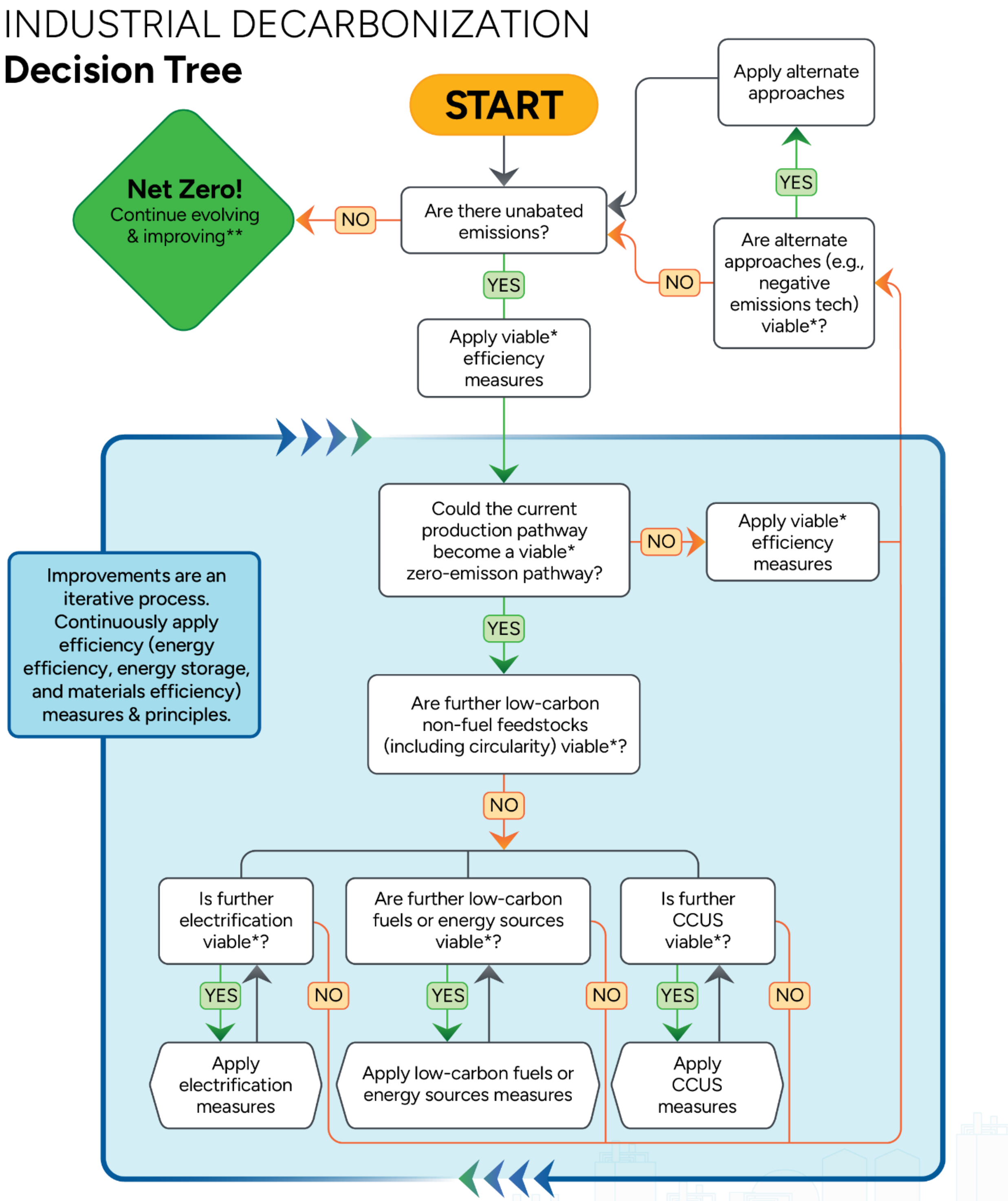
[98] Lori Bird and Katrina McLaughlin, "US Clean Energy Goals Hinge on Faster Permitting," World Resources Institute, February 9, 2023, www.wri.org/insights/clean-energy-permitting-reform-us.
[99] Rayan Sud and Sanjay Patnaik, "How does permitting for clean energy infrastructure work?" Brookings Institute, September 28, 2022, www.brookings.edu/articles/how-does-permitting-for-clean-energy-infrastructure-work/.
[100] Àlex Alonso-Travesset et al., "Economic and Regulatory Uncertainty in Renewable Energy System Design: A Review," *Energies* 16, 2 (January 2023): 882, doi.org/10.3390/en16020882.

2.4 Pathways to Overcoming Challenges and Barriers

Pathways are not a single decision, but rather a series of decisions over time. Decarbonization pathways require decision-making and investment under uncertainty. All pathways require parallel investments to achieve net zero GHG emissions by 2050. Due to the long lifetimes of industrial facilities and related infrastructure, timing is challenging for any pathway. Frameworks and data-informed decision tools were developed as part of this study to help map out and inform such decisions. To help visualize the optionality to achieve near zero GHG emissions within industrial subsectors, we introduced a decision tree framework that can support the evaluation and understanding of potential pathways.

Figure 8 shows this notional decision tree approach describing the decisions within the industrial decarbonization opportunity space. The specific approach to making technology choices for a particular industry or facility might deviate from the general version shown. Many decarbonization technologies in the opportunity space covered by this decision tree are currently commercially viable, whereas others are expected to become commercial in the coming decades. Further, several decarbonization measures will likely rely on the decarbonization of energy supply systems and the development/expansion of energy and industrial infrastructure. Such interdependencies require careful consideration of technology choice phasing, whether at a facility level or at an industry-wide scale, to avoid emission "lock-ins," potential stranded assets, or "dead-ends" in the future.

Decision trees are intended to help us understand the promising high-level pathways that industry can pursue and illustrate the general flow of the pathway models. These frameworks represent pathway that are options available in the models, which depend on inputs and assumptions. This decision tree, shown in Figure 8, also represents a continuous process that can be applied at different points of time.



*Viable implies currently available, cost-effective, and that the measures are deemed effective through social and environmental criteria and necessary

** Morrow, William III et al. 2017. "U.S. Industrial Sector Energy Productivity Improvement Pathways." U.S. Industrial Sector Energy Productivity Improvement Pathways (aceee.org)

Figure 8. An example of an industrial decarbonization decision tree

Sequencing and specific decarbonization strategies may vary. This figure is provided to facilitate discussion, to identify the barriers and opportunities in decarbonization pathways, and to better understand decision-making under uncertainty.

There are additional layers beneath the simple version shown in Figure 8 around the applied technologies, assumptions, and other key factors relevant to each pathway. Understanding potential pathways includes considering the following elements:

- The major production routes and/or unit operations for each industrial subsector
- The major decision points that might shape each pathway, the relative timing between now and 2050 for these decision points, and the information that will be needed for those decision points
- The primary factors that might determine how many facilities within a subsector would choose an individual production route, process, or technology
- The major similarities and differences in technologies and solutions across the major pathways and production routes
- Investments that could be made in parallel and as no-regrets strategies as well as those with potential risks for creating stranded assets
- The portion of each pathway that can be achieved through enhancing existing facilities versus constructing new facilities
- The major barriers to the successful development and accelerated deployment of key technologies and solutions within each pathway
- The major uncertainties across each pathway
- The economic, environmental, and societal impacts of each pathway.

2.4.1 Pathways Decision Factors

There are many factors that influence which pathway any given industrial facility might take to achieve emissions reductions. Example factors are provided in Table 2; this list is not intended to be all-encompassing but instead aims to show the types of factors a facility or company might consider in decision-making.

Table 2. Types of Factors That Can Influence Pathway Choice

Category	Example Factors
Business	• Product mix (steady or dynamic) • Domestic and international competition • Company-specific commitments • Potential return on investment and profit • Cost (e.g., financing, product cost, capital and operating expenses) • Secure and sustainable supply chains and customers • Risk tolerance and mitigation • Product impact • Practical feasibility within a given facility • Public perception and/or demand
Workforce	• Needed number of workers • Workers with the right skill sets • Workers near a specific facility location
Infrastructure availability	• Energy supply infrastructure: electricity, hydrogen, and bioenergy • Carbon capture, transport, and storage infrastructure • Logistics infrastructure for supply chain and transport needs
Policy	• Federal, state, and local regulations (environmental, workforce, etc.)

- International trade
- Taxes and incentives
- Corporate policies

Pathways taken by individual facilities, corporations, and industrial subsectors will be the collective sum of many decisions. Inputs and insights into the factors behind the decisions made by facilities, companies, and other organizations can inform DOE analysis and modeling—and ultimately DOE investments that, over time, will put the U.S. industrial sector on a path toward net zero GHG emissions by 2050. Determining the specific criteria can help assess the impacts of the pathways on these types of factors.

3 EVALUATING AND MODELING PATHWAYS TO U.S. INDUSTRIAL DECARBONIZATION

As discussed in Section 1.2, a decarbonization pathway is characterized as a sequence of technology deployments and retirements over time that allow U.S. industry to arrive at an established level of GHG emissions (such as low-carbon to near zero) within an established timeframe. There is no single pathway to net zero GHG emissions for the industrial sector overall, for specific subsectors, or even for an individual facility. Further, pathways will evolve as the future unfolds and new technologies become available.

This section dives into the impacts and evaluation criteria, which can be used to evaluate potential decarbonization pathways (technological, economic, environmental and health, and societal) (Section 3.1) as well as on the details of decarbonization pillars and modeled sensitivities used within this report (Section 3.2).

3.1 Industrial Decarbonization Pathways–Impact and Evaluation Criteria

Data-informed decision-making on decarbonization pathways requires a comprehensive set of information about diverse factors. These include decarbonization opportunities and barriers, as well as impacts and evaluation criteria, for individual facilities and across society. This section explores the impact and evaluation criteria that can be used to project the likelihood of different pathways' adoption by various industrial facilities and quantify the impacts of diverse pathways.

Industrial impact and evaluation criteria can be considered across four categories as illustrated in Figure 9: technological, economic, environmental and health, and societal. Societal criteria can additionally include implications related to EEJ; energy costs and infrastructure; workforce; and resilient supply chains.

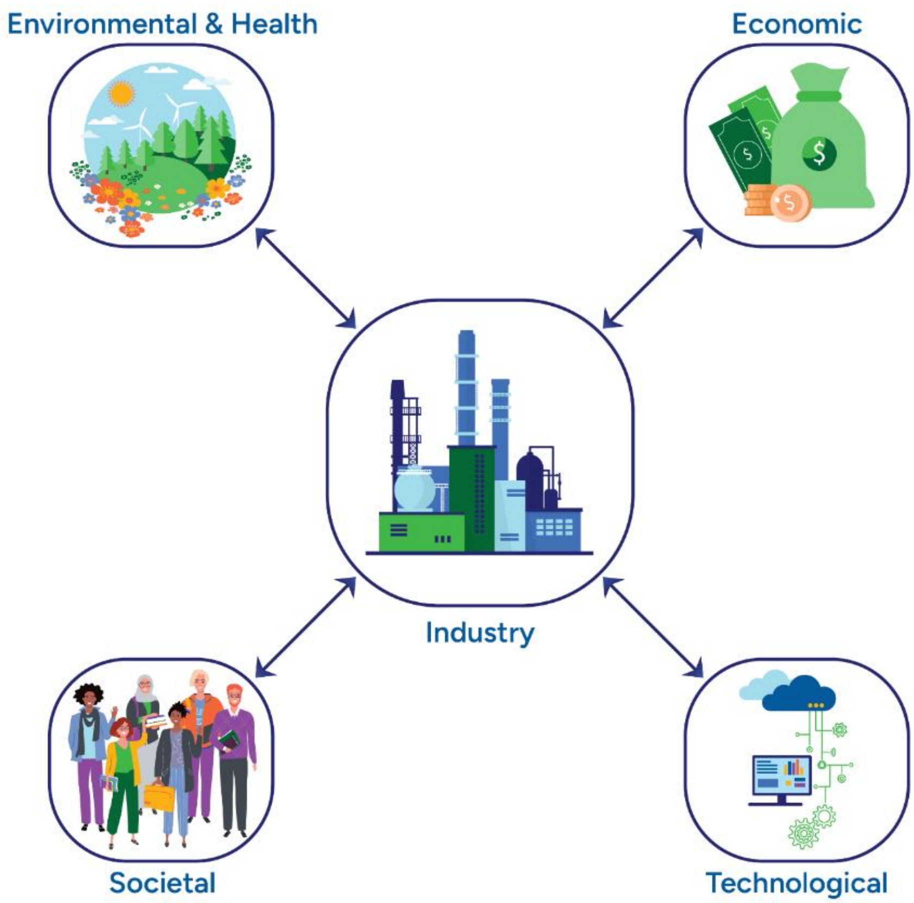


Figure 9. Industrial decarbonization impacts and evaluation criteria are considered within four categories: technological, economic, environmental and health, and societal

3.1.1 Technological

Technological criteria can highly depend on the industrial subsector, where factors such as product lifetime, efficiency, power output, or operational range could be key drivers. These criteria are essential to quantify and communicate the impacts of technology advancement. Primary technological criteria are the process or finished product energy (fuel, electricity, steam) and emissions intensity because the decarbonization infrastructure will require the efficient use of available energy and minimized emissions (including across the range of emission types shown in Table 1). Other technological criteria are needed to assess a decarbonization strategy's merits. The technological criteria spectrum is diverse and includes specific performance parameters, operationality, scalability, availability (technology or resource), critical material usage, and required expertise. As technologies mature, adoption concerns must be addressed. The Adoption Readiness Level framework identifies core risk areas around value proposition, market acceptance, resource maturity, and social license to operate; all of which are necessary elements to successfully deploy novel technologies.[101] A clear understanding of the baseline, target, and measured metrics helps better communicate a technology's potential impact over existing commercial benchmarks and should be recalculated at each development stage.

3.1.2 Economic

Economic criteria, include existing methodologies, such as TEA or front-end engineering design studies, which can provide data on cost intensive process steps and minimum sustainable price. A primary criterion for cost-effective industrial decarbonization strategies is financial. Developing technologies need to meet financial targets to become competitive, as immediately available solutions are often more financially competitive and cause delays to the deployment of developing technologies. In this regard, several different financial metrics apply to technology deployment, including capital investments, payback times, and return on investment—all of which are criteria prioritized by industry when evaluating decarbonization-related changes. Additionally, considerations of available technology choices, implementation timing, policy and regulatory changes, and market conditions are also critical. General cost-benefit analysis, or more specifically TEA, can help to understand the complexities and risks associated with these criteria by producing valuable estimates to benchmark a process or technology against another such as minimum sustainable price, net present value, and internal rate of return. Together, these methodologies can help highlight industrial priorities. However, many industrial concerns are not necessarily captured such as the need to better understand utility and fuel real time pricing, price disparity between electricity and natural gas, and the price of carbon due to their variability across regions and time of year.

3.1.3 Environmental and Health

Environmental and health criteria exist for air pollutants, toxic chemicals, waste, thermal pollution, and land use. They can be further leveraged in frameworks such as LCAs, which report metrics such as embodied energy, global warming product, water use, or ecotoxicity. Decarbonization pathways will be primarily evaluated based on their reductions in both direct and indirect GHG emissions. Industry has many other environmental impacts beyond GHG emissions that will also vary across pathways and need to be quantified, including criteria air pollutants, toxic chemicals, other air and water pollutants, waste, thermal pollution, and land use, as well as associated health impacts on respiratory and cardiovascular health to name a few. In the United States, disadvantaged communities are disproportionately exposed to these pollutants and health burdens as discussed in Section 1.1.1 and Section 2.2.2. Common industrial environmental targets include reducing emissions or energy use by some percentage, but additional metrics—such as water consumption reduction and improving carbon efficiency—are gaining importance when evaluating decarbonization pathways. Cumulative impact frameworks[102] developed over the last several years consider many of the environmental and health criteria outlined above, as well as other non-chemical stressors that relate to the built, natural, or societal environment.

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[101] U.S. Department of Energy, "Adoption Readiness Levels (ARL) Framework," accessed November 2024, www.energy.gov/technologytransitions/adoption-readiness-levels-arl-framework.
[102] U.S. Environmental Protection Agency, "Interim Framework for Advancing Consideration of Cumulative Impacts," accessed January, 2025, https://www.epa.gov/cumulative-impacts/interim-framework-advancing-consideration-cumulative-impacts.

3.1.4 Societal

As discussed in Section 2.3.1, societal criteria are not currently well defined and need further development. Criteria will vary from one community and region to another depending on their priorities and concerns, but they typically include broader implications related to EEJ, energy costs and infrastructure, workforce, and resilient supply chains, as discussed below. It is important for industry to connect directly with leaders and stakeholders in different communities when trying to understand their priorities and to consider them in their decarbonization planning.

Energy and Environmental Justice

Understanding the EEJ impacts of a subsector or technology is an intricate process and approaches vary greatly in terms of timeframes and quantitative rigor. For commercialized products and industries, the United Nations Environment Programme has suggested metrics and data sources for social LCAs.[103] This approach includes metrics such as cultural heritage protection policies and the percentage of workforce hired locally, which require "site visits" or "site-specific audits" to gather required data.[104] Although such a framework includes variables applicable to early-stage technologies, other frameworks are better suited for nascent applications. This might include researcher-developed worksheets including metrics such as toxic material use,[105] number of social science papers reviewed,[106] and stakeholder mapping.[107] As the economy decarbonizes, databases and tools like the EPA's Environmental Justice Screening and Mapping Tool[108] and EnviroAtlas are critical to developing standardized evaluation criteria to capture geospatial and qualitative EEJ impacts that can be overlooked by purely quantitative analyses.[109] Such qualitative impacts can include the perceived usefulness of a project and the intangible value placed on locations by a community. Although assessing these values can be challenging, these tools as well as public engagement, such as town hall events, can greatly assist decarbonization projects in effectively addressing EEJ concerns. Additional existing resources include the Justice Underpinning Science and Technology Research (JUST-R) metrics framework (for early research stages) and the Environmental Justice Science, Data, and Research Plan (for all research stages).[110,111]

Energy Costs and Infrastructure

Industrial decarbonization can impact the scale of the necessary energy infrastructure and the operating costs across the U.S. economy, which will in turn impact energy accessibility for American families and businesses. The coincident decarbonization of buildings, industry, and transportation compounds the operational pressure on clean electricity and other clean energy sources. In fact, load growth is one of the biggest drivers of increasing supply-side costs in clean energy markets.[112] In isolation, capital expenditures of decarbonization infrastructure and clean energy disincentivize initial investments from project developers. However, when the long-term levelized costs of investment are compared against the larger societal benefits of decarbonization, cost

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[103] Life Cycle Initiative, *Methodological Sheets for Subcategories in Social Life Cycle Assessment* (Paris: United Nations Environment Programme, 2021), www.lifecycleinitiative.org/library/methodological-sheets-for-subcategories-in-social-life-cycle-assessment-s-lca-2021/.
[104] Ibid.
[105] Taylor Uekert et al., "Strategies for Considering Environmental Justice in the Early-Stage Development of Circular Economy Technologies," *ACS Sustainable Chemistry & Engineering* 12, 22 (May 2024): 8307–8312, doi.org/10.1021/acssuschemeng.4c02205.
[106] Nikita S. Dutta et al., "JUST-R metrics for considering energy justice in early-stage energy research," *Joule* 7, 3 (March 2023): 431–437, doi.org/10.1016/j.joule.2023.01.007.
[107] Douglas Van Bossuyt and Jered Dean, "Toward Implementing Quantifiable Social Justice Metrics in the Design Process," *Proceedings of the ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* 2A (Aug. 2016), doi.org/10.1115/DETC2016-60189.
[108] U.S. Environmental Protection Agency, "EJSCREEN: Environmental Justice Screening and Mapping Tool," accessed October 2024, www.epa.gov/ejscreen.
[109] U.S. Environmental Protection Agency, "EnviroAtlas," accessed October 2024, www.epa.gov/enviroatlas.
[110] Julia Medeiros Coad, "A Path for Considering Equity in Early-Stage Research," National Renewable Energy Laboratory, February 22, 2023, www.nrel.gov/news/program/2023/a-path-for-considering-equity-in-early-stage-research.html.
[111] National Science and Technology Council, *Environmental Justice Science, Data, and Research Plan* (2024), www.whitehouse.gov/wp-content/uploads/2024/07/NSTC-EJ-Research-Plan-July-2024.pdf.
[112] Pieter Gagnon et al., *2023 Standard Scenarios Report: A U.S. Electricity Sector Outlook,* NREL/TP-6A40-87724 (National Renewable Energy Laboratory, 2024), www.osti.gov/biblio/2274777.

pressures are significantly decreased,[113] and investment becomes a favorable decision. Because infrastructure cannot be developed without local engagement, social licenses to operate become a primary criterion for understanding where societal and capital costs can be simultaneously managed and minimized. Societal costs of energy and infrastructure primarily refer to the costs of accessing energy faced by consumers; capital costs are primarily applicable to energy producers. DOE has existing tools capable of evaluating cost pressures in relation to societal factors, the most applicable of which is the Low-Income Energy Affordability Data (LEAD) tool. LEAD provides insights on energy burdens in low-income households.[114] Such information is valuable in determining priority stakeholders to engage for siting infrastructure development.

Workforce

Building, equipping, and maintaining a strong domestic workforce with high quality jobs will be integral to all industrial decarbonization pathways. Criteria such as overall job creation potential could play a key role in pathway prioritization. Workforce impacts over time will vary across different pathways and include changes in the nature and location of employment, the expertise and training required (including the applicability of those skills to other industries), health and safety concerns and requirements, and compensation. Regional partnerships that include employers, agencies, non-government organizations, and intermediaries can help industry meet their workforce development needs, including retraining and reskilling existing workers. Moreover, better tracking of statistics such as state-level labor market information and job opening duration can further help industry plan and meet workforce development needs.

Additional criteria for pathway evaluation can include industry-specified skill sets needed to broadly support these pathways, such as LCAs, carbon accounting, and closed loop management.[115,116] With these specifications, companies can measure workforce development targets, such as the distribution of these skill sets within their organization. Further, skill retraining alone is insufficient for transitioning workforces to a decarbonized economy.[117] Additional support such as the provision of healthcare, relocation, and educational assistance can provide better outcomes for workforces and should be tracked as key criteria. As organizations weigh their pathway options, the inclusion of worker wisdom in these decisions can provide lasting positive impacts on the workforce and ultimately enable success by giving agency to their real-world, hands-on experience while strengthening worker buy-in.[118]

Resilient Supply Chains: Broader Risks and Concerns

Decarbonizing industry will also require stable access to large quantities of critical materials. Ensuring access to critical materials requires domestic metal and mineral production as well as stable partnerships with other nations to secure these materials that are critical for industrial operation. Understanding each pathway's critical materials demand can help plan for alternate supply chains or material substitutions to strengthen resilience. The 2023 DOE *Critical Materials Assessment* defines emerging markets subject to supply chain bottlenecks. Within the defined markets, certain technologies (including but not limited to hydrogen electrolyzers, solar photovoltaics, electrical steel transformers, and power electronics) are both directly related to evaluating pathway viability and subject to volatile supply chains.[119]

Securing supply chains is a matter of quantifying and mitigating supply volatility. Supply chain resilience indicators also have broader national security implications because the maintenance of secure supply chains

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[113] Paul Denholm et al., *Examining Supply-Side Options to Achieve 100% Clean Electricity by 2035,* NREL/TP-6A40-81644 (National Renewable Energy Laboratory: 2022), www.osti.gov/biblio/1885591.
[114] U.S. Department of Energy, "Low-Income Energy Affordability Data (LEAD) Tool," accessed October 2024, www.energy.gov/scep/low-income-energy-affordability-data-lead-tool.
[115] Ibid.
[116] National Academies of Sciences, Engineering, and Medicine, *Developing and Assessing Ideas for Social and Behavioral Research to Speed Efficient and Equitable Industrial Decarbonization* (Washington, DC: National Academies Press, 2024), nap.nationalacademies.org/catalog/27815.
[117] Ibid.
[118] High Road Training Partnership, "Worker Voice," (UC Berkeley Labor Center, 2020), laborcenter.berkeley.edu/hrtp-essential-element-3-worker-voice/.
[119] U.S. Department of Energy, *Critical Materials Assessment*, DOE/EE-2756 (2023), www.energy.gov/sites/default/files/2023-07/doe-critical-material-assessment_07312023.pdf.

often involves actions by transnational third parties and foreign governments. Reducing exposure to unknown parties through secure third-party relationships is another key variable in managing supply chain resilience.[120] Risk and resilience impacts are important; however, they must be considered alongside GHG emissions (see Section 4.8 for examples of how GHG emissions can be assessed across supply chains). In addition, evaluating aggregate, distributional (e.g., across different regions, communities, and subsectors), and temporal impacts is critical for all metrics.

3.2 Decarbonization Pillars, Product Demand, and Modeled Sensitivities

The *Transformative Pathways* modeling involves the use of multiple decarbonization pillars and sensitivities to determine the technology impacts on near zero emissions pathways outcomes.

3.2.1 Industrial Decarbonization Pillars and Product Demand

The *Industrial Decarbonization Roadmap* and this modeling effort consider technology options across four cross-cutting decarbonization pillars: energy efficiency; industrial electrification; LCFFES; and CCUS.[121] Full definitions for the pillars can be found in the *Industrial Decarbonization Roadmap* Section 1 and are summarized in Table 3 in this report with manufacturing-specific examples. Beyond these pillars, product demand is an important factor to consider for modeling and considering decarbonization pathways.

Table 3. Decarbonization Pillars From the *Industrial Decarbonization Roadmap*[122]

Pillar	Energy Efficiency	Industrial Electrification	Low-Carbon Fuels, Feedstocks, and Energy Sources (LCFFES)	Carbon Capture, Utilization, and Storage (CCUS)
Definition	Advancements that minimize industrial energy demand, directly reducing the GHG emissions associated with fossil fuel combustion.	Technologies that use electricity for energy, rather than combusting fossil fuels directly, enabling the subsector to leverage advancements in low-carbon electricity from both grid and onsite generation sources.	Substitutions for fossil-based fuels, feedstocks, and energy sources to further reduce combustion- and process-associated industrial emissions.	Multi-component strategy for mitigating difficult-to-abate emissions involves capturing generated CO_2 before it can enter the atmosphere; using the captured CO_2 whenever possible; and storing captured CO_2 long-term to avoid atmospheric release.
Technology examples	• Variable frequency drives • Process integration • Strategic energy management	• Steam-generating heat pumps • Hot water heat pumps • Electric boilers • Electro-technologies (e.g., microwave, infrared, induction)	• Bio-based (biomass, biofuels, biogas) • Clean hydrogen • Nuclear • Geothermal • Solar-thermal	• Carbon capture and storage from large point source emissions (post-combustion and industrial processes) • E.g., amine absorption, calcium looping, oxy-fuel combustion

As noted in the *Industrial Decarbonization Roadmap,* boundaries between pillars can be indistinct because crosscutting actions, approaches, and infrastructure investments can accelerate progress and improvements

[120] Office of the Director of National Intelligence, *Protecting Critical Supply Chains: Building a Resilient Ecosystem* (2023), www.dni.gov/files/NCSC/documents/supplychain/Building-a-Resilient-Ecosystem.pdf.
[121] U.S. Department of Energy, *Industrial Decarbonization Roadmap*, DOE/EE-2635 (2022), www.energy.gov/industrial-technologies/doe-industrial-decarbonization-roadmap.
[122] Ibid.

across multiple pillars.[123] Beyond the four main pillars, material efficiency (including material substitution, resource conservation, and circular economy strategies) is an important crosscutting decarbonization lever that can have impacts across the four main pillars. For example, end-of-life materials could be used as low-carbon feedstocks within the LCFFES pillar, but these would need to be used in an energy-efficient manner. Because these strategies can be difficult to quantify and can have impacts outside the bounds of an industrial facility, material efficiency is not fully integrated into the modeling results, although certain considerations are included. Material efficiency strategies need further exploration and analysis, including defensible LCAs and TEAs. This section briefly introduces the four pillars and product demand considerations at a high level. As noted, more details on each pillar can be found in Section 1 of the *Industrial Decarbonization Roadmap*.

Energy Efficiency

Energy efficiency measures and system design are fundamentally important at all industrial decarbonization stages because they apply to incumbent and future technologies. Energy efficiency measures include (among others) production-side energy efficiency such as process intensification, process integration, onsite combined heat and power generation, waste heat recovery, smart manufacturing controls integration, and strategic co-location of facilities along a value chain for industrial symbiosis. Energy efficiency could potentially reduce as much as 467 MMT of industrial CO_2 emissions by 2050 according to some estimates.[124] These measures also indirectly reduce the onus and cost to decarbonize through other more direct approaches such as industrial electrification, LCFFES, and CCUS as well as the cost of decarbonizing the electric grid. DOE recently highlighted the energy efficiency progress made by its more than 280 manufacturing partners of the Better Buildings, Better Plants Program. These partners cover 3,600 facilities, account for 14% of the U.S. manufacturing energy footprint, and have cumulatively saved $11.8 billion and 2.4 quadrillion British thermal units (Btu) of energy since the program's inception in 2011.[125] Their annual energy intensity improvement rate is reported to be 1.8%.[126]

Energy efficiency barriers include inadequate awareness of efficiency measures and incentives; unfavorable return on investment due to low fossil energy cost and/or high additional equipment cost (particularly applicable to smart manufacturing); operations disruptions during retrofits; waste heat integration engineering constraints; lack of strategic energy management to ensure persistent improvements; and rebound effects from increased energy consumption as a result of increased energy efficiency that minimize net energy and cost savings. Facilities will need to balance efficiency investments in existing equipment with the long-term technology needs to reach net zero emissions and avoid making significant capital investments in potentially stranded assets. Other energy efficiency measures such as switching from one source of fossil fuel to another (e.g., coal to natural gas) are not considered a decarbonization pathway consistent with this report.

Industrial Electrification

Electrifying manufacturing processes can reduce GHG emissions and has the potential to reduce energy consumption and provide other benefits. As the grid capacity builds out and decarbonizes by 2050,[127] purchased electricity-related emissions will reduce as well. Industrial processes requiring low-to-medium grade temperature heat (less than 130 degrees Celsius (°C) to 500°C) represent 78% of industrial thermal energy

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[123] There are several examples that exemplify the crosscutting nature of technology investments. For example, smart manufacturing will drive advancements that will cut across pillars. More information can be found in references such as: U.S. Department of Energy, *National Smart Manufacturing Strategic Plan: To Facilitate More Rapid Development, Deployment and Adoption of Smart Manufacturing Technologies* (2022), www.osti.gov/biblio/1880185; Christopher R. Price et al., "Smart Manufacturing Pathways for Industrial Decarbonization and Thermal Process Intensification," *Smart and Sustainable Manufacturing Systems* 7, 1 (March 2023): 41-53, doi.org/10.1520/SSMS20220027, U.S. Department of Energy, *Quadrennial Technology Review 2015 Chapter 6 Technology Assessments: Innovating Clean Energy Technologies in Advanced Manufacturing, Advanced Sensors, Controls, Platforms and Modeling for Manufacturing* (2016), www.energy.gov/sites/prod/files/2015/11/f27/QTR2015-6C-Advanced-Sensors-Controls-Platforms-and-Modeling-for-Manufacturing.pdf.

[124] Lowell Ungar and Steven Nadel, *Halfway There: Energy Efficiency Can Cut Energy Use and Greenhouse Gas Emissions in Half by 2050* (American Council for an Energy-Efficient Economy, 2019), www.aceee.org/research-report/u1907.

[125] U.S. Department of Energy, *Partnering to Share Pathways and Solutions: Progress Report* (2023), betterbuildingssolutioncenter.energy.gov/resources/2023-better-buildings-progress-report.

[126] Ibid.

[127] Note: See Appendix B for more information on U.S. grid emissions factors assumed for this report.

demand.[128] Low-to-medium temperature processes are generally simpler to electrify than high-temperature and thus should be prioritized. Additionally, electrical process heating equipment has better temperature and process control, which could result in higher production rates and fewer maintenance requirements. To support higher rates of electrification at industrial facilities, additional technologies and approaches are needed. These includes thermal and electrical energy storage systems to provide onsite, on-demand energy; flexible processes to mitigate intermittent energy production; and integrated controls and communications to facilitate interactions with the grid.[129]

The electrification of fossil fuel-using industrial mechanical, thermal, and chemical processes can significantly reduce energy consumption and associated GHG emissions. This includes switching to heat pumps, electric boilers, electric furnaces, advanced electro-heating technologies (for instance, that rely on microwaves, infrared waves, electromagnetic induction, or plasma), electro-chemical and electrically assisted biological processes, membrane separation, and electrification of rotary equipment. Additional opportunities include the development of new process chemistries and production methods, such as catalytic reactors, which enable effective operation with reduced thermal input requirements and make them ideal for electrification.

Barriers to industrial electrification include clean electricity availability, reliability, and cost; inefficiencies and inadequacies in transmission and distribution infrastructure; scale-up risks and performance or quality trade-offs with electrified processes; the high capital cost of electricity-driven equipment; disruption and/or drastic reconfiguration of existing processes during retrofits; intermittency of renewable resources; material limitations under harsh environments; applicability of electrified alternatives; and constraints on the type, grade, and availability of feedstocks that could be processed (e.g., steel scrap in electric arc furnaces).

LCFFES

Industrial demand for process heat and certain carbon-intensive feedstocks has the potential to at least partially be met with low- and zero-carbon alternatives.[130] These alternatives are collectively termed LCFFES. Examples include:

- Low-carbon energy carriers and non-fossil fuel feedstocks (such as hydrogen; ammonia; synthetic fuels including e-fuels, sustainably sourced biomass, biogas,[131] and bioproducts; and chemical precursors from CO_2)
- Clean thermal energy sources (such as solar thermal, geothermal, or nuclear reactors)

Some strategies incorporating LCFFES can also integrate energy storage (such as thermal energy storage[132]) to develop more robust systems. Each LCFFES will have a unique set of approaches, barriers, and opportunities; this section provides broad examples on biomass, hydrogen, and thermal energy sources.

Biomass could be used as a low-carbon fuel either directly or through gasification for process heat in industrial processes, such as pulping liquor and waste wood in pulp and paper manufacturing. Conventional and alternative bio-feedstocks could substitute petroleum-based non-fuel feedstocks, such as production of sustainable aviation fuel from cellulosic feedstocks. Increased production and the use of biomass in industry could reduce GHG emissions if it is sustainably sourced, with appropriate considerations for impacts on land use, soil carbon, water quality and availability, air emissions, and biodiversity.[133] Barriers to biomass use in the industrial sector include varying regional availability, competition from other end uses such as electricity generation, timber, and

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[128] Renewable Thermal Collective, *The Renewable Thermal Vision* (2022), www.renewablethermal.org/vision/.
[129] Jaquelin Cochran et al., Grid Integration and the Carrying Capacity of the U.S. Grid to Incorporate Variable Renewable Energy, NREL/TP-6A20-62607 (National Renewable Energy Laboratory, 2015), www.osti.gov/biblio/1215010.
[130] Gregory P. Thiel and Addison K. Stark, "To decarbonize industry, we must decarbonize heat," *Joule* 5, 3 (March 2021): 531-550, doi.org/10.1016/j.joule.2020.12.007.
[131] U.S. Energy Information Administration, "Biomass explained: Landfill gas and biogas," December 2023, www.eia.gov/energyexplained/biomass/landfill-gas-and-biogas.php.
[132] U.S. Department of Energy, "Energy Storage for Manufacturing and Industrial Decarbonization Workshop," accessed November 2024, www.sandia.gov/ess/storm.
[133] See Chapter 6, Sustainability and Good Practices in U.S. Department of Energy, *2023 Billion-Ton Report*, ORNL/SPR-2024/3103 (2024), www.energy.gov/eere/bioenergy/2023-billion-ton-report-assessment-us-renewable-carbon-resources.

land use for food crop cultivation, and inconsistent carbon accounting practices that do not always accurately account for land use-related life cycle emissions.

Hydrogen is another potential LCFFES when obtained from water electrolysis using a clean energy source such as wind, solar, or nuclear or from the conversion of fossil, biomass, or waste-stream feedstocks through processes, such as steam methane or autothermal reforming of natural gas, methane pyrolysis, biomass gasification, and microbial conversion of wastes, with carbon capture and storage or use. Hydrogen is an important chemical feedstock today; it is annually produced at roughly 10 MMT in the United States, mostly by natural gas reforming.[134] Estimates of industrial clean hydrogen demand by 2050 vary, with steel, ammonia, and methanol production as key applications.[135,136] Barriers to the use of clean hydrogen in industry include relatively high production costs and the need for expanded storage, transport, and distribution infrastructure that is affordable, reliable, and safe. There are also end-use specific challenges. For example, blending hydrogen with natural gas can introduce compatibility issues with the current gas pipeline infrastructure (e.g., material fatigue and fracture).[137] In addition, the combustion of natural gas-hydrogen blends emits more NOx than natural gas alone,[138] and both hydrogen and natural gas-hydrogen blends require modifications to burners and heat exchangers due to different flame characteristics and heat transfer mechanisms compared to other gaseous or liquid hydrocarbon fuels.

Thermal energy sources supplied directly via clean energy (e.g., solar thermal, geothermal, nuclear reactors) could provide low- or zero-carbon process heat and/or drive thermodynamic power cycles. Barriers to solar thermal energy sources include intermittency, low areal density (i.e., limited solar flux), achievable temperature, and challenges associated with high-temperature heat transfer media.[139] For geothermal energy sources, challenges and opportunities differ between the near surface hydrothermal and nonhydrothermal applications and deep geothermal opportunities. Non-hydrothermal is significantly limited by its low reservoir temperature, often coupled with a heat pump, but has abundant geographic distribution. Hydrothermal sources offer modestly higher temperatures but have limited geographic distribution. Deep geothermal opportunities take advantage of the thermal gradient in the earth's crust, but they come with significant challenges, especially as they approach the depths necessary for higher temperature industrial process heat demands. For nuclear energy, advanced nuclear reactor designs using liquid metal, molten salt, or gas as coolant provide the potential for addressing higher temperature industrial process heat demand.[140] Although work is progressing to reduce the cost of nuclear energy projects, challenges for the rapid adoption of nuclear power include long project timeframes and elevated capital costs that stem from first-of-a-kind reactor technologies.

CCUS

In cases where CO_2 is produced as a byproduct of non-combustion chemical reactions such as calcining, fermentation, and gasification, the relatively high purity of CO_2 streams can allow economically viable carbon capture with lower additional treatment, cost, and energy expenditure. Such high purity sources already supply the merchant CO_2 market (currently at 14 MMT/year capacity)[141] and are likely sources for CO_2 utilization applications such as the synthesis of chemical precursors and e-fuels.[142] CO_2 generated from fuel combustion,

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[134] U.S. Department of Energy, *U.S. National Clean Hydrogen Strategy and Roadmap* (2023), www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap.
[135] Ibid.
[136] U.S. Department of Energy, *Pathways to Commercial Liftoff: Clean Hydrogen* (2023), liftoff.energy.gov/clean-hydrogen/.
[137] Kevin Topolski et al., *Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology*, NREL/TP 5400-81704 (National Renewable Energy Laboratory, 2022), www.osti.gov/biblio/1893355.
[138] Merve Ozturk et al., "An experimental study on the environmental impact of hydrogen and natural gas blend burning," *Chemosphere* 329 (July 2023), doi.org/10.1016/j.chemosphere.2023.138671.
[139] Gregory P. Thiel and Addison K. Stark, "To decarbonize industry, we must decarbonize heat," *Joule* 5, 3 (March 2021): 531-550, doi.org/10.1016/j.joule.2020.12.007.
[140] Ibid.
[141] Sarang Supekar and Steven J. Skerlos, "Market-Driven Emissions from Recovery of Carbon Dioxide Gas," *Environmental Science & Technology* 48, 24 (November 2014): 14615–14623, doi.org/10.1021/es503485z.
[142] Guiyan Zang et al., "Synthetic Methanol/Fischer–Tropsch Fuel Production Capacity, Cost, and Carbon Intensity Utilizing CO_2 from Industrial and Power Plants in the United States," *Environmental Science & Technology* 55, 11 (May 2021): 7595-7604, doi.org/10.1021/acs.est.0c08674.

which constitutes more than 72% of all industrial CO_2 emissions,[143] would require additional processes to separate CO_2 from exhaust flue gas streams, including those that use amine-based solvents, solid sorbents, calcium looping, membrane separation, cryogenic separation, and reactive capture. Carbon capture shows promise in significantly reducing emissions, including for industrial and power generation processes that produce low-CO_2 concentration streams. Yet, it might not be economically feasible due to the high capital costs of capture plants and the added parasitic energy loads.

Other CCUS barriers include the uncertainty of merchant and captive CO_2 markets in a low-carbon future; concerns around the feasibility, safety, and monitoring of a nationwide CO_2 pipeline transport and long-term CO_2 storage infrastructure; facilities' lack of proximity to a viable CO_2 storage location; and inadequate accounting guidelines on captured, reused, and stored carbon. Some industrial subsectors such as cement and concrete might need to rely on CO_2 capture in addition to electrification, low-carbon fuels, or other approaches, because these approaches do not avoid the release of CO_2 from limestone pyroprocessing that can comprise up to 60% of cement production emissions.[144]

Product Demand

Product demand influences emissions by driving production levels, energy use, and material consumption in each subsector. Incorporating demand forecasts and market trends into decarbonization models is important to accurately assess future emissions. Changes in product demand can be caused by shifts in consumer behavior, policy interventions, or increased material reuse and recycling. Demand reduction, such as through increased product efficiency or the use of alternative materials, can complement the supply-side levers represented by the pillars. Modeling constant or varying levels of product demand allows for more thorough exploration of emissions reduction possibilities and awareness of how decarbonization pathways interact with alternative demand scenarios.

3.2.2 Modeling Sensitivities

Understanding sensitivities[145] and future uncertainties is crucial in the decision-making process among a variety of fields, particularly for sustainability, manufacturing, and environmental planning. Sensitivity analyses assess how different variables or assumptions impact outcomes and results and help to identify the factors with most significant influences on the overall system or model.

There are a variety of sensitivities that could be assessed to help identify potential pathways. Specifically for this study, sensitivities are categorized as global or subsector-specific as summarized in Table 4.

Table 4. Defined Sensitivities Included in the Models to Evaluate Impacts on Potential Near Zero GHG Emissions Pathways

Application	Sensitivities
Global–harmonized definitions across all subsectors	1. Energy efficiency improvements, by technology maturity (low, mid, high) 2. Electricity price/availability/emission factors 3. Hydrogen price/availability/emission factors 4. Carbon capture price/availability/efficiency
Subsector-specific definitions	5. Market share of low-maturity technologies 6. Alternative energy sources 7. Changes in modeled demand 8. Feedstock availability and quality

[143] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022*, EPA 430-R-24-004 (2024), www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.
[144] U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Cement," (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_cement_energy_carbon_footprint_0.pdf.
[145] In this report, the term "sensitivities" is used as a shorthand for sensitivity analysis for the identified sources of uncertainty.

The globally-harmonized sensitivities for electricity, hydrogen, and CCS include three levels: nominal, low potential, and high potential. Energy efficiency included options for low, mid, and high per annum improvements depending on the technology maturity level. Specific values are discussed in Appendix A.

Subsector-Specific Sensitivities

Each subsector in Section 4 uses the sensitivities noted in Table 4 as well as several subsector-specific sensitivities. Examples are shared in the following, and full details can be found in each subsector's section.

Market share of low maturity technologies: Low maturity technologies represent early-stage innovations that are still in the research, conceptualization, or initial development phase. These technologies usually have a limited market share because they are not yet fully validated or commercialized. The market for low maturity technologies is often dominated by niche players, startups, or research institutions, with larger market actors showing interest primarily through investment or acquisition for future scaling. Although the direct commercial impact is small, the potential for growth remains significant as these technologies mature.

Alternative energy sources: The development and deployment of alternative energy sources, such as biomass or biogas, are sensitive to several factors that influence their implementation. Economic factors—such as the cost of production, government subsidies, and market demand—can heavily impact their adoption. Technological challenges—including efficiency rates, energy storage capabilities, and grid integration—also play a crucial role. Further, environmental conditions, such as geographic suitability for solar and wind power, can limit effectiveness. Political and regulatory landscapes, including policies on carbon emissions and fossil fuel incentives, can either hinder or accelerate the growth of alternative energy industries. These sensitivities make the transition to alternative energy complex and multifaceted.

Changes in modeled demand: Modeled subsector production is highly sensitive to a range of factors that can cause significant variability in forecasts. Economic growth and industrial activity directly influence product demand, with higher production typically leading to increased energy consumption. Technological advancements, such as material efficiency measures, policy changes, such as stricter regulations on emissions or energy use, and incentives for energy-saving technologies, can alter demand patterns. Societal factors, including behavioral changes and population growth, further complicate predictions. Last, external shocks such as economic recessions, pandemics (e.g., COVID-19), or geopolitical tensions can drastically shift product demand, making accurate modeling a complex challenge.

Feedstock availability and quality: Feedstock availability and quality are critical sensitivities in energy production, particularly for bioenergy, biomass, and other clean sources. Variability in feedstock supply can be influenced by factors such as climate conditions, agricultural yields, and land use changes. Feedstock quality, such as the moisture content, energy density, and chemical composition, affects the efficiency and output of energy conversion processes. Seasonal changes and competition for resources in food or other industrial subsectors can further limit access to high-quality feedstocks. Additionally, logistical issues, such as transportation and storage, can impact the consistency and reliability of the supply, making the stability of energy production reliant on both availability and quality.

The sensitivities described above were explored to develop the subsector-specific decarbonization pathways described below in Section 4. As noted in Section 1.2, the *Pathways* modeling approach extends and expands upon the *Industrial Decarbonization Roadmap* models. Through expert elicitation and stakeholder engagement, modeling frameworks and scenarios were developed that provide a starting point from which core scenarios with significant emissions reduction potential could be identified. Modeling assumptions and inputs were also informed by this engagement, as well as extensive literature review and the barrier and challenges, criteria, and other considerations shared in the sections above. Although a consistent approach was applied for the six subsectors, each model was adapted and customized to meet the specific subsector's characteristics. The models were iterated upon (including sensitivity analysis and variations in technologies/approaches across the four pillars) to then identify various near zero scenarios, with quantitative modeling outputs and learnings shared in this next section.

4 INDUSTRIAL SUBSECTOR PATHWAYS TO DECARBONIZATION

This section addresses the decarbonization pathways on an industrial subsector level. Table 5 provides a high-level description of the various industrial and industry-adjacent subsectors. Sections 4.1 through 4.6 delve into the modeled pathways for six energy- and emissions-intensive manufacturing subsectors—cement and concrete, chemicals, food and beverage, iron and steel, petroleum refining, and pulp and paper. Although other industrial subsectors are not yet modeled, current energy consumption, emissions, and high-level opportunities for decarbonization pathways are discussed in Section 4.7. Additionally, Section 4.8 provides an overview of supply chain implications for the industrial sector.

Table 5. Industrial Subsectors High-Level Description

Subsector	Description
Manufacturing (NAICS* 31-33)	Manufacturing encompasses facilities "engaged in the mechanical, physical, or chemical transformation of materials, substances, or components into new products".[146] • **Energy- and emissions-intensive manufacturing:** The highest energy consumers and emitters in manufacturing. Includes cement and concrete (Section 4.1), chemicals (Section 4.2), food and beverage (Section 4.3), iron and steel (Section 4.4), petroleum refining (Section 4.5), and pulp and paper (Section 4.6). • **Other manufacturing:** The remainder of manufacturing, including transportation equipment (including car and truck manufacturing), plastics, electronics, fabricated metals, aluminum (primary and secondary), glass, machinery, textiles, foundries, wood products, and miscellaneous manufacturing. See Section 4.7.1.
Non-manufacturing industrial (NAICS* 11, 21, 23)	Non-manufacturing includes the agriculture and forestry; mining, oil, and gas; and construction subsectors. See Section 4.7.2. • **Agriculture and forestry:** Includes animal production and aquaculture; crop production; forestry and logging; fishing, hunting, and trapping; and support activities for agriculture and forestry. • **Mining, oil, and gas:** Includes oil and gas extraction, mining (except oil and gas), and support activities for mining. • **Construction:** Includes construction of building, heavy and civil engineering construction, and specialty trade contractors.
Industry-adjacent	Emerging and existing facilities not explicitly included in the industrial sector definition but have operations and/or energy and emissions footprints similar to large-scale industrial facilities. See Section 4.7.3. • **Data centers:** Data centers are one of the most energy-intensive building types, largely driven by electricity consumption. These facilities are unique, dynamic, and growing as information and communications technology infrastructure expands. EIA collects information on data centers only if they are a subset of buildings for other uses.147 • **Water and wastewater treatment:** The delivery of water to buildings and facilities and the management and treatment of wastewater. Treating water for and from industrial processes and the broader economy is a significant source of emissions.

* North American Industry Classification System (NAICS). See U.S. Census Bureau, "North American Industry Classification System (NAICS): 2022 NAICS," accessed October 2024, www.census.gov/naics/.

Note that in the future, some reclassifications may need to occur as industrial subsectors evolve and emerge (e.g., agriculture shifting to controlled environment agriculture/indoor farming).

[146] U.S. Census Bureau, "North American Industry Classification System (NAICS): 2022 NAICS," accessed October 2024, www.census.gov/naics/?input=31&year=2022&details=31.

[147] EIA notes data points on data centers cannot yet be published as a separate building type due to lack of frame, small sample size, and low cooperation rates. See: U.S. Energy Information Administration, *2018 CBECS Data Center Pilot Results* (2021), www.eia.gov/consumption/commercial/reports/2018/pilot/.

The impact and evaluation criteria discussed in Section 3.1, as well as the decarbonization pillars, product demand, and sensitivities discussed in Section 3.2, were considered in selecting the pathways featured in this section. Sections 4.1 through 4.6 present numerous decarbonization pathways for cement and concrete, chemicals, food and beverage, iron and steel, petroleum refining, and pulp and paper. These pathways highlight the importance and impacts of both commercially available and emerging technologies toward deep industrial decarbonization. Likewise, this study seeks to refine and improve the understanding of potential pathways and the production routes within, including considerations highlighted in Section 2.4.

As such, this effort seeks to:

- Examine potential GHG emissions impacts of deploying a range of low- to high-maturity technologies across the decarbonization pillars of energy efficiency; industrial electrification;[148] LCFFES; and CCUS.
- Illustrate specific manufacturing subsector decarbonization pathways based on GHG reduction potential of relevant technologies.
- Utilize the best current understanding of decarbonization technologies and approaches and their technical potential, adoption readiness, subsector applicability, and emissions reduction potentials.
- Understand technologies that may be technically feasible but may not be considered as applicable due to other factors (such as high cost).

Modeling Scenarios and Pathways

For decarbonization of the overall industrial sector, specific subsectors, and even an individual industrial facility, there is no single pathway to net zero or near zero GHG emissions. Pathways will evolve as new technologies become available, and some pathways will be more challenging than others, while some may not become as economically viable as the future unfolds. Even more, the pathways may directly impact each other, as competition for limited resources, such as low-carbon fuels and feedstocks, could constrain the viability of certain pathways over time. Considering a range of potential pathway futures can help inform industry now and guide crucial corporate, government, and societal decision-making.

Identifying decarbonization pathways required modeling multiple scenarios for each subsector to assess that subsector's potential for decarbonization. Each scenario was defined by a set of assumptions around technologies, including their impacts and adoption levels. Some subsectors had a single set of assumptions that defined a single scenario with significant GHG emissions reductions by 2050, referred to as a "Core Near Zero" (CNZ) scenario. Other subsectors had multiple CNZ scenarios emerge, with competing assumptions. Each of these CNZ scenarios had significant GHG emission reductions by 2050, and these scenarios were termed by their defining characteristics. On the contrary, one subsector—refining—had an aggressive set of assumptions, but still had significant GHG emissions remaining in 2050 due to significant remaining demand for fossil fuels in the core scenario.

Furthermore, sensitivity analyses were run on these core scenarios to assess the impacts of the defining assumptions. Results shown in this section are examples of near zero subsector GHG emissions pathways modeled using the sensitivities noted in Section 3.2.2 and subsector-specific sensitivities. These scenarios were developed using modeling with its own constraints and limitations. Within the combinations of the core scenarios and corresponding sensitivities, modeled results that yielded the most promising decarbonization potential were identified as near zero pathways and included in this report.

Details are provided in the appendices and further information about modeling methodology, assumptions, and results will be made available in future DOE publications. This report is not a comprehensive review of scenarios and associated sensitivities that were modeled as a part of this effort but includes select candidate near zero pathways. Underlying all modeled gains is the assumption that emissions reductions persist without any backsliding of emissions reductions in subsequent years. Standardized energy and carbon management systems,

[148] The terms "industrial electrification" and "electrification" are used interchangeably throughout this report.

like those outlined in International Organization for Standardization (ISO) 50001–Energy management,[149] are key enablers of persistence.

The emissions categories included in the six manufacturing subsectors modeled for this report are provided in Table 6. The scope of this modeling primarily focuses on scope 1 and scope 2 emissions. However, scope 3 emissions are also important to consider when charting pathways to net zero GHG emissions industry and are included in a limited scope for cement and concrete, iron and steel, chemicals, pulp and paper, and refining.[150] Section 4.8 provides a discussion on the importance of supply chain emissions to decarbonization strategies with some subsector-specific examples. More information on modeling and assumptions can be found in Appendices A, B, and C.

Table 6. Scope of Emissions Included in the Transformative Pathways Modeling Effort

Industry Subsector	Electricity Generation CO2 Emissions (Scope 2)	Fuel-Related CO2 Emissions (Scope 1)	Process-Related CO2 Emissions (Scope 1)	CH4, N2O, and Other Non-CO2 GHG Emissions (Scope 1 and 2)	Subsector Production Coverage in Models
Cement	Included	Included	Included	Included	Full subsector coverage
Chemicals	Included	Included	Included	Included	Partial coverage [a]
Food and beverage	Included	Included	N/A[c]	Included	Partial coverage [b]
Iron and steel	Included	Included	Included [d]	Included	Full subsector coverage
Petroleum refining	Included	Included	N/A[c]	Included	Full subsector coverage
Pulp and paper	Included	Included	N/A[c]	Included	Full subsector coverage

Acronyms: carbon dioxide (CO_2), greenhouse gas (GHG), methane (CH_4), nitrous oxide (N_2O). Note: Scope 3 emissions were considered for cement and concrete with the emissions associated with SCMs, for iron and steel with the emissions associated with imported iron used in EAFs, and for chemicals, pulp and paper, and refining with the consideration of the emissions of the bio-feedstocks or biofuels. More details can be found in Section 4.

[a] For the chemicals subsector, a subset of high-volume, high-emitting chemicals accounting for 40% of total chemicals manufacturing GHG emissions[151,152,153] were included in the Transformative Pathways modeling: ethylene; propylene; butadiene; benzene, toluene, and xylenes (BTX) aromatics; chlorine; sodium hydroxide (caustic soda); sodium carbonate (soda ash); ethanol; methanol; and ammonia. A selection of cross-cutting decarbonization strategies are considered for the remaining chemicals to develop subsector-wide emissions reduction potentials. See Section 4.2 for details.

[b] For food and beverage manufacturing, a representative set of subsectors accounting for 78% of total food and beverage manufacturing GHG emissions[154,155,156] were included in the Transformative Pathways modeling: grain and oilseed milling; sugar; fruit and vegetable preserving and specialty; dairy product; animal slaughtering and processing; and beverages. See Section 4.3 for details.

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[149] International Organization for Standardization, "ISO 50001: Energy management," accessed November 2024, www.iso.org/iso-50001-energy-management.html.
[150] Scope 3 emissions were considered for cement and concrete with the emissions associated with SCMs, for iron and steel with the emissions associated with imported iron used in EAFs, and for chemicals, pulp and paper, and refining with the consideration of the emissions of the bio-feedstocks or biofuels.
[151] U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Chemicals" (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_chemicals_energy_carbon_footprint_0.pdf.
[152] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022*, EPA 430-R-24-004 (2024), www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.
[153] U.S. Energy Information Administration, "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data" (2021), www.eia.gov/consumption/manufacturing/data/2018/.
[154] Ibid.
[155] U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Food and Beverage" (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_food_beverage_energy_carbon_footprint.pdf.
[156] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022*, EPA 430-R-24-004 (2024), www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.

[c] No process-related emissions associated with food and beverage manufacturing, petroleum refining, or pulp and paper manufacturing are reported by the U.S. Environmental Protection Agency in the Inventory of U.S. Greenhouse Gas Emissions and Sinks.[157]

[d] In the iron and steel subsector, most process-related CO_2 emissions are related to coke consumption. Some studies categorize coke use under energy-related emissions, while others categorize coke use under process-related emissions. Regardless, emissions associated with coke consumption are included in the Transformative Pathways modeling. See Section 4.4 for details.

Nascent Technologies and Model Limitations

Based on this analysis and others,[158] it is likely that at least two-thirds of emissions reductions will come from the deployment of technologies that are yet not cost-effective or technically mature. Although some of these potential production routes were explored and included in this modeling effort, the models were limited by the data available. Nascent production routes that did not have reliable enough data for energy or emissions intensity or market adoption potential were, thereby, not directly modeled. In several subsectors, where significant market share is attributed to production routes that utilize CCUS in 2050, nascent, emissions-free production routes could be viewed as having an analogous potential impact as CCUS, from an emissions perspective only. This interpretation is supported by the generalized framework of the modeling that first looked at addressing emissions through alternative clean production routes that were included in the models while also reducing emissions through energy efficiency and low-carbon fuels interventions. Remaining emissions were then addressed with CCUS where possible.

This analogous interpretation is important when considering the decarbonization potential within a subsector, beyond what was directly modeled in this study. Nevertheless, it is important to be careful about conclusions drawn from this perspective, as nascent technologies, by definition, have several operational characteristics that are unknown or poorly defined. The reader is advised to consider the various sensitivities presented in this study when assessing a pathway's decarbonization potential. The adoptions of CCUS production routes were implemented around CCUS-specific assumptions, which will differ from other production routes. Ultimately, emissions trajectories over time may vary from the modeling results presented below, especially when considering nascent technologies that were not directly considered in the modeling. However, the *Transformative Pathways* models have been designed to be adaptable to allow updates or additions to technology options or new data as they become available, to model other industrial subsectors beyond the six presented in this report, and to incorporate stakeholder input.

4.1 Cement and Concrete

4.1.1 Introduction

Cement production is one of the most energy- and emissions-intensive industries worldwide, with global annual emissions of about 1.61 gigatons (Gt) CO_2,[159] accounting for around about 6% of global CO_2 emissions.[160] Concrete, of which cement is a main component, is the second most used substance in the world after water, with the United States producing over 306 million cubic meters (m^3) of ready-mix concrete in 2022.[161] Cement is the binding material that turns a combination of aggregates and water into concrete as a building material. Increasing demand for cement and concrete is anticipated in the coming decades, driven by several global megatrends, such as population growth and urbanization in developing countries and aging infrastructure in developed countries. There is a wide range for cement and concrete demand forecasts between 2023 and 2050, ranging from increases of 12% to 76%.[162,163,164] Forecasts project that concrete demand globally will increase from

[157] Ibid.
[158] U.S. Department of Energy, *Pathways to Commercial Liftoff: Industrial Decarbonization* (2023), liftoff.energy.gov/industrial-decarbonization/.
[159] Global Carbon Budget and Our World in Data, "Annual CO_2 Emissions from Cement," November 21, 2024, ourworldindata.org/grapher/annual-co2-cement.
[160] Rhodium Group, "The Global Cement Challenge," March 21, 2024, rhg.com/research/the-global-cement-challenge/.
[161] Concrete Financial Insights, "Ready Mixed Concrete Volume & Price Trends," accessed November 2024, concretefinancialinsights.com/us-concrete-industry-data.
[162] International Energy Agency, *Technology Roadmap: Low-Carbon Transition in the Cement Industry* (2018), www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry.
[163] Global Cement and Concrete Association, *Concrete Future: The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete* (2022), gccassociation.org/concretefuture/.
[164] Portland Cement Association, "Roadmap to Carbon Neutrality: A More Sustainable World is Shaped by Concrete" (2021), www.cement.org/a-sustainable-future/roadmap-to-carbon-neutrality/.

about 14 billion m^3 (about 34 Gt)[165] today to about 20 billion m^3 (about 49 Gt) in 2050, which would lead to an additional 3.8 Gt in CO_2 emissions in the absence of emissions reduction measures.[166]

Subsector Trends

The U.S. cement subsector produced 93 MMT of Portland and masonry cement in 2022, making the United States the fourth-largest producer of cement in the world behind China, India, and Vietnam.[167] The value of U.S. cement shipments in 2022 is estimated at $14.6 billion. The United States also imported about 25 MMT of hydraulic cement and 1 MMT of clinker in 2022, with Turkey, Canada, and Greece supplying over 65% of imported cement. Most U.S. cement plants use dry process kilns, which are more efficient than wet process kilns. About 80% of U.S. cement capacity is provided by modernized kilns with preheater and precalciner.[168] The U.S. cement and concrete subsector comprises a mix of a few multinational companies that collectively own a majority of installed cement capacity and several small and medium enterprises, which collectively employed over 176,000 people in 2021.[169] These companies manufacture a variety of cement and concrete products, including Portland cement, masonry cement, and ready-mix concrete, and supply materials for construction projects across the country. Additionally, there are several companies representing the upstream (mining, feedstocks, etc.) and downstream (logistics, mixing, precast concrete, etc.) parts of the cement and concrete value chain.

The most prevalent type of cement in the United States is Portland cement, and most Portland cement is used in the construction subsector to make concrete, mortar, or stuccos. Ready-mixed concrete producers are the largest purchaser of cement in the United States (70%–75% of total domestic shipments), followed by concrete product manufacturers (11%) and contractors (8%–10%).[170] Government procurement for public projects represent around half of U.S. demand for cement.[171]

State of Technology

Conventional cement manufacturing is comprised of crushing/grinding for preparation of raw meal, clinker production using pyroprocessing, which in turn comprises a calciner (also sometimes known as a pre-calciner) and a rotary kiln for sintering, mixing and finish grinding, and storage.[172] The cement calciner is a direct combustion solid-gas heat exchange where most of the carbonate in the raw meal decomposes. In the commonly used entrainment precalciner design, the fuel and raw meals are dispersed and suspended in a concurrent airflow. A flameless combustion reaction takes place, and the heat released is transferred to the raw meal particles whose state of suspension helps maximize heat transfer. This highly endothermic reaction takes place between 850°C and 900°C. Around 60% of the total fuel consumed and around 70% of CO_2 emissions in a cement plant are at the precalciner. The second step of the pyro-processing involves a rotary kiln, where the fusion of calcium silicates occurs. This slightly exothermic reaction, between 1,400°C and 1,500°C, catalyzes the agglomeration of melted raw materials into a viscous combination of liquids and solids. Some viscous material adheres to the rotary kiln refractory, reducing heat loss and protecting it from the flame. The fused crystal clinker is then cooled and sent to the finishing mill for grinding, mixing, and eventually made into cement.

Cement production in the United States is relatively dispersed throughout the country at 96 plants across 34 states and Puerto Rico, based on 2022 data.[173] Technology improvements have also led to diversification in the

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[165] Assumes an average density of concrete of 2,450 kg/m^3.
[166] Global Cement and Concrete Association, *Concrete Future: The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero Concrete* (2022), gccassociation.org/concretefuture/.
[167] U.S. Geological Survey. "Mineral Commodity Summaries 2023," (2023). doi.org/10.3133/mcs2023.
[168] Troy Hottle et al., "Environmental Life-Cycle Assessment of Concrete Produced in the United States," *Journal of Cleaner Production* 363 (April 2022), doi.org/10.1016/j.jclepro.2022.131834.
[169] U.S. Census Bureau, "Annual Survey of Manufactures: 2018–2021," accessed December 2024, www.census.gov/data/tables/time-series/econ/asm/2018-2021-asm.html.
[170] U.S. Geological Survey, "Mineral Commodity Summaries 2023," (2023). doi.org/10.3133/mcs2023.
[171] U.S. Department of Energy, *Pathways to Commercial Liftoff: Low-Carbon Cement* (2023), liftoff.energy.gov/industrial-decarbonization/low-carbon-cement/.
[172] U.S. Department of Energy, *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in the Manufacturing of Cement* (2017), www.osti.gov/biblio/1512370.
[173] U.S. Geological Survey, "Mineral Commodity Summaries 2023," (2023). doi.org/10.3133/mcs2023.

way cement is processed from the "meal", i.e., the raw feedstock for clinker production. Based on a recent analysis,[174] most production (97%) has now shifted to dry process kilns. Within this subset, 12% are equipped with a preheater and 80% with a combined preheater-precalciner system. Preheater and precalciner systems help with heating the meal to remove water. Dry processes result in lower GHG and criteria air pollutant emissions.[175] As such, most plants that used wet process kilns have now transitioned to dry kilns. The remaining plants are constrained by high sulfur ratios in the fuel, which can cause material build-up and disruption in preheating.[176] In 2018, coal was the predominant fuel source for U.S. cement plants, accounting for 41% of total fuel consumption, followed by petroleum coke (24%), natural gas (23%), and the remainder from other fuel sources.[177] Process emissions remain nearly identical across the production methods and variations in overall GHG emissions largely come from the fuels used in pyroprocessing.[178]

In addition to CO_2 emissions, the U.S. cement subsector produces several other pollutants that can pose significant environmental impacts if not controlled. According to the EPA,[179] particulate matter ($PM_{2.5}$ and PM_{10}), NOx, sulfur oxides, and carbon monoxide are released during cement manufacturing. Other pollutants in smaller quantities such as volatile organic compounds, ammonia, chlorine, and hydrogen chloride are also discharged. Emissions of metal compounds classified as volatile, semi-volatile, and nonvolatile are also of concern. These pollutants contribute to air quality degradation, smog formation, and respiratory health issues among nearby populations. The EPA regulates these emissions through stringent standards for air quality and emissions monitoring.

Efforts for CO_2 emissions reduction in the cement subsector to date have largely focused on energy efficiency improvements; switching to a greater share of lower carbon intensity fuels for pyroprocessing steps, such as natural gas and wastes, including municipal solid waste, waste tires, and waste biomass; and use of lower carbon supplementary cementitious materials (SCMs), such as fly ash, blast furnace slag, recycled cement kiln dust, and more recently, calcined clay as a substitute for clinker.[180] The average clinker-to-cement ratio in the United States, which indicates the amount of SCMs used, has hovered around 0.88–0.91 since the 2000s according to U.S. Geological Survey data. However, it has dropped steadily since 2021 to about 0.84[181] in 2023 due to increased use of SCMs. A lower clinker-to-cement ratio generally implies lower GHG emissions for a given amount of cement, since clinker has considerably higher embodied emissions compared to SCMs based on today's production technologies.

Decarbonization Technologies and Approaches

The subsector's pathway to reach near zero emissions in a sustainable and equitable manner will likely require major shifts in the way cement and concrete are produced and used. The analysis presented in this report and the underlying model build on several key studies published on the topic of cement and concrete decarbonization in both a global and a U.S.-specific context.[182] This section includes a summary of the candidate technologies and approaches used in the analysis.

Cement and concrete decarbonization measures include material efficiency and demand reduction, clinker substitution, alternative binders, retrofitting or replacement of incumbent clinker production with low-carbon

[174] Troy Hottle et al., "Environmental Life-Cycle Assessment of Concrete Produced in the United States," *Journal of Cleaner Production* 363 (April 2022), doi.org/10.1016/j.jclepro.2022.131834.
[175] See Figure 2 in Troy Hottle et al., "Environmental Life-Cycle Assessment of Concrete Produced in the United States," *Journal of Cleaner Production* 363 (April 2022), doi.org/10.1016/j.jclepro.2022.131834.
[176] Glenn Schumacher and Lindsay Juniper, "18 - Coal Utilization in the Cement and Concrete Industries," in *The Coal Handbook* (Second Edition), edited by Dave Osborne, 2:627–63, (Woodhead Publishing, 2023), doi.org/10.1016/B978-0-12-824327-5.00017-X.
[177] U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Cement," (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_cement_energy_carbon_footprint_0.pdf.
[178] See Figure 2 in Troy Hottle et al., "Environmental Life-Cycle Assessment of Concrete Produced in the United States," *Journal of Cleaner Production* 363, (April 2022), doi.org/10.1016/j.jclepro.2022.131834.
[179] U.S. Environmental Protection Agency, "Mineral Products Industry: Portland Cement Manufacturing." In AP-42, Fifth Edition, Volume 1: Stationary Point and Area Sources, 25, (2022), www.epa.gov/system/files/documents/2021-11/c11s06_updated_0.pdf.
[180] Ernst Worrell, Nathan Martin, and Lynn Price, "Potentials for Energy Efficiency Improvement in the U.S. Cement Industry," *Energy* 25, 12 (December 2000): 1189–1214, doi.org/10/bnp9qd.
[181] U.S. Geological Survey, "U.S. Geological Survey Mineral Commodity Summaries 2024 Data Release (Ver. 2.0, March 2024)," March 6, 2024, www.sciencebase.gov/catalog/item/65a6e45fd34e5af967a46749.
[182] See Appendix C for a list of relevant reports/studies.

production routes (including electrification and CCUS), and fuel switching. These measures cut across the pillars of industrial decarbonization. Table C-3 in Appendix C shows the major technologies and approaches that were considered in the *Transformative Pathways* modeling. Each of these decarbonization measures presents unique opportunities and challenges in reducing the emissions footprint of cement and concrete production, requiring careful consideration of technological feasibility, economic viability, regulatory frameworks, and market acceptance. Table C-3 also provides contextual notes on some of these dimensions.

Relative to cement production, the production of clinker—the intermediate product for cement that consumes most of the energy in the overall cement production process—has remained relatively stable in the United States. Therefore, the clinker-to-cement ratio in the United States has slightly decreased over the past five years. Given this trend, this ratio is an important indicator of the energy use and CO_2 emissions per metric ton of cement produced.

4.1.2 Modeling Approach

To model decarbonization pathways over the coming decades in the United States, the model captures both key stages of the cement production process and anticipated changes in concrete demand based on use case.

Market Demand Forecast

The compressive strength of concrete is affected by a variety of factors, such as the characteristics of aggregates, binders (e.g., cement, SCMs), and any additives that are included in the concrete mix, which is tailored to the intended end use. From present day through 2050, a shift toward both higher strength and lower carbon concrete solutions is likely. This will be driven by market initiatives that heighten sustainability as a central focus in construction to increase demand for concrete mixes that reduce embodied carbon while maintaining performance.[183]

Demand for 4,000 pounds per square inch (psi) concrete may increase as it is often specified for commercial applications that require durability and strength. Similarly, the percentage of high-strength concrete (above 5,000 psi) could also see an uptick as infrastructure projects increasingly prioritize resilience against climate impacts.[184] Conversely, the demand for lower-strength mixes, such as 2,500 psi, may decline as construction practices evolve to favor materials that contribute to sustainability goals via durability and resilience. The push for lightweight concrete options, particularly those with strengths around 3,000 psi, is expected to grow only in niche applications where weight reduction is critical.[185] Overall, although total concrete demand is projected to double by 2050 due to urbanization and infrastructure needs,[186] the composition of that demand will increasingly favor both higher-strength and lower-carbon options and is represented in the *Transformative Pathways* modeling.

Cement's embodied emissions can be reduced by lowering the clinker-to-cement ratio. Clinker makes up about 10% of concrete by mass, but it is responsible for more than 90% of concrete's carbon footprint, primarily from process emissions.[187] Currently, the average clinker-to-cement ratio is around 84% in the United States, and

[183] Structural Engineering Institute, "Committing to Net Zero," American Society of Civil Engineers, SE2050 (blog), accessed October 21, 2024, se2050.org/.
[184] Jeremy Gregory et al., "The Role of Concrete in Life Cycle Greenhouse Gas Emissions of U.S. Buildings and Pavements," *Proceedings of the National Academy of Sciences* 118, 37 (September 2021), doi.org/10.1073/pnas.2021936118.
[185] Ibid.
[186] U.S. Department of Energy, "U.S. Department of Energy Announces Plans To Create Low-Carbon Cement and Concrete Center of Excellence To Reduce Industrial Emissions," July 2024. www.energy.gov/eere/iedo/articles/us-department-energy-announces-plans-create-low-carbon-cement-and-concrete.
[187] Ben Skinner and Radhika Lalit, "With Concrete, Less Is More," Rocky Mountain Institute, January 17, 2023, rmi.org/with-concrete-less-is-more/.

there are active efforts to reduce this ratio by 2050, primarily through the increased use of SCMs such as fly ash, slag, and calcined clays, which can partially replace clinker without compromising performance.[188,189,190]

In the absence of a readily available and comprehensive mapping of cement and concrete stocks and their expected flows in future years, including diverse end use markets with considerations of varying strengths, formulations, and product types, the model first represents concrete as a representative mix of its constituents—primarily cement, aggregates, and water—based on 2018 average composition calculated from the consumption of these inputs. The ratio of cement to concrete is kept constant over time. Second, demand scenarios were developed to reflect different levels of concrete demand: flat, slightly decreasing (-0.5% per year), slightly increasing (+0.5% per year), and high (+1% per year).

Product and Emissions Flows

The model used for this analysis follows a cradle-to-gate approach, beginning with the extraction of raw materials and extending through to the grinding and blending of cement. This includes emissions from fuel combustion and electricity use for raw material extraction, processing, and transportation to the production facility. Concrete, primarily composed of aggregates, water, and cement, is widely used across many sectors due to its unique structural capabilities. The embodied emissions of raw materials were included in the analysis to evaluate the impact of substituting raw inputs (primarily SCMs) during cement production. Since clinker production causes significant CO_2 emissions, its partial replacement with SCMs is central to the model. SCMs considered in this analysis include fly ash, blast furnace slag, and limestone calcined clay cement (LC3). The model also includes decarbonization strategies such as fuel switching and lower-carbon clinker production through the addition of carbon capture units to today's best available conventional pyroprocessing technologies, as well as emerging novel production routes such as indirect calcining and electrification of the calciner and kiln (see Table C-3 for a summary of decarbonization technologies and approaches modeled). Figure 10a shows the flow of materials starting from raw material inputs to final cement and concrete products in the model, and Figure 10b shows the general clinker-based cement and concrete manufacturing process with various energy inputs and pyroprocessing technologies (both incumbent and future) represented in the model.

[188] Ibid.
[189] Liam McLoughlin, "GIC Highlights 10 Trends Shaping the Future of Concrete," Aggregates Business, April 2024, www.aggbusiness.com/ab9/news/gic-highlights-10-trends-shaping-future-concrete.
[190] Karen L. Scrivener , Vanderley M. John, and Ellis M. Gartner, "Eco-Efficient Cements: Potential Economically Viable Solutions for a Low-CO_2 Cement-Based Materials Industry," *Cement and Concrete Research* 114 (December 2018): 2–26, doi.org/10.1016/j.cemconres.2018.03.015.

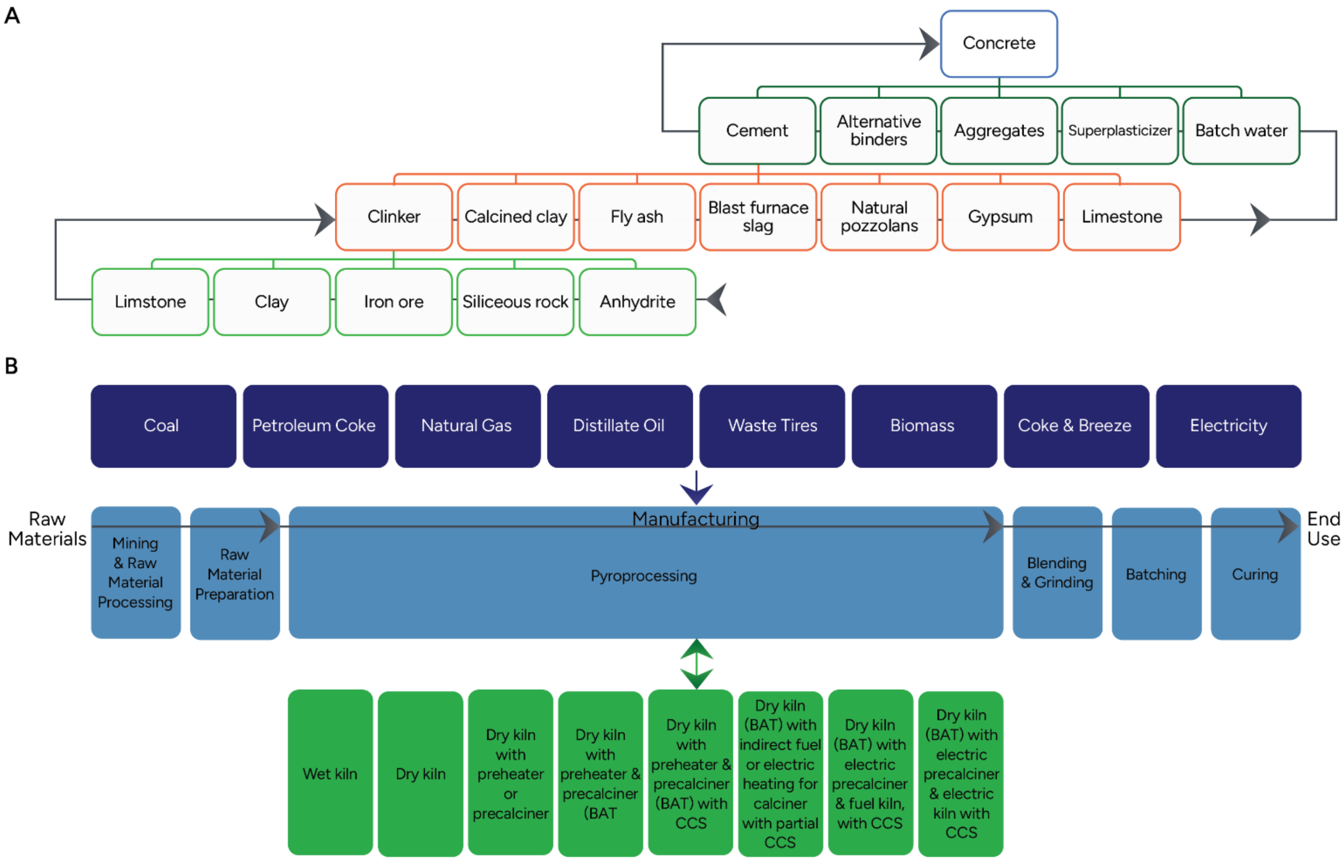

Figure 10. Flow of (a) raw materials, intermediate products, and final products, and (b) energy and emissions as modeled in this analysis

Although this report largely emphasizes plant-level emissions (scope 1 and scope 2), it recognizes that demand for decarbonized cement interacts with the broader supply chain and scope 3 emissions, particularly in the sourcing of raw materials and transportation of final products. As such, embodied scope 3 emissions of key material feedstocks (e.g., calcined clay) are included in the GHG emissions analysis to prevent shifting of environmental burdens from the production of cement and concrete upstream. The transition toward low-carbon cement production will inevitably influence the broader life cycle emissions of the construction subsector, as concrete is expected to remain a key material in meeting future infrastructure needs. However, such downstream scope 3 emissions, including those from the use phase of cement products, concrete production, end-of-life processes such as recycling or disposal, and transportation beyond the cement production facility, are excluded. Additionally, the construction and maintenance of production facilities themselves are not considered in the model.[191]

Clinker Production Routes

This analysis considers eight clinker production technologies—two "incumbent" and six "next generation". These eight production routes do not include clinker production via electrochemical processes or alternative binders. These nascent, clean production routes were not at sufficient maturity to reliably be incorporated into the model with respect to their energy intensities or market adoptions. Acknowledging this limitation, the analogous viewpoint of assessing the decarbonization potential of CCS-enabled clean clinker production as a rough analogue for the decarbonization potential of these nascent clean production routes only in 2050 would be instructive in roughly gauging their potential. Notably, this analogous viewpoint would not correctly capture the adoption rates of nascent production routes and their full emissions impacts. The emissions for the cement

[191] These exclusions were made due to the focus on direct and major upstream emissions from cement production and the challenges in obtaining consistent data on downstream emissions and facility constitution.

subsector with these nascent production routes included could potentially significantly deviate from the included modeled results.

The incumbent technologies include conventional wet kiln and dry kiln pyroprocessing without CCS. Next generation technologies include conventional dry kiln with preheater and precalciner[192] with and without CCS, dry kiln with electric calciner and fuel-based kiln with CCS (also referred to as partially electrified process), dry kiln with electric calciner and electric kiln with CCS (also referred to as fully electrified process), dry kiln with indirect fuel combustion heat-based calcining with CCS, and dry kiln with indirect heating electric-based calcining with CCS. Energy requirements for each of these routes is found in Appendix C.

Electrification of the calciners and rotary kiln offers a cleaner, more precise, and more controllable process compared to conventional fuel-based calcining. Several designs to replace or retrofit the existing calciners have been proposed and studied. These include externally heated electric resistance-based rotary systems, microwave-based systems, and plasma-based systems. A summary of the most promising technologies in each of these electrification approaches can be found elsewhere in the literature.[193] Indirect heat-based calcining, currently being piloted by the LEILAC project,[194] is another potentially promising pathway to electrification of clinker production. Besides potential efficiency gains, a key advancement offered by electrification of the calciner and kiln is that it eliminates fuel combustion as a source of heat, which allows the process CO_2 from the calcining and sintering steps to be captured at a high concentration (greater than 95%) and therefore lead to lower cost and simpler capture plant design. Therefore, electrification of the clinker production process could be potentially viewed as an enabler of CCS at scale.

Amine-based post-combustion capture with a 90% capture efficiency is the nominal technology assumed for CO_2 capture in cases where the fuel combustion CO_2 is mixed with process CO_2. The heat and electricity for CO_2 capture and compression is assumed to be provided by an auxiliary natural gas-based cogeneration plant on site. The CO_2 generated from natural gas combustion is assumed to also be captured, and the net fuel and electricity demand for the overall CO_2 capture process (capturing CO_2 from clinker production and the auxiliary plant) is estimated using modified closed-form expressions from Supekar and Skerlos.[195] Capture of process CO_2 not mixed with fuel combustion CO_2, as in the case of indirect heating-based calcination and partial or full electrification, is assumed to need negligible heat, and the only major energy demand associated with CO_2 capture in these routes considered in this analysis is for CO_2 compression. Although other promising CO_2 capture technologies such as oxyfuel combustion, membrane and cryogenic separation, and calcium looping were not considered in this analysis, the effect on net CO_2 emissions from the clinker production and capture process will be more or less identical with these technologies included and with only the amount of fuel and electricity required for capture varying across capture technologies.

Clinker-to-Cement Ratio

In the *Transformative Pathways* modeling, the clinker-to-cement ratio is assumed to decrease through 2050 with increasing adoption of clinker alternatives under different scenarios. Although identified as promising approaches to reducing cement emissions, alternative binders and electrochemical routes using silicates as feedstocks are not included in this study. However, from the perspective of this model framework, inclusion of these approaches would be operationally similar to increased use of SCMs. Increasing use of clinker alternatives, including SCMs and alternative binders and chemistries, will lower the overall need for CCS due to the decreasing demand for clinker. Further details can be found in Appendix C.

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[192] Modeled as best available technology based on U.S. Department of Energy, *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in the Manufacturing of Cement* (2017), www.osti.gov/biblio/1512370.
[193] Sebastian Quevedo Parra and Matteo C. Romano, "Decarbonization of Cement Production by Electrification," *Journal of Cleaner Production* 425 (November 2023), doi.org/10.1016/j.jclepro.2023.138913.
[194] LEILAC Consortium, "LEILAC Technology Roadmap to 2050 – A Cost-Effective Path to Carbon Neutral Industrial Production," September 2021. www.calix.global/wp-content/uploads/2021/10/LEILAC-Roadmap-2021.pdf.
[195] Sarang D. Supekar and Steven J. Skerlos, "Sourcing of Steam and Electricity for Carbon Capture Retrofits," *Environmental Science & Technology* 51, 21 (November 2017), doi.org/10/gkc3vd.

Decarbonization Decision-making

The general approach to determining which decarbonization pillar out of energy efficiency, LCFFES, electrification, and CCUS should be prioritized and adopted in approaching near zero emissions from the cement and concrete subsector is guided by the flowchart shown in Figure 11. Ultimately, the decisions suitable for a given facility or industrial entity will largely be dependent on constraints and limitations unique to them. More information on the modeling logic can be found in Appendix C.

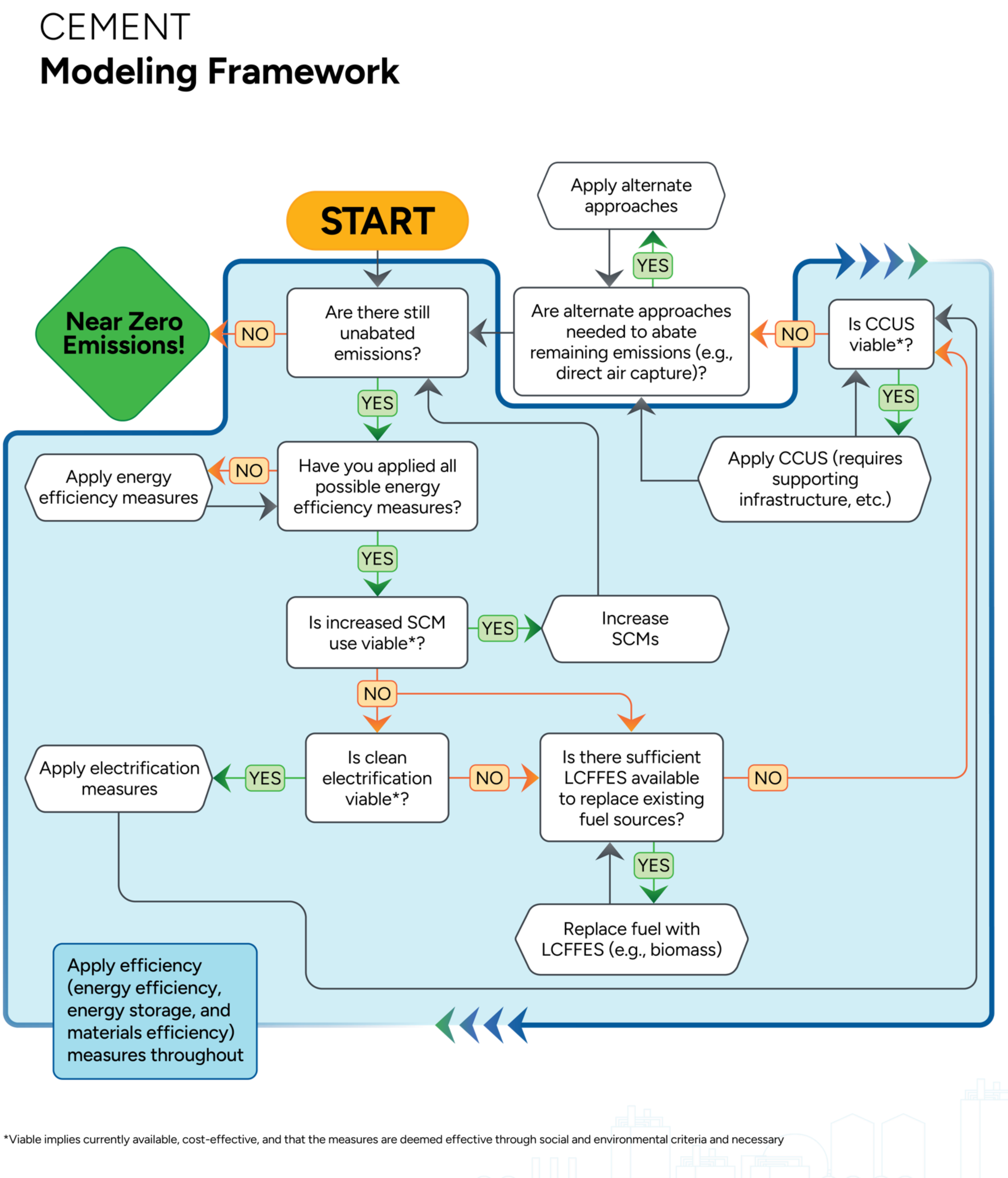

Figure 11. Cement and concrete subsector decarbonization modeling framework

4.1.3 Business as Usual Scenario and Near Zero Pathways

Under the BAU scenario, GHG emissions in 2050 are roughly flat compared to 2018. This assumes a continuation of current policies and technology trends, including incumbent clinker production technologies remaining the dominant production route, coal and petroleum coke remaining the dominant energy sources, and a modest decrease in clinker-to-cement ratio.

From the scenario and sensitivities that were modeled (detailed in Appendix C), two core near zero pathways emerged: one with high adoption of clean clinker production routes and moderate adoption of SCMs (Figure 12), and the other with moderate adoption of clean clinker production routes and high adoption of SCMs (Figure 13). These pathways are not wholly distinct, in that they rely on the same interventions, including fuel switching, SCMs, and cleaner clinker production, but to differing degrees, detailed in Table 7.

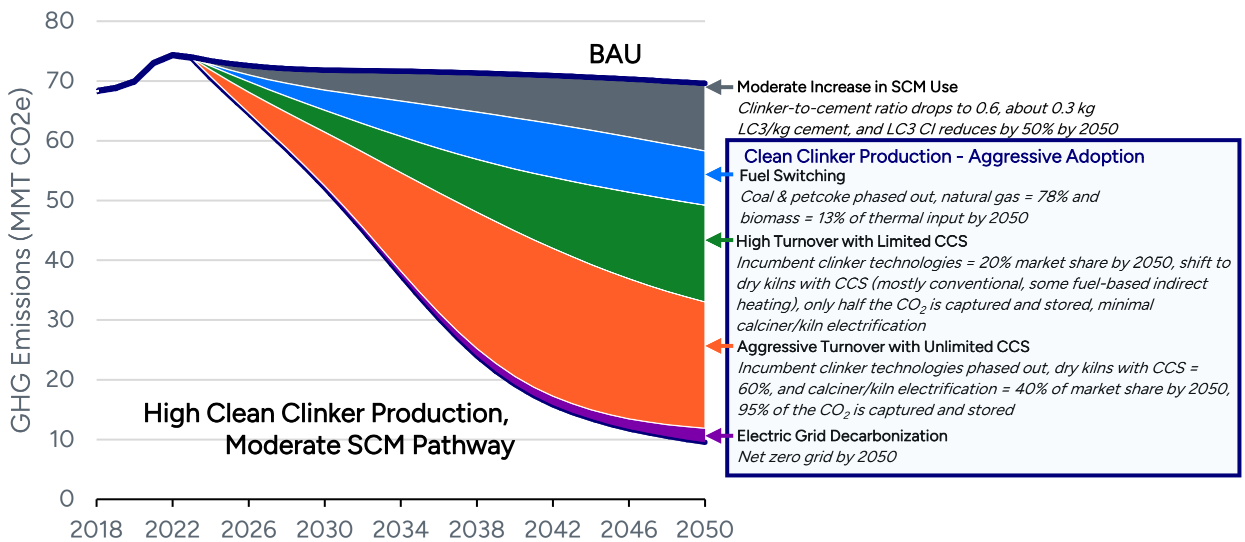

Figure 12. Annual GHG emissions reductions, U.S. cement and concrete manufacturing–High Clean Clinker Production, Moderate SCM pathway (MMT CO_2e/year), 2018–2050

The emissions impact of the interventions (for the year 2050) in the box on the right can be functionally equivalent to nascent clean clinker production routes that were not explicitly considered in the model. The emissions impact of the interventions (for 2050) within the bracket can be functionally equivalent to nascent clean cement production routes. In both instances, a change in the interventions would change the shape of the wedges. Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C. Source: Transformative Pathways modeling.

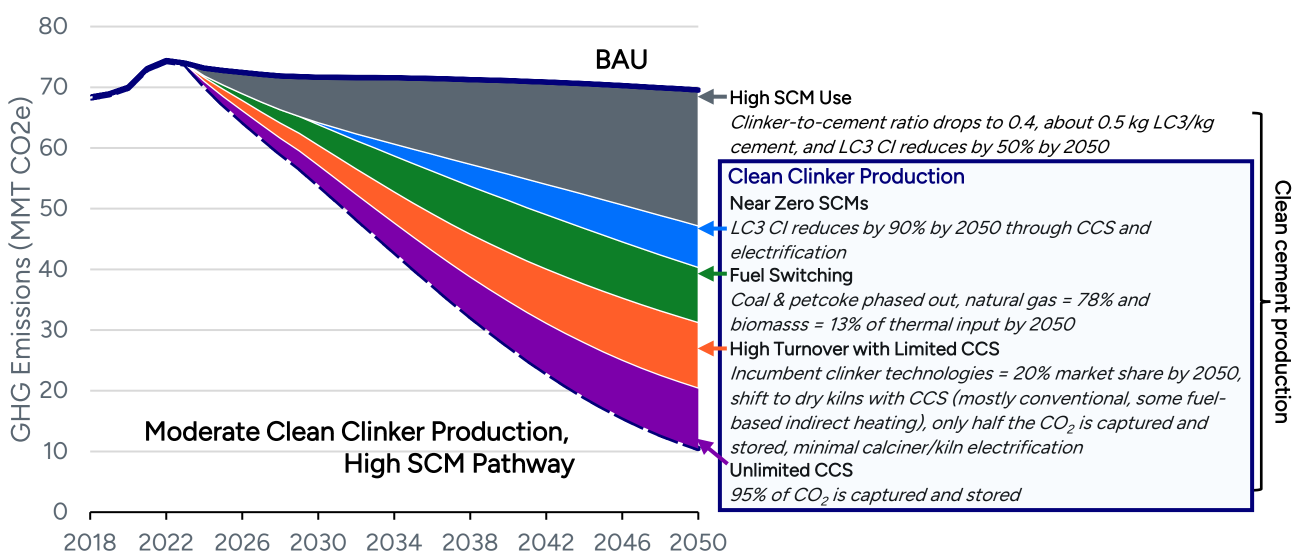

Figure 13. Annual GHG emissions reductions, U.S. cement and concrete manufacturing–Moderate Clean Clinker Production, High SCM pathway (MMT CO_2e/year), 2018–2050

The emissions impact of the interventions (for the year 2050) in the box on the right can be functionally equivalent to nascent clean clinker production routes that was not explicitly considered in the model. The emissions impact of the interventions (for 2050) within the brackets can be functionally equivalent to nascent clean cement production routes. In both instances, a change in the interventions would change the shape of the wedges. Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C. Source: Transformative Pathways modeling.

Table 7. Cement and Concrete BAU Scenario and Near Zero Pathways Key Assumptions

Scenario	SCM vs. Clinker Use	Technology 2050 Market Share	CCUS	LCFFES	Electrification
BAU	• Clinker-to-cement ratio (2050): 0.8 • LC3 dominant SCM substituting clinker (about 0.1 kg LC3/kg cement by 2050) • LC3 carbon intensity (2050): 0.15 kg CO2e/kg • Clinker carbon intensity (2050): 0.15 kg CO2e/kg	• Incumbent clinker technologies: over 80% • Dry kilns with CCS: about 7%	50% of CO_2 captured and stored	Thermal input share by 2050: 45% coal and petroleum coke, 40% natural gas, 9% biomass, 5% opportunity fuels	Electric grid emissions factor reduced 67% by 2050 compared to 2018 (see Appendix B)
High Clean Clinker Production, Moderate SCM near zero pathway	• Clinker-to-cement ratio (2050): 0.6 • LC3 dominant SCM substituting clinker (0.3 kg LC3/kg cement by 2050) • LC3 carbon intensity (2050): reduced by 50% • Clinker carbon intensity (2050): 0.18 kg CO2e/kg	• Incumbent clinker technologies: 0% • Dry kilns with CCS (mostly conventional, some fuel-based indirect heating): 60% • Calciner/kiln electrification: 40%	95% of CO_2 captured and stored	• Coal and petroleum coke nearly phased out by 2050 • Thermal input share by 2050: 78% natural gas accounts, 13% biomass, 6% opportunity fuels	• Calciner/kiln electrification • Net zero emissions electric grid by 2050 (see Appendix B)
Moderate Clean Clinker Production, High SCM Adoption near zero pathway	• Clinker-to-cement ratio (2050): 0.4 • LC3 dominant SCM substituting clinker (0.5 kg LC3/kg cement by 2050) • LC3 carbon intensity (2050): reduced by 90% • Clinker carbon intensity (2050): 0.03 kg CO2e/kg	• Incumbent clinker technologies: 20% • Dry kilns with CCS (mostly conventional, some fuel-based indirect heating): 70% • Electrified technologies: 9%	95% of CO_2 captured and stored	Same as other near zero pathway	• Minimal calciner/kiln electrification • Net zero emissions electric grid by 2050 (see Appendix B)

Product demand for all scenarios: 0.5% per year increase, resulting in about 28% increase in cement production between 2018 and 2050.

In both pathways, fuel switching from coal and petroleum coke (petcoke) to natural gas and biomass provide modest decarbonization potential (about 13%) compared with BAU in 2050. SCMs can have varying impacts on decarbonization potential, dependent on the magnitude of adoption. The Moderate Clean Clinker Production, High SCM pathway, which decreases clinker-to-cement ratio to 0.4 and utilizes near zero SCMs, has about a 40% reduction in emissions by 2050 due to SCMs. On the other hand, the High Clean Clinker Production, Moderate SCM pathway, which decreases clinker-to-cement ratio to 0.6, only has a 16% reduction in emissions by 2050 due to SCMs. In both pathways, the remaining emissions must be addressed by clean clinker production technologies. The corresponding adoption of clinker production technologies that were assumed in the *Transformative Pathways* modeling are shown in Figure 14 for the High Clean Clinker Production, Moderate SCM pathway and Figure 15 for the Moderate Clean Clinker Production, High SCM pathway. Table 8 summarizes the distribution of production routes for each pathway in 2050.

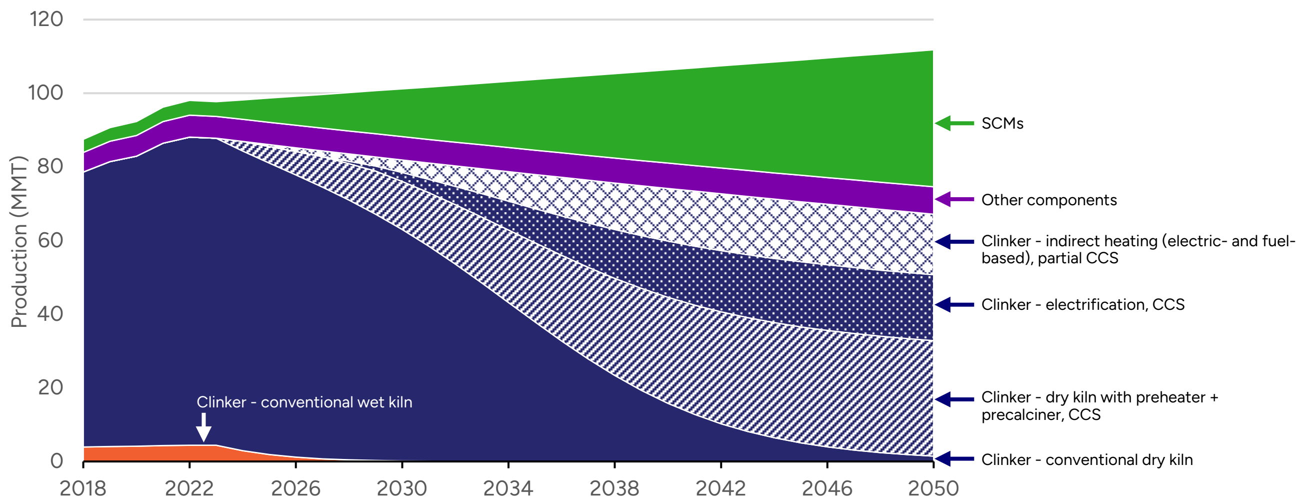

Figure 14. U.S. clinker production by technology–High Clean Clinker Production, Moderate SCM pathway, 2018–2050 (including incumbent technology turnover levels and corresponding production mixes)

Alternative cleaner clinker production technologies were represented as production routes with CCS. Blue patterned areas denote cleaner clinker production technologies compared with the incumbent conventional dry kiln technology. Details on assumptions can be found in Appendix C. Source: Transformative Pathways modeling.

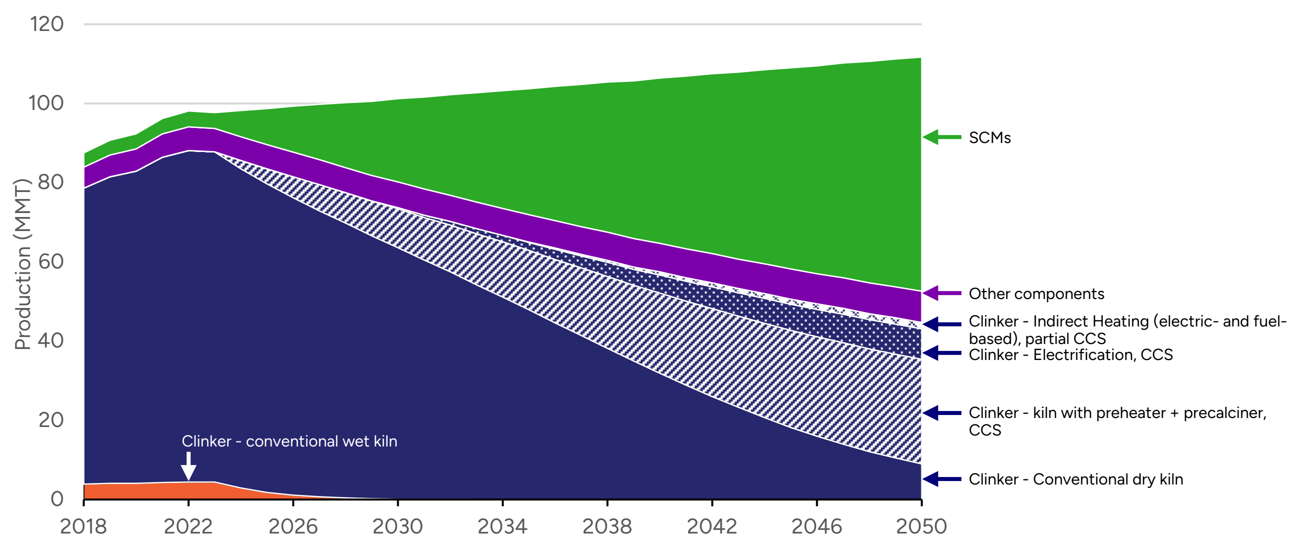

Figure 15. U.S. clinker production by technology–Moderate Clean Clinker Production, High SCM pathway, 2018–2050 (including incumbent technology turnover levels and corresponding production mixes)

Alternative cleaner clinker production technologies were represented as production routes with CCS. Blue patterned areas denote cleaner clinker production technologies compared with the incumbent conventional dry kiln technology. Details on assumptions can be found in Appendix C. Source: Transformative Pathways modeling.

Table 8. Distribution of Production Routes in 2050 for the Two Near Zero Pathways

Production Route	High Clean Clinker Production, Moderate SCM Pathway		Moderate Clean Clinker Production, High SCM Pathway	
	Total Production (MMT)	Share of Production	Total Production (MMT)	Share of Production
Clinker - Conventional Wet Kiln	0	0%	0	0%
Clinker - Conventional Dry Kiln	1.5	1%	9	8%
Clinker - Dry kiln with preheater + precalciner, CCS	31.4	28%	26.4	24%
Clinker - Electrification, CCS	17.9	16%	7.7	7%
Clinker - Indirect Heating (electric- and fuel-based), partial CCS	16.4	15%	1.6	1%
Other components	7.5	7%	7.9	7%
SCMs	37.2	33%	59.1	53%

Alternative cleaner clinker production technologies were represented as production routes with CCS.

Replacing clinker with SCMs is likely to be the preferred decarbonization measure over cleaner clinker production due to low capital and operating cost considerations.[196] In this work, most clinker substitution is assumed to occur through the increased use of LC3. Although LC3 has a lower carbon intensity than conventionally produced clinker, it still has an appreciable embodied emissions of about 0.29 kg CO_2/kg LC3.[197] Despite the assumption of gradually falling emissions intensity of LC3 from 0.29 to about 0.18 kg CO_2/kg LC3 through higher efficiency and process electrification measures,[198] a cleaner clinker production mix from CCS and other technologies expected in the near zero pathways would lead to overall clinker emissions intensity dropping below that of LC3. By applying efficiency measures, electrification, and possible carbon capture to the production of LC3, the annual emissions in the Moderate Clean Clinker Production, High SCM pathway may be reduced to levels identical to the High Clean Clinker Production, Moderate SCM pathway (around 10 MMT CO_2e) by 2050.

In addition to fuel switching and conventional SCMs, broad adoption of clean clinker production approaches is needed. As noted previously, this was represented as aggressively utilizing CCS on incumbent and nascent clinker production technologies (e.g., electrification of kiln) and SCM production, given the limitations of modeling. However, there are many adoption barriers to a high CCS future, of which ready access to CO_2 storage sites, high capital and operating costs, and physical plant footprint are just a select few. Lowering the cost and parasitic energy burden of CO_2 capture through advanced amines, oxyfuel combustion, cryogenic separation, and membrane separation is necessary for large-scale deployment of CCS. A survey of current cement plant locations relative to potential CO_2 storage locations shown in Figure 16 indicates that over half the cement plants (and 52% of installed capacity) fall outside a 100-mile radius of the nearest CO_2 storage site.

[196] Izhar Hussain Shah et al., "Cement Substitution with Secondary Materials Can Reduce Annual Global CO_2 Emissions by up to 1.3 Gigatons," *Nature Communications* 13, 1 (September 2022): 5758, doi.org/10.1038/s41467-022-33289-7.
[197] Ibid.
[198] Haitang Zhu et al., "Low Carbon and High Efficiency Limestone-Calcined Clay as Supplementary Cementitious Materials (SCMs): Multi-Indicator Comparison with Conventional SCMs," *Construction and Building Materials* 341, (July 2022), doi.org/10.1016/j.conbuildmat.2022.127748.

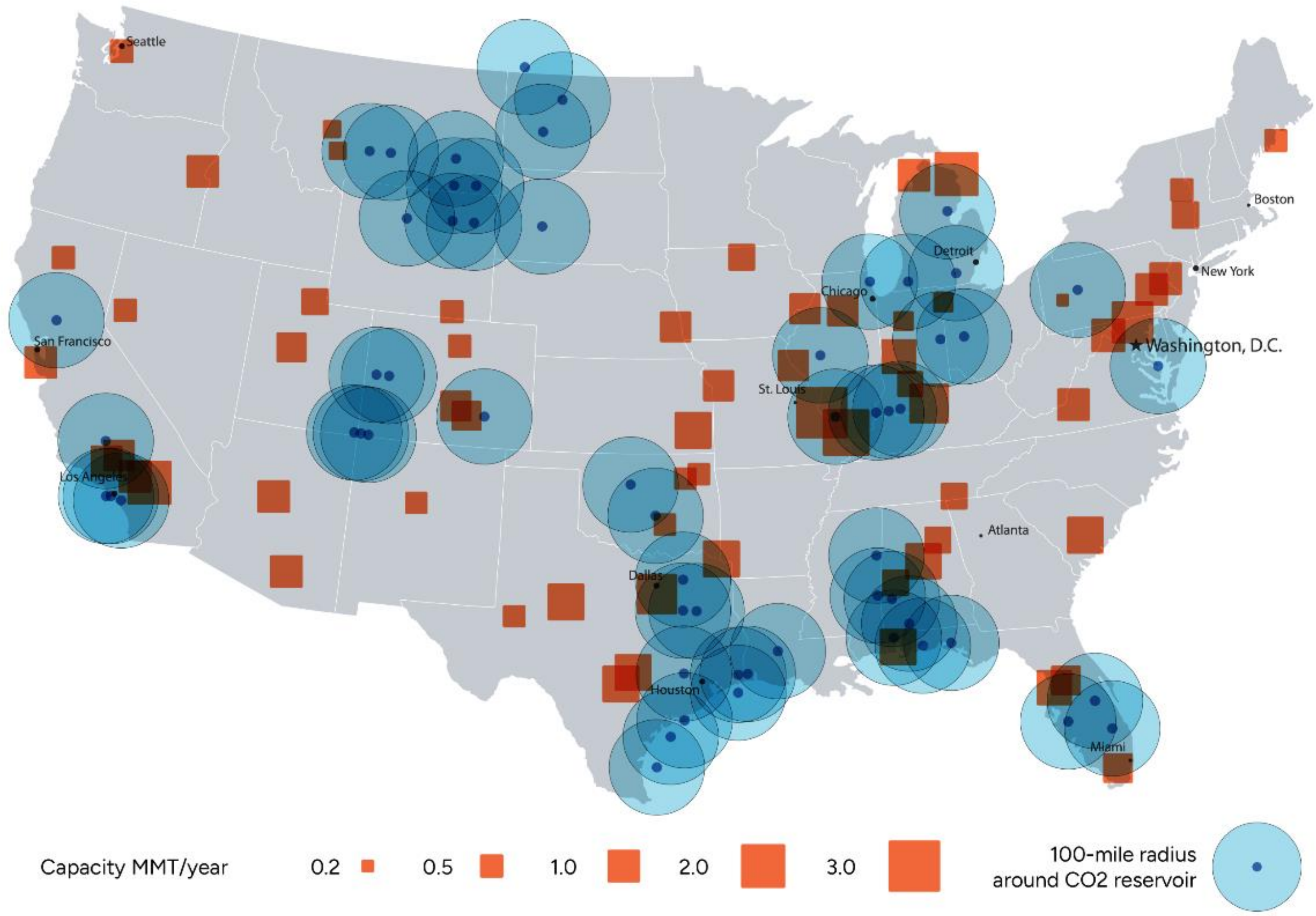

Figure 16. Location of U.S. cement plants (squares) mapped against locations of candidate CO_2 storage locations mapped (dots)

Shaded bubbles around the dots indicate a 100-mile radius around the CO_2 reservoir. Data sources: Portland Cement Association Plant Information Summary; U.S. Environmental Protection Agency, "Facility Level Information on GreenHouse gases Tool (FLIGHT)," August 2024, ghgdata.epa.gov/ghgp/main.do; Udayan Singh, Erica M. Loudermilk, and Lisa M. Colosim "Accounting for the role of transport and storage infrastructure costs in carbon negative bioenergy deployment," Greenhouse Gases Science and Technology 11, 1 (February 2021): 144-164, doi.org/10.1002/ghg.2041.

Nascent electrified technologies that reduce or eliminate the use of combustible fuels during pyroprocessing could help to produce high purity CO_2 and alleviate the issue of high energy burden of carbon capture.[199] However, to see any significant adoption, these electrified technologies need to be demonstrated and deployed to show viability before 2035. In the absence of commercially viable electrified technologies around this time, existing commercially demonstrated high efficiency dry kiln technology (with preheater + precalciner) with CCS is likely to be locked-in for near-to-mid-term clinker production, limiting penetration of electrified alternatives.

Given the challenges of CCS and electrification, a broader combination of technologies should be considered for subsector decarbonization. There is opportunity for innovative and emerging technologies. Alternative approaches to produce clinker or cement while minimizing emissions, such as novel SCMs, electrochemical production routes, alternative binders, may become opportune decarbonization approaches by 2050, if sufficiently scaled and demonstrated.

4.1.4 Key Takeaways

The modeling effort yielded two distinct decarbonization pathways where aggressive decarbonization interventions could reduce the subsector's GHG emissions to approximately 10 MMT CO_2e in 2050, down from 68 MMT CO_2e in 2018. It is important to note that the analysis lacked implementation of novel clinker production routes, such as electrochemical processes or alternative binders. Future efforts may work to incorporate these

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[199] Ron M. Jacob and Lars-André Tokheim, "Electrified Calciner Concept for CO_2 Capture in Pyro-Processing of a Dry Process Cement Plant," *Energy* 268 (April 2023), doi.org/10.1016/j.energy.2023.126673.

routes, but they must be commercially viable against clinker pyroprocessing with CCS by around 2035 if they are to have an appreciable market share by 2050 and prevent lock-in of CCS production routes. With this in mind, the two pathways that emerged from this analysis, coupled with acknowledged model limitations, can help frame the landscape of the decarbonization decisions and investments ahead for this subsector.

The two modeled pathways were:

- High Clean Clinker Production, Moderate SCM
- Moderate Clean Clinker Production, High SCM

The modeled pathways both relied, though to differing degrees, on increased usage of SCMs (represented as limestone calcined clay in the modeling) and clean clinker production (represented as CCS-enabled clean clinker production in the modeling).

For clinker production, both modeled pathways relied on CCS in addition to fuel switching that replaced coal and petroleum coke with natural gas and biomass. These interventions resulted in modeled pathways that leveraged CCS-enabled clean clinker production to cover 80%–100% of clinker production in 2050.

Both pathways relied on increased usage of SCMs, requiring SCM production to accelerate. This will involve a significant shift in supply chains as well as the adaptation of building codes to allow for higher percentages of SCM adoption. Utilizing SCMs to offset clinker is an intervention with near term reductions but risks locking in the feedstocks of limestone and calcined clay, which collectively, though primarily from the calcining of the clays, have significant embodied emissions (currently estimated to be 0.29 kg CO_2e/kg SCM). These embodied emissions limit the long-term potential of a pathway unless they are addressed with scope 3 interventions, as they were to varying degrees in the two pathways. It is important to remember that clean clinker may also be accomplished via novel production routes (not modeled) separately or in combination with CCS-enabled clinker production. As clinker production moves toward clean production (via CCS-enabled clinker or novel clinker production routes), tradeoffs between the emissions of SCMs versus clinker, as well as other economic, technological, environmental, and societal impacts, will need to be balanced. Novel clinker production routes even allow for the possibility of clean cement production accomplished with minimal use of SCMs.

The increased use of SCMs that outpaced cement demand resulted in a decrease in clinker demand. For the High Clean Clinker Production, Moderate SCM pathway, approximately 10% of clinker production will be retired, while for the Moderate Clean Clinker Production, High SCM pathway, almost half of clinker production facilities will wind down. As a result, these pathways point to the potential for a coalescing of clinker capacity around geographically favorable sites, i.e., those that are near CO_2 storage locations.

This potential high technology turnover will face challenges in retiring the incumbent clinker facilities. The desire to avoid stranded assets and workforce impacts will naturally deter these retirements. Creative solutions to mitigate these issues will be necessary if this is the chosen pathway. Decisions will need to be made in this decade and the next as to which pathway, or if an alternative clinker production route, is more feasible and how best to facilitate its adoption.

4.2 Chemicals

4.2.1 Introduction

U.S. chemicals manufacturing plays a crucial role in the nation's economy, contributing significantly across various economic sectors. This subsector met 13% of the global chemicals demand, as the United States was the second largest producing country in 2022.[200] Over 70,000 products are produced through more than 11,000 facilities, of which over two-thirds are owned and operated by small- and medium-sized enterprises.[201] Similarly, employment within this subsector is extensive, directly employing 529,000 and indirectly involving nearly 4.1

[200] U.S. Cybersecurity and Infrastructure Security Agency, "Chemical Sector Profile," March 2022, www.cisa.gov/resources-tools/resources/chemical-sector-profile.
[201] Ibid.

million individuals across research, manufacturing, and transportation throughout the United States.[202] Although chemical plants are distributed across the country, the highest concentrations are found in California, Texas, Ohio, Illinois, and Pennsylvania.[203]

Chemicals manufacturing is also the largest exporting subsector in the United States, responsible for over 9% of U.S. exports in 2022.[204] Although U.S. chemicals producers also import numerous inputs essential to their production processes, the country remains a net exporter in the subsector with exports valued at $125.3 billion in 2020.[205] Needless to say, the chemicals subsector holds significant strategic importance both domestically and internationally with demand that is projected to grow.

As one of sixteen Critical Infrastructure Sectors identified by the Department of Homeland Security, nearly every state hosts some form of chemical production. However, some segments are concentrated in regions where feedstocks are more readily available, such as primary petrochemicals with 80% of production located in Texas and Louisiana. More than half of all chemical products by weight are transported less than 250 miles from the manufacturing site, each with its unique physical properties leading to the distinct challenges during transportation that contribute specifically to its emissions profile.[206] Federal and state agencies regulate the manufacturing, storage, processing, transportation, and use of chemicals through various mechanisms. These regulations extend beyond just chemical manufacturing and include inspections, licensing, toxic substances control, emissions tracking, and safety protocols.

In 2018, the chemicals manufacturing subsector accounted for 28% of total GHG emissions and 25% of primary energy consumption for U.S. manufacturing.[207] With increasing emphasis on sustainability and growing pressures from competition, reducing GHG emissions in the U.S. chemicals subsector has become crucial. Emissions in this subsector stem from fuel combustion, the use of sorbents and carbonates, and various industrial processes. CO_2 is the dominant GHG emitted across most chemical production subsectors, except in nitric acid and adipic acid production that primarily release N_2O as a byproduct. Additionally, small amounts of methane are emitted across all subsectors, mainly due to the combustion of fossil fuels or the processing of off-gases for energy recovery or volatile organic compounds and hazardous air pollutant control.[208]

Chemicals manufacturing is comprised of multiple subsectors[209] covering numerous chemicals. Figure 17 shows the total GHG emissions (both process and combustion) of the top 12 emitting subsectors plus the remainder of the chemicals subsector, with the top three (other basic organic chemicals, petrochemicals, and plastics materials and resins) accounting for 50%.[210]

[202] Ibid.
[203] Ibid.
[204] Ibid.
[205] Ibid.
[206] Ibid.
[207] Ibid.
[208] U.S. Environmental Protection Agency, *2011-2023 Greenhouse Gas Reporting Program Sector Profile: Chemicals Sector (Non-Fluorinated)*, October 2024, www.epa.gov/ghgreporting/ghgrp-chemicals-sector-profile.
[209] Divided into 29 six-digit coded North American Industry Classification System (NAICS) subsectors.
[210] From analysis of U.S. Energy Information Administration, "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data," 2021, www.eia.gov/consumption/manufacturing/data/2018/ and U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022*, EPA 430-R-24-004 (2024), www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.

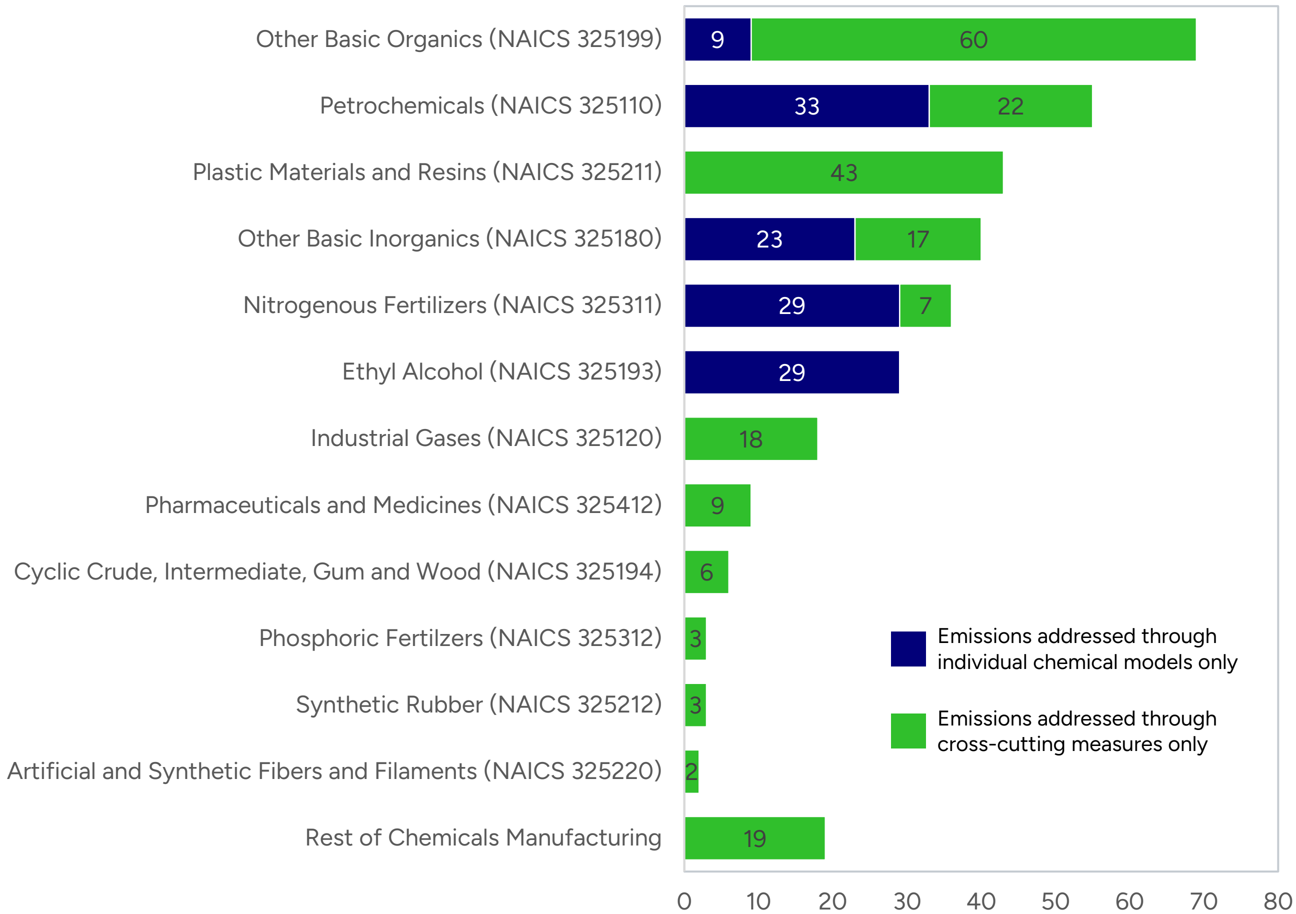

Figure 17. U.S. chemical manufacturing subsectors 2018 emissions (MMT CO_2e) by North American Industry Classification System (NAICS) category

Acronyms: carbon dioxide equivalent (CO_2e); million metric tons (MMT); North American Industry Classification System (NAICS). The named chemicals (methanol, ethylene, propylene, butadiene, BTX aromatics, chlorine, soda ash, ammonia, and ethanol) are those included in the individual modeling results presented in this and included in the dark green bars. The light green bars are the subsector emissions to be addressed through cross-cutting measures only. Includes scope 1 (onsite process and combustion) and scope 2 (offsite combustion) emissions. Data sources: From analysis of U.S. Energy Information Administration, "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data" (2021), www.eia.gov/consumption/manufacturing/data/2018/ and U.S. Environmental Protection Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022, EPA 430-R-24-004 (2024), www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.

Complex interdependencies between different processes and the heterogeneity of chemical production present significant challenges for energy analysis and decarbonization strategy development. Unlike more homogeneous subsectors, diverse chemicals manufacturing processes often yield multiple co-products, rendering it difficult to design straightforward decarbonization pathways. However, addressing these challenges is vital to reducing emissions and improving subsector sustainability.

4.2.2 Modeling Approach

Modeling Scope

This analysis primarily focuses on high-volume, energy- and emission-intensive basic chemicals, including (i) ethylene, (ii) propylene, (iii) butadiene, (iv) benzene-toluene-xylene (BTX) aromatics, (v) chlor-alkali (co-production of chlorine and sodium hydroxide), (vi) soda ash, (vii) ethanol, (viii) methanol, and (ix) ammonia. Together, these chemicals account for approximately 40% of total U.S. chemicals subsector GHG emissions in 2018 (see Figure 17). These nine chemicals were chosen to be modeled based on three key factors. First, they are major contributors to current industrial emissions, as they are produced in large quantities and are among the most energy- and emissions-intensive chemicals. Decarbonizing them offers a significant opportunity for large-scale emissions reductions. Second, addressing the direct (scope 1) and indirect (scope 2) emissions from these chemicals can impact emissions throughout the value chain, contributing to scope 3 emissions reductions (see Section 4.8 for examples). Lastly, the projected future demand for these chemicals is expected to grow substantially,[211] making their decarbonization critical for sustainable industrial growth and long-term emissions reduction.

The remaining 60% of subsector emissions come from the production of hundreds of other chemicals. These additional chemicals also need to be considered for subsector-wide decarbonization. Although some unit operations are similar across different chemicals manufacturing processes, decarbonization strategies vary based on factors such as feedstock composition, boiling points, and heating and cooling requirements. These variations make estimation of the potential to reduce emissions across the entire chemicals subsector challenging. Nevertheless, this analysis considers cross-cutting measures that could be applied across all chemicals manufacturing. In the future, the study could be expanded to include process-specific measures for additional segments of the chemicals subsector, similar to the detailed analysis of the nine aforementioned chemicals.

The *Transformative Pathways* modeling evaluated emissions reduction strategies from 2018 to 2050 and considers historical and projected production growth. Multiple decarbonization pathways are proposed, leveraging a range of low-carbon and sustainable energy technologies. This section focuses on a Core Near Zero (CNZ) pathway and sensitivities for decarbonizing the U.S. chemicals subsector. A central element of this transition is the increased use of alternative low-carbon feedstocks, including sustainable materials such as hydrogen, biomass, captured CO_2, and waste materials, which replace traditional fossil-based feedstocks and reduce the overall emissions footprint. Each pathway varies in its adoption of low-carbon and sustainable energy technologies, presenting technical solutions that could be further developed and economically scaled to achieve long-term decarbonization goals.

Modeling Framework

Transforming the chemicals manufacturing requires a comprehensive view of the anticipated decarbonization pillars and emerging technologies, considering their viability over varying timeframes up to mid-century and beyond, as influenced by techno-economic factors. Figure 18 illustrates the iterative modeling framework process that continues until near zero or net zero emissions are achieved, incorporating solutions that may not yet be commercially available.

[211] See Appendix C (Table C-4) for information on assumed production growth rates.

CHEMICALS
Modeling Framework

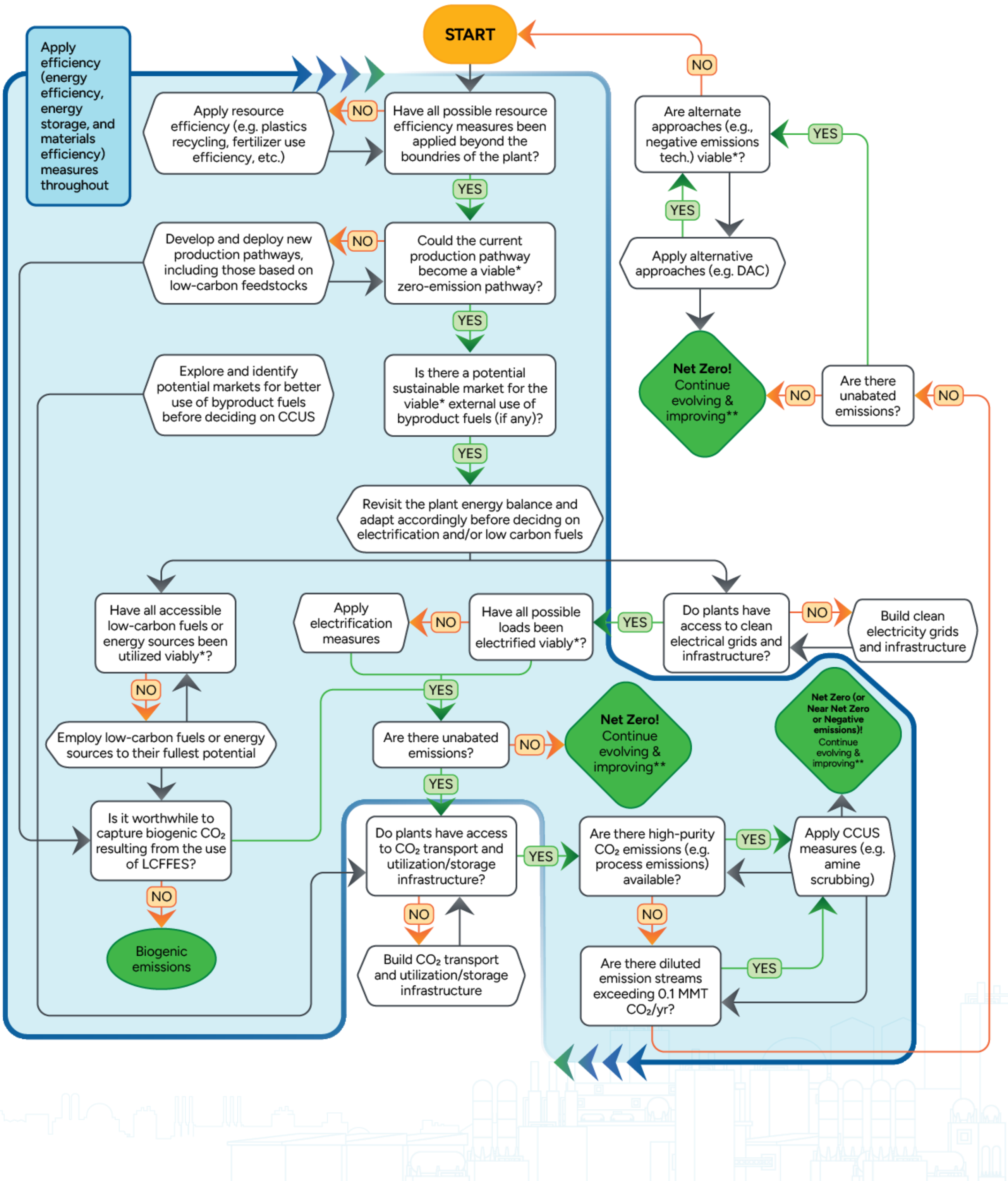

Figure 18. Chemicals manufacturing subsector decarbonization modeling framework

Production Growth

Figure 19 illustrates the production volumes of key high-volume, energy- and emissions-intensive basic chemicals from 2010 to 2050 used for this modeling, with growth in the rest of the chemicals subsector shown as indices, where 1.0 represents the reference production level in the base year 2018. The production indices for the rest of the chemical subsector are based on a subset of about 40 other chemicals, with their cumulative historical production trends extrapolated into the future. Since these indices are used to scale the overall energy demand and corresponding emissions of the remaining chemical subsector, the absolute production volumes for these chemicals are not analyzed individually and, as such, are not shown in the figure.

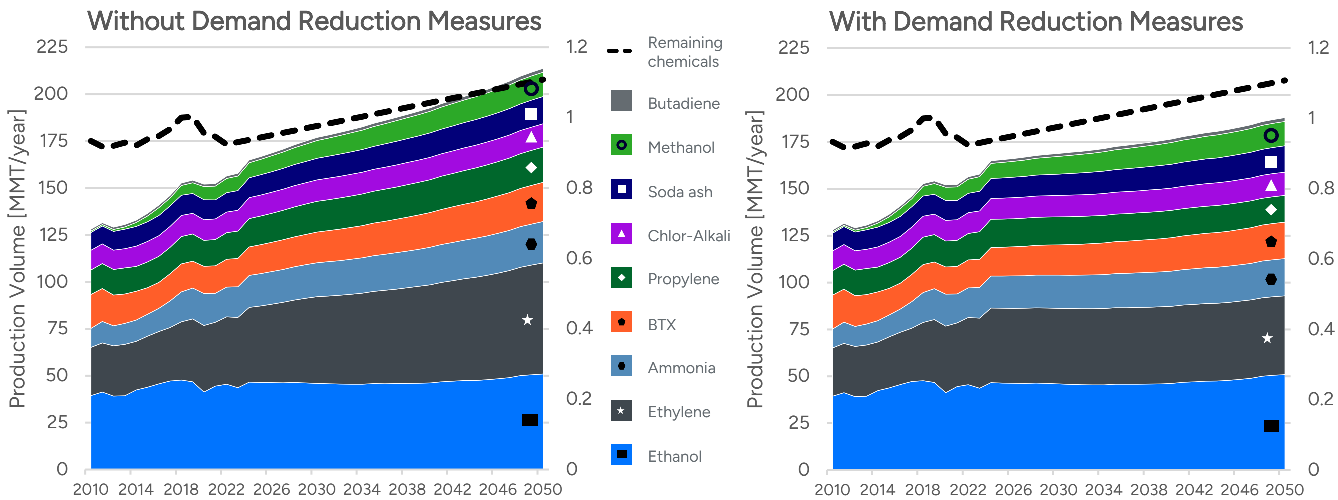

Figure 19. U.S. chemicals estimated production volumes from 2010 to 2050 without (left) and with (right) demand reduction measures

See Table C-4 in Appendix C for additional detail on assumed chemicals production growth rates.

The data up to 2020 primarily reflect historical trends (based on multiple data sources and assumptions, see Table C-4 in Appendix C for more details), indicating a 20% overall growth in the production of key chemicals from 2010 to 2020. In recent years, the U.S. chemicals subsector has experienced demand growth alongside decreasing feedstock and energy costs, driven by the increased availability of inexpensive shale gas.

Projections generated from modeling the chemicals subsector's decarbonization and presented in Figure 19 (left) indicate a 41% growth in the production of these nine chemicals between 2020 and 2050. However, if demand reduction measures—such as plastics recycling (impacting ethylene, propylene, and BTX demand), glass recycling (impacting soda ash demand), and fertilizer use efficiency (reducing ammonia demand)—are implemented, overall growth may be moderated, with a projected 24% increase between 2020 and 2050 (see Figure 19–right). More information on assumed chemicals production growth rates can be found in Appendix C.

These future production demand projections are based on several assumptions, including assumed rates of which are detailed in Appendix C (see Table C-5). Although broad structural changes to the chemicals and materials supply chains would have a substantial impact on specific chemical manufacturing, it should be noted that only a small subset of demand reduction measures is analyzed in this study. Hence, a broader analysis that investigates the supply chain impacts and accounts for the economy-wide changes linked to how end-use materials and products are consumed in all economic sectors is needed to better understand the decarbonization pathways of chemicals manufacturing subsector.

Production Routes

For the nine chemicals modeled, a total of 45 conventional and emerging production routes were identified for inclusion (see Table 9). Variations of plant configurations and energy-efficient incumbent technologies were examined in addition to these 45 routes. The research community is developing additional clean manufacturing technologies that are currently not included in these production routes but could be considered in a future update, such as electrochemical oxidative coupling of methane (OCM) for ethylene production, electrochemical ammonia synthesis, and electrochemical ethanol manufacturing. Currently, comprehensive techno-economic data for these nascent technologies and processes is lacking and not included in the *Transformative Pathways* modeling. As key data becomes available through DOE funding and other research efforts aimed at further developing these technologies, these innovative concepts should be revisited. Future analyses and modeling can then assess their impact, commercial viability, expected market entry, and other relevant factors.

Within the framework of assessing decarbonization potential of different interventions, CCUS was modeled as a variation in plant configuration, an additional process to added existing production routes, and not modeled as a new, distinct production route. Because of this modeling framework in the chemicals subsector, the analogous viewpoint needs to be used with more caution. Applying it to CCUS-enabled production routes is less problematic than using the viewpoint to assess decarbonization potential, as is required in this subsector. This perspective should be taken with caution, and best viewed from only a 2050 perspective. The implementation of CCUS in the chemicals analysis was limited in most instances to 70%, or less, of emissions that remained after other decarbonization interventions. It was also implemented in many instances as a retrofit to existing assets as well as having market adoption parameters that were defined by the maturity of amine based CCUS technologies. Interpreting CCUS enabled production as analogous to clean production could be underestimating the decarbonization potential of a clean nascent production route in lieu of CCUS enabled production route.

Table 9. Production Routes Considered for the Manufacturing of Nine Key Basic Chemicals

Subsector	Chemical	Conventional Production Routes	Emerging Low-Carbon Production Routes
Petrochemicals (NAICS 325110)	Ethylene	• Steam cracking (natural gas liquids (NGL)) • Steam cracking (naphtha) • Steam cracking (gas oil)	• Electrified steam cracking • Methanol-to-olefins (MTO) (ethylene) • Ethanol dehydration
	Propylene	• Steam cracking • Fluidized catalytic cracking	• Propane catalytic dehydrogenation (PDH) • Metathesis • Electrified steam cracking • Methanol-to-olefins (MTO) (propylene)
	Butadiene	• Steam cracking	• Electrified steam cracking • Direct glucose to butadiene • Ethanol to butadiene • Butane dehydrogenation (BDH)
	Benzene, toluene, and xylenes (BTX aromatics)	• Pygas from naphtha steam cracking • Reformate from catalytic reformers • Toluene disproportionation • Toluene hydrodealkylation	• Methanol-to-aromatics (MTA) • Biomass-to-aromatics
Basic Inorganic Chemicals (NAICS 325180)	Chlor-alkali	• Mercury cell technique • Diaphragm cell technique • Membrane cell technique	• Oxygen depolarized cathode (ODC)
	Soda ash	• Monohydrate process • Carbonation process (Searles lake)	• Electrified monohydrate process

Basic Organic Chemicals (NAICS 325193, 325199)	Ethanol	• Dry milling • Wet milling	• Electrified dry milling • Syngas fermentation
	Methanol	• Steam methane reforming (SMR)	• Autothermal reforming (ATR) • Biomass gasification • Water electrolysis /CO2 to methanol
Nitrogenous Fertilizers (NAICS 325311)	Ammonia	• Steam methane reforming (SMR) • Coal gasification • Ammonia synthesis only	• Autothermal reforming (ATR) • Water electrolysis • Methane pyrolysis • Biomass gasification

4.2.3 Business as Usual Scenario, Core Near Zero Pathway, and Sensitivities

A Core Near Zero (CNZ) decarbonization pathway was developed across the four key pillars to evaluate the GHG emissions reduction potential in the U.S. chemicals subsector. This CNZ pathway also incorporates external emissions reductions factors such as a cleaner electric grid and the increased use of clean hydrogen. The BAU scenario assumes slow energy efficiency gains and gradual adoption of CCUS technologies, reflecting current practices and policies. In contrast, the CNZ pathway (and associated sensitivities shown in Appendix C) assumes ambitious energy efficiency improvements, shifts to low-carbon fuels and feedstocks, increased electrification, and higher CO_2 capture rates at chemical plants. Additionally, Appendix C provides chemical-specific assumptions. The CNZ pathway maximizes the adoption of clean technologies to approach net zero emissions and serves as a baseline for comparing the effect of sensitivities, which explore how different assumptions could either accelerate or hinder the adoption of key technologies.

Specifically, the CNZ pathway assumes ambitious improvements in energy efficiency, a shift to low-carbon fuels and feedstocks, and increased electrification compared to the BAU scenario. Based on the maximum realistic adoption levels of pillar-specific technologies (see below starting at Section 4.2.3.1 for details), this pathway further assumes that by 2050, 70% of the remaining CO_2 emissions from U.S. chemicals plants (excluding a few exceptions explained below) will be captured by CCUS, after considering the adoption of other decarbonization technologies within the other three pillars. The sensitivities in Appendix C deviate from the core assumptions in the ways described below:

Changes in Modeled Demand (CNZ–Increased Recycling): This sensitivity examines the impact of increased recycling rates compared to baseline assumptions for demand reduction. The baseline assumes that recycling rates for major materials (for example, polyethylene, polyethylene terephthalate, polypropylene, and container glass) will rise to 50% by 2050, in alignment with EPA recycling goals for consumer materials.[212] In this sensitivity, while maintaining other assumptions from the CNZ pathway, higher recycling rates—up to two-thirds of recyclable materials—are assumed. An exception is made for butadiene, which is primarily recycled in an open-loop system. This means that its end-use materials cannot always be recycled back into the same products, but they can still be repurposed in other forms without impacting the upstream demand for butadiene in the production of downstream chemical products. As a result, the impact on demand reduction is expected to be negligible. However, a conservative maximum of 5% closed-loop recycling by 2050 is assumed. The higher rates reflect potential future investments in recycling, including the expansion of traditional mechanical recycling practices as well as the development and implementation of more advanced methods, such as chemical recycling.

Efficiency Improvements (CNZ–Best Available Technologies): This sensitivity evaluates the full adoption of best available technologies (BAT) compared to baseline assumptions and higher rates of autonomous energy efficiency improvements. The CNZ pathway assumes that conventional processes will adopt BAT at a

[212] U.S. Environmental Protection Agency, "U.S. National Recycling Goal," February 22, 2024, www.epa.gov/circulareconomy/us-national-recycling-goal.

substantially high level for energy efficiency gains by 2050, although a significant number of processes will still have room to exploit BAT. In this sensitivity, all conventional plants are assumed to reach BAT levels by 2050. Additionally, autonomous energy efficiency improvements include incremental and anticipated technological advancements within routine plant operations over time. Slightly higher rates for individual technologies are assumed, reflecting more selective, active, and durable catalyst systems, greater heat integration, improved operating conditions, and increased low to mid maturity technology efficiencies over time.

Clean Hydrogen; Alternative Energy Sources (CNZ–Hydrogen): This sensitivity assumes that clean hydrogen can be supplied at competitive rates for industrial thermal energy. In contrast to the CNZ pathway, which does not consider hydrogen as a fuel (relying only on byproduct hydrogen from certain processes), this ambitiously assumes hydrogen will be blended with natural gas at 20% by volume and delivered through existing natural gas infrastructure. This level of blending requires minimal retrofits to current burners and heating systems, allowing most equipment to accommodate the blend with limited modifications.[213] However, due to hydrogen's lower calorific value per unit of volume, a 20% hydrogen-natural gas blend replaces only 7% of the process heat demand currently fulfilled entirely by natural gas.

CCUS Infrastructure (CNZ–Low CCUS): In this sensitivity, while keeping all other assumptions the same as in the CNZ pathway, lower carbon capture rates of up to 10% are applied to the remaining CO_2e emissions after exhausting other decarbonization opportunities at the levels assumed in the CNZ pathway. Although more than 5,000 miles of CO_2 pipelines currently exist in the United States, the network would need to expand significantly to meet the country's net zero goals. Estimates suggest that the required CO_2 pipeline infrastructure to accommodate future large-scale CCUS projects in the United States could range from 30,000 to 96,000 miles.[214] Given the scale of development needed by mid-century, this sensitivity assumes a scenario where CCUS infrastructure does not expand as required to meet net zero emissions targets, leading to lower rates of CCUS adoption.

Market Share of Emerging Technologies; Feedstock Availability (CNZ–Aggressive): This sensitivity combines multiple strategies, including increased recycling, full BAT adoption, hydrogen as a fuel, and rapid grid decarbonization. It also assumes a more aggressive adoption of emerging technologies, with approximately 50% of chemicals manufacturing incorporating transformative technologies, such as electrification and bio-based production routes, by 2050. Although challenges with affordable biomass transport remain, the United States has an estimated 300 to 400 MMT of dry biomass resources per year[215] as feedstock for bio-based chemical production. While the CNZ pathway is already ambitious, this more aggressive sensitivity pushes the limits further by adopting these additional decarbonization strategies.

Importantly, each chemical was individually assessed, and the assumptions with these sensitivities explored, to develop the comprehensive assumptions defining the CNZ pathway for each chemical. The following sections present the CNZ pathway for each chemical and the pillar-specific impacts for the nine chemicals, which account for 40% of total subsector GHG emissions. Additionally, the results include the impact of cross-cutting decarbonization measures studied for the remainder of the chemical subsector, aiming to mitigate part of the remaining 60% of subsector GHG emissions.

4.2.3.1 Ethylene

Ethylene in the United States is currently produced exclusively through the steam cracking of fossil resources. Steam cracking can be divided into two categories: (1) light feedstock cracking, which uses natural gas liquids (NGLs) such as ethane, propane, and butane (accounting for 97% of current production), and (2) heavy feedstock cracking, which uses naphtha (2%) and heavy gas oils (1%). The United States has a competitive advantage in ethylene production due to its low-cost, domestically sourced ethane feedstock. This advantage supports the growth of downstream ethylene products and other ethane-based petrochemicals, as well as their exports, thereby driving industrial output and job creation. U.S. exports of ethane and ethane-based

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[213] Kevin Topolski et al., *Hydrogen Blending into Natural Gas Pipeline Infrastructure: Review of the State of Technology*, NREL/TP-5400-81704 (National Renewable Energy Laboratory: 2022), www.osti.gov/biblio/1893355.
[214] U.S. Department of Energy, *Pathways to Commercial Liftoff: Carbon Management* (2023), liftoff.energy.gov/carbon-management/.
[215] U.S. Department of Energy, "Billion-Ton 2023 Data Portal," accessed November 2024, bioenergykdf.ornl.gov/bt23-data-portal.

petrochemicals increased by 135% from 2014 to 2023, driven by a surge in ethane production and the expansion of export infrastructure.[216]

Figure 20 illustrates the annual GHG emissions reduction from 2018 to 2050 through the implementation of different decarbonization interventions for the CNZ pathway, while Figure 21 shows the corresponding market adoption of current and future technologies for the BAU scenario and CNZ pathway. By 2050, annual CO_2e emissions from ethylene are projected to decrease to around 8 MMT in the CNZ pathway. Since over 60% of ethylene is used in manufacturing recyclable plastics (Appendix C), a higher rate of increased recycling by 2050 (as in the CNZ–Increased Recycling sensitivity) could reduce an additional cumulative 35 MMT CO_2e between 2018 and 2050, compared to the CNZ pathway (see Figure C-2 in Appendix C). Additionally, all production routes considered reduced CO_2e emissions compared to incumbent steam cracking processes (Figure 20). Details on assumptions for ethylene model can be found in Table C-6 and sensitivity results can be found in Figure C-2 in Appendix C.

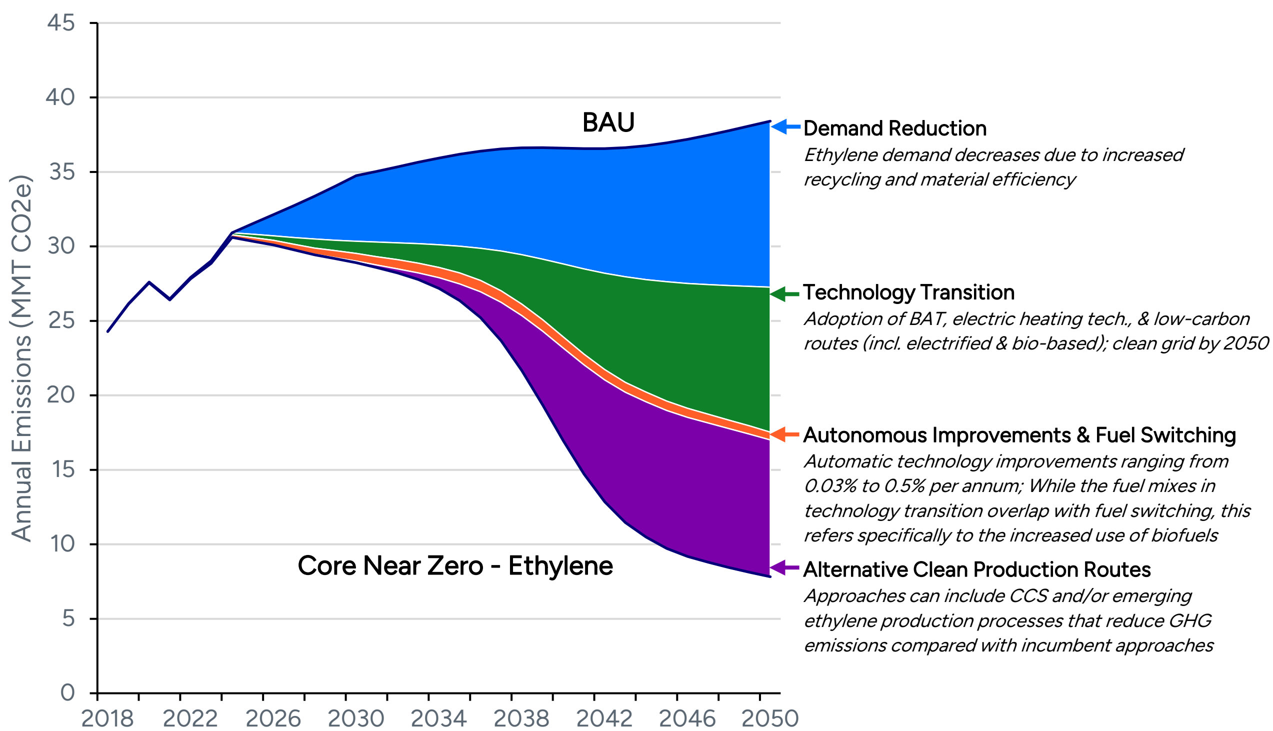
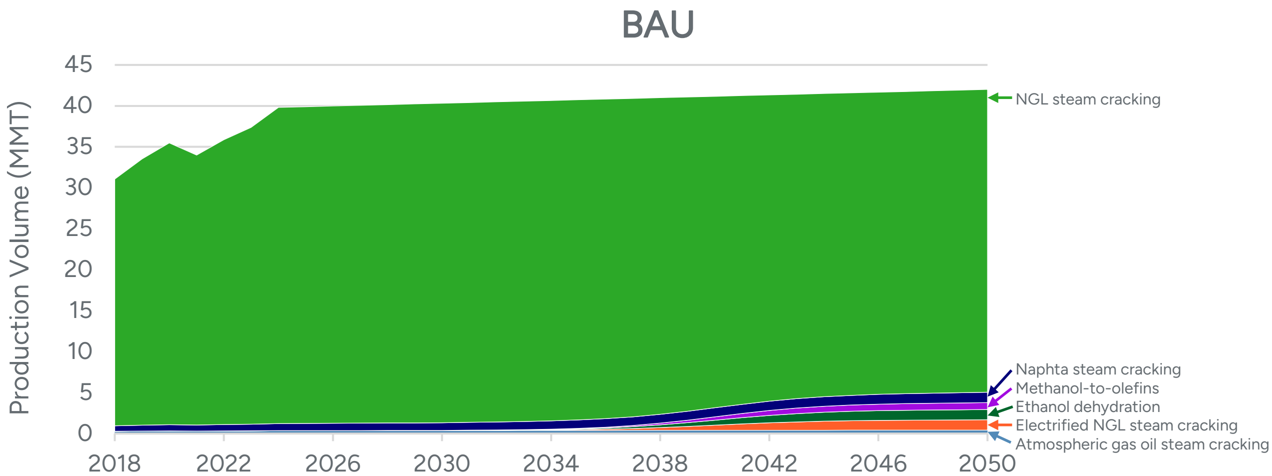


Figure 20. Annual GHG emissions reductions, U.S. ethylene production–Core Near Zero pathway (MMT CO_2e/year), 2018–2050

Note: the shape of the area for alternative clean production routes may change depending on the technologies that are adopted. Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C (see Table C-6). Source: Transformative Pathways modeling.

[216] U.S. Energy Information Administration, "U.S. exports of ethane and ethane-based petrochemicals rose 135% from 2014 to 2023," November 4, 2024, www.eia.gov/todayinenergy/detail.php?id=63604.



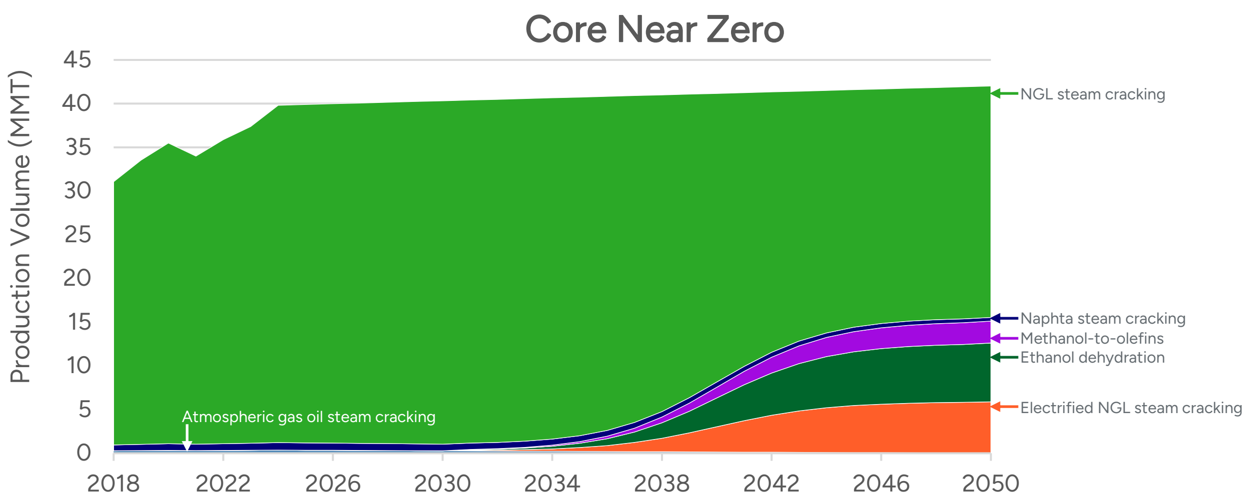


Figure 21. U.S. ethylene production route market share–BAU scenario (top) and Core Near Zero pathway (bottom), 2018–2050

Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C (see Table C-6). Source: Transformative Pathways modeling.

The CNZ pathway in Figure 20 for ethylene includes contributions from various decarbonization pillars. The impacts of these technologies are discussed below, along with potential risks, barriers, and policy changes that could influence the pace of technology adoption in ethylene manufacturing.

Energy efficiency: Energy efficiency refers to technical improvements in all steam cracking products, including ethylene. These technologies encompass optimizing the heat balance of the furnace, enhancing furnace coils to reduce coking and buildup, employing membrane separation to remove unreacted alkanes, and designing new distillation columns with features such as divided walls or heat integration. Many of these efficiency improvements require further investment and innovation to achieve the necessary scale for industrial deployment. These changes present low barriers to application, as efficiency improvements would lower energy inputs and, consequently, may reduce operating costs, despite the potential need for capital investments in new unit operations. Most existing infrastructure will remain in place, and workers can easily adapt to smaller changes rather than a complete plant redesign, ensuring high product yields and fewer incidents.

Electrification: Electrification has a notable impact, as it is adopted at significant rates driven by extensive research into electrifying various stages of production. In particular, electrified steam cracking has the potential to decarbonize a major energy input for steam cracking by reducing the GHG intensity of electricity across each pathway. Additionally, the electrification pillar has the greatest impact in the years closer to 2050, due to the expected reduction in emission factors of the electric grid by that time. If electrified cracking is adopted more rapidly than projected after 2030, and once the electric grid has been substantially decarbonized, there could be a significant overall effect from this pillar. However, this is considered less likely due to constraints on electrified cracking capacities, the capital required for this transition, and the substantial load this would add to the grid if not phased in carefully over time. Electrified steam cracking could therefore benefit from the integration of nuclear reactors to help meet high electricity demand.

The electrochemical reduction of CO_2 and the electrochemical process for oxidative coupling of methane (OCM) are among the most promising electrified manufacturing routes. However, they are currently at low maturity and lack good-quality data for modeling. Additionally, substantial performance improvements and long-term stability enhancements are needed to make these technologies demonstrable and deployable before 2050. Therefore, they are not considered in this study but will be addressed in future research.

LCFFES: The impact of this pillar is significant albeit at a more moderate contribution to ethylene decarbonization, as it requires new process chemistry and cannot be easily integrated into existing production methods. Methanol-to-olefins (MTO) is assumed to be adopted at low rates due to two key factors: (a) the process produces equal amounts of propylene,[217] requiring production to account for a major coproduct, and (b) it is not practiced at scale in the United States. Although MTO is a commercial process and currently accounts for approximately 21% of global methanol use—up from 0% in 2010[218,219]—existing capacity is concentrated in China where low-cost coal-derived methanol drives its adoption.[220] However, the United States has the potential to enter the commercial MTO market by producing low-cost methanol from clean sources (see Section 4.2.3.7). Ethanol dehydration is another promising route for ethylene production. In the United States, ethanol is bio-sourced from corn, and this process is already in use internationally to some extent. According to the IEA, bioethanol dehydration is more cost-competitive and efficient compared to other alternatives. However, the corn-to-ethanol pathway presents challenges such as scope 3 emissions, land use, and fertilizer application (see Section 4.2.3.9). Therefore, although ethanol dehydration is expected to play a larger role, its adoption is approached conservatively.

This pillar also includes the use of low-carbon fuels like hydrogen. Increasing hydrogen use in tail gas for process heat would reduce emissions by decreasing methane combustion. For hydrogen to have a more substantial impact on industrial decarbonization, greater volumes of competitively priced clean hydrogen need to be made available for industrial process heat. However, the feasibility of operating an industrial system entirely on hydrogen for process heat is still under research. Some chemical plants are exploring onsite clean hydrogen generation for process heat. For instance, ExxonMobil is planning to build a large-scale facility for low-carbon hydrogen production at its petrochemical plant in Baytown, Texas. This facility aims to produce up to 1 billion cubic feet per day of hydrogen via autothermal reforming (ATR) of natural gas with CCUS. Part of this hydrogen could be supplied by reforming methane byproduct separated from the tail gas of their steam cracker, while the byproduct hydrogen from the tail gas could be optimally combined with ATR hydrogen. The plant aims to capture and store over 98% of the associated CO_2, with operations expected to begin in 2027 or 2028.[221]

Similarly, Linde is constructing a $2 billion facility to supply clean hydrogen to Dow's ethylene cracking plant at its manufacturing site in Fort Saskatchewan, Canada, with the goal of operating one of the world's first net zero ethylene crackers.[222] Although the techno-economic aspects of these projects require further investigation, this study developed an additional scenario focused on ethylene manufacturing. In this scenario, up to 56% of U.S. steam cracking capacity (excluding older plants) could switch to onsite hydrogen generation via the ATR route

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[217] A. C. Dimian and C. S. Bildea, "Energy efficient methanol-to-olefins process," *Chemical Engineering Research and Design* 131 (2018): 41–54, doi.org/10.1016/j.cherd.2017.11.009.
[218] International Energy Agency, *The Future of Petrochemicals: Towards a More Sustainable Chemical Industry* (2018), www.iea.org/reports/the-future-of-petrochemicals.
[219] Kelly Cui and Mackenzie Wood, "Can China's CTO and MTO industries survive the threat of massive steam cracker investment?" Wood Mackenzie, September 6, 2019, www.woodmac.com/news/can-chinas-cto-and-mto-industries-survive-the-threat-of-massive-steam-cracker-investment/.
[220] International Energy Agency, *The Future of Petrochemicals: Towards a More Sustainable Chemical Industry* (2018), www.iea.org/reports/the-future-of-petrochemicals.
[221] Darren W. Woods, "Low-carbon hydrogen: Fueling our Baytown facilities and our net-zero ambition," ExxonMobil, January 30, 2023, corporate.exxonmobil.com/news/viewpoints/low-carbon-hydrogen.
[222] Aniqah Majid, "Linde will supply clean hydrogen to Dow's 'world-first' net zero ethylene cracker," *The Chemical Engineer*, August 30, 2024, www.thechemicalengineer.com/news/linde-will-supply-clean-hydrogen-to-dow-s-world-first-net-zero-ethylene-cracker/.

for hydrogen-based process heat (a mix of tail gas hydrogen and SMR-CCS hydrogen). The results indicate that adopting hydrogen-based cracking in more than half of the cracker facilities could reduce over 60% of CO_2 emissions from ethylene production.

CCUS: As shown in Figure 20, alternative clean production routes have a significant impact, as the model results still projected non-negligible use of fossil fuels and direct CO_2 emissions from ethylene production. This intervention was modeled as CCUS but could also be achieved with nascent, clean production routes. The extensive pipeline infrastructure along the U.S. Gulf Coast, where much of the country's ethylene is produced, mitigates the challenge of transporting captured CO_2, a barrier that exists in other regions. However, CCUS comes with significant costs and barriers, as detailed in Section 3.2.1.

4.2.3.2 Propylene

In 2018, nearly 46% of U.S. propylene was produced through fluid catalytic cracking (FCC), while 41% was produced through light/heavy steam cracking. The shale gas boom has led to a shift in the feedstock for steam cracking toward "lighter" ethane feeds. These lighter feeds result in lower propylene yields as a co-product, which currently account for less than 41% of total U.S. propylene production. At the same time, the increased availability of propane from shale gas has made it more feasible to produce propylene on-purpose via propane dehydrogenation (PDH), which now accounts for 10% of U.S. production. The remaining 3% is produced through metathesis.

For modeling purposes, all CO_2 emissions from steam cracking are allocated to propylene production, following the approach used in the ethylene model (see Section 4.2.3.1). The lower propylene yields from steam cracking of NGLs, primarily ethane, result in a higher emissions intensity per metric ton of propylene. Consequently, the annual GHG emissions reduction from the CNZ pathway shown in Figure 22 reflect this allocation. Figure 23 shows the corresponding market adoption of current and future technologies for the BAU scenario and CNZ pathway. A similar methodology is used in the butadiene model, discussed in Section 4.2.3.3.

To avoid double counting, emissions from all steam-cracking production routes are allocated exclusively to ethylene production in the aggregate scenario, as detailed in the ethylene section (see Section 4.2.3.1). Furthermore, emissions from FCC units fall under the refining subsector; however, for the sake of modeling overall propylene production, they are also included. These emissions are relatively small compared to the overall emissions from the chemical subsector. Details on assumptions for the propylene model can be found in Table C-7 and sensitivity results can be found in Figure C-3 in Appendix C.

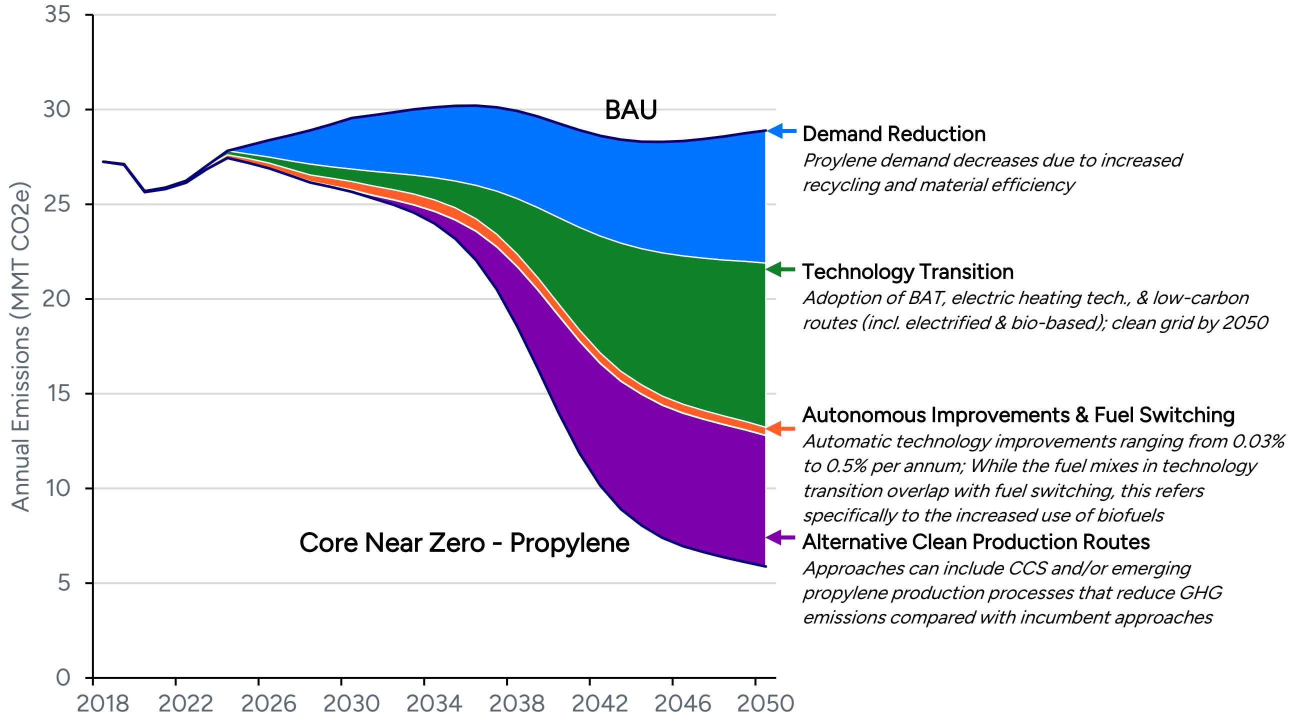


Figure 22. Annual GHG emissions reductions, U.S. propylene production–Core Near Zero pathway (MMT CO_2e/year), 2018–2050

Note: The shape of the area for alternative clean production routes may change depending on the technologies that are adopted. Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C (see Table C-7). Source: Transformative Pathways modeling.

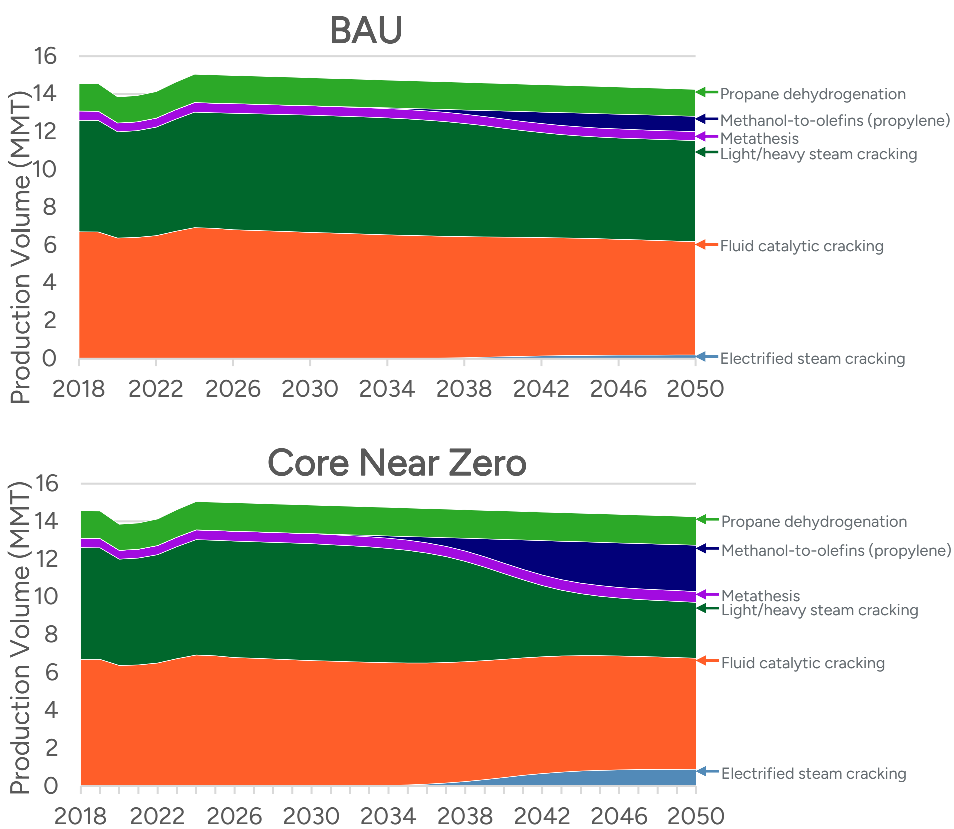


Figure 23. U.S. propylene production route market share–BAU scenario (top) and Core Near Zero pathway (bottom), 2018–2050

Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C (see Table C-7). Source: Transformative Pathways modeling.

Figure 22 shows annual emissions reductions for the CNZ pathway through the implementation of different decarbonization interventions, and the contribution of various technologies in the CNZ pathway are shown in Figure 23, based on market shares given in Appendix C. By 2050, emissions from propylene manufacturing are projected to fall to around 6 MMT CO_2e per year in the CNZ pathway. Since nearly half of propylene is used in polypropylene production (see Appendix C), a higher rate of recycling by 2050 (CNZ–Increased Recycling sensitivity) could reduce an additional cumulative 20 MMT CO_2e between 2018 and 2050 (see Figure C-3 in Appendix C). All production routes considered reduce emissions compared to steam cracking and FCC.

Energy efficiency: Energy efficiency refers to technical improvements for all steam cracking products, including propylene. The same technologies that reduce energy use in each stage of ethylene steam cracking also apply to propylene, which is mainly produced as a coproduct. For FCC, energy reductions can come from replacing fractionation trays with structured packing, improving automation and process control, and adjusting heat flow in downstream processes to minimize energy consumption.

On-purpose technologies utilize other olefins from steam cracking or different feedstocks to meet propylene demand. Propane dehydrogenation (PDH) energy improvements include optimizing hydrogen byproduct recovery for fuel or feedstock, combusting excess tail gas to convert CH_4 to CO_2 and reduce GHG emissions, and enhancing operational efficiency through process optimization, including catalyst and membrane conditions, and adjusting temperature and pressure. For olefin metathesis, improvements focus on catalyst usage and production conditions.

Electrification: Like ethylene, electrified steam cracking has a significant impact due to the projected decrease in grid emissions intensity and the high efficiency of the electrified alternative. This technology utilizes existing infrastructure to minimize plant redesign, leading to a notable adoption rate. However, its overall impact is relatively lower than other pillars due to the limitations outlined in the ethylene section (see Section 4.2.3.1).

LCFFES: MTO is assumed to be adopted at limited rates for the same reasons outlined in the ethylene section (see Section 4.2.3.1). Despite being the only route considered for this pillar, its contribution to overall decarbonization is significant. Additionally, alternative fuels like renewable natural gas (RNG) are modeled to be gradually introduced as a fraction of total natural gas fuel use.

CCUS: The role of CCUS is reflected, along with alternative clean production routes for propylene, in Figure 22. This intervention has one of the largest effects due to the continued high use of fossil fuels across all projected production routes. This intervention was modeled as CCUS, but could also be achieved with nascent, clean production routes. Although energy consumption can be reduced through efficiency measures or shifted toward decarbonized electricity, the ongoing reliance on natural gas, tail gas, refinery gas, and liquefied petroleum gas leads to significant CO_2 emissions. These emissions were modeled to be directly mitigated through CCUS. Like ethylene and other chemicals, this pillar can be implemented after optimizing the applications of other pillar-specific technologies, with adoption rates varying by pathway. Without the additional clean propylene production intervention (or with low adoption of CCUS explored in the CNZ–Low CCUS sensitivity in Appendix C), only half of propylene manufacturing can be decarbonized, even with the exploitation of decarbonization technologies in other pillars.

4.2.3.3 Butadiene

Butadiene is currently produced entirely as a byproduct of steam cracking. Figure 24 shows annual emissions reductions, by intervention, for the CNZ pathway for butadiene, with technology adoption rates shown in Figure 25. The results suggest potential annual emissions reductions to approximately 7 MMT CO_2e by 2050 in the CNZ pathway. In the CNZ–Increased Recycling sensitivity (see Figure C-4 in Appendix C), which includes limited recycling of butadiene-based products, cumulative emissions decrease further by about 6 MMT CO_2e between 2018 and 2050, highlighting the need for closed-loop recycling techniques. The CNZ pathway for butadiene manufacturing incorporates all decarbonization pillars, with detailed impacts described below. Details on assumptions for the butadiene model can be found in Table C-8 and sensitivity results can be found in Figure C-4 in Appendix C.

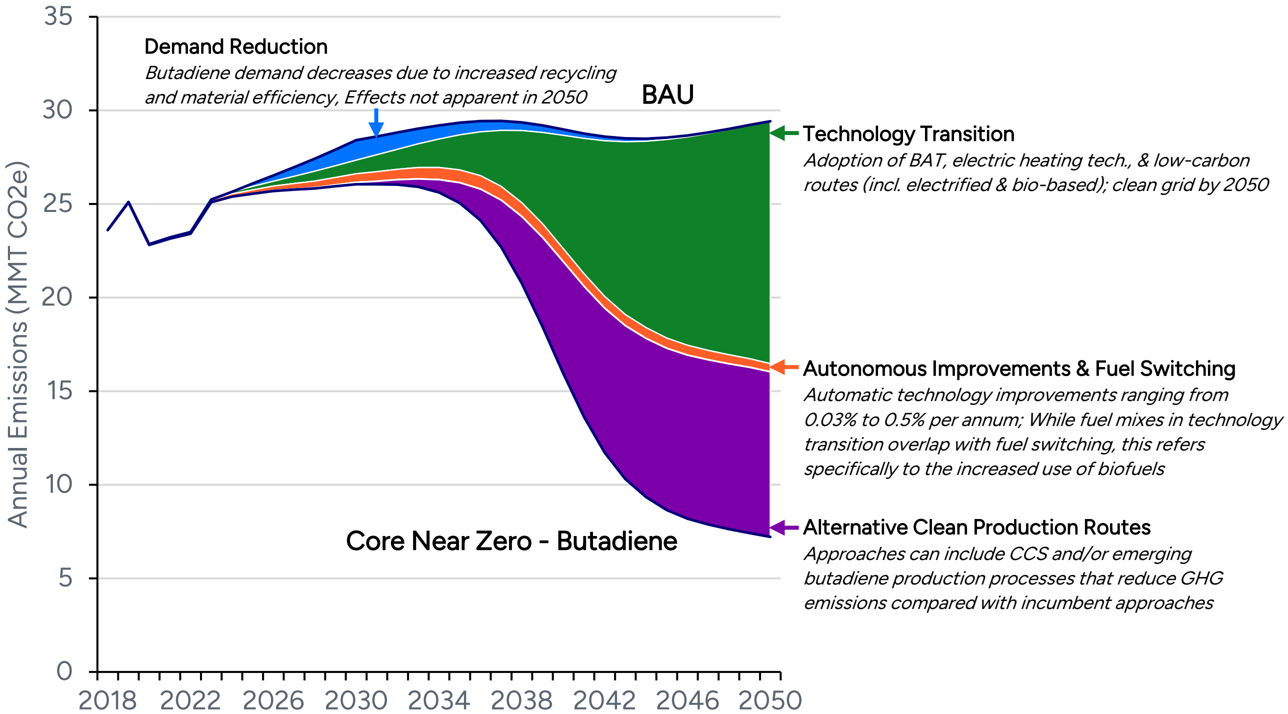


Figure 24. Annual GHG emissions reductions, U.S. butadiene production–Core Near Zero pathway (MMT CO_2e/year), 2018–2050

Note: The shape of the area for alternative clean production routes may change depending on the technologies that are adopted. Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C (see Table C-8). Source: Transformative Pathways modeling.

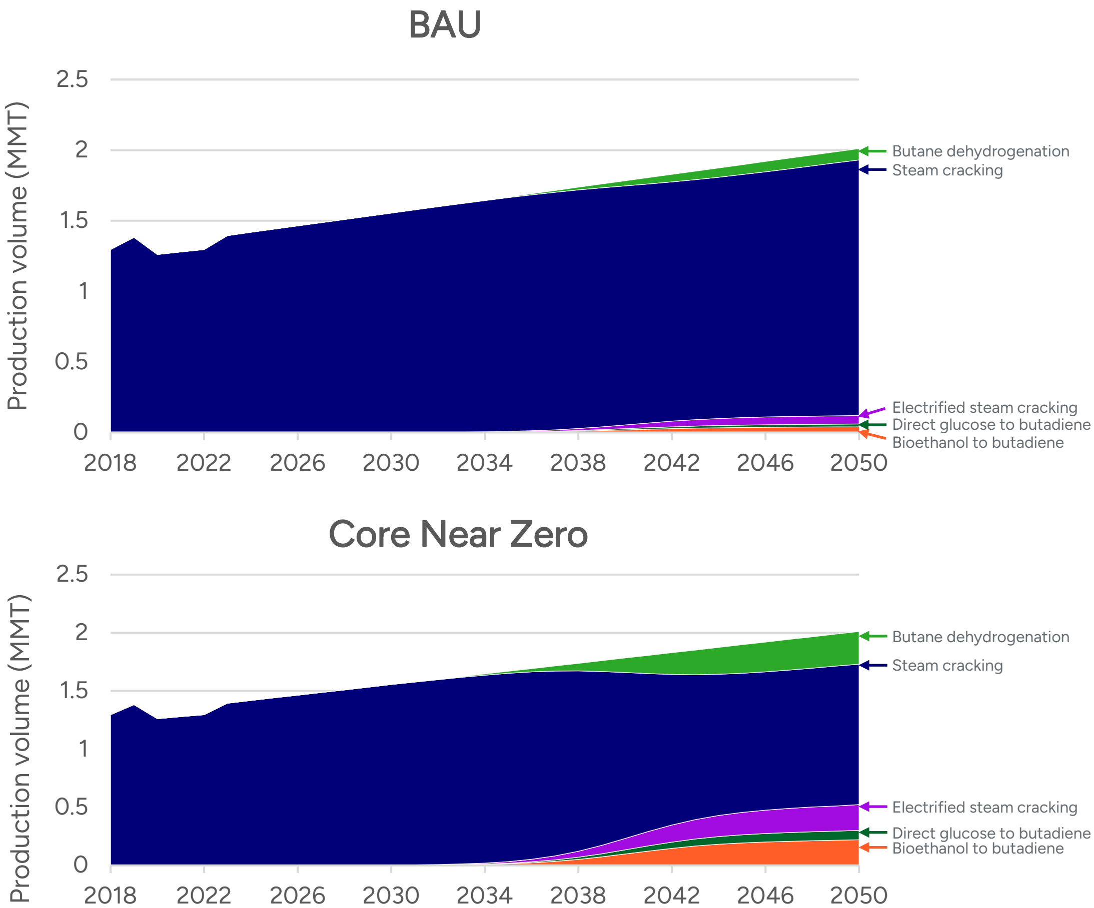


Figure 25. U.S. butadiene production route market share–BAU scenario (top) and Core Near Zero pathway (bottom), 2018–2050

Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C (see Table C-8). Source: Transformative Pathways modeling.

Energy efficiency: Energy efficiency involves technical improvements in steam cracking for high-value chemical products, including butadiene, and is crucial due to butadiene's current reliance on this process. This reliance is expected to shift partly toward more efficient manufacturing routes, such as on-purpose butane dehydrogenation, as alternative low-carbon technologies for ethylene and propylene production reduce steam cracking's market share in high-value chemicals manufacturing. In addition to the techniques previously discussed, the choice of extraction solvent for butadiene separation in steam cracking impacts overall energy use. Recent transitions to lower-energy solvents, like N-methylpyrrolidone (NMP), have reduced this demand, although NMP is toxic and poses embryotoxic risks.[223] Emerging technologies, such as hydrogen-selective membrane reactors for butane dehydrogenation, also show promise for reducing energy consumption. While currently viable only when n-butane is available at low cost, this technology holds potential for decarbonization due to its relatively low energy intensity as future demand increases. In the CNZ–BAT sensitivity (see Figure C-4 in Appendix C), fully exploiting the best practices for these technologies could yield an additional cumulative emissions reduction of 19 MMT CO_2e during the 2018 to 2050 period.

Electrification: Electrified steam cracking for high-value chemicals, including butadiene, has the greatest impact closer to 2050 due to projected reductions in grid emissions. This pathway offers similar benefits, such as eliminating direct CO_2 emissions (scope 1) and utilizing existing steam-cracking infrastructure.

LCFFES: Bioethanol and glucose as feedstocks currently require lower energy inputs compared to butadiene from steam cracking, with potential for further reductions as technology scales. These production routes rely on

[223] Burkhard Flick et al., "Embryotoxic potential of N-methyl-pyrrolidone (NMP) and three of its metabolites using the rat whole embryo culture system," *Toxicology and Applied Pharmacology* 237, 2 (June 2009): 154–167, doi.org/10.1016/j.taap.2009.02.024.

large amounts of steam, assumed to be primarily produced from fossil fuels, with some contribution from bio-waste associated with feedstock procurement. Significant opportunities for decarbonization exist if steam can be sourced from low-carbon alternatives. These routes offer moderate decarbonization benefits due to lower energy inputs and the absence of non-fuel CO_2 emissions (even though process emissions from steam cracking are already low). However, their long-term application is projected to be limited due to their lack of technology maturity and the absence of large-scale implementation in the United States. Additionally, the bioethanol pathway faces challenges such as Scope 3 emissions, land use concerns, and fertilizer application, as discussed in the ethanol section (see Section 4.2.3.9). This pillar also includes the increased use of low-carbon fuels, such as RNG and hydrogen in tail gas, as previously discussed for steam cracking. In the CNZ–Aggressive sensitivity (see Figure C-4 in Appendix C), which assumes increased adoption of bio-based feedstocks and additional hydrogen blended with natural gas for process heat, annual emissions from butadiene manufacturing could decrease from 7.2 MMT CO_2e in the Core Near Zero pathway to 4.5 MMT CO_2e.

CCUS: The intervention of alternative clean production, shown in Figure 24, is significant. This was modeled as implementing CCUS and has a relatively larger impact due to the continued use of steam cracking when not employing all-electric technologies, as well as the steam requirements for LCFFES routes when the steam is generated from fossil fuels. However, this remains one of the more expensive options available for decarbonization. The effect of CCUS is shown in Figure 24, and without CCUS or in the CNZ–Low CCUS sensitivity (see Figure C-4 in Appendix C), annual GHG emissions could only be reduced to about 50% of the projected emissions in 2050 under the BAU scenario.

4.2.3.4 BTX Aromatics

BTX aromatics plants are configured in various ways, depending on factors such as the desired product portfolio, feedstock quality and quantity, technology choices, byproduct utilization, and plant integration. The primary raw materials for BTX aromatics production are sourced from refinery catalytic naphtha reformers (reformate) and steam crackers (pygas). Reformate extraction accounts for approximately 77% of total production, while pygas extraction contributes around 11%. Other conventional production routes, including toluene disproportionation (TDP) and toluene hydrodealkylation (HDA), make up 12% and 1% of total U.S. production, respectively.

The modeling results for BTX aromatics emphasize the importance of adopting low-carbon technologies tailored to each pillar to advance decarbonization efforts in U.S. BTX aromatics production. Figure 26 illustrates how various decarbonization levers impact emissions while Figure 27 provides the BAU and CNZ share of production routes. Annual emissions in the CNZ pathway are projected to decrease by just under 80% compared to 2018, reaching 1.5 MMT CO_2e by 2050. Details on assumptions for the BTX aromatics model can be found in

Table C-9 and sensitivity results can be found in Figure C-5 in Appendix C.

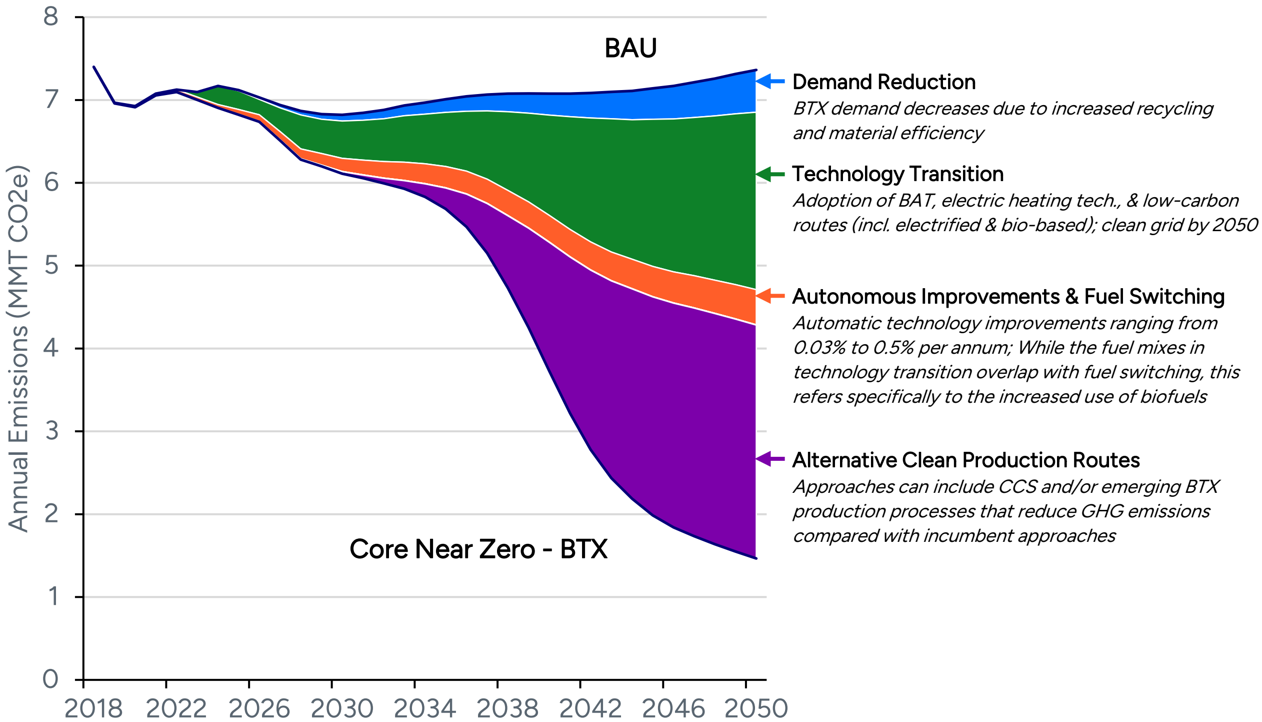


Figure 26. Annual GHG emissions reductions, U.S. BTX aromatics production–Core Near Zero pathway (MMT CO_2e/year), 2018–2050

Note: The shape of the area for alternative clean production routes may change depending on the technologies that are adopted. Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C (see Table C-9). Source: Transformative Pathways modeling.

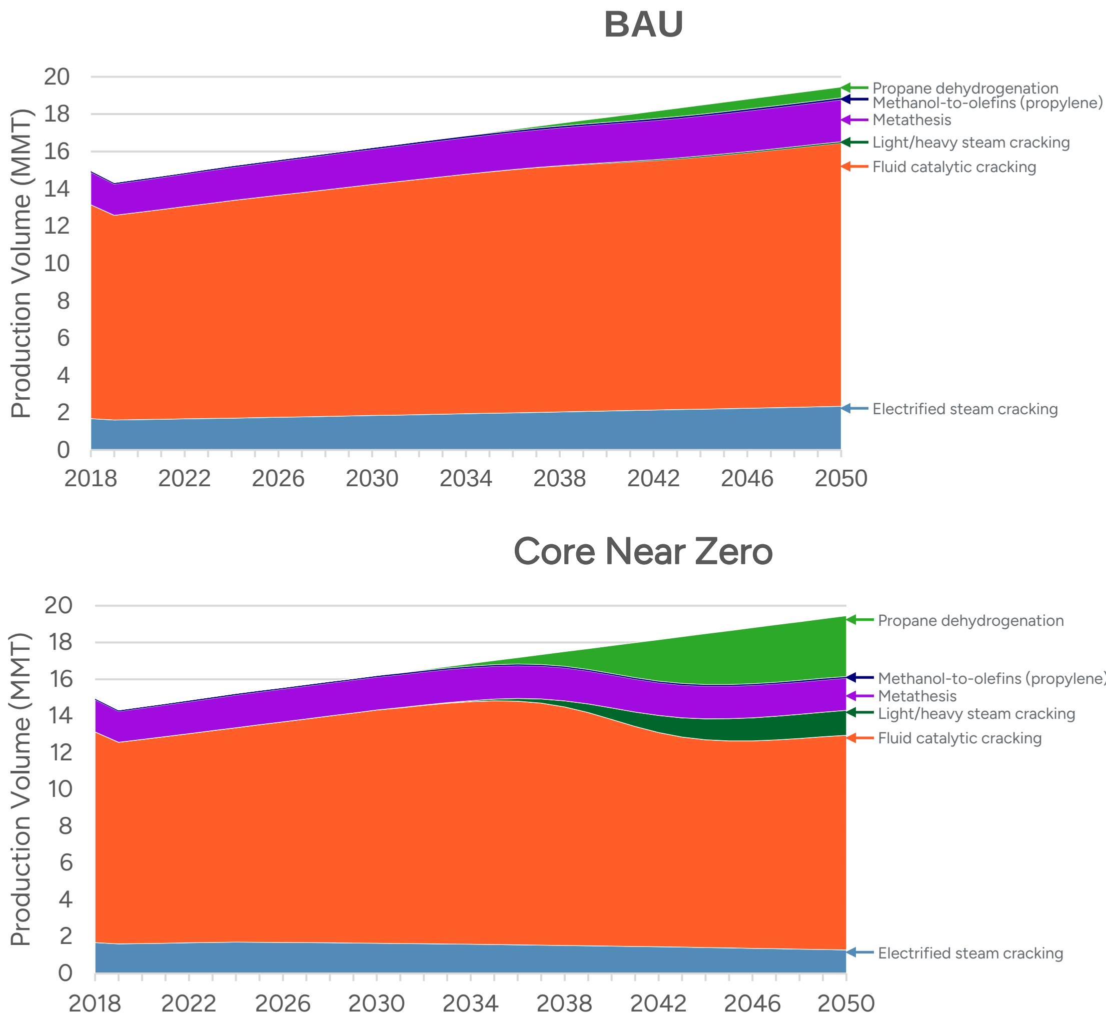


Figure 27. U.S. BTX aromatics production route market share–BAU scenario (top) and Core Near Zero pathway (bottom), 2018–2050

Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C (see Table C-9). Source: Transformative Pathways modeling.

Paraxylene is a key BTX component used to produce polyethylene terephthalate (PET), which is recyclable. Currently, the recycling rate of PET is 15% (see Appendix C), with an assumption that it will rise to 50% by 2050 in the Core Near Zero pathway. In the CNZ–Increased Recycling sensitivity (see Figure C-5 in Appendix C), where the PET recycling rate is assumed to exceed 50%—potentially reaching two-thirds by 2050—BTX aromatics manufacturing could cumulatively save an additional 2 MMT CO_2e between 2018 and 2050. The impacts of other major technologies within each pillar are discussed below.

Energy efficiency: The breakdown of BTX production from reformate and pygas until 2050 relies on assumptions regarding the refining subsector and steam cracking. In the Core Near Zero pathway, 76% of BTX production in 2050 is projected to continue along current production routes; however, a substantial transition toward more energy-efficient practices is anticipated. Key measures to enhance the overall energy efficiency of BTX production include heat integration (such as recovering heat from toluene and o-xylene distillation column overhead vapors), process intensification (involving single extractive distillation columns or divided wall columns), advanced process control, and optimization strategies.

Electrification: Although the potential opportunities for electrification in BTX extraction plants are somewhat limited, it plays a significant role in achieving emissions reductions by 2050, primarily due to the decarbonization of the electric grid that effectively address the current scope 2 emissions attributed to BTX aromatics production. A substantial portion of scope 2 emissions arises from compression operations that facilitate the separation and processing of different aromatic compounds. Future investments in R&D focused on electrified heating technologies have the potential to further enhance electrification efforts. However, no electrified heating applications for BTX have been specifically considered in this study.

LCFFES: LCFFES plays a pivotal role, accounting for approximately 30% of the emissions reduction targeted in the Core Near Zero pathway by 2050. A significant portion of these reductions stems from the shift from conventional BTX manufacturing to methanol-to-aromatics (MTA) and biomass-to-aromatics (bio-aromatics) routes. Changes in upstream catalytic reforming and steam cracking processes, combined with the growing demand for BTX, present an opportunity to bridge the demand gap through further development and adoption of MTA and bio-aromatics. MTA is projected to contribute moderately to the anticipated growth in U.S. BTX manufacturing by 2050, as outlined in the Core Near Zero pathway (Appendix C). However, the primary impact of this transition relates to the emissions footprint of hydrogen production for methanol and, to some extent, the demand for CO_2 feedstock. The MTA process utilizes clean hydrogen-based methanol as a feedstock, requiring approximately 4.3 metric tons of methanol per metric ton of BTX produced. Thus, substantially reducing the carbon footprint of methanol production (see methanol Section 4.2.3.7) is essential for MTA's feasibility.

Emerging bio-aromatics technologies developed by Anellotech, Virent, and other companies aim to produce BTX from renewable, non-edible (or woody) biomass. Anellotech and its exclusive licensing partner, Axens, are in discussions to commercialize the process by constructing a 500 metric ton per day commercial plant in the near future.[224] Similarly, Virent is collaborating with leading companies such as Marathon Petroleum Corporation, Johnson Matthey, BP, and Toray Industries to scale up and commercialize their technology.[225] Although the supply chain and economics of these processes have yet to be fully explored, bio-aromatics are chemically identical to their petroleum-derived counterparts and can be further purified and separated using established commercial technologies. As a result, an ambitious market share for bio-aromatics is assumed for bio-aromatics in the Core Near Zero pathway by 2050 (see Appendix C).

Additionally, lignin, a byproduct of agricultural and cellulose pulp mills, holds promise as a sustainable alternative feedstock for petroleum-based chemicals, particularly in BTX production and subsequent petrochemical manufacturing processes. However, commercial implementation of lignin-derived BTX faces significant challenges, including the variable structure and reactivity of isolated lignin, which is influenced by biomass type, fractionation method, and severity of the fractionation process. Furthermore, the process demands large quantities of solvents and substantial high-pressure steam, complicating operational feasibility. Ongoing research is addressing these challenges, but current development stages suggest that commercial maturity may not be achieved until 2050.

More generally, the availability and maturity of low-carbon technologies suitable for large-scale BTX manufacturing is a major obstacle to decarbonizing BTX aromatics production. In addition to the shift to low-carbon feedstocks, transitioning from natural gas to RNG further contributes to emissions reductions within this decarbonization pillar. In an aggressively ambitious sensitivity (see CNZ–Aggressive in Figure C-5 in Appendix C), achieving a 50% market share for MTA and bio-aromatics combined with other decarbonization measures results in an 86% reduction in emissions by 2050, which is 7% more than the reduction projected in the Core Near Zero pathway.

CCUS: Alternative clean production routes, with CCUS as the modeled intervention, is anticipated to play a key role in achieving the near zero target outlined in the CNZ pathway, with a projected annual emissions reduction of 3 MMT CO_2e by 2050 (see Figure 26). A substantial portion of this reduction could come from capturing CO_2 emissions during xylenes fractionation in conventional systems. However, despite CCUS's potential to lower overall BTX aromatics production emissions, the high initial investment costs present a substantial barrier to widespread adoption. Further development of CO_2 pipeline networks and storage infrastructure is needed to

[224] Anellotech, "Anellotech's Bio-TCatTM Technology for Making Bio p-Xylene, Toluene and Benzene from Woody Biomass Is Ready for Commercialization," December 14, 2021, anellotech.com/press/anellotechs-bio-tcat-technology-making-bio-p-xylene-toluene-and-benzene-woody-biomass-ready.
[225] Virent, "Our Technology," accessed November 2024, www.virent.com/technology/.

substantially increase CO_2 capture from chemicals manufacturing facilities, such as BTX aromatics extraction plants, which are typically highly integrated with upstream processes.

4.2.3.5 Chlor-Alkali

At the core of chlor-alkali processes is the electrolysis cell, with current technologies divided into three categories: diaphragm, membrane, and mercury cells. The technology distribution in 2018 is assumed based on literature sources, which suggest that the diaphragm cell technique held the largest share at 51%, while membrane and mercury cells accounted for 48% and 1%, respectively.[226,227] However, according to the latest estimates in 2021, the landscape has shifted, and the membrane cell technique has surpassed the 50% mark, emerging as the dominant method in domestic chlor-alkali production.[228]

Figure 28 shows the annual emissions reductions achieved through the application of decarbonization technologies for the CNZ pathway, based on the technology adoption routes outlined in Figure 29 and detailed in Appendix C. A more comprehensive exploration of the impact of each decarbonization pillar and its associated low-carbon technologies is discussed below. Details on assumptions for the chlor-alkali model can be found in Table C-10 and sensitivity results can be found in Figure C-6 in Appendix C.

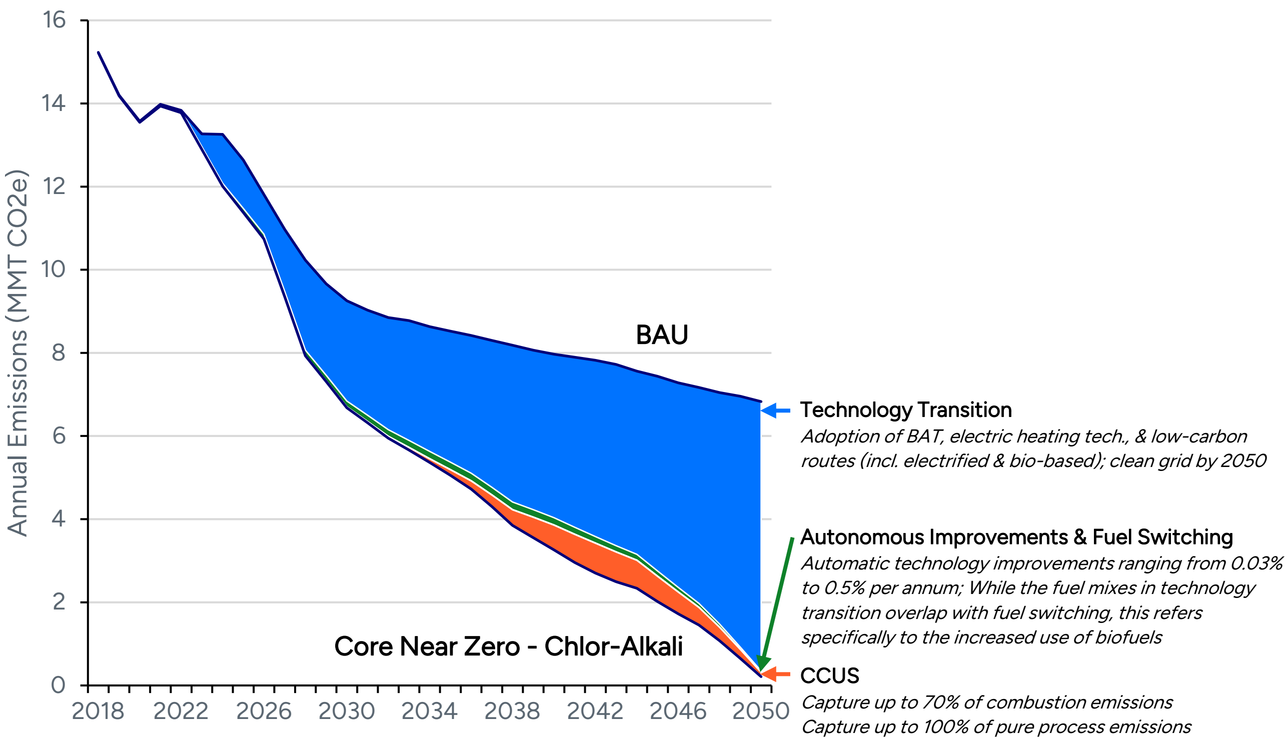
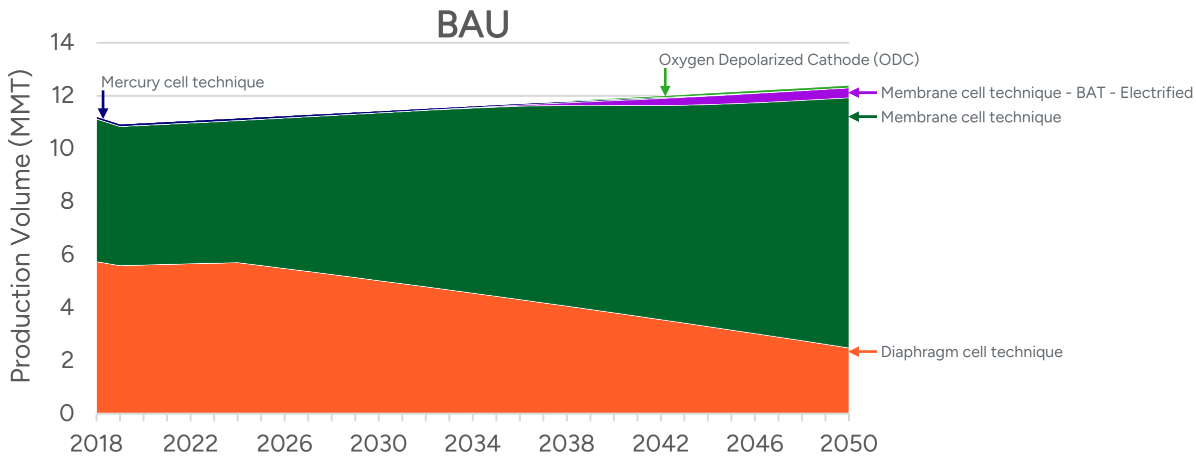


Figure 28. Annual GHG emissions reductions, U.S. chlor-alkali production–Core Near Zero pathway (MMT CO_2e/year), 2018–2050

Note: Impact of demand reduction was not evaluated. The shape of the area for alternative clean production routes may change depending on the technologies that are adopted. Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C (see Table C-10). Source: Transformative Pathways modeling.

[226] Hazel Kruez et al., "Impact of EPA's Proposed Asbestos-Diaphragm Chlor-Alkali Rulemaking," Chemical Market Analytics, July 2022, www.americanchemistry.com/content/download/11507/file/Impact-of-EPAs-Proposed-Asbestos-Diaphragm-Chlor-Alkali-Rulemaking.pdf.
[227] Dong-Yeon Lee, Amgad A. Elgowainy, and Qiang Dai, *Life Cycle Greenhouse Gas Emissions of By-Product Hydrogen from Chlor-Alkali Plants*, ANL/ESD-17/27 (Argonne National Lab, 2017), doi.org/10.2172/1418333.
[228] Hazel Kruez et al., "Impact of EPA's Proposed Asbestos-Diaphragm Chlor-Alkali Rulemaking," Chemical Market Analytics, July 2022, www.americanchemistry.com/content/download/11507/file/Impact-of-EPAs-Proposed-Asbestos-Diaphragm-Chlor-Alkali-Rulemaking.pdf.



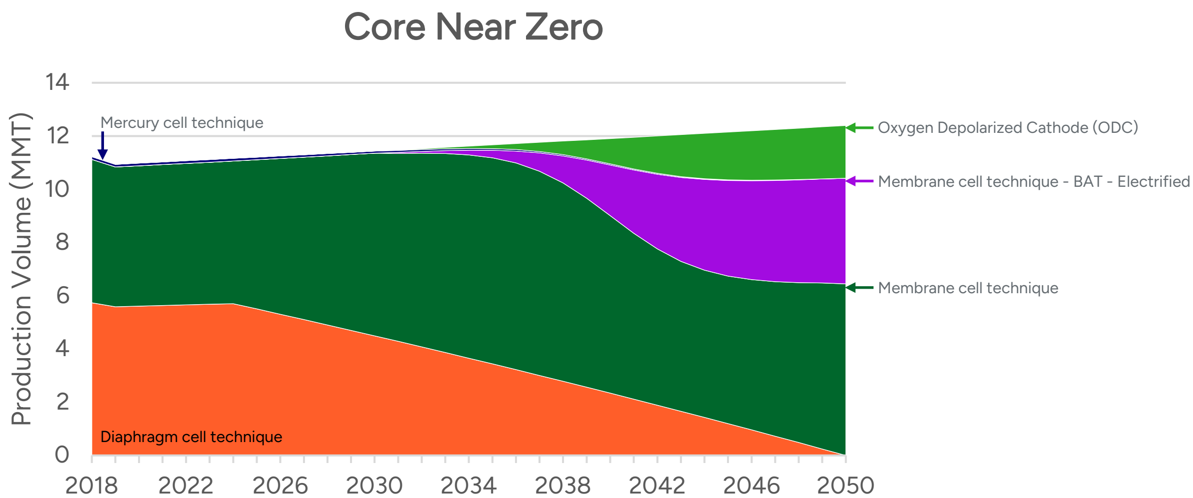


Figure 29. U.S. chlor-alkali production route market share–BAU scenario (left) and Core Near Zero pathway (right), 2018–2050

Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C (see Table C-10). Source: Transformative Pathways modeling.

Energy efficiency: Transitioning from the diaphragm cell technique, which consumes approximately 30% more energy, to membrane cell techniques offers significant energy efficiency gains. Within membrane cell technology, a further classification distinguishes between monopolar and bipolar configurations based on cell construction and assembly rather than electrochemical reactions. Bipolar configurations contribute to electricity savings by minimizing inter-cell voltage losses. These systems have been commercially deployed and may be preferable due to their lower electricity demand. To optimize energy savings, it is also crucial to incorporate high-performance membranes, electrodes, coatings, and high-purity brine. This multifaceted approach enhances the overall efficiency of membrane cell techniques and underscores the importance of technological advancements in each component of the system.

The oxygen depolarized cathode (ODC) technique is an emerging low-carbon pathway, considered in this work, has been commercialized by Bayer, which established a 20,000 metric ton per annum chlorine production plant in Europe in 2011.[229] The ODC technique integrates a fuel cell into an electrolyzer, reducing oxygen on the cathode side instead of producing hydrogen and resulting in a voltage reduction of approximately one volt and a 30% decrease in electricity consumption compared to the membrane cell technique. However, net electricity

[229] Alexis Michael Bazzanella and Florian Ausfelder, *Technology Study: Low Carbon Energy and Feedstock for the European Chemical Industry* (2019), cefic.org/a-solution-provider-for-sustainability/a-journey-to-sustainability/low-carbon-energy-and-feedstock-for-the-european-chemical-industry-study/.

savings are lower due to the air separation units required for high-purity oxygen production. A significant drawback is the cessation of hydrogen co-production, which limits the potential hydrogen supply, even in small quantities, as a valuable fuel in the evolving hydrogen economy. Consequently, the adoption of ODC and its electrified variant is expected to be limited to regions where small amounts of co-produced hydrogen may not find sufficient infrastructure and transport for cost-effective end-use purposes.

Electrification: Chlor-alkali manufacturing is highly electricity-intensive, and the emissions intensity of chlor-alkali is closely tied to the emissions intensity of the electric grid. A substantial reduction in CO_2 emissions is anticipated as low-carbon electricity generation becomes more integrated. Even with just 5% electrified steam generation across chlor-alkali plants, electrification emerges as the primary driver of chlor-alkali decarbonization by 2050 under the BAU scenario.[230]

Additional reductions can be achieved by electrifying steam generation using high-temperature heat pumps (HTHPs). However, a key limitation is their capacity, as only a few suppliers—primarily in Europe—can achieve sink temperatures of 165°C or higher, surpassing the typical 145°C process steam temperature required in state-of-the-art membrane cell-based chlor-alkali plants,[231] at a MW scale. Another challenge for heat pump adoption is the lack of waste heat from the process, leading to high temperature lifts and low coefficients of performance (COPs). Alternatively, electric boilers can directly replace conventional steam generation, although they require more electricity compared to HTHPs. For either technology to be viable for caustic concentration, electricity-to-fuel price ratios must become competitive to encourage the transition toward process heat electrification.

LCFFES: Approximately 40%–50% of the by-product hydrogen generated from U.S. chlor-alkali processes is currently utilized through combustion to provide process heat, accounting for an estimated 20% of the overall fuel mix. The remaining 30%–40% is sold to the merchant hydrogen market, while about 10%–30% is vented.[232] Optimizing the use of all by-product hydrogen to meet the energy demands of a chlor-alkali plant can be achieved through the implementation of hydrogen fuel cell combined heat and power (CHP) systems. These systems have the potential to completely replace the facility's natural gas demand. Hydrogen fuel cells can offer more than twice the efficiency of traditional combustion technologies. However, significant challenges remain, particularly regarding fuel cell costs and durability. Moreover, some plants may continue to rely on natural gas for process heat (see Appendix C).

CCUS: The contribution of CCUS in the context of chlor-alkali manufacturing is negligible. Chlor-alkali production is already heavily reliant on electricity, and concurrent efforts to decarbonize the electric grid along with the deployment of commercially available technologies for electrified steam generation, such as HTHPs and electric boilers, could substantially reduce CO_2 emissions. This approach would leave only a small amount of CO_2 emissions from large combustion boilers in a few facilities to be captured.

4.2.3.6 Soda Ash

Soda ash is a key raw material for glass manufacturing. In 2018, about 47% of total U.S. soda ash consumption was used by the glass manufacturing subsector.[233] U.S. soda ash manufacturing primarily utilizes natural processes, refining trona ore and sodium-carbonate-rich brines. This gives U.S. producers an advantage in lower production costs and reduced environmental impacts compared to synthetic soda ash, which involves higher energy consumption and emissions. The United States also stands out as a major exporter due to these advantages. More specifically, more than half of U.S. soda ash production, accounting for 59%, was directed toward exports.[234] The landscape may shift with the rising demand for glass, particularly in the context of solar photovoltaic production, suggesting a potential increase in both domestic consumption and export demand.

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[230] In the BAU scenario, the U.S. electric grid emissions factor is assumed to decreased by 68% between 2018 and 2050. See Appendix B for details on grid emissions factor assumptions.
[231] Thomas Brinkmann et al., *Best Available Techniques (BAT) Reference Document for the Production of Chlor-Alkali*, (Seville, Spain: European IPPC Bureau, 2014), dx.doi.org/10.2791/13138.
[232] Dong-Yeon Lee, Amgad Elgowainy, and Qiang Dai, "Life cycle greenhouse gas emissions of hydrogen fuel production from chlor-alkali processes in the United States," *Applied Energy* 217, (May 2018): 467–479, doi.org/10.1016/j.apenergy.2018.02.132.
[233] U.S. Geological Survey, *2018 Minerals Yearbook: Soda Ash [Advance Release]* (2022), pubs.usgs.gov/myb/vol1/2018/myb1-2018-soda-ash.pdf.
[234] Ibid.

Figure 30 illustrates the annual GHG emissions reduction from 2018 to 2050 through the implementation of different decarbonization interventions for the CNZ pathway for soda ash, while Figure 31 shows the corresponding market adoption of current and future technologies driving these emissions reductions. The modeled results estimate annual soda ash manufacturing emissions reductions of approximately 2.5 MMT CO_2e by 2050 in the CNZ pathway. In 2018, only 9% of U.S. soda ash produced was used for local container glass manufacturing, which has a current recycling rate of 25%–30%.[235] In the CNZ–Increased recycling sensitivity (see Figure C-7 in Appendix C), assuming a recycling rate of two-thirds for container glass, cumulative emissions reductions are projected to reach an additional 1.2 MMT CO_2e between 2018 and 2050. However, this study does not account for recycling outside of the United States, which limits the full breadth of potential impact from increased recycling. Details on assumptions for the soda ash model can be found in

Table C-11 and sensitivity results can be found in Figure C-7 in Appendix C.

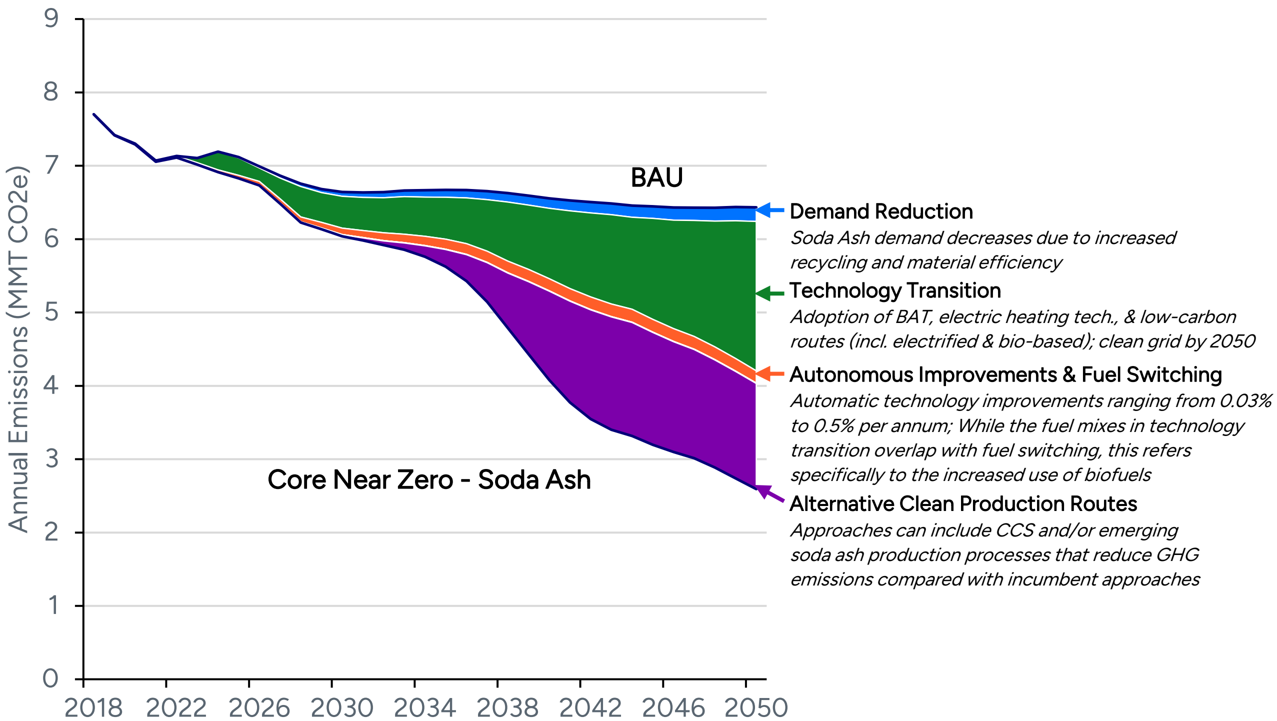
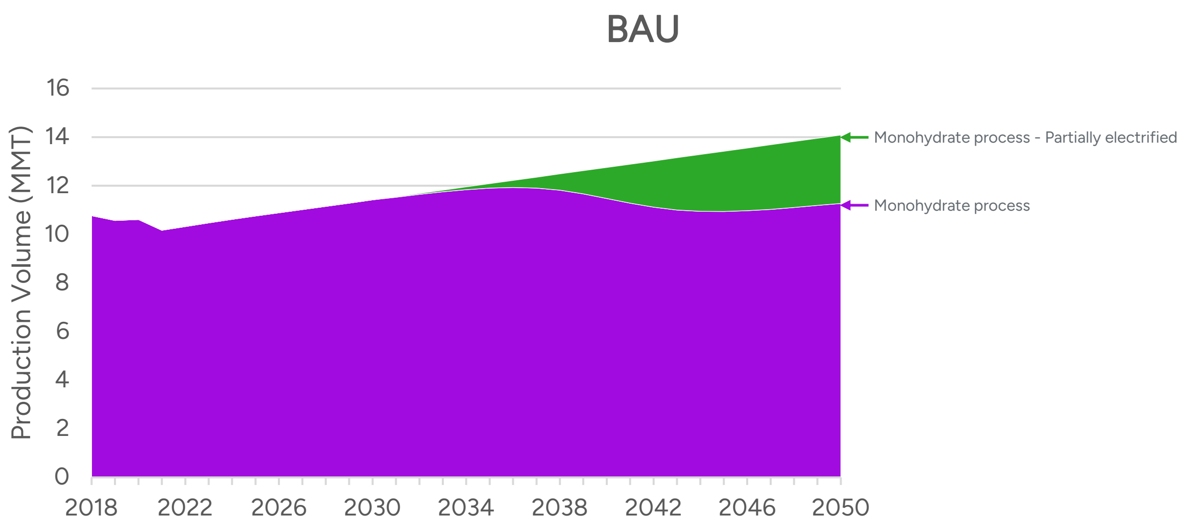


Figure 30. Annual GHG emissions reductions, U.S. soda ash production—Core Near Zero pathway (MMT CO_2e/year), 2018–2050

Note: The shape of the area for alternative clean production routes may change depending on the technologies that are adopted. Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C (see Table C-11). Source: Transformative Pathways modeling.

[235] Ibid.



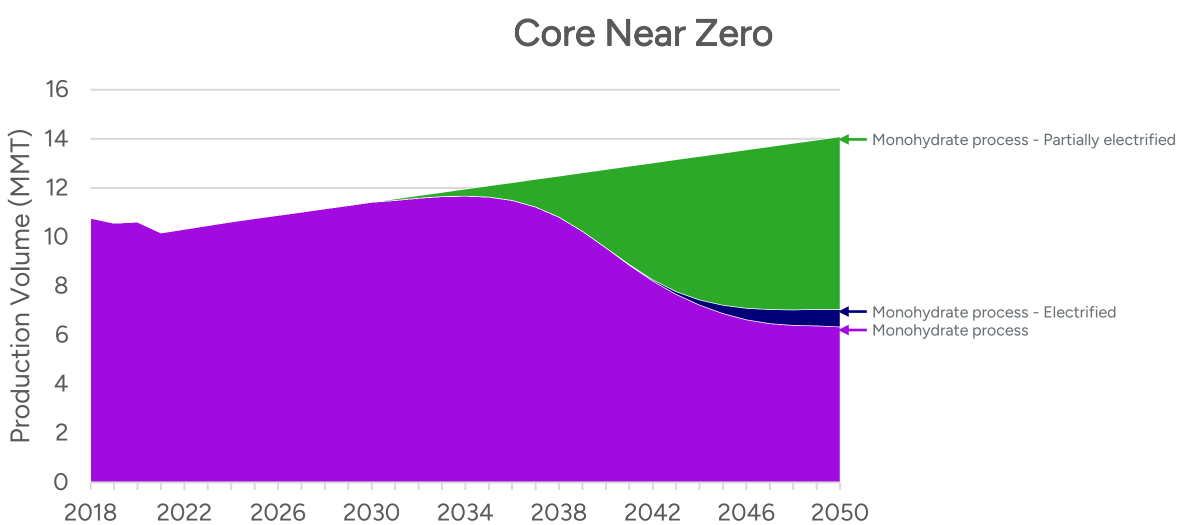


Figure 31. U.S. soda ash production route market share–BAU scenario (left) and Core Near Zero pathway (right), 2018–2050

Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C (see Table C-11). Source: Transformative Pathways modeling.

The impacts of key pillar-specific decarbonization technologies are discussed below:

Energy efficiency: Due to the limited number of plants globally using the natural (monohydrate) process, there is a scarcity of publicly available data detailing specific energy efficiency measures and their implementation. This lack of information hinders precise estimates of opportunities for improving energy efficiency. Despite these constraints, available data indicates that U.S. facilities have largely transitioned from triple-effect evaporators to mechanical vapor recompression systems for crystallization, as well as from direct-fired dryers to steam dryers. These changes have already led to a notable reduction in overall plant energy demand, highlighting the potential for further energy efficiency improvements in the Core Near Zero pathway. Additionally, significant energy savings within the BAT variant of the incumbent process can primarily be attributed to heat integration and a shift to rotary steam dryers, rather than fluidized bed steam dryers. Plants that lag in adopting these best practices should consider these measures as 'low-hanging fruit' for enhancing efficiency, both economically and practically.

Electrification: Decarbonizing U.S. soda ash manufacturing through electrification is closely linked to the decarbonization of the electric grid, which serves as a catalyst for the widespread adoption of electrified process heat supply. To achieve significant reductions in GHG emissions, the electrification of steam generation for crystallization and drying is proposed through the deployment of HTHP and electric boilers, respectively. Although the limitations in heat pump capacities and higher temperature lifts have been identified as potential constraints, the utilization of waste heat from calciners presents an opportunity to address these challenges by enabling lower temperature lifts and higher COPs. This approach may result in reduced electricity demand and corresponding operating costs. Additionally, several projects have explored the technical feasibility of microwave-induced calcination.[236,237] The microwave-induced calcination of trona ore at relatively moderate temperatures could represent one of the first applications of this electromagnetic technology in large-scale industrial processes. A conservative estimate suggests a 25% energy savings for electrified calcination using microwaves; however, the timeline for commercialization and the associated costs of this technology remain uncertain.

LCFFES: Based on EPA facility-level GHG emissions data,[238] three out of four reporting facilities have disclosed emissions linked to coal, which may be associated with the calcination step. In contrast, one facility has exclusively reported CO_2 emissions originating from natural gas. This divergence may be attributed to the use of rotary gas-fired calciners, a technology that other facilities could potentially adopt as a substitute for coal. Considering the operational experiences observed in the United States, the complete transition from coal to natural gas, RNG, and/or blended hydrogen is evaluated across various production routes, exhibiting promising decarbonization potential.

CCUS: The decarbonization potential of alternative clean production for soda ash, modeled as CCUS, is significant. The production of soda ash via the monohydrate process generates both combustion-related and process CO_2 emissions. Although there is potential for future efficiency improvements and the electrification of process heat, the inherent chemistry of the process leads to the unavoidable release of CO_2 during the calcination of trona ore. Consequently, carbon capture becomes a critical measure for achieving near zero emissions, as shown in Figure 30. In the absence of CCUS (or in the CNZ–Low CCUS sensitivity, see Figure C-7 in Appendix C), there is only a 42% annual emissions reduction or less relative to emissions projected in the BAU scenario in 2050, this should be compared to the 80% reduction in the CNZ pathway. At a California facility that produces soda ash from rich brines, CO_2 capture from the CHP plant for carbonation is already operational.[239] This valuable operational experience could be leveraged by other facilities, provided they have access to CO_2 transport infrastructure for potential long-term storage and/or utilization. However, exploration of nascent, clean production routes may also yield emissions reduction comparable to that of CCUS.

4.2.3.7 Methanol

Methanol demand is expected to more than double by 2050 (Figure 19), driven primarily by its increased use as both feedstock and fuel. With global methanol demand growing, particularly driven by China's MTO plants, U.S. methanol producers are increasingly focusing on exports to China. Methanol is used in various applications, such as an alternative transportation fuel in China and blended into motor gasoline abroad to improve combustion efficiency and reduce air pollution. These markets are viewed as the primary opportunity for new U.S. plants, as domestic demand alone may not be sufficient to absorb the increased supply.[240,241]

As a result, the growth in methanol production leads to a rise in annual emissions, from 9.2 MMT CO_2e per year in 2018 to 18.7 MMT CO_2e per year by 2050 in the BAU scenario. In contrast, the Core Near Zero pathway shows that despite the significant rise in demand, annual emissions from methanol production can be reduced to 1 MMT CO_2e per year by 2050. Figure 32 illustrates the annual GHG emissions reductions achieved through the application of decarbonization technologies for the CNZ pathway, based on the adoption rates of production

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236 Sibel Gezer and Umit Atalay, "Assessment of soda ash calcination treatment of Turkish trona ore," *E3S Web Conf.* 8, (September 2016), doi.org/10.1051/e3sconf/20160801013.
237 Morgana L. Fall et al., *Energy Efficient Microwave Hybrid Processing of Lime for Cement, Steel, and Glass Industries*, DE-EE0003472 (2012), www.osti.gov/biblio/1034621.
238 U.S. Environmental Protection Agency, "Facility Level Information on GreenHouse gases Tool (FLIGHT)," August 2024, ghgdata.epa.gov/ghgp/main.do.
239 U.S. Environmental Protection Agency, "Title 40 CFR Part 60 -- Standards of Performance for New Stationary Sources," November 21, 2024, www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-60?toc=1.
240 Lane Kelly, "New US methanol capacity will depend on exports to China," February 9, 2018, www.icis.com/explore/resources/news/2018/02/09/10192325/new-us-methanol-capacity-will-depend-on-exports-to-china/.
241 U.S. Energy Information Administration, "New methanol plants expected to increase industrial natural gas use through 2020," February 21, 2019, www.eia.gov/todayinenergy/detail.php?id=38412.

routes outlined in Figure 33. A detailed discussion of the impacts of these key technologies is provided below. Details on assumptions for the methanol model can be found in Table C-12 and sensitivity results can be found in Figure C-8 in Appendix C.

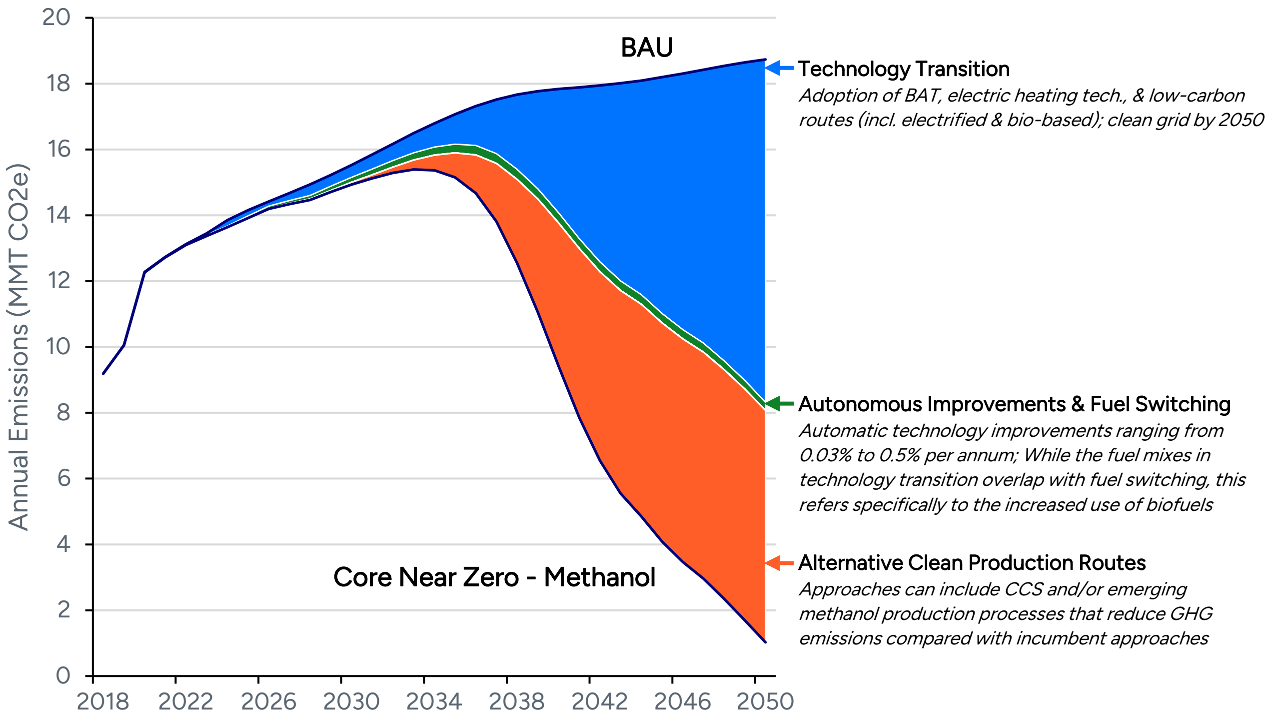

Figure 32. Annual GHG emissions reductions, U.S. methanol production—Core Near Zero pathway (MMT CO_2e/year), 2018–2050

Note: Impact of demand reduction was not evaluated.The shape of the area for alternative clean production routes may change depending on the technologies that are adopted. Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C (see Table C-12). Source: Transformative Pathways modeling.

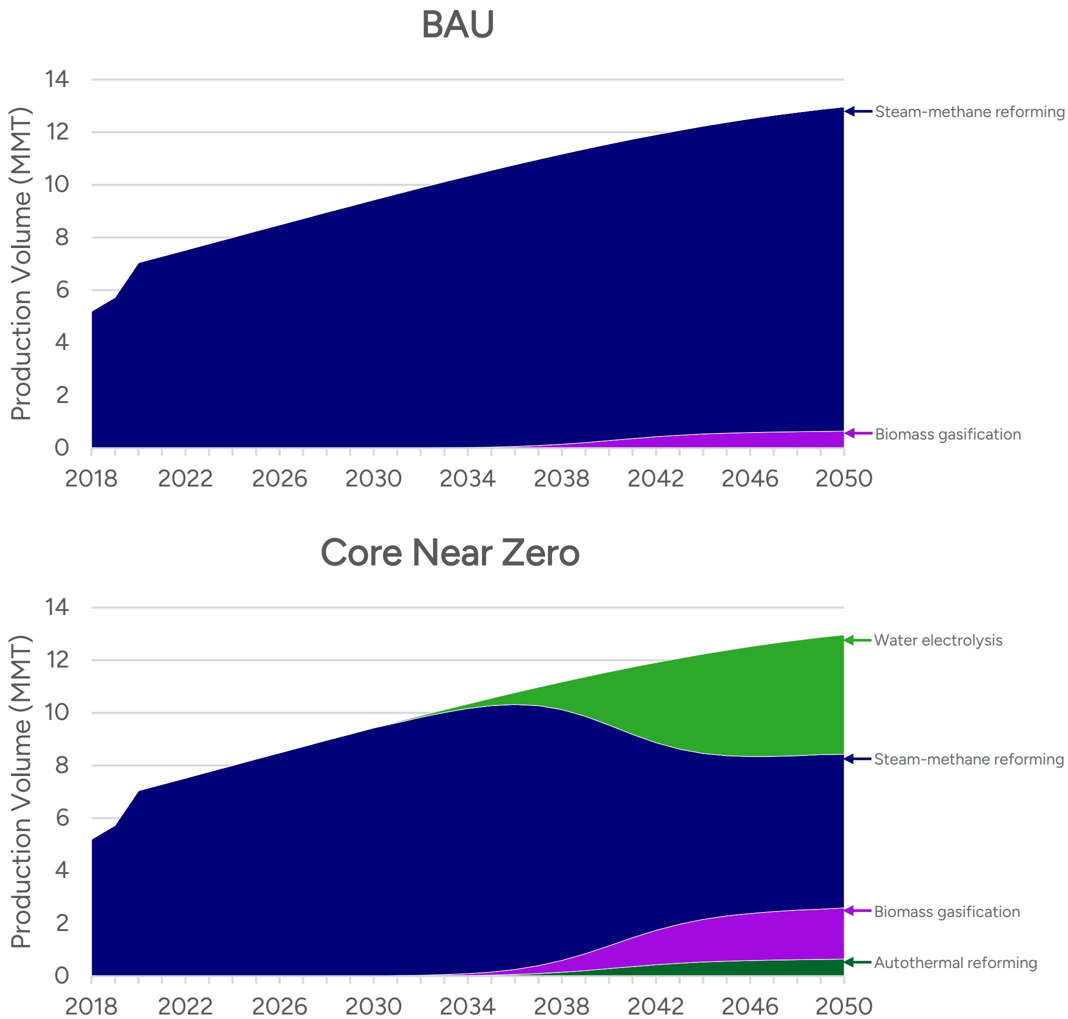

Figure 33. U.S. methanol production route market share—BAU scenario (left) and Core Near Zero pathway (right), 2018–2050

Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C (see Table C-12). Source: Transformative Pathways modeling.

Energy efficiency: U.S. methanol plants can enhance their production processes and achieve greater energy efficiency by adopting a range of best practices and technologies. Key strategies include advanced heat integration, the use of efficient catalysts, and optimized process control. Although the potential for energy efficiency improvements is somewhat limited, it remains crucial to employ catalysts for both carbon monoxide and CO_2 hydrogenation that are highly active and selective toward methanol. Advancements in hydrogen production, particularly in the reforming such as autothermal reforming, also play a major role in improving energy efficiency (see further discussion in the ammonia Section 4.2.3.8 for specific technologies applicable to conventional SMR).

Electrification: The shift toward electrification in methanol manufacturing is primarily driven by the increasing adoption of e-methanol and the simultaneous decarbonization of the electric grid. In the Core Near Zero pathway, which aims to produce 4.5 MMT of e-methanol by 2050, approximately 6.2 MMT CO_2 and 0.9 MMT clean hydrogen would be required. This process would require approximately 43 terawatt-hours (TWh) of clean electricity from the grid.

A significant hurdle in e-methanol production is its cost, particularly due to the expense associated with producing hydrogen through electricity-intensive electrolysis. Currently, the estimated production cost of e-methanol ranges from $900 to $1,400 per MT when CO_2 is sourced from industrial processes.[242] If CO_2 is

[242] M. Jibran S. Zuberi, Arman Shehabi, and Prakash Rao, "Cross-sectoral assessment of CO_2 capture from U.S. industrial flue gases for fuels and chemicals manufacture," *International Journal of Greenhouse Gas Control* 135, (June 2024), doi.org/10.1016/j.ijggc.2024.104137.

captured through direct air capture, the costs rise to $1,200 to $2,400 per metric ton. The future cost of clean electrolytic hydrogen production depends on reductions in the cost of electrolyzers, improvements in clean power generation, and advancements in electrolyzer efficiency and durability. Expected improvements in these areas could lower e-methanol production costs to between $250 and $630 per metric ton by 2050.[243]

In addition to e-methanol, companies are exploring low-carbon methanol processes to reduce the carbon intensity of methanol production from natural gas. One such approach involves electrifying the heating requirements in the reforming step, where natural gas is converted into hydrogen/syngas. Replacing natural gas combustion with electrical heating powered by clean energy (eSMR) eliminates combustion-related CO_2 emissions. However, significant process CO_2 emissions, typically greater than fuel emissions, are still generated. These can be captured and combined with hydrogen produced through water electrolysis using clean nuclear or renewable electricity. These electrified processes, along with various configurations of clean methanol production, offer hybrid solutions that could gradually introduce e-methanol while reducing carbon emissions from methanol facilities. The implementation of these hybrid solutions requires detailed modeling and assessments, which are planned for future work.

LCFFES: The transition to bio-methanol is a key element in this pillar, with a focus on utilizing waste biomass resources. Both commercial bio-methanol facilities and global demonstration projects are centered around leveraging waste and by-product streams from various industrial processes, underscoring the economic viability of bio-methanol production. Key feedstocks include municipal solid waste, agricultural residues, waste streams, and black liquor from the pulp and paper subsector. In the Core Near Zero pathway, producing 1.9 MMT of bio-methanol through biomass gasification by 2050 will require over 3.5 MMT of dry biomass. Due to the variability in bio-feedstock sourcing and the potentially high transport costs, strategically locating future bio-methanol facilities near specific biomass sources will be essential for minimizing costs and enhancing overall feasibility. In the CNZ–Aggressive sensitivity (see Figure C-8 in Appendix C) for methanol production, emerging routes surpass 50% market adoption, with the share of bio-methanol ambitiously set at 30%.

In 2019, global methanol production nearly doubled from 2001 levels, to 98 MMT,[244] and U.S. capacity increased sevenfold between 2010 and 2018, with continued rapid growth.[245] As new methanol plants are developed, they are expected to adopt cleaner technologies, positioning bio-methanol as a major contributor to methanol manufacturing's energy transition. Innovative solutions include the integration of bio- and e-methanol production in a single facility as a hybrid low-carbon process, in which excess biogenic CO_2 from bio-methanol production can be used as the CO_2 source for e-methanol production, using clean hydrogen. However, these hybrid solutions require further R&D. In terms of the fuel energy mix, switching to RNG offers emissions reduction potential, although its overall contribution to CO_2 abatement remains relatively small and was limited to 10% or less adoption in the models.

CCUS: Alternative clean production routes, including CCUS, is a significant intervention (see Figure 32). Given the significant CO_2 emissions associated with conventional SMR-based process, the role of CCUS could extend beyond just producing clean hydrogen. This is particularly relevant when considering the CO_2 feedstock required for e-methanol production, which can be sourced from industrial flue gases or direct air capture. Although bio- and e-methanol capacity is largely expected to provide low-carbon methanol for use as both feedstock and fuel, the captured CO_2 is not always stored long-term. When methanol is used as fuel, the CO_2 is eventually released, meaning there is no long-term credit for CO_2 utilization in e-methanol. However, using captured CO_2 for methanol production has the potential to displace emissions associated with the conventional methanol production from natural gas. This highlights the need for a comprehensive life cycle analysis and carbon accounting to assess the full environmental impact of methanol production, distribution, and use. On a different note, capturing biogenic CO_2 emissions from bio-methanol production using waste biomass could lead to negative emissions. For the bio-methanol production route (biomass gasification), bioenergy with carbon capture and sequestration could potentially drive methanol production to net-negative emissions with a high

[243] International Renewable Energy Agency and Methanol Institute, *Innovation Outlook: Renewable Methanol* (2021), www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol.
[244] Ibid.
[245] U.S. Energy Information Administration, "New methanol plants expected to increase industrial natural gas use through 2020," February 21, 2019, www.eia.gov/todayinenergy/detail.php?id=38412.

enough adoption rate (30% vs the 15% adoption rate in the CNZ pathway), as illustrated in the CNZ–Aggressive sensitivity (see Figure C-8 in Appendix C). A promising approach involves integrating e-methanol and bio-methanol production within a single bioenergy with carbon capture and utilization plant, offering the potential to create a net carbon-neutral cycle in e-methanol production.

4.2.3.8 Ammonia

The continuous expansion of ammonia capacity in the United States has driven an increase in natural gas production. In 2022, U.S. producers operated at approximately 86% of their rated capacity.[246] According to the U.S. Geological Survey, there has been a steady rise in annual U.S. ammonia production since 2010, growing over 40% from 10.1 MMT to 17 MMT in 2020.[247] As domestic production has outpaced demand, the United States has witnessed a reduction in its reliance on imported ammonia, decreasing from 40% in 2010 to 13% in 2020.[248] In the base year of 2018, the 15.9 MMT of ammonia produced resulted in estimated CO_2 emissions of 27.2 MMT, contributing nearly 8% to the overall scope 1 and 2 emissions from the U.S. chemicals subsector.

The annual GHG emissions reductions achieved through the application of decarbonization technologies for the CNZ pathway are shown in Figure 34, based on the adoption rates outlined in Figure 35. CO_2 emissions from ammonia manufacturing are projected to decrease to approximately 1.1 MMT by 2050 in the CNZ pathway. Material efficiency measures, such as improved fertilizer use-efficiency, offer only modest reductions in emissions, and even when implemented, emissions are expected to remain relatively steady due to increased net ammonia demand by 2050 in the BAU scenario. Details on assumptions for the ammonia model can be found in Table C-13 and sensitivity results can be found in Figure C-9 in Appendix C.

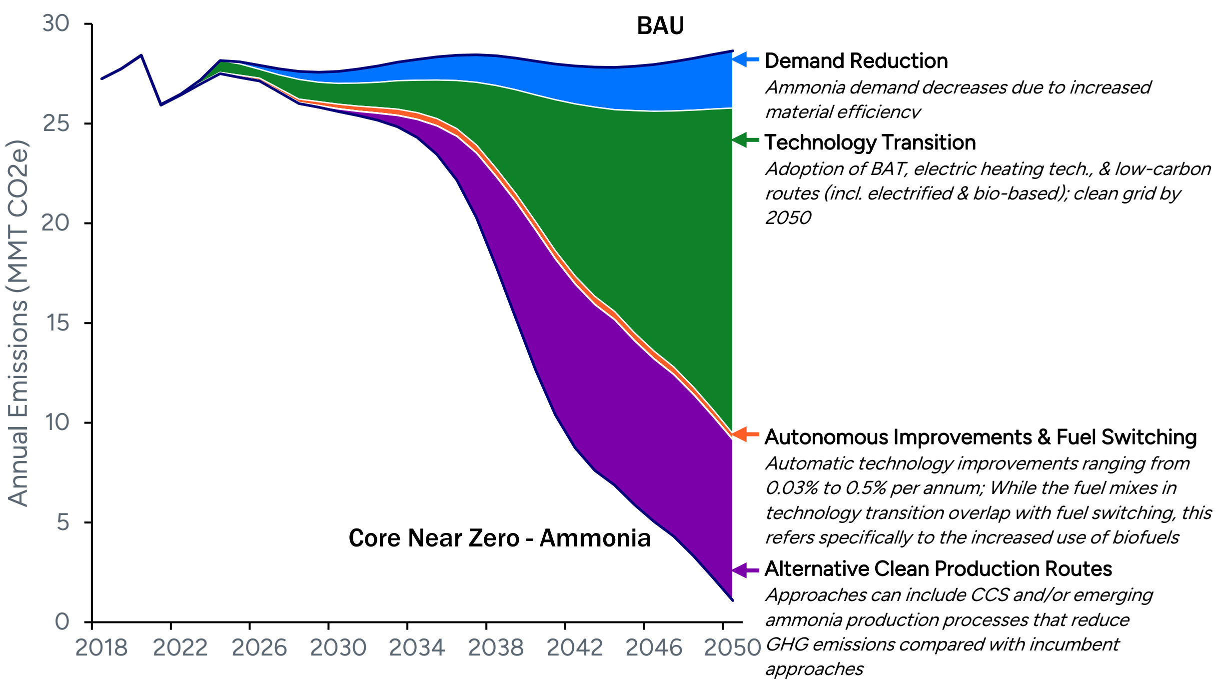

Figure 34. Annual GHG emissions reductions, U.S. ammonia production–Core Near Zero pathway (MMT CO_2e/year), 2018–2050

Note: The shape of the area for alternative clean production routes may change depending on the technologies that are adopted. Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C (see Table C-13). Source: Transformative Pathways modeling.

[246] U.S. Energy Information Administration, "Natural Gas Weekly Update," April 1, 2021, www.eia.gov/naturalgas/weekly/archivenew_ngwu/2021/04_01/.
[247] U.S. Geological Survey, *2018 Mineral Yearbook: Nitrogen [Advance Release]* (2021), d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/atoms/files/myb1-2018-nitro.pdf.
[248] U.S. Energy Information Administration, "Natural Gas Weekly Update," April 1, 2021, www.eia.gov/naturalgas/weekly/archivenew_ngwu/2021/04_01/.

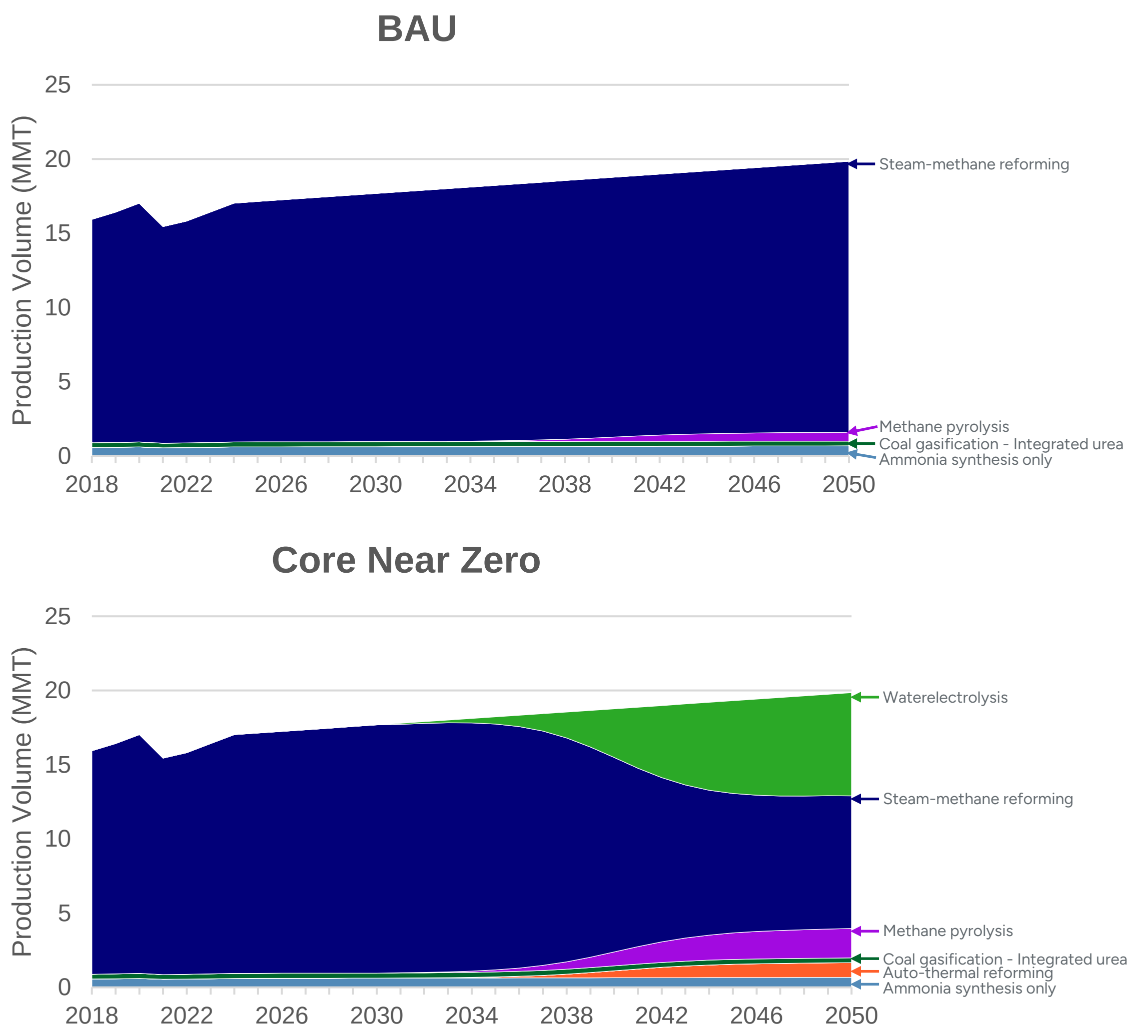

Figure 35. U.S. ammonia production route market share–BAU scenario (left) and Core Near Zero pathway (right), 2018–2050

Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C (see Table C-13). Source: Transformative Pathways modeling.

An ammonia-specific sensitivity was developed to explore the sensitivity of ammonia-related emissions to changing demand (see Figure C-9 in Appendix C), given ammonia's emerging role as both a fuel and a hydrogen carrier. Ammonia has significant potential as a zero-carbon fuel, especially in shipping, where commercial engines are expected to become available by 2025.[249] However, ammonia is toxic, and its combustion produces small amounts of NOx emissions, necessitating more stringent safety measures than those required for traditional fuels. Additionally, ammonia shows promise in stationary power generation, replacing natural gas and coal for both baseload and peaking power applications. However, international agencies have primarily projected its use for power generation only in Japan,[250,251] partly due to anticipated regulatory frameworks regarding NOx emissions, ammonia slip, fuel quality and standards in other countries. As a result, this application is not considered for use in the United States. Ammonia also offers a solution to hydrogen storage and distribution challenges, with advancements like ammonia crackers enabling large-scale hydrogen production. These developments position ammonia as a key player in the energy transition.

As a result, ammonia demand could double by 2050 compared to baseline projections (Figure 19), driven by its use in shipping and as a hydrogen carrier. In the BAU scenario, coupled with this increased demand sensitivity,

[249] Anne Kirsten Fredericksen, "Ammonia will become one of the key green marine fuels," DTU, June 11, 2024, www.dtu.dk/english/newsarchive/2024/06/ammonia-will-become-one-of-the-key-green-marine-fuels.
[250] International Renewable Energy Agency and Ammonia Energy Association, *Innovation Outlook: Renewable Ammonia* (2022), www.irena.org/publications/2022/May/Innovation-Outlook-Renewable-Ammonia.
[251] International Energy Agency, *Ammonia Technology Roadmap* (2021), www.iea.org/reports/ammonia-technology-roadmap.

ammonia-related emissions could reach around 60 MMT CO_2e annually by 2050. However, demand is expected to be largely met by cleaner technologies such as water electrolysis and methane pyrolysis, to produce hydrogen for ammonia. As a result, in this sensitivity, electrification could contribute up to 60% of the emissions reductions needed for ammonia production to approach near zero emissions. However, the success of these efforts will depend on the decarbonization of the electric grid or the availability of onsite clean electricity generation (refer to the later discussion under 'electrification').

A detailed discussion of pillar-specific technologies and their impacts is presented below.

Energy efficiency: Although energy efficiency improvements in ammonia production contribute significantly to emissions reductions, their impact is considerably lower than that of electrification and CCUS by 2050. In 2018, the process energy (excluding feedstock) required to produce one metric ton of ammonia from natural gas (conventional SMR) was, on average, approximately 20% higher than the energy performance levels of BAT. The adoption of BAT, along with improved operational and maintenance practices as well as enhanced process heat integration, will be crucial in achieving higher energy performance across various production routes from 2018 to 2050.

Energy efficiency and best practices in ammonia manufacturing involve a range of technologies. Key examples include pre-reformers, advanced CO_2 removal systems with improved solvents, isothermal shift conversion, low-temperature desulfurization, and low-pressure catalysts for ammonia synthesis. The U.S.-based company Starfire Energy is working to commercialize ammonia synthesis using low-temperature catalysts and separation methods like adsorption or absorption (e.g., a sorbent-enhanced Haber-Bosch synthesis loop). This approach allows operations at lower temperatures and pressures, enabling flexible operation and cost-effective scaling of the manufacturing process.[252]

Electrification: The shift toward electrification in ammonia manufacturing is driven by the growing adoption of green ammonia, methane pyrolysis, and the simultaneous decarbonization of the electric grid. In the CNZ Pathway, which aims to produce 6.9 MMT of green ammonia by 2050, approximately 1.2 MMT clean hydrogen will be required. This, in turn, necessitates 71 TWh of electricity from the grid. However, a major challenge for green ammonia production is its cost, particularly the expense of providing hydrogen through the electricity-intensive electrolysis process. The viability of electrolysis-based green ammonia depends on further reductions in clean power costs, decreases in the capital cost of electrolyzers, and improvements in efficiency and durability.

Plasma methane pyrolysis uses electrical plasma to split methane into hydrogen and carbon atoms without combustion, producing no process emissions. This technology was pilot tested by Monolith in Seaport, California (2013–2015), the company launched its first small-scale unit, Olive Creek 1, in 2020, and commissioned the larger Olive Creek 2 in Nebraska in 2023, with plans to begin ammonia production in 2024.[253] This process has a low carbon footprint, as carbon black, the co-product, is used in steel, tires, and printers, preventing emissions. However, it requires 25%–45% more natural gas feedstock than traditional methods, potentially increasing upstream GHG emissions (scope 3).[254,255] Nevertheless, since carbon black production from the conventional thermal cracking of petroleum products is emissions-intensive, adopting methane pyrolysis contributes to reducing the environmental footprint of both ammonia and carbon black. IEA projects that this technology could account for about 10% of U.S. ammonia production by 2050, as assumed in this analysis (see Appendix C). Its expansion, however, is limited by the potential oversupply of carbon black, which may require export markets for profitability.[256]

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[252] International Renewable Energy Agency and Ammonia Energy Association, *Innovation Outlook: Renewable Ammonia* (2022), www.irena.org/publications/2022/May/Innovation-Outlook-Renewable-Ammonia.
[253] Chris Mesrobian, "Taking Methane Pyrolysis from Concept to Industrial Plant," Invited Presentation to Advanced Research Projects Agency—Energy, (January 2021), arpa-e.energy.gov/sites/default/files/2021-01/08%20OK%20-Monolith_ARPAE_MethanePyrolysis2021_v3.pdf.
[254] International Energy Agency, *Ammonia Technology Roadmap* (2021), www.iea.org/reports/ammonia-technology-roadmap.
[255] International Renewable Energy Agency and Ammonia Energy Association, *Innovation Outlook: Renewable Ammonia* (2022), www.irena.org/publications/2022/May/Innovation-Outlook-Renewable-Ammonia.
[256] International Energy Agency, *Ammonia Technology Roadmap* (2021), www.iea.org/reports/ammonia-technology-roadmap.

IEA projects a more than 50% decline in the costs of electrolyzers and methane pyrolysis by 2050, driven by technological advancements and increased deployment across the energy system.[257] However, capital costs are expected to remain higher than those for SMR-based ammonia production until around 2030.[258] Beyond 2030, these costs are projected to decrease, enabling rapid deployment, as assumed in the CNZ pathway. The rapid decarbonization of the grid in the latter pathway would further accelerate the adoption of electrified technologies. With increased adoption of electrified production routes, which could make up to 50% of the ammonia market share under the CNZ–Aggressive sensitivity (see Figure C-9 in Appendix C), even greater GHG emissions reductions could be achieved, provided sufficient clean electricity is available.

An additional opportunity for electrification, not considered in this study, is the replacement of natural gas heating with electrified heating in conventional SMR, referred to as "eSMR" by Haldor Topsoe. The cost-efficient scale of this electrified system could be up to two orders of magnitude smaller than a conventional SMR unit, due to intensified contact between the ohmic heater and the catalyst layer. This downsizing potential could reduce the carbon intensity of ammonia production by about 30%.[259] Haldor Topsoe has a demonstration plant at Aarhus University's research facility in Foulum, Denmark, designed to validate its electrified technology for cost-competitive production of sustainable methanol, with plans to expand to other sustainable products like clean hydrogen and green ammonia.[260] However, insufficient technical data and relevant information limited its inclusion in the current analysis, although it is planned for future research.

LCFFES: In the context of decarbonizing ammonia, the contribution of the LCFFES pillar is relatively small, amounting to only about 1 MMT CO_2e savings by 2050 compared to the 2018 baseline. This limited impact is primarily due to the anticipated use of RNG as an alternative to fossil natural gas for process heat. Furthermore, bio-based production routes are not expected to play a significant role in the decarbonization of ammonia production. However, certain location-specific conditions could offer limited opportunities where the biomass gasification route might overcome techno-economic challenges. For example, in isolated communities with limited access to fossil-based or electrolysis-based ammonia, and a specific need for urea fertilizer, low-cost biomass or animal waste could serve as a viable feedstock for bio-ammonia. In such cases, a biomass-to-urea process could be implemented, even though it may produce more CO_2 than required for urea production. This scenario presents an opportunity for scalable bioenergy with carbon capture and sequestration, enabling the production of carbon-negative ammonia and fertilizers.

CCUS: Alternative clean production routes have a significant impact on decarbonizing ammonia production. This intervention was modeled as implementing CCUS due high purity process emissions, offering a cost-effective approach to emissions reduction within a near zero framework. However, this could also be achieved with nascent, clean production routes.

In ammonia manufacturing, CO_2 is routinely captured and often used in an integrated process for urea production. The integration of ammonia and urea production is driven by material and energy efficiency, cost-effectiveness, and the ability to use CO_2 emissions from ammonia production as a key feedstock for urea, resulting in a more sustainable and economical operation. The inherent CO_2 capture process in ammonia manufacturing generates a highly concentrated CO_2 stream, which can be captured beyond what is required for urea production and then must be compressed and dehydrated for transport and storage. High purity process CO_2 emissions capture is one of the most cost-effective ways to significantly reduce CO_2 emissions from ammonia production. However, capturing CO_2 from the dilute flue gas streams generated by fuel combustion in ammonia production may require chemical absorption technology, similar to that used to separate CO_2 from the feedstock stream. This would necessitate additional investment in capture equipment beyond what is currently installed in commercial ammonia plants. Other CCUS technologies for ammonia manufacturing include physical

[257] Ibid.
[258] Ibid.
[259] Kevin Rouwenhorst, "Electrified Methane Reforming Could Reduce Ammonia's CO_2 Footprint – Ammonia Energy Association," Ammonia Energy Association, August 29, 2019, www.ammoniaenergy.org/articles/electrified-methane-reforming-could-reduce-ammonias-co2-footprint/.
[260] Ulrik Frøhlke, "Topsoe Puts Demonstration Plant into Operation for Production of Sustainable Methanol from Biogas - Significant Global Carbon Emission Reduction Potential," Advanced BioFuels USA, October 18, 2021, advancedbiofuelsusa.info/topsoe-puts-demonstration-plant-into-operation-for-production-of-sustainable-methanol-from-biogas-significant-global-carbon-emission-reduction-potential/.

absorption using liquid solvents like Selexol and Rectisol, as well as physical adsorption and cryogenic capture.[261] Further analysis is needed to investigate and compare the techno-economic characteristics of each of these capture technologies in ammonia production.

Although CCUS is not inherent to the ATR process, ATR produces only one high-purity CO_2 stream and may not require supplemental methane combustion,[262] potentially achieving higher capture rates than SMR. As a result, integrating CO-Shift and CCUS with the ATR process could emerge as a cost-effective approach for large-scale production of low-carbon hydrogen for ammonia. This positions CCUS as a key driver for ATR adoption. However, its implementation is limited in this study due to its reliance on fossil fuels and the limited scale of deployment, with preference given to other low-carbon production routes, such as water electrolysis and methane pyrolysis.

Although CO_2 capture is somewhat common in U.S. ammonia plants, with roughly 10% of process CO_2 captured in 2020, only a small fraction of this (less than 2 MMT CO_2 per year) is geologically stored.[263] This fraction primarily originates from four to five large-scale ammonia CCUS projects operating in different U.S. states, where the captured CO_2 is transported via pipelines and used for enhanced oil recovery.[264] The projected adoption of CCUS-equipped SMR production routes (or SMR-CCS hydrogen) contributes significantly to emission reductions. Factors such as low natural gas prices, established incentives and policies, and experience from existing projects position the United States for a rapid deployment of this technology.

4.2.3.9 Ethanol

The United States is the largest producer of ethanol, accounting for 55% of the world's fuel ethanol production.[265] According to EIA's Annual Energy Outlook (AEO) reference case, from 2017 to 2022, the United States exported approximately 8% to 10% of its ethanol production.[266] The AEO projects a decline in ethanol use for transportation fuel, with the assumption that any ethanol not consumed domestically will be exported. The export share is expected to rise from 9% in 2022 to 22% by 2050. However, as vehicle electrification progresses, there may be opportunities to shift production capacity toward other products rather than ethanol exports. Notably, sustainable aviation fuels (SAF) are a key target, and ethanol could serve as a non-fossil chemical feedstock for producing high-value chemicals. This analysis considers ethanol as a feedstock for ethylene and butadiene production, with projected volumes remaining well within the anticipated 22% excess ethanol available for export.

U.S. ethanol production is notable for being primarily derived from corn. Figure 36 presents the annual GHG emissions reductions achieved through the application of decarbonization technologies for the CNZ pathway, based on the adoption of production routes provided in Figure 37. The CNZ pathway achieves net zero emissions before 2040, primarily due to the capture of high-purity biogenic CO_2 emissions from fermentation. Although this analysis focuses on scope 1 and scope 2 emissions, it is important to note that significant scope 3 emissions are associated with ethanol production, including emissions from corn farming, fertilizer and chemical applications, land use change, transportation, and downstream combustion in vehicles. Within the scope of this analysis, credits are allocated for capturing biogenic CO_2 through bioenergy with carbon capture and sequestration, which offsets the non-biogenic emissions from ethanol production. Since biogenic process CO_2 emissions exceed energy-related emissions, capturing these emissions in large quantities results in net zero emissions, as shown in Figure 36. Annual GHG emissions reductions, U.S. ethanol production–Core Near Zero

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[261] International Energy Agency, "ETP Clean Energy Technology Guide," October 22, 2024, www.iea.org/data-and-statistics/data-tools/etp-clean-energy-technology-guide.
[262] Mark Zoback and Dirk Smit, "Meeting the challenges of large-scale carbon storage and hydrogen production," *Proceedings of the National Academy of Sciences* 120, 11 (March 2023), doi.org/10.1073/pnas.2202397120.
[263] Estimated based on U.S. Environmental Protection Agency, "Supply, Underground Injection, and Geologic Sequestration of Carbon Dioxide," 2024, www.epa.gov/ghgreporting/supply-underground-injection-and-geologic-sequestration-carbon-dioxide
[264] International Renewable Energy Agency and Ammonia Energy Association, *Innovation Outlook: Renewable Ammonia* (2022), www.irena.org/publications/2022/May/Innovation-Outlook-Renewable-Ammonia.
[265] David Kramer, "Whatever happened to cellulosic ethanol?" *Physics Today* 75, 7 (July 2022): 22–24, doi.org/10.1063/PT.3.5036.
[266] U.S. Energy Information Administration, "Annual Energy Outlook 2023," 2023, www.eia.gov/outlooks/aeo/.

pathway (MMT CO_2e/year), 2018–2050. Details on assumptions for the ethanol model can be found in Table C-14 and sensitivity results can be found in Figure C-10 in Appendix C.

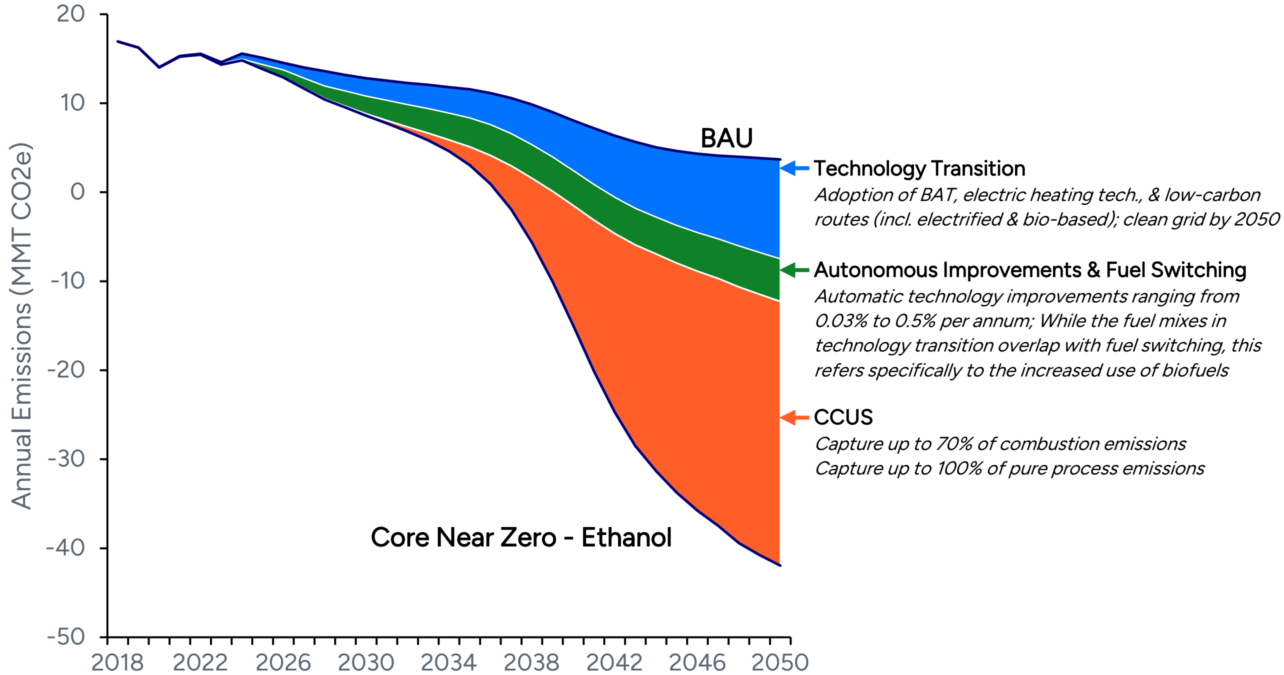

Figure 36. Annual GHG emissions reductions, U.S. ethanol production–Core Near Zero pathway (MMT CO_2e/year), 2018–2050

Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C (see Table C-14). Source: Transformative Pathways modeling.

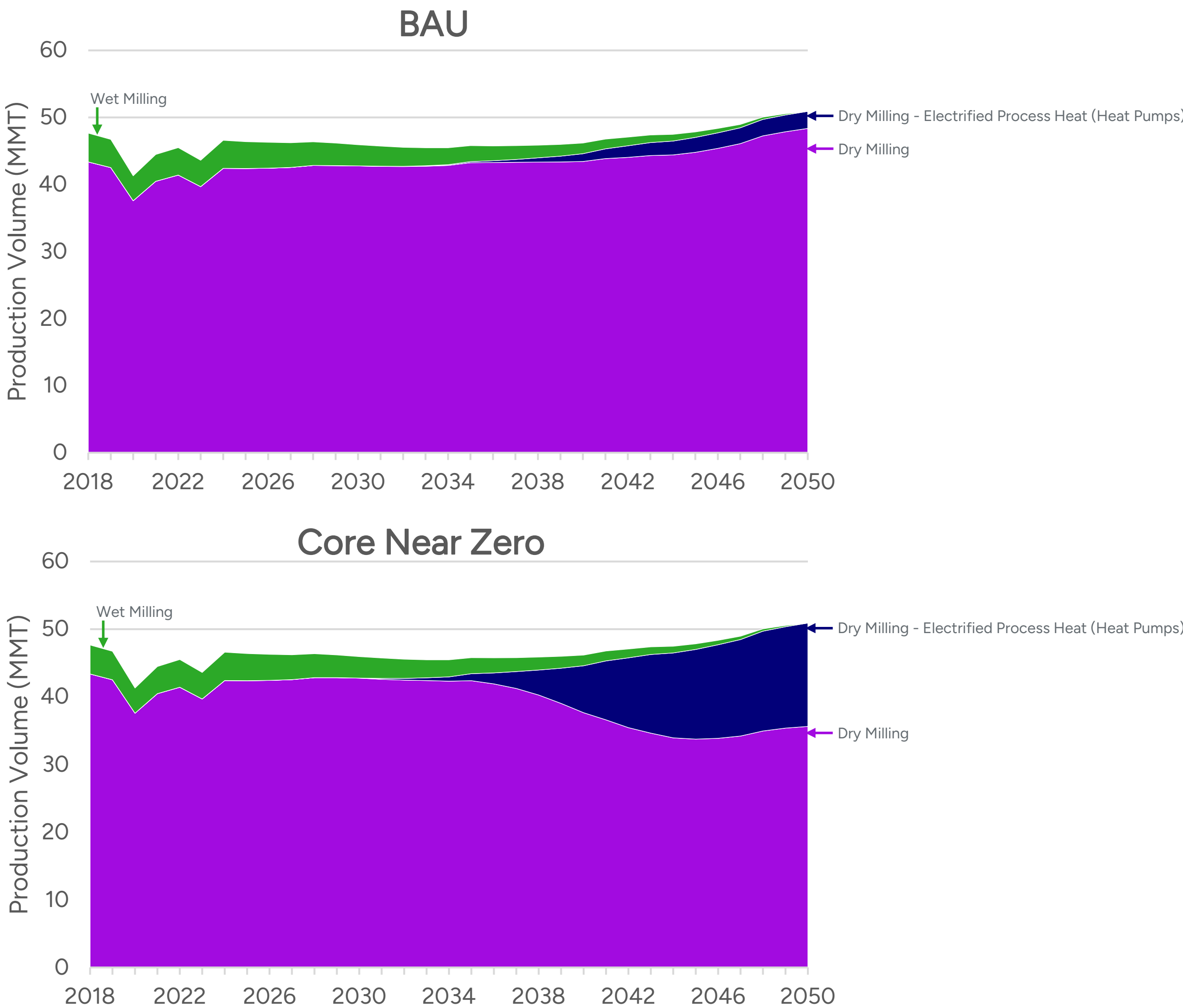

Figure 37. U.S. ethanol production route market share—BAU scenario (left) and Core Near Zero pathway (right), 2018–2050

Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C (see Table C-14). Source: Transformative Pathways modeling.

Note: This figure does not account for the significant scope 3 emissions associated with ethanol production, such as those from corn farming, fertilizer and chemical application, land use change, transportation, and downstream combustion in vehicles. Including scope 3 emissions from ethanol production would prevent achieving net zero emissions, as shown in Figure 38 below. Therefore, the results in this figure should not be misinterpreted. Additionally, the impact of demand reduction was not evaluated. However, to avoid misinterpretation due to the boundary conditions described above, the assumptions in the CNZ Pathway (see Table C-14 in Appendix C) are combined with ethanol life cycle considerations (scope 3), based on the results from Lee et al. 2021.[267] This provides a more comprehensive perspective, as illustrated in Figure 38. If scope 3 emissions are also considered, the application of decarbonization measures—including biogenic fermentation CO_2 capture—has the potential to reduce ethanol life cycle emissions by over 80%, ultimately reaching near zero levels. Furthermore, the application of decarbonization technologies across the entire ethanol supply chain could further enhance emissions reductions.

[267] Uisung Lee et al., "Retrospective analysis of the U.S. corn ethanol industry for 2005–2019: implications for greenhouse gas emission reductions," *Biofuels, Bioproducts and Biorefining* 15, 5 (May 2021): 1318–1331, doi.org/10.1002/bbb.2225.

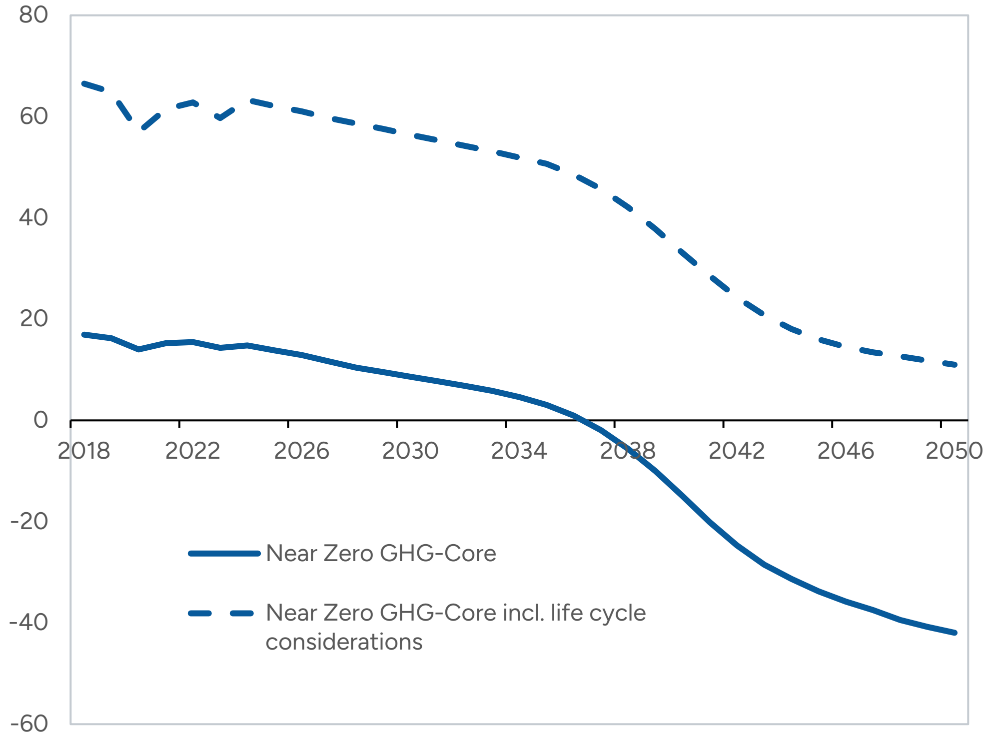

Figure 38. Annual GHG emissions, U.S. ethanol production (with and without life cycle considerations)–Core Near Zero pathway (MMT CO_2e/year), 2018–2050

Source: Transformative Pathways modeling.

A detailed discussion of pillar-specific technologies and their impacts is presented below.

Energy efficiency: The energy efficiency pillar includes a wide variety of process improvements and energy-efficient technologies available to ethanol producers. This has been an area of rapid progress over the past three decades. Energy intensity at corn ethanol facilities decreased by 50% from 1990 to 2010.[268] Additionally, from 2005 to 2019, ethanol plants on average reduced energy demand by 24%, lowered direct CO_2 emissions by 30%, and increased ethanol yield per mass of corn feedstock by 6.5%.[269] Further decarbonization potential remains as ethanol producers transition to best practices. Specifically, based on a 2018 USDA-commissioned report[270] and a 2019 ANL report,[271] the energy requirement of the most efficient ethanol plants is only 59%–65% of the average mill surveyed.

Examples of energy-efficient technologies available to ethanol manufacturers include high-gravity fermentation, improved temperature control, corn fiber ethanol, and the use of new enzymes or yeast strains to improve efficiency through increased ethanol yields. Energy requirements for separating water from ethanol downstream of the fermenter could be reduced through advanced distillation technologies or alternative de-watering technologies such as membrane separations. A 2015 DOE report[272] highlighted ethanol as having the greatest R&D energy savings potential for chemicals, largely based on the promise of advanced distillation technologies. Both advanced distillation and membrane separation technologies are currently in the mid-maturity research phase. Additionally, 31% of thermal energy use is associated with drying distillers' grains (DGS), meaning nearly

[268] Melissa J. Scully et al., "Carbon intensity of corn ethanol in the United States: state of the science," *Environmental Research Letters* 16, 4 (March 2021), doi.org/10.1088/1748-9326/abde08.
[269] Uisung Lee et al., "Retrospective analysis of the U.S. corn ethanol industry for 2005–2019: implications for greenhouse gas emission reductions," *Biofuels, Bioproducts and Biorefining* 15, 5 (May 2021): 1318–1331, doi.org/10.1002/bbb.2225.
[270] J. Rosenfeld et al., *A Life-Cycle Analysis of the Greenhouse Gas Emissions from Corn-Based Ethanol*, ICF for U.S. Department of Agriculture (2018), www.usda.gov/sites/default/files/documents/LCA_of_Corn_Ethanol_2018_Report.pdf.
[271] May Wu, *Energy and Water Sustainability in the U.S. Biofuel Industry*, ANL/ESD-19/5 (Argonne National Laboratory, 2019), www.osti.gov/biblio/1571243.
[272] U.S. Department of Energy, *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Chemical Manufacturing* (2015), www.osti.gov/biblio/1248749.

30% of emissions could be avoided by transitioning to 100% wet DGS, due to the energy savings from avoided drying. However, this may be limited by logistical challenges associated with wet DGS's shorter shelf life.

Electrification: The decarbonization impact of electrification is tied to decarbonization of the U.S. electric grid, combined with the application of electric HTHPs. Specifically, ethanol fermentation is an exothermic process that requires cooling, but more than half of an ethanol facility's energy requirement is for process heating during distillation. A HTHP can provide heat up to approximately 165°C, which is higher than the temperature required for ethanol distillation. A 2022 American Council for an Energy-Efficient Economy report[273] highlighted that ethanol dry milling is well-positioned for the electrification of process heating through industrial heat pumps, with an energy savings potential of up to 90%, accompanied by a modest increase in electricity demand. Similarly, the literature also suggests that heat integration via HTHPs could decrease heating and cooling energy requirements by 19%–88%, depending on the heat integration configuration considered.[274] Electrified process heating may also offer additional opportunities for DGS, depending on logistical and facility-specific factors. However, the techno-economic challenges of applying HTHPs, as discussed earlier, remain.

LCFFES: In the context of low-carbon fuels, two primary alternatives are of interest: biomass-based fuels, such as corn stover gasification, and RNG derived from biogas. Discarded corn stover has sufficient energy to meet all fuel and electricity requirements for ethanol production using existing CHP technologies. However, its implementation is hindered by higher fuel and capital costs compared to inexpensive natural gas. For instance, one facility reverted to natural gas after investing in biomass gasification equipment because the operating costs of biomass CHP were significantly higher, adding approximately $0.18 per gallon of ethanol.[275] Current research, such as Lincolnway Energy's project funded by DOE's Bioenergy Technologies Office, is exploring biogas technologies that utilize stillage and corn stover to reduce the carbon intensity of a 90-million-gallon ethanol plant.[276] Replacing natural gas with RNG from manure biogas presents another substantial emission reduction opportunity, as highlighted in the RFA roadmap. Although this report conservatively assumes a maximum 35% share of biofuels in the fuel mix for ethanol manufacturing by 2050 in the Core Near Zero pathway, a 2021 study[277] estimates that if a higher adoption rate of 50% is assumed, direct emissions from ethanol refining could be reduced by 31% with biomass and 39% with RNG.

Additionally, multiple low-carbon feedstock technologies are currently in RDD&D stages that are not included in the presented decarbonization pathways. These technologies encompass lignocellulosic fermentation, syngas fermentation, and electrochemical production from CO_2. Lignocellulosic fermentation, or "second-generation ethanol," has garnered significant research and policy support over the past 20 years. Although it has been deployed at a commercial scale, widespread adoption remains limited, with production volumes under 1% of national capacity. This process uses waste or residue biomass, offering potential life cycle emission reductions by minimizing concerns over fertilizer emissions and land use without directly competing with food resources. However, it is more expensive and energy-intensive than first-generation corn ethanol due to the additional pre-processing step of enzymatic hydrolysis required to convert lignocellulosic biomass into sugars, followed by conventional ethanol production processes. Ongoing research aims to overcome technical barriers to make cellulosic ethanol more cost-effective. For example, Project SaFFiRE, funded by DOE's Bioenergy Technologies Office, is demonstrating low-emission ethanol production from corn stover, which can be upgraded to SAF.[278] Syngas fermentation has reached high maturity level, with a joint venture between LanzaTech and Shougang Group focused on anaerobic fermentation of off-gases from steel mills and municipal solid waste. Although

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[273] Ed Rightor et al., *Industrial Heat Pumps: Electrifying Industry's Process Heat Supply with Industrial Heat Pumps* (American Council for an Energy-Efficient Economy, 2022), www.aceee.org/research-report/ie2201.
[274] Laszlo Hegely and Peter Lang, "Reduction of the energy demand of a second-generation bioethanol plant by heat integration and vapour recompression between different columns," *Energy* 208, (October 2020), doi.org/10.1016/j.energy.2020.118443.
[275] Isaac Emery, *Pathways to Net-Zero Ethanol: Scenarios for Ethanol Producers to Achieve Carbon Neutrality by 2050*, Informed Sustainability Consulting (2022), d35t1syewk4d42.cloudfront.net/file/2146/Pathways%20to%20Net%20Zero%20Ethanol%20Feb%202022.pdf.
[276] Luke Geiver, "Two Fuels, One Place," Ethanol Producer Magazine, April 9, 2023, ethanolproducer.com/articles/two-fuels-one-place-20080.
[277] Hui Xu, Uisung Lee, and Michael Wang, "Life-cycle greenhouse gas emissions reduction potential for corn ethanol refining in the USA," *Biofuels, Bioproducts and Biorefining* 16, 3 (February 2022): 671–681, doi.org/10.1002/bbb.2348.
[278] U.S. Department of Energy. "With BETO Support, SAFFiRE Renewables Breaks Ground on Sustainable Aviation Fuel Production Pilot Plant." September 3, 2024. www.energy.gov/eere/bioenergy/articles/beto-support-saffire-renewables-breaks-ground-sustainable-aviation-fuel.

challenges persist, such as low productivity rates due to gas-liquid mass transfer limitations, published life cycle analyses[279,280] indicate that this process could reduce GHG emissions by over 60% compared to conventional gasoline. Finally, electrochemical ethanol production from CO_2 is currently at low maturity. Northern Illinois University is leading a project on the scalable integration of CO_2 capture and electrocatalytic conversion, funded by DOE.[281]

CCUS: Corn fermentation to ethanol produces high-purity CO_2 (>99%) from a single point source at the fermentation vessel. CO_2 from ethanol fermentation requires minimal processing and can be captured and compressed at a low cost. DOE's *Pathways to Commercial Liftoff: Carbon Management* report[282] places the cost of CCUS at ethanol plants between $18 and $26 per metric ton, with a U.S. Government Accountability Office report[283] also estimating the costs to be below $35 per metric ton. Commercial CO_2 capture technologies have been available and in use for many years. Between 2005 and 2019, CO_2 capture rates at U.S. ethanol plants increased by 63%.[284] Today, approximately one-quarter of ethanol facilities capture CO_2, making ethanol production the leading industrial subsector in capturing CO_2 and supplying it to the economy.[285]

If all U.S. ethanol plants captured and sequestered their fermentation emissions, approximately 45 MMT CO_2 emissions could be reduced annually. This is roughly double the combustion emissions reported for the entire U.S. cement subsector in 2018 and represents about 14% of the total GHG emissions from the entire chemicals subsector in the same year. Although few ethanol sites have commercially integrated CCUS today, with most CO_2 being supplied to the food-grade CO_2 market, at least 34 ethanol facilities are in advanced stages of development with integrated CCUS.[286] Summit Carbon Solutions is developing a project to collect CO_2 from more than 30 U.S. ethanol plants for geological storage in North Dakota.[287] Other relevant projects include Red Trail Energy, Blue Flint, White Energy, Alto Ingredients, One Earth Energy, Marquis Energy, Great Plains Inc., and Carbon America.[288,289]

Under the carbon accounting system used in this model, these fermentation emissions are considered biogenic because they originate from corn, meaning that their capture results in negative emissions potential. The installation of new capture equipment is estimated to contribute 60%–66% of U.S. ethanol manufacturing's decarbonization potential from 2018 to 2050 across all decarbonization pathways. However, carbon capture depends on the development of transportation and storage infrastructure, as most midwestern ethanol facilities are not co-located with geologic sequestration sites. Current policies incentivize these developments; federal tax incentives passed in 2017 help cover these costs. Moreover, biofuels sold in California for transportation that are associated with geologic CO_2 storage can earn additional incentives of nearly $200 per metric ton of CO_2 through the Low Carbon Fuel Standard marketplace. Given these incentives and synergies, biofuel facilities are poised to lead the near-term growth of CO_2 capture in the United States.[290] While challenges remain, capturing fermentation emissions is one of the most impactful and cost-effective actions an ethanol producer can take.

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279 Ademola Owoade et al., "Progress and development of syngas fermentation processes toward commercial bioethanol production," *Biofuels, Bioproducts and Biorefining* 17, 5 (February 2023): 1328–1342, doi.org/10.1002/bbb.2481.
280 Robert M. Handler et al., "Life Cycle Assessments of Ethanol Production via Gas Fermentation: Anticipated Greenhouse Gas Emissions for Cellulosic and Waste Gas Feedstocks," *Ind. Eng. Chem. Res.* 55, 12 (December 2015): 3253–3261, doi.org/10.1021/acs.iecr.5b03215.
281 U.S. Department of Energy, *CX-102101: Scalable Integration of CO_2 Capture and Electrocatalytic Conversion to Organic Liquids* (2021), www.energy.gov/nepa/articles/cx-102101-scalable-integration-co2-capture-and-electrocatalytic-conversion-organic.
282 U.S. Department of Energy, *Pathways to Commercial Liftoff: Carbon Management* (2023), liftoff.energy.gov/carbon-management/.
283 U.S. Government Accountability Office, *Technology Assessment - Decarbonization: Status, Challenges, and Policy Options for Carbon Capture, Utilization, and Storage* (2022), www.gao.gov/assets/gao-22-105274.pdf.
284 Uisung Lee et al., "Retrospective analysis of the U.S. corn ethanol industry for 2005–2019: implications for greenhouse gas emission reductions," *Biofuels, Bioproducts and Biorefining* 15, 5 (May 2021): 1318–1331, doi.org/10.1002/bbb.2225.
285 U.S. Environmental Protection Agency, "Supply, Underground Injection, and Geologic Sequestration of Carbon Dioxide," November 5, 2024, www.epa.gov/ghgreporting/supply-underground-injection-and-geologic-sequestration-carbon-dioxide.
286 U.S. Government Accountability Office, *Technology Assessment - Decarbonization: Status, Challenges, and Policy Options for Carbon Capture, Utilization, and Storage* (2022), www.gao.gov/assets/gao-22-105274.pdf.
287 Susanne Schill, "Ethanol Producers, Advocates Aim for Net-Zero Ethanol by 2050," Great Plains Institute, December 13, 2021, betterenergy.org/blog/ethanol-producers-advocates-aim-for-net-zero-ethanol-by-2050/.
288 Ibid.
289 Ethanol Producer Magazine, "Carbon America plans CCS projects at 2 Colorado ethanol plants," May 11, 2022, ethanolproducer.com/articles/carbon-america-plans-ccs-projects-at-2-colorado-ethanol-plants-19256.
290 Sustainable Development Solutions Network, *Roadmap to 2050: The Land-Water-Energy Nexus of Biofuels* (2021), www.unsdsn.org/resources/roadmap-to-2050-the-land-water-energy-nexus-of-biofuels/.

However, even with baseline bioenergy with carbon capture and sequestration rates only seeing slight increases by 2050, net zero emissions could still be achieved under the CNZ–Low CCUS sensitivity through aggressive energy efficiency improvements, electrification, and adoption of low-carbon fuels. Finally, due to the relatively small size of ethanol facilities compared to larger chemical manufacturing plants and boilers, capturing combustion-related emissions from ethanol production is not as cost-effective and is not considered for CCUS in any pathway.

4.2.3.10 Remaining Chemicals

As mentioned above, a selection of cross-cutting decarbonization strategies is considered for the remaining U.S. chemicals subsector. The remaining chemicals were not modeled with the same level of detail as the other chemicals. As such a GHG Reduction Scenario is presented, see Figure 39, as opposed to a CNZ pathway. Due to the heterogeneity of the sector, this analysis of the remaining chemicals only broadly assesses GHG reduction potential with more modest assumptions around implementation of decarbonization measures and does not look at process specific technology turnover. Figure 39 illustrates the annual GHG emissions reductions from 2018 to 2050 for the remaining chemicals production. GHG emissions from the remaining chemicals are projected to decrease to approximately half of their 2050 levels compared to the BAU scenario. Details on the assumptions for the remaining chemicals model can be found in Table C-15 in Appendix C.

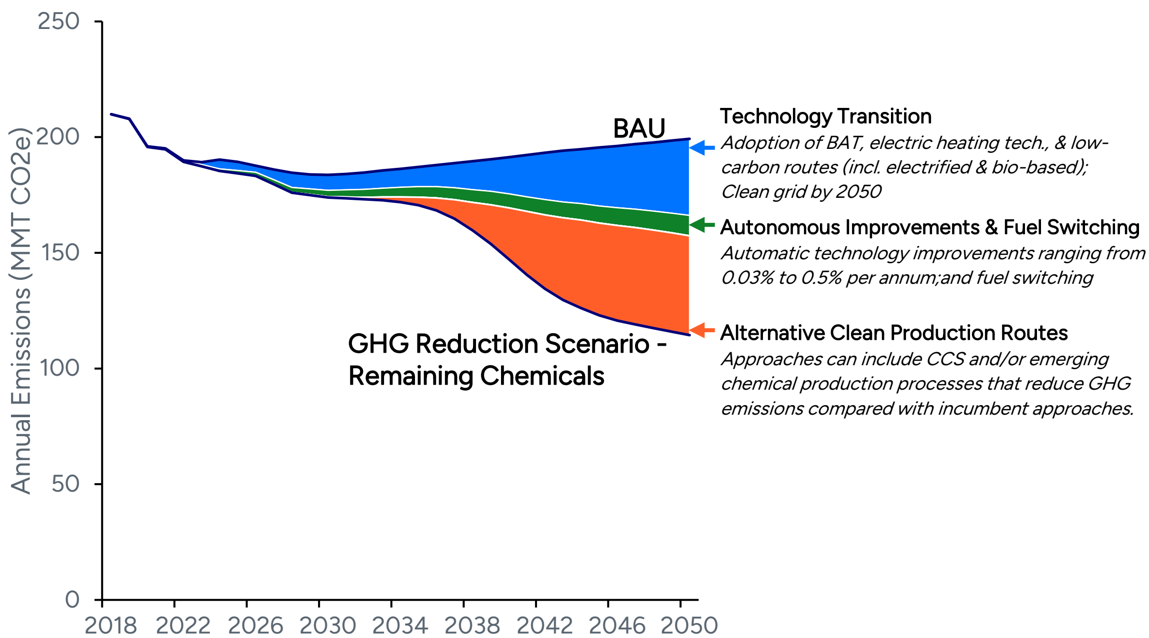


Figure 39. Annual GHG emissions reductions, remaining U.S. chemicals production (MMT CO_2e/year), 2018–2050

Note: The adoption of nascent production technologies for the remaining chemicals can drastically change the decarbonization potential and shape of the alternative clean production area. This analysis only considered modest of adoption of CCS as a clean chemicals production intervention. Additionally, the impact of demand reduction was not evaluated. Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C (see Table C-15). Source: Transformative Pathways modeling.

For the remaining chemicals, this study applies energy efficiency improvement rates consistent with those used in the deep dives for the other modeled chemicals, ensuring a unified approach across all chemical models. This is complemented by maintaining consistent levels of grid decarbonization, reinforcing the potential for reduced emissions footprints. In terms of electrification, this analysis adopts a conservative assumption that only 20% of steam demand will be electrified through electric boilers and HTHPs by 2050. This reflects the understanding that, although the technical barriers to electric steam generation are surmountable, significant economic challenges remain. Currently, U.S. industrial electricity prices are roughly four to five times higher than those of inexpensive natural gas (per equivalent energy unit), highlighting the need for more competitive electricity-to-fuel price ratios. However, if grid-purchased electricity becomes substantially decarbonized and the price differential between electricity and natural gas narrows, the chemicals subsector may experience higher levels of electrification in the future.

Moreover, the assumptions applied in this model regarding RNG and hydrogen as a fuel are consistent with those in other chemical models, ensuring alignment in the drivers and barriers to their adoption across chemicals production. The adoption of alternative clean production routes can have significant impact. The *Transformative Pathways* modeling assumed the implementation of CCUS and adopts a conservative capture rate of up to 30% by 2050 for the remaining chemicals. This cautious approach is justified by the lack of detailed investigations into process-specific measures for these chemicals, highlighting the need for careful consideration before relying on CCUS as a last resort. Overall, the assumptions and their impacts on the chemicals subsector strike a careful balance between optimism for technological advancements and a pragmatic assessment of current techno-economic realities.

4.2.4 Aggregated Near Zero Pathways for U.S. Chemicals

The CNZ pathway for the entire chemicals subsector by 2050 aims for near zero emissions by 2050, with a significant reduction from projected BAU levels. It is important to note that capturing large quantities of pure CO_2 from the fermentation process in ethanol production significantly contributes to emissions reduction, given the high volume of ethanol produced in the United States. This influences the CCUS pillar's contribution to overall decarbonization of the chemicals subsector. However, because ethanol manufacturing is unique in several respects, two perspectives are presented below: results for eight of the chemicals modeled (excluding ethanol) in Figure 40 and the whole chemicals subsector (including ethanol) in Figure 41, to clearly highlight which pillars contribute most to decarbonization in the chemicals subsector without ethanol. Similarly, due to the limited focus on decarbonization opportunities for the 'remaining chemicals' manufacturing, high emissions from the rest of the chemicals subsector reduce the impact of the decarbonization technologies analyzed for the eight major chemicals (excluding ethanol). Therefore, Figure 40 isolates the impact of decarbonization pillars for these eight chemicals, presenting both perspectives: with and without ethanol and the remaining chemicals subsectors.

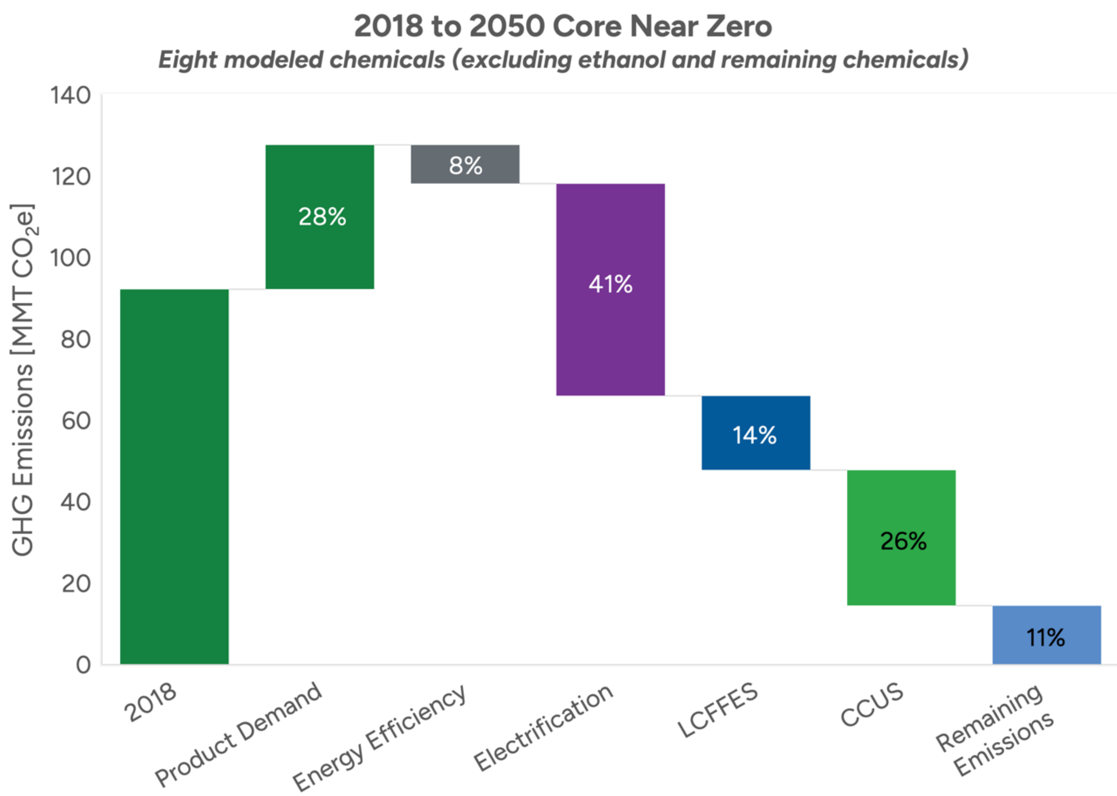


Figure 40. Impact of decarbonization pillars on GHG emissions, eight of the U.S. chemicals modeled (without ethanol and remaining chemicals)–Core Near Zero pathway (MMT CO_2e), 2018–2050

Chemicals included: methanol, ethylene, propylene, butadiene, BTX aromatics, chlorine, soda ash, and ammonia. This figure may differ from the associated Roadmap figure due to further modeling considerations and additional chemicals modeled. Details on assumptions, parameters, and timing of transformative technology application can be found in the Appendix C. Source: Transformative Pathways modeling.

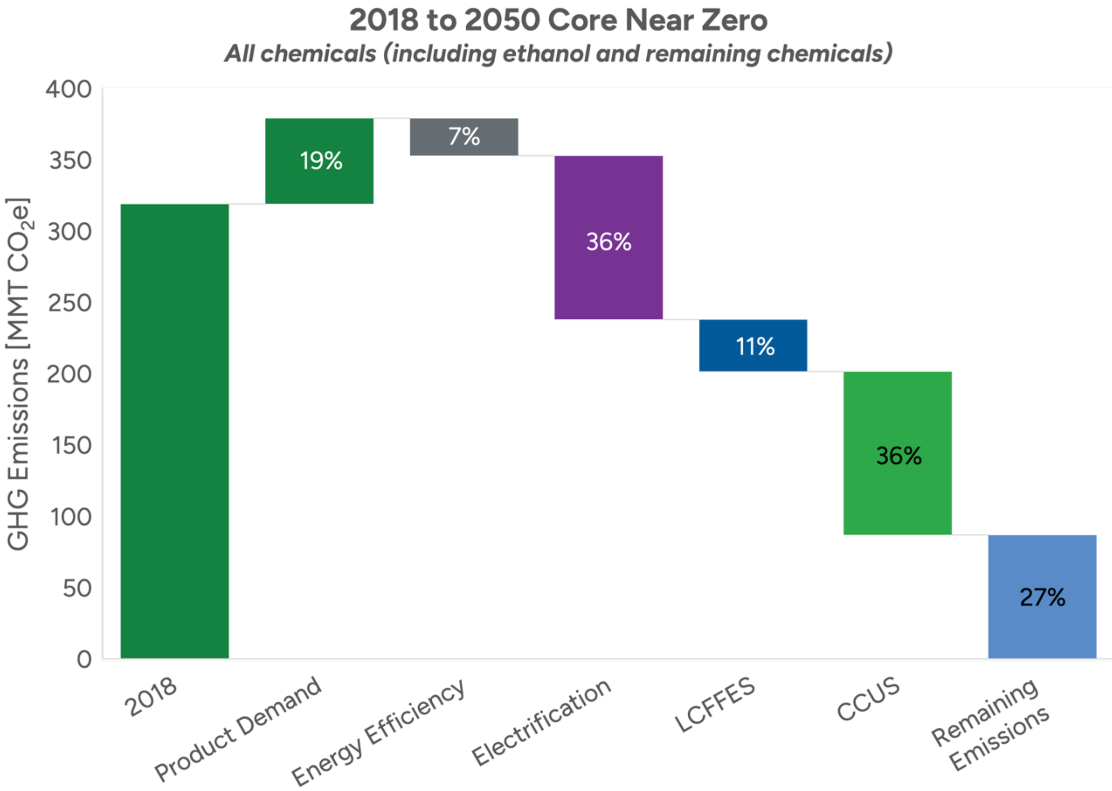


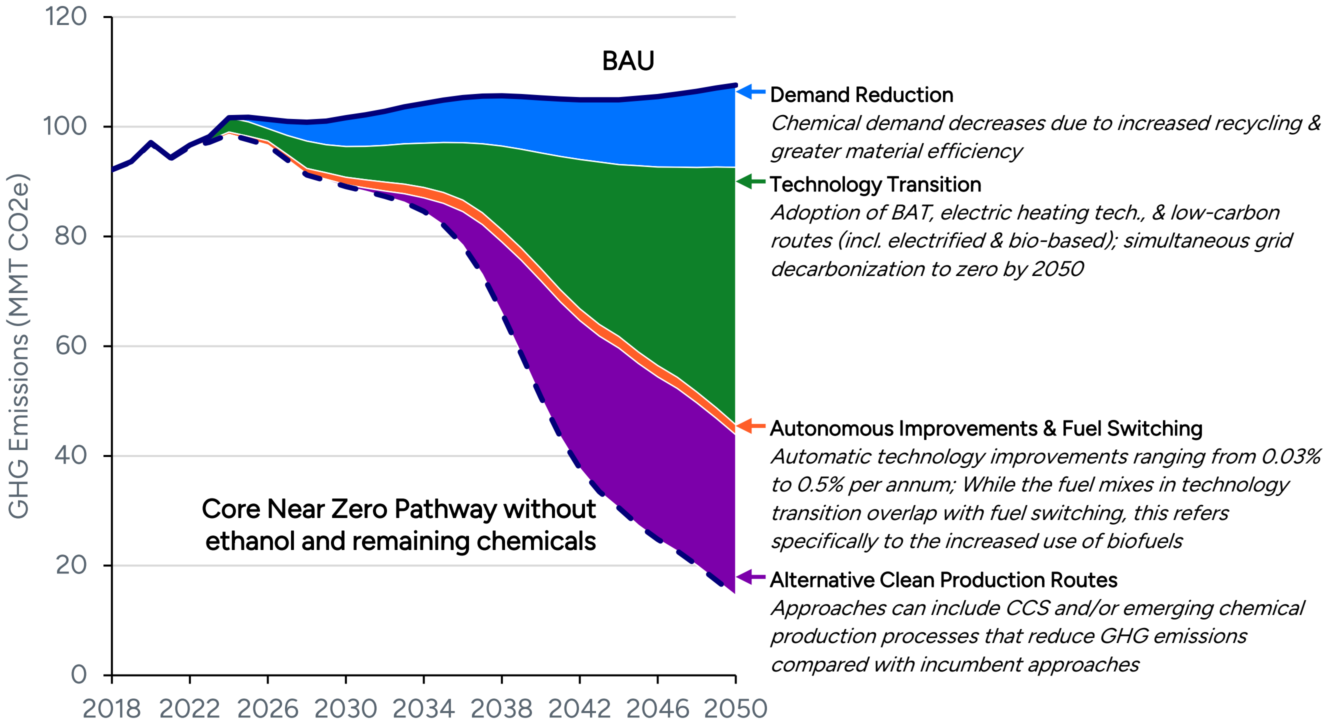
Figure 41. Impact of decarbonization pillars on GHG emissions, all of U.S. chemicals manufacturing (including ethanol and remaining chemicals)–Core Near Zero pathway (MMT CO_2e), 2018–2050

This figure may differ from the associated Roadmap figure due to further modeling considerations and additional chemicals modeled. Details on assumptions, parameters, and timing of transformative technology application can be found in the Appendix C. Source: Transformative Pathways modeling.

The results show significant differences, illustrating the potential contribution of various pillars to emissions reductions by 2050 compared to the 2018 baseline: energy efficiency (8%), electrification (41%), LCFFES (14%), and CCUS (26%).

However, when the entire chemicals subsector is analyzed without exclusions, electrification and CCUS emerge as equal contributors to emissions reductions, each accounting for 30% of the total reduction by 2050 (Figure 41). The overall goal for the chemicals subsector is to achieve annual emissions of 87 MMT CO_2e by 2050, representing a reduction of over 75% from the projected 380 MMT CO_2e in the BAU scenario. When ethanol and the remaining chemicals are excluded (Figure 40), the potential emissions reduction is estimated at just under 90%, from the projected annual emissions of 128 MMT CO_2e in the BAU scenario.

Achieving near zero emissions within the chemicals subsector requires comprehensive efforts across all of chemicals production and decarbonization pillars. Figure 42 illustrates the total annual emissions of the modeled chemicals and the effects of decarbonization interventions to go form the BAU scenario to the CNZ pathway, making a clear distinction between the inclusion of ethanol and remaining chemicals. However, as discussed earlier, ethanol production has significant scope 3 emissions associated with it, hence these results should not be misconstrued, for the reasons explained in the ethanol section (see Section 4.2.3.9).



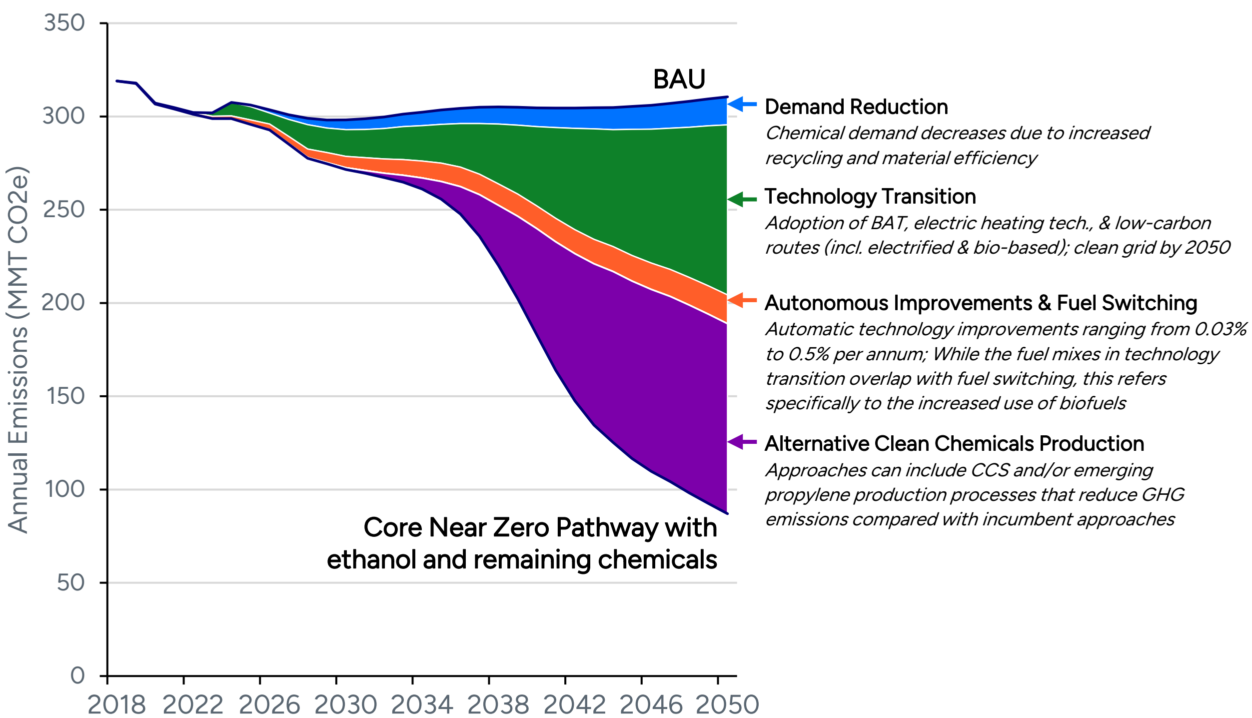


Figure 42. Annual GHG emissions reductions, U.S. chemicals manufacturing–Core Near Zero pathway (MMT CO_2e/year), 2018–2050, without ethanol and remaining chemicals (top) and with ethanol and the remaining chemicals (bottom)

Top figure includes eight of the modeled chemicals (methanol, ethylene, propylene, butadiene, BTX aromatics, chlorine, soda ash, and ammonia). Ethanol is excluded since has significant associated scope 3 emissions, hence these results should not be misconstrued for the reasons explained in the ethanol section (see Section 4.2.3.9). Source: Transformative Pathways modeling.

4.2.5 Key Takeaways

Decarbonizing the U.S. chemicals subsector with the goal of near zero GHG emissions requires adoption of specific manufacturing pathways and technologies. This transition involves shifting energy- and emissions-intensive processes toward low-carbon solutions, with a focus on enhancing energy and resource efficiency. This analysis has evaluated how advancements and best practices can effectively reduce energy demand and emissions while supporting economic growth, in line with the goal of near zero emissions.

Nine key chemicals were modeled that account for approximately 40% of the GHG emissions from the subsector. Decarbonization interventions were explored that involved demand reduction potential, transitioning to alternative production routes, energy efficacy, and fuel switching. Each chemical modeled had its own distinct takeaways, summarized by pillar in Section 4.2.3 above.

Broadly speaking, the greatest effects were seen through transitioning to the identified new production routes and through adopting additional clean production routes, which were represented as CCUS in the model. Transitioning to these new production routes (those included in the model and nascent production routes not included) will have key challenges that need to be addressed.

- **Transitioning to low-carbon manufacturing:** Overcoming challenges in shifting from energy-intensive processes while ensuring that alternative cleaner pathways for all co-products develop at a similar pace.
- **Water stress:** Emerging industrial processes, such as large-scale electrolysis and bio-feedstock production, require careful planning for water usage and resource availability.
- **Plastic waste management**: The diversity of plastics, combined with single-stream recycling in the United States, leads to contamination and reduced plastic quality. High costs and complexities further hinder high recycling rates.
- **Retrofitting challenges:** Chemical facilities face significant downtime, costs, and compatibility issues due to the high degree of integration of unit operations when retrofitting for decarbonization.
- **Energy efficiency improvements:** Internal capital limitations, competing projects, retrofitting risks, and logistical challenges, such as space constraints, pose obstacles to enhancing energy efficiency.
- **Electrification demands:** Transitioning chemicals subsectors to electrified processes will increase the demand for clean electricity, requiring grid capacity and infrastructure upgrades.
- **Competition with low-cost fossil fuels:** Low-cost fossil fuels hinder the adoption of electrified technologies and alternative fuels, such as clean hydrogen and RNG, despite their significant potential to reduce emissions by 2050.
- **Supply chain disruptions:** Decreases in demand for gasoline and natural gas can impact the availability and cost of chemical feedstocks. Developing resilient supply chains that adapt to these disruptions is essential toward preparing the subsector for a market-wide adoption of LCFFES.
- **CCUS adoption:** Widespread adoption of CCUS faces challenges due to high costs, regulatory uncertainties, and the need for extensive infrastructure and CO_2 transport systems.

Furthermore, this analysis outlines key milestones for the U.S. chemicals subsector to track progress and guide the subsector toward achieving 2050 emissions reduction goals. The associated modeling used for this report will be regularly updated to incorporate new advancements and adjust strategies as needed. To support U.S. chemicals subsector decarbonization, the following key takeaways are provided for all stakeholders (some of which are also applicable to other subsectors):

- **Establish plant-level benchmarking schemes:** To advance sustainability in the chemicals subsector, public-private partnerships should establish plant-level benchmarking schemes that focus on energy performance and GHG reduction targets. Fiscal incentives can encourage widespread adoption of these schemes. DOE and EPA could collaborate to set ambitious yet achievable emission reduction targets, with regular updates to incorporate technological advancements and market changes. These targets should be flexible to account for varying operational scales and regional differences, ensuring effective tracking of progress and accountability.
- **Prioritize decarbonization of high-volume, emissions-intensive chemicals production:** Investments in RDD&D, risk mitigation, and public-private partnerships can support the transition of emissions-intensive processes to low-carbon alternatives, as outlined for each chemicals subsector (see Table 9). For instance, technologies and policies that facilitate electrification—such as the scaling of electrolyzer technologies—

and the use of low-carbon fuels and feedstocks are essential for decarbonizing the nine high-volume, energy-intensive platform chemicals studied.

- **Apply a holistic approach to RDD&D:** To transition the chemicals subsector to a low-emissions future, it is essential to navigate its complexity, process integration, and intricate supply chain interdependencies. This transformation requires a multifaceted approach, incorporating the various parallel technology pathways outlined in this report. A key challenge is the energy-intensive co-manufacturing of chemicals through processes like steam cracking, where shifting to low-carbon alternatives for one product can disrupt the entire supply chain. Therefore, a holistic strategy is needed, combining policymaking and RDD&D efforts to develop and deploy low-carbon solutions across all interdependent chemical manufacturing processes. This approach ensures both sustainable growth and the continued flow of supply chains. Additionally, new processes must account for the high optimization of existing chemical properties and supply chains, ensuring product purities and standards are met for seamless integration into downstream processes.
- **Invest in sustainable chemical feedstocks:** Investment in the production of sustainable feedstocks, particularly clean hydrogen, bioethanol, CO_2, and waste biomass, is essential for decarbonizing the chemicals subsector and enhancing competitiveness in chemicals manufacturing. For example, the Hydrogen Shot initiative, which aims to reduce clean hydrogen costs by 80% to $1 per kg, could significantly transform the subsector.[291] However, challenges remain in adopting electrolysis-based hydrogen, particularly due to the higher energy intensity of electrified processes and the need for a low-carbon grid.
- **Improve waste collection and recycling:** Reducing reliance on single-use plastics, except for essential applications, and improving waste management practices are necessary for decreasing plastic waste and achieving the recycling rates outlined in this study. A comprehensive approach should include investments in expanding mechanical recycling, developing chemical recycling technologies, enhancing deposit-return systems, and introducing fiscal measures such as a revenue-neutral plastic consumption levy, with proceeds directed toward addressing plastic pollution.
- **Enhance cross-sectoral collaboration:** Enhancing cross-sector integration can significantly reduce costs through economies of scale and process optimization, while enabling infrastructure sharing. Byproducts from one facility, such as hydrogen from chemical plants or lignin from the pulp and paper subsector, can be repurposed as feedstocks in other subsectors, improving energy and resource efficiency. To maximize these synergies, fostering cross-subsector collaboration and exploring industrial symbiosis opportunities is key. This approach not only drives cost savings but also promotes sustainability across subsectors.
- **Strengthen emissions and life cycle assessments:** Developing LCA tools and data is essential for defining the environmental profiles of chemical products. Transparent LCA information can drive market demand for low-carbon products. Evaluating alternative feedstocks, including their carbon accounting and life cycle emissions, is critical, especially as bio-based pathways are explored. A comprehensive approach, from raw material extraction to end-of-life, will provide a holistic understanding of environmental impacts, guiding informed decisions for sustainable practices in the chemicals subsector.
- **Promote electrification and infrastructure development:** Prioritizing electrification is key to decarbonizing the U.S. chemicals subsector. Key RDD&D efforts should focus on overcoming barriers, improving economics, and scaling up electrified technologies, such as green hydrogen and electrified steam cracking. The expansion of electrified steam generation, including HTHP systems and electric boilers, could meet over 50% of process heat demand. However, these initiatives depend on the decarbonization of the electric grid. Competitive electricity prices and low-carbon grid electricity production are essential to support electrification. At the same time, the increased electricity demand from industrial electrification presents challenges for utilities, necessitating strategic grid management and infrastructure upgrades. Collaborative efforts between industry and utilities are needed to ensure reliable grid operations and facilitate the transition to electrified technologies.
- **Develop CCUS infrastructure:** Effective CCUS deployment requires robust CO_2 emissions regulations, such as tax incentives or emissions trading systems, to encourage investment. Expanding CO_2 transport and storage infrastructure is also critical. Initial efforts should focus on regions like the Gulf Coast, where many

[291] U.S. Department of Energy, "Hydrogen Shot," accessed November 2024, www.energy.gov/eere/fuelcells/hydrogen-shot.

petrochemical facilities are concentrated, to address subsector-specific needs. This can be followed by expanding infrastructure to other regions, leveraging the experience gained from the initial developments.

- **Transition to binding agreements:** Given the long development timelines and high capital and operational costs, policy interventions are needed. Once technologies are proven at scale, policies can help accelerate their deployment, particularly for energy- and emissions-intensive chemical processes. It is recommended to transition to legally binding commitments with technology end-users, moving beyond voluntary agreements, to meet emissions reduction targets. Key prerequisites include scaling clean technologies, providing economic incentives, and offering technical and workforce support.
- **Foster stakeholder dialogue:** A comprehensive dialogue among all key stakeholders—researchers, technology providers, chemicals end-users, and policymakers—is essential to overcoming barriers and promoting the adoption of low-carbon technologies. Although innovation is crucial, a collaborative framework must be developed to ensure both carbon neutrality and global competitiveness. Ongoing monitoring, evaluation, and transparent communication are vital, supported by reliable data. A clear institutional framework is also key to defining responsibilities across the entire value chain, ensuring coordinated and cost-efficient action.
- **Address environmental justice and societal impact:** Environmental and health impacts from chemical manufacturing and pollution have historically harmed disadvantaged communities, particularly those in redlined areas, leading to poorer health outcomes.[292] Decarbonizing the chemicals subsector presents an opportunity to reduce emissions while offering economic, environmental, and health benefits, particularly to workers and local communities. To achieve this, integrating sustainable chemistry[293] and environmental justice perspectives is critical. Low-carbon technologies can improve air quality, reduce land and water use, and lower hazardous waste, while public-private partnerships will drive the necessary innovation. Engaging with local communities and tailoring solutions to specific regional needs is vital for achieving equitable health and economic outcomes. Tools like the EPA's Environmental Justice Screening and Mapping Tool[294] and other environmental justice tools can help guide these efforts.

4.3 Food and Beverage

4.3.1 Introduction

In 2018, the food and beverage manufacturing subsector accounted for 8% of total and 6% of onsite GHG emissions and 10% of primary energy and 9% of onsite energy use for U.S. manufacturing.[295] This subsector will need to make important contributions to reaching net zero industrial sector emissions and is critical because of its role in the economy and projected growth. In contrast to other emissions-intensive manufacturing subsectors that are often concentrated in a few geographic locations, the food and beverage manufacturing subsector is widely dispersed throughout the country, meaning that emissions reductions can benefit a larger number of communities. In 2019, there were over 38,000 food and beverage manufacturing facilities in the United States, with the highest number in California (6,041), New York (2,611), and Texas (2,485).[296]

[292] Eun Kyung Lee, et al., "Health outcomes in redlined versus non-redlined neighborhoods: A systematic review and meta-analysis," *Social Science & Medicine* 294 (October 2021), doi.org/10.1016/j.socscimed.2021.114696.
[293] As defined in the *Sustainable Chemistry Report* (August 2023) by the National Science and Technology Council, sustainable chemistry is the chemistry that produces compounds or materials from building blocks, reagents, and catalysts that are readily-available and renewable, operates at optimal efficiency, and employs renewable energy sources; this includes the intentional design, manufacture, use, and end-of-life management of chemicals, materials, and products across their life cycle that do not adversely impact human health and the environment, while promoting circularity, meeting societal needs, contributing to economic resilience, and aspiring to perpetually use elements, compounds, and materials without depletion of resources or accumulation of waste. www.whitehouse.gov/wp-content/uploads/2023/08/NSTC-JCEIPH-SCST-Sustainable-Chemistry-Federal-Landscape-Report-to-Congress.pdf
[294] U.S. Environmental Protection Agency, "EJSCREEN: Environmental Justice Screening and Mapping Tool," accessed October 2024, www.epa.gov/ejscreen.
[295] U.S. Department of Energy, "Manufacturing Energy and Carbon Footprints: 2018 MECS," accessed October 2024, www.energy.gov/eere/iedo/manufacturing-energy-and-carbon-footprints-2018-mecs.
[296] U.S. Department of Agriculture Economic Research Service, "Food and Beverage Manufacturing," October 9, 2024, www.ers.usda.gov/topics/food-markets-prices/processing-marketing/food-and-beverage-manufacturing/.

Food and beverage manufacturing is essential to the U.S. economy, accounting for $463 billion value add, $1 trillion in sales, and employing over 1.7 million workers in 2021.[297,298] Manufacturing is part of the larger food and beverage supply chain as shown in Figure 43. The full supply chain is comprised of five main stages: agriculture, manufacturing, distribution/transportation, wholesale and retail, and consumption. Post-harvest processing (which falls between the agriculture and manufacturing stages) and warehousing (which falls between manufacturing and wholesale and retail) also account for a non-negligible amount of energy consumption and emissions and for which data is not generally available.

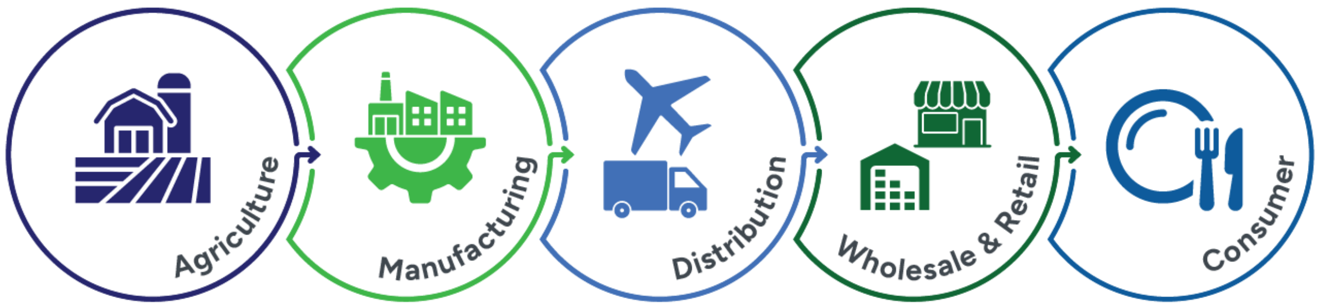


Figure 43. Food and beverage manufacturing is a key stage of the larger interconnected supply chain

It is difficult to determine the energy or emissions intensity of any given supply chain or product due to a combination of the subsector's interconnectedness and heterogeneity, with thousands of facilities nationwide producing vastly different products at vastly different capacities Based on scope and data availability, this report focuses on the manufacturing stage only, with the perspective that we must also consider how the United States will decarbonize the entire food supply chain. Agriculture is discussed as part of other industrial subsectors in Section 4.7.2.

Table 10 provides the energy consumption and emissions for the six modeled food and beverage subsectors in 2018: grain and oilseed milling (NAICS 3112); sugar (NAICS 31131); fruit and vegetable preserving and specialty food (NAICS 3114); dairy products (NAICS 3115); animal slaughtering and processing (NAICS 3116); and beverages (NAICS 3121). The remaining subsectors (not modeled) are accounted for in the seventh category, rest of food and beverage manufacturing. A detailed breakdown of energy end use, energy loss, and emissions for the subsector can be found in the Manufacturing Energy and Carbon Footprint: Food and Beverage.[299]

Table 10. Food and Beverage Manufacturing Subsectors Energy Consumption and Emissions, 2018

NAICS Code	Subsector	Fuel consumption (TBtu)	Electricity consumption (TBtu)	Onsite emissions (MMT CO_2e)	Total emissions (MMT CO_2e)
3112	Grain and Oilseed Milling*	196	50	10	17
31131	Sugar*	102	4	5	5
3114	Fruit and Vegetable Preserving and Specialty Food*	95	34	5	10
3115	Dairy Products*	83	39	5	10

[297] U.S. Census Bureau, "Annual Survey of Manufactures: 2018–2021," accessed October 2024, www.census.gov/data/tables/time-series/econ/asm/2018-2021-asm.html.
[298] U.S. Department of Agriculture Economic Research Service, "Food and Beverage Manufacturing," October 9, October 2024, www.ers.usda.gov/topics/food-markets-prices/processing-marketing/food-and-beverage-manufacturing/.
[299] U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Food and Beverage," (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_food_beverage_energy_carbon_footprint.pdf.

3116	Animal Slaughtering and Processing*	170	108	9	24
3121	Beverage*	65	46	3	9
	Rest of food and beverage manufacturing**	188	82	9	22
311, 312	Food and Beverage Manufacturing Total	899	363	45	96

* Subsectors included in this modeling effort.

** The "rest of food and beverage manufacturing" subsectors that were not modeled (and associated NAICS codes) are confectionary products (NAICS 31134 and 31135); seafood products (3117); bakeries & tortillas (3118); other food (3119); and tobacco manufacturing (3122).

Data sources: U.S. Department of Energy, 2018 Manufacturing Energy Consumption Survey: Food and Beverage Manufacturing Energy and Carbon Footprint, accessed October 2024, www.energy.gov/sites/default/files/2021-12/2018_mecs_food_beverage_energy_carbon_footprint.pdf; U.S. Energy Information Administration, "Manufacturing Energy Consumption Survey (MECS)," accessed October 2024, www.eia.gov/consumption/manufacturing/; U.S. Environmental Protection Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022, EPA 430-R-24-004 (2024), www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.

These six subsectors accounted for 79% of total food and beverage manufacturing onsite energy consumption and 78% of emissions in 2018.[300] Future work may consider the decarbonization pathways for the rest of food and beverage manufacturing (including confectionary products (NAICS 31134 and 31135); seafood products (3117); bakeries & tortillas (3118); other food (3119); and tobacco manufacturing (3122)) and other parts of the food supply chain, although the lack of data availability on actual energy consumption and emissions at the same level as MECS poses a challenge.

4.3.2 Modeling Approach

The *Transformative Pathways* modeling estimated the impacts of the four decarbonization pillars (energy efficiency, industrial electrification, LCFFES, and CCUS) across the six food and beverage manufacturing subsectors highlighted in Table 10, focusing on the decarbonization pathways for end uses available in the baseline data source of MECS 2018. Table 11 provides a summary of key subsector characteristics, including thermal processes and temperature ranges and main decarbonization technologies considered.

[300] See Table 10 notes for references.

Table 11. Food and Beverage Manufacturing Subsectors Modeled

Subsector	Example products	Major baseline energy source(s)	Thermal unit processes and temperature profiles (°Fahrenheit (F))	Main end use decarbonization technologies considered
Grain and Oilseed Milling	Flour, breakfast cereal, vegetable oil, industrial feed, corn syrup	Natural gas	• Hot air: drying (130–625°F) • Steam: evaporation, cooking, dewatering (120–365°F) • Hot water: steeping (120–130°F)	• Steam-intensive subsectors (up to 70% of baseline fuel usage): steam generating heat pumps (SGHPs) will be dominant with some electric boilers. • Major opportunities for drying processes (25%–30% of baseline fuel usage) include advanced electro-heating dryers, electric dryers/ovens, and membrane pre-concentrators
Sugar	Beet sugar, cane sugar, molasses	Natural gas, coal, bagasse	• Hot air: drying (175–195°F) • Steam: evaporation, distillation, heating (130–250°F)	
Fruit and Vegetable Preserving and Specialty Food	Canned fruits and vegetables, fruit preserves, frozen juice	Natural gas	• Hot air: drying (75–160°F) • Steam: pasteurization, sterilization, evaporation, exhausting (120–250°F) • Hot water: cooking (150–212°F)	
Dairy Product	Condensed milk, soy milk, cheese, ice cream, frozen yogurt	Natural gas	• Hot air: drying (up to 480°F) • Steam: sterilization, heating, evaporation (70–275°F) • Hot water: pasteurization (145–165°F)	• Steam-intensive subsector (up to 50% of baseline fuel usage); SGHPs (primary) will be dominant with some electric boilers. • Major opportunities for drying processes (up to 30% of fuel usage) include advanced electro-heating dryers, and electric dryers. • Hot water heat pumps (HWHPs) and electric water heaters applicable for hot water generation (up to 15% of fuel usage)
Animal Slaughtering and Processing	Hot dogs, frozen turkey, bacon, packaged meat	Natural gas, electricity	• Hot air/flame: drying, curing and smoking, singeing (85–1,500°F) • Steam: rendering (240–250°F) • Hot water: scalding, heating, cleaning, pasteurization and sterilization (113–250°F)	• Primarily, HWHPs and electric water heaters applicable for hot water generation (up to 55%–70% of fuel usage)
Beverage	Soft drinks, beer, wine, bottled water	Natural gas, electricity	• Hot air: drying (120–300°F) • Steam: boiling (200–220°F) • Hot water: fermentation, wort mashing, pasteurizing, cleaning (40–220°F)	

See Appendix C for more information on each subsector.

Because food and beverage manufacturing encompasses many different products and is not dependent on specific production routes akin to a subsector like chemicals, this modeling approach focuses on decarbonization options for the energy supply for these end uses, namely steam, hot air, and hot water which account for a majority of subsector energy consumption and emissions. A full breakdown of energy and emissions by process can be found in the Food and Beverage Manufacturing Footprint,[301] but is organized by onsite generation (e.g., boilers, CHP), process energy (e.g., process heating, machine drive), and non-process energy [e.g., facility heating, ventilation, and air conditioning (HVAC)]. The largest energy consuming and emitting processes for food and beverage manufacturing include process heating, machine drive, and onsite steam generation from boilers and CHP. Projected production values were based on extensive food supply chain mass flow analysis work conducted by ORNL and summarized in Appendix C.[302]

Figure 44 shows the fossil fuel consumption to produce steam, hot air, and hot water for the subsector in 2018. Natural gas is overwhelmingly utilized across all process heating mediums, whereas a small proportion of other fossil fuels are employed for heating purposes. As noted in Table 10 and Table 11, the grain and oilseed milling subsector consumes the largest amount of fossil fuel, owing to steam usage in processes such as cooking, conditioning, oil desolventizing, and evaporation. The animal slaughtering and processing subsector consumes the second largest share of fossil fuel energy, within which the largest share of energy consumption is attributed to generating hot water for processes such as cleaning, scalding, pasteurization, and sterilization. The fruit and vegetable manufacturing subsector employ steam as the major process heating medium, followed by low-temperature hot air for processes such as drying and dehydration. Dairy product manufacturing utilizes steam for sterilization and evaporation, and hot air dryers for drying and atomizing processes. Sugar manufacturing typically utilizes steam for evaporation and distillation, and hot air dryers to produce sugar crystals. The beverage manufacturing subsector uses hot water as the major process heating medium for processes such as fermentation, pasteurizing, and cleaning.

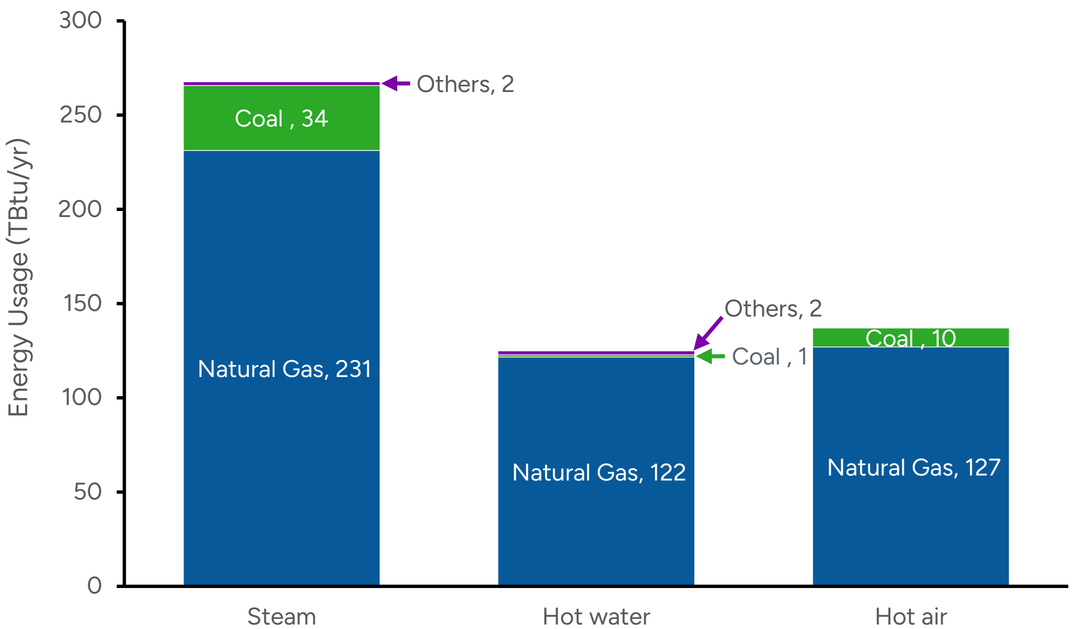


Figure 44. Breakdown of fossil fuel usage type for process heating mediums, such as steam, hot water, and hot air in food and beverage manufacturing

"Others" include fuels such as distillates, diesel, and hydrocarbon gas liquids. See Appendix C for details and references.

Literature review was conducted to identify the applicable thermal unit processes, estimated temperature ranges, required heating mediums (hot water, steam, and hot air), and fuel breakdown by subsector to better define the process heating, boilers, and CHP categories from MECS and determine the most applicable decarbonization solutions. As shown in Figure 45, most food and beverage manufacturing process fuel

[301] Ibid.

[302] References for this food loss and waste work include U.S. Department of Energy, *Sustainable Manufacturing and the Circular Economy*, by Kristina Armstrong et al., DOE/EE-2696 (January 2023), www.osti.gov/biblio/1963668.; Dong et al., "A framework to quantify mass flow and assess food loss and waste in the US food supply chain." *Communications Earth & Environment* 3, 1 (April 2022). www.osti.gov/biblio/1861231; and U.S. Department of Agriculture, "Loss-Adjusted Food Availability Documentation," November 12, 2020, www.ers.usda.gov/data-products/food-availability-per-capita-data-system/loss-adjusted-food-availability-documentation/.

consumption fall in the low and medium temperature ranges (below 212°F). Overall, the subsector utilizes majority of energy to support processes such as drying and heating.

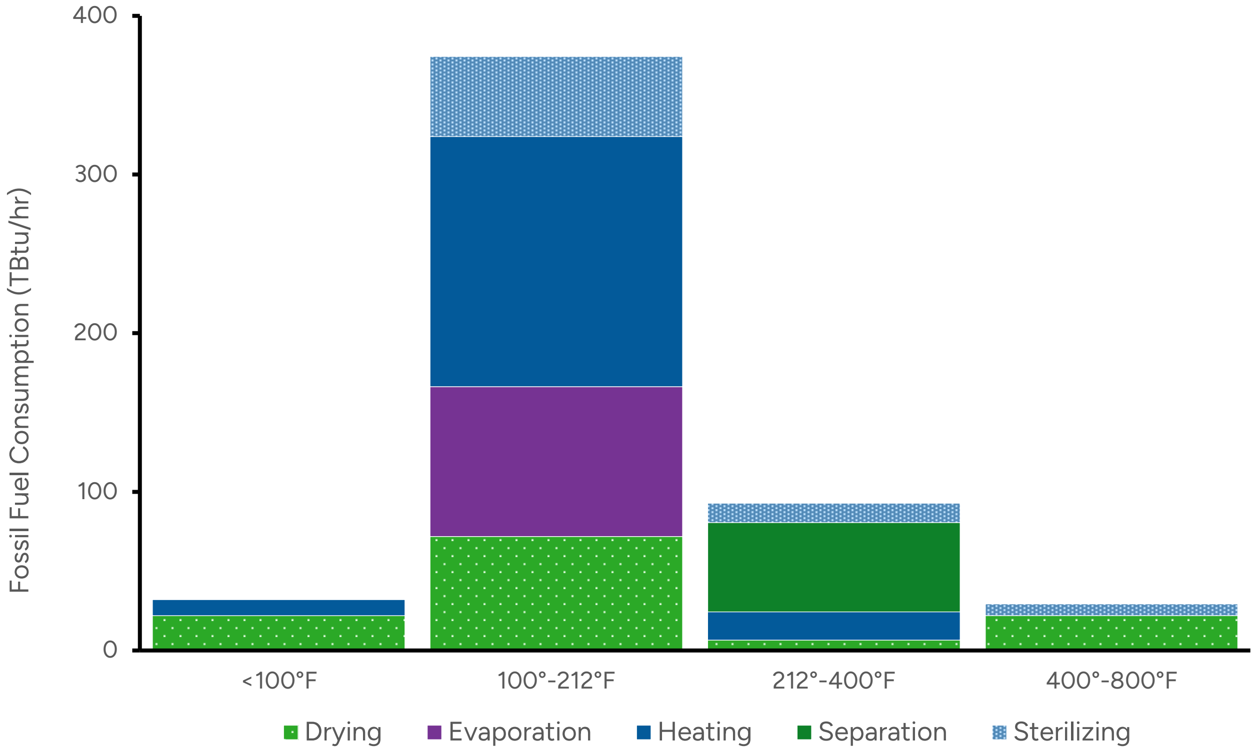


Figure 45. Food and beverage thermal process fossil fuel consumption for defined temperature ranges, 2018

Literature review was conducted to identify the applicable thermal unit processes, estimated temperature ranges, required heating mediums (hot water, steam, and hot air), and fuel breakdown by subsector to better define the EIA MECS process heating, boilers, and CHP categories. See Appendix C for details and references.

Figure 46 provides an overview of the modeling framework for food and beverage manufacturing. For this subsector, energy efficiency can be considered as a priority pillar due to significant opportunities for boilers, dryers, and machine drives such as air compressors, pumps, fans and refrigeration compressors. Although, all the listed opportunities in the framework are important, refrigeration-based energy efficiency opportunities are unique to the subsector as there is a large need for cooling and refrigeration of materials prior to, during, and after the manufacturing process. Further advanced opportunities such as process integration through pinch analysis have an integral role in incorporating heating and cooling processes to reduce corresponding end-use energy requirements. This is followed by electrification, LCFFES for remaining fuel needs, and CCUS for instances where a large enough remaining emissions output exists.

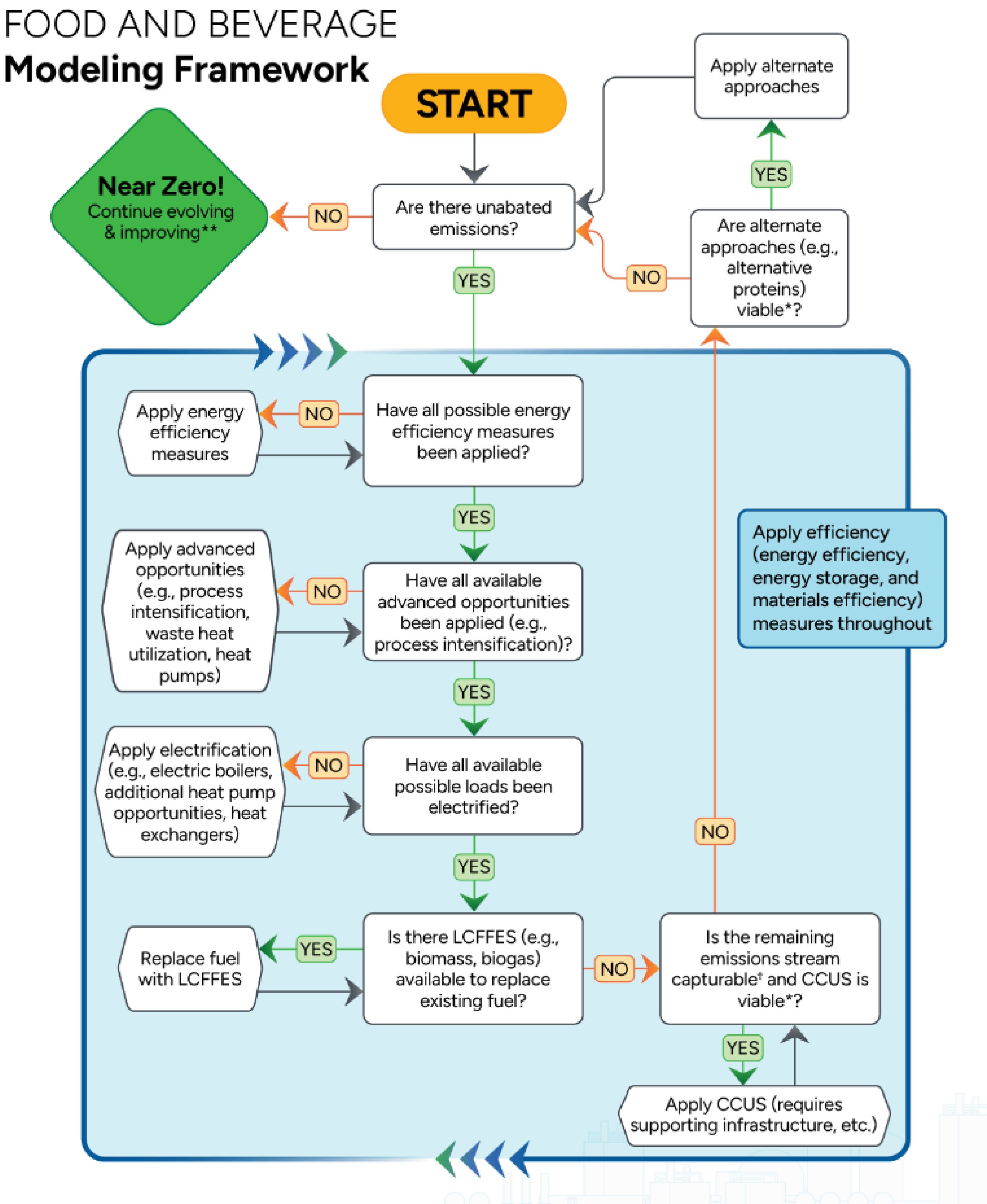


Figure 46. Food and beverage manufacturing decarbonization modeling framework

4.3.3 Subsector-Specific Sensitivities

Between the 2018 baseline and 2050, the *Transformative Pathways* modeling explored a wide range of variables surrounding the four decarbonization pillars across the six focus food and beverage manufacturing subsectors. This helped identify key levers that represent the most significant decarbonization impact. The impacts of these variables were adjusted to investigate sensitivities over a range of scenarios, from BAU to the most aggressive yet plausible near zero pathways for the food and beverage manufacturing. The anticipated impacts of variables can be further adjusted as appropriate to refine the model and reflect additional information or data as they become available. Below is not a complete list of all the subsector-specific sensitivities that are investigated, but it represents some of the most impactful on the modeled results. These are in addition to the sensitivities covered in Section 3.2.2.

Lower maturity technologies: Advanced electro-heating technologies such as infrared drying and heating, microwave and ohmic heating, radio frequency drying and heating, and membrane pre-concentrators are less mature compared to technologies like heat pumps. Further, they do not offer as significant of an energy efficiency improvement as heat pumps. As a consequence, less mature technologies are assumed to have a relatively lower market share by 2050. Although these technologies have high potential to reduce energy usage, uptake is expected to be low because they are further from commercialization and adoption and they may be limited to only specific processes.

Alternative LCFFES: Because most food and beverage manufacturing processes fall in the low and medium temperature range (see Figure 45), electrification technologies and energy efficiency measures are expected to address most, if not all, of these operations. However, LCFFES is still a key decarbonization lever especially for addressing subsector emissions for harder-to-electrify processes. Certain food and beverage manufacturing subsectors already consume a portion of LCFFES, namely sugar manufacturing which uses bagasse as a fuel and grain and oilseed milling, animal slaughtering and processing, and beverage manufacturing subsectors which utilize some wood chips and bark as fuel. In general, applicable LCFFES for this subsector would likely include a mix of hydrogen, biomass, biofuels, biogas, and solar-thermal power. This sensitivity focuses on the impacts of adjusting the level of LCFFES adoption across the subsector. Continued analysis is planned to further disaggregate low-carbon fuel applicability and availability by food and beverage manufacturing subsector and individual processes.

Changes in consumer demand and consumption: U.S. food and beverage manufacturing is driven by what consumers choose to drink and eat and what is available. Several factors may impact future subsector demand and production. New food options, such as meat alternatives, could change the expected demands and impacts of the food supply chain. Overall changes in consumer habits or behaviors would also have an impact on the demand for manufactured food. One key potential driver of demand change is a reduction in consumer-level generated waste. Although food waste occurs in the initial food supply chain stages (agriculture and manufacturing), most of it is repurposed in some way (e.g., animal feed, industrial uses, land application, anaerobic digestion). Conversely, over 30% of food purchased for consumption ends up wasted, usually in a landfill, an incinerator, or sewer.[303] Other methods of reducing food loss and waste (FLW) include improved packaging materials or design or new processing techniques. This sensitivity focuses on the impacts that food loss and waste reduction or general changes in demand would have on production within the manufacturing stage.

4.3.4 Business as Usual Scenario and Near Zero Pathways

Business as Usual

The BAU scenario leverages projections from the EIA's Annual Energy Outlook 2023 (AEO23).[304] It assumes an adoption rate of energy efficiency measures in line with AEO23's Technology Possibility Curve.[305] It also assumes a low rate of electrification, including slow heat pump adoption, again in line with AEO23's projections and no further increase in the use of LCFFES beyond MECS 2018 levels. No CCUS is assumed as implemented. The BAU sees a steady decrease in emissions until the early 2030s, mostly attributed to energy efficiency measures in process heating, machine drive, and refrigeration, after which the rate of decarbonization is projected to slow. Although there is a decrease in the electric grid emissions factor, the overall emissions will not be affected

[303] Dong et al., "A framework to quantify mass flow and assess food loss and waste in the US food supply chain." *Communications Earth & Environment* 3, 1 (April 2022). www.osti.gov/biblio/1861231.
[304] U.S. Energy Information Administration, "Annual Energy Outlook 2023," 2023, www.eia.gov/outlooks/aeo/.
[305] Average year-on-year energy efficiency improvements between 0.05% and 0.25% were assumed.

significantly as it will be balanced by the growth in production. The CO_2e emissions of the six modeled subsectors decrease by 25% between 2018 (76 MMT CO_2e) and 2050 (57 MMT CO_2e) due to electric grid emissions factor reduction, energy efficiency improvements, and a low level of industrial electrification. This shows the subsector cannot reach near zero GHG emissions by 2050 continuing along the current BAU trajectory.

Core Near Zero Pathway

A near zero or net zero emissions food and beverage manufacturing subsector will require comprehensive decarbonization technology adoption across multiple pillars. The Core Near Zero (CNZ) pathway shown in Figure 47 is ambitious, which assumes high penetration of efficiency and electrification measures along with a fully decarbonized electric grid by 2050. Additionally, the remaining fuel demand is met by LCFFES. In this pathway, the CO_2e emissions of the six modeled subsectors decrease by 99% between 2018 (75.7 MMT CO_2e) and 2050 (0.3 MMT CO_2e). During the same period, total production for these subsectors increases about 19% due to expected growing population demand. Electrification makes the largest contribution to CO_2e emissions reductions followed by energy efficiency. The LCFFES pillar has the next highest contribution, providing a target that the subsector will need to meet after energy efficiency and electrification measures are taken into consideration. CCUS has limited potential in food and beverage manufacturing, as the subsector is comprised of mostly small-scale facilities and lower concentration of point-source CO_2 emissions where CCUS would likely not be considered economical. The remaining less than 1% emissions could be addressed with alternate approaches powered by clean energy sources other than those included in the *Transformative Pathways* modeling (e.g., negative emissions technologies, alternative proteins.

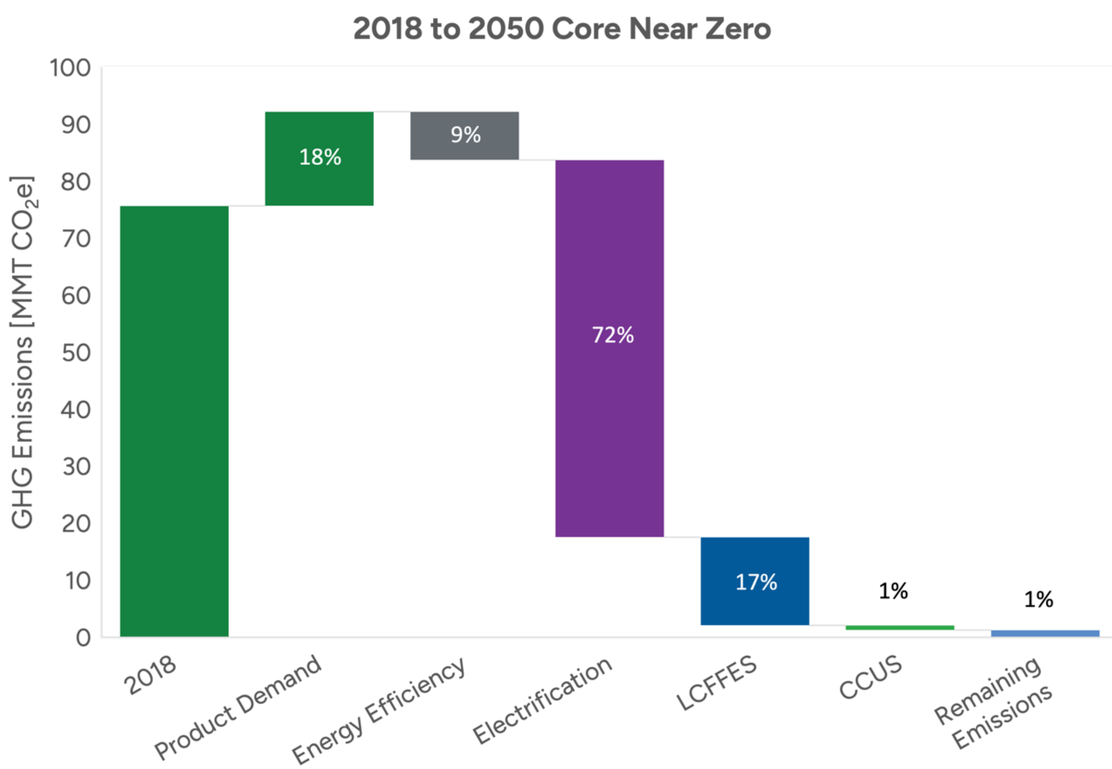


Figure 47. Impact of decarbonization pillars on GHG emissions, six U.S. food and beverage manufacturing subsectors–Core Near Zero pathway (MMT CO_2e), 2018–2050

The subsectors modeled are grain and oilseed milling; sugar; fruit and vegetable preserving and specialty food; dairy products; animal slaughtering and processing; and beverages. These subsectors accounted for 79% of energy consumption and 78% of emissions for all of food and beverage manufacturing in 2018 (see Table 10). CCUS is excluded as it is assumed it will not have significant impact. This figure may differ from the associated Roadmap figure due to further modeling considerations and additional food and beverage manufacturing coverage modeled. Details on assumptions, parameters, and timing of transformative technology application can be found in the Appendix C. Source: Transformative Pathways modeling.

Although the CNZ pathway includes assumptions that pertain to all the identified technologies, it is one possible pathway of many. Depending on economic, regulatory, technological availability, and other factors, different pathways may emerge. Further, the CNZ pathway does not encompass pathways that could lead to a further decrease in absolute annual emissions, and therefore, the cumulative emissions through 2050. With this considered, four alternative near zero pathways were modeled and are summarized in the next section and Appendix C.

Alternative Near Zero Pathways

The industrial decarbonization pathways modeled and discussed in this report present high-impact approaches to reducing subsector GHG emissions. These pathways include a strong focus on near-term options (e.g., energy efficiency) that can yield early impacts, expand learning, and enable future strategies. However, resources also should be committed to adoption of transformative technology opportunities in the medium and long term that will be crucial for larger GHG emissions reductions.

Four alternative near zero GHG emissions pathways for food and beverage manufacturing were considered beyond the CNZ. These pathways underscore the impacts of adopting different technologies and improving process efficiencies on the overall annual subsector GHG emissions through 2050. These alternative near zero pathways include:

- Impact of increased LCFFES consumption (CNZ–LCFFES)
- Impact of maximized energy efficiency and other efficiency measures uptake (CNZ–Max Eff)*
- Impact of increased advanced electrification technologies (beyond heat pumps) (CNZ–Adv Elec)*
- Impact of reduced food loss and waste (FLW) (CNZ–FLW)*

* This section includes a comparison of the CNZ–LCFFES pathway to CNZ as it is the most significantly different. The CNZ–Max Eff, CNZ–Adv Elec, and CNZ–FLW pathways have similar trajectories to the CNZ with more minor differences and are detailed in Appendix C. Additional information on methodology, assumptions, and results for all modeled pathways can be found in Appendix C. This report is not a comprehensive review of pathways, scenarios, and associated modeling sensitivities that were run as part of this effort.

A combined view of the modeled annual emissions between 2018 and 2050 by end use (hot water, hot air, steam, and others[306]) compared to BAU is shown below for the CNZ (Figure 48) and CNZ–LCFFES (Figure 49) pathways. The BAU scenario sees a steady decrease in emissions until the early 2030s, after which the rate of decarbonization is projected to slow. Although there will be a decrease in the electric grid emissions factor (see Appendix B), the overall emissions will not be affected significantly as it will be balanced by the growth in production. The initial decrease in GHG emissions for the BAU is mostly attributed to the energy efficiency measures in process heating, machine drives, and refrigeration. As shown in Figure 48 for the CNZ pathway, high adoption of steam-generating heat pumps (SGHPs) account for the largest fuel intensity reduction for steam and hot air, with hot water and other end uses impacted by high adoption of HWHPs. For the CNZ–LCFFES pathway in Figure 49, fuel intensity reductions come from a combination of higher levels of LCFFES consumption and moderate levels of SGHPs and HWHPs adoption. The tables and figures below provide additional detail on the technologies and adoption levels assumed for the pathways.

[306] Other end uses includes machine drive, process cooling and refrigeration, facility HVAC, other process uses, and other nonprocess uses.

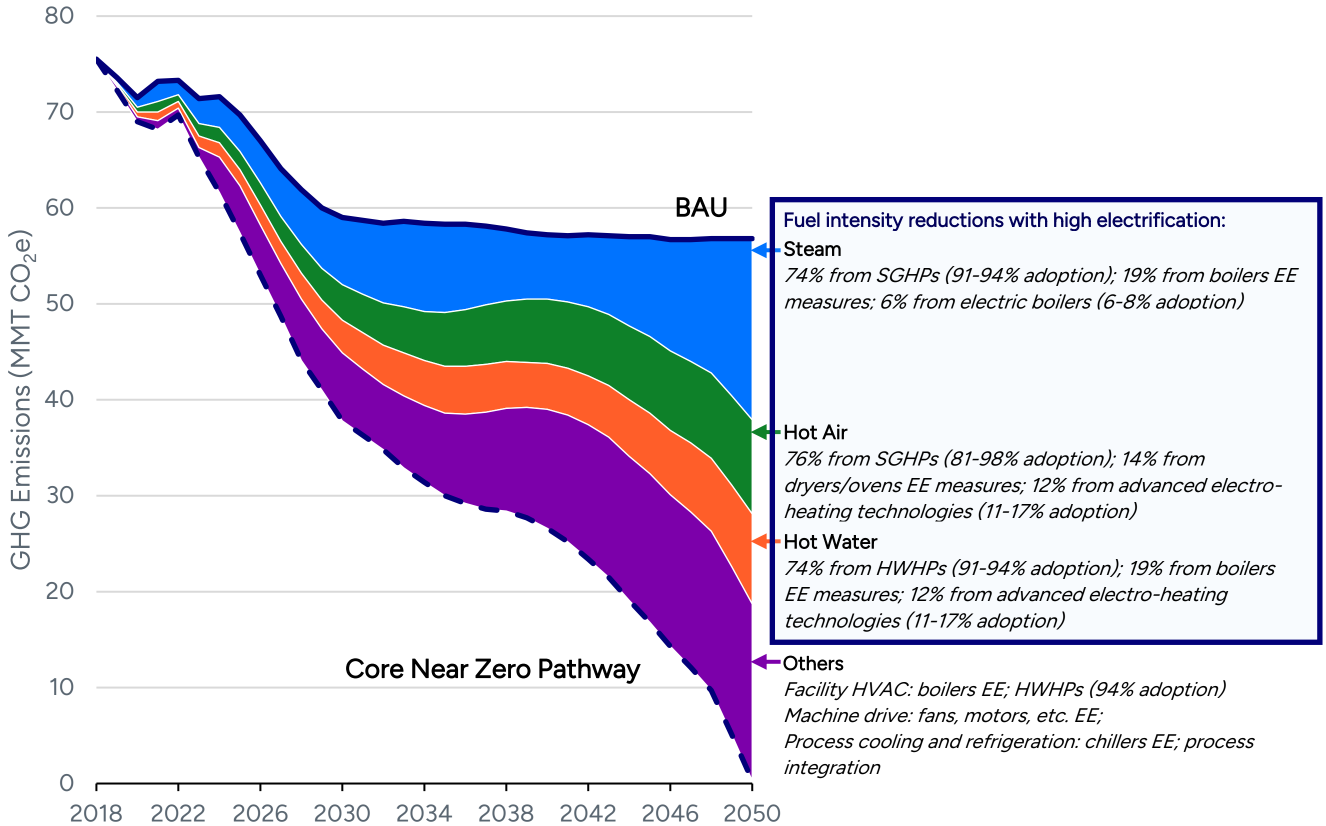


Figure 48. Annual GHG emissions reductions, U.S. food and beverage manufacturing*—Core Near Zero pathway (MMT CO_2e/year), 2018–2050

* The subsectors modeled are grain and oilseed milling; sugar; fruit and vegetable preserving and specialty food; dairy products; animal slaughtering and processing; and beverages. These subsectors accounted for 79% of energy consumption and 78% of emissions for all of food and beverage manufacturing in 2018 (see Table 10). "Others" in the figure includes machine drive, process cooling and refrigeration, facility HVAC, other process uses, and other nonprocess uses. Acronyms/abbreviations: BAU (business as usual), CO_2e (carbon dioxide equivalent), EE (energy efficiency), HVAC (heating, ventilation, and air conditioning), HWHP (hot water heat pump), MMT (million metric tons), SGHP (steam-generating heat pump). Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C. Source: Transformative Pathways modeling.

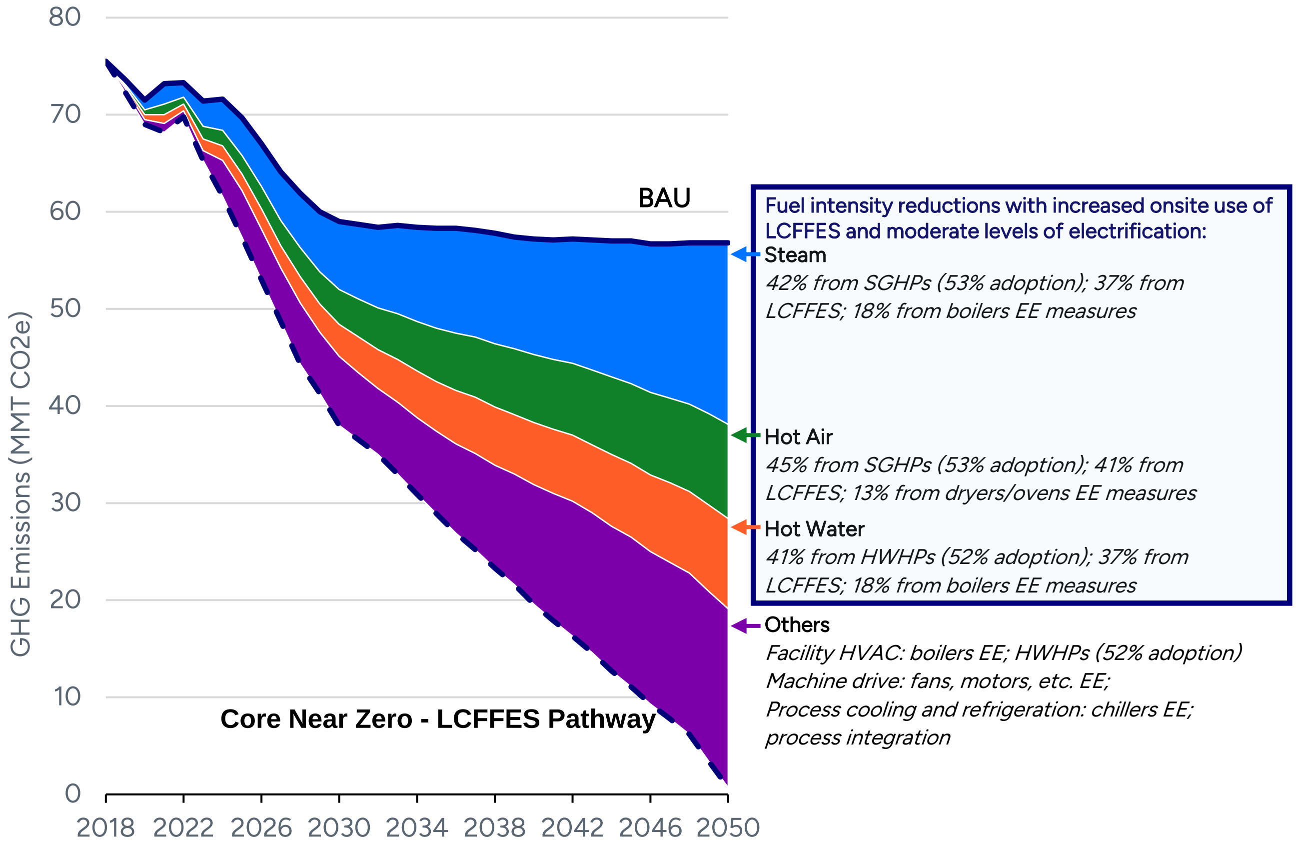


Figure 49. Annual GHG emissions reductions, U.S. food and beverage manufacturing*—Core Near Zero—LCFFES pathway (MMT CO_2e/year), 2018–2050

* The subsectors modeled are grain and oilseed milling; sugar; fruit and vegetable preserving and specialty food; dairy products; animal slaughtering and processing; and beverages. These subsectors accounted for 79% of energy consumption and 78% of emissions for all of food and beverage manufacturing in 2018 (see Table 10). "Others" in the figure includes machine drive, process cooling and refrigeration, facility HVAC, other process uses, and other nonprocess uses. Acronyms/abbreviations: BAU (business as usual), CO_2e (carbon dioxide equivalent), EE (energy efficiency), HVAC (heating, ventilation, and air conditioning), HWHP (hot water heat pump), MMT (million metric tons), SGHP (steam-generating heat pump). Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C. Source: Transformative Pathways modeling.

Table 12 provides an overview of key assumptions for the BAU scenario, CNZ pathway, and CNZ–LCFFES pathway around specific decarbonization technologies and measures as well as the resulting energy consumption share of electricity, LCFFES, and other fuels (such as natural gas, coal, etc.) by 2050. As noted above, the CNZ pathway leans heavily on electrification technologies (especially the use of steam generating and hot water heat pumps) with LCFFES meeting the remaining fuel demand while the CNZ–LCFFES prioritizes use of LCFFES (while also considering there may be availability limitations in the future). More details are provided in the remainder of this section and in Appendix C.

Table 12. Percent Adoption of Technologies Across Food and Beverage Facilities for the BAU Scenario, CNZ Pathway, and CNZ–LCFFES Pathway

Key Assumption	BAU	CNZ pathway	CNZ–LCFFES pathway
Energy efficiency measures (2050 adoption rates)	22%–44%	88%–92%	Same as CNZ
Electrification technologies (2050 adoption rates)			
Steam-generating heat pumps (SGHPs)	8%	81%–94%	53%
Hot water heat pumps (HWHPs)	4%	92%	52%
Electric boilers	1%	6%–8%	3%
Advanced electro-heating technologies	3%	11%–17%	6%
Share of 2050 energy consumption (averaged across the six modeled subsectors)			
LCFFES	6%	8%	35%
Electricity	33%	92%	65%
Other fuels (natural gas, coal, etc.)	60%	0%	0%
Electric grid emissions factor (see Appendix B)	Reduced 67% 2018–2050	Reduced 100% 2018–2050	Same as CNZ

More details on assumptions across pathways can be found in Appendix C. CCUS is not included in these pathways as it is not expected to have signification subsector-wide potential, although there could be opportunities for CCUS to be applied in facilities with large boilers. LCFFES would include a mix of biomass, biogas, hydrogen (mixed with natural gas), and solar thermal. The same production values are assumed for the BAU, CNZ, and CNZ–LCFFES. Some values shown as a range as they vary by subsector and/or end use. 2050 adoption rates are the portion of that technology's share across applicable end uses (e.g., SGHPs are deployed across 81%–94% of steam/hot air demand (varies by subsector and specific temperature range)).

For all pathways, LCFFES adoption in the decades surrounding 2030 is assumed primarily to have drop-in technologies that could employ low-carbon fuels such as biomass, biofuels, and hydrogen. Any hydrogen combustion is assumed to be blended up to a proportion where the existing burners would not require tangible retrofits, whereas biogas is assumed to be combusted with minor changes to the burners such as adjusting the air-fuel ratio. As facilities begin to replace their existing equipment as it approaches end-of-life, various opportunities such as electrification or burners that can combust raw biogas, dual fuels, or higher blends of hydrogen into existing natural gas systems (or standalone hydrogen as source) could be employed. When the transition of existing to newer technologies occurs, it is estimated that the subsector would move primarily toward electrification in all pathways with a portion of remaining fuel demand met by LCFFES, except the CNZ–LCFFES pathway which prioritizes LCFFES use.

The modeled results from Figure 48 and Figure 49 are expanded upon below to show the impact of specific decarbonization technologies and measures on the fuel intensity for steam (Figure 50), hot air (Figure 51), and hot water (Figure 52) for the CNZ and CNZ–LCFFES pathways.[307] In Figure 50 (steam), the fuel intensity reduction by 2050 for the CNZ pathway is attributed to SGHPs (74% of fuel intensity reduction), with boiler energy efficiency accounting for 18% to 19% reduction, and electric boilers accounting for 6% reduction. The

[307] See Figures in Appendix C for comparison of all pathways. CNZ and CNZ–LCFFES are shown only here as they are the most significantly different pathways for the subsector.

CNZ–LCFFES pathway has lower comparative adoption of SGHPs and electric boilers, and instead has increased adoption of LCFFES to reduce emissions from steam production and consumption (37% reduction by 2050).

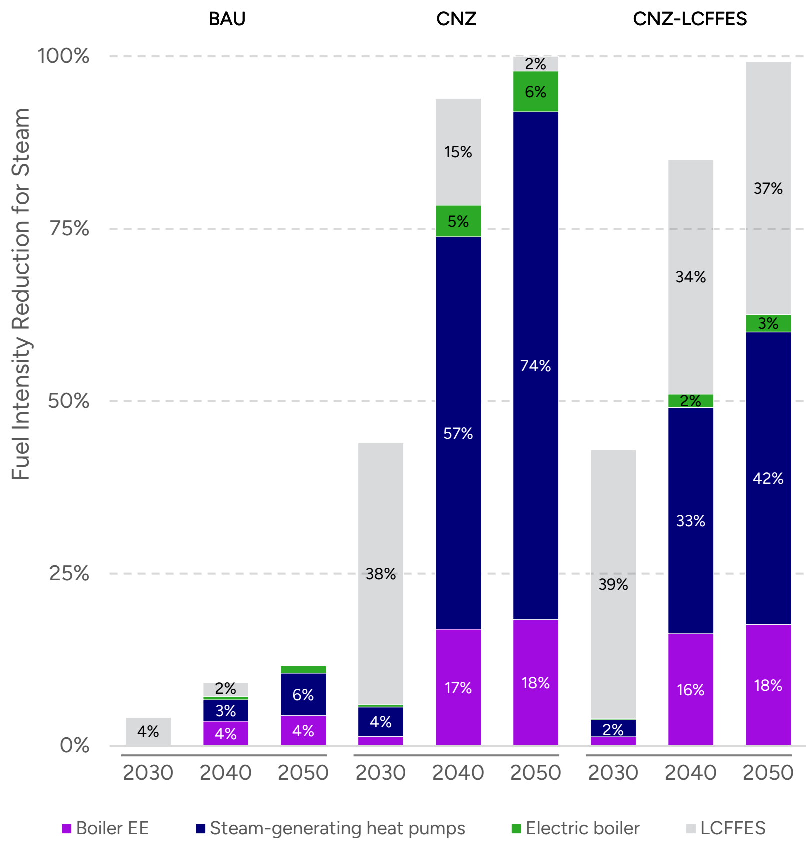


Figure 50. Steam generation fuel intensity reductions by decarbonization measure, six U.S. food and beverage manufacturing subsectors, 2030–2050

The subsectors modeled are grain and oilseed milling; sugar; fruit and vegetable preserving and specialty food; dairy products; animal slaughtering and processing; and beverages. These subsectors accounted for 79% of energy consumption and 78% of emissions for all of food and beverage manufacturing in 2018 (see Table 10). Acronyms/abbreviations: BAU (business as usual), CNZ (Core Near Zero), EE (energy efficiency), LCFFES (low-carbon fuels, feedstocks, and energy sources), CNZ–LCFFES (impact of increased LCFFES consumption). Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C. Source: Transformative Pathways modeling.

Figure 51 provides an overview of the impact of decarbonization measures to reduce the fuel intensity of hot air generation for the CNZ and CNZ–LCFFES pathways compared to the BAU scenario. The intensity reduction by 2050 for the CNZ pathway is mainly from SGHPs (76% reduction), followed by dryers and ovens energy efficiency measures (14% reduction), advanced electro-heating technologies (12% reduction), increased LCFFES consumption (11% reduction). The CNZ–LCFFES pathway has higher adoption of LCFFES by 2050 (accounting for 41% fuel intensity reduction), though limited assumed availability results in SGHPs (45% reduction), dryers/ovens energy efficiency measures (13% reduction), and advanced electro-heating technologies (5% reduction) still playing a key role in helping the subsector reach near zero. Process integration and membrane pre-concentrators account for a small intensity reduction in both pathways (2% and 1% respectively).

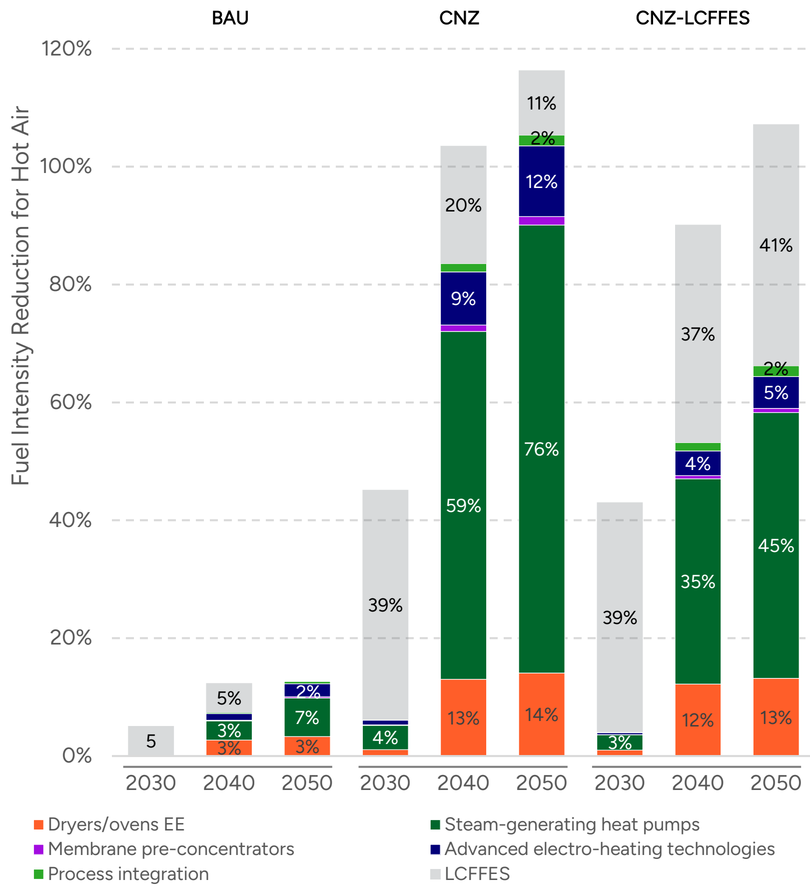


Figure 51. Hot air generation fuel intensity reductions by decarbonization measure, six U.S. food and beverage manufacturing subsectors, 2030–2050

The subsectors modeled are grain and oilseed milling; sugar; fruit and vegetable preserving and specialty food; dairy products; animal slaughtering and processing; and beverages. These subsectors accounted for 79% of energy consumption and 78% of emissions for all of food and beverage manufacturing in 2018 (see Table 10). Acronyms/abbreviations: BAU (business as usual), CNZ (Core Near Zero), EE (energy efficiency), LCFFES (low-carbon fuels, feedstocks, and energy sources), CNZ–LCFFES (impact of increased LCFFES consumption). Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C. Source: Transformative Pathways modeling.

Figure 52 provides an overview of the impact of decarbonization measures to reduce the fuel intensity of hot water generation by pathway. HWHPs account for the majority of fuel intensity reduction (74%) for the CNZ pathway and 41% reduction for the CNZ–LCFFES pathway. LCFFES is the next highest measure to reduce the hot water fuel intensity for the CNZ–LCFFES pathway at 37% and only accounts for a <1% reduction by 2050 for the CNZ. Boiler energy efficiency measures account for a 19% reduction for the CNZ pathway and 18% for the CNZ–LCFFES pathway. Electric boilers and process integration account for the remainder for both pathways.

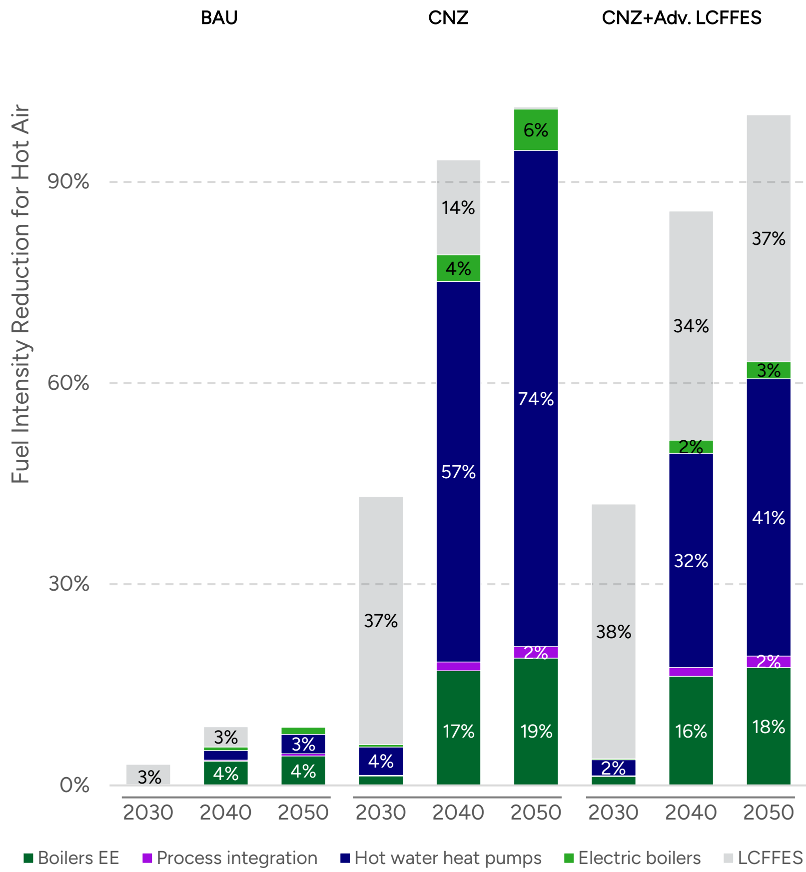


Figure 52. Hot water generation fuel intensity reductions by decarbonization measure, six U.S. food and beverage manufacturing subsectors, 2030–2050

The subsectors modeled are grain and oilseed milling; sugar; fruit and vegetable preserving and specialty food; dairy products; animal slaughtering and processing; and beverages. These subsectors accounted for 79% of energy consumption and 78% of emissions for all of food and beverage manufacturing in 2018 (see Table 10). Acronyms/abbreviations: BAU (business as usual), CNZ (Core Near Zero), EE (energy efficiency), LCFFES (low-carbon fuels, feedstocks, and energy sources), CNZ–LCFFES (impact of increased LCFFES consumption). Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C. Source: Transformative Pathways modeling.

The remainder of this section provides an overview of the impacts of the CNZ–LCFFES pathway. Additional details and assumptions for this and the additional pathways can be found in Appendix C.

Impact of Increased LCFFES Consumption (CNZ–LCFFES Pathway)

This pathway refers to a substantial increase in the adoption of increased LCFFES consumption, including biomass, biogas, hydrogen, and solar thermal, and decreased electrification over the CNZ. The CNZ pathway assumes maximum possible electrification of process heating, hot water, and steam applications. Beyond that, the remaining fuel consumption of processes are met through LCFFES opportunities. This pathway assumes comparatively lower electrification, while doubling the impacts of LCFFES. It should be noted that LCFFES, such as biofuels, may have limited availability, which is acknowledged in this pathway by limiting the magnitude of LCFFES adoption using various assumptions from literature which have modeled “high LCFFES scenarios” in their projections.[308,309,310,311] Key factors, assumptions, and impacts for this pathway are summarized in Table 13 and additional details can be found in Appendix C.

[308] International Energy Agency, *Outlook for Biogas and Biomethane: Prospects for Organic Growth* (2020), www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth.

[309] International Renewable Energy Agency, *Companies in Transition towards 100% Renewables: Focus on Heating and Cooling*, ISBN:978-92-9260-323–6 (2021), www.irena.org/Publications/2021/Feb/Companies-in-transition-towards-100-percent-renewable-energy-Focus-on-heating-and-cooling.

[310] Steve Griffiths et al., “Industrial decarbonization via hydrogen: A critical and systematic review of developments, socio-technical systems and policy options,” *Energy Research & Social Science* 80 (October 2021), doi.org/10.1016/j.erss.2021.102208.

[311] International Renewable Energy Agency, *Solar Heat for Industrial Processes–Technology Brief*, ISBN: 978-92-95111-61-5 (2015), www.irena.org/publications/2015/Jan/Solar-Heat-for-Industrial-Processes.

Table 13. CNZ–LCFFES Food and Beverage Manufacturing Pathway Key Factors, Assumptions, and Impacts

Key Factor	Assumptions and Impact
Higher LCFFES integration	• Increased use of low-carbon fuels and energy sources including biomass, biogas, hydrogen, photovoltaic solar, and solar thermal • Increased use of low-carbon fuels (bagasse, wood chips/bark, agricultural wastes, etc.) in subsectors that already utilize them (e.g., sugar manufacturing)
Blended clean H_2 in natural gas pipelines	• Clean H_2 blended in natural gas supply (up to 20%) would offset overall fuel emissions
Lower H_2-to-natural gas cost ratio	• Clean H_2 is affordable and available
Higher electricity-to-natural gas cost ratio	• Cost of electricity is higher compared to the cost of LCFFES
Lower adoption of electrification technologies	• Higher cost of electricity would economically prohibit electrification technology adoption
Higher overall efficiencies	• Existing processes and technologies are more efficient to maximize cost savings

Specific LCFFES use within food and beverage manufacturing would depend upon the application. Combustion of biogas, biomass, or hydrogen (mixed with natural gas) could play a role in the future to meet certain industrial heating needs, particularly those satisfied through steam generation. Solar thermal power (e.g., concentrating solar power) paired with energy storage technologies could also be adopted by the subsector to meet certain thermal demands.[312] However, LCFFES is heavily reliant on availability and production of these low-carbon fuels and energy sources at sufficient quality and quantity and may not be able to fully offset electrification technologies. The subsector will also need to maximize energy efficiency related opportunities which, in turn, helps reduce the demand for LCFFES. To further realize cost savings, this pathway assumes LCFFES-related costs are comparable to natural gas, while being substantially cheaper than electricity usage costs. In such pathways, facilities will opt toward utilizing LCFFES to gain cost savings and achieve significant GHG emissions reductions. Although LCFFES such as biomass and biogas significantly reduce non-biogenic emissions, their combustion still results in local pollutants emissions (such as particulate matters, nitrogen oxides, carbon monoxides, sulfur dioxides, among others), which require permits and implementation of proper air pollution control devices.[313]

Overall impact: Table 14 provides an overview of how this pathway impacts the six food and beverage manufacturing subsectors.

[312] Ibid.
[313] U.S. Energy Information Administration, "Biomass explained Biomass and the environment," April 17, 2024, www.eia.gov/energyexplained/biomass/biomass-and-the-environment.php.

Table 14. Impact of Increased LCFFES Adoption Near Zero Food and Beverage Manufacturing Pathway (CNZ–LCFFES) by Subsector

Subsector	BAU cumulative emissions (2018–2050) (MMT CO_2e)	CNZ cumulative emissions (2018–2050) (MMT CO_2e)	CNZ–LCFFES cumulative emissions (2018–2050) (MMT CO_2e)	Pathway Impact (compared to CNZ)
Grain and Oilseed Milling	491	297	268	• 17% and 14% reductions in steam generation cumulative emissions; These subsectors are steam-heavy, and LCFFES application will have greater short- to medium-term non-biogenic emissions reductions than electrification (see Table 11). Further, electrification adoption is comparatively reduced than the CNZ, while LCFFES is increased, thereby reducing cumulative non-biogenic emissions.
Sugar	173	101	92	• 9% reduction in steam generation-based emissions; higher SGHPs COPs lead to comparatively greater emissions reductions
Fruit and Vegetable Preserving and Specialty Food	251	149	143	• 15% reduction in steam generation-based emissions
Dairy Product	271	161	152	• 12% reduction in hot water generation-based emissions • 17% reduction in steam generation-based emissions
Animal Slaughtering and Processing	630	374	359	• 17% reduction in steam generation-based emissions • 7% reduction in hot water generation-based emissions
Beverage	212	135	132	• 9% reduction in steam generation-based emissions; higher SGHPs COPs lead to comparatively greater emissions reductions

4.3.5 Key Takeaways

The near zero pathways and modeled results described in this report are intended to illustrate a few of many possible decarbonization pathways for food and beverage manufacturing. The most likely eventual pathway for the food and beverage manufacturing subsector would include a mix of adopting energy efficiency measures, significant opportunity for electrification, utilizing LCFFES (as available and appropriate), and FLW reduction measures. Because of the significant potential impact of electrification, subsector decarbonization will depend on decarbonization of the electric grid.

Especially compared to other subsectors, food and beverage manufacturing decarbonization pathways and choices will likely be dictated by food safety regulations. For example, non-contact heating and cooling requirements or other guidelines that ensure non-edible contaminants do not come into contact with the food product could limit the viability of certain technologies/opportinuties (e.g., waste heat utilization) or require implementation considerations that would lead to suboptimal emissions reductions from that technology/opportunity. In some cases, the risk of not meeting U.S. Food and Drug Administration regulations even if proven otherwise could impede adoption of certain technologies/strategies (e.g., non-thermal sterilization).

Other factors that will influence eventual pathway choice include:

- Operational costs, such electricity, natural gas (especially relative to electricity), consumables
- Capital costs, including sunk costs of existing equipment
- Availability of energy source and/or decarbonization technology, e.g., availability of biogas (sufficient quantity and quality)
- Impact on regulatory compliance in addition to U.S. Food and Drug Administration food safety regulations
- Level of risk to product, specifically whether a decarbonization technology or strategy impacts product quality (e.g., throughput, taste, color)

No regrets strategies include investments in demonstration and deployment, especially given that there are commercially available or mature options (e.g., heat pumps, dual-fuel process heating or steam generating equipment) that can help the subsector make significant progress toward near zero emissions. Manufacturers will have to consider their pathways options before existing equipment reaches end-of-life and is scheduled to be replaced.

Process integration and waste heat utilization: Decarbonizing heat with hot water and steam generating heat pumps offer the largest emissions reductions impact per the modeling. The subsector includes sufficient heat pump source heat opportunities through compressor waste heat (both air and refrigeration), hot spent cleaning water, and dryers and bio-CHPs waste heat. The impact is proportional to the quality and quantity of waste heat process integration. Identifying available waste heat and improving heat integration will be important steps within this subsector to fully optimize opportunities.

Addressing high-temperature process heat needs: Higher temperature (greater than 300°F) processes could be more challenging to address with heat pumps in the short to medium term but could be addressed with other technologies or methods such as advanced electro- and non-electro-heating technologies, hybrid HTHP-assisted dryers, or LCFFES (such as biomass, biogas, hydrogen-blends, concentrated solar thermal process heating, and solar photovoltaics).

LCFFES: As shown in the CNZ–LCFFES pathway, low-carbon fuels can be a key decarbonization lever for this subsector, specifically for medium-to-high temperature heating where drying and generating steam is comparably difficult with commercially available decarbonization technologies such as heat pumps. Further, some LCFFES could be implemented as a dual-fuel retrofit with existing boilers and process heating technologies thereby reducing implementation costs and timelines. However, LCFFES application will be contingent upon its availability (which may vary by region), generation capabilities, and costs, which is why the amount of LCFFES included in the CNZ–LCFFES pathway. LCFFES such as concentrated solar thermal heat and solar photovoltaics could have opportunities in a number of food and beverage facilities, as 22% are located in regions with great solar irradiation such as California and Texas.[314,315]

CCUS: CCUS may be only applicable to the largest of boilers within the subsectors such as grain and oilseed milling and beverage manufacturing. It is not expected to have a significant emissions reduction impact subsector-wide since food and beverage manufacturing mostly consists of small-scale facilities and lower concentration of point-source CO_2e emissions where CCUS would not be considered economical compared to other decarbonization measures.

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[314] Caitlin Murphy et al., *The Potential Role of Concentrating Solar Power within the Context of DOE's 2030 Solar Cost Targets*, NREL/TP-6A20-71912 (National Renewable Energy Laboratory, 2019), www.osti.gov/biblio/1506623.
[315] U.S. Census Bureau, "County Business Patterns," October 30, 2024, www.census.gov/programs-surveys/cbp.html.

Energy efficiency opportunities: The subsector utilizes a high magnitude of motors for process cooling and refrigeration, air compressors, pumps and fans; Premium efficiency motors with variable speed control and high system-wide efficiencies offers both decarbonization and productivity benefits. The productivity benefits improve this strategy's financial viability and could be a key first step for the subsector.

Thermal storage opportunity: The subsector operations vary seasonally and are batch-based in many cases. This could potentially affect process integration, but it could be addressed with short-to-medium duration thermal storage. This will be particularly important in the adoption of heat pump systems and process integration strategies that optimize waste heat. Storage will allow facilities to align waste heat availability with thermal demands. Given the subsector's temperature demands, hot water could be a viable energy storage medium and more complex materials (e.g., salt hydrates) may not be needed.

Facility design: In general, better facility design could lower decarbonization technology implementation costs. Design for new facilities should consider minimizing distances across which heat needs to be transferred, selecting equipment with readily capturable waste heat, or allocating floor space appropriately—considerations that may not be possible to implement optimally or at all in an existing facility. This could include working with architecture and engineering firms that understand the requirements for a decarbonized facility. Even though a properly designed new facility would support successful subsector decarbonization efforts, it is not required, and existing facilities can also adopt technologies or approaches discussed in this report.

Changes to product demand and FLW/supply chain optimization: Changes in consumer demand, including preferences for certain products, and food loss and waste reduction can affect the choices industrial entities make in decarbonizing their operations. For example, plant-based meat, seafood, and milk, among other alternative proteins may make up an increased portion of the food and beverage market by 2050. A shift to a more vegetarian diet could increase production in other food and beverage subsectors while decreasing animal slaughtering and processing production. This could also be accompanied by diversification of proteins with plant-based and/or lab-grown alternatives, including fermentation-derived meat products. The food and beverage supply chain can be optimized with the intent of both minimizing spoilage and waste, while providing continuity for product safety such as traceability of products from farm to retail. Food waste varies across subsectors at both production and consumer levels; better FLW management could significantly reduce emissions from subsectors such as grain and oilseed milling and dairy subsectors by 10% and 14%, respectively. Research into improved food packaging such that the shelf-life of products is improved could help to reduce FLW. However, any new type of packaging would have to meet all U.S. Food and Drug Administration requirements, not require significant changes to distribution and storage infrastructure, not impact the quality of the food or beverage (taste, color, etc.) and be recyclable.

Supply chain emissions considerations: Although the *Transformative Pathways* modeling focused on scope 1 and 2 emissions for manufacturing only, it is important to consider the results in context with the entire food and beverage supply chain. Agriculture is responsible for a significant amount of overall industrial sector emissions, mainly from non-energy-related emissions (see 4.7.2). Future modeling efforts could consider a more holistic life cycle scope when considering the entire food supply chain, though challenges exist around data availability, quality, and consistency when considering other stages beyond manufacturing. Additionally, the emissions and energy impacts for emerging areas such as alternative proteins or controlled-environment agriculture would have a higher impact in the agriculture vs. manufacturing stage.

Connections to other subsectors: Although the *Transformative Pathways* modeling was limited to within individual subsectors, connections between subsectors should be considered in a holistic approach to industrial sector-wide decarbonization. Food and beverage manufacturing shares connections with the agriculture subsector and other manufacturing subsectors such as plastics, glass, or aluminum for packaging needs in manufactured food and beverage products. Decarbonization solutions may be integrated across subsectors or supply chain stages, and the entire life cycle of food and beverage products should be considered.

4.4 Iron and Steel

4.4.1 Introduction

Iron and steel manufacturing is one of the most energy- and emissions-intensive subsectors worldwide, accounting for around a quarter of global manufacturing GHG emissions.[316] The U.S. iron and steel subsector produced 82 MMT of crude steel in 2022, about 4% of global production, and ranked as the fourth-largest steel producer in the world behind China, India, and Japan.[317] As of 2023, direct employment in U.S. iron and steel mills and steel product manufacturing facilities was 317,000.[318] U.S. iron, steel, and ferroalloys manufacturing also generated around $17 billion of income after taxes in 2023.[319]

In 2022, about 28% of U.S. steel was produced by facilities known as integrated mills, which use a blast furnace (BF) integrated with a basic oxygen furnace (BOF), known as the BF-BOF integrated steel mills (process shown in Figure 53).[320] The remaining 72% of U.S. steel production came from electric arc furnace (EAF) facilities[321] (process shown in Figure 54), utilizing various sources of iron such as direct reduced iron (DRI), hot-briquetted iron (HBI), and even pig iron, along with varying amounts of scrap. EAF-produced steel can have a significantly lower carbon footprint than BF-BOF-produced steel, depending on the source of iron and degree of scrap used in the EAF or BOF,[322] as well as the source of electricity.

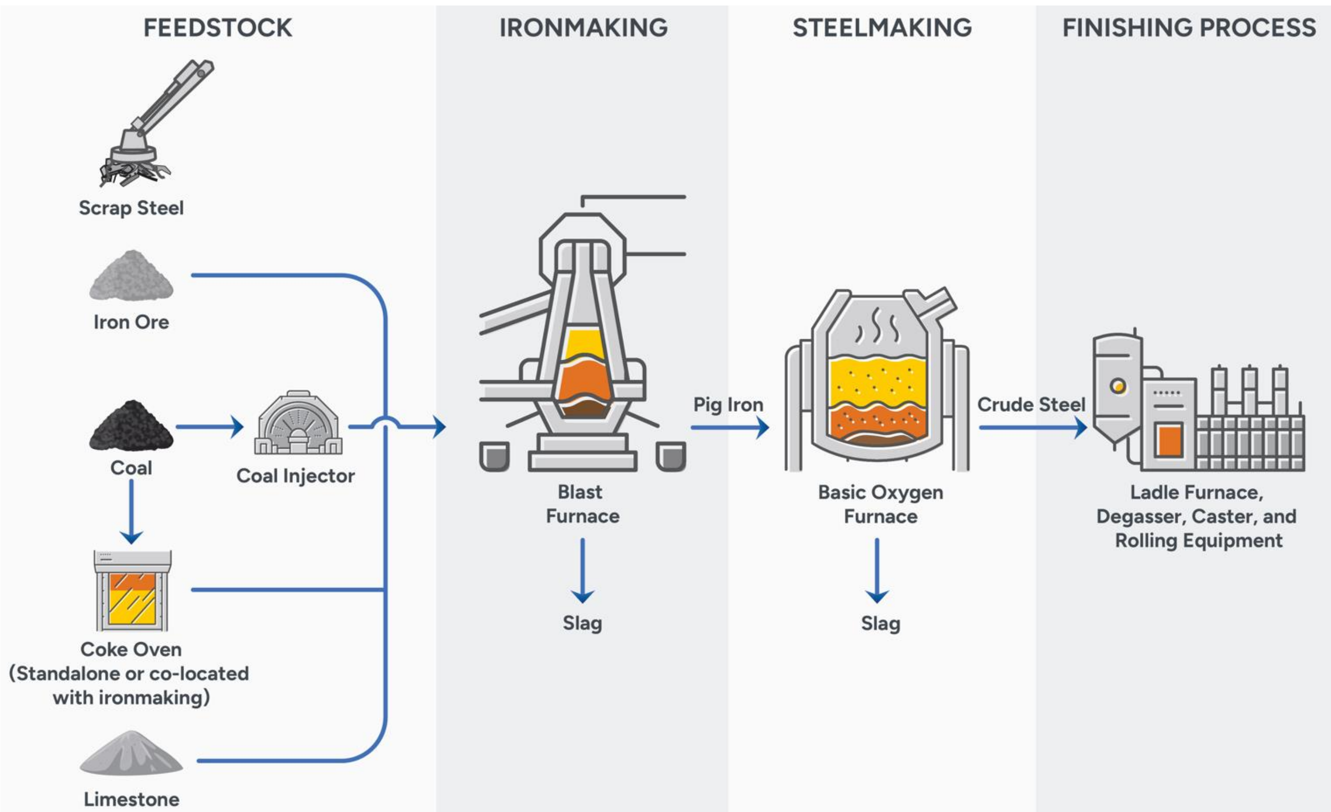

Figure 53. Integrated steel mill process flow diagram

[316] International Energy Agency, *Iron and Steel Technology Roadmap - Towards More Sustainable Steelmaking* (2020), www.iea.org/reports/iron-and-steel-technology-roadmap.
[317] U.S. Geological Survey, *Mineral and Commodity Summary* (2023), pubs.usgs.gov/periodicals/mcs2023/mcs2023-iron-steel.pdf.
[318] U.S. Bureau of Labor Statistics, "Employed Persons by Detailed Occupation and Age," January 26, 2024, www.bls.gov/cps/cpsaat11b.htm.
[319] Federal Reserve Bank of St. Louis, "Quarterly Financial Report: U.S. Corporations: Iron, Steel, and Ferroalloys: Income (Loss) After Income Taxes," September 10, 2024, fred.stlouisfed.org/series/QFR115371USNO.
[320] U.S. Geological Survey, *Iron and Steel Mineral and Commodity Summary* (2024), pubs.usgs.gov/periodicals/mcs2024/mcs2024-iron-steel.pdf.
[321] Ibid.
[322] Ali Hasanbeigi and Cecilia Springer, *How Clean is the U.S. Steel Industry,* Global Efficiency Intelligence (2019), www.globalefficiencyintel.com/us-steel-industry-benchmarking-energy-co2-intensities.

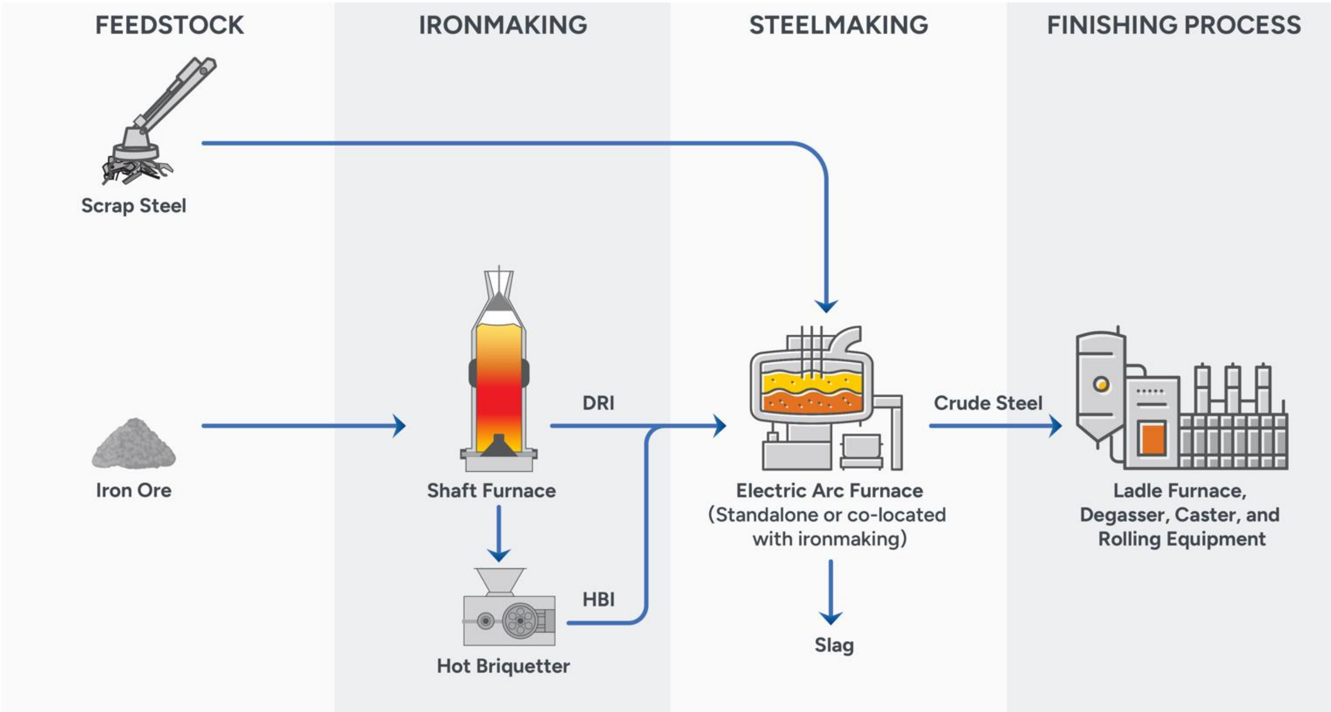

Figure 54. Steel mini-mill process flow diagram with direct reduced iron (DRI) input

In 2018, U.S. iron and steel manufacturing emitted a total of 100 MMT CO_2e, which accounted for 9% of total U.S. manufacturing emissions.[323] For the same year, iron and steel mills accounted for 1,469 TBtu of primary energy consumption, about 7% of the total U.S. manufacturing energy consumption.[324] Natural gas represented the largest share of subsector energy consumption (37%), followed by coke and breeze[325] (28%), electricity (17%), blast furnace and coke oven gases (16%), coal (2%), and a small amount (<1%) of petroleum coke, distillate fuel oil, and waste gas.[326, 327]

U.S. iron and steel production in 2022 included eight integrated mills using the BF-BOF production route (including one with BF-BOF-EAF), one DRI-EAF mill, and 105 EAF mini-mills.[328, 329, 330] U.S. iron and steel production was predominantly concentrated in the industrial regions of the Midwest (especially around the Great Lakes) and the Northeast due to historical accessibility to key raw materials such as iron ore and coal and proximity to manufacturing and automotive subsectors. However, there has been significant expansion of mini-mills in the South. The subsector consists of small and medium-sized enterprises as well as multinational giants such as Nucor, Cleveland-Cliffs, U.S. Steel, and Steel Dynamics. These giants have flourished over several decades or even centuries and contribute to over 40% of U.S. iron and steel subsector revenue. Their long-

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323 See All Manufacturing and Iron & Steel footprints at U.S. Department of Energy, "Manufacturing Energy and Carbon Footprints: 2018 MECS," accessed October 2024, www.energy.gov/eere/iedo/manufacturing-energy-and-carbon-footprints-2018-mecs.
324 Ibid.
325 Breeze is finely powdered coke, usually less than 1/2 inch. See U.S. Energy Information Administration, "Glossary coke_breeze," accessed November 2024, www.eia.gov/tools/glossary/index.php?id=coke_breeze.
326 U.S. Energy Information Administration, "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data," 2021, www.eia.gov/consumption/manufacturing/data/2018/. See Table 3.2. Energy Consumption as a Fuel by Manufacturing Industry and Region and Table 5.2 Energy Consumed as a Fuel by End Use by Manufacturing Industry with Net Electricity.
327 U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Iron and Steel," (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_iron_steel_energy_carbon_footprint.pdf.
328 U.S. Geological Survey, *Iron and Steel Mineral and Commodity Summary* (2024), pubs.usgs.gov/periodicals/mcs2024/mcs2024-iron-steel.pdf.
329 U.S. Geological Survey, *Iron and Steel Mineral and Commodity Summary* (2023), pubs.usgs.gov/periodicals/mcs2023/mcs2023-iron-steel.pdf.
330 Global Steel Monitor, "Global Steel Plant Tracker," April 2024, globalenergymonitor.org/projects/global-steel-plant-tracker/.

standing presence has naturally created barriers for new competitors attempting to enter the market.[331] The market dynamics of the U.S. iron and steel subsector show relatively tight profit margins due to high energy costs, labor costs, and global competition. The domestic iron and steel subsector has reduced production capacities in the past due to these high operational costs and competition from foreign producers, especially those from China, despite stable demand.

A critical component of iron and steel manufacturing is the flow, import, and export of steel scrap within the subsector. Standalone EAF steel producers combine scrap with varying amounts of ore-based metallics, such as pig iron and DRI, to improve quality, while integrated steel producers use up to 25% scrap, most of it produced internally, in BOF steelmaking.[332] The United States' trade deficit in steel products (e.g., flat products, pipe and tube) has persisted for well over a decade.[333] As shown in Figure 55, semi-finished products produced from U.S. crude steel only account for 60% of domestic consumption. The remaining 40% (about 34 MMT) of semi-finished products are either imported or produced from imported feedstock. Meanwhile, the United States exports only 8 MMT of intermediate steel products but is a net exporter of post-consumer or old steel scrap, which represents a significant opportunity to displace imports with domestic recycling. Also shown in Figure 55, the U.S. iron and steel subsector utilized 5 MMT of internal scrap, 27 MMT of old scrap, and 23 MMT of forming and fabrication scrap (total of 55 MMT) for crude steel production, which corresponds to a recycled content of 62% in U.S. steelmaking.[334, 335] The majority of the remaining old scrap was either exported or lost to landfill or hibernating stock.[336] Another study estimated that approximately 70 MMT of old scrap could be available for recycling.[337]

[331] Vlad Khaustovich, "Iron & Steel Manufacturing in the US - Market Research Report (2024-2029), IBIS World, October 2024, www.ibisworld.com/united-states/market-research-reports/iron-steel-manufacturing-industry/#IndustryStatisticsAndTrends.
[332] Edwin Basson, "World Steel in Figures 2023," World Steel Association, accessed October 2024, worldsteel.org/data/world-steel-in-figures-2023/.
[333] International Trade Administration, "United States Steel Imports Report," accessed October 2024, www.trade.gov/data-visualization/united-states-steel-imports-report.
[334] Barbara K. Reck et al., "Assessing the Status Quo of U.S. Steel Circularity and Decarbonization Options," in *Technology Innovation for the Circular Economy: Recycling, Remanufacturing, Design, Systems Analysis and Logistics*, N. Nasr (Ed.), 2024, doi.org/10.1002/9781394214297.ch17.
[335] United Nations Environment Programme, *Recycling Rates of Metals: A Status Report* (2011), www.unep.org/resources/report/recycling-rates-metals-status-report.
[336] Edwin Basson, "World Steel in Figures 2023," World Steel Association, accessed October 2024, worldsteel.org/data/world-steel-in-figures-2023/.
[337] Daniel Cooper et al., "The Potential for Material Circularity and Independence in the U.S. Steel Sector," *Journal of Industrial Ecology* 24, 4 (August 2020): 748–762, dx.doi.org/10.1111/jiec.12971.

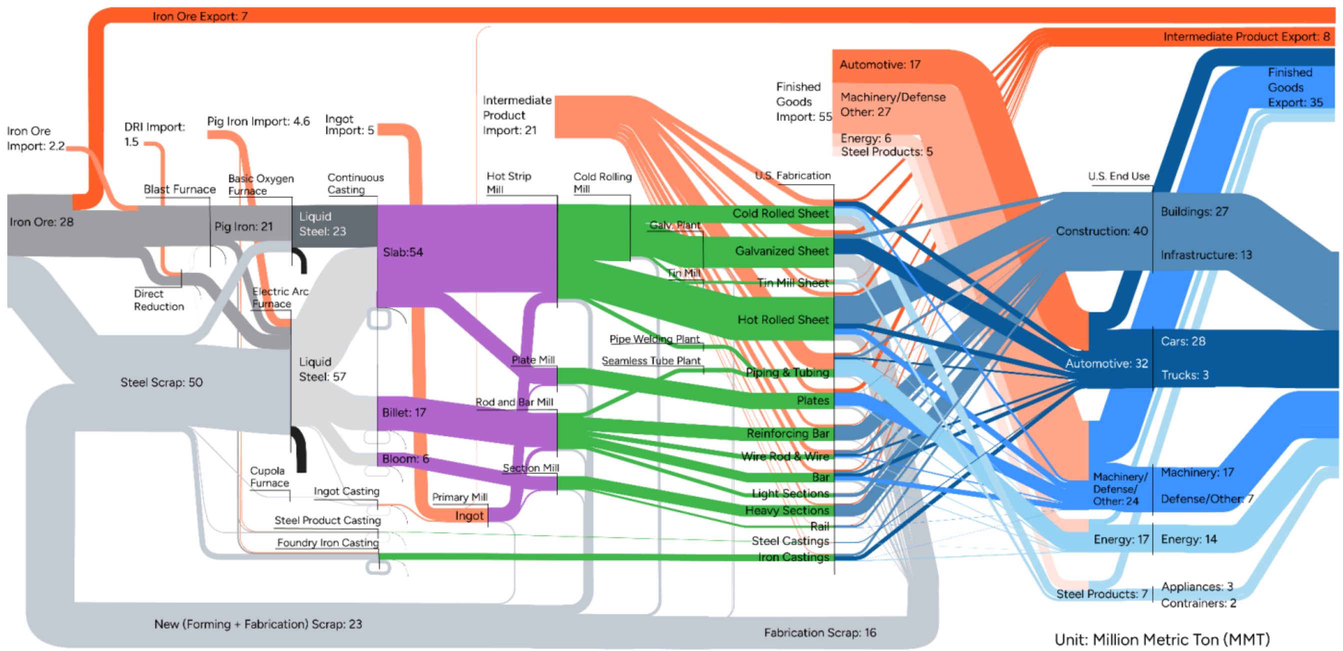

Figure 55. Sankey diagram of 2023 U.S. iron and steel making material flows

Created with subsector expert inputs on pig iron and DRI flows. For methodology, see Reck et al. (2024).[338] Values are in million metric tons (MMT).

Regarding the supply chain, the steel subsector is considered critical for national security,[339] given its importance in infrastructure, defense, and essential manufacturing subsectors. Decarbonizing the steel subsector further intersects with national security as the shift to low-carbon production technologies such as H_2-based steelmaking and carbon capture can reduce dependency on fossil fuels, enhance energy independence, and create competitive advantages for U.S. producers.[340]

4.4.2 Modeling Approach

The *Transformative Pathways* modeling explores existing (see Figure 53 and Figure 54) and emerging production routes. When considering these routes, it is helpful to distinguish between ironmaking and steelmaking processes to acknowledge the role of steel scrap. In the United States, some scrap is also used in BOFs, and in a few cases, even in BFs, helping to further reduce emissions associated with the primary production route. This substantial difference in emissions is a critical factor driving the analysis of flows of primary and secondary within the steel subsector. Understanding these production routes is essential to inform strategies for reducing the overall carbon intensity of the iron and steel subsector, and it is a primary focus of this study.

Production routes are defined as a combination of processes to arrive at a functional unit of crude steel and the degree of scrap used in that route. The production routes considered for this modeling are summarized in Table 15 below, where the process preceding the dash represents ironmaking and the process following the dash represents steelmaking.

[338] Barbara K. Reck et al., "Assessing the Status Quo of U.S. Steel Circularity and Decarbonization Options," in *Technology Innovation for the Circular Economy: Recycling, Remanufacturing, Design, Systems Analysis and Logistics*, N. Nasr (Ed.), 2024, doi.org/10.1002/9781394214297.ch17.
[339] U.S. Department of Defense, *Securing Defense-Critical Supply Chains* (2022), media.defense.gov/2022/Feb/24/2002944158/-1/-1/1/DOD-EO-14017-report-securing-defense-critical-supply-chains.pdf.
[340] David Foster et al., *The Roosevelt Project: Iron and Steel Decarbonization by 2050: An Opportunity for Workers and Communities* (MIT Center for Energy and Environmental Policy Research, 2024), ceepr.mit.edu/wp-content/uploads/2024/07/The-Roosevelt-Project-Iron-and-Steel-Decarbonization-by-2050.pdf.

Table 15. Iron and Steel Subsector Production Routes

Production Route	Shorthand	Scrap %
Blast Furnace–Basic Oxygen Furnace	BF-BOF	up to 30%
Blast Furnace–Basic Oxygen Furnace, with CCS	BF-BOF-CCS	up to 30%
Natural Gas DRI–Integrated EAF	NG-DRI-iEAF	up to 50%
Natural Gas DRI–Integrated EAF, CCS	NG-DRI-iEAF-CCS	up to 50%
Hydrogen DRI–Integrated EAF	H2-DRI-iEAF	up to 50%
Natural Gas DRI–Standalone EAF	NG-DRI-sEAF	up to 90%
Blast Furnace–Standalone EAF	BF-sEAF	up to 90%
Hydrogen DRI–Standalone EAF	H2-DRI-sEAF	up to 90%
Molten Oxide Electrolysis–Standalone EAF	MOE-sEAF	up to 90%
Aqueous Electrolysis–Standalone EAF	AqE-sEAF	up to 90%
Standalone EAF with 100% scrap feed	EAF-100scrap	fixed at 100%

For ironmaking, blast furnaces have been and continue to be the dominant production route. However, DRI has increased its market share and can be paired with natural gas (NG) or hydrogen inputs. Recent announcements from Cleveland-Cliffs[341] and ArcelorMittal[342] to produce HBI, a denser and more compact form of DRI, has increased domestic capacity for DRI by 81%, compared with 2019.[343] Consequently, annual U.S. DRI production rose from 14% of total pig iron production in 2019 to 26% in 2022.[344] Additionally, there are emerging low-maturity electrolysis ironmaking processes of molten oxide electrolysis (MOE) and aqueous electrolysis (AqE, or electrowinning).

For steelmaking, the hot metal output of blast furnaces and scrap is fed into basic oxygen furnaces. Cooled pig iron output of blast furnaces, direct reduced iron, MOE and AqE outputs, and significant amounts of scrap can be fed into EAFs. Distinctions are made between an integrated EAF (iEAF) with DRI ironmaking (i.e., hot feeds) and a standalone EAF (sEAF) with cold feeds. Furthermore, downstream finishing processes are included (i.e., the ladle furnace, degassing, casting, hot rolling, cold rolling, annealing). Carbon capture and storage (CCS) is then considered as an ancillary step for the integrated production routes of BF-BOF and NG-DRI-iEAF.

The current modeling framework (see Figure 56) and approach do not yet distinguish between the quality of feedstocks, including both ore and scrap. However, future iterations of the model will incorporate these aspects to address the emerging issues related to feedstock quality. Specifically, processes such as scrap beneficiation (e.g., managing copper content), ore beneficiation, and alternative production routes (e.g., using electric smelting furnaces instead of electric arc furnaces to process lower-quality materials) will be integrated.

Although this iteration does not explicitly model the quality variations in feedstocks, future scenario development will include detailed parameters to capture the effects of different scrap qualities. For example,

[341] Cleveland-Cliffs, "Toledo - Direct Reduction Plant," accessed October 2024, www.clevelandcliffs.com/operations/steelmaking/toledo-dr-plant.
[342] Midrex, "MIDREX® Direct Reduction Plants 2022 OPERATIONS SUMMARY," 2023, www.midrex.com/tech-article/midrex-direct-reduction-plants-2022-operations-summary/.
[343] U.S. Geological Survey, *2019 Minerals Yearbook: Iron Ore [Advance Release]*, 2024, pubs.usgs.gov/myb/vol1/2019/myb1-2019-iron-ore.pdf.
[344] U.S. Geological Survey, "2022 Minerals Yearbook: Iron and Steel tables-only release," d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/media/files/myb1-2022-feste-ert.xlsx.

scenarios featuring "high scrap" conditions will allow for an initial understanding of the impact of scrap quality on production outcomes. These future enhancements aim to provide a more refined analysis of the role of scrap beneficiation and other process adjustments in optimizing production routes.

The *Transformative Pathways* modeling did not include biomass-based ironmaking and steelmaking pathways, but they should be addressed in future iterations. Bio-coke or biochar can be used as partial substitutes for fossil-based coke and coal in the BF-BOF process. Bio-coke can be used in the blast furnace as a reducing agent and structural support for the burden material. Biochar can be injected through tuyeres as a replacement for pulverized coal injection. Studies suggest that up to about 20% of fossil coke can be replaced with bio-coke without significant alterations to the furnace operation.[345] Within the model, biochar can be used in EAFs as a substitute for fossil-based carbon materials. Biochar can be used to create foaming slag, which improves energy efficiency and protects the furnace lining. Up to 100% substitution of injected carbon with biochar is technically feasible.[346]

Additionally, several low-maturity technologies (including molten salt electrolysis and advanced hydrogen DRI involving plasma) have been excluded due to lack of data around production intensities and feedstock requirements. Some existing processes were restricted by the feedstock inputs they could accept. This included blast furnaces without HBI, scrap, or lump ore. Carbon capture was restricted to BF-BOF and natural gas DRI only. For finishing processes, continuous casting, near net shape casting, and hydrogen-fueled reheat furnaces were also not included in this iteration of the modeling, but they are planned for inclusion in future iterations.

[345] Biochar Today, "Biochar: A Sustainable Solution for the Steel Industry," June 16, 2024, biochartoday.com/2024/06/16/biochar-a-sustainable-solution-for-the-steel-industry/.
[346] Ibid.

IRON AND STEEL
Modeling Framework

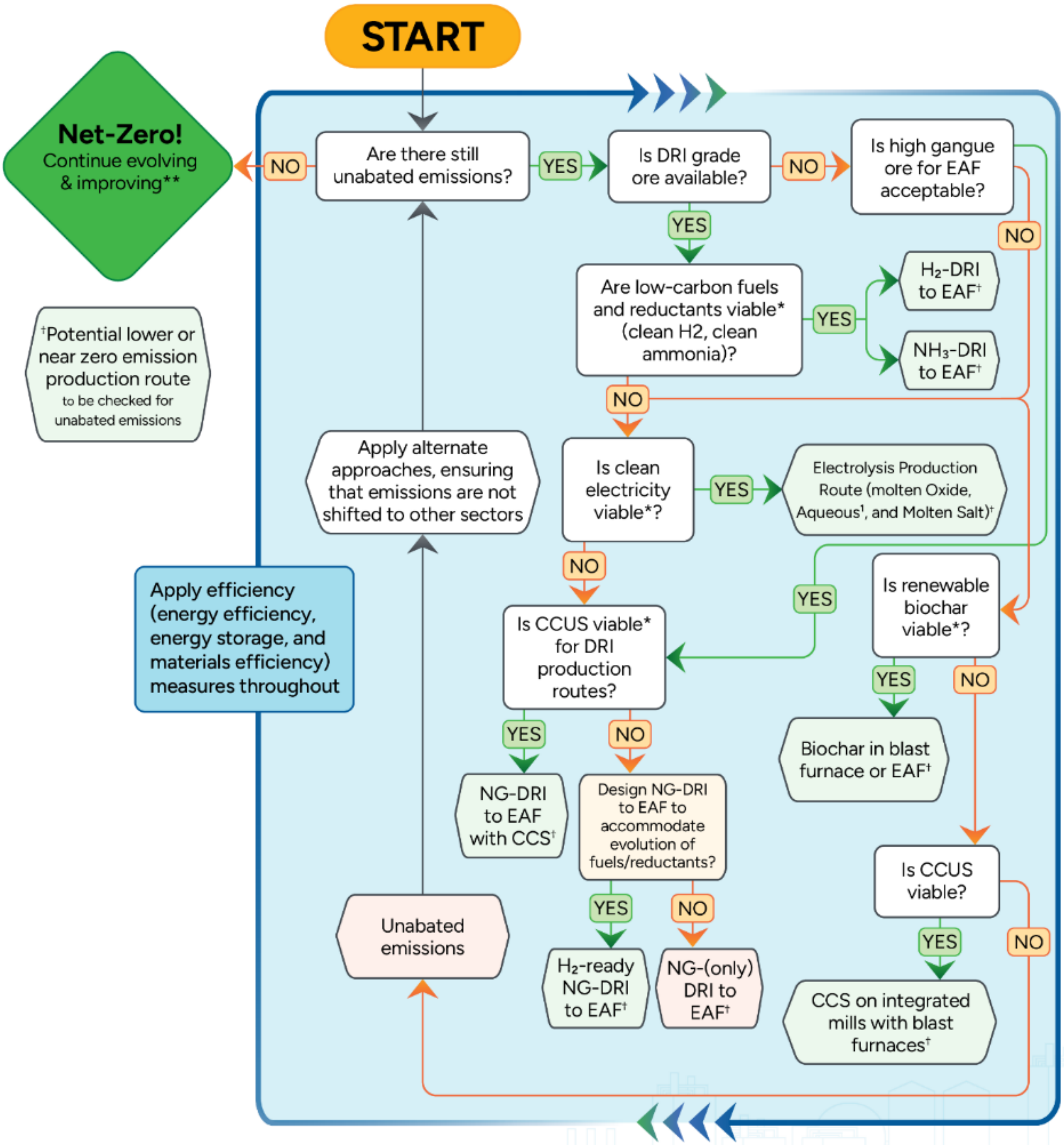

Figure 56. Iron and steel modeling framework

4.4.3 Subsector-Specific Sensitivities

Table C-39 in Appendix C provides a comprehensive summary of the iron and steel subsector-specific sensitivities related to different production routes, alongside universally applicable metrics such as energy efficiency, electric grid emission factors, and hydrogen emission factors that are implemented across all industrial subsectors. The analysis includes three core emissions scenarios (higher, mid, and lower), which range from a conservative "higher emissions" scenario to an aggressive "lower emissions" scenario, targeting deep decarbonization by 2050. This section provides a high-level overview of some of these key sensitivities.

Inclusion of lower-maturity processes: Two lower-maturity ironmaking processes were included in the model: MOE and AqE. Sensitivities were explored where the sum market shares for ironmaking in 2050 for production routes involving these processes were capped at 0%, 3%, and 6%. Carbon capture and storage (CCS) processes were explored in other global CCS-specific sensitivities and thus were not included in these sensitivities.

Changes in modeled production: Three different production projections out to 2050 were included as possible production trajectories. These include a reference projection of 104 MMT in 2050,[347] which assumes a constant level of direct imports of iron intermediaries and crude steel. For the two remaining sensitivities modeled for this projection, one allowed direct imports to take a linear path to near zero in 2050 with apparent consumption held fixed that resulted in 134 MMT domestic crude steel production in 2050, while the other allowed direct imports to double their 2018 relative percentage by 2050 with apparent consumption held fixed that result in 78 MMT domestic crude steel production in 2050.

Alternative low-carbon fuels and energy sources: Hydrogen, whether blended with natural gas or used in its pure form, is modeled for the DRI process. Other low-carbon fuels previously tested by industry include renewable natural gas and biochar, which provide alternative biogenic carbon inputs to the EAF process.[348] In this *Transformative Pathways* analysis, hydrogen was treated as being produced off-site and an associated national average scope 2 emission factor was used. This emission factor would be a composite of all hydrogen supplied. Different sensitivities around hydrogen emission factors were used in the analysis, to account for different assumptions around hydrogen production nationally. The near zero hydrogen emission factor trajectory assumes the emission factor for hydrogen goes to near zero in 2050, aligning with the trajectory of the grid emission factors and electrolytically produced hydrogen. Additionally, scenarios where all hydrogen is produced using conventional methods with and without CCS were also run. Lastly, a sensitivity was included where the hydrogen emission factor goes to near zero by 2035, with emission factors derived from the electrolytically produced hydrogen in the 2023 Standard Scenarios *High Demand Growth and Hydrogen Economy with 100% CO_2 Reduction by 2035* scenario.[349]

Changes in feedstock availability and utilization: Three different end-of-life iron and steel scrap projections out to 2050 were included as possible scrap trajectories. These include a reference projection of 63.5 MMT in 2050, which assumes a constant recycling rate (2018 value of 63.5%) applied to end-of-life scrap availability projections. For the two remaining sensitivities, one kept the recycling rate fixed at 63.5% and eliminated scrap exports, which resulted in 78.8 MMT of scrap in 2050. The other sensitivity halved the 2018 scrap availability into 2050, which resulted in only 24 MMT of scrap in 2050.

4.4.4 Business as Usual Scenario and Near Zero Pathways

Considering the variety of sensitivities presented in the previous section, Table C-40 in the appendix outlines the core scenarios examined in this report, including the core near zero (CNZ) scenarios, ranging from the most conservative BAU trajectory to the most aggressive technology adoption (e.g., high hydrogen adoption) and scrap-recycling scenarios (e.g., high hydrogen with increased scrap).

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[347] Yongxian Zhu, Kyle Syndergaard, and Daniel R Cooper, "Mapping the Annual Flow of Steel in the United States," *Environ Sci. Technol.* 1, 53 (August 2019): 11260–11268. doi.org/10.1021/acs.est.9b01016.
[348] PR Newswire, "Steel Dynamics Announces Location of Planned Biocarbon Production Operations -- A Meaningful Strategic GHG Reduction Initiative," November 2, 2022, www.prnewswire.com/news-releases/steel-dynamics-announces-location-of-planned-biocarbon-production-operations--a-meaningful-strategic-ghg-reduction-initiative-301666935.html.
[349] Pieter Gagnon et al., *2023 Standard Scenarios Report: A U.S. Electricity Sector Outlook*, NREL/TP-6A40-87724 (National Renewable Energy Laboratory, 2024), www.osti.gov/biblio/2274777.

Under the BAU trajectory, GHG emissions in 2050 can decrease by 34% (32 MMT CO_2e) compared to 2018 when coupled with decarbonization of scope 2 emissions, specifically grid electricity and purchased hydrogen. BAU only decreases by 14% without the corresponding reduction in scope 2 emissions. However, continuing along the current BAU trajectory will not achieve the deep decarbonization required to meet domestic and international climate targets. The traditional BF-BOF production route, which relies heavily on coal, represents a major obstacle to decarbonization. Approximately 30% of U.S. steel production is through BF-BOF, which is responsible for significant emissions due to its dependence on high-carbon coke. Simply enhancing the efficiency of these processes will not deliver the level of emissions reduction needed to reach near zero. On the other hand, efficiency improvement through upgrading/replacing inefficient plants may prolong the lifetime of primary steelmaking facilities and lead to stranded investment risks in the context of deep decarbonization.[350]

Two distinct near zero pathways emerged from the scenarios and sensitivities modeled. One pathway continues to use integrated mills and relies heavily on CCS (Figure 57) and results in annual emissions of 8 MMT CO_2e in 2050. The other pathway utilizes hydrogen as the iron reducing agent for DRI (Figure 58) and will achieve substantial emissions reduction (to 5 MMT CO_2e in 2050) even in the absence of CCS. Both pathways build on scope 2 emissions reduced through a clean electric grid and add in clean EAF and clean finishing reaching 100% capacity by 2050.

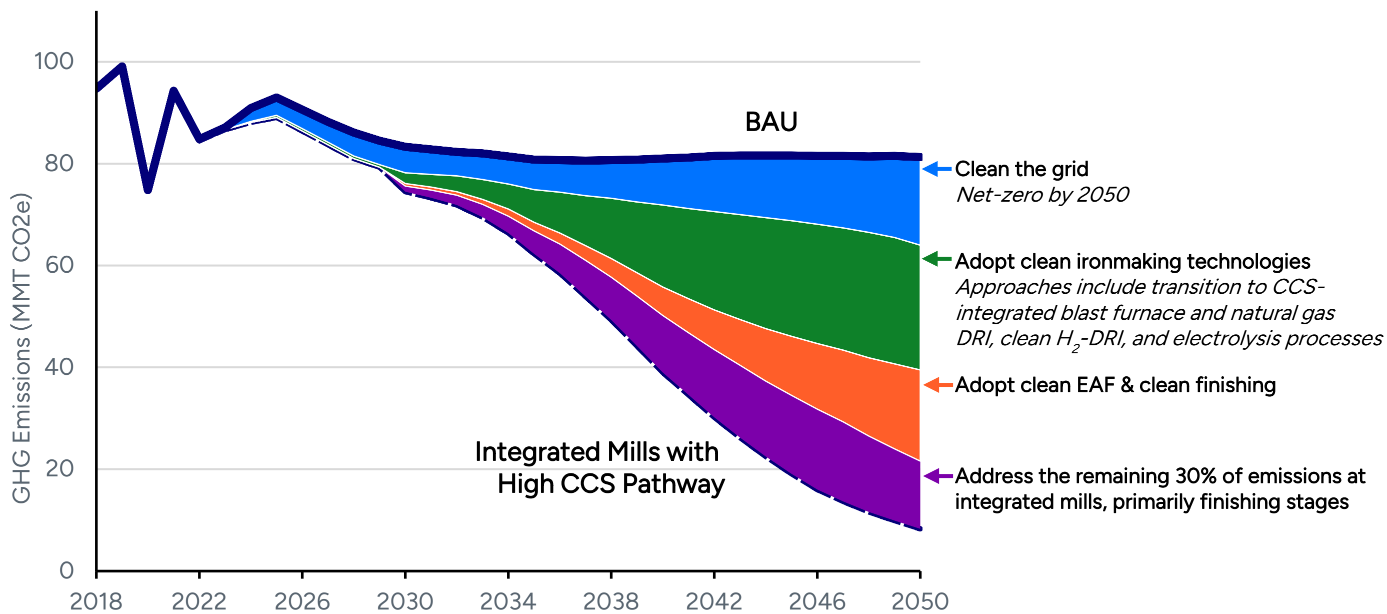


Figure 57. Annual GHG emissions reductions, U.S. iron and steel manufacturing–Integrated Mills with High CCS pathway (MMT CO_2e/year), 2018–2050

Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C. Source: Transformative Pathways modeling.

[350] Ruochong Xu et al., "Plant-by-Plant Decarbonization Strategies for the Global Steel Industry," *Nature Climate Change* 13, (September 2023): 1067–1074, doi.org/10.1038/s41558-023-01808-z.

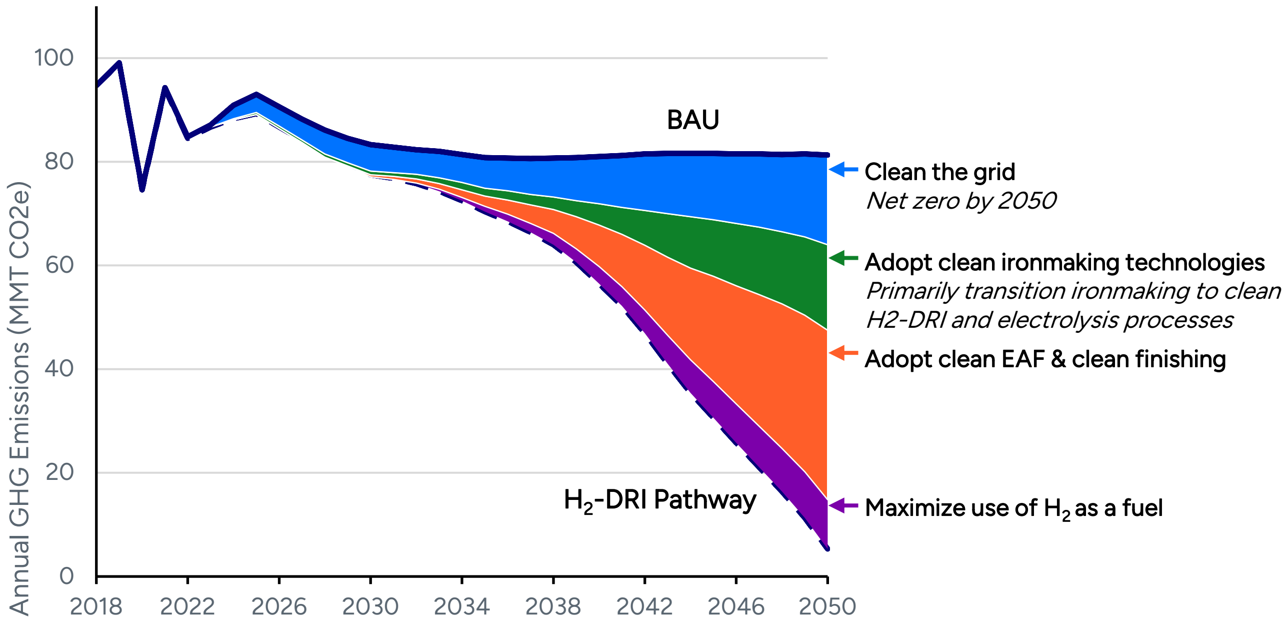


Figure 58. Annual GHG emissions reductions, U.S. iron and steel manufacturing–Hydrogen-Direct Reduced Iron pathway ($MMT\ CO_2e$/year), 2018–2050

Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C. Source: Transformative Pathways modeling.

Both pathways were built form the core scenario assumption of 70% CCS to be applied to existing integrated mills, and then allowed to increase up to 100%. As can be seen in Figure C-29 in Appendix C, CCS was an essential component of the IM-CCS pathway. Figure C-30 in Appendix C shows the role of CCS is significantly diminished in the H_2-DRI pathway, and ultimately excluded. Additionally, both pathways allowed the use of hydrogen as a fuel, blended up to 30% with natural gas by volume (up to 10% by energy content) and up to 100% in hydrogen-ready burners in H_2-DRI facilities. As shown in Figure C-29 and Figure C-30, the role of hydrogen as a fuel was more impactful in the H_2-DRI pathway compared to the IM-CCS pathway, and thus it was excluded from the IM-CCS pathway.

The choice between these pathways requires near-term decisions regarding domestic ironmaking capacity. Unconsidered continued investments in integrated mills may lock in that pathway and the higher CCS requirement, while movement toward the H_2-DRI pathway will require increasing hydrogen production capacity and consideration of its transportation and supply chain logistics. The aggressive timelines necessary for either integrated mills with CCS or hydrogen-ready DRI build-out can be seen in Figure 59, which shows the breakdown of sources of iron for steelmaking for each pathway.

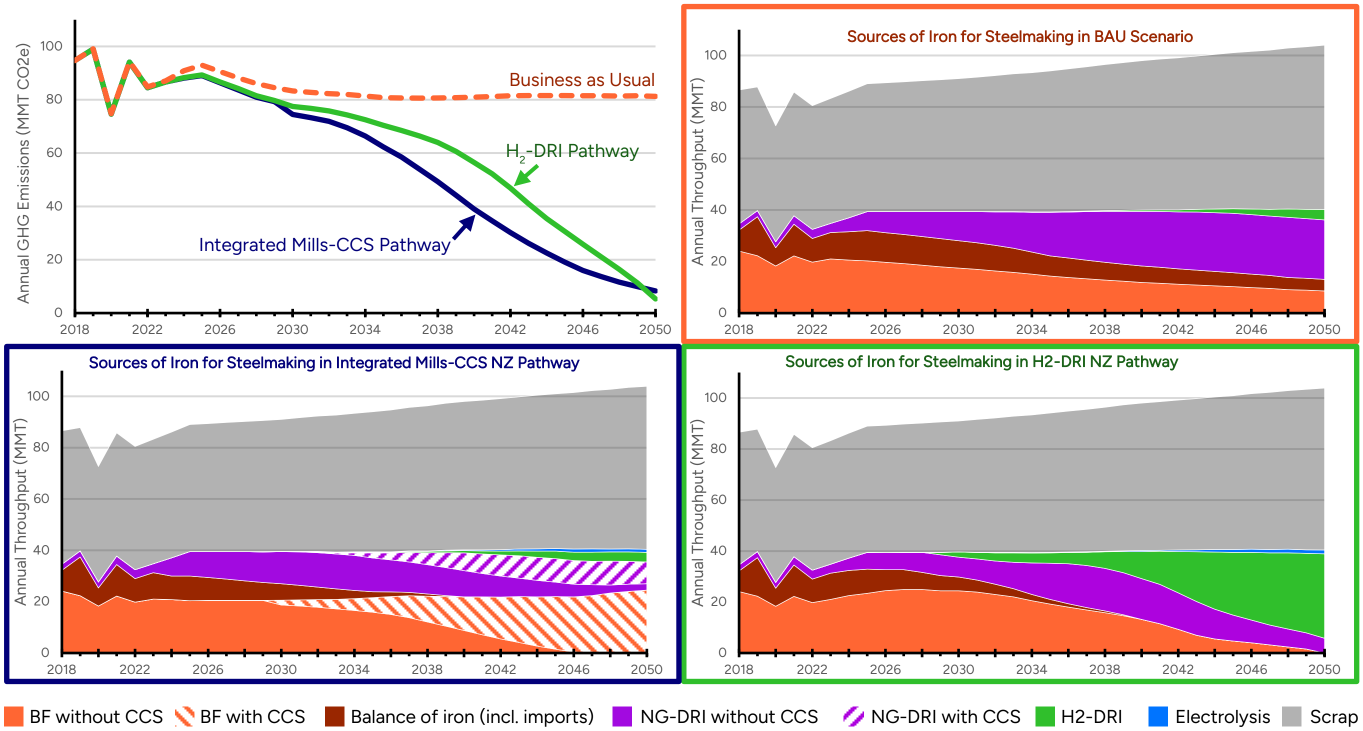
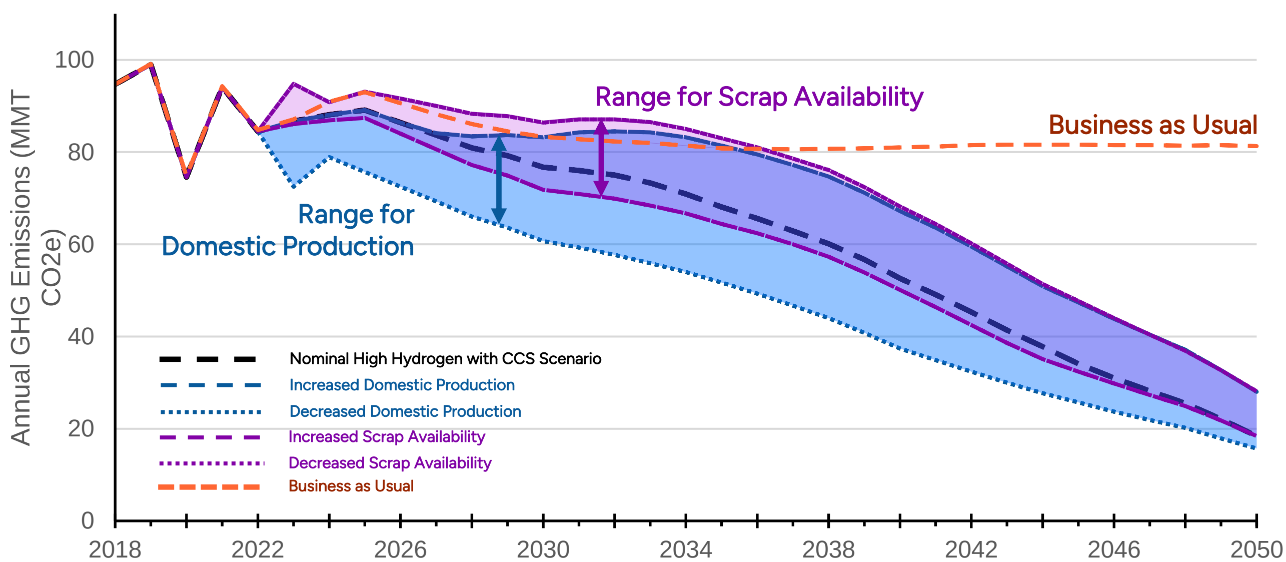


Figure 59. Annual GHG emissions (top left) and sources of iron for U.S. steelmaking for BAU scenario (top right), IM-CCS pathway (bottom left), and H_2-DRI pathway (bottom right), 2018–2050

Top left: annual emissions for BAU scenario, IM-CCS pathway, and H_2-DRI pathway. Top right: Sources of iron for steelmaking in the BAU scenario. Bottom left: Sources of iron for steelmaking in the IM-CCS pathway. Bottom right: Sources of iron for steelmaking in the H_2-DRI pathway. Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C. Source: Transformative Pathways modeling.

Figure 60 shows the effects of production and scrap projections due to imports and exports on the H_2-DRI pathway. It is important to note that the role of scrap and domestic production were examined against the core scenario, the nominal high hydrogen with 70% CCS scenario, not a near zero pathway. The bar chart in Figure 60 shows how these scrap and production scenarios could influence the makeup and scale of domestic ironmaking capacity in 2050.



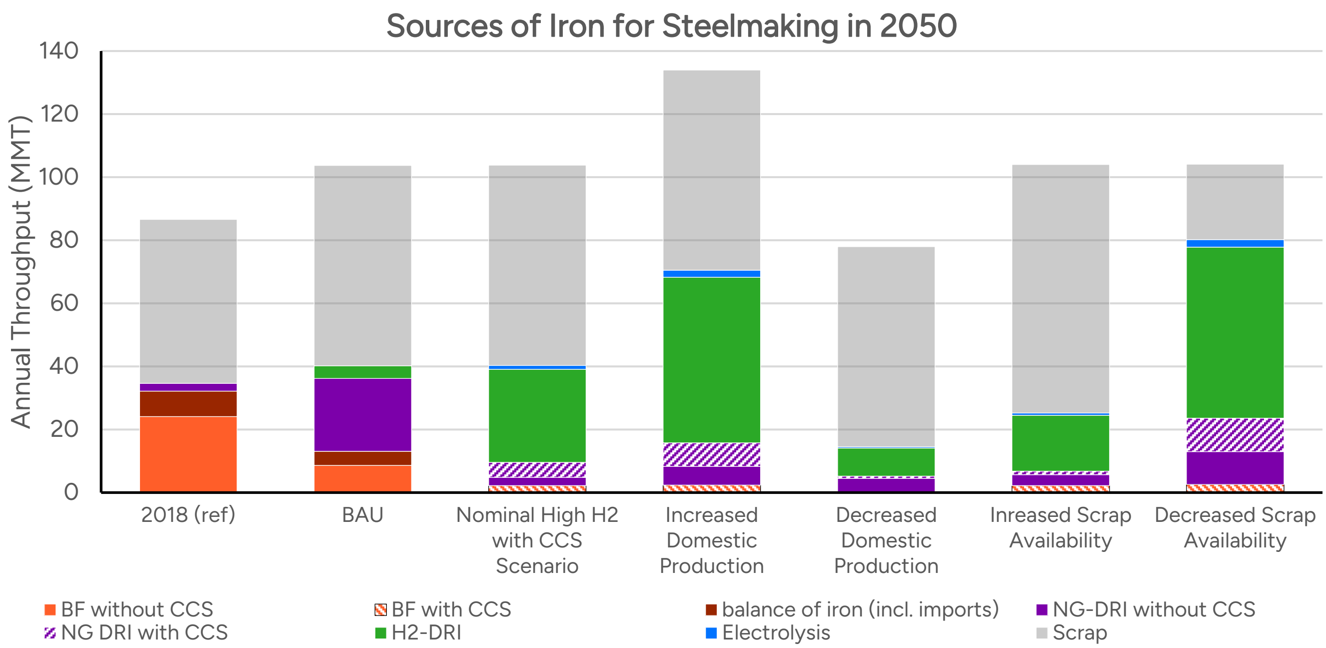


Figure 60. Impact of scrap availability and domestic production on annual GHG emissions, 2018–2050 (top) and corresponding sources of iron in 2050 (bottom)

Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C. Source: Transformative Pathways modeling.

The role of imports in the U.S. iron and steel market is substantial, currently accounting for about 25% of domestic crude steel consumption (over 60% if considering indirect import of iron and steel in finished products, e.g., vehicles and appliances).[351] Additionally, exports have a significant role in scrap, represented as a final destination for almost a quarter of merchant scrap.[352] According to the domestic production sensitivities and scrap projections shown in Figure 60, these assumptions will have major GHG impacts and will result in between 15 and 30 MMT CO_2e per year by 2050. There will be major implications on domestic ironmaking capacity, both in terms of scale and composition. Strategically rebalancing the roles of these imports and exports would have significant effects on domestic ironmaking.

The GHG emissions reductions impacts by decarbonization pillar between 2018 and 2050 are shown below for the IM-CCS pathway (Figure 61) and the H_2-DRI pathway (Figure 62). A brief discussion of each pillar's role follows.

[351] American Iron and Steel Institute, "Steel Imports Up 2.3% in June vs. May," July 26, 2022, www.steel.org/2022/07/steel-imports-up-2-3-in-june-vs-may/.
[352] U.S. Geological Survey, "2022 Minerals Yearbook: Iron and Steel tables-only release," d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/media/files/myb1-2022-feste-ert.xlsx.

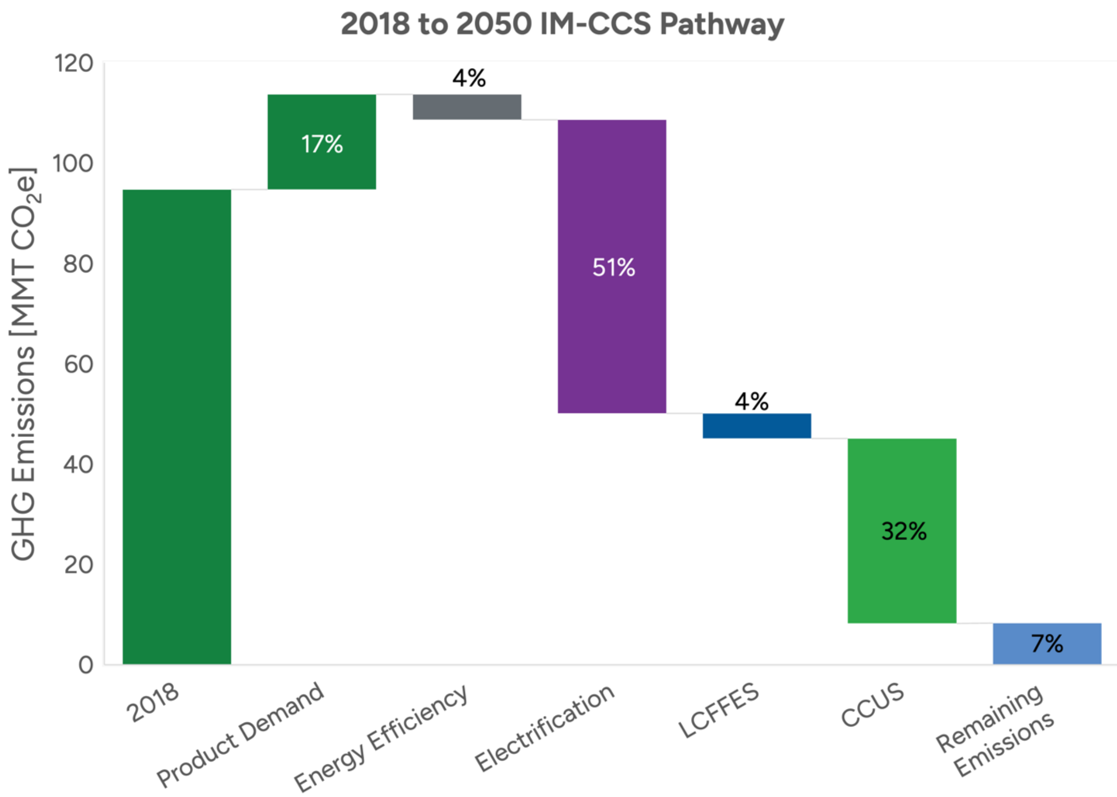


Figure 61. Impact of decarbonization pillars on GHG emissions, U.S. iron and steel manufacturing–IM-CCS pathway (MMT CO_2e), 2018–2050

Note that 18 MMT CO_2e reduction from clean finishing is attributed to electrification, but could instead be attributed to LCFFES if low-carbon fuel alternatives are used instead of electrifying the finishing processes. Additionally, 13 MMT CO_2e associated with CCS on finishing processes at integrated mills is attributed to CCS and could be attributed to electrification or LCFFES if those approaches are adopted instead. This figure may differ from the associated Roadmap figure due to further modeling considerations. Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C. Source: Transformative Pathways modeling.

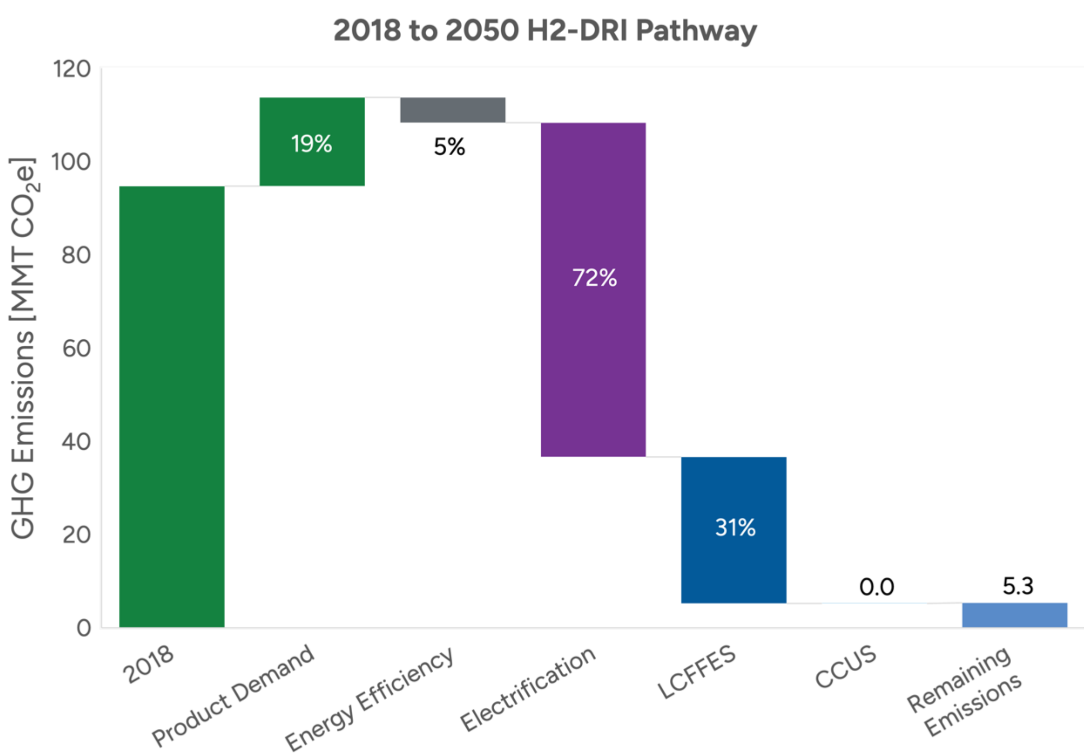


Figure 62. Impact of decarbonization pillars on GHG emissions, U.S. iron and steel manufacturing–H_2-DRI Pathway (MMT CO_2e), 2018–2050

Note that 23 MMT CO_2e is attributed to electrification from clean finishing, but this could be attributed to low-carbon fuel alternatives that are used instead of electrifying the finishing processes. This figure may differ from the associated Roadmap figure due to further modeling considerations. Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C. Source: Transformative Pathways modeling.

Energy efficiency: The U.S. iron and steel subsector has historically concentrated on enhancing its energy efficiency, and best practices have already approached the thermodynamic limit.[353] The scope for increased energy efficiency of conventional technology is limited. Therefore, the model assumes 0.1%–0.25% annual energy efficiency improvement. Although enhancements in energy efficiency are impactful for emission reductions, their effects are considerably less potent than other interventions.

Electrification: Electrification is a crucial decarbonization pillar for the iron and steel subsector. Its impact is increasingly driven by the adoption of EAF processes and, in the long term, the electrification of finishing processes such as ladle furnace, rolling, and annealing. In the core modeled scenarios, the transition to EAF production, utilizing inputs such as NG-DRI, H_2-DRI, or scrap, is essential for displacing traditional BF-BOF production. The EAF's ability to adapt to varying amounts of scrap input makes it an ideal solution for a future focused on high recycling. In addition, EAFs primarily utilize electricity as its energy source (with about 10%–20% of energy provided by natural gas for preheating and chemical energy from carbon, oxygen, and other feedstocks), allowing it to readily benefit from grid decarbonization efforts. To fully decarbonize the EAF process, it is necessary to eliminate the natural gas and fossil carbon usage which accounts for around 10 MMT CO_2e in 2050. This could be done through methods such as electrifying preheating and replacing pulverized coal with biomass (an LCFFES intervention).

Electrification is crucial not only for primary production processes but also for finishing processes such as reheat, annealing, and pickling furnaces. Cleaning of the finishing phase is essential across all sensitivities to approach near zero GHG emissions, which are projected to be around 20 to 25 MMT CO_2e in 2050 under reference production trajectories. The cleaning of the finishing stages was modeled as being electrified, but it could also be accomplished with low-carbon fuels. If it is electrified, subsector electricity demand is expected to increase from 66 TWh in 2018 to approximately 250 TWh by 2050.

Electrolytic methods such as molten oxide electrolysis and aqueous electrolysis have been proposed as ways to produce iron direct extraction from oxygen in molten oxide mediums or aqueous electrolytes using electricity, without the need for carbon reduction. However, early stakeholder feedback suggests that the adoption of electrolysis-based production methods might remain limited by 2050 due to a myriad of challenges. The primary obstacles include high energy consumption and significant technical hurdles that require substantial R&D investment and technological breakthroughs to achieve industrial scalability. The future viability of these methods will heavily depend on the availability of low-cost, clean electricity and successful scaling from laboratory to industrial levels. Investments in innovation and decarbonization technologies are critical for their adoption, and commercialization is contingent on competitive production costs and successful R&D outcomes.[354, 355]

LCFFES:[356] Low-carbon fuels can play a critical role in decarbonizing the iron and steel subsector, particularly through NG-DRI, H_2-DRI, and the use of scrap. In the short term, if BF production continues its historic trend, demand will need to be met with NG-DRI using H_2 mix fuel, and in the long term with H_2-DRI (or NG-DRI with carbon capture). The projected subsector demand for hydrogen is 5.6 MMT in 2050 under the high hydrogen sensitivity, with hydrogen fuel used at 100% for H_2-DRI and 30% for NG-DRI. However, the adoption of NG-DRI and H_2-DRI faces significant challenges. Natural gas availability and fluctuating costs coupled with the need for extensive carbon capture and storage infrastructure affect the feasibility of NG-DRI with CCS. On the other hand, H_2-DRI is constrained by the high costs and the need for vast clean energy capacity to scale up clean hydrogen production. In addition, the DRI process is highly restrictive regarding the quality of feedstock iron ore

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353 Timothy G. Gutowski et al., "The Energy Required to Produce Materials: Constraints on Energy-Intensity Improvements, Parameters of Demand," *Philosophical Transactions of the Royal Society A* 371, 1986 (March 2013), doi.org/10.1098/rsta.2012.0003.

354 Matthew S. Humbert et al., "Economics of Electrowinning Iron from Ore for Green Steel Production," *Journal of Sustainable Metallurgy* 10, (August 2024): 1679–1701, doi.org/10.1007/s40831-024-00878-3.

355 Zach Winn, "Making Steel with Electricity," *MIT News*, May 22, 2024, news.mit.edu/2024/mit-spinout-boston-metal-makes-steel-with-electricity-0522.

356 Note that scrap could also be considered a low-carbon feedstock, and its role is paramount in the subsector. The use of scrap and the implications of different assumptions of scrap availability are discussed throughout.

pellets—since it occurs in the solid state, impurity removal during the ironmaking phase is challenging. Additional processing, such as introducing an intermediate smelter between the DRI and EAF processes, may be required to manage impurity concerns.

Another LCFFES strategy for the iron and steel subsector involves decarbonizing fossil fuel feedstocks, such as replacing pulverized coal and the injected natural gas with charcoal and renewable or synthetic natural gas (produced by a clean energy source, such as nuclear), respectively, in EAF production. Charcoal, which can be produced with relatively lower life cycle emissions compared to coal, offers a potential reduction in the emissions footprint associated with EAF steel production. Brazilian integrated long steel producer Aço Verde do Brasil has experimented with this method at one of their steel mills.[357] Nonetheless, the scalability of this approach hinges on the availability of high-quality charcoal that meets the specific requirements of the EAF process. In the United States, Steel Dynamics recently selected Columbus, Mississippi, as the site for their first biocarbon production facility.[358]

CCUS: Carbon capture and storage (CCS) plays an important role in the IM-CCS pathway. Despite the current high capital expenditures (CAPEX) and operational expenses (OPEX), CCS has potential to reduce the subsector's GHG emissions from integrated mills for both traditional BF-BOF and NG-DRI-iEAF production routes. For these production routes, significant GHG emissions exist in the steelmaking and finishing stages that are assumed to be addressed with CCS with a 95% capture efficiency across the entire mill. The most ambitious capture rate of integrated mills has been projected to be 69% in recent studies, with capture of some downstream process regarded as impractical.[359, 360]

For the IM-CCS pathway, addressing all the emissions at the integrated mills is essential to achieving near zero GHG emissions in 2050 (about 8 MMT CO_2e). The scenario for IM-CCS initially assumed 70% adoption of CCS for integrated mills (with 95% capture efficiency subsequently applied) as an approximation to the 69% maximum capture potential for integrated mills. This scenario still had significant GHG emissions remaining in 2050 (28 MMT CO_2e). To achieve a near zero pathway, a sensitivity to this scenario was analyzed to approximate the capture of these remaining emissions, either through more ambitious capture across the entire integrated mill (which was modeled) or by implementing clean EAF and clean finishing technologies (the effect of which is approximated by the effect of more aggressive CCS adoption).

For BF-BOF, post-combustion CCS technologies capture CO_2 after the steelmaking process by implementing gas separation units and CO_2 compression systems. This technology can be retrofitted to existing BF-BOF plants, but it requires significant capital investment, particularly for infrastructure related to CO_2 transport and storage, which is often lacking. The potential for CCS at existing integrated mills is shown in Figure 63 below, showing all integrated mills lie within 100 miles of an identified CO_2 storage site.[361] Additionally, CO_2 capture processes incur an energy penalty, increasing the overall energy consumption of steel production.

[357] Mandy Chan and Daniel Boero Vargas, "How These 5 Steel Producers Are Taking Action to Decarbonize Steel Production," World Economic Forum, June 25, 2024, www.weforum.org/agenda/2024/06/5-steel-producers-have-overcome-challenges-to-decarbonize-steel-production/.
[358] Steel Dynamics, "Steel Dynamics Announces Location of Planned Biocarbon Production Operations — A Meaningful Strategic GHG Reduction Initiative," November 2, 2022, ir.steeldynamics.com/steel-dynamics-announces-location-of-planned-biocarbon-production-operations-a-meaningful-strategic-ghg-reduction-initiative/.
[359] Jorge Perpiñán et al., "Integration of Carbon Capture Technologies in Blast Furnace Based Steel Making: A Comprehensive and Systematic Review," *Fuel* 336 (March 2023), doi.org/10.1016/j.fuel.2022.127074.
[360] Guiyan Zang et al., "Cost and Life Cycle Analysis for Deep CO_2 Emissions Reduction of Steelmaking: Blast Furnace-Basic Oxygen Furnace and Electric Arc Furnace Technologies," *International Journal of Greenhouse Gas Control* 128, (September 2023), doi.org/10.1016/j.ijggc.2023.103958.
[361] Udayan Singh, Erica M. Loudermilk, and Lisa M. Colosim "Accounting for the role of transport and storage infrastructure costs in carbon negative bioenergy deployment," Greenhouse Gases Science and Technology 11, 1 (February 2021): 144-164, doi.org/10.1002/ghg.2041.

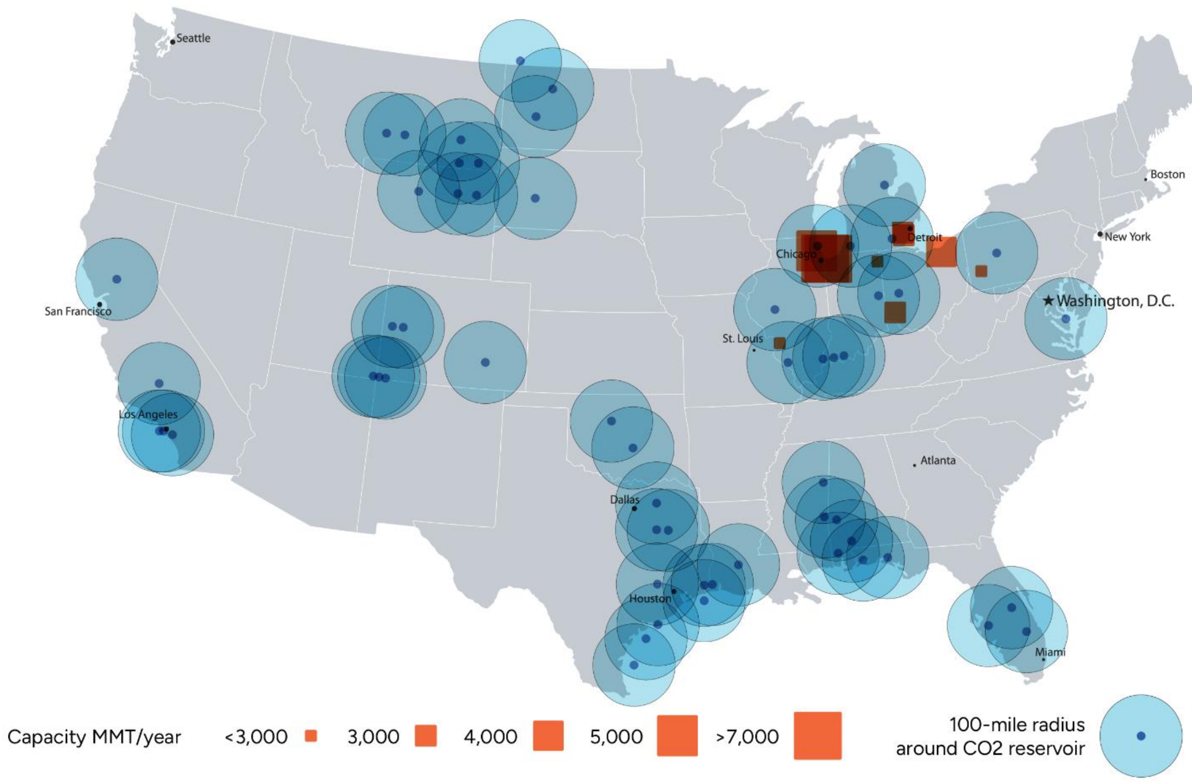

Figure 63. Location of U.S. integrated mills (squares) mapped against locations of candidate CO_2 storage locations mapped (dots)

Shaded bubbles around the dots indicate a 100-mile radius around the CO_2 reservoir. Data sources: Udayan Singh, Erica M. Loudermilk, and Lisa M. Colosim "Accounting for the role of transport and storage infrastructure costs in carbon negative bioenergy deployment," Greenhouse Gases Science and Technology 11, 1 (February 2021): 144-164, doi.org/10.1002/ghg.2041.

The adoption of CCUS in NG-DRI plants faces similar challenges, with the added complexity of integrating the technology into existing or new facilities that may require new infrastructure for CO_2 handling. Pathways for both new and existing facilities may require high CAPEX and OPEX costs, making the economic feasibility heavily dependent on future carbon pricing, government policies, and policy incentives. Technological advancements in CCUS are expected to lower costs over time, but regulatory hurdles, public concerns over the safety of CO_2 storage, and the availability of suitable storage sites remain key obstacles.

Additionally, with current CCS technologies, the maximum capture rate may be constrained by the cost-effectiveness of capturing low-CO_2-concentration flue gas. Moreover, long-term liability for stored CO_2, the environmental impact of managing byproducts such as amine salts, and the risk of increased steel production costs remain concerns for widespread adoption of CCUS in the steel subsector.[362, 363, 364]

4.4.5 Key Takeaways

Decarbonizing the U.S. iron and steel subsector is a necessary but complex endeavor, requiring a multifaceted approach that spans technological innovation, financial strategies, and structural shifts. The subsector must overcome significant challenges, including technological barriers, cost issues, raw material quality constraints, and scrap supply limitations. Addressing these challenges through aggressive innovation, strategic investments, supportive policies, and comprehensive planning is essential to meet climate targets and ensure the subsector's sustainable future. Strong, coordinated action today will pave the way for a resilient, competitive, and low-carbon iron and steel subsector that supports the nation's economic and environmental goals.

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[362] Ashok Kumar, "The Blast Furnace: A Vital Tool in Climate Neutral Ore-Based Steelmaking," *Transactions of the Indian Institute of Metals* (May 2023), doi.org/10.1007/s12666-023-02978-2.
[363] Xavier d'Hubert, "Flue Gas Cleaning to Optimize CO_2 Capture," *Iron & Steel Technology*, August 2024, www.aist.org/getmedia/bc50654c-ac72-406b-83b7-69a8ed732050/August-2024_138-150_1.pdf.
[364] CaptureMap, "Big Role for CCUS in the Iron and Steel Industry," April 2023, www.capturemap.no/big-role-for-ccus-in-the-iron-and-steel-industry/.

Two distinct decarbonization pathways emerged from the modeling for iron and steel. These pathways align in the steelmaking and finishing stages but differ in the ironmaking stage. The distinct approaches to ironmaking that define these pathways are: (1) the continued use of integrated mills, which necessitates heavy reliance on CCS, and (2) the hydrogen-DRI pathway, which focuses on hydrogen as a reducing agent and fuel, achieving significant emissions reduction with little to no reliance on CCS.

There are important limitations in the modeling that need to be acknowledged. As discussed previously, only two electrolysis production routes were included, and their adoptions were severely constrained. Nascent production routes, included and not included in the model, have the potential to fulfill the necessary role of clean iron production identified in the model.

The ironmaking stage in the identified pathways requires disparate capacity build-out, supporting infrastructure, and broader decarbonization measures (e.g., CO_2 pipelines or clean-hydrogen availability), and decisions are required in the near term (within the next 3 to 5 years). Investments in integrated mills may lock the subsector into CCS dependence, while pursuing the H_2-DRI pathway demands building up hydrogen production, infrastructure, and hydrogen-ready DRI capacity. The impacts of the identified pathways were quantified in the model. There is more uncertainty around the nascent production routes. Regardless, new ironmaking capacity that aligns with a clean production route is needed soon, and it could come from a combination of either identified pathway or from nascent production routes.

Utilizing scrap to the maximum extent possible is common to both pathways, necessitating the continuation of existing EAF in the CCS pathway and the expansion of new EAF capacities in the H_2 pathway. Decarbonizing both existing and new EAFs, as well as finishing processes, are essential steps.

In summary, the decisions made in the coming years will be pivotal in realizing near zero GHG emissions targets for the iron and steel subsector. Pathways to near zero GHG emissions are available, but they require substantial investment and careful navigation to avoid lock-in.

4.5 Petroleum Refining

4.5.1 Introduction

Petroleum refining plays a key role in the energy supply chain by delivering fuels for transportation and industrial applications, feedstocks to the petrochemical subsector, and other value-added products. As of 2023, there were approximately 120 operating petroleum refineries located across the United States. The United States has the highest refining capacity in the world, with a total processing capacity of over 18 million barrels of crude oil per day (bbl/day).[365, 366]

Overall, the United States produces about 298 billion gallons of refined petroleum products annually.[367] More than four-fifths is used to produce transportation fuels, including 148 billion gallons of motor gasoline, 75 billion gallons of distillate fuel oil (diesel, renewable diesel, biodiesel, and renewable heating oil), and 26 billion gallons of jet fuel.[368] Most of the remaining 48 billion gallons is used for other products, including asphalt and road oil, lubricants, waxes, petrochemical feedstocks, and other miscellaneous products.[369]

The U.S. petroleum refining subsector is one of the highest GHG-emitting manufacturing subsectors, with scope 1 and scope 2 emissions accounting for an estimated 244 MMT CO_2e in 2018.[370] This estimate only includes the

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[365] U.S. Energy Information Administration, "Number and Capacity of Petroleum Refineries," June 2024, www.eia.gov/dnav/pet/pet_pnp_cap1_dcu_nus_a.htm.
[366] Energy Institute, *2023 Statistical Review of World Energy*, ISBN 978-1-78725-379-7 (2023), www.energyinst.org/__data/assets/pdf_file/0004/1055542/EI_Stat_Review_PDF_single_3.pdf.
[367] Ibid.
[368] U.S. Energy Information Administration, "Refinery and Blender Net Production," October 31, 2024, www.eia.gov/dnav/pet/pet_pnp_refp_dc_nus_mbbl_m.htm.
[369] Ibid.
[370] U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Petroleum Refining," (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_petroleum_refining_energy_carbon_footprint.pdf.

direct and indirect emissions associated with the conversion of crude oil to refined products and not the extraction of crude oil nor the eventual combustion of refinery products in the transportation sector.

Impact of Refining Capacity on Emissions: U.S. refining emissions are most directly impacted by the total subsector capacity. As such, understanding the factors that impact U.S. refining capacity is key to develop a subsector decarbonization strategy, including the following:

- Domestic crude oil production has shown continued steady growth through the decade, and the United States became a net exporter of petroleum and petroleum-related products briefly in 2019 and again in 2022 and 2023.[371] Both feedstock and utility costs for U.S. petroleum refineries have decreased significantly in the last 15 years, giving them a global cost advantage.
- With rapid advances in hydraulic fracturing and increased oil well productivity, domestic petroleum output has grown sharply, providing lower-cost, readily available feedstock and fuel to U.S. refineries. U.S. crude oil has also become relatively light compared against imported oil.[372] The quality of the crude is expected to have an impact on emissions as refiners make operations modifications to accommodate domestic light crudes.
- Although demand for some refinery products has been projected to decline domestically and in other Organization for Economic Co-operation and Development countries, these reductions may not outweigh strong increasing demands in the global south as their economies grow.[373] As refining products are traded globally, any decline in domestic demand for refining products can be offset by increasing exports, which will support refining capacity. Additional information on petroleum trade and economic data is provided in Appendix C.

Based on the above, the *Transformative Pathways* modeling forecasts assumed a relatively stable and continuous refining capacity through 2050. However, due to the strong dependence of refining emissions on refining capacity, sensitivity cases were developed that demonstrate the potential impacts of significant reductions in refining capacity on total refining emissions.

Figure 64 shows both the historical refining capacity dating back to 2000 and the projected U.S. refining capacity based on different market conditions. The EIA AEO 2023 Reference Case projects a modest increase in U.S. refinery utilization, increasing by 6% over the next few years and remaining relatively flat through 2050.[374] This expected demand growth forecasted by the AEO 2023 Reference Case runs sharply in contrast to what would be necessary in achieving net zero emissions globally via capacity reduction. The IEA World Energy Outlook projects a decline in North American refinery runs of 10% under their Stated Policies Scenario (STEPS) and 61% under their Announced Pledges Scenario (APS), driven by declining domestic demand in the former case and driven by both declining domestic and declining global demand in the latter case.[375] The International Energy Agency[376] argues that worldwide oil demand would need to fall from 97 million barrels per day today to 77 million barrels per day in 2030 and 24 million barrels per day in 2050 to mitigate the worst impacts of climate change. This level of change would constitute a significant shift away from historical trends.

[371] U.S. Energy Information Administration, "Petroleum & Other Liquids," accessed November 2024, www.eia.gov/petroleum/data.php.
[372] Ibid.
[373] Intergovernmental Panel on Climate Change, "Climate Change 2022: Mitigation of Climate Change," accessed November 2024, www.ipcc.ch/report/ar6/wg3/.
[374] U.S. Energy Information Administration, *Annual Energy Outlook 2023*, 2023, www.eia.gov/outlooks/aeo/.
[375] International Energy Agency, *World Energy Outlook 2023* (2023), www.iea.org/reports/world-energy-outlook-2023.
[376] International Energy Agency, *Net Zero Roadmap: A Global Pathway to Keep the 1.5°C Goal in Reach* (2023), www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach.

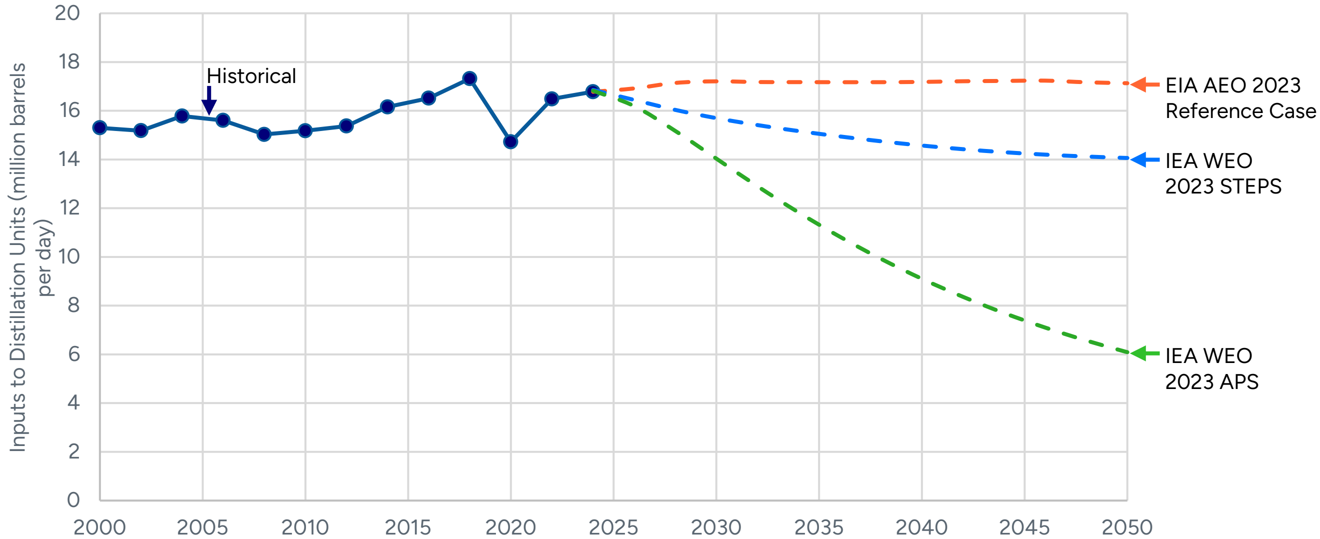

Figure 64. Historical and projected refinery utilization based on gross inputs to atmospheric crude oil distillation units

Projections are derived from the EIA AEO 2023 Reference Case (U.S. Energy Information Administration, Annual Energy Outlook 2023, 2023, www.eia.gov/outlooks/aeo/) and IEA World Energy Outlook (WEO) 2023 Stated Policies Scenario (STEPS) and Announced Pledges Scenario (APS) (International Energy Agency, World Energy Outlook 2023 (2023), www.iea.org/reports/world-energy-outlook-2023).

The *Transformative Pathways* modeling considers three primary scenarios, which are further defined and discussed in subsequent sections.

- Business as business (BAU) scenario: minimal decarbonization and high demand for liquid transportation fuel in 2050 (AEO 2023 Reference Case)
- Core scenario (CS): aggressive, balanced decarbonization across pillars, partial deployment of sustainable fuel production routes, and high demand for liquid transportation fuel in 2050 (AEO 2023 Reference Case)
- Core Near Zero (CNZ) pathway: aggressive, balanced decarbonization across pillars, maximum deployment of sustainable fuel production routes, and low demand for liquid transportation fuel in 2050 (IEA APS)

To note, additional sensitivities are considered in the analysis, which inform the development of the decarbonization scenarios. Sensitivities are introduced in Section 0 and further discussed in Appendix C.

4.5.2 Modeling Approach

The *Transformative Pathways* modeling explored existing and emerging production routes for producing refinery products. Production routes are defined as a combination of processes that utilize a specific type of feedstock and are reported in units of throughput (bbl/day). The production routes considered for the modeling are summarized in Table 16 below, where percent contribution of a given feedstock is reported relative to total throughput per a given scenario. Data is shown for the BAU, CS, and CNZ pathway, which apply different market considerations (high vs. low demand for liquid transportation fuel) and different levels of deployment of alternative feedstock production routes.

Table 16. Refining Subsector Production Routes by Feedstock

Production Route – Feedstock	Share of Total Refining Throughput (%) *		
	BAU Scenario (high demand)	Core Scenario (high demand)	Core Near Zero Pathway (low demand)
Petroleum Crude	99%	93%	47%
Pyrolysis bio-oil coprocessing (Coprocessing)	0%	5%	3%

Waste oils from fats, oils, and greases (FOGs)	1%	2%	5%
Advanced Biofuel	0%	0%	45%

*Note: In 2050, the total refining throughputs for high and low demand scenarios are approximately 17 million bbl/day and 7.5 million bbl/day, respectively.

Coprocessing: The coprocessing output assumes that 15% of fluid catalytic cracker (FCC) feedstock is replaced with bio-oil. This is based on estimates of the total amount of pyrolysis oil that could be generated with existing feedstocks and the limits of processing pyrolysis oil in existing FCC units without significant coking or degradation of product yields.[377] This 15% feed limit caps the overall impact of coprocessing at less than 5% of total throughput in 2050. This is considered a transitional production route, as it may leverage existing refinery infrastructure and support scale-up of the bioeconomy.

FOGs: Products such as renewable diesel, biodiesel, and synthetic paraffinic kerosene (SPK, a component of sustainable aviation fuel) represent a growth area for the refining subsector. Production capacity for renewable diesel and sustainable aviation fuel is expected to nearly double from 3 billion gallons per year at the end of 2022 to 5.9 billion gallons per year at the end of 2025,[378] surpassing relatively stagnant biodiesel production capacity of 2.1 billion gallons per year at the end of 2022.[379] Although the FOG feedstock production route has achieved some commercial success, further growth is likely to be limited by supply constraints.[380] Thus even under near zero conditions (high production route deployment and low demand/smaller total refining throughput), FOG impact is limited.

Advanced Biofuel: To address the limitations and challenges of producing fuels from bio-oils and FOG waste oils, expansion to lignocellulosic and non-FOG waste feedstocks could offer more substantial emissions mitigation. The *2023 Billion-Ton Report* finds that more than 1 billion tons per year of biomass could be sustainably produced in the United States, excluding food-based energy crops, equating to over 60 billion gallons of sustainably produced liquid fuels.[381] Given the more nascent state of technological development for both feedstock pre-processing and bio-oil refining, it is expected this production route would require the construction of standalone biorefinery assets.

Criticality of Demand: In the case of each alternative feedstock, alternative production routes are limited by availability of feedstock. Figure C-31 and Figure C-32 in Appendix C further examine the refining production route impact assuming high and low demand, respectively. A Core Scenario (CS) was constructed as a blend of multiple decarbonization measures that reflects the average decarbonization potential of the U.S. refining subsector. The CS includes only deployment of commercially available alternative feedstock production routes: coprocessing and FOGs. From the CS, impacts of advanced biofuel deployment were evaluated relative to changes in demand. Under high demand conditions in Figure C-31, the relative share of coprocessing grows larger than FOGs by 2050, because coprocessing share is proportional to total refining throughput. Leveraging all sustainable biomass resources, advanced biofuels production could reach an estimated maximum market share of 15%–17% by 2050. However, this clearly demonstrates that alternative feedstock production routes are limited by supply availability. No single route will clearly equal or replace crude refining under high demand conditions in the 2050 timeframe. Figure C-32 and Table 16 illustrate that the CS coupled with advanced biofuels under a low demand scenario creates a CNZ pathway where alternative feedstock production routes reach market parity with traditional petroleum crude. To note, the total refining capacity in the CNZ pathway is over 50% lower than the BAU in 2050, which infers a partial transition to zero-emission mobility by 2050.

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[377] Michael Talmadge et al., "Techno-Economic Analysis for Co-Processing Fast Pyrolysis Liquid with Vacuum Gasoil in FCC Units for Second-Generation Biofuel Production," *Fuels* 293 (June 2021), doi.org/10.1016/j.fuel.2020.119960.
[378] U.S. Energy Information Administration, *Annual Energy Outlook 2023*, 2023, www.eia.gov/outlooks/aeo/.
[379] U.S. Energy Information Administration, "Monthly Energy Review," October 2024, www.eia.gov/totalenergy/data/monthly/index.php.
[380] Tim Fitzgibbon, Khush Nariman, and Brian Roth, "Converting Refineries to Renewable Fuels: No Simple Switch," McKinsey & Company, June 21, 2023, www.mckinsey.com/industries/oil-and-gas/our-insights/converting-refineries-to-renewable-fuels-no-simple-switch.
[381] U.S. Department of Energy, *2023 Billion-Ton Report*, ORNL/SPR-2024/3103 (2024), www.energy.gov/eere/bioenergy/2023-billion-ton-report-assessment-us-renewable-carbon-resources.

Modeling Framework

A transformation of the petroleum refining subsector will require a holistic view of the anticipated decarbonization pillars and technologies that may become viable and available over varying timeframes out to mid-century and beyond. These pathways are assessed starting with a modeling framework depicted in Figure 65 and can be used to develop a broad strategy. This figure represents the barriers and near-, medium-, and long-term opportunities for refinery decarbonization that may be applicable to a specific refinery. Many decarbonization technologies in the opportunity space covered by this modeling framework are currently commercially viable, while others are expected to become commercial in the coming decades. Further, several petroleum refining decarbonization measures will likely rely on decarbonization of energy supply systems and development/expansion of energy and industrial infrastructure. Such interdependencies necessitate a careful consideration of technology choices, whether at a facility-level or a subsector-wide scale, to avoid investments that limit subsequent decarbonization efforts or create potential stranded assets in the future.

The modeling framework in Figure 65 informed the analysis that resulted in the decarbonization pathways that are described in the following section. To note, the *Transformative Pathways* modeling is not inclusive of all possible technologies. For example, production routes such as e-fuels are not included, due to lack of available data to make reasonable assumption. However, it is recognized that U.S. refining decarbonization may be achieved in part by pathways not explicitly considered in this report. Additional details on analysis boundary conditions that inform the *Transformative Pathways* modeling are provided in Appendix C.

REFINING
Modeling Framework

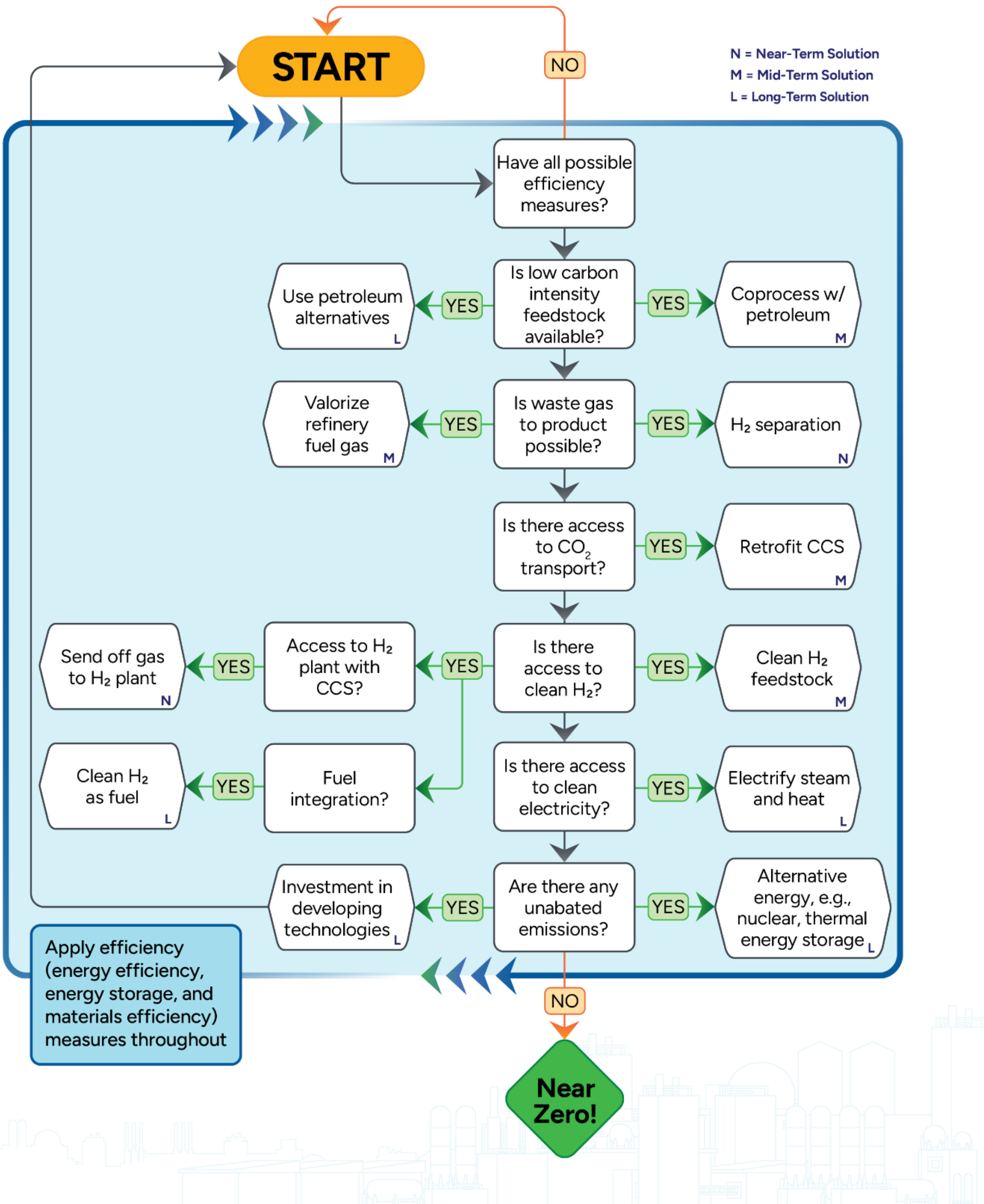

Figure 65. Petroleum refining modeling framework, including barriers and near-, mid-, and long-term solutions

4.5.3 Subsector-Specific Sensitivities

The Core Scenario for the petroleum refining subsector was created based on technologies evaluated across decarbonization pillars and the deployment of commercially ready alternative feedstock production routes (coprocessing and FOGs). A sensitivity analysis was conducted to measure the impact of subsector-specific metrics, as well as universal metrics such as energy efficiency, grid decarbonization, carbon capture, etc. Please refer to Appendix C for more detailed results of the sensitivity analysis. Below is not a complete list of all the subsector-specific sensitivities that were investigated, but it highlights some of the most impactful on the modeled results.

Hydrogen feedstock and carbon capture: Given the high utilization of hydrogen feedstock in petroleum refining, subsector decarbonization is highly sensitive to the carbon intensity (CI) and the relative amount of low-CI hydrogen available to the subsector. Maintaining the status quo of 100% fossil-based hydrogen may reduce the 2050 decarbonization outcomes by up to 15%, while increasing the utilization of low-CI hydrogen feedstock from 50% to 75% of total hydrogen feedstock consumption will increase maximum decarbonization potential of the CS by up to 15%. The analysis factors in both equipping existing on-site hydrogen production with carbon capture technology and the purchase of merchant low-CI hydrogen. Carbon capture deployment also highly affects decarbonization outcomes in the refining subsector in the context of hydrogen. Carbon capture is very attractive because it represents a sink for excess refinery fuel gas to generate the steam necessary to regenerate sorbents. Hydrogen production units represent a likely candidate for initial deployment of capture technology, due to the relative purity of the waste stream.

Energy efficiency: Efficiency is also a very sensitive decarbonization lever. Should the 1%-per-year reduction of energy intensity reported in the Core Scenario be halved, this results in a nearly 10% reduction in maximum subsector decarbonization by 2050. The EIA AEO estimates reduction in energy intensity at a rate of 0.3% per year, though some major refiners surveyed in the analysis estimate annual energy intensity reductions of 0.3%–0.5% per year.[382, 383] This further reinforces that investment in energy efficiency measures will be critical to achieving aggressive reductions in energy intensity rates.

Alternative feedstocks: Scaled across the subsector, biofuels could reach an estimated maximum market share of 15%–17% by 2050. Coupled with pyrolysis bio-oil coprocessing and FOG feedstocks, alternative feedstock production routes may displace approximately 20% (4 million bbl per day) of current market demand. Aggressive deployment of advanced biofuels may offset some petroleum crude throughput, increasing the maximum decarbonization of the subsector by up to an additional 10%,[384] in part by accounting for the self-generated fuels that are produced from sustainable feedstocks and consumed on-site. Note, this analysis does not take credit for Scope 3 emissions impacts via combustion of sustainable fuels in the transportation sector. However, should these emissions be included in the accounting, the effective Scope 3 emissions reductions from downstream sustainable fuels may be several times higher than the abated Scope 1 and 2 emissions at petroleum refineries.

Demand: Changes in demand represent the single most impactful sensitivity. Reduction in overall demand for liquid transportation fuel from the BAU (AEO 2023 Reference Case) to the Core Near Zero Pathway (IEA APS) pushes the subsector to greater than 90% decarbonization.

4.5.4 Business as Usual Scenario and Near Zero Pathways

Business as Usual

The BAU scenario leverages projections from the EIA AEO 2023 Reference Case, including refining capacity (high demand for transportation fuels), electrical grid emission factor, and the capacity of FOG in the subsector. A 0.5%-per-year reduction in energy intensity is assumed to 2050. Coprocessing and advanced biofuel

382 Marathon Petroleum, "Sustainability," 2024, www.marathonpetroleum.com/Sustainability/.
383 Shell, "Sustainability Report 2022," 2023, reports.shell.com/sustainability-report/2022/.
384 Troy R. Hawkins et al., *The Role of Biofuels and Biomass Feedstocks for Decarbonizing the U.S. Economy by 2050*, NREL/TP-5100-87279, ANL-23/56, PNNL-34336, INL/RPT-23-74427,
ORNL/SPR-2023/3134 (2024), www.osti.gov/biblio/2337775.

feedstock production routes are not deployed, and no hydrogen feedstock is decarbonized. No CCUS is assumed in the scenario. The BAU sees a steady decrease in emissions, primarily due to energy efficiency measures (e.g., process heating improvements and smart manufacturing). Although the subsector does not consume much electricity, minor decarbonization is realized via BAU grid decarbonization. The BAU achieves an emissions reduction of approximately 30 MMT CO_2 by 2050 but highlights that the status quo is insufficient to achieve near zero emissions by 2050.

Core Scenario

The CS uses the EIA AEO 2023 Reference Case refining capacity, which assumes steady, high demand for liquid transportation fuels to 2050. Figure 66 shows the relative impact decarbonization levers will have to move the petroleum refining subsector from BAU to the CS. Together, they yield approximately a 130 MMT CO_2 (about 55%) reduction in emissions from the 2018 baseline.

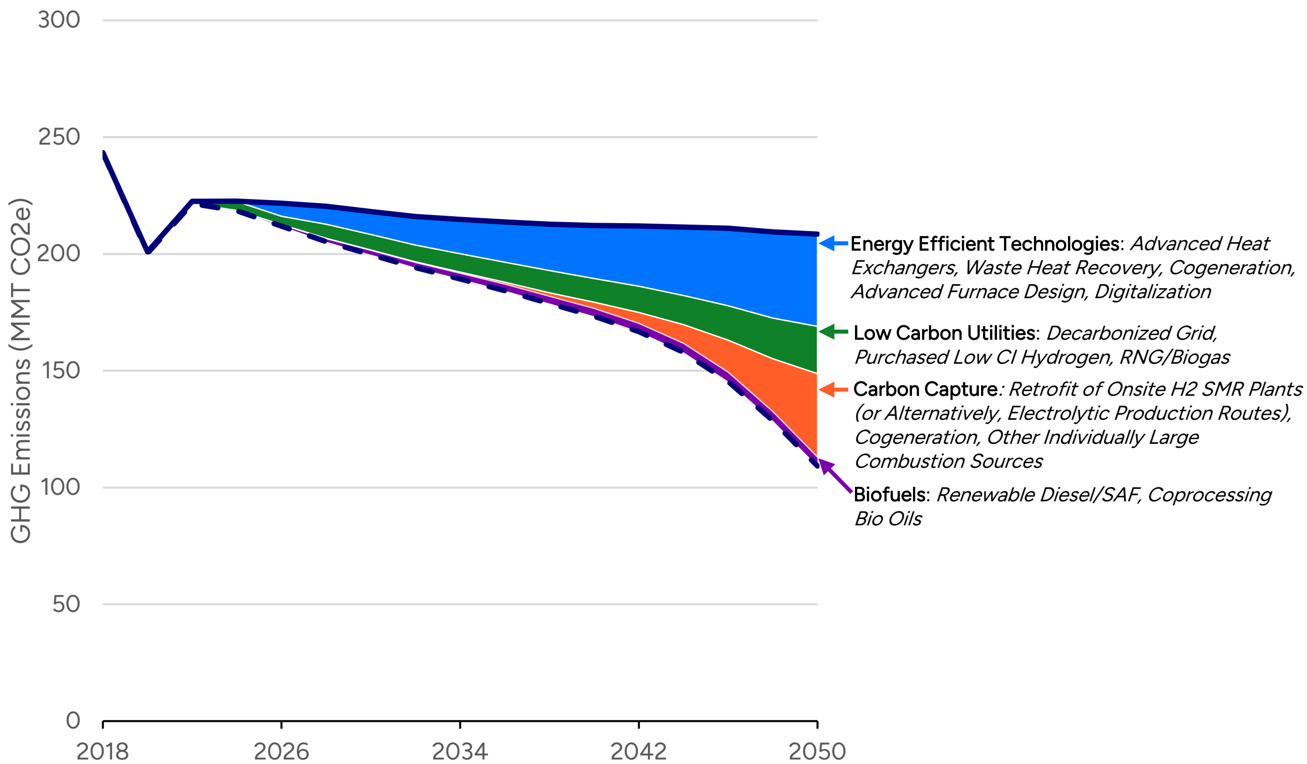

Figure 66. Annual GHG emissions reductions, U.S. petroleum refining—Core Scenario (MMT CO_2e/year), 2018–2050

The CS for the petroleum refining subsector was created based on technologies evaluated across the decarbonization pillars. The adoption rates of these technologies were maximized, while factoring in limited economic, regulatory, and infrastructure constraints. The CS also maintains an energy balance within the system on steam, refinery fuel gas, power, and hydrogen. See Appendix C for details regarding the parameters of the CS.

The CS demonstrates that even with aggressive deployment of decarbonization measures and maximum commercialization of coprocessing and FOG production routes, the subsector remains difficult to decarbonize under a future scenario with high demand for liquid transportation fuels. If demand for refinery products remains high, alternative feeds will not be sufficient to significantly offset or reduce petroleum crude throughput.

Core Near Zero Pathway

The Core Near Zero (CNZ) pathway differs from the CS in two primary areas: (1) it uses the low demand refining capacity, IEA APS; and (2) it includes the deployment of advanced biofuels.

Figure 67 illustrates the relative impact of decarbonization levers that will have to move the petroleum refining subsector from a BAU scenario to the Core Near Zero Pathway. In short, the CS decarbonization conditions are coupled with low demand for liquid transpiration fuel (IEA APS) and maximum deployment of advanced biofuels. This represents a scenario where all available alternative feedstock production routes are completely maximized. As previously noted, biofuels could reach an estimated maximum market share of 15%–17% by 2050 if scaled across the subsector. Along with pyrolysis oil coprocessing and FOG feedstocks, alternative feedstock production routes may displace approximately 20% (4 million bbl per day) of current market demand.

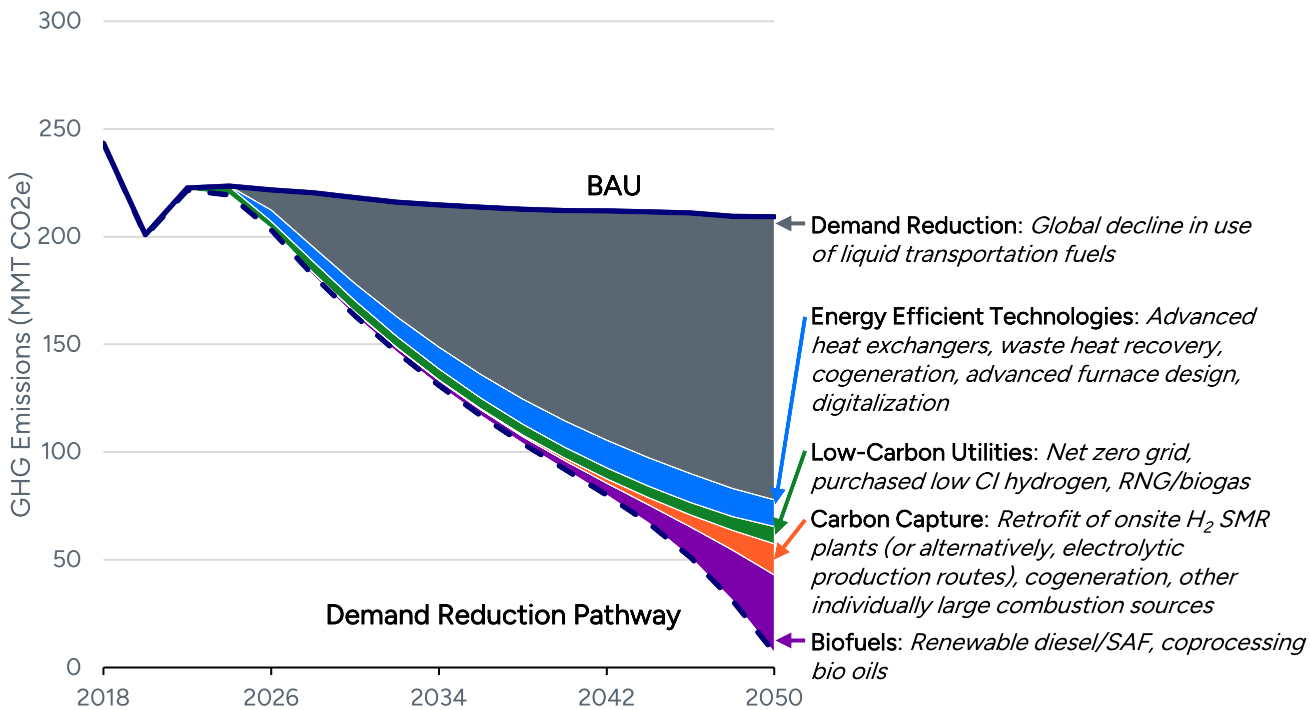

Figure 67. Annual GHG emissions reductions, U.S. petroleum refining—Core Near Zero pathway (MMT CO_2e/year), 2018–2050

Under the CNZ pathway, total refining throughput is 8 million barrels per day in 2050, composed of approximately 4 million barrels per day of petroleum crude and 4 million barrels per day of alternative feedstock production routes. For reference, the BAU scenario maintains a relatively steady 17 million barrels per day throughput from 2018 to 2050. The transition from BAU to the CNZ pathway will result in more than 50% reduction in overall demand for liquid fuels. The petroleum crude remaining in the subsector by 2050 is decarbonized mostly through energy efficiency, as low-carbon utilities and carbon capture (particularly in the context of production of low-CI hydrogen feedstock).

In summary, the CNZ pathway is a blend of multiple decarbonization measures that reflect the average decarbonization potential of the U.S. refining subsector through aggressive deployment of decarbonization technologies, maximum utilization of alternative feedstock production routes, and a low demand for liquid transportation fuel. Ultimately, decarbonization at the facility level will depend on numerous factors, including geography and the size and complexity of individual refineries. A further discussion of these considerations is included in Appendix C.

4.5.5 Key Takeaways

Decarbonizing the petroleum refining subsector requires a strategic and integrated approach. Although the U.S. petroleum refining subsector accounted for 5% of total U.S. energy-related CO_2 emissions in 2020, the transportation sector that consumes the fuels from refining accounted for over 30% of total U.S. economy emissions.[385] Refineries play a pivotal role in the transition toward a low-carbon future through the supply of low-carbon liquid transportation fuels. Thus, simultaneous pursuit of RDD&D decisions for refining and transportation decarbonization is imperative. This collaborative effort will ensure a synchronized and cohesive strategy, optimizing the collective impact on GHG emissions.

As noted in this analysis, low-CI hydrogen feedstock and carbon capture offer significant decarbonization potential, but it will require rapid infrastructure development to achieve decarbonization targets outlined in the CS. Energy efficiency improvement remains a critical component to refinery decarbonization and offers near-term opportunity using known technologies. However, refiners must identify major energy efficiency opportunities and avoid the financial barrier of implementing energy efficiency over many small opportunities for adoption rates to maintain the aggressive 1% per-year improvement rate used in the Core scenario. On the other hand, electrification may have a limited role in the subsector's decarbonization, particularly due to the need for refiners to find a use for self-generated fuels. Moreover, significant deployment of electric boilers will necessitate a rebalancing of facility energy sources and consideration of impacts to waste heat used to generate steam.

The prospect of producing liquid hydrocarbon-based fuels from a broader suite of alternative feedstocks, including sustainable biomass, recycled materials, and CO_2 (e.g., e-fuels), is a promising, albeit emerging, pursuit. While many of these feedstocks are not explicitly modeled in the results in this report, these innovations hold the potential to be highly impactful, allowing for a substantial reduction in net emissions by offsetting traditional crude feedstocks. Leveraging the existing infrastructure in the liquid transportation fuel market makes this approach not only environmentally impactful but also economically viable, particularly in the near term. However, in the long term, developing and deploying alternative feedstocks supply chains and cost-competitive conversion processes are crucial.

Addressing the challenges of reducing direct emissions from the petroleum refining subsector has the potential to significantly impact the total U.S. GHG emissions. However, the level of effort needed to implement these improvements will be significant and require investment on multiple fronts. In addition, these investment strategies will need to support concurrent efforts to decarbonize the transportation sector as well as be flexible enough to adapt to changing product demands. By developing an integrated strategy that includes new energy-efficient technologies, infrastructure investments, and technologies that generate lower-carbon transportation fuels, the refining subsector will be well positioned to meet the desired decarbonization goals being developed for this industry.

4.6 Pulp and Paper

4.6.1 Introduction

Pulp and paper manufacturing creates a wide variety of products, including graphic papers, newsprint, containerboard, linerboard, tissue, and specialty paper. In 2022, the United States produced approximately 49 million metric tons of paper and paperboard, which constituted about 24% of global paper and paperboard production.[386] As of 2023, this subsector accounted for more than 4% of the U.S. gross domestic product.[387, 388] This subsector also accounted for about 12% of U.S. manufacturing primary energy consumption in 2018, the third largest consumer in manufacturing after the chemicals and petroleum and coal products subsectors.[389] This subsector emitted 6% of the total U.S. manufacturing GHG emissions in 2018.[390]

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[385] U.S. Department of Energy, *Industrial Decarbonization Roadmap*, DOE/EE-2635 (2022), www.energy.gov/industrial-technologies/doe-industrial-decarbonization-roadmap.
[386] Statista Research, "United States Pulp and Paper Industry - Statistics & Facts," September 19, 2024, www.statista.com/topics/5268/us-pulp-and-paper-industry/.
[387] Ibid.
[388] NCASI, "Pulp and Paper Manufacturing," accessed November 2024, www.ncasi.org/pulp-paper-manufacturing/.
[389] U.S. Department of Energy, "Manufacturing Energy and Carbon Footprints (MECS 2018)," accessed November 2024, www.energy.gov/eere/iedo/manufacturing-energy-and-carbon-footprints-2018-mecs.
[390] Ibid.

To achieve industrial decarbonization at national and global scales, decarbonizing the pulp and paper subsector is imperative. The market dynamics of this subsector are complex, especially given rapid changes in consumer demands. Recent years have seen a growth in digital and electronic media, leading to a decrease in newsprint and graphic papers. On the other hand, there has also been growth in hygiene- and packaging-related products, leading to a change in the relative proportions of the different pulp and paper products over time. Quantifying the emissions from these different product types is essential to accurately model the subsector emissions.

The global pulp and paper subsector has reduced its energy and emissions intensity by an average of almost 3% per year between 2010 and 2022, with the use of energy efficiency principles, fuel switching, combined heat and power, and increased recycling.[391] A similar trend has been seen for U.S. pulp and paper manufacturing.[392] EIA expects a similar reduction of about 2% in the subsector fuel-related CO_2e emissions by 2050 compared to 2022 in its reference case.[393]

At the mill level, process heating operations, steam generation, and cogeneration are major drivers of energy consumption, as shown in Figure 68. On-site emissions from pulping operations are largely from the recovery boiler (66% of on-site emissions), followed by the auxiliary boiler (26%). The remaining 8% are from the lime kiln.[394] Typical opportunities to reduce these emissions include increasing efficiency, recovering waste heat, and considering alternative processes. Beyond plant-level emissions, the emissions associated with wood and pulp procurement can also add to the overall footprint. About 38% of all roundwood harvested in the United States is consumed by pulp and paper mills,[395] impacting the subsector's scope 3 emissions, which are outside the scope of this report.

[391] International Energy Agency, "Paper," July 11, 2023, www.iea.org/energy-system/industry/paper.
[392] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022*, EPA 430-R-24-004 (2024), www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.
[393] U.S. Energy Information Administration, *Annual Energy Outlook 2023*, "Table 26. Paper Industry Energy Consumption" (2024), www.eia.gov/outlooks/aeo/data/browser/#/?id=37-AEO2023&cases=ref2023&sourcekey=0.
[394] Sunkyu Park, "Technical Challenges to Reduce Energy Use in Pulping and Chemical Recovery," presented at U.S. Department of Energy Decarbonization Challenges and Priorities in Forest Products Industry Workshop, September 12, 2023, Atlanta, GA, www.energy.gov/sites/default/files/2023-11/Process%20Energy%20Eff-Sunkyu%20Park_NCSU.pdf.
[395] Consuelo Brandeis et al., *Status and Trends for the U.S. Forest Products Sector,* U.S. Department of Agriculture (2020), doi.org/10.2737/SRS-GTR-258.

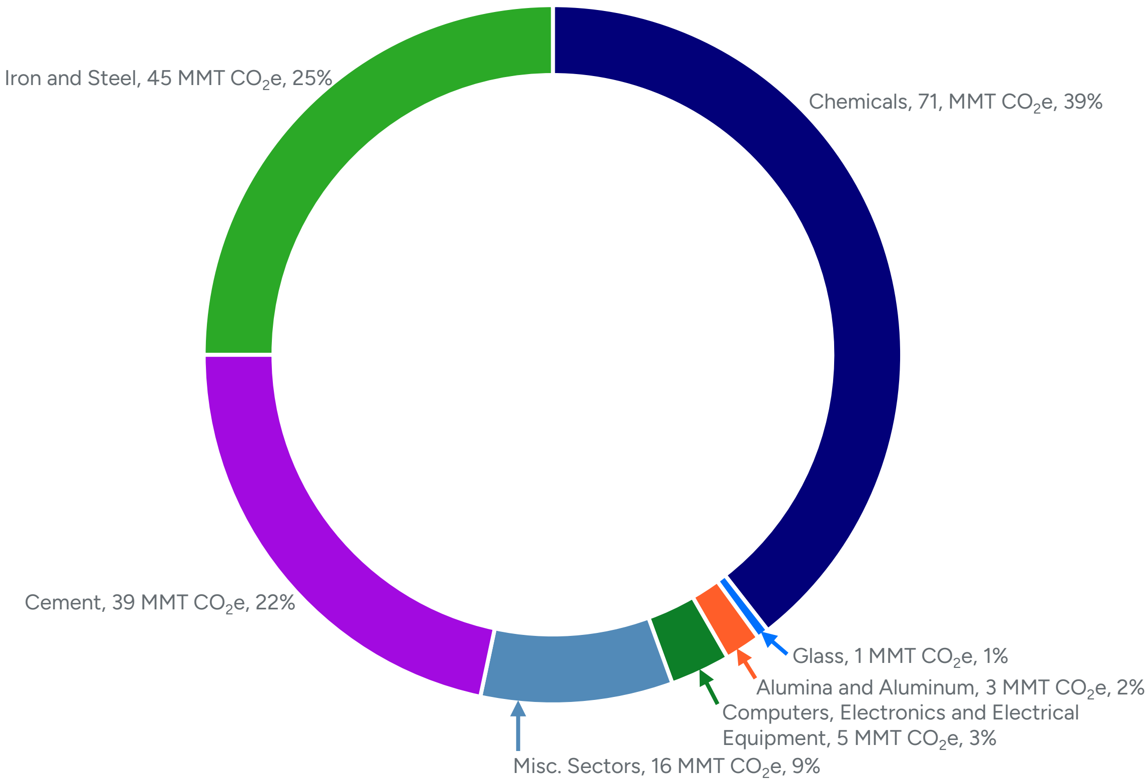

Figure 68. Typical energy (fuel and electricity) consumption for the pulp and paper subsector in gigajoules per metric ton (GJ/t)

Note: *Recovery boiler uses black liquor as fuel. Sources: U.S. Department of Energy, "Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Pulp and Paper Manufacturing" (2015), www.osti.gov/biblio/1248750; Jibran Zuberi, Ali Hasanbeigi, and William Morrow, Electrification of U.S. Manufacturing With Industrial Heat Pumps, LBNL-2001478, (Lawrence Berkely National Laboratory, 2022), eta.lbl.gov/publications/electrification-us-manufacturing; H. L. Brown, B. B. Hamel, and B. A. Hedman, Energy Analysis of 108 Industrial Processes (1996), www.osti.gov/biblio/5576602; U.S. Department of Energy, Pulp and Paper Industry Energy Bandwidth Study (2006), www.osti.gov/biblio/1218635.

To reach near zero by 2050, the pulp and paper subsector needs more aggressive GHG emissions reductions than seen historically.[396] Considering the different products and their emissions intensities together helps determine which decarbonization technologies are appropriate for specific mills. Tomberlin et al. (2020) studied the GHG intensity of different pulp and paper products based on self-reported mill data and data-mined emissions factors.[397] The production volume and emissions intensity indicate the high contribution of paperboard to overall subsector emissions. With e-commerce playing a major role in how customers purchase goods and services, production of paperboard and packing paper products can be expected to increase, which can potentially also increase the total subsector GHG emissions.

Recycling is expected to play an important role in decarbonizing this subsector. In this report, the production processes for recycled products are modeled separately, but the transportation energy for wastepaper products is out of scope. Recycled paperboard can have slightly higher scope 1 and scope 2 emissions than unbleached paperboard. However, when including biogenic emissions, recycled paperboard has the lowest emissions amongst the paperboard types,[398] leading to a need for careful consideration and modeling of sensitivities on carbon accounting.

[396] See U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022*, EPA 430-R-24-004 (2024), www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.
[397] Kristen E. Tomberlin, Richard Venditti, and Yuan Yao, "Life Cycle Carbon Footprint Analysis of Pulp and Paper Grades in the United States Using Production-Line-Based Data and Integration," *BioRes.* 15, 2 (April 2020): 3899–3914, doi.org/10.15376/biores.15.2.3899-3914.
[398] Ibid.

4.6.2 Modeling Approach

The *Transformative Pathways* modeling considered multiple pulp and paper products and production processes. The pulp and paper subsector is diverse; multiple products are manufactured through different production routes and are used for a myriad of purposes. In 2022, the United States produced approximately 67.5 MMT of paper and paperboard which constituted about 16.2% of the global paper and paperboard production. Of this total, 8.3 MMT were graphic papers such as newsprint, printing, and writing papers. Wrapping and packaging paper and paperboard accounted for the largest portion of production that year at roughly 50.9 MMT, a slight increase from 2020, which included 3.7 MMT of packaging paper, 2.5 MMT of wrapping paper, 8.4 MMT of carton board, and 36.2 MMT of case materials or corrugated board. The United States also produced 6.9 MMT of household and sanitary papers and 1.3 MMT of other paper and paperboard in 2022.[399]

This modeling effort includes projected production volumes of the pulp and paper subsector from 2018 to 2050. The EIA AEO projects a slight reduction in the value of shipments in the next few years, but then expects an overall increase leading to a 0.3% growth in 2050 compared to 2022.[400] This is comparable to multiple subsector reports.[401] Some reports have been more optimistic, stating 5% growth per annum in the upcoming decade.[402] This could be an impact due to the different product types that are part of the subsector. A widely cited McKinsey & Company article predicts the growth or decline of the product types that vary by a large factor.[403] This modeling includes projections on how production volumes will change over time, planned capacity changes, and extrapolations from previous production volume data to develop the values pictured in Figure 69. A key takeaway is an increase in packaging paper and paperboard production volumes expected by 2050. This can present an opportunity to increase recycled content in packaging paper and paperboard products. However, increased recycled content can lead to slightly higher emissions, when not considering biogenic emissions.

[399] Food and Agriculture Organization of the United Nations, *Pulp and Paper Capacities, Survey 2023–2025*, ISSN 0255-7665 (2024), openknowledge.fao.org/handle/20.500.14283/cd2190t.
[400] U.S. Energy Information Administration, *Annual Energy Outlook 2023*, "Table 26. Paper Industry Energy Consumption" (2024), www.eia.gov/outlooks/aeo/data/browser/#/?id=37-AEO2023&cases=ref2023&sourcekey=0.
[401] Fortune Business Insights, "North America Pulp and Paper Market to Reach USD 65.10 Billion by 2029," *Yahoo! Finance,* April 26, 2022, finance.yahoo.com/news/north-america-pulp-paper-market-083500514.html.
[402] Allianz Trade, "Paper Sector Risk Report," accessed November 2024, www.allianz-trade.com/en_US/resources/sector-reports/paper.html.
[403] Peter Berg and Oskar Lingqvist, "Pulp, Paper, and Packaging in the Next Decade: Transformational Change," McKinsey & Company, August 7, 2019, www.mckinsey.com/industries/paper-and-forest-products/our-insights/pulp-paper-and-packaging-in-the-next-decade-transformational-change.

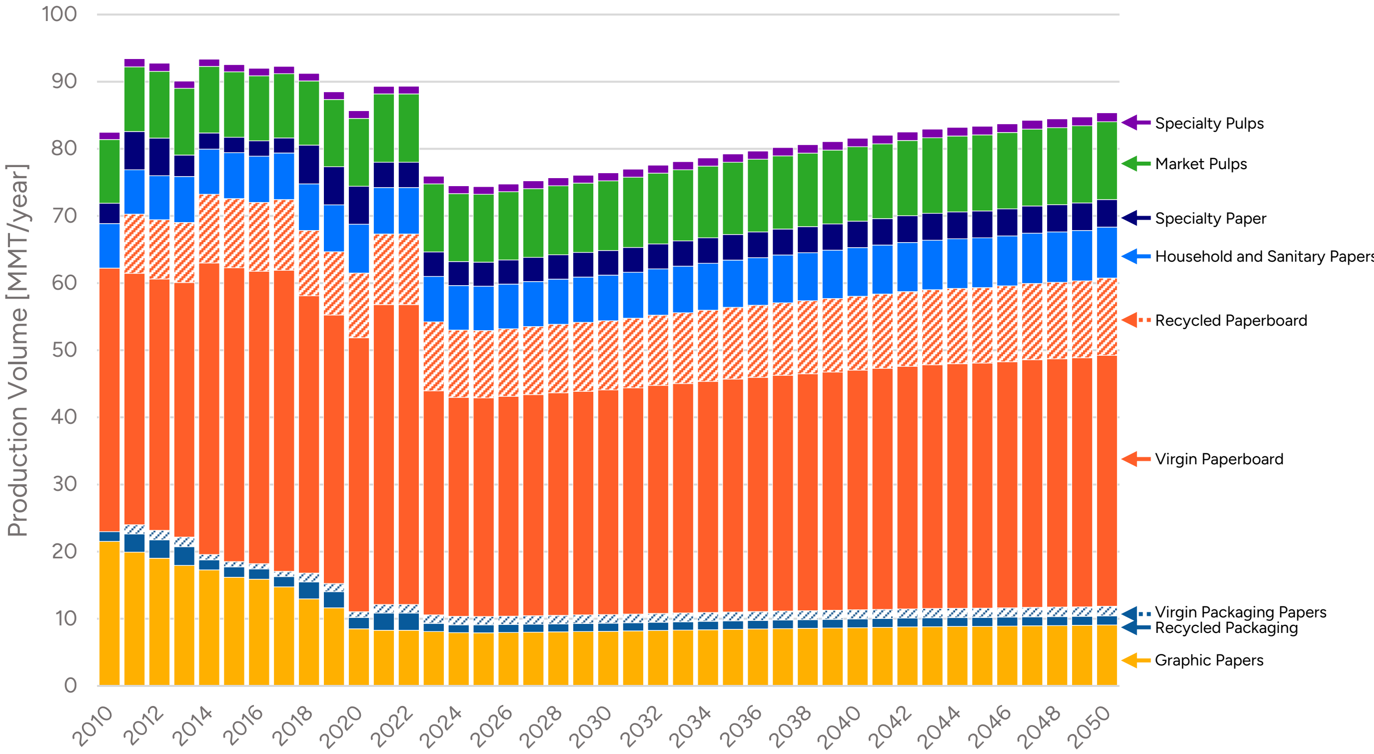

Figure 69. Pulp and paper subsector production volumes by product type, 2010–2050

Source: Transformative Pathways modeling.

This report focuses on the Kraft process as the dominant production route globally. The Kraft process is efficient and produces higher quality pulp, while handling various wood species easily as feedstocks and allows for chemical recycling. Broad product groups are considered in this analysis to account for the different pulp and paper product types and the production mill types, as shown in Table 17. The production routes are modeled in a generalized manner so that implementing decarbonization technologies can be more easily modeled. Virgin pulp and paper products are all based on lumber. The basic process flow for this subsector can be seen in Figure 70, with the flow of the lumber through the wood preparation step to the pulping process, followed by the papermaking step. With the increase in recycled content, the paper recycling step has gained more importance over time. Table C-44 in Appendix C provides the assumed unit operations and energy intensities for each product type in the subsector model.

Although the Kraft process is predominant in pulping, alternatives for pulping include deep eutectic solvents, membrane separation process, and alternative sources of fiber. These were not included in the analysis due to the low maturity of these technologies and lack of reliable data on energy intensities and market adoption. Adoption of these alternative pulping processes may significantly alter the decarbonization potential of the interventions that were explored, though some interventions may not be applicable.

Table 17. Pulp and Paper Products and the Associated Production Process/Mill Types Considered in This Analysis

Mill Type	Products
Pulping mill	• Market pulp • Specialty pulp
Integrated mill (both pulping and papermaking in the same facility)	• Graphic paper • Virgin packaging paper and paperboard
Non-integrated mill, domestic and/or imported pulp as input	• Tissue paper • Specialty paper
Non-integrated mill, recycled fiber as input	• Recycled packaging paper and paperboard

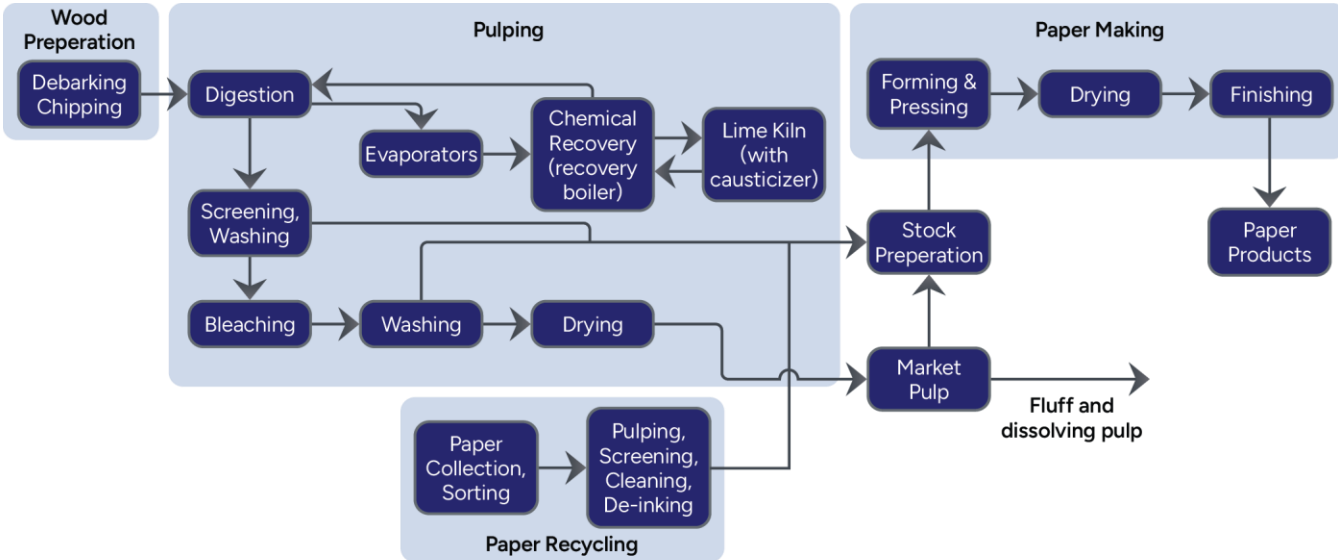

Figure 70. Flow diagram of the pulp and paper subsector

Adapted from U.S. Department of Energy, Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Pulp and Paper Manufacturing (2015), www.osti.gov/biblio/1248750.

Multiple technologies, within unit processes as well as across unit processes, can be considered in parallel for decarbonizing this subsector. The choices will depend on different decisions based on specific conditions, such as availability of clean energy resources or low-carbon fuels. As part of this effort, a modeling framework (Figure 71) was developed to present the alternative technologies considered in this analysis along with the different decision points that could lead to multiple technology choices.

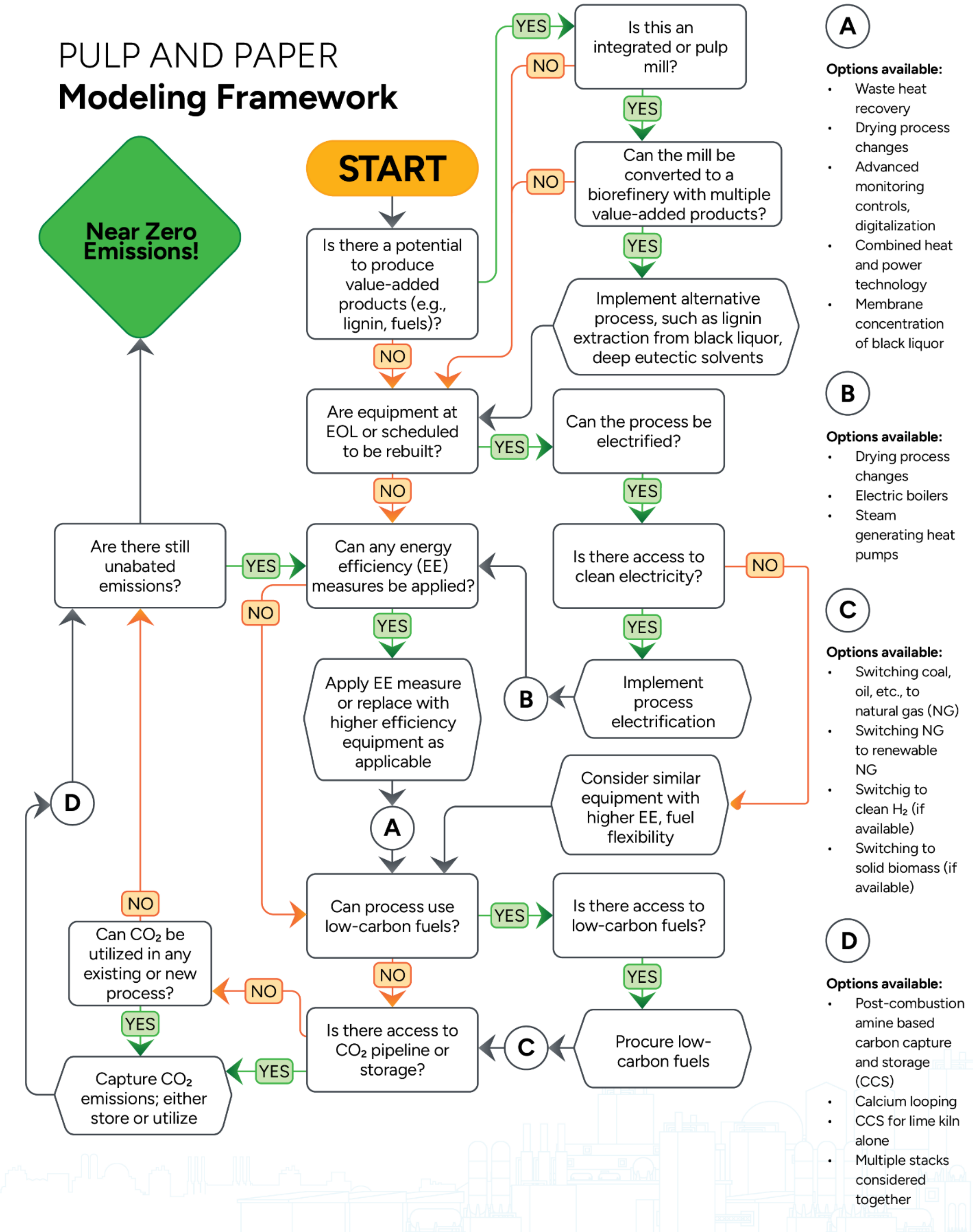

Figure 71. Pulp and paper modeling framework

4.6.3 Subsector-Specific Sensitivities

Impacts of expected changes in the subsector beyond the modeled scenarios are evaluated using the sensitivities summarized in Section 3.2.2 and below in Table 18. Table C-45 and Table C-46 in Appendix C provide the sensitivity analysis results.

Table 18. Assumptions Considered Under Each Sensitivity for Pulp and Paper Model

Sensitivity	Assumptions Considered
Use of clean H2 as a fuel	Baseline near zero assumes 12% H2 fuel consumption in the fuel mix for tissue production. This sensitivity considers 0% H2 fuel consumption throughout the subsector.
Increased electrification	Baseline near zero assumes up to 20% replacement of auxiliary boiler with electric boilers.
Increased energy efficiency	Baseline near zero assumption plus increased recovery boiler efficiency by replacement instead of rebuilding.
Increased recycled content	Baseline near zero assumption plus modified medium demand with 50% of packaging paper and paperboard from recycled fibers.
Impact of demand changes and demand reduction	Baseline near zero assumption plus modified medium demand with 50% reduction in demand for packaging paper and paperboard.
Domestic production vs. Imports	Baseline near zero assumption plus modified medium demand with 50% of pulp imported instead of domestically produced.

Use of clean H_2 as a fuel: Hydrogen applicability is limited for pulp and paper, with low adoption (about 4% of total subsector fuel use) for tissue drying. For this subsector, the low potential hydrogen use case sensitivity is considered, where there is no availability of hydrogen for combustion. Hydrogen is also not blended with natural gas in this sensitivity.

Increased electrification: Electrification is limited to drying processes and auxiliary boilers in this subsector. In the baseline near zero scenario, up to 20% of the auxiliary boilers are electrified, either as electric boilers or steam-generating heat pumps. For the pulp and paper subsector, a high potential electricity use case sensitivity is considered, where the electrification technology adoption is maximized to understand the maximum potential of this pillar. The cost of electricity was assumed to be about twice that of natural gas, as most of the pulp and paper mills are located in areas of higher electricity rates.

Near zero without carbon capture: Carbon capture is an attractive technology for this subsector as it can lead to net-negative emissions. However, given the vagaries of CCS costs and availability of storage options, CCS adoption could be limited. An alternative pathway to reaching near zero emissions in this subsector is considered, which would not depend on the deployment of carbon capture technologies, i.e., low potential CCUS sensitivity.

Increased energy efficiency: To address the importance of this pillar, sensitivities regarding the energy efficiency improvements of technologies based on maturity levels are considered. Additionally, the impact of equipment replacements instead of rebuilds for certain equipment, e.g., recovery boiler, is also considered.

Increased recycled content: Increasing recycled content in higher-quality paper products is limited due to the low maturity of such technologies. This sensitivity focuses on evaluating the impact of increasing recycled content with higher yield and product quality on subsector emissions.

Impact of demand changes and demand reduction: Product reuse or packaging innovations can lead to overall reduction in production demand, while the consumer demand remains the same. Some recent technological developments in the pulp and paper subsector that have the potential to be deployed to reduce demand for products in the subsector include increased digitization, increased recycled content, use of alternative pulps such as hemp, cotton etc., reusable packaging and transport boxes, and moving away from multi-level packaging by adopting a ship-in-own-container approach. This sensitivity assesses the impact of demand reduction on subsector emissions.

Domestic production vs. imports: Feedstock choices can play a key role in the overall subsector emissions and have broader impacts on resiliency and resource independence. As imports offset domestic pulp production, the impact to paper products emissions intensity can be unclear. This sensitivity assesses the impact of shifting the imports to domestic production and vice versa.

Impact of biogenic emissions and their capture potential: The subsector emissions do not account for all of the energy consumption during the production processes due to a substantial use of biomass-based fuels, such as pulping liquor and waste wood, that emit biogenic emissions.[404] Biogenic emissions have been broadly considered to be net zero emissions due to CO_2 uptake during the biomass growth period.[405] However, biogenic emissions in this subsector can be more than 50% of the total emissions if included.[406] It might then be imperative to broaden decarbonization goals to include biogenic carbon emissions to the fossil fuel and process emissions, especially for this subsector.[407] Including the scope 2 emissions from electricity generation and biogenic emissions, the total CO_2e emissions for this subsector would be more than doubled, to around 184 MMT CO_2e per year.[408] Including biogenic emissions can change technology choices (e.g., switch from LCFFES to electrification or increased H_2 use), which are assessed in this sensitivity.

4.6.4 Business as Usual Scenario and Near Zero Pathways

Under the BAU scenario, GHG emissions in 2050 decreases by roughly 19% (21 MMT CO2e) compared to 2018, but significant unabated emissions remain. BAU assumes slow technology adoption and limited implementation of lower-maturity technologies, consistent with current trends in the market. Electrification accounts for most of the emissions reductions in the BAU scenario compared to 2018; however, this will only be realized if the electric grid is decarbonized.

A near zero pulp and paper subsector is fundamentally driven by increased biomass use, decarbonizing steam generation, and improving energy efficiency of core unit processes and equipment, including drying, debarking, digestion, and the lime kiln. Figure 72 illustrates the annual GHG emissions reduction from 2018 to 2050 through the implementation of different decarbonization interventions for the CNZ pathway. The contribution of the decarbonization pillars in the CNZ pathway is shown in Figure 73.

[404] Kristen E. Tomberlin, Richard Venditti, and Yuan Yao, "Life Cycle Carbon Footprint Analysis of Pulp and Paper Grades in the United States Using Production-line-based Data and Integration," *BioRes.* 15, 2 (April 2020): 3899-3914, doi.org/10.15376/biores.15.2.3899-3914.
[405] Hamed Kouchaki-Penchah et al., "Impact of Biogenic Carbon Neutrality Assumption for Achieving a Net-Zero Emission Target: Insights from a Techno-Economic Analysis," *Energy and Climate* 57, 29 (July 2023), doi.org/10.1021/acs.est.3c00644.
[406] Kristen E. Tomberlin, Richard Venditti, and Yuan Yao, "Life Cycle Carbon Footprint Analysis of Pulp and Paper Grades in the United States Using Production-line-based Data and Integration," *BioRes.* 15, 2 (April 2020): 3899-3914, doi.org/10.15376/biores.15.2.3899-3914.
[407] Hamed Kouchaki-Penchah et al., "Impact of Biogenic Carbon Neutrality Assumption for Achieving a Net-Zero Emission Target: Insights from a Techno-Economic Analysis," *Energy and Climate* 57, 29 (July 2023), doi.org/10.1021/acs.est.3c00644.
[408] Kristen E. Tomberlin, Richard Venditti, and Yuan Yao, "Life Cycle Carbon Footprint Analysis of Pulp and Paper Grades in the United States Using Production-Line-Based Data and Integration," *BioRes.* 15, 2 (April 2020): 3899–3914, doi.org/10.15376/biores.15.2.3899-3914.

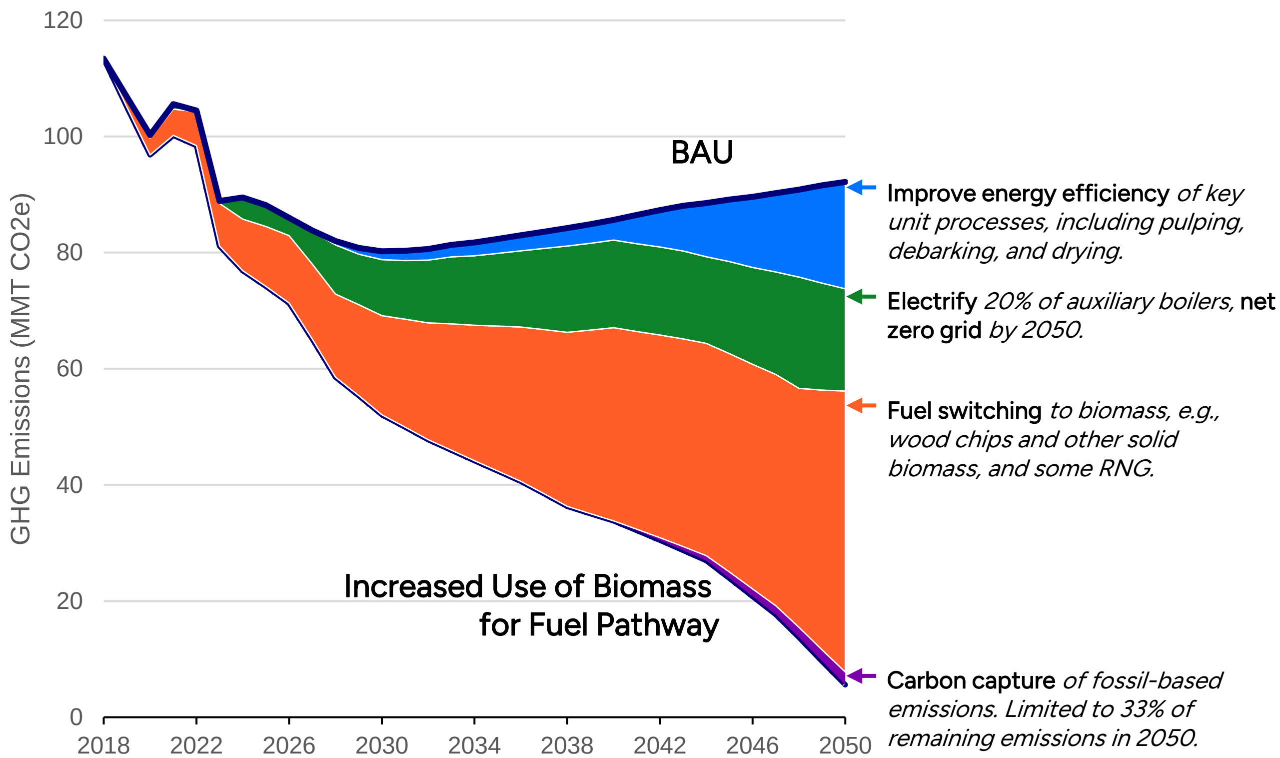

Figure 72. Annual GHG emissions reductions, U.S. pulp and paper manufacturing–Core Near Zero pathway (MMT CO_2e/year), 2018–2050

Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C. Source: Transformative Pathways modeling.

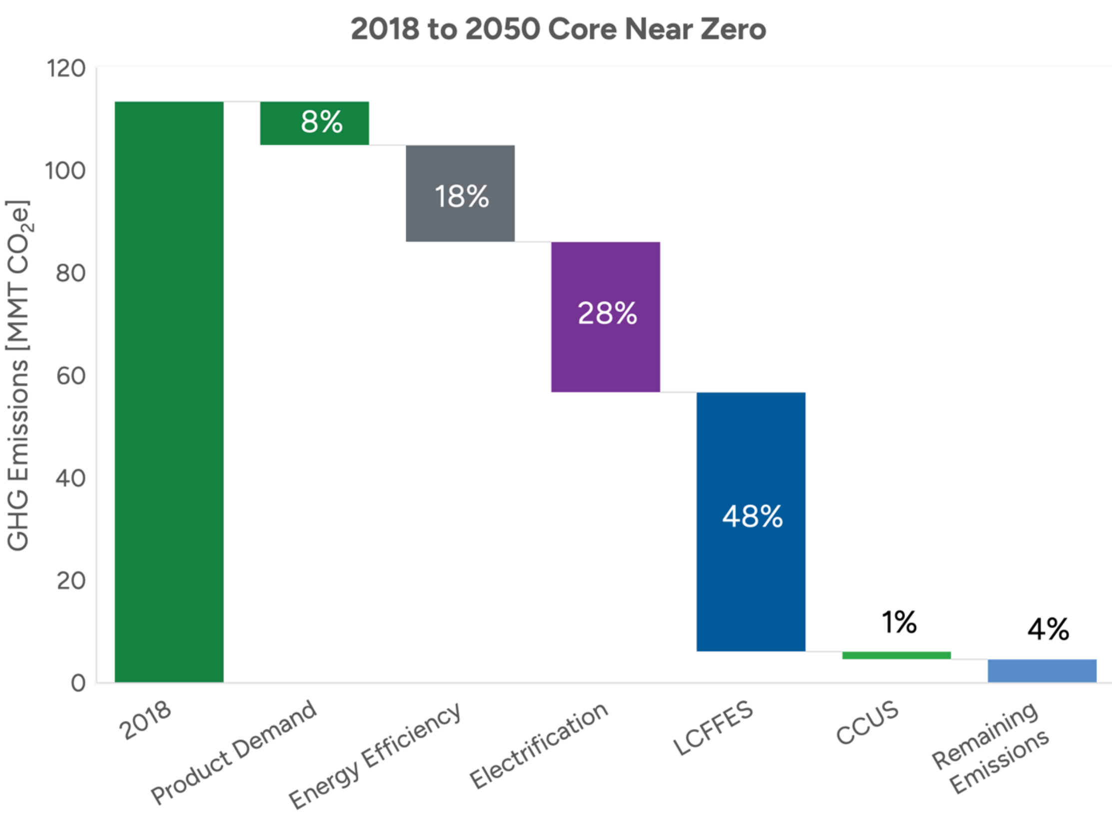

Figure 73. Impact of decarbonization pillars on GHG emissions, U.S. pulp and paper manufacturing–Core Near Zero pathway (MMT CO_2e), 2018–2050

Details on assumptions, parameters, and timing of transformative technology application can be found in Appendix C. Source: Transformative Pathways modeling.

The Core Near zero pathway increases consumption of low-carbon biomass for fuel, with up to 80% in the fuel mix for non-integrated mills and up to 100% for mills with pulping operations. The pulp and paper subsector already uses a significant proportion of LCFFES, primarily in the form of black liquor and waste wood chips, and the *Transformative Pathways* modeling assumes a transition to more biomass-based fuels, such as wood chips and other solid biomass products. Hydrogen has limited applicability, and clean hydrogen is only considered as a fuel for tissue production, where there are cases of H_2 use in Yankee dryers. Although not considered in the *Transformative Pathways* modeling, renewable natural gas or biogas, solar thermal energy, geothermal, and nuclear energy sources provide other viable LCFFES alternatives that can be useful on a case-by-case basis, depending on location and other factors.

The Core Near Zero Pathway also broadly adopts energy efficiency measures across all paper products, including technologies that are not currently widely implemented, such as advanced debarking methods and wet end process optimization. Table C-46 through Table C-50 in Appendix C detail adoption rates assumed for the *Transformative Pathways* modeling.

Beyond electrified drying technologies, electrification is limited to the auxiliary boilers. The auxiliary boiler can produce about 59% of the steam requirement across the subsector, depending on the mill type.[409] In the CNZ pathway, electric boilers are assumed to produce a maximum of 20% of total steam generated, compared with 1%–3% under BAU. A high electrification sensitivity evaluated the impact of further increasing the share of steam generated through electric boilers from 20% to 50%. Although this sensitivity resulted in a different energy mix, there was virtually no impact on the emissions trajectory compared with the CNZ pathway, as seen in Figure C-38 and Figure C-39.

Increasing the biomass consumption (as a fuel) will require an assessment of the supply chain to ensure there is sufficient volume and infrastructure to meet these needs. Due to the increased use of biomass-based LCFFES, biogenic emissions can be expected to increase, while the scope 1 emissions will be lowered significantly. Electrification, as a decarbonization lever, will largely be dependent on the viability of electric alternatives to meet steam demands. Although electric boilers are a high-maturity technology, risks and barriers to their broad implementation still exist. The main barrier is the operating cost (electricity) and the investment necessary to replace auxiliary boilers with new electric boilers. Steam-generating heat pumps could also be utilized instead of electric boilers to supplement steam from the recovery boiler—though not considered in the *Transformative Pathways* modeling. However, heat pumps need to be further evaluated for use in this subsector.[410]

Impact of Increased Recycled Content, Imports, and Demand Reduction

Three additional sensitivities were assessed to evaluate the decarbonization impact on the pulp and paper subsector: increased recycled content, increased imports, and demand reduction. Increased recycling is expected to reduce the demand for virgin products, such as packaging papers and virgin pulp, while increasing the pulp imports is expected to reduce domestic market pulp production. Finally, demand reduction assumes a decrease in production of pulp and paper products. Production volumes for these three sensitivities can be found in Figure C-40; decarbonization impact can be found in Figure C-39.

Increasing recycled content and imports had virtually no impact on the emissions trajectory, and demand reduction only has a modest impact. With aggressive adoption of decarbonization technologies at the facility level, the source of pulp and paper input may have little effect on emissions reduction.

Although these sensitivities illustrate that these strategies may have minor decarbonization potential, impacts beyond emissions should be considered. For example, increasing either recycling or imports can reduce the virgin pulp production. This can lead to pulp mill closures. Although these mills may close, they can also potentially undergo adaptive reuse to produce value-added products to support other industrial or energy

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409 U.S. Department of Energy, "2018 Manufacturing Static Energy Sankey Diagrams," December 2021, www.energy.gov/sites/default/files/2022-06/2018_mecs_all_manufacturing_sankey.pdf.

410 Jibran Zuberi, Ali Hasanbeigi, and William Morrow, *Electrification of U.S. Manufacturing With Industrial Heat Pumps*, LBNL-2001478, (Lawrence Berkeley National Laboratory, 2022), eta.lbl.gov/publications/electrification-us-manufacturing.

subsectors. Although imports can lead to low production emissions due to lack of domestic pulping operations, the final emission intensity of the product may become unclear because of lacking data or transparency. Alternatively, increased domestic production could allow for better assessment of final product emission intensity while supporting domestic reliance. However, this could lead to a need for increased mill capacity beyond what is currently available in the United States.

Impact of Biogenic Emissions

The subsector emissions do not account for all the energy consumption during the production processes due to a substantial use of biomass-based fuels, such as black liquor and waste wood, that emit biogenic emissions.[411] More than 50% of total subsector emissions fall into this category.[412] Biogenic emissions have been broadly considered to be net zero emissions due to the carbon dioxide (CO_2) uptake during the biomass growth period.[413] This provides a unique opportunity in the pulp and paper subsector to capture the biogenic emissions, allowing this subsector to go beyond near zero or net zero toward net-negative emissions.

In this modeling effort, the focus has been on analyzing scopes 1 and 2 emissions. However, the potential of capturing biogenic emissions should be understood, given its decarbonization potential. Figure 74 presents the pulp and paper subsector emissions from 2018 to 2050 under the BAU and Core Near Zero pathway, and also shows the change in emission profile under the Core Near Zero pathway if all the biogenic emissions are captured, while including the emissions for upstream wood procurement.[414, 415] Considering the impact of capturing biogenic emissions can change technology choices (e.g., increasing CCUS), which need to be assessed further. If 100% of all biogenic emissions are captured, the subsector emissions can become net-negative, roughly -130 MMT CO_2e. Apart from capturing and storing the biogenic emissions, the carbon in these emissions can also be used to produce other value-added products, either after capture or through utilization in integrated biorefinery approaches.[416] Such technologies also have the potential to decarbonize other subsectors, such as the chemicals subsector, by supplying low-carbon feedstocks. The modeling effort does not currently include these inter-sectoral impacts but will be considered in future work.

[411] Kristen E. Tomberlin, Richard Venditti, and Yuan Yao, "Life Cycle Carbon Footprint Analysis of Pulp and Paper Grades in the United States Using Production-line-based Data and Integration," *BioRes.* 15, 2 (April 2020): 3899–3914, doi.org/10.15376/biores.15.2.3899-3914.
[412] Ibid.
[413] Hamed Kouchaki-Penchah et al., "Impact of Biogenic Carbon Neutrality Assumption for Achieving a Net-Zero Emission Target: Insights from a Techno-Economic Analysis," *Energy and Climate* 57, 29 (July 2023), doi.org/10.1021/acs.est.3c00644.
[414] Kristen E. Tomberlin, Richard Venditti, and Yuan Yao, "Life Cycle Carbon Footprint Analysis of Pulp and Paper Grades in the United States Using Production-Line-Based Data and Integration," *BioRes.* 15, 2 (April 2020): 3899–3914, doi.org/10.15376/biores.15.2.3899-3914.
[415] U.S. Environmental Protection Agency, *Emission Factors for Greenhouse Gas Inventories* (2024), www.epa.gov/system/files/documents/2024-02/ghg-emission-factors-hub-2024.pdf.
[416] Pratima Bajpai, *Biorefinery in the Pulp and Paper Industry*, Academic Press (2013), sciencedirect.com/book/9780124095083.

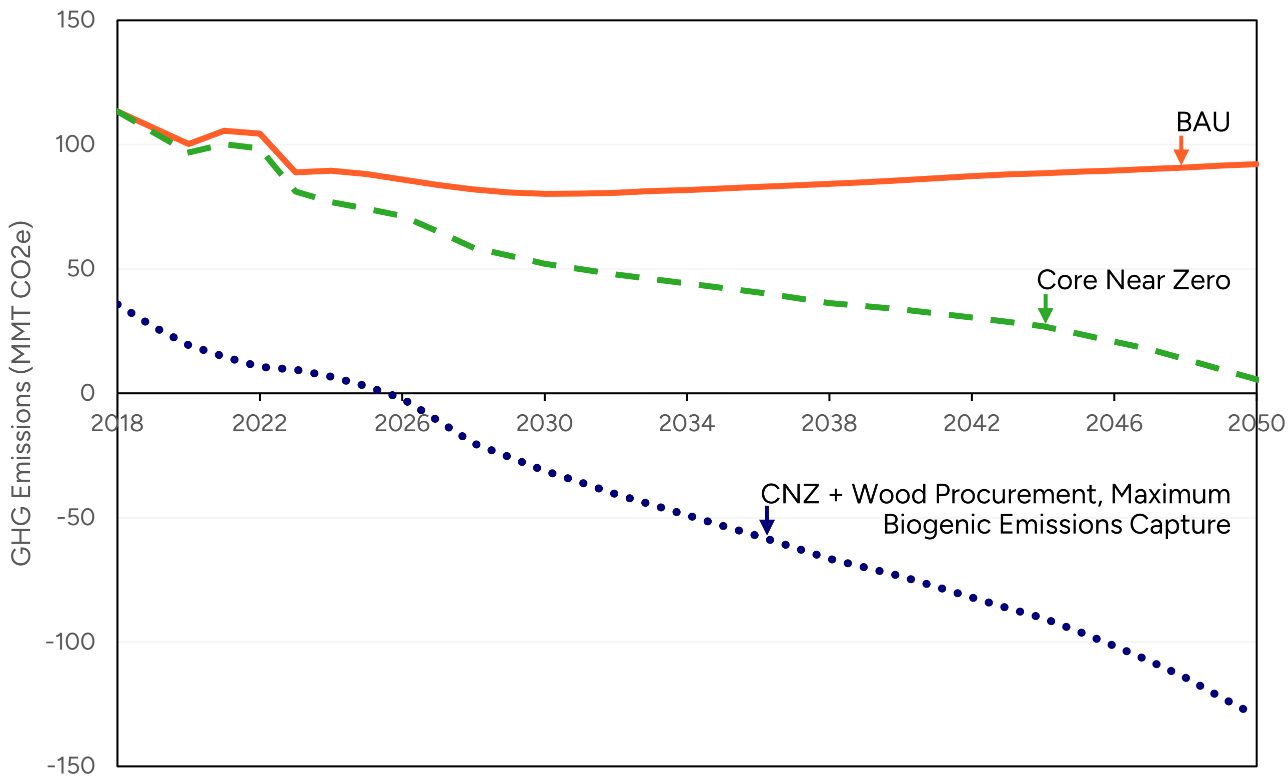

Figure 74. Annual GHG emissions, U.S. pulp and paper manufacturing–BAU scenario, Core Near Zero pathway, and Core Near Zero pathway (including wood procurement emissions with potential capture of all biogenic emissions) (MMT CO_2e/year), 2018–2050

4.6.5 Key Takeaways

Under the BAU scenario, the U.S. pulp and paper subsector is projected to only reduce its emissions by 19% between 2018 and 2050, falling well short of the U.S. goal of net zero GHG emissions by 2050. The Core Near Zero pathway has the potential to reduce 95% of emissions (6 MMT CO_2e) in 2050, down from 113 MMT CO_2e in 2018. The Core Near Zero pathway largely relies on energy efficiency improvement of core unit processes, fuel switching to biomass, and electrifying steam generation and drying; all of which highlight the need to focus extensively on decarbonization of the subsector's operation to enable emissions reduction. More aggressive electrification of the auxiliary boiler for steam generation had negligible effects. Moreover, increasing recycling and imports and reducing demand also had minimal effects, which may indicate that broad adoption of the decarbonization interventions in the Core Near Zero pathway is robust to changing feedstocks, but more analysis is needed.

An increasing reliance on biomass-based fuels will commensurately increase biogenic emissions. Although biogenic emissions are largely understood to be net zero, they should still be considered to understand the impact of carbon capture on the subsector's emissions trajectory. More aggressive technology adoption, especially CCS, can lead to net zero and potentially negative emissions for this subsector by 2050 with a mix of existing and innovative technologies.

It is important to note that the analysis centered around the Kraft process and did not evaluate alternative production routes like deep eutectic solvents and alternative sources of fiber, given the limitations in the data. The decarbonization interventions evaluated in the *Transformative Pathways* modeling may have very different effects for these alternative production routes, and some may not be applicable at all. Thus, as key decarbonization decisions and investments are considered, these limitations should be kept in mind.

The recommendations below illustrate key steps to enable ambitious near zero and net zero GHG emissions targets:

- Broaden the scope to consider biogenic carbon emissions when considering pulp and paper subsector decarbonization.
- Studies to understand the availability of sustainably grown biomass and interactions between pulp and paper and other subsectors.
- RDD&D of alternate approaches for pulping, paper drying, and other subsector processes.
- RDD&D in expanding the pulp and paper facilities to biorefinery facilities that can produce conventional pulp and paper and value-added products, such as biofuels, biochemicals, and bioplastics, which can aid decarbonization of pulp and paper and other subsectors.

Limitations to the existing analysis can be overcome by:

- Inclusion of more explicit biogenic carbon emissions calculations.
- Inclusion of alternative pulping technologies.
- Expansion to understand the impact/tradeoffs of shifting domestic production to imported pulp (domestic capacity, emissions intensity of final product).
- Comparison of pulp and paper production capacity needs under different sensitivities.
- Impact of excluding CCUS as a decarbonization pillar on the technology splits between the other three decarbonization pillars.
- Expand on demand reduction/material efficiency (currently modeled as a simple reduction in product demand, which can instead increase recycled content in products beyond packaging paper and paperboard).

4.7 Emissions in Other Industrial Subsectors

Excluding the subsectors discussed in Sections 4.1 through 4.6, the rest of industry is large and diverse and accounts for nearly half of the industrial sector's energy-related emissions in 2018, as shown in Figure 4. Figure 75 provides an overview of the relative scale of scope 1 and scope 2 energy- and non-energy-related emissions for the non-manufacturing and other manufacturing subsectors in 2018. The remainder of industry includes:

- Other manufacturing subsectors (the manufacturing subsector excluding cement and concrete, chemicals, food and beverage, iron and steel, petroleum refining, and pulp and paper)—these include glass, aluminum, plastics and rubber products, transportation equipment, and others. See Section 4.7.1.
- The non-manufacturing subsector, which is comprised of agriculture and forestry; mining, oil, and gas; and construction. See Section 4.7.2.
- Industry-adjacent subsectors—data centers, water and wastewater treatment. See Section 4.7.3.

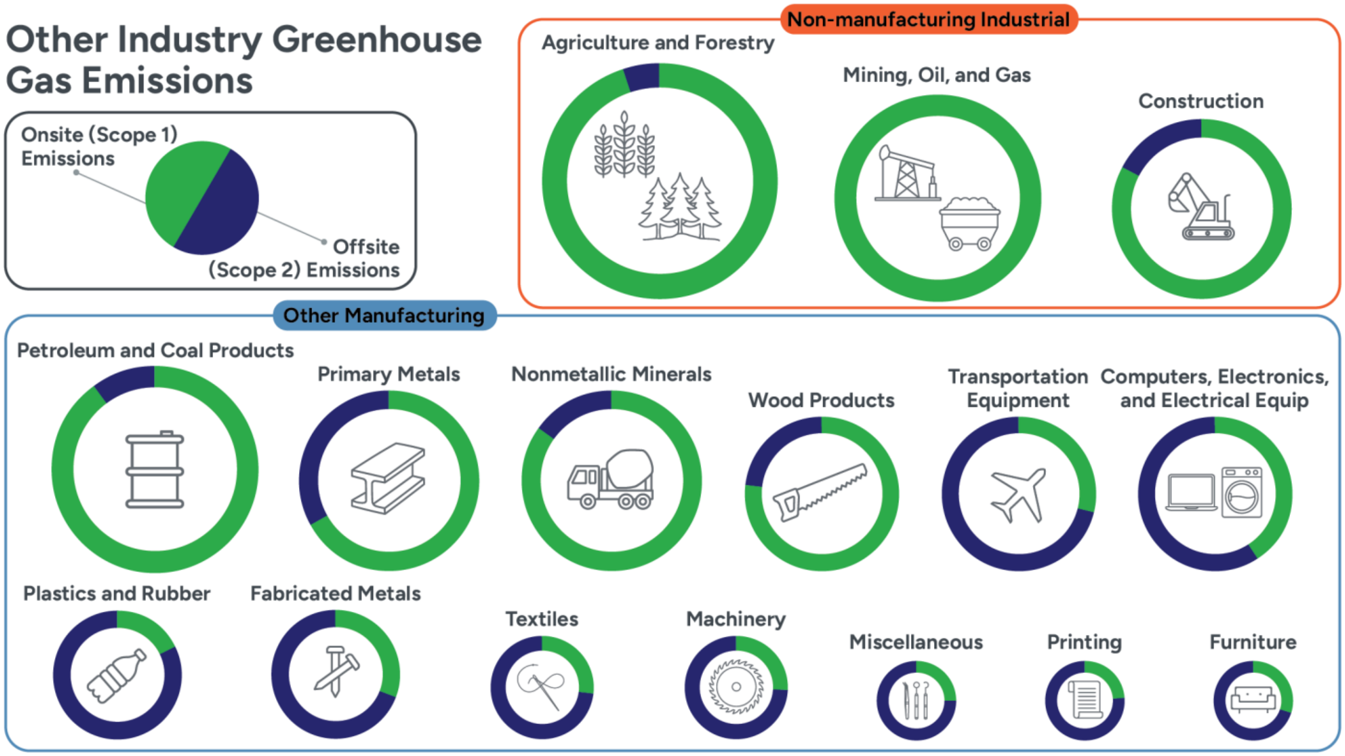

Figure 75. Scale and breakdown of total scope 1 and scope 2 emissions from other industrial subsectors, 2018

Data source: U.S. Department of Energy, "Environmentally Extended Input-Output for Industrial Decarbonization Analysis (EEIO-IDA) Tool," accessed October 2024, www.energy.gov/eere/iedo/articles/environmentally-extended-input-output-industrial-decarbonization-analysis-eeio.

These subsectors have not been modeled as extensively as those discussed in Section 4, but possible decarbonization pathway options can be considered as discussed in the rest of this section. Below are brief descriptions of each subsector, along with examples of decarbonization pathways and opportunities for that subsector. Future work will be undertaken to better understand the impact of decarbonization opportunities in a consistent format comparable to the existing *Transformative Pathways* modeling.

4.7.1 Other Manufacturing

"Other manufacturing" includes the manufacturing subsectors aside from the six covered in detail in Sections 4.1 through 4.6 and includes the subsectors noted in Table 19. The total GHG emissions in other manufacturing accounted for about 23% of total manufacturing emissions in 2018.[417]

Table 19. 2018 Energy Consumption and Emissions from Other Manufacturing Subsectors

NAICS code	Subsector	Onsite energy consumption (TBtu)	Primary energy consumption (TBtu)	Onsite emissions1 (MMT CO2e)	Total emissions2 (MMT CO2e)
313–316	Textiles	92	183	2	9
321	Wood Products	386	544	4	15
326	Plastics and Rubber Products	256	562	5	27

[417] U.S. Department of Energy, "Manufacturing Energy and Carbon Footprints (MECS 2018)," accessed November 2024, www.energy.gov/eere/iedo/manufacturing-energy-and-carbon-footprints-2018-mecs.

3272, 327993	Glass	185	272	9	15
3313	Aluminum	208	372	9	21
3315	Foundries	92	160	2	7
332	Fabricated Metals	254	479	7	24
333	Machinery	145	299	4	14
334, 335	Computers, Electronics, and Electrical Equipment	184	393	9	24
336	Transportation Equipment	345	659	9	32
	Remainder of Other Manufacturing*	736	1,031	50	75
31–33	*All Manufacturing*	*14,744*	*19,663*	*780*	*1,165*

[1] Includes onsite energy-related (combustion) and process emissions.

[2] Includes onsite and offsite energy-related (combustion) and onsite process emissions.

* Excludes the six subsectors in Sections 4.1 through 4.6 and the subsectors listed in the rows above. Includes NAICS 323 Printing and Related Support, rest of NAICS 324 Petroleum Products (excluding NAICS 324111 Petroleum Refining), rest of NAICS 327 Nonmetallic Mineral Products (excluding NAICS 3272, 327993 Glass and NAICS 327310 Cement), NAICS 3314 Nonferrous Metals, NAICS 337 Furniture and Related Products, and NAICS 339 Miscellaneous Manufacturing.

Source: U.S. Department of Energy, "Manufacturing Energy and Carbon Footprints (MECS 2018)," accessed November 2024, www.energy.gov/eere/iedo/manufacturing-energy-and-carbon-footprints-2018-mecs

Process heating systems and thermal loads are vital in these subsectors for different operations (e.g., melting, heat treatment, molding, soldering, and drying). These processes require significant energy inputs, typically achieved through the combustion of fossil fuels or use of steam, and lead to substantial GHG emissions. The high temperatures needed for melting metals like recycled aluminum, shaping plastics, or curing paints in automotive production contribute not only to direct emissions from furnaces and heaters but also to indirect emissions associated with steam consumption. The challenge for these subsectors is to balance the essential need for precise temperature control and thermal processing with the urgent need to reduce their GHG emissions footprint while maintaining production quality and efficiency.

Alumina and Aluminum

In 2018, the U.S. alumina and aluminum subsector (NAICS 3313) accounted for 372 TBtu of primary energy consumption and 21 MMT CO_2e total emissions.[418] Primary aluminum production relies on electrolytic reduction processes and melting, demanding substantial thermal energy. The GHG emissions come largely from process emissions (CO_2 released during the electrolysis process using carbon anodes, accounting for 12.1%) and energy-related emissions from fossil fuel combustion for electricity generation (70.6%).[419] In secondary aluminum production, process heating systems are used to melt scrap aluminum. This process contributes to GHG emissions, primarily from the combustion of natural gas in furnaces. However, secondary production using recycled aluminum requires only 5% of the energy used in primary production, decreasing production-related

[418] U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Alumina and Aluminum," (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_alumina_aluminum_energy_carbon_footprint_0.pdf.

[419] Gudrun Saevarsdottir, Halvor Kvande, and Barry J. Welch, "Aluminum Production in the Times of Climate Change: The Global Challenge to Reduce the Carbon Footprint and Prevent Carbon Leakage," *JOM* 72, (2020): 296–308, doi.org/10.1007/s11837-019-03918-6.

emissions by about 93% and thus significantly reducing the subsector's energy and emissions footprint.[420, 421] The primary aluminum subsector accounted for approximately 90% of global aluminum emissions in 2019, while secondary aluminum manufacturing accounted for the remaining 10%.[422]

Aluminum recycling is widely used today, satisfying 36% of demand, with 75% of all aluminum ever manufactured still in use.[423, 424] Continued efforts to increase aluminum recovery and recycling are critical to further subsector decarbonization. However, current recycling processes produce aluminum with impurities. These impurities cause secondary aluminum to be diluted or downcycled, preventing recycled aluminum from being applicable to all primary aluminum applications.[425]

In addition to expanding recycling efforts, other pathways toward decarbonizing the aluminum subsector include transitioning to clean energy and implementing CCUS technologies. Although hydro and geothermal power have already been employed within the subsector to take advantage of the round-the-clock power that they produce, they are location-dependent and thus limited in their capacity to decarbonize the subsector at large. Onshore wind and solar are more flexible in this regard and rank among the most cost-competitive clean energy options. However, they are intermittent in nature, leading to the need for storage solutions and power purchase agreements (as a means of balancing supply and demand). Scalable CCUS technologies stand to be as effective as clean energy source adoption, but at present, these technologies are immature and have limited availability. A long-term strategy would likely require adopting multiple pillar approaches to successfully decarbonize aluminum production.

One of the most impactful ways to decarbonize process emissions is implementing inert anodes.[426] Use of inert anodes would eliminate direct emissions from carbon anode consumption, emitting O_2 instead of CO_2.[427] Additionally, inert anode usage would mitigate emissions associated with carbon anode production, a process that is quite emissions-intensive.[428] Although promising inert anode materials have been identified, researchers have yet to find a material that is suitable for industrial application, preventing inert anodes from currently being deployed commercially.[429]

An additional approach to decarbonizing process emissions is to adopt technologies that can provide heat and steam without fossil fuels.

Glass

In 2018, the U.S. glass manufacturing subsector (NAICS 3272, 327993) accounted for 272 TBtu of primary energy consumption and 15 MMT CO_2e total emissions.[430] Producing 1 kg of glass in a gas-fired furnace generates about 0.6 kg of CO_2–0.45 kg from fossil fuel combustion and 0.15 kg from the dissociation of

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420 The Aluminum Association, "Infinitely Recyclable," accessed November 2024, www.aluminum.org/Recycling.

421 Sai Krishna Padamata, Andrey Yasinskiy, and Peter Polyakov, "A Review of Secondary Aluminum Production and Its Byproducts," *JOM* 73 (2021), 2603–2614, doi.org/10.1007/s11837-021-04802-y.

422 World Economic Forum, *Aluminium for Climate: Exploring Pathways to Decarbonize the Aluminium Industry* (2020), weforum.org/docs/WEF_Aluminium_for_Climate_2020.pdf.

423 Gudrun Saevarsdottir, Halvor Kvande, and Barry J. Welch, "Aluminum Production in the Times of Climate Change: The Global Challenge to Reduce the Carbon Footprint and Prevent Carbon Leakage," *JOM* 72 (2020): 296–308, doi.org/10.1007/s11837-019-03918-6.

424 Robert F. Service, "Red Alert," *Science,* August 20, 2020, www.science.org/content/article/red-mud-piling-can-scientists-figure-out-what-do-it.

425 Sai Krishna Padamata, Andrey Yasinskiy, and Peter Polyakov, "A Review of Secondary Aluminum Production and Its Byproducts," *JOM* 73 (2021), 2603–2614, doi.org/10.1007/s11837-021-04802-y.

426 World Economic Forum, *Aluminium for Climate: Exploring pathways to decarbonize the aluminium Industry* (2020), weforum.org/docs/WEF_Aluminium_for_Climate_2020.pdf.

427 Yong He et al., "Recent Progress of Inert Anodes for Carbon-Free Aluminium Electrolysis: A Review and Outlook," *Journal of Materials Chemistry A* 45 (August 2021), doi.org/10.1039/D1TA07198J.

428 Gudrun Saevarsdottir, Halvor Kvande, and Barry J. Welch, "Aluminum Production in the Times of Climate Change: The Global Challenge to Reduce the Carbon Footprint and Prevent Carbon Leakage," *JOM* 72 (2020): 296–308, doi.org/10.1007/s11837-019-03918-6.

429 Yong He et al., "Recent Progress of Inert Anodes for Carbon-Free Aluminium Electrolysis: A Review and Outlook," *Journal of Materials Chemistry A* 45 (August 2021), doi.org/10.1039/D1TA07198J.

430 See detailed manufacturing energy and carbon footprint for energy use and loss and emissions by end use: U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Glass and Glass Products" (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_glass_energy_carbon_footprint.pdf.

carbonate raw.[431] This subsector includes four distinctive parts: container, specialty, fiber, and flat glass. Each part of the subsector has its own unique challenges in decarbonization and circularity.

This subsector uses process heating for melting, forming, and annealing glass products, demanding continuous operation of high-temperature furnaces. Glass production involves heating raw materials to temperatures above 1,500°C, using furnaces typically fueled by natural gas and/or electricity.[432] This high-temperature process results in significant GHG emissions through direct combustion and indirect electricity consumption, in addition to the process-related emissions.

One barrier to lowering glass manufacturing energy and emissions intensity is the lack of available technology to operate electricity-powered flat glass furnaces. Experts with an optimistic view toward decarbonization purport that emissions can be significantly reduced through a combination of deep electrification and hybrid technology installation that will allow for switching between electricity and gas, especially if the gas comprises clean hydrogen. Decarbonization levers for glass subsector high-temperature heat use include fuel switching (to biomethane or clean hydrogen), electrification (assuming a clean grid), energy efficiency (waste heat recovery, oxyfuel furnaces), and CCS.[433] Breakthroughs in thermodynamic science, raw material use, CCUS, hydrogen, and other electrification options could enable an even greater reduction of emissions.

Other promising approaches to decarbonizing glass furnaces include the integration of energy recovery systems to reduce energy waste, new refractory development, and computational modeling. Onsite energy generation, in addition to lowering emissions, can protect manufacturing sites against energy price volatility and lend them greater autonomy and continuity of operations.

The downstream life cycle phases of end-product disposal and reuse could realize decarbonization benefits through material efficiency. Circular economy strategies, such as increased glass product recycling and straight product reuse, could help reduce container glass energy use and associated emissions. One metric ton of recycled glass (also known as cullet) saves 1.2 metric tons of virgin raw materials and avoids 60% of CO_2 emissions.[434] Further research to enable more cullet use in container glass and make it viable in flat glass would have significant impact on reducing emissions. Section 4.8 includes an example of glass production emissions reductions from a supply chain perspective.

Fabricated Metals

In 2018, the U.S. fabricated metals subsector (NAICS 332) accounted for 479 TBtu of primary energy consumption and 24 MMT CO_2e total emissions.[435] Fabricated metals manufacturing includes processes like welding, forging, and heat treating. These processes often use direct-fired furnaces and electric induction heaters, leading to direct GHG emissions from combustion of fuels and indirect emissions from electricity use.

A broad of set of decarbonization approaches are applicable for light manufacturing, including fabricated metals. These include improvement of energy efficiency for motor-driven systems, heat pumps for low-to-medium-temperature process heat, smart manufacturing/Industry 4.0 approaches to improve material efficiency, and clean energy integration.[436]

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[431] Nora Wintour, *The Glass Industry: Recent Trends and Changes in Working Conditions and Employment Relations*, International Labour Organization, Working Paper No. 310, www.ilo.org/publications/glass-industry-recent-trends-and-changes-working-conditions-and-employment.

[432] Dylan D. Furszyfer Del Rio et al., "Decarbonizing the Glass Industry: A Critical and Systematic Review of Developments, Sociotechnical Systems and Policy Options," *Renewable and Sustainable Energy Reviews* 155 (March 2022), doi.org/10.1016/j.rser.2021.111885.

[433] Ibid.

[434] F.J. Davies, "European Container Glass Industry," *Glass Technology* 34, (1993):4–9.

[435] See detailed manufacturing energy and carbon footprint for energy use and loss and emissions by end use: U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Fabricated Metals" (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_fabricated_metals_energy_carbon_footprint.pdf.

[436] Ernst Worrell and Gale Boyd, "Bottom-up Estimates of Deep Decarbonization of U.S. Manufacturing in 2050," *Journal of Cleaner Production* 330 (January 2022), doi.org/10.1016/j.jclepro.2021.129758.

Transportation Equipment

In 2018, the U.S. transportation equipment manufacturing subsector (NAICS 336) accounted for 659 TBtu of primary energy consumption and 32 MMT CO_2e total emissions.[437] Car and truck manufacturing uses process heating in painting, drying, metalworking, and part curing. The GHG emissions are attributed to the combustion of fuels for direct heating and the significant electricity consumption for operations like paint curing and drying. Efforts to reduce emissions include optimizing process efficiency and adopting low-emissions technologies, such as electrotechnologies and low-carbon fuels.[438]

Other decarbonization pathways might include incentivizing original equipment manufacturers to enhance the energy efficiency of manufacturing processes, shifting toward sustainable material use in car component production, and transitioning to electric vehicles and hydrogen-powered fuel cell electric vehicles, as well as other clean transportation options, to reduce life cycle emissions. However, electric vehicles are not without complications. The battery cells needed to power these vehicles, and the additional aluminum required to manufacture them, can actually increase life cycle vehicle emissions. Nonetheless, material efficiency, use of materials with lower embodied emissions, resource conservation, and clean energy sources present a path toward reducing these emissions.

Plastics

In 2018, the U.S. plastics and rubber products manufacturing subsector (NAICS 326) accounted for 562 TBtu of primary energy consumption and 27 MMT CO_2e total emissions.[439] The production of plastics is largely fossil-fuel-based: About 98% of plastic products generated today are from petroleum feedstocks.[440] Electricity accounts for over 60% of energy consumed in this subsector, primarily used for process heating and machine driven equipment, such as materials processing and fans.[441] Natural gas largely makes up the balance of energy consumed and is used for cogeneration, boilers, process heating, and facility HVAC.[442]

Because most plastics-related emissions are upstream emissions from the chemicals subsector, one of the more prominent decarbonization pathways for plastics focuses on the monomer production process. This approach tends to center around ethylene, a foundational component of plastics (see Section 4.2.3.1). Scope 1 (onsite) emissions may be curbed via process optimization (to mitigate energy and material losses), as well as energy efficiency measures to prevent electricity and steam generation, transmission, and distribution losses.

Foundries

In 2018, the U.S. foundries subsector (NAICS 3315) accounted for 160 TBtu of primary energy consumption and 7 MMT CO_2e total emissions.[443] Foundries are heavy users of process heating for melting and casting metals, generating considerable GHG emissions from the combustion of natural gas and coke and breeze.[444]

Approaches to foundry decarbonization include transitioning from fossil fuels to clean energy sources, enhancing energy efficiency (e.g., by improving process controls, using liquid metal as a feedstock, employing process automation/digitization, etc.), implementing energy recovery and recycling (e.g., via waste heat

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[437] See detailed manufacturing energy and carbon footprint for energy use and loss and emissions by end use: U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Transportation Equipment" (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_transportation_equipment_energy_carbon_footprint.pdf.
[438] Deloitte, *Automotive Pathways to Decarbonization* (2023), www.deloitte.com/global/en/issues/climate/pathways-to-decarbonization-automotive.html.
[439] See detailed manufacturing energy and carbon footprint for energy use and loss and emissions by end use: U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Plastics and Rubber Products" (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_plastics_rubber_energy_carbon_footprint.pdf.
[440] Jenna R. Jambeck and Imari Walker-Franklin, "The Impacts of Plastics' Life Cycle," *One Earth* 6, 6 (June 2023): 600–606, doi.org/10.1016/j.oneear.2023.05.015.
[441] U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Plastics and Rubber Products" (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_plastics_rubber_energy_carbon_footprint.pdf.
[442] Ibid.
[443] See detailed manufacturing energy and carbon footprint for energy use and loss and emissions by end use: U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Foundries" (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_foundries_energy_carbon_footprint.pdf.
[444] Ibid.

recovery methods such as regenerative burners), adopting CCUS, using low-carbon materials, and improving resource utilization (e.g., in the vein of circular economy).[445, 446] However, the U.S. foundries subsector is very heterogenous, and the ways in which these decarbonization approaches are implemented will be dependent on an individual facility's processes and constraints, such as the availability of alternative fuels or energy sources and appropriate infrastructure.

Computers, Electronics, and Electrical Equipment

In 2018, the U.S. computers, electronics, and electrical equipment manufacturing subsector (NAICS 334 and 335) accounted for 393 TBtu of primary energy consumption and 24 MMT CO_2e total emissions.[447] The electronics manufacturing subsector uses process heating in soldering and printed circuit board manufacturing, with GHG emissions mainly from electricity use. The precision required in these processes limits immediate shifts to lower-emissions technologies, placing emphasis on sourcing clean energy and enhancing energy efficiency.

The U.S. electronics subsector includes facilities that produce semiconductors, light-emitting diodes, microelectromechanical systems, liquid crystal displays, and photovoltaic cells.[448] For the United States, the semiconductor etching and chamber cleaning process is the leading source of emissions in this subsector (nearly 74%), followed by fuel combustion processes (12%), fluorinated heat transfer fluids (10%), and processes that use N_2O (4%).[449] The etching and chamber cleaning processes possessed a large footprint due to their use of fluorinated gases—such as perfluorocarbons, sulfur hexafluoride, nitrogen trifluoride, and hydrofluorocarbons—that possess high global warming potential (GWP). In addition to direct emissions, the subsector has significant indirect emissions related to electricity use (for equipment, heating, cooling, lighting, etc.) and supply chain (raw materials, product use, transportation, end-of-life, etc.).

One approach to decarbonizing this subsector focuses on sustainable manufacturing, using developments in artificial intelligence and the Internet of Things (IoT). These developments can enhance process automation and sensor technology, both of which can be leveraged to tighten energy efficiency measures such as repairing leaks, improving material use, and minimizing waste, among others. The introduction of lower-GWP gases (as a replacement for fluorinated GHGs) into production processes, coupled with other process optimization efforts, is another promising decarbonization pathway for the subsector. In the absence of lower-GWP gas use, abatement (thermal, catalytic, plasma, etc.) may be employed as a GHG mitigation strategy.

Textiles

In 2018, the U.S. textiles manufacturing subsector (NAICS 313, 314, 315, and 316) accounted for 183 TBtu of primary energy consumption and 9 MMT CO_2e total emissions.[450] In textiles, process heating is used for drying, curing, and chemical processing. The subsector's GHG emissions come from both direct fuel combustion and indirect electricity consumption. The highest emitting processes include dyeing and finishing, yarn preparation, fiber production, and fabric production, among others. Fabric types, in addition to production processes, also play a role in defining the textiles subsector's overall emissions footprint. For example, producing natural fibers such as cotton, linen, and wool tends to result in lower emissions than synthetic fibers like polyester and nylon, which require more chemical processing.

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[445] Katerina Kermeli et al., "Energy Efficiency Potentials in the EU Industry: Impacts of Deep Decarbonization Technologies," *Energy Efficiency* 15, 68 (December 2022), doi.org/10.1007/s12053-022-10071-8.
[446] Ernst Worrell et al., *Energy Efficiency Improvement and Cost Saving Opportunities for the U.S. Iron and Steel Industry* (Lawrence Berkeley National Laboratory, 2010), www.osti.gov/biblio/1026806.
[447] See detailed manufacturing energy and carbon footprint for energy use and loss and emissions by end use: U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Computers, Electronics and Electrical Equipment" (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_computers_electronics_electrical_equipment_energy_carbon_footprint.pdf.
[448] U.S. Environmental Protection Agency, *2011–2017 Greenhouse Gas Reporting Program Industrial Profile: Electronics Manufacturing Sector* (2018), www.epa.gov/sites/default/files/2018-10/documents/electronics_manufacturing_2017_industrial_profile.pdf.
[449] Ibid.
[450] See detailed manufacturing energy and carbon footprint for energy use and loss and emissions by end use: U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Textiles" (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_textiles_energy_carbon_footprint.pdf.

Decarbonizing textiles at large can be achieved through the introduction of closed-loop systems, which enable materials recycling and sustainable production processes. Developments needed in recycling include sorting automation, improvements in chemical fiber separation safety, and innovations in textile waste use. A transition toward regenerative agriculture upstream would also help to lower emissions within the textiles subsector.

The Apparel Impact Institute has outlined a multi-step pathway specifically toward decarbonization for apparel manufacturing, although some, if not all, of the suggested solutions can be applied across the textiles subsector: maximize material efficiency, scale sustainable materials and processes (e.g., recycled, as opposed to virgin, polyester), accelerate development of next-generation preferred materials (e.g., plant-based leather), maximize energy efficiency across apparel manufacturing, eliminate coal in textile mills, and shift to 100% clean electricity in manufacturing.[451] Common barriers to these ends include technical limitations to the recycling of materials; higher costs associated with recycling, sustainable material use, and new production equipment; and constraints on the availability, quality, and/or affordability of sustainable materials and clean energy sources.[452]

Machinery

In 2018, the U.S. machinery manufacturing subsector (NAICS 333) accounted for 299 TBtu of primary energy consumption and 14 MMT CO_2e total emissions.[453] This subsector utilizes process heating for metalworking processes such as welding and heat treating. GHG emissions are primarily from direct combustion of fuels in furnaces and indirect emissions from electricity usage. Decarbonization opportunities include optimizing heat recovery, changing machine design to meet emerging needs, and utilizing cleaner fuels and feedstocks for production.[454]

Wood Product Manufacturing

In 2018, the U.S. wood products manufacturing subsector (NAICS 321) accounted for about 384 TBtu of energy consumption and 15 MMT CO_2e emissions.[455] This subsector includes facilities that manufacture wood products, such as lumber, plywood, veneers, wood containers, wood flooring, wood trusses, manufactured homes (i.e., mobile homes), and prefabricated wood buildings. The top three distinct raw materials consumed include softwood and hardwood sawlogs/sawtimber, pulpwood and chips, and biomass.[456] Life cycle emissions for wood products other than the manufacturing phase include upstream emissions from raw materials extraction and transportation (e.g., open burning/decomposition of logging residue) and downstream emissions from waste product and end product disposal or reuse (e.g., landfill emissions from decomposition of wood products).[457]

Decarbonization strategies identified for wood product manufacturing include energy efficiency, specifically targeting emissions from electricity generation and onsite heat production that could be reduced by installing energy- efficient equipment at facilities or deploying systems for waste heat capture and reuse. Electrification strategies can also help achieve decarbonization, given the lower heat requirements compared to other industrial subsectors. Electrification options include ultraviolet wood curing, industrial heat pumps, and electric machine drives.[458] In addition, a 2018 report examining electrification opportunities also emphasized the low-temperature process heating requirements, compared to other subsectors, and the relatively low CHP adoption

[451] Apparel Impact Institute, *Annual Impact Report 2022* (2023), apparelimpact.org/wp-content/uploads/2024/01/Aii_ImpactReport_2022_230421_web.pdf.
[452] Walter Leal Filho et al., "Reducing The Carbon Footprint of the Textile Sector: An Overview of Impacts and Solutions," *Textile Research Journal* 94, 15–16 (March 2024), doi.org/10.1177/00405175241236971.
[453] See detailed manufacturing energy and carbon footprint for energy use and loss and emissions by end use: U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Machinery" (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_machinery_energy_carbon_footprint.pdf.
[454] Simon Rees et al., "Climate Disruption and the Path to Profits for Machinery Makers," BCG, October 27, 2020, www.bcg.com/publications/2020/how-machinery-makers-can-mitigate-climate-disruption.
[455] From analysis of U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Forest Products" (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_forest_products_energy_carbon_footprint_0.pdf, and U.S. Energy Information Administration, "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data" (2021), www.eia.gov/consumption/manufacturing/data/2018/.
[456] Anders Van Sandt et al., "Improving Models of Wood Products Plant Locations With Restricted Access Data," *Forest Policy and Economics* 167 (October 2024), doi.org/10.1016/j.forpol.2024.103303.
[457] Clean Energy Transition Institute, "Wood Products," accessed October 2024, www.cleanenergytransition.org/cmm/wood-products.
[458] Ibid.

in wood products manufacturing, further reinforcing the opportunity for decarbonization through deployment of existing technologies.[459]

The downstream life cycle phases of waste product disposal and reuse, delivery and end use, and end-product disposal and reuse could realize decarbonization benefits through material efficiency. Circular economy strategies, such as increased wood product recycling and use of biomass waste streams throughout the product value chain (e.g., forest residues and lumbermill/sawmill biomass residue), could help reduce energy use and associated emissions across the subsector.

Considering a more global perspective, in 2005, European markets created policies to curb carbon emissions from coal, driving European demand growth for wood pellets imported from the United States. As a result, U.S. wood pellet production increased by 14% annually from 2009 to 2019, with roughly 76% of pellet production capacity coming from the southern United States due to regional advantages in this type of wood product manufacturing.[460] As U.S. pellets remain an established strategy for economic opportunity in the southern United States and a decarbonization strategy in the European Union and United Kingdom, additional investigation into similar fuel-switching strategies may yield carbon mitigation and GHG emissions reduction benefits from domestically available resources.

Rest of Manufacturing

Other than the six energy- and emissions-intensive subsectors covered in Sections 4.1 through 4.6 and those listed above in this section, the rest of the manufacturing subsector includes printing and related support (NAICS 323); the rest of petroleum and coal products (NAICS 324), excluding petroleum refining (NAICS 324110); other nonmetallic mineral products (NAICS 327), excluding glass and glass products (NAICS 3272 and 327993) and cement (NAICS 327310); nonferrous metals (except aluminum) (NAICS 3314); furniture and related products (NAICS 337); and miscellaneous manufacturing (NAICS 339).

Together, these subsectors account for roughly 6% of total U.S. manufacturing emissions.[461] Although they differ greatly in their processes and products, their energy consumption is largely concentrated in process heating, machine-driven equipment, and facility HVAC, where electricity and natural gas constitute an overwhelming majority of the energy consumed in these end uses.[462] Therefore, improving the energy efficiency of these processes and switching to lower-carbon energy sources, including electricity, are key decarbonization opportunities that cross-cut the rest of manufacturing.

4.7.2 Non-Manufacturing Industrial Subsectors

Aside from manufacturing, the remainder of industry includes the agriculture and forestry; mining, oil, and gas; and construction subsectors. The energy consumption and GHG emissions of these subsectors can be characterized at the top level, but detailed information for energy types and end uses are typically not readily available. Table 20 provides an overview of the scope 1, 2, and 3 emissions for these non-manufacturing subsectors in 2018. Scope 1 non-energy-related emissions were the highest, mainly stemming from the agriculture subsector.

Table 20. 2018 GHG Emissions from the Non-Manufacturing Industrial Subsectors

Subsector	Scope 1 Energy-related (MMT CO_2e)	Scope 1 Non-energy-related (MMT CO_2e)	Scope 2 (MMT CO_2e)	Scope 3 (MMT CO_2e)
Agriculture and forestry [a]	58	560	34	63

[459] Jeff Deason et al., *Electrification of Buildings and Industry in the United States: Drivers, Barriers, Prospects, and Policy Approaches* (Lawrence Berkeley National Laboratory, 2018), www.osti.gov/biblio/1430688.
[460] Anders Van Sandt et al., "Improving Models of Wood Products Plant Locations With Restricted Access Data," *Forest Policy and Economics* 167 (October 2024), doi.org/10.1016/j.forpol.2024.103303.
[461] See Table 19.
[462] U.S. Energy Information Administration, "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data" (2021), www.eia.gov/consumption/manufacturing/data/2018/.

Subsector	Scope 1 Energy-related (MMT CO_2e)	Scope 1 Non-energy-related (MMT CO_2e)	Scope 2 (MMT CO_2e)	Scope 3 (MMT CO_2e)
Mining, oil, and gas	35	148	0	52
Construction	123	0	26	316
Total	**215**	**708**	**60**	**431**

[a]Emissions from Forestry only account for 9 MMT CO_2e of total emissions from Agriculture and Forestry (715 MMT CO_2e).

Sources: Data compiled from multiple EIA and EPA sources: U.S. Energy Information Administration, "Monthly Energy Review," October 2024, www.eia.gov/totalenergy/data/monthly/index.php (see Tables 11.1 through 11.5); U.S. Environmental Protection Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022, EPA 430-R-24-004 (2024), www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022; U.S. Department of Energy, "Environmentally Extended Input-Output for Industrial Decarbonization Analysis (EEIO-IDA) Tool," accessed October 2024, www.energy.gov/eere/iedo/articles/environmentally-extended-input-output-industrial-decarbonization-analysis-eeio.

Agriculture and Forestry

Agriculture and forestry involve raising and harvesting crops, animals, and timber. As noted in Section 4.3, the U.S. food and beverage supply chain is composed of multiple stages, beginning with agriculture and followed by manufacturing (when products are prepared and packaged for eventual consumption), wholesale and retail, and consumption (at both homes and food service providers). Because the food supply chain is so interconnected, accounting for decarbonization impacts within only one specific stage can be difficult. Additionally, significant data gaps exist within food and beverage manufacturing and across the entire food supply chain. Along with the stages mentioned above, areas of the supply chain with non-negligible energy consumption and emissions (and for which data is generally not available) include post-harvest processing (between agriculture and manufacturing) and warehousing (between manufacturing, wholesale, and retail). Furthermore, each supply chain stage results in different profiles of GHG emissions based on the season and location of food demand. In particular, produce that is out of season or has a short shelf life may require various modes of transportation over diverse distances, long-term storage in climate-controlled facilities, and/or local cultivation in dedicated indoor farms.[463]

Outdoor operations, such as those for grains, livestock, and forestry, typically favor diesel fuel for an energy source, mostly used for mobile equipment. Indoor operations, such as nurseries and greenhouses, predominantly consume natural gas for space heating. Operations such as dairy, poultry, and eggs rely heavily on electricity for space cooling, lighting, and refrigeration. Subsector-wide, irrigation constitutes about one-seventh of agriculture and forestry energy consumption, over half of which is electricity and nearly a third is natural gas.

Notably, agriculture and forestry products contribute about 5% of domestic energy production, including ethanol, biodiesel and renewable diesel, biogas, and fuel wood.[464] The industrial sector consumes almost half of this energy, primarily through combustion of wood and wood waste in wood products and paper subsectors, and the transportation sector has the second-highest consumption at about one-third, primarily through biofuels.[465] Expansion of the bioenergy economy is an important decarbonization opportunity for this subsector. Additional decarbonization technology opportunity areas that may overlap with the manufacturing subsector include distributed or controlled environment agriculture and agrivoltaics (i.e., installation of solar panels on agricultural land).

As shown in Table 20, agriculture and forestry non-energy-related emissions were significantly larger than energy-related emissions in 2018.[466] Beef cattle was responsible for over a third of the subsector total energy-related and non-energy-related emissions. Large contributors were methane emissions associated with enteric fermentation from feed digestion and nitrous oxide emissions from soil in pasturelands. Poultry and eggs were the next largest, at 15% of subsector emissions, and corn was third, at 10%. Those three in combination were

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[463] Arash Farokhi Soofi, Saeed D. Manshadi, and Araceli Saucedo, "Farm Electrification: A Road-Map to Decarbonize the Agriculture Sector," *The Electricity Journal* 35, 2 (March 2022), doi.org/10.1016/j.tej.2022.107076.
[464] U.S. Energy Information Administration, "Biomass Explained," July 30, 2024, www.eia.gov/energyexplained/biomass/.
[465] Ibid.
[466] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022*, EPA 430-R-24-004 (2024), www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.

about half of all agricultural emissions. Scope 2 emissions from grid-purchased electricity were the largest energy-related source, followed closely by diesel fuel combustion.

Strategies for controlling methane emissions from beef cattle operations include improving nutritional quality of feed to aid digestibility and implementing effective manure management methods, such as composting and anaerobic digestion.[467] It is also possible to select cattle with better feed conversion ratios, leading to lower methane emissions per unit of meat produced.[468] Likewise, the environmental footprint of egg production is influenced by the nutritional value of their feed, and manure management with anaerobic digesters can minimize manure methane emissions.[469] As for indirect emissions from corn, conservation tillage and crop rotation can help reduce emissions,[470] and enhanced-efficiency fertilizers, along with precision agriculture, can help to mitigate the substantial N_2O emissions (40% of CO_2e per year) from the denitrification of agricultural soils.[471]

Agroforestry, biochar application, and no-till systems are technologies that offer significant GHG mitigation potential through carbon sequestration, including the potential to offset more GHG than is currently emitted through the entire agricultural subsector. Further research is needed to address this sequestration potential with consideration of variability in soils, climate, and agricultural practices.[472]

Compared with agriculture, forestry emissions are minor, only accounting for 9 MMT CO_2e of the total 715 MMT CO_2e. These emissions are primarily from scope 1 combustion of fuels for forestry operations as well as upstream scope 3 energy emissions from electricity and fuels.[473] Decarbonizing scope 1 emissions could include transitioning to low-carbon fuels, if possible, though the distributed nature of forestry operations may make this a challenge. Given the relatively minor contribution of emissions, U.S. forest land has significant potential to serve as a natural carbon sink. Forest land GHG mitigation strategies include afforestation and reforestation, where land is converted to forest; reduction of deforestation, where forest land is preserved; and improved forest management, such as increasing forest productivity and extending timber harvest rotations; among others. Together these mitigation strategies have the potential to reach net sequestration of 1 Gt CO_2e per year in 2050.[474]

Mining, Oil, and Gas

The mining, oil, and gas subsector includes the extraction of energy, metallic and non-metallic minerals, and other resources from the Earth's surface and underground. Emissions come from a combination of onsite fuel combustion and fugitive releases and non-energy combustion such as flaring.[475] As shown in Table 21, the main source of emissions for the subsector is scope 1 non-energy-related, followed by scope 3 and scope 1 energy-related.

[467] Daniela F. Cusack et al., "Reducing Climate Impacts of Beef Production: A Synthesis of Life Cycle Assessments Across Management Systems and Global Regions," *Global Change Biology* 27, 9 (May 2021): 1721–1736, doi.org/10.1111/gcb.15509.
[468] Ibid.
[469] F. Grassauer, V. Arulnathan, and N. Pelletier, "Towards a Net-Zero Greenhouse Gas Emission Egg Industry: A Review of Relevant Mitigation Technologies and Strategies, Current Emission Reduction Potential, and Future Research Needs," *Renewable and Sustainable Energy Reviews* 181 (July 2023), doi.org/10.1016/j.rser.2023.113322.
[470] U.S. Department of Agriculture, "Climate Change," October 17, 2024, www.ers.usda.gov/topics/natural-resources-environment/climate-change/.
[471] Brittany Staie et al., *Pathways for Agricultural Decarbonization in the United States*, NREL/TP-5100-86071, National Renewable Energy Laboratory (2024), www.osti.gov/biblio/2282713.
[472] Ibid.
[473] U.S. Department of Energy, "Environmentally Extended Input-Output for Industrial Decarbonization Analysis (EEIO-IDA) Tool," accessed October 2024, www.energy.gov/eere/iedo/articles/environmentally-extended-input-output-industrial-decarbonization-analysis-eeio.
[474] U.S. Environmental Protection Agency, *Greenhouse Gas Mitigation Potential in the U.S. Forestry and Agriculture Sector*, EPA 430-R-23-004 (2024), www.epa.gov/system/files/documents/2024-03/epa-430-r-23-004-mitigation-report_full_report_v2.pdf.
[475] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022*, EPA 430-R-24-004 (2024), www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.

Table 21. 2018 GHG Emissions from the Mining, Oil, and Gas Subsector

Subsector	Scope 1 Energy-related (MMT CO_2e)	Scope 1 Non-energy-related (MMT CO_2e)	Scope 2 (MMT CO_2e)	Scope 3 (MMT CO_2e)
Oil and gas	14	101	0	31
Mining	21	46	0	12
Total	**35**	**148**	**0**	**52**

Sources: Data compiled from multiple EIA and EPA sources: U.S. Energy Information Administration, "Monthly Energy Review," October 2024, www.eia.gov/totalenergy/data/monthly/index.php (see Tables 11.1 through 11.5); U.S. Environmental Protection Agency, Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022, EPA 430-R-24-004 (2024), www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022; U.S. Department of Energy, "Environmentally Extended Input-Output for Industrial Decarbonization Analysis (EEIO-IDA) Tool," accessed October 2024, www.energy.gov/eere/iedo/articles/environmentally-extended-input-output-industrial-decarbonization-analysis-eeio.

Natural gas extraction is by far the largest source of GHG emissions, at over half of the subsector total. Oil extraction accounts for one-quarter of the total subsector emissions, coal mining for about one-sixth, and the rest of mining for one-twelfth. Within oil and gas, total non-energy-related emissions, most of which were due to methane leakage, exceeded energy-related emissions by roughly seven-to-one. On the other hand, emissions associated with the energy use in oil and gas come mostly from the combustion of self-produced lease and plant fuels.[476]

Coal mining shows a similar trend, with non-energy-related emissions (mostly related to methane leakage) higher than energy-related emissions—but by over eight-to-one. Fuel use for off-grid generators is a common and significant energy consumer across the mining, oil, and gas subsector. However, most energy use within oil and gas is for motor drives to run drilling equipment, pumps, and compressors, whereas within mining, energy use varies significantly from site to site. On average, about half of energy use in mining is for drilling, blasting, digging, and extracting ore using various equipment for materials-handling and ancillary demands (e.g., ventilation and dewatering); the other half of energy use is for concentration. This latter stage separates barren waste rock from valuable minerals through crushing and grinding, followed by physical separation (e.g., gravity, flotation, magnetic) and chemical separation (e.g., froth flotation, leaching).

Tracking the progress of GHG emissions reductions against a projected baseline target in the mining, oil, and gas subsector is complex. However, digital technologies can significantly enhance these operations and help reduce GHG emissions. For example, automated machinery can operate more efficiently than human-operated equipment, reducing fuel consumption and emissions, and IoT devices can monitor equipment and environmental conditions in real time, allowing for more precise control and optimization of energy use. Additionally, predictive maintenance using sensors and data analytics can prevent breakdowns and ensure machines run efficiently, reducing unnecessary energy consumption and subsequent emissions.[477] Furthermore, implementing systems that monitor and manage energy use can help identify areas where energy is being wasted and suggest improvements.[478]

Another form of decarbonization for this subsector involves reducing combustion emissions from trucks and subsurface heavy equipment through the use of alternatives such as battery electric vehicles.[479] For example, Rio Tinto announced in May 2024 a collaboration with Broken Hill Proprietary Company to test electrified haul trucks for their mining operations.[480] In addition to reducing combustion emissions, using battery electric vehicles can

[476] As defined by EIA, lease and plant fuels are "natural gas used in well, field, and lease operations (such as gas used in drilling operations, heaters, dehydrators, and field compressors) and as fuel in natural gas processing plants." See U.S. Energy Information Administration, "Glossary: Lease and plant fuel," accessed October 2024, www.eia.gov/tools/glossary/index.php?id=Lease.
[477] Putri Azmira R Azmi et al., "A Review of Predictive Analytics Models in the Oil and Gas Industries," *Sensors* 24, 12 (June 2024), doi.org/10.3390/s24124013.
[478] Mohamad Issa et al., "Renewable Energy and Decarbonization in the Canadian Mining Industry: Opportunities and Challenges," *Energies* 16, 19 (September 2023), doi.org/10.3390/en16196967.
[479] Hosein Kalantari, Agus P. Sasmito, and Seyed Ali Ghoreishi-Madiseh, "An Overview of Directions for Decarbonization of Energy Systems in Cold Climate Remote Mines," *Renewable and Sustainable Energy Reviews* 152, (December 2021), doi.org/10.1016/j.rser.2021.111711.
[480] Rio Tinto, "Rio Tinto and BHP Collaborate on Battery-Electric Haul Truck Trials in the Pilbara" (May 2024). www.riotinto.com/en/news/releases/2024/rio-tinto-and-bhp-collaborate-on-battery-electric-haul-truck-trials-in-the-pilbara.

also reduce particulate emissions and noise pollution. For surface-level heavy equipment, dual-fuel diesel hydrogen engines may be a more appropriate option.[481,482]

Since methane dominates the emissions for coal, gas, and oil, methane leakage management technologies are one of the most impactful decarbonization levers. Reducing fugitive methane emissions is crucial and economically beneficial for producers. These emissions largely result from leakages, which can be detected using various technologies, from satellites to handheld cameras. Emerging technologies like drone-mounted sensors and mobile equipment are also gaining traction within the subsector.[483, 484]

Additional decarbonization strategies can be considered for oil and gas extraction. Process improvements have likely already been employed where they are economically advantageous, but innovations such as advanced reservoir management techniques may not be as widespread as are necessary. Such techniques have helped reduce water use per barrel of oil produced, lowering the overall energy use and CO_2 emissions.[485]

Venting is a major source of methane emissions (in addition to flaring, mentioned earlier). Venting occurs during emergency pressure releases and can be minimized by capturing and re-injecting the gas. Tank vents are particularly challenging to measure and mitigate, but new technologies are being developed to address this issue.[486]

Another technology option that could reduce the emissions intensity of oil and provides CO_2 storage is enhanced oil recovery using CO_2 (CO_2-EOR).[487] CO_2-EOR involves injecting CO_2 into oil reservoirs to increase oil recovery while simultaneously storing CO_2 underground. This method not only helps in reducing the emissions footprint of oil production but also contributes to carbon sequestration.[488, 489]

Construction

Construction includes establishments engaged in the construction, design, and engineering of residential and non-residential buildings, as well as infrastructure such as highways and utility systems. Most emissions[490] in this subsector come from fuel combustion in mobile equipment for excavation, grading, materials-handling, transportation, and so forth. In 2018, an estimated three-quarters of emissions stemmed from gasoline and diesel fuel combustion, which also includes combustion in smaller uses such as onsite electricity generation. The next-largest source, at about 15%, was indirect emissions associated with purchased electricity, which is typically used for tools and other equipment, as well as worksite lighting. The remaining emissions were from lubricants, natural gas, and other fuels. Natural gas and other manufactured gases are often used to provide temporary space heating for worksites and the proper curing of concrete during colder times of the year.

In addition to energy, the construction subsector consumes significant amounts of materials such as sand, stone, and gravel used in site work; cement and concrete mix for in situ and precast concrete slabs; steel for

[481] Hosein Kalantari, Agus P. Sasmito, and Seyed Ali Ghoreishi-Madiseh, "An Overview of Directions for Decarbonization of Energy Systems in Cold Climate Remote Mines," *Renewable and Sustainable Energy Reviews* 152 (December 2021), doi.org/10.1016/j.rser.2021.111711.
[482] Robson Lage Figueiredo, José Margarida da Silva, and Carlos Enrique Arroyo Ortiz, "Green Hydrogen: Decarbonization in Mining," *Cleaner Energy Systems* 5 (August 2023), doi.org/10.1016/j.cles.2023.100075.
[483] Rob West, "Mechanics of the Energy Transition," *Oxford Energy Forum* 121 (March 2020), issue on Decarbonization Pathways for Oil and Gas, www.oxfordenergy.org/wpcms/wp-content/uploads/2020/03/OEF121.pdf.
[484] Darcy Spady and Jackson Hegland, "Easy and Economic Solutions to Mitigating Methane Emissions," *Oxford Energy Forum* 121 (March 2020), issue on Decarbonization Pathways for Oil and Gas, www.oxfordenergy.org/wpcms/wp-content/uploads/2020/03/OEF121.pdf.
[485] Ahmad O. Al Khowaiter and Yasser M. Mufti, "An Alternative Energy Transition Pathway Enabled by the Oil and Gas Industry," *Oxford Energy Forum* 121 (March 2020), issue on Decarbonization Pathways for Oil and Gas, www.oxfordenergy.org/wpcms/wp-content/uploads/2020/03/OEF121.pdf.
[486] Darcy Spady and Jackson Hegland, "Easy and Economic Solutions to Mitigating Methane Emissions," *Oxford Energy Forum* 121 (March 2020), issue on Decarbonization Pathways for Oil and Gas, www.oxfordenergy.org/wpcms/wp-content/uploads/2020/03/OEF121.pdf.
[487] Colin Ward, "CO_2-Enhanced Oil Recovery for Decarbonization," *Oxford Energy Forum* 121 (March 2020), issue on Decarbonization Pathways for Oil and Gas, www.oxfordenergy.org/wpcms/wp-content/uploads/2020/03/OEF121.pdf.
[488] National Energy Technology Laboratory, *Enhanced Oil Recovery*, Program 157 (2024), netl.doe.gov/sites/default/files/2024-10/Program-157.pdf.
[489] U.S. Department of Energy, "Enhanced Oil Recovery," accessed November 2024, www.energy.gov/fecm/enhanced-oil-recovery.
[490] U.S. Census Bureau, Economic Census: Construction Using National Energy Price Data from EIA and Emissions Factors from EPA and Breakdown of Non-Highway Fuel Use from DOT, FHWA, Highways Statistics Series, www.fhwa.dot.gov/policyinformation/statistics.cfm (Table MF-24), and EIA Distillate Fuel Oil and Kerosene Sales by End Use, www.eia.gov/dnav/pet/PET_CONS_821USE_A_EPD2D_VCN_MGAL_A.htm.

structural members such as cables, rebars, and framing; and many others. These materials have large energy and environmental footprints, and the construction subsector could play an important role in motivating low-GHG emissions manufacturing as green buildings proliferate. Finally, construction and demolition waste are substantial, more than twice that of municipal solid waste by weight,[491] and resource circularity could be an important way to decarbonize.[492, 493]

Most journal articles regarding this subsector's decarbonization speak to reducing emissions associated with cement and steel from a life cycle perspective. These approaches are covered in Sections 4.1 and 4.4, respectively. Material substitutions can also be considered, such as fiber-reinforced polymer instead of steel rebars for reinforcing concrete structural elements and alternative cement (e.g., geopolymer) to replace Portland cement.[494] Other emissions-intensive building materials can also see reductions in emissions intensity. Substituting mineral wool for polystyrene insulation when possible, decarbonizing plastics through electrification and carbon capture, and using recycled gypsum in plasterboards could be considered.[495]

Building information models can aid in decreasing life cycle emissions by enabling the optimization of materials and energy inputs through planning processes across design, construction, and maintenance stages. A 2023 journal article notes life cycle emissions for a highway system could be decreased through the use of a pavement management system, a form of building information model, thanks to optimized construction and maintenance.[496] In addition to reducing demolition waste, other decarbonization approaches include decreasing the use of emissions-intensive materials; optimizing construction and maintenance material and energy flows; reducing emissions from fuel combustion in mobile equipment; and improving the efficiency of onsite lighting and temporary space heating.

4.7.3 Industry-Adjacent Subsectors

Industry-adjacent subsectors considered within the *Transformative Pathways* framework include data centers and water and wastewater treatment. These types of facilities can have operations and/or energy demands similar to large-scale industrial facilities.

Data Centers

Data centers revolve around information technology infrastructure—e.g., servers, storage, networking equipment, and supporting auxiliary equipment—and provide significant computational resources for information and communications technology. Data centers are also one of the fastest-growing subsectors globally, which adds to the existing uncertainty about the anticipated level of electricity demand in future years (both worldwide and within the United States).[497] These buildings consume 10 to 50 times more energy per floor space than a typical commercial building and currently account for about 2% of total U.S. electricity consumption.[498] Emissions estimates focus on electricity consumption for operation of electronic equipment (e.g., servers, data storage, and networking) and infrastructure such as equipment cooling, space conditioning,

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[491] U.S. Environmental Protection Agency, "Construction and Demolition Debris: Material-Specific Data," November 8, 2024, www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/construction-and-demolition-debris-material.
[492] Amit Kumar Jaglan and Neha Korde, "Capturing the Opportunity for Decarbonization in the Construction Industry: Emission-Free, Effective, and Resilient Solutions," *Engineering Proceedings* 53, 1 (October 2023), doi.org/10.3390/IOCBD2023-15184.
[493] Banu Sizirici et al., "A Review of Carbon Footprint Reduction in Construction Industry, from Design to Operation," *Materials* 14, 20 (October 2021), doi.org/10.3390/ma14206094.
[494] Sami Sbahieh, Mohammad Zaher Serdar, and Sami G. Al-Ghamdi, "Decarbonization Strategies Of Building Materials Used In The Construction Industry," *Materials Today: Proceedings* (September 2023), doi.org/10.1016/j.matpr.2023.08.346.
[495] Ida Karlsson et al., "Roadmap for Decarbonization of the Building and Construction Industry—A Supply Chain Analysis Including Primary Production of Steel and Cement," *Energies* 13, 16 (August 2020), doi.org/10.3390/en13164136.
[496] Anne de Bortoli, Yacine Baouch, and Mustapha Masdan, "BIM Can Help Decarbonize The Construction Sector: Primary Life Cycle Evidence From Pavement Management Systems," *Journal of Cleaner Production* 391, (March 2023), doi.org/10.1016/j.jclepro.2023.136056.
[497] Electric Power Research Institute, *Powering Intelligence: Analyzing Artificial Intelligence and Data Center Energy Consumption* (2024), www.epri.com/research/products/000000003002028905.
[498] U.S. Department of Energy, "Data Centers and Servers," accessed November 2024, www.energy.gov/eere/buildings/data-centers-and-servers.

and power conversion. About half of energy use is for servers, a third for infrastructure, and most of the remaining sixth is for data storage.[499]

The amount of data center equipment has grown rapidly over recent years, but the associated energy consumption has not grown proportionally. Equipment has become more efficient, for example, through smaller transistor sizes in microchips and solid-state storage mediums, as well as more advanced power conversion devices. Data centers have also grown larger with higher utilization levels, leading to economies of scale and more efficient cooling.[500] Although data centers constitute a significant driver of electricity demand growth, their impact is complex and related to the broader role that information technology plays across the energy economy. Furthermore, as individual data centers grow, their local impacts on power system infrastructure may inhibit subsector growth or incentivize demand-side management to reduce peak loads and provide load flexibility.

Flexible data centers are designed to adapt to varying power and cooling demands, reducing carbon emissions and costs through innovative designs and resource management.[501] Key strategies include the accurate prediction of capacity, implementing geo-distributed load shifting to balance workloads, capturing and analyzing workload resource needs over time, and allocating and managing power efficiently within the data center.[502]

In addition to adapting to load flexibility, both deploying grid-scale clean energy and maximizing the energy efficiency of data centers are essential for decarbonization efforts.[503] Key strategies for data center energy efficiency improvements are optimizing cooling systems, using "free" cooling methods such as direct-expansion-based cooling, and optimizing fan/pump speeds.[504]

Other strategies include improving data management policies in data centers to reduce emissions and digital waste. Data centers are not directly responsible for managing data; their customers must adopt better practices to identify valuable data and eliminate redundant or "dark" data. Education on this front is critical to avoid digital waste and spiraling emissions.[505]

Water and Wastewater Treatment

The water and wastewater (W/WW) treatment subsector comprises a complex network of W/WW treatment systems providing potable water and sanitary sewage services via wastewater treatment and management.[506] A typical treatment plant involves a series of pipelines and sewer networks on the intake and return ends, pumping stations, primary treatment (sedimentation, filtration), secondary treatment (chemical and/or biological), and tertiary treatment (disinfection). A byproduct of wastewater treatment plants (WWTPs) is sludge, which is either incinerated, landfilled, sold as product (e.g., fertilizers and biosolids), or sent to an anaerobic digestor for biogas production.[507]

Commercial and industrial wastewater treatment accounted for a total of 100 MMT CO_2e emissions in 2018 (less than 1% of total U.S. GHG emissions) but can account for up to 30% to 40% of municipal-level energy

[499] Arman Shehabi et al., *United States Data Center Energy Usage Report*, LBNL-2001637, Lawrence Berkeley National Laboratory, (2024), eta-publications.lbl.gov/sites/default/files/2024-12/lbnl-2024-united-states-data-center-energy-usage-report.pdf.
[500] Arman Shehabi et al., *United States Data Center Energy Usage Report*, LBNL-1005775, (Lawrence Berkeley National Laboratory, (2016), www.osti.gov/biblio/1372902..
[501] U.S. Department of Energy, "Clean Energy Resources to Meet Data Center Electricity Demand," August 12, 2024, www.energy.gov/policy/articles/clean-energy-resources-meet-data-center-electricity-demand.
[502] Andrew A. Chien et al., *Beyond PUE: Flexible Datacenters Empowering the Cloud to Decarbonize* (2022), par.nsf.gov/biblio/10400420.
[503] U.S. Department of Energy, "Clean Energy Resources to Meet Data Center Electricity Demand," August 12, 2024, www.energy.gov/policy/articles/clean-energy-resources-meet-data-center-electricity-demand.
[504] Otto Van Greet and David Sickinger, *Best Practices Guide for Energy-Efficient Data Center Design*, DOE/GO-102024-6283, Federal Energy Management Program (2024), www.osti.gov/biblio/2417618.
[505] Dlzar Al Kez et al., "Exploring the Sustainability Challenges Facing Digitalization and Internet Data Centers," *Journal of Cleaner Production* 371 (October 2022), doi.org/10.1016/j.jclepro.2022.133633.
[506] U.S. Cybersecurity and Infrastructure Security Agency, "Water and Wastewater Systems," accessed October 2024, www.cisa.gov/topics/critical-infrastructure-security-and-resilience/critical-infrastructure-sectors/water-and-wastewater-sector.
[507] Miae Ha et al., *Opportunities for Recovering Resources from Municipal Wastewater*, ANL/ESD-21/11, Argonne National Laboratory (2022), www.osti.gov/biblio/1876441.

consumption in areas lacking a primary manufacturing presence.[508] Emissions from this subsector are mainly from three functions: energy-related emissions from electricity consumed for pumping water; energy-related emissions from electricity consumed for aeration to accelerate microbial activity and organic matter decomposition; and energy-related and fugitive emissions from anaerobic digestors that reduce sludge volume and produce biogas. The energy and emissions profile of individual facilities is dependent on the watershed and discharge network, fuel sources used for electricity production, and the myriad W/WW treatment configurations deployed to meet regulations.[509] Rising population and industrialization, coupled with stringent water quality requirements, are expected to increase W/WW subsector production, treatment, and energy demand.

Water conservation and management are often overlooked when water is perceived as having sufficient availability at low cost to manufacturers. Water is a critical industrial resource, and so to reduce risk, it is important to consider resource, environmental, and economic trade-offs of water efficiency measures.[510] To measure the actual economic potential of adopting cost-effective water-conserving technologies, water valuation metrics should go beyond the amount paid for water sources and include internal and opportunity costs associated with the realization of water risks.[511]

Important strategies to decarbonize the W/WW subsector and improve resource efficiency include 1) altering the fuel profile for electricity generation feeding the subsector; 2) making system upgrades to enhance process- and facility-level energy efficiency; 3) looking beyond carbon (i.e., understanding and curtailing fugitive emissions such as CH_4 and N_2O); and 4) identifying and integrating resource recovery opportunities. As a critical infrastructure, the W/WW subsector supports and tightly interacts with the residential, commercial, and industrial sectors and enables multi-faceted circular pathways for water reuse and resource recovery. Measures include reuse (e.g., cascading rinse waters, returning boiler condensate), servicing and retrofitting cooling systems, repairing leaks, and exploring alternative water sources (e.g., gray water), particularly for end uses that do not require potable water.

As part of a highly electrified subsector, W/WW treatment plants can reduce their emissions footprints by increasing clean energy penetration (e.g., installing onsite solar panels and wind turbines); transitioning from diesel-powered to electric-powered equipment; and use of low-carbon fuels, such as hydrogen and biofuels. Reducing the energy input required for W/WW treatment processes can lower indirect emissions from electricity use. Electricity consumption can be significantly reduced through system upgrades that optimize existing processes, such as improving aeration efficiency, minimizing water leakage, reducing pumping energy usage by replacing old and inefficient pumps, and installing variable frequency drives on pumps and motors.[512]

Energy efficiency can be enhanced through innovations such as advanced sensor technologies, real-time data analytics, and process automation, which help reduce operational inefficiencies and lower emissions footprints.[513, 514] For example, smart manufacturing and digital twins[515] allow WWTPs to optimize processes through data analytics, machine learning, and automation. More specifically for W/WW treatment facilities,

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[508] 2018 electricity consumption estimated at 120 TWh/year from Electric Power Research Institute, *Water & Sustainability (Volume 4): U.S. Electricity Consumption for Water Supply* (2002), www.circleofblue.org/wp-content/uploads/2010/08/EPRI-Volume-4.pdf,not including irrigation and livestock which is included in Agriculture and Forestry. Fugitive emissions of 42.5 MMT CO_2e in 2018 from domestic and industrial wastewater treatment from U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022*, EPA 430-R-24-004 (2024), www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.
[509] Vincent C. Tidwell, Barbie Morel, and Katie Zemlick, "Geographic Footprint of Electricity Use for Water Services in the Western U.S.," *Environmental Science & Technology* 48, 15 (June 2014): 8897–8904, doi.org/10.1021/es5016845.
[510] Unique Karki and Prakash Rao, "Techno-economic Analysis of the Water, Energy, and Greenhouse Gas Emissions Impacts from the Adoption Of Water Efficiency Practices In The U.S. Manufacturing Sector," *Resources, Conservation and Recycling* 196 (September 2023), doi.org/10.1016/j.resconrec.2023.107054.
[511] Sujit Das et al., "A Review of Water Valuation Metrics: Supporting Sustainable Water Use in Manufacturing," *Water Resources and Industry* 29 (June 2023), doi.org/10.1016/j.wri.2022.100199.
[512] Shalini Nakkasunchi et al., "A Review of Energy Optimization Modelling Tools for the Decarbonisation of Wastewater Treatment Plants," *Journal of Cleaner Production* 279 (January 2021), doi.org/10.1016/j.jclepro.2020.123811.
[513] Wenjin Zhang, Nicholas B. Tooker, and Amy V. Mueller, "Enabling Wastewater Treatment Process Automation: Leveraging Innovations in Real-Time Sensing, Data Analysis, and Online Controls," *Environmental Science: Water Research & Technology* 6, 11 (September 2020): 2973–2992, doi.org/10.1039/D0EW00394H.
[514] Zhiyong Jason Ren and Krishna Pagilla (Ed.), *Pathways to Water Sector Decarbonization, Carbon Capture and Utilization* (2022), doi.org/10.2166/9781789061796.
[515] A digital twin is a virtual representation of a physical object, system, or process that uses real-time data and feedback to simulate, predict, and optimize performance and operations.

digital twins—virtual models of physical plants—allow operators to simulate performance, identify inefficiencies, and minimize carbon emissions.[516] In this way, comprehensive energy management systems can be used to conduct regular energy audits, which allow facilities to monitor energy use, identify inefficient facility operations, and optimize those operations to reduce energy consumption.[517]

Wastewater treatment commonly leads to methane emissions as biogenic materials break down under anaerobic conditions. WWTPs often use anaerobic digestors to facilitate such processes while capturing the resulting methane, which helps reduce scope 2 and 3 emissions through enhanced energy recovery (powering the plant via combined heat and power systems using captured methane)[518, 519] and reduced sludge production. However, this process incurs higher scope 1 emissions due to inherent methane emissions, which can have higher global warming potential than the indirect emissions from electricity use from the facilities' perspective.[520] Therefore, enabling resource recovery in wastewater treatment presents a unique interplay of capturing wasted energy vs. emissions release.

To reduce methane emissions, anaerobic digestors can be optimized by controlling temperature, pH, or retention time.[521, 522] Techniques such as chemical precipitation, filtration, and biological pre-treatment can reduce the organic load entering anaerobic digestors, thereby reducing methane production.[523] Implementing advanced treatment technologies such as membrane bioreactors and aerobic granular sludge can also reduce the amount of organic material that breaks down into methane.[524, 525] Alternatively, co-digestion of organic sludge such as food, oil, and grease waste enhances the biogas generation capacity of anaerobic digestors to enhance resource recovery. Furthermore, a microalgal photobioreactor without aeration can effectively upgrade methane-rich biogas, which enhances the capture and utilization of methane produced for further downstream use as renewable natural gas.[526, 527]

Emerging approaches include bioelectrochemical energy recovery, which utilizes microbial systems to convert chemical energy from organic compounds into electrical energy. These systems operate under anaerobic conditions, providing efficient wastewater treatment while generating clean electricity directly from organic substrates.[528, 529] Microbial fuel cells represent a promising technology for direct biological conversion of organic matter into electricity, potentially offering higher efficiency and lower energy costs compared to traditional

[516] Ai-Jie Wang et al., "Digital Twins for Wastewater Treatment: A Technical Review," *Engineering* 36, (May 2024): 21–35, doi.org/10.1016/j.eng.2024.04.012.
[517] U.S. Department of Energy, "50001 Ready Program," accessed October 2024, www.energy.gov/eere/iedo/50001-ready-program.
[518] Umesh Ghimire, Gideon Sarpong, and Veera Gnaneswar Gude, "Transitioning Wastewater Treatment Plants toward Circular Economy and Energy Sustainability," *ACS Omega* 6, 18 (April 2021), doi.org/10.1021/acsomega.0c05827.
[519] Mariana Cardoso Chrispim, Miklas Scholz, and Marcelo Antunes Nolasco, "Biogas Recovery for Sustainable Cities: A Critical Review of Enhancement Techniques and Key Local Conditions for Implementation," *Sustainable Cities and Society* 72, (September 2021), doi.org/10.1016/j.scs.2021.103033.
[520] Cuihong Song et al., "Methane Emissions from Municipal Wastewater Collection and Treatment Systems," *Environmental Science & Technology* 57, 6 (February 2023), doi.org/10.1021/acs.est.2c04388.
[521] Umesh Ghimire, Gideon Sarpong, and Veera Gnaneswar Gude, "Transitioning Wastewater Treatment Plants toward Circular Economy and Energy Sustainability," *ACS Omega* 6, 18 (April 2021), doi.org/10.1021/acsomega.0c05827.
[522] Prathap Parameswaran et al., "Chapter 5: Energy and Resource Recovery Using the Anaerobic Digestion," in *Pathways to Water Sector Decarbonization, Carbon Capture and Utilization*, IWA Publishing (2022), doi.org/10.2166/9781789061796_0067.
[523] Ibid.
[524] Ibid.
[525] Boyan Xu et al., "Chapter 11: Decarbonization Potentials in Intensified Water and Wastewater Systems Using Membrane-Related Technologies," in *Pathways to Water Sector Decarbonization, Carbon Capture and Utilization*, IWA Publishing (2022), doi.org/10.2166/9781789061796_0187.
[526] Meiyue Ding et al., "Enhanced Nutrient Removal and Bioenergy Production in Microalgal Photobioreactor Following Anaerobic Membrane Bioreactor for Decarbonized Wastewater Treatment," Bioresource Technology 364 (November 2022), doi.org/10.1016/j.biortech.2022.128120.
[527] Prathap Parameswaran et al., "Chapter 5: Energy and Resource Recovery Using the Anaerobic Digestion," in *Pathways to Water Sector Decarbonization, Carbon Capture and Utilization*, IWA Publishing (2022), doi.org/10.2166/9781789061796_0067.
[528] Ibid.
[529] Shalini Nakkasunchi et al., "A Review of Energy Optimization Modelling Tools for the Decarbonisation of Wastewater Treatment Plants," *Journal of Cleaner Production* 279 (January 2021), doi.org/10.1016/j.jclepro.2020.123811.

methods.[530] Finally, energy storage solutions to store excess clean onsite energy for use during periods of high demand or low generation may be employed to help alter the electricity load profile.[531]

The materials and chemicals used in water treatment processes also contribute to the W/WW subsector non-biogenic emissions footprint. Strategies to reduce these embodied emissions include using materials and chemicals that are sustainably sourced and have lower embodied emissions. Novel technologies such as anaerobic membrane bioreactors, aerobic granular sludge, and forward osmosis systems reduce both energy consumption and emissions. These technologies reduce the demand for chemical additives, improve water quality, and lower the overall emissions footprint.[532, 533] Also, the use of microalgal biotechnology decreases the need for chemical inputs and reduces embodied emissions by utilizing CO_2.[534] Implementing recycling and reuse practices for materials and chemicals can further these efficiencies.[535]

Without undermining the potential presented for the W/WW subsector, challenges such as costs of capital improvements, aging infrastructure, high regulatory constraints, and lack of skilled workforce pose barriers to the adoption of innovative alternatives.

4.7.4 Near Zero Emissions Pathways and Technologies

Each subsector has a unique energy profile regarding major energy-consuming processes and equipment, types of non-energy-related emissions, and decarbonization opportunities, some of which overlap with those already discussed above. This section provides a high-level view of short-, mid-, and long-term decarbonization opportunities for the other industrial subsectors.

Short-Term Pathways

Some examples of short-term decarbonization pathway actions for other industrial subsectors might include:

- **Deployment of energy efficiency** measures could include improved furnace efficiency and waste heat recovery in the glass subsector,[536] use of oxyfuel combustion to improve energy efficiency in high-temperature processes such as forging and heat treatment in fabricated metals, and improved plastic production processes, namely in existing processes or equipment (such as steam cracking or naphtha catalytic cracking units).
- **Approaches to address fugitive methane emissions** are a critical need, as methane has high global warming potential, and a substantial leakage of methane exists throughout all stages of oil and gas extraction and from underground coal mining. Furthermore, additional methane is leaked from wastewater treatment plants and from dairy, poultry, and swine farms. Captured methane could be used for energy, offsetting natural gas demand.
- **Onsite clean energy generation** could be deployed to reduce purchased grid electricity or reduce fuel consumption for electric generators. Agrivoltaics could provide clean electricity, improve agricultural productivity, and provide other ancillary benefits.
- **Electrification of drilling equipment, pumps, and compressors** could improve energy efficiency and reduce emissions as the electric grid decarbonizes or in combination with onsite clean energy generation. Current equipment typically runs on diesel fuel or self-generated gases.

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[530] Perry L. McCarty, Jaeho Bae, and Jeonghwan Kim, "Domestic Wastewater Treatment as a Net Energy Producer–Can This be Achieved?" *Environmental Science & Technology* 45, 17 (July 2011), doi.org/10.1021/es2014264.
[531] Shalini Nakkasunchi et al., "A Review of Energy Optimization Modelling Tools for the Decarbonisation of Wastewater Treatment Plants," *Journal of Cleaner Production* 279 (January 2021), doi.org/10.1016/j.jclepro.2020.123811.
[532] Boyan Xu et al., "Chapter 11: Decarbonization Potentials in Intensified Water and Wastewater Systems Using Membrane-Related Technologies," in *Pathways to Water Sector Decarbonization, Carbon Capture and Utilization*, IWA Publishing (2022), doi.org/10.2166/9781789061796_0187.
[533] Siyu Wang, S. "Innovative MBR-RO Processes for Reclamation of Municipal Wastewater to High-Grade Product Water," Nanyang Technological University (2022), doi.org/10.32657%2F10356%2F161632.
[534] Umesh Ghimire, Gideon Sarpong, and Veera Gnaneswar Gude, "Transitioning Wastewater Treatment Plants Toward Circular Economy and Energy Sustainability," *ACS Omega* 6, 18 (April 2021), doi.org/10.1021/acsomega.0c05827.
[535] Ibid.
[536] Christopher W. Sinton, "Deep Decarbonization of Glassmaking," *American Ceramic Society Bulletin* 102, 4 (May 2023), ceramics.org/wp-content/uploads/2023/05/May-2023_Feature.pdf.

- **Heat pumps and geothermal energy** applications include space conditioning for indoor agriculture (e.g., greenhouses and vertical farming) and livestock (e.g., poultry, swine, and dairy). In the construction subsector, air source heat pumps could be used for temporary space conditioning and water heating.
- **Sustainable biogenic fuel and feedstock sources** provide low-carbon alternatives, such as biomass as an option for process heat and bio-based plastics.

Mid-Term Pathways

Some examples of mid-term decarbonization pathway actions for other industrial subsectors might include:

- **Reductions in process-related emissions** can be realized, for example, in aluminum smelting by using inert anodes (comprising ceramics, metal alloys, cermet, etc.), in addition to carbothermic reduction or multipolar electrolytic cells.
- **Increased material circularity** could involve maximizing scrap metal use in the fabricated metals subsector and increasing recycling rates for aluminum and plastics. Options for plastics include chemical and mechanical recycling as well as demand side management (decreased use of single-use plastics such as polyethylene terephthalate bottles, food containers, stirrers, cutlery, bags, wet wipes, etc.).
- **Supply chain decarbonization** can be affected at most stages. An example is implementing sustainable agriculture processes to grow cotton used in the textile subsector.
- **Hybridization and electrification of mobile equipment** could reduce energy use for mobile equipment such as tractors, combines, loaders, and haulers. The majority of construction, about half of agriculture and forestry, and a quarter of mining energy use goes toward these applications. The engines typically use diesel fuel but could be paired with electric motors for improved efficiency or replaced with fully electric drives.
- **Improved agricultural practices** such as improved soil management and optimized application of fertilizers could reduce nitrous oxide emissions and avoid upstream emissions associated with production of agricultural chemicals. This could be accomplished within the context of precision agriculture and use of sensors and controls to measure and offer GHG mitigation emissions strategies and support productivity and sustainability.
- **Broader mining supply chain electrification** could be supported by changes to extraction and concentration processes. Some types of mineral processing have shifted toward leaching and solvent extraction (e.g., copper) because of degrading ore quality and lack of suitable ore types for conventional approaches. Rather than refining ores through elevated temperatures, electrowinning is used to achieve high purity levels. In the case of iron ore, electricity-based refining (e.g., direct reduced iron to electric arc furnace) requires higher iron content feeds than conventional blast furnaces (see Section 4.4 for more details for iron and steel manufacturing). Processing at mines could be modified to meet the necessary standards.
- **Feed additives for livestock** could reduce methane emissions from enteric fermentation that occurs during digestion. A variety of supplements to animal feed have been suggested to inhibit the production of methane. Methane constitutes a loss of feed energy, and its reduction could be beneficial beyond reducing GHG emissions. However, any changes to animal diets must be proven against adverse effects to health and production.
- **Increased production of bioenergy and bioproducts** can be accomplished through a variety of pathways that transform biomass to useful products and intermediaries. Agricultural and forestry waste residues, municipal wastewater sludge, and animal manure, among other sources, can be used to produce biofuels, biochemicals, and bio-feedstocks for traditional refining and chemicals subsectors, as well as biogas that could be used directly or upgraded to pipeline quality renewable natural gas.
- **Carbon capture and sequestration** could be deployed at natural gas processing plants and current oil fields that employ EOR, transforming those fields into long-term CO_2 storage. Natural gas processing plants strip CO_2 from raw gas and generate relatively high-purity streams, which reduce capture costs. Some plants already capture those emissions for EOR and have the associated pipeline infrastructure in place. Current EOR mostly uses terrestrial sources of CO_2, but anthropogenic sources could be used instead.

Long-Term Pathways

Longer-term decarbonization pathways and actions will depend on what is adopted in the short and medium term. Additional information and input are needed to better understand and estimate the net zero pathways for the rest of industry, which will help the industrial sector as a whole reach net zero emissions by 2050, and to comprehend what specific challenges and barriers those pathways may face.

4.8 Emissions Reductions Across Supply Chains and the Industrial Ecosystem

Successful industrial decarbonization will not only require targeted efforts within industrial subsectors, as detailed above in Section 4, but must also consider the supply chains associated with these industries to fully assess emissions and other impacts. Collectively, the industrial ecosystem (as described in Section 2) includes industrial processes, production systems, and interconnected industrial partners; synergies are created through value chains. All parts of the industrial ecosystem contribute to the embodied energy and embodied emissions of a product. Life cycle analysis is an important methodological construct used to quantify the energy and GHG emissions impacts (as well as additional environmental impact factors). GHG emissions impacts are often organized into three scopes: scope 1 (onsite emissions), scope 2 (emissions associated with the use of grid electricity), and scope 3 (emissions upstream and downstream of product manufacturing) (see Figure 76).

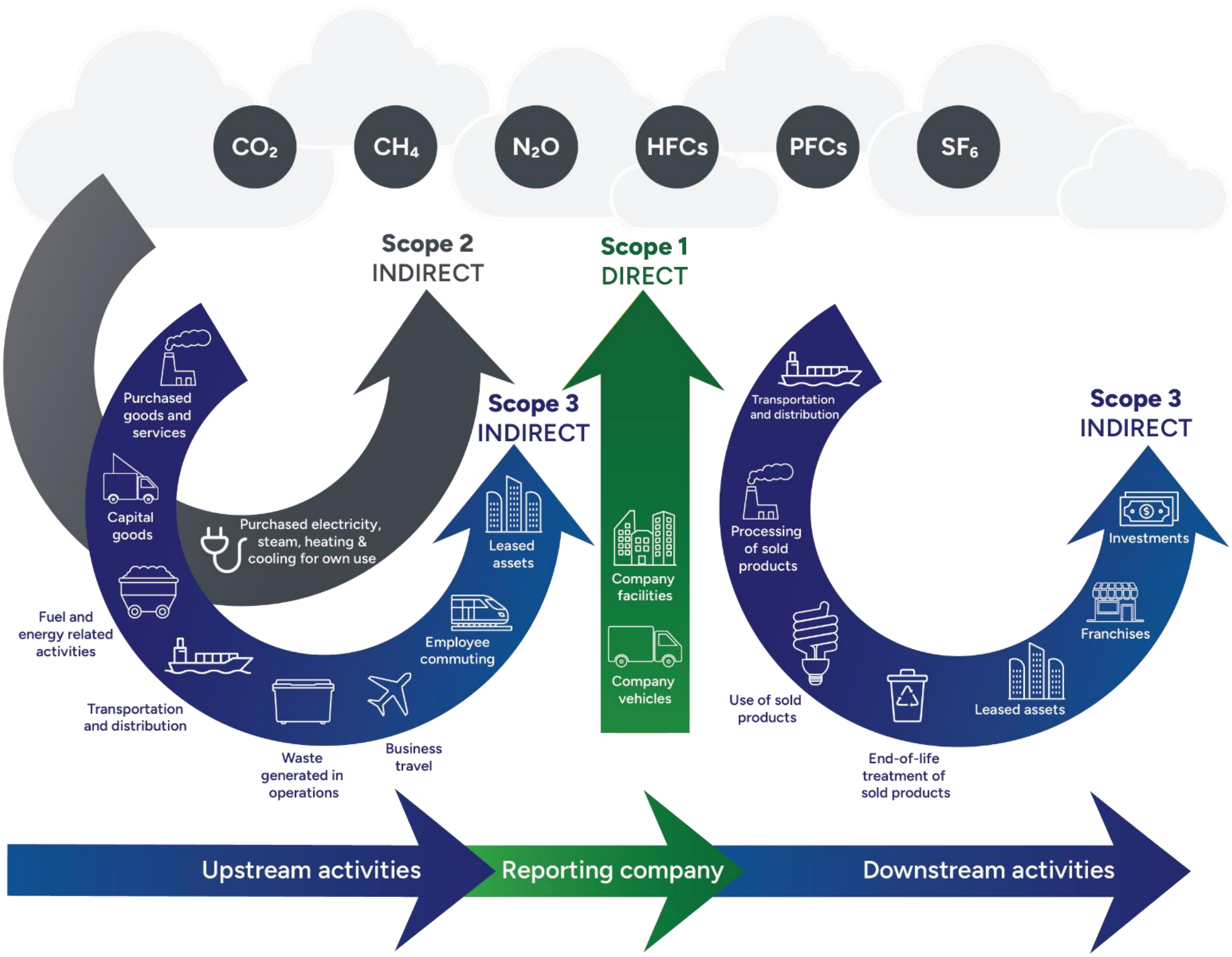

Figure 76. A full accounting of industrial GHG emissions includes scope 1, 2, and 3 emissions from activities across supply chains

Figure adapted with permission from World Resources Institute from Greenhouse Gas Protocol, Corporate Value Chain (Scope 3) Accounting and Reporting Standard, (2011), ghgprotocol.org/corporate-value-chain-scope-3-standard. Colors, icons, and font were changed.

Although the modeling featured in Section 4.1 through 4.6 focuses on scopes 1 and 2 emissions, some subsectors expand the bounds and do consider a broader systems perspective for specific scenarios or factors. For example, Appendix C includes petroleum refining modeled results for scenarios with either a scope 1, scope 2, or scope 3 emphasis, since the subsector will consider scope 3 emissions in all decarbonization strategies, particularly the impact that decarbonized or biogenically-derived liquid fuels will have on downstream transportation sector emissions. The pulp and paper section (Section 4.6) notes that even with the modeled results reaching near zero, biogenic carbon emissions will still need to be eliminated completely and should be considered when targeting scope 3 emissions reductions. For a wider supply chain perspective, the food and beverage modeling results (see Appendix C) consider a pathway exploring the impacts to the manufacturing stage's energy usage and emissions if food loss and waste were to be reduced in downstream supply chains.

Although many decarbonization solutions focus on scopes 1 and 2 emissions, there is an interconnectivity across the industrial ecosystem as subsectors buy and sell materials or services to and from one another. A life cycle perspective is required to address upstream and downstream scope 3 emissions, considering the entire value chain from raw material extraction to production, distribution, product use, and eventual disposal or reuse. This perspective can help identify optimization opportunities through increased material efficiency, use of lower-carbon materials, or adoption of alternative production processes that reduce overall emissions and embrace circular economy principles to reduce waste and promote reuse. A full accounting of emissions including scope 3 helps ensure that emissions are not simply being shifted to other parts of the industrial ecosystem, reducing effectiveness in achieving net zero industrial emissions goals.

4.8.1 Example – GHG Emissions in the Chemicals Supply Chain

The chemical subsector exemplifies the importance of assessing supply chain considerations when pursuing industrial decarbonization. Many chemicals, and chemical feedstocks including high volume products such as ethylene and propylene, are derived from fossil resources. Co-products of the fossil fuel industry are also used for chemicals production; for example, sulfuric acid (a primary component of fertilizers) is produced almost entirely in the United States as a byproduct of natural gas de-sulfurization.

An evaluation of the decarbonization potential of supply chains should include considerations of *reverse supply chains*; that is, recovery and reprocessing of end-of-life materials, which can enable a circular economy. Although the U.S. steel subsector is heavily dependent upon secondary steel (U.S. steelmaking has a recycled content of about 62%),[537] the chemicals subsector utilizes very limited amounts of end-of-life materials. For example, less than 10% of end-of-life plastics are reprocessed into new chemicals products,[538] and a recent analysis shows that in the United States only 10% of the chemicals produced each year are recycled, with recycling rates varying from 0% to 40% depending on the chemical class.[539]

An evaluation of virgin vs. reprocessed routes to polypropylene (PP) demonstrates the emissions reduction potential for a high-volume chemical product. Figure 77 shows that 2,200 kg of CO_2 are emitted per metric ton of PP produced via virgin production. A significant portion of these emissions come from the use of fuels and raw materials. With recycling, GHG emissions can be reduced to between around 500 to 1,800 kg of CO_2 per metric ton PP (about 18% to 77% emissions reduction), depending on the recycling method used,[540] with further reductions possible with a decarbonized electric grid. In this case, the reduction of scope 3 emissions attributable to "raw materials" caused overall emissions to decrease, but this may not be the case for reprocessing of other materials.

[537] Barbara K. Reck et al., "Assessing the Status Quo of U.S. Steel Circularity and Decarbonization Options," in *Technology Innovation for the Circular Economy: Recycling, Remanufacturing, Design, Systems Analysis and Logistics*, N. Nasr (Ed.)., 2024, doi.org/10.1002/9781394214297.ch17.
[538] Taylor Uekert et al., "Technical, Economic, and Environmental Comparison of Closed-Loop Recycling Technologies for Common Plastics," *ACS Sustainable Chemistry & Engineering* 11, 3 (January 2023): 965–978, doi.org/10.1021/acssuschemeng.2c05497.
[539] Taylor Uekert, "Mapping the end-of-life of chemicals for circular economy opportunities," *RSC Sustainability* 11 (October 2024), doi.org/10.1039/D4SU00517A.
[540] Sarah L. Nordahl et al., "Complementary roles for mechanical and solvent-based recycling in low-carbon, circular polypropylene," *Proceedings of the National Academy of Sciences* 120, 46 (November 2023), doi.org/10.1073/pnas.2306902120.

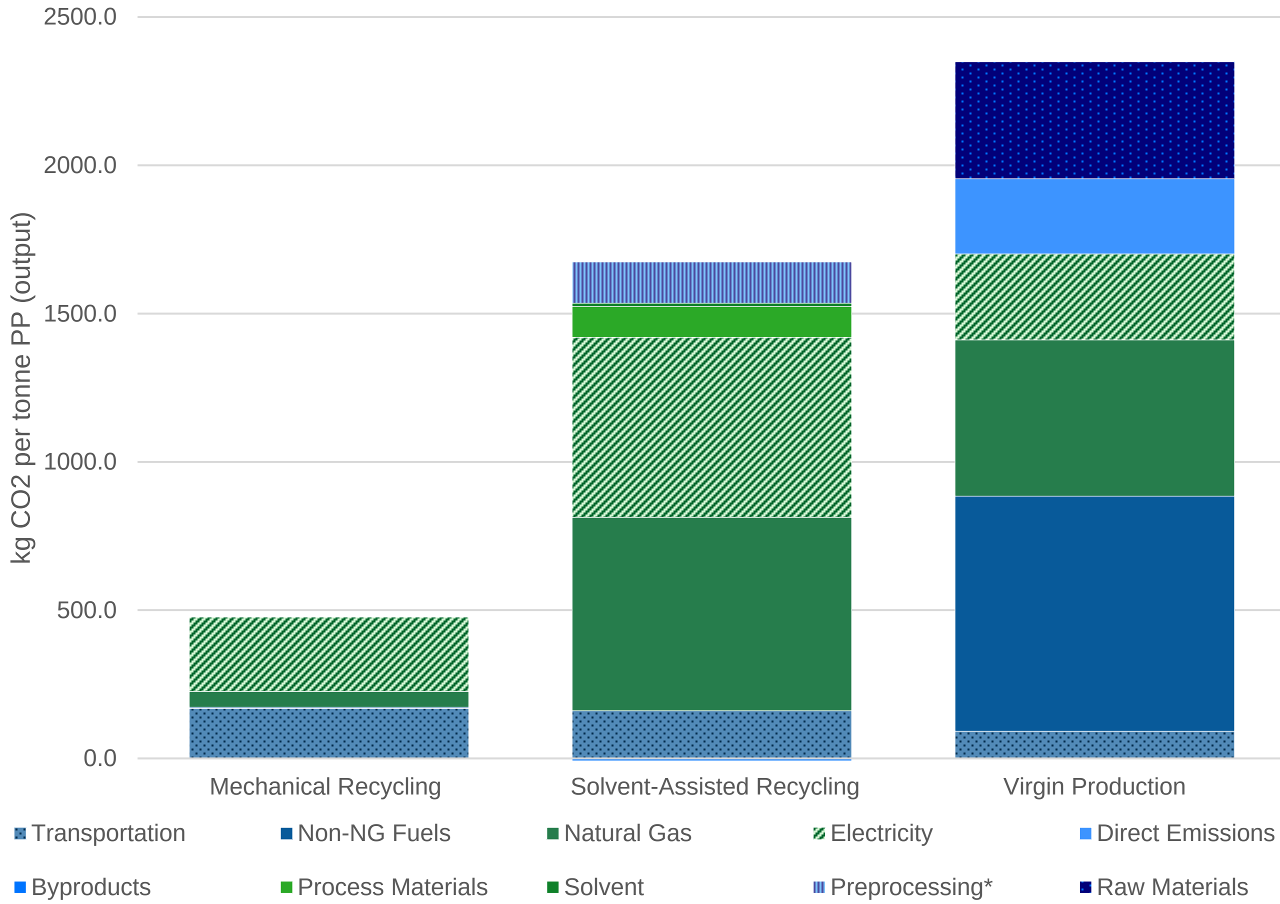

Figure 77. Life cycle greenhouse gas impacts from virgin production and recycling pathways for polypropylene

"Solvent-Assisted Recycling" refers to mechanical recycling with solvent-assisted upgrading. In the case of solvent-assisted recycling, "process" refers to dissolution and extrusion. Created with data from Sarah L. Nordahl et al., "Complementary roles for mechanical and solvent-based recycling in low-carbon, circular polypropylene," Proceedings of the National Academy of Sciences 120, 46 (November 2023), doi.org/10.1073/pnas.2306902120.

4.8.2 Example – GHG Emissions in the Glass Supply Chain

Glass manufacturing provides another case study of how decarbonization at the facility level can affect the subsector's scopes 1, 2, and 3 emissions.[541] In glass manufacturing, natural gas is typically burned to melt glass precursors. This natural gas can be replaced with hydrogen or the furnace itself can be replaced with fully electric heating powered by clean energy. Converting a furnace to run on hydrogen directly reduces scope 1 emissions. Electrifying a furnace also decreases scope 1 emissions; however, this can simply displace emissions into the scope 2 category without net benefit if the grid itself is not decarbonized. Scope 3 emissions may not be influenced by either of these changes; however, scope 3 emissions may increase if hydrogen fuel is generated without clean electricity.

A lever to reduce scope 3 emissions in these decarbonization scenarios is the inclusion of recycled glass (also known as cullet) as a precursor material. Cullet has lower embodied emissions as it does not require the same mining and processing as virgin material. Figure 78 shows that incorporation of increased cullet decreases scope 3 emissions. Additionally, increased cullet use can also decrease scope 1 emissions because it can be melted at lower temperatures and does not release process emissions via chemical reactions (shown as scope 1-Decomp in Figure 78) like virgin materials.

[541] Greg Avery and Alberta Carpenter, *Supply Chain Energy and Greenhouse Gas Analysis Using the Materials Flows through Industry (MFI) Tool: Examination of Decarbonization Technology Scenarios for the U.S. Glass Manufacturing Sector*, NREL/TP-6A20-83730 (National Renewable Energy Laboratory, 2023), doi.org/10.2172/1924235.

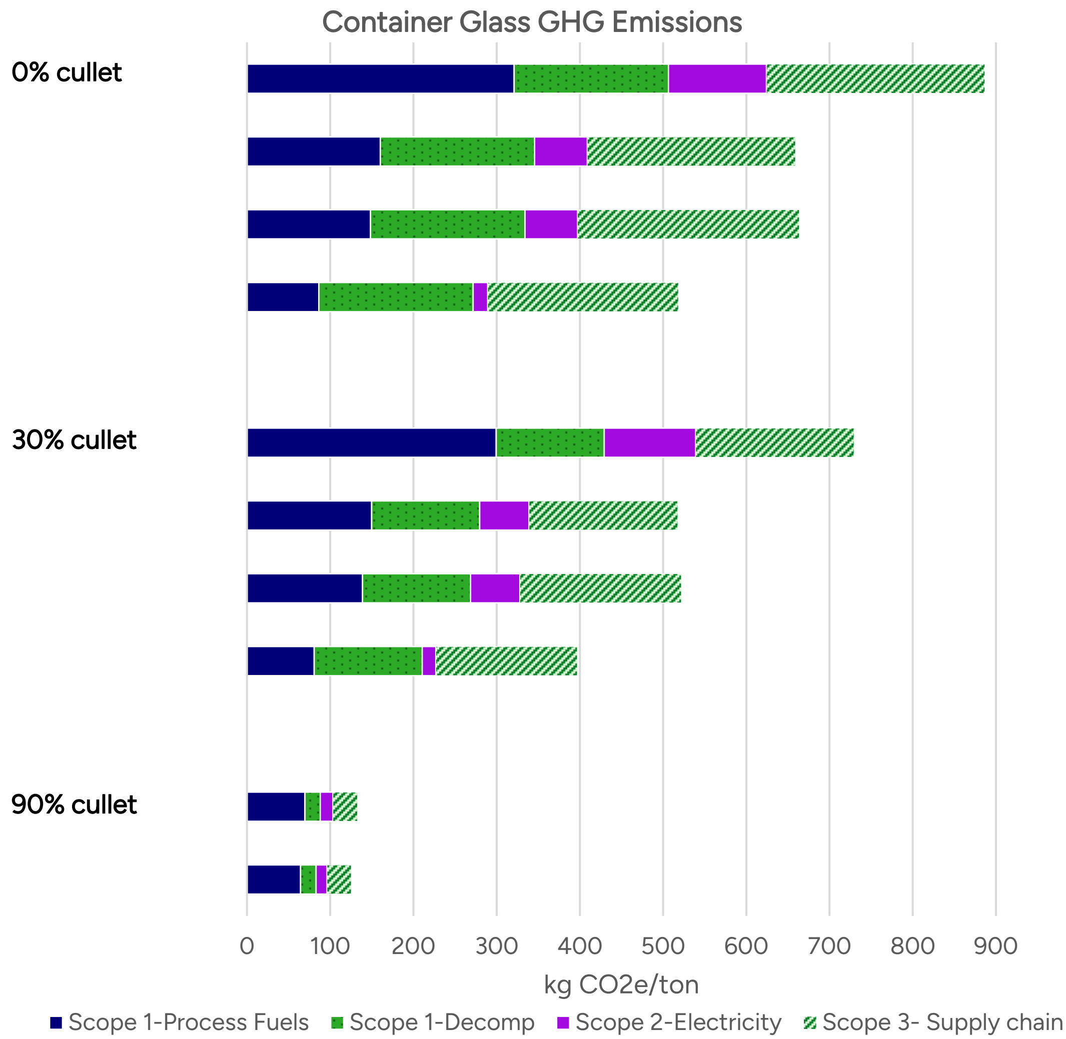

Figure 78. GHG emissions reductions resulting from increasing level of recycled glass (cullet)

Acronyms/abbreviations: H_2 (hydrogen), RE (renewable energy), SOTA (state of the art), Data source: Greg Avery and Alberta Carpenter, Supply Chain Energy and Greenhouse Gas Analysis Using the Materials Flows through Industry (MFI) Tool: Examination of Decarbonization Technology Scenarios for the U.S. Glass Manufacturing Sector, NREL/TP-6A20-83730 (National Renewable Energy Laboratory, 2023), doi.org/10.2172/1924235.

Although glass is not currently one of the top emitting U.S. industrial subsectors,[542] this could change as the economy decarbonizes. Several clean energy technology solutions are projected to deploy at very aggressive rates, including solar which utilizes glass panels. Solar production at these accelerated rates will be beyond the current capacity of the U.S. glass manufacturing subsector, forcing dependence on foreign manufacturing systems that may be very carbon intensive. Glass is a key component in the scope 3 emissions of photovoltaic panels. Analysis has shown that the manufacturing location can double the embodied carbon content of a solar panel, further emphasizing the importance of supply chain analysis to quantify industrial emissions impacts.[543]

4.8.3 Considerations and Strategies to Decarbonize Across a Transforming Industrial Ecosystem

Meeting decarbonization targets will require significant changes to the flow of energy and materials in and across industrial subsectors and existing supply chains as well as the creation of new supply chains. Industry has evolved to depend on the ready supply and current price points of fossil inputs. Successful transition of fossil

[542] In 2018, glass manufacturing accounted for 15 MMT CO_2e emissions or about 1% of total U.S. manufacturing emissions. See U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Glass and Glass Products," (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_glass_energy_carbon_footprint.pdf.

[543] Hope M. Wikoff, Samantha B. Reese, and Matthew O. Reese, "Embodied energy and carbon from the manufacture of cadmium telluride and silicon photovoltaics," *Joule* 6, 7 (July 2022): 1710–1725, doi.org/10.1016/j.joule.2022.06.006.

energy supply chains as well as others discussed below will require strategic planning to ensure reliability and affordability. A carefully managed approach will be essential to allow industry to adapt and invest in new technologies without compromising operational stability.

Effective supply chain management and optimization are essential to navigate the complexities of industrial decarbonization. Flexibility is key to adapting to changing regulations, shifting resource availability, and evolving market dynamics. Strategies such as demand forecasting and supplier diversification can help industrial subsectors anticipate and respond to these changes, ensuring a resilient supply chain that can meet sustainability targets while maintaining operational stability. Transparency is equally critical; it should be integrated into every aspect of supply chain transitions, providing visibility into emissions, sourcing, practices, and environmental impacts that are increasingly called for.

In the context of decarbonization across the industrial ecosystem, changes to LCFFES provide a useful illustration of the extent of supply chain transformation required. Traditional fossil fuel-based supply chains will be replaced with new networks for biofuels, clean hydrogen, synthetic fuels, bio-based feedstocks, and other sources. This will require completely new infrastructures and increased materials flows to support them.

As one example, the production of clean hydrogen via electrolysis increases demand for electrolyzer components such as membranes, electrodes, and catalysts like platinum, iridium, and nickel. The electricity needed for electrolysis increases clean energy demands, thereby increasing demand for clean electricity technologies such as photovoltaic components, wind turbines, and energy storage systems, which in turn increases demand for lithium, rare earth elements, and high-grade silicon. Additionally, the large water requirement for electrolysis may increase demand for desalination and water recycling facilities and their requisite materials. The transportation of hydrogen will require upgraded pipelines and storage materials, resulting in increased demand for stainless steel and hydrogen-compatible polymers. Other supply chain impacts to consider based on increased demand for clean hydrogen include changes to port facilities for shipping liquefied natural gas adapted to handle liquid hydrogen (or other hydrogen carriers such as ammonia), and an increased need for electric grid construction materials like steel, concrete, and copper for transmission lines. The increased demand for clean energy is likely to favor areas with good energy resources and associated infrastructure, possibly shifting industrial hubs and requiring new transportation routes. This range of impacts for just one technology within the LCFFES suite showcases the extensive ripple effects of these supply chain changes, highlighting the complexity and scale of change.

4.8.4 GHG Emissions Reductions Across the Industrial Ecosystem – Resource and Material Efficiency Approaches

Raw materials extraction and processing contribute to about 50% of global GHG emissions.[544, 545] Materials and resources entering, used or produced within, and leaving industrial facilities have embodied emissions, and efficient use of materials and resources (including circularity and alternative processes, feedstocks, and innovative products) can reduce U.S. industry's environmental impacts and the upstream and downstream emissions that reach the broader economy. More efficient use of materials and resources and proper siting of industrial facilities can mitigate negative impacts and provide environmental and societal benefits.

Material efficiency can be defined as the use of material resources per unit output for a product system,[546] including providing material services with less material production and processing.[547] Material efficiency can be achieved by reducing the amount of material used to manufacture a product or producing less waste, either through more material-efficient manufacturing or by using waste materials (both pre- and post-consumer) in

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[544] Ellen MacArthur Foundation, *Completing the Picture: How the Circular Economy Tackles Climate Change*, (2021), www.ellenmacarthurfoundation.org/publications/completing-the-picture-climate-change.
[545] International Resources Panel, *Global Resources Outlook 2019: Natural Resources for the Future We Want*, (2019), www.resourcepanel.org/reports/global-resources-outlook.
[546] See page 53 in U.S. Department of Energy, *Quadrennial Technology Review 2015 Chapter 6 Technology Assessments: Innovating Clean Energy Technologies in Advanced Manufacturing, Sustainable Manufacturing* (2016), www.energy.gov/sites/prod/files/2016/05/f31/QTR2015-6L-Sustainable-Manufacturing.pdf.
[547] Julian M. Allwood et al., "Material efficiency: A white paper," *Resources, Conservation and Recycling* 55, 3 (January 2011): 362–381, doi.org/10.1016/j.resconrec.2010.11.002.

another product or process.[548] Material efficiency and sustainable manufacturing measures include (among others):

- Redesigning, reusing, repurposing, and recycling, especially energy and carbon-intensive industrial products and commodities, as well as their substitution with functionally identical (or better) alternatives with lower embodied carbon.
- Lowering the energy, material, and other resource demands of a manufacturing facility through waste reduction. Fewer resources are used to produce the same amount of goods. Further, waste reduction can reduce costs (waste disposal and overall energy, material, and resource costs since more of these go into the product), dependence on outside entities to accept the waste, and risk of environmental hazard associated with toxic waste transportation and processing.

More broadly, a circular economy can retain materials' value over longer timeframes, minimize waste, and generate potential economic and environmental benefits compared to the linear "take-make-waste" economy.[549] Barriers to material circularity and efficiency include absent or inadequate reverse supply chain infrastructure for collection and transport of products at end-of-life or end-of-use, scale-up risks and performance or quality trade-offs with alternative substitutes, higher costs relative to linear supply chains, concerns around labor costs, possible job losses, regulatory standards, and rebound effects.

Ultimately, a systems-level approach is needed for industrial ecosystem decarbonization, considering the full industrial sector and other economic sectors, to decarbonize not just individual facilities or subsectors, but also decarbonize the full supply chains. An increased understanding of supply chains can further help to identify vulnerabilities due to labor or capital costs, regional regulations and incentives, or resource availability, all while facilitating decarbonization goals. Increasing the understanding of supply chains can help determine where innovation hubs could be/are beneficial and where decarbonization efforts would be most effective.

[548] U.S. Department of Energy, *Sustainable Manufacturing and the Circular Economy*, by Kristina Armstrong et al., DOE/EE-2696 (2023), www.osti.gov/biblio/1963668.
[549] U.S. Department of Energy, *Circularity for Secure and Sustainable Products and Materials: A Draft Strategic Framework* (2024), www.energy.gov/eere/articles/us-department-energy-solicits-feedback-its-plan-increase-products-and-materials.

5 CONCLUSIONS AND CONSIDERATIONS

Existing U.S. industrial production processes have been optimized for costs, production, yield, and other factors over decades; however, many of these processes will be neither competitive nor sustainable in a future global net zero economy. Industrial sector transformation will allow for U.S. technology leadership, greater energy and resource efficiencies, emissions reductions, reduced human health impacts, and equitable distributions of the benefits and burdens of a production-based economy. This report explores the factors that underpin this transformation, with industrial sector decarbonization as a fundamental requirement for sustainable global competitiveness. Section 1 frames the opportunity for a transformation in the context of additional requirements, including U.S. innovation, manufacturing resilience, and environmental justice. Section 2 describes the industrial ecosystem framework that was used to identify transformation opportunities alongside key challenges and barriers to decarbonization; Sections 3 and 4 present and evaluate (qualitatively and quantitatively) specific and actionable transformation pathways for six U.S. industrial subsectors and the rest of industry. This section provides a high-level overview of key conclusions from this report and key considerations for U.S. industrial transformation moving forward. Detailed findings for each subsector can be found in Section 4.

During this study, several high-level takeaways have emerged, as discussed below.

- No single pathway exists for the industrial sector overall or for any individual subsector, as steps can and will change as the future unfolds. Competition across different possible pathways will be essential to success.
    - A variety of technologies, practices, and approaches are needed to achieve near zero emissions within and across U.S. industrial subsectors. Not every technology choice or pathway is equivalent, as some will prove to be more challenging or less economically viable than others.
    - The specific selection and sequence of technology deployments and retirements over time will depend upon the specific requirements for a certain facility, company, or region.
    - RDD&D is needed to advance viable solutions that will need to be adopted at scale in the marketplace.
- Targeting energy-related emissions will not directly address emissions from inefficient materials flows and chemistry-associated (process) emissions.
    - New production routes can provide pathways to near zero emissions by 2050 for most industrial subsectors; however, thoroughly efficient production processes are required throughout supply chains.
- Incremental solutions are insufficient to achieve desired GHG emissions reductions.
    - Although energy efficiency improvements will provide emissions reductions and productivity benefits, mature industrial processes are reaching practical limitations for improvement rates.
    - There is a need for revolutionary changes within and beyond the industrial sector. A range of process heating operations can be met via highly efficient industrial electrification but will require clean electricity to be available at an accelerated rate. There will be competition for certain low-carbon energy and feedstock inputs—such as biomass, which must be produced sustainably, and hydrogen, which must be produced cleanly and at competitive cost—that allow for industrial adoption for expanded applications.
- An industrial transformation must not result in adverse outcomes.
    - There is a need for more thoroughly sustainable manufacturing operations that not only reduce GHG emissions but also consider other environmental and human health impacts.
    - Rapid adoption of technologies that can partially, yet not fully, reduce emissions can play an important role in cumulative emission reductions. To prevent carbon lock-in, however, such technologies must be retired as lower-emissions technologies come online.

- Industrial sector transformation will be accompanied by significant changes across the industrial ecosystem. Significantly modified and new industrial infrastructure must not impose additional or new burdens on communities in which industry operates.

5.1 Transformative Pathways Approach

This study analyzed and modeled six energy- and emissions-intensive industrial subsectors. As a direct follow-on to the *Industrial Decarbonization Roadmap*,[550] this study expanded on the modeling scope to include additional production routes and technologies and addressed cross-sectoral and cross-economy challenges that will arise with a transformation of the U.S. industrial sector. As such, this study:

- Identified subsector-specific strategic pathways to achieve a globally competitive, near zero GHG emissions U.S. industrial sector by 2050.
- Identified the technological, economic, societal, and environmental and health impacts associated with the scale and pace of an industrial transformation–though not discretely modeled in this work.
- Presented strategies, targeted pathways, and metrics for overcoming challenges and barriers.

This report was informed by literature review, workshops,[551,552] an RFI,[553] and expert input to gather information on viable[554] technologies and strategies and estimate their associated emissions reductions by decarbonization pillar and production routes for all subsectors. The *Transformative Pathways* modeling estimated technology impacts and emissions reduction potential of various decarbonization interventions that are available or anticipated to be available to each subsector. The analysis considers major production routes; factors affecting how facilities will evaluate and choose technologies; timing for technology deployments; major uncertainties, risks, and barriers; and differing pathways for retrofits vs. greenfield facilities. While these frameworks show technology leadership transitions and emissions reduction potentials at the level of entire U.S. industrial subsectors, they can also be adapted for more specific use cases. Decisions and choices around technologies and pathways will ultimately be determined by the specific constraints within a region, state, and locale, with unique considerations for any individual industrial subsector or company. Hence, the frameworks are intended to be:

- **Specific:** The frameworks provide a starting point for more targeted use cases, varying with factors applicable to the "user."
- **Adaptable:** Although the outputs of the models use assumptions about, for example, anticipated changes and aggregated uptake of technologies over time for a given industrial subsector, modeling frameworks can be adapted for differing assumptions and possible futures.
- **Iterative:** Frameworks will evolve over time as technologies change and emerge, as economic and policy conditions change, as barriers are overcome, etc.

5.2 Cross-Cutting Key Takeaways

Industrial transformation, as highlighted in this report, will involve changes not only within the industrial sector but across the entire U.S. economy. Although specific subsectors will need specialized decarbonization pathways, there are cross-cutting strategies that can be implemented across all U.S. industrial subsectors:

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550 U.S. Department of Energy, *Industrial Decarbonization Roadmap*, DOE/EE-2635 (2022), www.energy.gov/industrial-technologies/doe-industrial-decarbonization-roadmap.

551 U.S. Department of Energy, "U.S. Department of Energy Workshop on Transforming Industry—Strategies for Decarbonization," accessed December 2024, www.energy.gov/eere/iedo/events/us-department-energy-workshop-transforming-industry-strategies-decarbonization.

552 U.S. Department of Energy, "Pathways to U.S. Industrial Transformations Workshop to Inform Impacts of Energy, Equity, and Environmental Justice on Decarbonizing the Industrial Sector," accessed December 2024, www.energy.gov/eere/iedo/events/pathways-us-industrial-transformations-workshop-inform-impacts-energy-equity-and.

553 U.S. Department of Energy, "Department of Energy Seeks Input on Technology Pathways to Decarbonize America's Industrial Sector," May 2024, www.energy.gov/eere/iedo/articles/department-energy-seeks-input-technology-pathways-decarbonize-americas.

554 Viable implies currently available, cost effective, and meets relevant technological, economic, environmental and health, and societal criteria.

- Develop technologies consistent with the pathways described herein that address not only competitiveness considerations but also environmental justice and societal impacts to ensure decarbonization measures are improving the health and economies of U.S. communities.
- Decarbonize the U.S. electric grid, in parallel with industrial investments, to ensure multiple pathways are viable for each subsector and can be complemented through the development of CCUS infrastructure and corresponding deployment strategies.
- Continue stakeholder engagement with industry, technology innovators, local communities, non-profit organizations, regulators, policy makers, and others. Decarbonization will be a deep, far-reaching transformation of the industrial sector and, as such, necessitates meaningful dialogues between all involved and affected stakeholders.

Different subsectors (and pathways within subsectors) will rely on different combinations of the decarbonization pillars to reach near zero GHG emissions by 2050. This report represents an aggregate view of the decarbonization potential of U.S. industrial subsectors; however, the most viable pathways may vary by region, organization, or facility. Overall, a balanced approach and investment of resources across the industrial ecosystem are needed to achieve net zero GHG industrial emissions. The roles of key industrial decarbonization levers (energy efficiency, material and resource efficiency, LCFFES, industrial electrification, and CCUS) from an industrial ecosystem perspective can be found below.

Energy Efficiency

Energy efficiency will have a pervasive role across all subsectors, with the potential to improve existing operations (e.g., with uptake of state-of-the-art technologies and practices) and continually improve emerging technologies. Although energy efficiency may have limited impact compared with other decarbonization pillars (ranging from 1%–22% emissions reduction for the subsectors evaluated in the *Transformative Pathways* modeling) and may not bring about transformational changes, it is often the lowest-hanging fruit, provides cost savings, and is the first intervention considered by industrial entities, as shown in the industrial decarbonization decision tree (Figure 8). Energy efficiency should be considered not only as a distinct intervention but also in combination with others, such as electrification and low-carbon fuels, to maximize decarbonization potential. Efficiency measures should be applied continuously as technologies, processes, and operations evolve.

Material and Resource Efficiency

Material and resource efficiency will have an essential role in decarbonizing the industrial sector and improving sustainability across the industrial ecosystem (see Section 4.8.4). The *Transformative Pathways* modeling explored the role of material efficiency, to varying degrees. For iron and steel, high scrap utilization was found to be essential for all decarbonization pathways. Current recycled content in U.S. steelmaking stands at approximately 62% (Figure 55). The modeling sensitivities explored increasing this to 95% (see Figure C-27 in Appendix C), which can be achieved through such interventions as decreasing scrap lost to landfill, minimizing hibernating stock, and assessing the role of scrap import/export. The current modeling framework does not incorporate feedstock quality, but future scenario development will capture effects of varying scrap qualities. More information can be found in Section 4.4.

Regarding the chemicals subsector, this study explored an increased recycling sensitivity. Achieving an effective recycling rate requires mitigating challenges of contamination in plastic recycling and pursuing alternatives to single-use materials (see Section 4.2 and Appendix C). Although recycling concrete was not explicitly modeled, the use of recycled inputs, such as recycled cement kiln dust, can be incorporated as SCMs (see Section 4.1). For pulp and paper, recycling showed minimal impacts because the technology adoption in the near zero pathway constrained the decarbonization potential of other impacts (see Section 4.6).

Efficient resource utilization is challenging to quantify since impacts encompass embodied energy and carbon across supply chains. For example, any individual facility in a supply chain may or may not be able to adapt existing processes and operations to handle differing materials inputs. Further, materials changes can affect by-products/co-products, resulting in impacts across the industrial ecosystem, sometime with unintended deleterious consequences. Careful materials flow analysis and life cycle analysis are required to fully characterize the net energy and environmental impacts for all technological changes through supply chains.

Material efficiency initiatives may increase costs and complexity in the short term as supply chains are reconfigured to handle alternative materials. Entrenched practices and the need for new infrastructure investment and collaboration between stakeholders can create resistance to adoption. However, despite these initial challenges, material and resource efficiency holds great potential as an ultimately cost-effective strategy for emissions reduction. By optimizing material use and minimizing waste, subsectors can reduce energy demand and raw material dependency, lowering overall costs in the long term.

LCFFES

Low-carbon fuels and energy sources have broad applicability as a decarbonization lever for process heat. In particular, high-temperature processes can be addressed with low-carbon fuels, such as hydrogen and renewable natural gas, as well as clean energy sources, such as concentrating solar thermal and nuclear. Although the *Transformative Pathways* modeling primarily assumed electrification as the decarbonization lever for low-to-medium process heat, hard-to-electrify processes within this temperature range can also use low-carbon fuels and energy sources, such as biomass and geothermal. The direct use of these low-carbon fuels and energy sources at industrial facilities is dependent on availability, accessibility, and facility/process requirements. Especially for low-carbon energy sources such as geothermal and concentrating solar thermal, regional and temporal variation must be considered.

Low-carbon feedstocks will play a role primarily in decarbonizing industrial processes that include material transformations. The *Transformative Pathways* modeling considered the direct replacement of fossil-based feedstocks, such as replacing pulverized coal with charcoal; reduction in the amounts of emissions-intensive materials, such as using SCMs to reduce clinker content in cement; and use of recycled content to reduce virgin material use, such as steel scrap and recycled chemicals (e.g., polyethylene, polypropylene).

In particular, hydrogen has broad decarbonization potential as a feedstock and fuel across the iron and steel, chemicals, and refining subsectors. The *Transformative Pathways* modeling quantified the role that hydrogen would play in the modeled subsectors (including the nine chemicals modeled for the chemicals subsector). Cumulatively, for the six subsectors, modeled hydrogen demand (as both feedstock and fuel) rose from 9.8 MMT in 2018 to 16.4 MMT in 2050. This increase was driven by an emergent demand of 5.6 MMT in iron and steel (for the H_2-DRI pathway) and an increase from 3.8 to 6.0 MMT in the chemicals subsector for the nine modeled chemicals. Demand for hydrogen decreased in refining, and there were minimal instances of hydrogen use in pulp and paper and food and beverage and none in cement. U.S. industry currently produces 10 MMT of hydrogen annually, almost all of which is consumed by the refining and chemicals subsectors.[555] If clean hydrogen initiatives are realized, hydrogen production can reach 50 MMT by 2050 and surpass industrial demand.[556]

Biomass as a low-carbon energy source is expected to play a role in decarbonizing low-temperature process operations. As estimated by DOE, around one billion tons of sustainably sourced biomass can be made available annually in the United States.[557] This biomass can come from diverse sources in the form of biowastes and is deployable in all subsectors due to its combustible nature. Combined with CCS, biomass pathways could lead to negative emissions in some subsectors. Biogenic emissions are an important consideration when identifying decarbonization pathways with biomass. They are broadly considered net zero, but accounting for biogenic emissions can significantly change technology choices. For further discussions on the impact of biogenic emissions, see Section 4.2.3.9 (ethanol) and Section 4.6.4 (pulp and paper). Although biomass was present in most subsector pathways, there were no instances of its use in iron and steel.

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[555] U.S. Department of Energy, *U.S. National Clean Hydrogen Strategy and Roadmap* (2023), www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap.
[556] Ibid.
[557] U.S. Department of Energy, *2023 Billion-Ton Report*, ORNL/SPR-2024/3103 (2024), www.energy.gov/eere/bioenergy/2023-billion-ton-report-assessment-us-renewable-carbon-resources.

Industrial Electrification

Industrial electrification will play a significant role in decarbonizing low- to medium-heat processes—such as steam generation, separations, and drying—that are common across many industrial subsectors. Electrifying these processes often depends on technologies that, while mature, lack broad commercial deployment (e.g., heat pumps and electric boilers). Roughly 78% of industrial thermal demand could be decarbonized through electrification, which in such cases is considered a decarbonization pathway.[558] However, electrification can also play a role in decarbonizing high-temperature processes. High-temperature processes have already been electrified in select cases (e.g., electric arc furnace steelmaking), but more is needed. For instance, clinker calcination and steel finishing processes offer potential for electrification. Electrifying industry will also require supporting technologies and approaches, such as energy storage, grid interactivity, and auxiliary components like controls and communications.

The *Transformative Pathways* modeling indicates that electrification can help decarbonize the food and beverage, iron and steel, pulp and paper, and chemicals subsectors and, to a lesser degree, the cement subsector, with demand remaining flat in refining. The cumulative electricity demand in the six modeled subsectors (including the nine modeled chemicals for the chemicals subsector) was 440 TWh in 2018 and is predicted to be almost 1,200 TWh by 2050 in the CNZ pathways. This increase is driven by over 350 TWh of increased demand in food and beverage, 180 TWh in iron and steel, 110 TWh in chemicals, 90 TWh in pulp and paper, and 20 TWh in cement.

Underpinning industrial electrification as a viable near zero decarbonization pathway is grid decarbonization and the availability of clean electricity. Although the pathways presented in this report assume clean and available electricity by 2050 (see Appendix B), coordinated and significant action is needed to overcome the challenges in realizing this future, including increasing clean electricity generation capacity and upgrading transmission and distribution infrastructure.

CCUS

The application of CCUS is highly dependent on the processes used within each industrial subsector. Carbon capture has greater technical potential for large point-source emissions from relatively high-purity CO_2 streams, such as those from calcination, fermentation, and gasification. Post-combustion emissions can also be captured but require additional processes to purify the exhaust flue streams. Although carbon capture can reduce industrial point-source emissions that are ultimately released into the atmosphere, implementing these systems inherently adds cost from the high capital and the energy[559] required for their operation. CCUS also faces system-level challenges that must be addressed, including a lack of CCUS infrastructure (e.g., pipelines and storage), uncertainty of merchant and captive CO_2 markets, and a need for accounting guidelines for captured, reused, and stored carbon.

Nonetheless, carbon capture will likely be a necessary intervention to achieve near zero industrial emissions. However, its utility as a decarbonization lever will depend on several factors, including the availability of alternative pathways that may diminish its need, proximity to sequestration sites, and physical facility constraints. For example, over half of installed cement capacity is outside a 100-mile radius of CO_2 storage sites, limiting the application of CCS for these facilities (see Figure 16). Moreover, broad deployment of low-carbon SCMs can reduce clinker demand, reducing the process and combustion emissions associated with calcination, thereby limiting the role of CCS in the subsector (see Section 4.1.3). In iron and steel, the H_2-DRI pathway (compared with the IM-CCS pathway) minimizes the need for carbon capture through the use of DRI produced with clean hydrogen, clean hydrogen fuel, and clean EAF and finishing (see Section 4.4.4).

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[558] Renewable Thermal Collective, *The Renewable Thermal Vision* (2022), www.renewablethermal.org/vision/.
[559] See Appendix B for CCUS energy demands assumed for the *Transformative Pathways* modeling.

5.3 Subsector-Specific Key Takeaways

High-level takeaways for the six industrial subsectors modeled in this report are provided in this section. A full perspective for each subsector can be found in Section 4.

5.3.1 Cement and Concrete

- Two pathways were identified where aggressive decarbonization interventions could reduce the subsector's annual GHG emissions to approximately 10 MMT CO_2e in 2050, down from 68 MMT CO_2e in 2018.
  - High Clean Clinker Production, Moderate SCM pathway (see Figure 79)
  - Moderate Clean Clinker Production, High SCM pathway (see Figure 80)
- The pathways were not fully distinct in that they both increased usage of SCMs, to differing degrees (represented as limestone calcined clay in the modeling), and clean clinker production (represented as CCS-enabled clean clinker production in the modeling).
- The modeling was limited in that it lacked implementation of novel clinker production routes, such as those using electrochemical conversion, or nascent technologies for clinker alternatives.
- Both modeled pathways leveraged CCS-enabled clean clinker production to represent 80%–100% of clinker production in 2050. The pathways differed in the amount of clinker demand required in 2050, as higher SCM adoption resulted in lower clinker demand. Both pathways showed significant demand reduction in clinker, such that clinker production coalesced around sites more suitable for geologic storage.
  - Clean clinker could alternatively be accomplished with novel clinker production routes (not modeled), separately or in combination with CCS-enabled clinker production.
  - For novel clinker production routes to have any appreciable market share by 2050, they must be commercially viable against conventional clinker pyroprocessing with CCS before 2035.
- Both modeled pathways leveraged SCMs to reduce clinker content in cement in 2050, 40% for the High Clean Clinker Production, Moderate SCM pathway and 60% for the Moderate Clean Clinker Production, High SCM pathway. Utilizing SCMs to offset clinker represents a decarbonization intervention with near-term GHG reduction at the risk of locking in a feedstock with significant embodied emissions. These embodied emissions limit the long-term potential of a pathway utilizing SCMs unless these embodied emissions are also addressed, as they are in the Moderate Clean Clinker Production, High SCM pathway.
- As clinker production moves toward clean production, tradeoffs between the emissions of SCMs versus clinker, as well as other environmental, economic, technological, and societal impacts, need to be balanced.
- In addition to clean clinker production, the analysis also identified fuel-switching from coal and petcoke to natural gas and biomass as a decarbonization opportunity. Although the impacts on GHG emissions may be less, they are still necessary to achieve near zero GHG emissions by 2050.

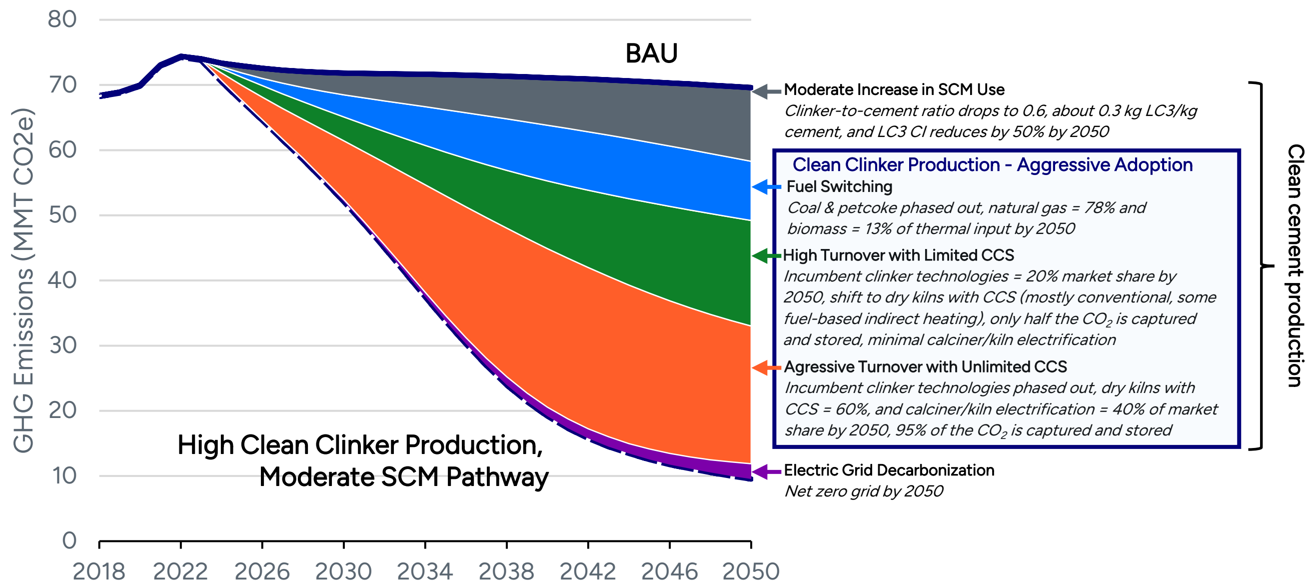

Figure 79. Annual GHG emissions reductions, U.S. cement and concrete manufacturing–High Clean Clinker Production, Moderate SCM pathway (MMT CO_2e/year), 2018–2050

The emissions impact of the interventions (for the year 2050) in the box on the right can be functionally equivalent to nascent clean clinker production routes that were not explicitly considered in the model. The emissions impact of the interventions (for 2050) within the bracket can be functionally equivalent to nascent clean cement production routes. In both instances, a change in the interventions would change the shape of the wedges. Details on assumptions, parameters, and timing of transformative technology application can be found in Section 4.1 and Appendix C. Source: Transformative Pathways modeling.

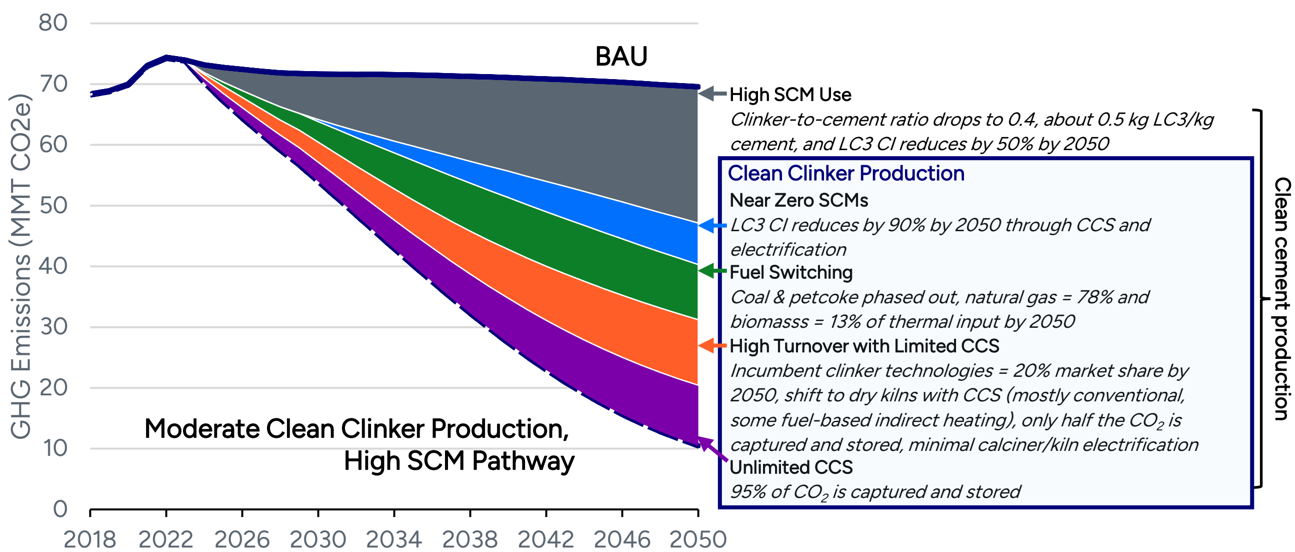

Figure 80. Annual GHG emissions reductions, U.S. cement and concrete manufacturing–Moderate Clean Clinker Production, High SCM pathway (MMT CO_2e/year), 2018–2050

The emissions impact of the interventions (for the year 2050) in the box on the right can be functionally equivalent to nascent clean clinker production routes that were not explicitly considered in the model. The emissions impact of the interventions (for 2050) within the bracket can be functionally equivalent to nascent clean cement production routes. In both instances, a change in the interventions would change the shape of the wedges. Details on assumptions, parameters, and timing of transformative technology application can be found in Section 4.1 and Appendix C. Source: Transformative Pathways modeling.

5.3.2 Chemicals[560]

- This subsector is especially challenging to decarbonize given the wide range of products, large thermal footprint, current reliance on energy- and emissions-intensive feedstocks and processes, and dependence on co-manufacturing of certain chemicals.
- Although interventions along the decarbonization pillars provide substantial decarbonization potential, innovative clean chemicals production technologies are needed to reach near zero emissions (represented as CCS-enabled clean production in the modeling). Without these innovations, achieving near zero or absolute net zero emissions does not seem feasible for most chemicals, with the exception of ethanol[561] and chlor-alkali.
- Decarbonization pathways and pillar impacts will vary by chemical; for example, ethanol has large proportions of high-purity CO_2 emissions and therefore higher CCUS emissions reduction potential than some of the other chemicals modeled.
- Methanol, ethanol, ammonia, and CO_2 are critical feedstocks for future chemicals manufacturing that should be prioritized for further research.
- The production costs of clean hydrogen underpin the economics of methanol and ammonia production emissions reduction.
- Beyond the four decarbonization pillars, material recycling is another major lever for reducing chemicals subsector emissions, especially for those with existing recycling methods, such as ethylene, propylene, and BTX.

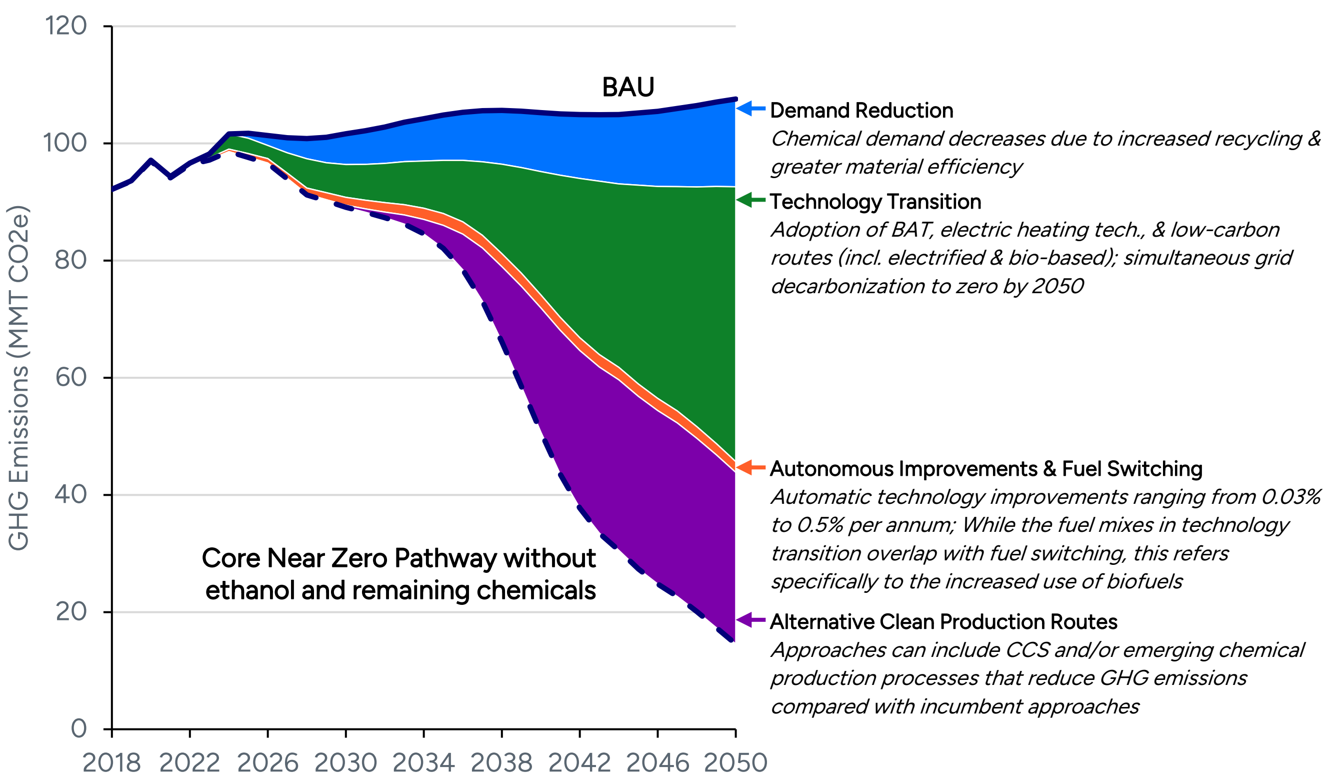

Figure 81. Annual GHG emissions reductions, U.S. chemicals manufacturing*—Core Near Zero pathway (MMT CO_2e/year), 2018–2050

[560] This work modeled individual pathways for nine individual high-volume, energy- and emission-intensive basic chemicals which accounted for 40% of U.S. chemicals subsector GHG emissions in 2018. This included ethylene, propylene, butadiene, BTX aromatics, chlor-alkali (co-production of chlorine and sodium hydroxide), soda ash, ethanol, methanol, and ammonia. Modeling was also conducted for the chemicals that accounted for the remaining 60% of emissions but only considered cross-cutting measures (e.g., electrification).

[561] Ethanol is excluded in certain summary figures since has significant associated scope 3 emissions, hence these results should not be misconstrued for reasons explained in the ethanol section (see Section 4.2.3.9).

* Figure includes results for eight of the modeled chemicals (methanol, ethylene, propylene, butadiene, BTX aromatics, chlorine, soda ash, and ammonia). Ethanol is excluded since it has significant associated scope 3 emissions; hence, these results should not be misconstrued for reasons explained in the ethanol section (see Section 4.2.3.9). Source: Transformative Pathways modeling.

5.3.3 Food and Beverage[562]

- Multiple feasible near zero pathways exist for this subsector, driven largely by decarbonizing hot water, hot air, and steam production. Two pathways are featured in Section 4.3:
- CNZ pathway, which focuses on electrification (mainly through high adoption of heat pumps), high adoption of energy efficiency measures, and adoption of LCFFES to meet remaining fuel demand (see Figure 82)
- CNZ–LCFFES pathway, which focuses on LCFFES adoption, high adoption of energy efficiency measures, and lower comparative adoption of electrification technologies (see Figure 83)
- Each near zero pathway presented has a 99% CO_2e emissions reduction by 2050 compared to 2018. Although the pathways shown lean heavily into the impact of individual pillars, electrification, energy efficiency, and LCFFES will all be needed to reach emissions reduction goals. CCUS is not expected to make a significant impact in the subsector but might be considered for individual facilities with large point-source emissions.
- The most likely eventual decarbonization pathway would include a mix of energy efficiency measures, increases in electrification, and utilization of LCFFES (as available and appropriate). Decisions around technology and pathway choice will depend on multiple factors, including the accessibility and availability of low-carbon fuels, clean electricity, and other energy sources and the processes within individual facilities.
- No-regrets strategies include investments in demonstration and deployment, especially since the subsector can greatly benefit from commercially available or mature technologies (e.g., heat pumps, dual-fuel process heating, or steam-generating equipment).
- Changes in consumer demand, including preferences for certain products, food loss and waste reduction, and food safety regulations can affect the choices industrial entities make in decarbonizing their operations.
- Although the *Transformative Pathways* modeling focused on scope 1 and 2 emissions for manufacturing only, it is important to consider the results in context with the entire food and beverage supply chain. Agriculture is responsible for a significant amount of overall industrial sector emissions, mainly from non-energy-related emissions (see Section 4.7.2). Future modeling efforts could consider a more holistic life cycle scope when considering the entire food supply chain, though challenges exist around data availability, quality, and consistency when considering other stages beyond manufacturing. Additionally, the emissions and energy impacts for emerging areas such as alternative proteins or controlled-environment agriculture would have a higher impact in the agriculture vs. manufacturing stage.

[562] This report modeled individual pathways for six subsectors that accounted for 78% of U.S. food and beverage manufacturing GHG emissions in 2018. This included grain and oilseed milling, sugar, fruit and vegetable preserving and specialty food, dairy products, animal slaughtering and processing, and beverages.

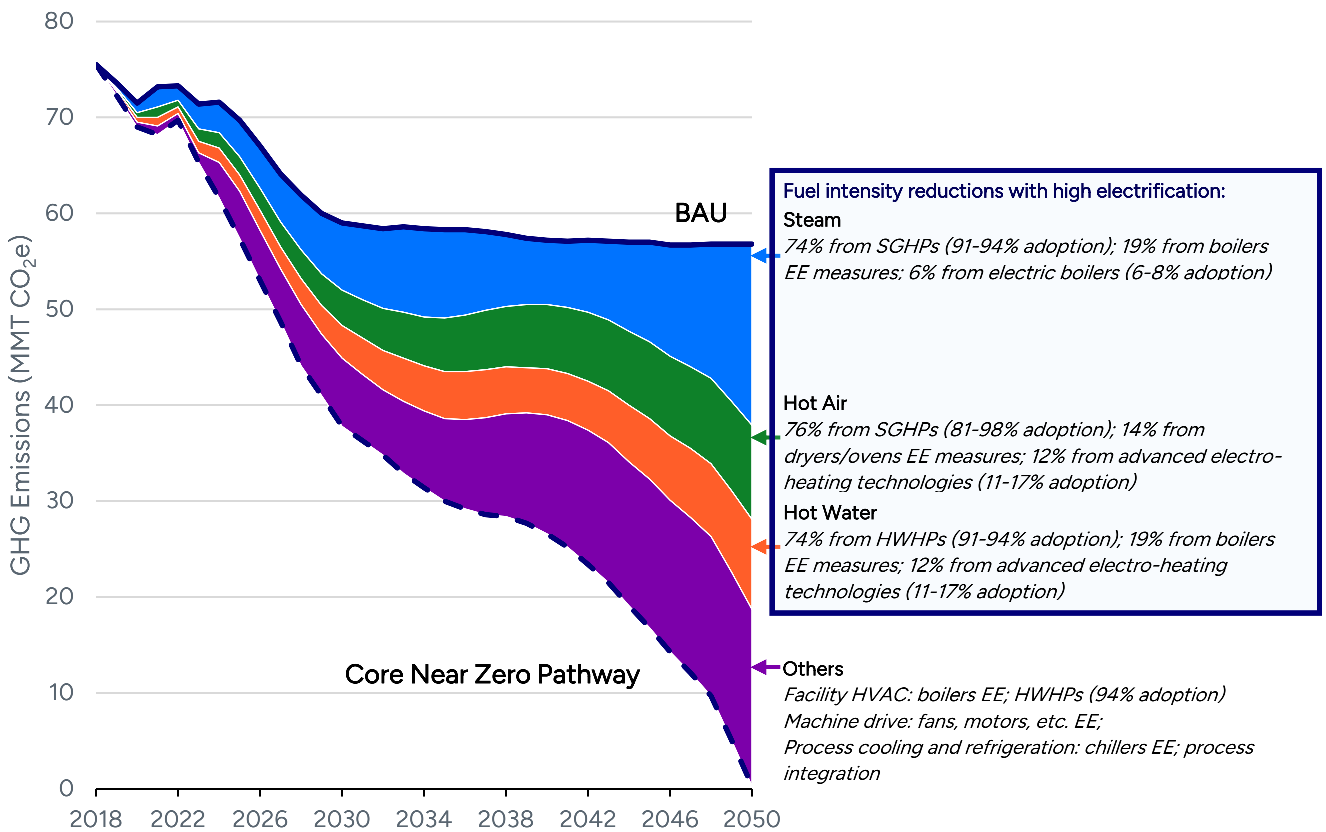

Figure 82. Annual GHG emissions reductions, U.S. food and beverage manufacturing*—Core Near Zero pathway (MMT CO_2e/year), 2018–2050

* Figure includes results for six modeled food and beverage manufacturing subsectors (grain and oilseed milling; sugar; fruit and vegetable preserving and specialty food; dairy products; animal slaughtering and processing; and beverages). These subsectors accounted for 78% of emissions for food and beverage manufacturing in 2018 (see Table 10). Acronyms/abbreviations: BAU (business as usual); CO_2e (carbon dioxide equivalent) EE (energy efficiency); GHG (greenhouse gas); HWHP (hot water heat pump); MMT (million metric tons); SGHP (steam-generating heat pump). Details on assumptions, parameters, and timing of transformative technology application can be found in Section 4.3 and Appendix C. Source: Transformative Pathways modeling.

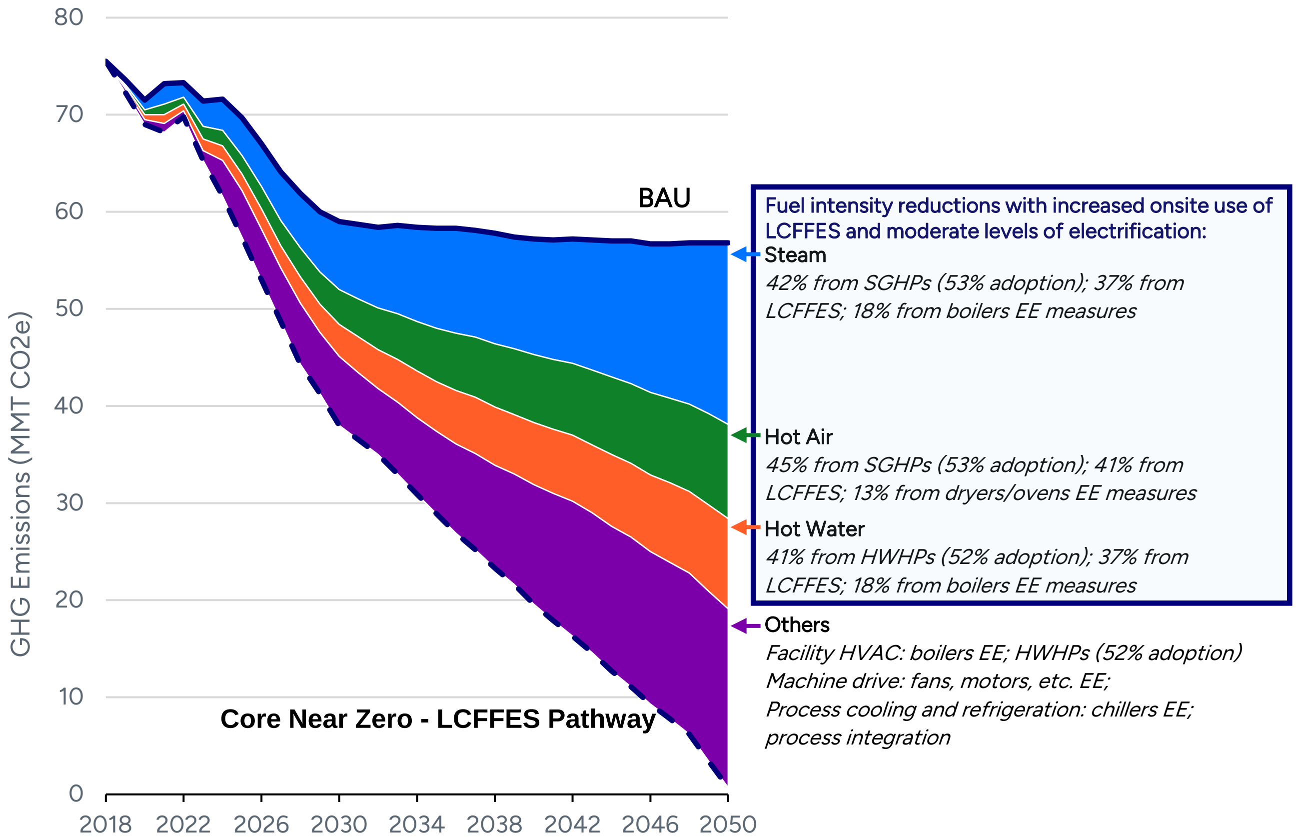

Figure 83. Annual GHG emissions reductions, Food and beverage manufacturing*—Core Near Zero—LCFFES pathway (MMT CO_2e/year), 2018–2050

* Figure includes results for six modeled food and beverage manufacturing subsectors (grain and oilseed milling; sugar; fruit, and vegetable preserving and specialty food; dairy products; animal slaughtering and processing; and beverages). These subsectors accounted for 78% of emissions for food and beverage manufacturing in 2018 (see Table 10). Acronyms/abbreviations: BAU (business as usual); CO_2e (carbon dioxide equivalent) EE (energy efficiency); GHG (greenhouse gas); HWHP (hot water heat pump); LCFFES (low-carbon fuels, feedstocks, and energy sources); MMT (million metric tons); SGHP (steam-generating heat pump). Details on assumptions, parameters, and timing of transformative technology application can be found in Section 4.3 and Appendix C. Source: Transformative Pathways modeling.

5.3.4 Iron and Steel

- Two distinct decarbonization pathways emerged for iron and steel. These pathways align in the steelmaking and finishing stages but differ in the ironmaking stage. The distinct approaches to clean production in the ironmaking stage that define these pathways are:
  - Integrated mills with CCS (IM-CCS) (see Figure 84)
  - Hydrogen-ready DRI (H_2-DRI) with evolution toward hydrogen as fuel and reductant (see Figure 85)
- Electrolytically produced iron was limited in its representation in the *Transformative Pathways* modeling and severely constrained in its implementation. It is acknowledged that these nascent production routes can collectively represent another alternative pathway for clean production in the ironmaking stage.
- These distinct ironmaking clean production routes require disparate capacity build-out, supporting infrastructure, and broader decarbonization measures (e.g., CO_2 pipelines or clean hydrogen availability), and decisions are required in the near term (within the next three to five years) on which pathway to pursue. Utilizing scrap to the maximum extent possible is common to all pathways.
- Regardless of the pathway, the EAF plays a significant role in steelmaking, even when maintaining high BF-BOF production capacity, due to its role in production processes with high scrap charge. Fully decarbonizing EAFs with respect to the process emissions from the charge carbon and the natural gas used primarily in the preheating is essential for a NZ GHG emissions reduction pathway and can account for up to 15 MMT of annual CO_2e emissions.

- It is essential that finishing stage emissions are addressed in all pathways. Even in an integrated mill with CCS, capturing emissions from the finishing stage may not be considered practical. These emissions can account for up to 20 MMT of annual CO_2e emissions. Electrification or low-carbon fuels are two options for addressing these emissions.

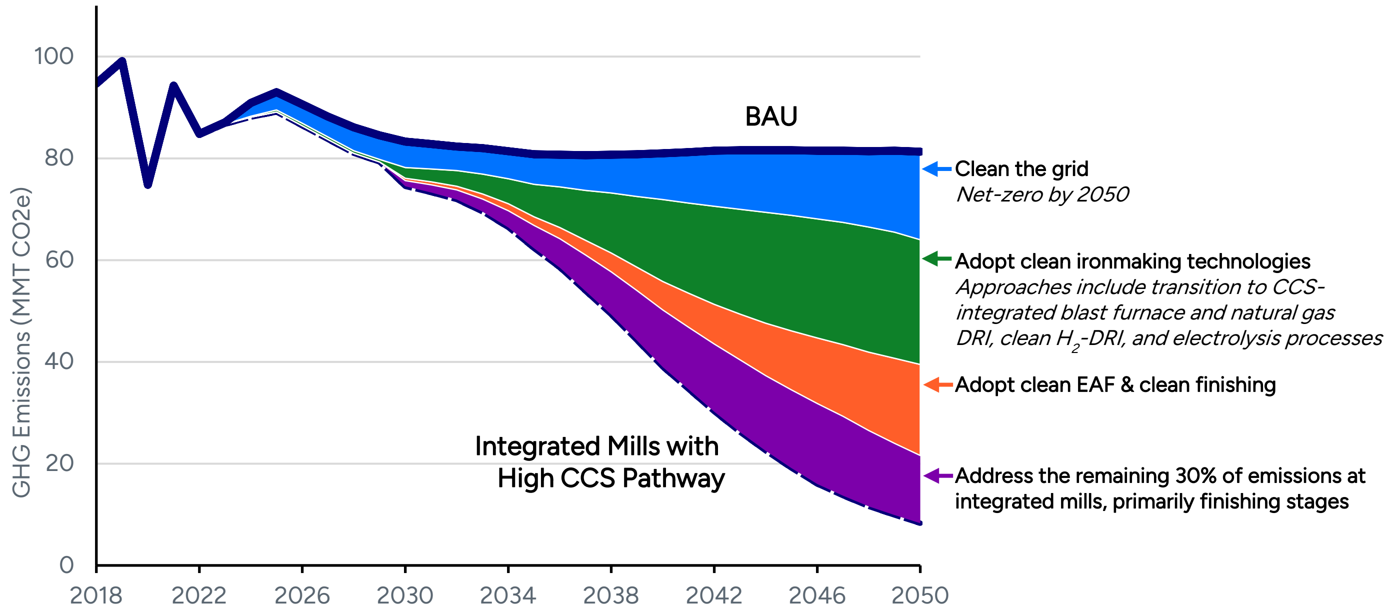

Figure 84. Annual GHG emissions reductions, U.S. iron and steel manufacturing–Integrated Mills with High CCS pathway (MMT CO_2e/year), 2018–2050

Details on assumptions, parameters, and timing of transformative technology application can be found in Section 4.4 and Appendix C. Source: Transformative Pathways modeling.

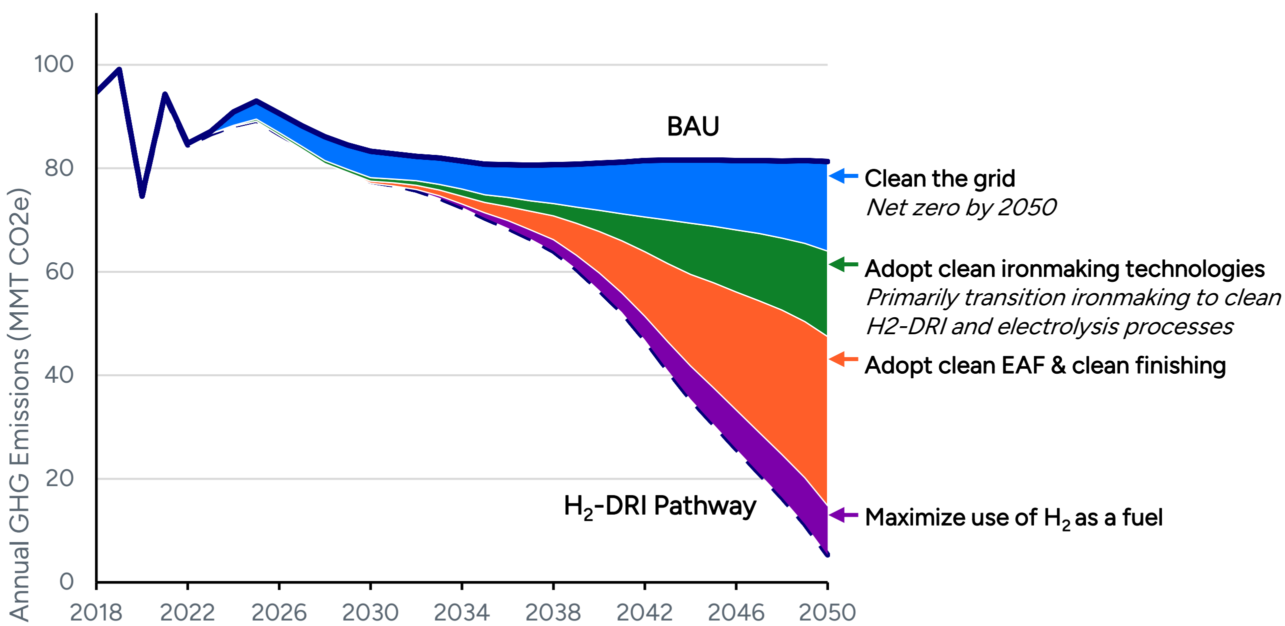

Figure 85. Annual GHG emissions reductions, U.S. iron and steel manufacturing–Hydrogen-Direct Reduced Iron pathway (MMT CO_2e/year), 2018–2050

Details on assumptions, parameters, and timing of transformative technology application can be found in Section 4.4 and Appendix C. Source: Transformative Pathways modeling.

5.3.5 Petroleum Refining

- Although the impact is far less than demand reduction, achieving near zero emissions will require:
- Energy efficiency improvements using known technologies, especially in the near- and mid-term.

- Production of liquid-hydrocarbon-based fuels from a broader suite of alternative feedstocks, including woody biomass and agricultural wastes.
- Low CI hydrogen and CCS, both of which will require major infrastructure development.
- Deployment of biofuels to displace demand for fuels derived from petroleum crude.
- Electrification may have a limited role in refining decarbonization, particularly due to the need for refiners to find a use for self-generated fuels, regardless of feedstock used in fuels production.
- In the long term, it is imperative to develop and deploy the supply chains for alternative feedstocks, including the sourcing of material, the cost-competitive conversion processes for sustainable materials, and the infrastructure to transport sustainable feedstocks (e.g., bio-oil) to refining operations.
- Reducing demand for fuels derived from petroleum crude is necessary to reach near zero emissions, even when the adoption of other decarbonization interventions is maximized. Demand reduction alone accounts for over half of emissions reduction compared with 2018.
- Refineries play a pivotal role in the transition toward a low-carbon future through the supply of low-carbon liquid transportation fuels. Thus, it is imperative that RDD&D decisions for refining and transportation decarbonization be pursued in tandem and investments be balanced between onsite and product decarbonization.

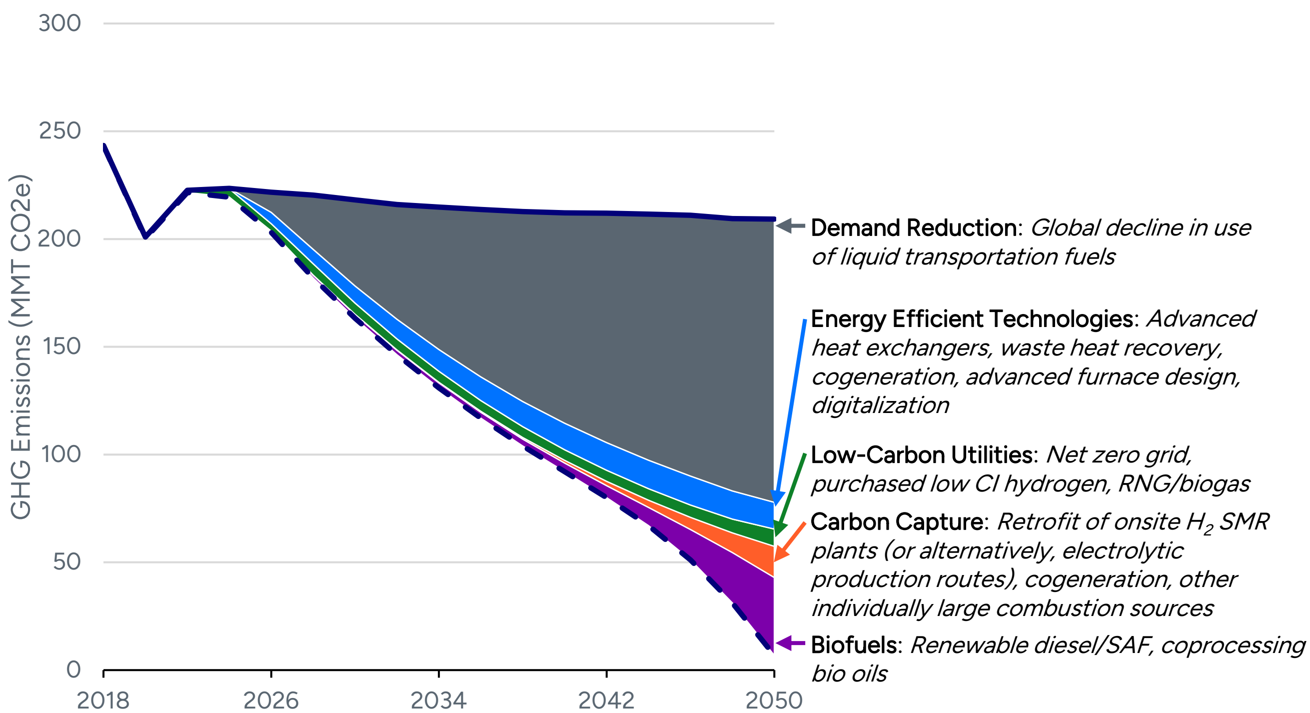

Figure 86. Annual GHG emissions reductions, U.S. petroleum refining–Core Near Zero pathway (MMT CO_2e/year), 2018–2050

Details on assumptions, parameters, and timing of transformative technology application can be found in Section 4.5 and Appendix C. Source: Transformative Pathways modeling.

5.3.6 Pulp and Paper

- The Core Near Zero pathway could reduce the subsector's emissions to approximately 6 MMT CO_2e by 2050, a 95% reduction compared with 2018. This reduction is largely driven by increased biomass use and improved energy efficiency of existing core unit processes, including drying and steam generation.
- The modeling was limited in that it lacked implementation of alternative pulping technologies, such as deep eutectic solvents and alternative fibers. Considering these alternative production routes can significantly change the impact of the interventions explored in the *Transformative Pathways* modeling.

- Electrification was considered for drying technologies and steam generation from the auxiliary boiler. Aggressive electrification of the auxiliary boiler (from 20% in the Core Near Zero pathway to 50%) had minimal impact on emissions reduction. Steam-generating heat pumps and more nascent electrification technologies were not considered as part of this approach but can presumably offer decarbonization potential.
- Broad adoption of the technologies in the Core Near Zero pathway minimizes the impact of recycling, imports, and demand reduction on the subsector's decarbonization potential.
- Although the estimated reductions reach near zero GHG emissions, biogenic emissions should be considered, especially due to increased biomass consumption proposed as the primary decarbonization intervention.
- This subsector has the opportunity to produce other value-added products through an integrated biorefinery approach. A cross-sectoral analysis is needed to evaluate the overall decarbonization impact of such an approach.

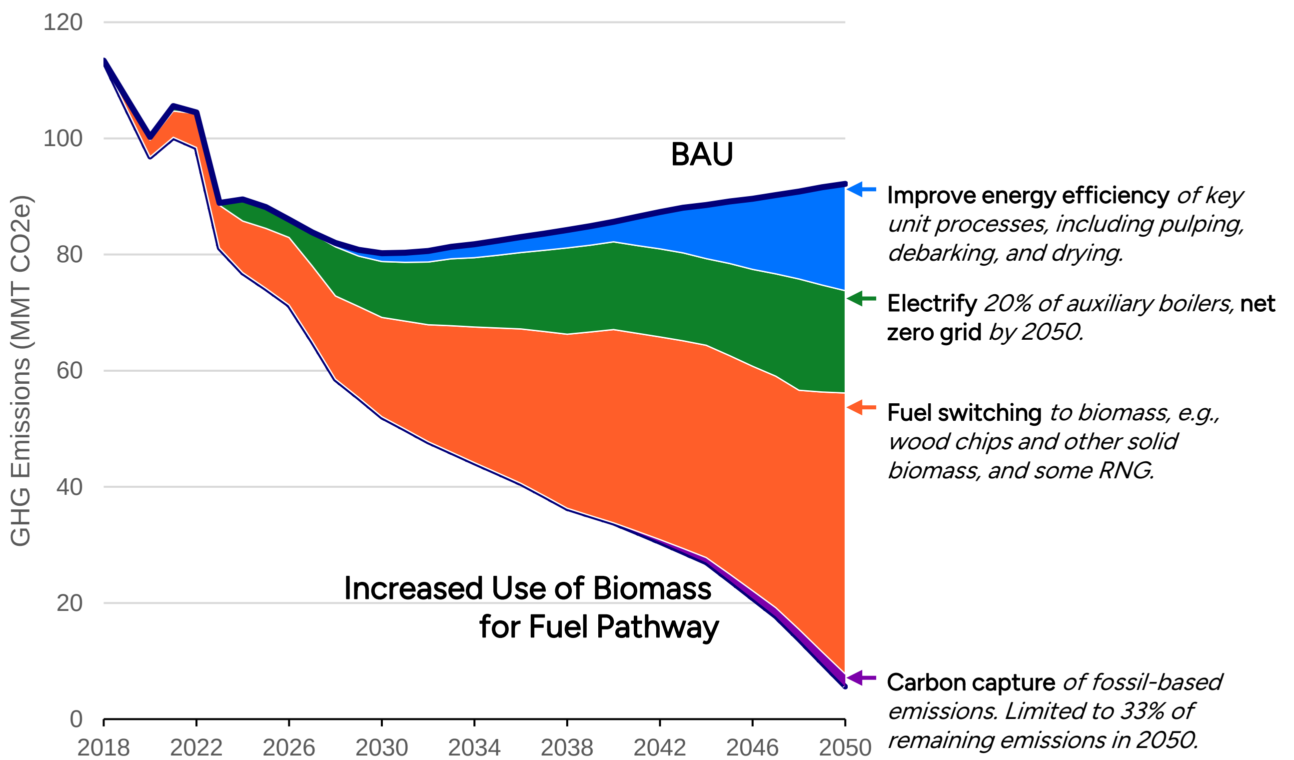

Figure 87. Annual GHG emissions reductions, U.S. pulp and paper manufacturing—Core Near Zero pathway (MMT CO_2e/year), 2018–2050

Details on assumptions, parameters, and timing of transformative technology application can be found in Section 4.6 and Appendix C. Source: Transformative Pathways modeling.

5.3.7 Rest of Industry

The "rest of industry" is large and diverse, representing nearly half of the industrial sector's energy-related emissions in 2018. Each subsector within this category will require a unique approach to developing decarbonization pathways.

In the *Transformative Pathways* modeling, "rest of industry" is defined as other manufacturing (the rest of the manufacturing subsector excluding cement and concrete, chemicals, food and beverage, iron and steel, pulp and paper, and petroleum refining), the nonmanufacturing subsector (agriculture and forestry; mining, oil, and gas; and construction), and industry-adjacent subsectors (data centers, water and wastewater treatment). Since these subsectors account for the remaining 50% of industrial sector emissions, it is important to consider possible decarbonization pathway options. Each subsector has a unique energy profile regarding major energy-consuming processes and equipment, types of non-energy-related emissions, and decarbonization opportunities.

Decarbonizing the long tail of industrial sector emissions is challenging, given the scale and variability across the remaining subsectors. Although not explicitly modeled in this study, the fundamental decarbonization pillars and approaches within the study can be applied. Although reductions in scope 1 and 2 emissions are important for these subsectors, scope 3 emissions become an increasingly important target for emissions reductions and decarbonization opportunity analysis,[563] since many are downstream in supply chains and use output from the energy- and emissions-intensive industrial subsectors, such as chemicals, iron and steel, cement and concrete, and petroleum refining (see Section 4.8 for additional details on supply chain emissions).

In the short term, decarbonization pathways for other industrial subsectors might include adoption of energy efficiency measures, onsite clean energy generation, heat pumps and geothermal energy deployment, or switching to low-carbon fuel or energy sources. Mid-term pathways could include hybridization and electrification of equipment or addressing supply chain emissions through measures such as increased material circularity. Longer-term decarbonization pathways will depend on what is adopted in the short and medium terms; additional information and input are needed to better understand and develop decarbonization pathways for the rest of industry to help the industrial sector as a whole reach net zero emissions by 2050.

5.4 Considerations for U.S. Industrial Transformation

Industrial transformation will require actions at many levels--including individual industrial facilities and organizations, technology providers, public and private capital allocators, and local, state, and federal policymakers--that may have far-reaching impacts across domestic and international supply chains and markets. Realizing this vision will be difficult, as there are numerous challenges and barriers to overcome, including around industrial ecosystem complexity, ensuring an equitable transition, addressing existing thermal system and process emissions, the cost uncertainty of industrial technologies and transitions, availability of infrastructure, and the need for emerging (or nonexistent) decarbonization technologies (see Section 2.2 and Section 2.3 for full details). The following topics will require careful consideration.

Key consideration: Innovations are needed to catalyze industrial transformation.

Investments in industrial decarbonization technologies and infrastructure to date are impactful but insufficient to reach a net zero emissions industrial sector by 2050. These investments are designed to foster innovation, improve the competitiveness of U.S. companies, and reduce greenhouse gas emissions across the sector. Now is the time to build on these investments and make the innovations needed to drive down emissions, help communities, improve well-being, and increase U.S industry's competitiveness.

Although the scale of these and other DOE and government efforts are substantial and unprecedented, with the potential to drastically reduce emissions from some of the most carbon-intensive industrial subsectors, more investment is needed to reach government and private sector 2050 goals and targets.[564] The transformation of the industrial sector will necessitate coordinated action across federal, state, and local governments, as well as significant private sector investment and innovation.

The pathway to industrial decarbonization has many systemic barriers. It is imperative to decarbonize while accelerating economic growth, increasing job opportunities for Americans, and improving health outcomes for industrial-adjacent communities.

[563] U.S. Department of Energy, "Environmentally Extended Input-Output for Industrial Decarbonization Analysis (EEIO-IDA) Tool," accessed October 2024, www.energy.gov/eere/iedo/articles/environmentally-extended-input-output-industrial-decarbonization-analysis-eeio.
[564] U.S. Energy Information Administration, "Issues in Focus: Inflation Reduction Act Cases in the AEO 2023," 2023, www.eia.gov/outlooks/aeo/IIF_IRA/.

Key consideration: Industrial transformation must include efficient utilization of energy, resources, and materials across the industrial ecosystem.

Transformation of the U.S. industrial sector should utilize a robust industrial ecosystem and integrate sustainable practices while maintaining competitiveness. This ecosystem approach involves collaboration between public and private sectors, investment in cutting-edge technologies, and investments in the workforce. The goal is to create a resilient and inclusive industrial sector that can thrive in a low-carbon economy, ensuring that the benefits of decarbonization are shared broadly and equitably. Critical to success are transformations that occur beyond the boundaries of any individual plant, including promoting the most efficient use of natural resources, driving circular manufacturing concepts, and decarbonizing the entire industrial supply chain.

Industry can lower the emissions intensity of production, reduce waste, and minimize energy demand by promoting material and resource efficiency. This includes strategies like lightweighting, material substitution, recycling, and remanufacturing to increase resource efficiency, which can lead to substantial emissions reductions throughout product life cycles. These approaches also align with circular economy principles, further driving sustainability by keeping materials in use for longer periods. Improving material and resource efficiency not only supports decarbonization but also enhances cost-effectiveness and competitiveness, helping industry transition to a more sustainable, low-carbon future.

The boundary conditions of this *Pathways* report were an analysis of scope 1 and 2 emissions. However, scope 3 emissions from upstream and downstream supply chains play a critical role in industrial decarbonization as noted in Section 4.8. Industrial decarbonization will require transformation across the entire supply chain, including careful consideration of resource extraction, feedstocks processing, onsite manufacturing, and downstream product use, and recycling waste back into manufacturing processes. Collaboration across supply chains is needed to identify key areas for emissions reductions, such as through material substitution, circular economy practices, and transportation efficiency. As industry transitions to cleaner energy sources and more sustainable practices, an integrated supply chain approach will be essential for meeting the nation's net zero goals.

Key consideration: Transformation of the industrial sector will require actionable measures.

A transformation will require collective action within and beyond the industrial sector to promote innovation with comprehensive approaches that span the entire innovation pipeline.

Transform the marketplace. Clean energy and low-carbon RDD&D serve as the first step toward realizing the industrial transformation. As noted in *Pathways to Commercial Liftoff: Industrial Decarbonization*, decarbonization of eight energy- and emissions-intensive industrial subsectors may require more than double the available funding from the public sector.[565] Clearly the private sector will play a significant role in decarbonization. Important here is strong public-private partnership and a recognition that new markets and supply chains must emerge to support the transition. Examples include access to cost competitive clean hydrogen, clean electricity, and carbon capture technology and infrastructure, as well as the development of robust supply chains for alternative feedstocks and end-of-life circular remanufacturing concepts.

Invest in capital and invest in people. Not to be lost is the magnitude of this transformation, which will require boots-on-the-ground to build critical infrastructure. This will require efficient investment of capital to ensure the engineering, procurement, construction, and commissioning of clean energy and large decarbonization projects are delivered on time and on budget. A trained and diverse workforce of the future must be ready to help deliver emissions reductions and realize the economic opportunity of industrial decarbonization.

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[565] U.S. Department of Energy. *Pathways to Commercial Liftoff: Industrial Decarbonization* (2023). liftoff.energy.gov/industrial-decarbonization/

Key strategies and initiatives include:

- **Continued Investment in Research, Development, Demonstration, and Deployment**: Funding RDD&D that focuses on breakthrough technologies to reduce emissions and increase energy efficiency across the adoption readiness scale, including support for early-stage research, prototype development, and first-of-a-kind pilot demonstration. Innovative clean production routes are particularly needed for cement and concrete, chemicals, and iron and steel.
- **Expansion of Public-Private Partnerships**: Collaborate with government, industry leaders, academic institutions, and national laboratories to accelerate the commercialization of new technologies and bridge the gap between research and market deployment. Coordinated support between these institutions will enable improvements to the adoption readiness of these technologies to further accelerate their utilization and preemptively mitigate potential deployment hurdles.
- **Technology Deployment Projects**: Funding large, commercial-scale deployment projects helps validate the performance and economic viability of new technologies in real-world industrial settings, which will be crucial for gaining industry acceptance and scaling up innovations. This will be especially useful for subsectors where decarbonization interventions are already commercially available or mature, such as food and beverage.
- **Support Technical Assistance and Workforce Development**: Provide technical assistance to help industry implement energy-efficient and low-carbon practices and technologies. Investments in the workforce can ensure that the industrial sector has the skilled labor needed to adopt and maintain new decarbonization technologies and approaches.
- **Inform Policy and Regulatory Support**: Industry and federal agencies should work together to inform smart policies and incentives that encourage the adoption of clean energy technologies, industrial energy efficiency, and emissions reductions.
- **Expand Innovative Funding Mechanisms**: Organize alternative funding programs, prizes, and challenges to spur innovation and engage a broader community of innovators to foster market competition.

By leveraging these strategies, we can create a robust ecosystem that supports continuous industrial sector innovations and transformations, ultimately leading to significant emissions reductions and enhanced energy efficiency.

Key consideration: People, communities, and the environment are a central part of an industrial transformation.

An industrial transformation requires investments beyond industrial operations, facilities, and supply chains. Investments in the next generation of American workers and engaging with communities can fundamentally transform the industrial sector to achieve ambitious emissions reduction targets and ensure a sustainable and equitable future for all. Although there is a need and opportunity to invest in the people working within industry through education and training to meet documented industry needs and create stable, well-paying American jobs, developing robust and clean manufacturing and industrial operations will also provide an economic engine for communities, regions, and the nation overall. Input is needed from the full range of stakeholders to reach a truly transformed industrial sector. There is an opportunity for everyone to engage and provide input into our shared future.

Looking Forward

This study represents emissions reductions pathways and potentials for technologies and subsectors today. Decarbonizing industry will be challenging and requires ambitious and urgent action. This study represents an aggregation of the technical potential with considerations of aggregate boundary conditions–e.g., low to high adoption of specific technologies. Industrial decarbonization pathways presented here are rolled up to the national perspective for six subsectors; there will be many individual pathways for an industrial subsector, and specific entities will have unique constraints and considerations that may dictate specific pathway choices.

Decarbonizing the other subsectors that comprise the industrial sector are just as important. Although diverse and not explicitly modeled, this work provides general interventions along the four decarbonization pillars and material and resource efficiency that serve as a starting point to tailor appropriate pathways that can result in substantial emissions reduction.

Beyond the work that informed this report, the *Transformative Pathways* models will further evolve and expand to better characterize the six subsectors included in this report (as well as other industrial subsectors) and inform decision makers, including the addition of more nascent production routes and technologies. Future plans include publication of subsector assessments that will provide a deeper exploration of the scenarios and sensitivities and the underlying assumptions and inputs that inform this and subsequent modeling efforts.

Collectively, the *National Blueprint for a Clean and Competitive Industrial Sector,*[566] which outlines five strategies to guide near-term federal government coordination to enable a low-carbon U.S. industrial sector, the *Industrial Decarbonization Roadmap,*[567] the *Pathways to Commercial Liftoff* reports,[568] and this report provide a comprehensive DOE perspective of strategic approaches to realize a more sustainable industrial sector.

Although work will continue to inform the wider community on the *Transformative Pathways* modeling and subsector assessments, the core message remains the same: Transformation provides the opportunity to maintain America's status as a global industrial leader, strengthen the American workforce and communities, and reduce environmental and health impacts. To do so, we must catalyze innovation and embrace the next generation of industrial technologies; the pathways identified in this report demonstrate tangible ways to achieve this vision.

[566] U.S. Department of Energy, *The National Blueprint for a Clean & Competitive Industrial Sector* (2024), www.energy.gov/sites/default/files/2024-11/20241114-National_Blueprint_to_Enhance_a_Clean_and_Competitive_Industrial_Sector_1.pdf
[567] U.S. Department of Energy, *Industrial Decarbonization Roadmap*, DOE/EE-2635 (2022), www.energy.gov/industrial-technologies/doe-industrial-decarbonization-roadmap.
[568] U.S. Department of Energy, "Liftoff Reports," accessed October 2024, liftoff.energy.gov/

APPENDIX A. MODELING DETAILS

The *Transformative Pathways* analysis and modeling presented in this document is based on Microsoft Excel models that estimate energy- and process-related emissions for select industrial processes, informed by assumed feedstocks, manufacturing technologies, energy intensities, and energy sources. The model fundamentally calculates the aggregate energy and emissions impacts for individual subsectors based on adoption rates, energy sources, and in context with other technologies included in the model.

For this modeling framework, each pathway can be formalized as a set of time-dependent assets comprising of numerous technologies that are deployed to produce a set of manufactured goods to meet a certain demand, while pursuing some sort of objective(s) and acting under a certain set of constraints or rules. These objectives and constraints can emerge from economic, environmental, societal, technical, or operational factors. A decarbonization pathway, by definition, would therefore include an explicit emissions reduction goal or constraint. See Section 1.2 for more information on how this report defines pathways.

The *Transformative Pathways* modeling employs a bottom-up approach to analyze energy-intensive processes in U.S. manufacturing subsectors and explore how technological advancements and best practices can mitigate emissions without hindering economic growth. *Transformative Pathways* primarily focuses on scope 1 and scope 2 emissions, while also acknowledging that the identified low-carbon technologies and pathways may have broader implications for scope 3 supply chain emissions. Scope 3 emissions are included in a limited scope for cement and concrete, iron and steel, chemicals, pulp and paper, and refining.[569]

The modeling focuses on evaluating a wide range of technology options, from low to high maturity, with the goal of reducing near zero or net zero U.S. manufacturing GHG emissions by 2050. This includes developing decarbonization pathways tailored to major processes, assessing the technological impacts, particularly in the areas outlined in the decarbonization pillars from the *Industrial Decarbonization Roadmap*: energy efficiency; industrial electrification; LCFFES; and CCUS.[570] Additionally, the modeling identifies and examines the factors influencing the widespread adoption of these pillar-specific technologies, including both barriers and drivers.

The general goal of this modeling was customization to capture subsector nuance but harmonization across all subsectors for key inputs, outputs, and carbon accounting. Specifically, there are two overarching model structures: one that fully replaces incumbent production routes with alternative ones (Figure A-1: cement and concrete, chemicals, and iron and steel models) and a second that is limited to the incumbent processes but focuses with greater resolution on specific modifications to process units (Figure A-2: food and beverage, petroleum refining, and pulp and paper models).

[569] Scope 3 emissions were considered for cement and concrete with the emissions associated with SCMs, for iron and steel with the emissions associated with imported iron used in EAFs, and for chemicals, pulp and paper, and refining with the consideration of the emissions of the bio-feedstocks or biofuels.
[570] U.S. Department of Energy. *Industrial Decarbonization Roadmap*. DOE/EE-2635 (2022). www.energy.gov/industrial-technologies/doe-industrial-decarbonization-roadmap.

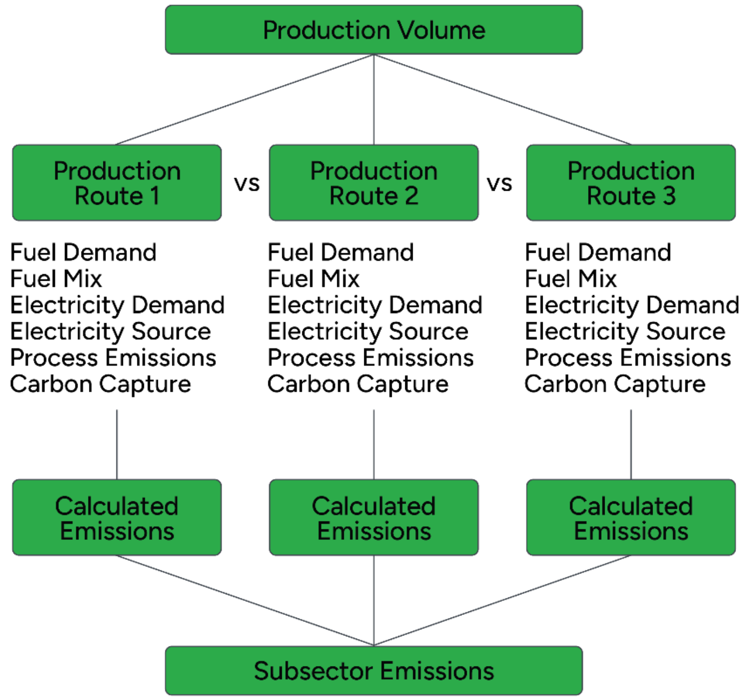

Figure A-1. Model structure and flow for alternative production routes

This model structure was used for the cement and concrete, chemicals, and iron and steel models.

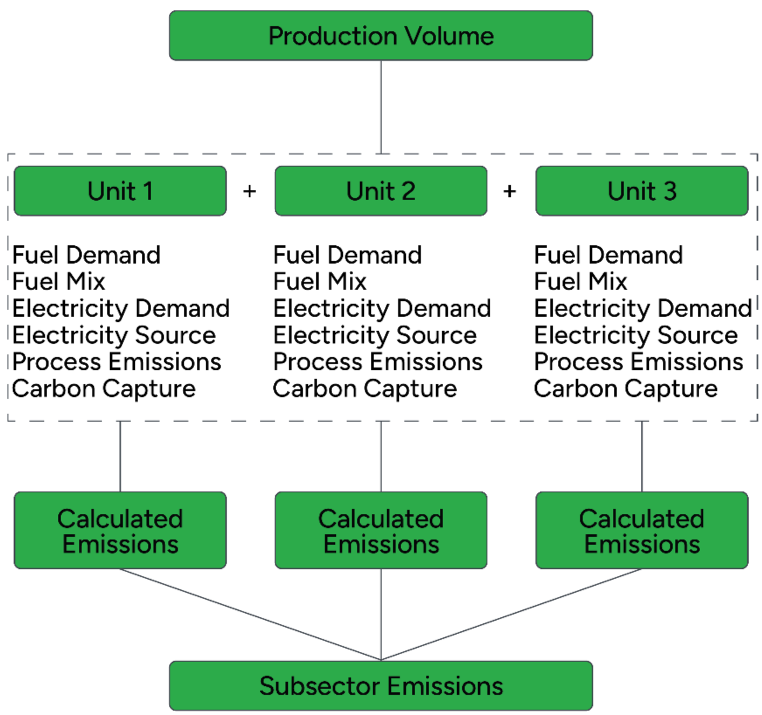

Figure A-2. Model structure and flow for higher resolution of a production route

This model structure was used for the food and beverage, petroleum refining, and pulp and paper models.

Moreover, the modeling frameworks for this effort offers a general path and prioritizes key measures such as energy efficiency, electrification, and CCUS. However, other drivers—such as capacity increases, lower maintenance costs, improved yields and quality, and customer demand—also influence technologies but are not fully captured by the modeling frameworks. Therefore, the modeling frameworks should not be considered an optimal decision-making flow but rather a simplification of a complex series of choices that are intended to provide utility in prioritization, interconnections, and general thought processes. It is also important to note that while the presented modeling frameworks helped conceptualize decarbonization solutions for the subsectors studied, instances of limited relevant information led to assumptions that may not fully align with the modeling frameworks. Each subsectors modeling framework can be found in Section 4.

Each model starts with a forecast of production volume from 2018 to 2050 in annual increments. Today's facilities and technologies are defined as a baseline and key upcoming technologies are identified. In practice, the model assigns an energy intensity impact to each identified technology. Note that the energy intensities assigned in the model are based on data gathered exogenously and can be adjusted/updated by the model user as technologies change and more detailed information becomes available.

As the overall manufacturing of products shifts from traditional to next-generation technologies, the model calculates the potential impact on energy intensity. This required energy is then used to predict associated emissions by adding assumptions for the energy sources used each year (specifically: onsite-generated electricity, grid electricity, and specific fuel types—each with an associated level of emissions per energy unit). In this way, energy-related emissions are predicted over time. At the same time, process emissions are calculated for each assumed technology and feedstock. Specifically, "process emissions" refer to onsite GHG emissions that are typically produced in a chemical reaction from the feedstock during manufacturing. Energy- and process-related emissions are added together for each year. Finally, the impact of assumed CCUS technologies is applied based on process-specific details to give the final magnitude of remaining emissions.

These models are limited to technology-based solutions. They also depend on significant literature review and calculations from the user to accurately input the appropriate adoption rates and simultaneous energy-related impacts of key technologies. A key benefit of this effort is significantly increased resolution and nuance for technology impact in each considered subsector. Calculations are bottom-up where possible and specifically customized for subsector details, such as paper mill recovery boilers, the cement subsector's clinker-to-cement ratio, and the petroleum refining subsector's process integration.

The models leverage and expand on what was included in the *Industrial Decarbonization Roadmap*,[571] including through added time resolution (annual basis for 2018 through 2050); expanded bottom-up analysis to capture specific technologies or process units; increased resolution for input variables such as fuel sources, non-energy process emissions, multiple CCUS technologies, and electricity-related emissions; added nuance to calculations for carbon capture, electrification, onsite electricity generation, and hydrogen use; standardized carbon accounting; and disaggregated emissions results for onsite vs. offsite, biogenic vs. non-biogenic, and carbon sequestration vs. utilization. Additionally, pillar breakdown calculations were refined to more accurately capture adoption of technologies and to separate industrial electrification from LCFFES.

To date, IEDO has focused rigorous analysis mainly on the manufacturing subsector because of more readily available data (e.g., EIA's Manufacturing Energy Consumption Survey). The energy consumption and GHG emissions of the non-manufacturing subsectors of agriculture and forestry; construction; and oil, mining, and gas can be characterized at the top level (see Section 4.7.2), but detailed information for energy types and end uses are not readily available. Water and wastewater treatment and data centers are also included in this report (Section 4.7.3) for discussion and consideration given similarities between their processes and energy consumption to large-scale industrial facilities.

Model Variables

Table A-1 provides an overview of key variables within the models. The same variables (fuel demand, fuel mix, etc.) are applied for each subsector and inputs are defined for each sub-unit (e.g., specific unit operations or equipment categories).

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[571] U.S. Department of Energy. *Industrial Decarbonization Roadmap*. DOE/EE-2635 (2022). www.energy.gov/industrial-technologies/doe-industrial-decarbonization-roadmap.

Table A-1. Key Model Variables for Transformative Pathways Analysis

Variable	Description
Production	Annual production for 2018 through 2050
Technology adoption rate	Percent adoption of a given technology across the subsector
Energy intensity	Disaggregated by energy carrier (i.e., fuel- and electricity- based energy); includes gate-to-gate energy intensity (gigajoules/metric ton of product)
Steam	Attributed to fuel or electricity based on production method (e.g., electrification technology for steam generation shifts energy demand from fuel to electricity)
Fuel mix	Disaggregated into a specific fuel type (e.g., natural gas, biomass, diesel)
Fuel emissions intensity	Emissions factor (e.g., kg CO2e/gigajoule) and biogenic factor for each fuel type
LCFFES	Specified emissions factor by year based on the types of LCFFES (e.g., hydrogen, biomass)
Electricity mix	Specified onsite vs. grid electricity generation
Electricity emissions intensity	Emissions factor based on assumed technology source [e.g., kg CO_2e/megawatt-hour(MWh)]
Energy efficiency	Assumed rates of energy efficiency improvements based on operational improvements and technology adoption
Process emissions	Included non-energy process emissions (e.g., metric tons of CO2e/metric ton of product) for relevant subsectors (see Table 6)
CCUS	Included CCUS technology and adoption rate details

Additional detail on carbon accounting, industrial electrification in context with grid decarbonization, product demand/production volumes, and combined heat and power (CHP) is provided below.

Carbon accounting. Non-biogenic emissions are reported but credit is given to the capture of both biogenic and non-biogenic emissions. Thus, significant capture of biogenic emissions has the potential to produce net negative emissions values. The utilization vs. storage of all captured carbon has been disaggregated as a variable within this model. However, credit for both is included in the CCUS pillar in the output figures.

Industrial electrification with grid decarbonization. The impact of electric grid decarbonization is attributed to the electrification pillar. If a process is electrified without adjusting for grid decarbonization, emissions will often increase. Thus, the two variables must be considered within the same pillar's calculations to accurately capture electrification benefits. See Appendix B for more details on assumed U.S. electric grid emissions factor.

Product demand/production volumes. Within these models, additional sensitivity analysis can be conducted by varying production across each scenario to consider the impacts of demand reduction or other factors. Modeling constant or varying levels of product demand allows for more thorough exploration of emissions reduction possibilities and awareness of how decarbonization pathways interact with alternative demand scenarios.

Combined heat and power. Energy-intensive subsectors such as those modeled here may currently use CHP systems to efficiently generate heat and electricity simultaneously.[572] Prime movers, such as gas turbines,

[572] For example, 30% of the food and beverage manufacturing subsector's 2018 energy consumption was for powering CHP systems. See: U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Food and Beverage," (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_food_beverage_energy_carbon_footprint.pdf.

microturbines, boilers with steam turbines, or reciprocating engines are used to convert fuel (typically natural gas) into heat and power. These systems achieve typical combined efficiencies of over 60%, but also emit GHGs from the combustion of natural gas or hydrocarbons. To decarbonize industry, strategies for decarbonizing CHP are needed. In the *Transformative Pathways* models, each end use demand or process was examined and decarbonization options were considered. Since CHP is not an end use but an energy conversion step, decarbonization pathways for CHP were not directly modeled. In practice, however, decarbonizing CHP will require consideration of the interdependencies between the dual energy flows coming from the CHP system, as well as interdependencies between the facility and the system more broadly. For example, if a facility previously utilized steam generated from a CHP system removes or reduces its steam utilization, it will lower the electrical output of the CHP system. Consequently, the facility will need to examine and implement strategies for acquiring additional clean electricity. Conversely, if a CHP system is currently fueled using byproduct-based fuels, elimination of the CHP system would require the facility to develop a mitigation strategy consider methods for disposing of these previously used byproducts.

Key Data Sources

This Microsoft Excel-based modeling work leverages multiple different sources of publicly available data for the key variables noted in Table A-1. Inputs and impacts are calculated on an annual basis for 2018 through 2050.

A main data source for the *Transformative Pathways* modeling is the EIA MECS,[573] released every four years with extensive energy consumption data for individual manufacturing subsectors (from three- to six-digit NAICS codes). The energy consumption data are broken down by individual end use within manufacturing facilities and by type. The latest data year available from MECS is 2018 and was released in 2021. The next data year of 2022 is expected to be released sometime in 2025. An extensive analysis of the MECS data and presentation of manufacturing subsector energy consumption and emissions is available from the IEDO *Manufacturing Energy and Carbon Footprints*.[574]

EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks*[575] is another key data source and provides economy-wide GHG emissions, energy-related industrial emissions, and detailed non-energy-related (or process) emissions for individual industrial subsectors or products. Other EIA references utilized for this modeling include the Annual Energy Outlook (which includes projections out to 2050),[576] Monthly Energy Review (which also provides historical energy consumption),[577] "Petroleum & Other Liquids,"[578] among others. Subsector-specific references are discussed in Section 4 and the Appendices.

Modeling Sensitivities

Sensitivities and future uncertainties are crucial in the decision-making process in a variety of fields, particularly for sustainability, manufacturing, and environmental planning. A sensitivity analysis allows stakeholders to assess how different variables or assumptions impact outcomes and results and identify which factors have the most significant influences on the overall system or model. This assessment allows for the identification and understanding of risks or opportunities that could emerge. Future uncertainties account for any unpredictable changes that may have a potential long-term or chronic effect. Examples of these changes include technological advancements, policy shifts, or consumer preferences.

Due to a variety of factors, there is a wide range of potential future uncertainties. These uncertainties can be derived from initial assumptions made about the market that are no longer relevant as consumer preferences

[573] U.S. Energy Information Administration, "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data," 2021, www.eia.gov/consumption/manufacturing/data/2018/.
[574] U.S. Department of Energy, *Manufacturing Energy and Carbon Footprints (MECS 2018)*, accessed November 2024, www.energy.gov/eere/iedo/manufacturing-energy-and-carbon-footprints-2018-mecs.
[575] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2022*, EPA 430-R-24-004 (2024), www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2022.
[576] U.S. Energy Information Administration. "Annual Energy Outlook 2023." 2023. www.eia.gov/outlooks/aeo/.
[577] See Tables 11.1 through 11.5 in U.S. Energy Information Administration, "Monthly Energy Review," October 2024, www.eia.gov/totalenergy/data/monthly/index.php.
[578] U.S. Energy Information Administration, "Petroleum & Other Liquids," accessed November 2024, www.eia.gov/petroleum/data.php.

change. Another example includes policy implementations which may more aggressively target GHG emissions reductions. Specifically for this study, sensitivities are categorized as "globally harmonized" or "subsector-specific" (see Section 3.2.2). Globally harmonized sensitivities included energy efficiency, electricity, hydrogen, and CCUS, while subsector-specific sensitivities are discussed in Section 4 and Appendix C.

Energy Efficiency

Table A-2 provides an overview of the low, mid, and high energy efficiency (EE) per annum (p.a.) improvements assumed for low-, mid-, and high-maturity technologies.

Table A-2. Energy Efficiency Modeling Sensitivities

	Low EE	Mid EE	High EE
High maturity	Up to 0.1% improvement p.a.	Up to 0.3% improvement p.a.	Up to 0.5% improvement p.a.
Mid maturity	Up to 0.4% improvement p.a.	Up to 0.8% improvement p.a.	Up to 1.2% improvement p.a.
Low maturity	Up to 1.0% improvement p.a.	Up to 2.0% improvement p.a.	Up to 2.5% improvement p.a.

Electricity

Beyond each subsector's core scenario assumptions around electricity price, availability, and emissions factors, two sensitivities were considered: low and high potential.

Low potential. For this sensitivity, emissions factors are assumed to follow the BAU trajectory and availability of clean electricity is assumed to be limited in some locations. The price yield is $25/MMBtu or a price ratio of five times that of natural gas.

High potential. This sensitivity assumes there will be full availability of clean electricity to meet all industrial demand by 2050. Emissions factors follow the current net zero trajectory used for the modeling (see Appendix B). Electricity has a price yield of $15/MMBtu nationally and has price ratio of two times that of natural gas. This also accounts for a slight increase in efficiency. Additionally, it is assumed that some lower-cost regions would have a price yield of $10/MMBtu or a price ratio of 1.33 times that of natural gas. This sensitivity also assumes cost parity or better with natural gas by 2050 for subsector-specific industrial sites with off-grid production with potential incorporation of battery or thermal storage with electrified heating.

Hydrogen

Beyond each subsector's core scenario assumptions around hydrogen price, availability, and emissions factors, two sensitivities were considered: low and high potential. More details on assumed hydrogen emissions factors can be found in Appendix B.

High potential. This sensitivity assumes no limitations to the full regional availability to meet all industrial hydrogen demand. Hydrogen is assumed to have a price yield of $7.5/MMBtu therefore, this results in a price ratio of 1.5 times natural gas. It assumes there would be a 30% max blending with natural gas, except in CCUS processes. Hydrogen for large industrial sites with favorable conditions allow for cost parity or better with natural gas with the emissions factor approaching zero.

Low potential. This sensitivity assumed that clean hydrogen would only be available and used in refining, chemicals, and iron and steel (for DRI as a reductant only). No hydrogen blending with natural gas is assumed. Hydrogen would not be used as fuel, except from onsite tail gas.

CCUS

Beyond each subsector's core scenario assumptions around CCUS price, availability, and efficiency, two sensitivities were considered: and high potential.

High potential. This sensitivity assumed that there is not full CCUS regional availability to meet all chemicals and refining demand but more availability for iron and steel and cement and concrete. CCUS cost is assumed to be greater than $85/ton CO_2 captured.

Low potential. Within this sensitivity, CCUS cost is assumed to be greater than $200/ton CO_2 captured.

APPENDIX B. CROSS-SUBSECTOR MODELING ASSUMPTIONS

This appendix provides information on assumptions that were consistently applied to the modeled subsectors: U.S. electric grid emissions factor, hydrogen emissions factor, fuels (other than hydrogen) emissions factors, and CCUS.

U.S. Electric Grid Emissions Factor

The GHG emissions factors used to represent the U.S. electric grid, and thus the offsite electricity consumed by industry in this modeling, were derived from scenarios created in national energy systems models (EIA's National Energy Modeling System [NEMS][579] and the National Renewable Energy Laboratory's (NREL's) Regional Energy Deployment System [ReEDS][580]). There are two annual studies that project the evolution of the U.S. grid under various scenarios that use these models: EIA's Annual Energy Outlook (AEO)[581] (using NEMS) and NREL's Standard Scenarios (using ReEDS).[582] The output of these models is a mix of different types of capacity which evolve over time and operational profiles that correspond to an evolution of electricity generation over time to meet the constraints imposed on the model.

The NEMS and ReEDS models and corresponding annual releases consider the evolution of the grid with varying degrees of technologies, costs, and granularity. At the time of this analysis, the most recent annual releases are the 2023 Standard Scenarios[583] and AEO 2023.[584] Within these studies, many different scenarios are included, testing for different sensitivities. There were 56 scenarios in the 2023 Standard Scenarios and 19 in AEO 2023.

The scenario chosen to represent the business as usual (BAU) scenario within this modeling effort was the Reference scenario from AEO 2023, referred to as *AEO2023 Reference* henceforth. The scenarios chosen for the *Transformative Pathways* models from the 2023 Standard Scenarios included: *High Renewable Energy Cost* (aka Conservative Renewable Energy (RE) and Battery Cost and Performance), *High Hydrogen Production and High Demand Growth*, *High Hydrogen Production and High Demand Growth with a 95% reduction in* CO_2 *by 2050*, and *High Hydrogen Production and High Demand Growth with a 100% reduction in* CO_2 *by 2035*.

Furthermore, 2023 Standard Scenarios used to derive the *Transformative Pathways* near zero scenarios grid emissions factors, *High Hydrogen Production and High Demand Growth with a 95% reduction in* CO_2 *by 2050,* required modification of one data point to align with the scenario parameters. That was the substitution of the single data point, the emissions factor in 2050 with the emissions factor from the side-case scenario used here, the *High Hydrogen Production and High Demand Growth with a 100% reduction in* CO_2 *by 2035* scenario.

Additionally, the 2023 Standard Scenarios start with modeled year 2024, and run every two years. The emissions factors for the odd-numbered years required interpolation and were simply calculated as the average of the emissions factors for the nearest even-numbered years. The emissions factor for all scenarios for 2023 was taken from *AEO 2023 Reference*. Last, the emissions factors for 2010–2022 are reported from EPA's Emissions & Generation Resource Integrated Database (eGRID),[585] with an added 6% losses for transmission and distribution.

Methodology and Assumptions

Figure B-1 shows the annual U.S. electric grid emissions factors between 2018 and 2050 assumed for the *Transformative Pathways* modeling for the BAU and Near Zero scenarios. The national electric grid emissions

[579] U.S. Energy Information Administration, "Documentation of the National Energy Modeling System (NEMS) modules," accessed November 2024, www.eia.gov/outlooks/aeo/nems/documentation/.
[580] National Renewable Energy Laboratory, "Regional Energy Deployment System," accessed November 2024, www.nrel.gov/analysis/reeds/
[581] U.S. Energy Information Administration, "Annual Energy Outlook 2023," 2023, www.eia.gov/outlooks/aeo/.
[582] Pieter Gagnon et al., *2023 Standard Scenarios Report: A U.S. Electricity Sector Outlook,* NREL/TP-6A40-87724 (National Renewable Energy Laboratory, 2024), www.osti.gov/biblio/2274777.
[583] Ibid.
[584] U.S. Energy Information Administration, "Annual Energy Outlook 2023," 2023, www.eia.gov/outlooks/aeo/.
[585] U.S. Environmental Protection Agency, "Historical eGRID data," January 30, 2024, www.epa.gov/egrid/historical-egrid-data.

factor for a given year was defined as the total CO_2e emissions from the combustion of fuels for grid electricity generation, divided by the total grid electricity supplied to end loads. To derive the emissions factors from the 2023 Standard Scenarios and AEO 2023, two different methodologies were used, owing to the different natures of the models, and the data they output.

Figure B-1. Annual U.S. grid-purchased electricity emissions factors by scenario used for the *Transformative Pathways* modeling

The *AEO 2023 Reference* scenario models electric generation by fuel type out to 2050. Using historical trendlines for heat rates by fuel and year, from Table 8.1 of EIA's Electric Power Annual,[586] trends were forecast out to 2050. The generation that was modeled that did not reach the grid was accounted for and assumed to be of the same overall composition of generation, and the total generation was reduced proportionally. Ultimately, the electric grid emissions factors for the *AEO 2023 Reference scenario* were extracted by summing the total CO_2e emissions for electricity that were bound for the grid divided by the total grid-supplied end use of electricity.

Within the supplied datasets for the 2023 Standard Scenarios is the total CO_2e emissions per year at national, state, and balancing area resolution. Additionally, the datasets also supply the total end use, transmission, distribution, direct air capture, storage, and electrolyzer loads that were exogenously fed into ReEDS. The total end use was defined as all loads not associated with the supplying the grid electricity to the end user—the end use, direct air capture, and electrolyzer loads. The grid emissions factors were then computed as the total CO_2e emissions divided by the sum of the three loads (end use, direct air capture, and electrolyzer).

Hydrogen Emissions Factors

Hydrogen Sources and Emissions

Hydrogen (H_2) is evaluated in the *Transformative Pathways* modeling due to its multiple decarbonization applications. The main role of H_2 is as a fuel and/or feedstock. For *Transformative Pathways*, three key types of hydrogen sources were identified and are listed in Table B-1 below. Steam methane reforming (SMR) H_2 is

[586] U.S. Energy Information Administration, "Electric Power Annual," October 25, 2024, www.eia.gov/electricity/annual/.

defined as the conventional benchmark. SMR-CCS H_2 is defined as H_2 produced from SMR with the addition of CCS. Last, clean H_2 denotes H_2 produced via electrolysis powered by clean electricity such as wind and solar. The associated reported emissions factors for each of the three types of H_2 are also summarized in Table B-1. Note that there are many different possible references for H_2 emissions factors. The *Transformative Pathways* modeling prioritized references with U.S.-based values and were cross-referenced with the 2023 *U.S. National Clean Hydrogen Strategy and Roadmap*.[587]

Table B-1. Hydrogen Sources and Reported Emissions Factors

Hydrogen source defined in *Transformative Pathways* models	Definition	Reported emissions factors (kg CO_2/kg H_2)	Reference(s)
SMR	H_2 produced from SMR	10	[1]
SMR-CCS	H_2 produced from SMR with CCS	1–4.1	[2]–[4]
Clean	H_2 produced from electrolysis powered by clean energy sources	0.3–4.6	[5]–[8]

References:

[1] Pingping Sun et al., "Criteria air pollutants and greenhouse gas emissions from hydrogen production in US steam methane reforming facilities," Environmental science & technology 53, 12 (April 2019): 7103-7113, doi.org/10.1021/acs.est.8b06197.

[2] Guido Collodi, Giuliana Azzaro, and Noemi Ferrari, Techno-economic evaluation of SMR based standalone (Merchant) plant with CCS (IEAGHG, 2017), ieaghg.org/publications/techno-economic-evaluation-of-smr-based-standalone-merchant-hydrogen-plant-with-ccs/.

[3] International Energy Agency, The Future of Hydrogen (2019), www.iea.org/reports/the-future-of-hydrogen.

[4] Thomas Longden et al., "'Clean' hydrogen?–Comparing the emissions and costs of fossil fuel versus renewable electricity based hydrogen," Applied Energy 306, (January 2022), doi.org/10.1016/j.apenergy.2021.118145.

[5] U.S. Department of Energy, U.S. National Clean Hydrogen Strategy and Roadmap (2023), www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap.

[6] Lea R. Winter et al., "Mining nontraditional water sources for a distributed hydrogen economy," Environmental Science & Technology 56, 15 (July 2022): 10577-10585. doi.org/10.1021/acs.est.2c02439.

[7] Kiane de Kleijne et al., "The many greenhouse gas footprints of green hydrogen," Sustainable Energy & Fuels 6, (August 2022): 4383-4387, doi.org/10.1039/D2SE00444E.

[8] Tom Terlouw et al., "Large-scale hydrogen production via water electrolysis: a techno-economic and environmental assessment," Energy & Environmental Science 15, (July 2022): 3583-3602. doi.org/10.1039/D2EE01023B.

SMR H_2 represents the current state of the art, produced via the SMR process with a reported emissions factor of up to 10 kg CO_2/kg H_2 for the United States.[588] SMR-CCS H_2 can be produced by integrating CCS on SMR. Depending on the degree of CCS integration, about 55% to 90% of the CO_2 emitted from the SMR plants can be captured.[589] The lower bound represents the current practice where CO_2 is captured from the shifted syngas using methyl diethanolamine. Carbon capture can be maximized by scrubbing CO_2 from flue gas, using solvents such as monoethanolamine. As a result, the emission factor of SMR-CCS H_2 can range between 0.8–4.3 kg CO_2/kg H_2).[590,591,592] Therefore, the models use 4.1 kg CO_2/kg H_2 as a current emission factor for SMR-CCS H_2, which decreases to 1 kg CO_2/H_2 in 2050 using linear extrapolation. Note that fugitive emissions from the natural gas supply chain could significantly increase (i.e., double)[593] the emissions factor but is not considered in this analysis.

For clean H_2, emissions are mostly associated with the type and emissions of the electricity that powers the electrolyzer. The H_2 generated through electrolysis using current U.S. grid electricity has an emission factor of

[587] U.S. Department of Energy, *U.S. National Clean Hydrogen Strategy and Roadmap* (2023), www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap.
[588] Pingping Sun et al., "Criteria air pollutants and greenhouse gas emissions from hydrogen production in US steam methane reforming facilities," *Environmental science & technology* 53, 12 (April 2019): 7103-7113, doi.org/10.1021/acs.est.8b06197.
[589] Guido Collodi, Giuliana Azzaro, and Noemi Ferrari, *Techno-economic evaluation of SMR based standalone (Merchant) plant with CCS* (IEAGHG, 2017), ieaghg.org/publications/techno-economic-evaluation-of-smr-based-standalone-merchant-hydrogen-plant-with-ccs/.
[590] Ibid.
[591] International Energy Agency, *The Future of Hydrogen* (2019), www.iea.org/reports/the-future-of-hydrogen.
[592] Thomas Longden et al., "'Clean' hydrogen?–Comparing the emissions and costs of fossil fuel versus renewable electricity based hydrogen," *Applied Energy* 306, (January 2022), doi.org/10.1016/j.apenergy.2021.118145.
[593] Robert W. Howarth and Mark Z. Jacobson, "How green is blue hydrogen?" *Energy Science & Engineering* 9, 10 (October 2021): 1676-1687, doi.org/10.1002/ese3.956.

around 20 to 25 kg CO_2/kg H_2,[594] which is not considered clean given that the renewable composition within the current U.S. grid is still less than 50%.[595] Many studies report the emission factors for clean hydrogen to be from 0.3 to 4.6 kg CO_2/kg H_2 depending on the electricity source (various types of wind and solar).[596,597,598.599] Therefore, a cumulative average value of 2.5 kg CO_2/kg H_2 is used as a starting point for current clean H_2 production and performed linear extrapolation to reach net zero emissions by 2050. All emission factors were converted to kg CO_2/GJ using the higher heating value of 141.7 MJ/kg for H_2.

Hydrogen Supply and Demand

Predicting the availability of various H_2 sources for industrial decarbonization requires complex modeling efforts. The *Transformative Pathways* modeling identified two major references that estimate H_2 availability.[600,601] Specifically, availability from both sources were extracted and compared in Figure B-2. Even though the projected H_2 supply by 2050 has large uncertainties, the percentage of clean H_2 within the clean and SMR-CCS H_2 available is somewhat similar between the two reports. Therefore, a high-level estimate of the availability of three types of H_2 was determined based on the projected SMR H_2, and the averaged clean H_2 percentage from the two references within the remaining clean and SMR-CCS H_2. Linear extrapolations were conducted to generate annual availability between data points provided by the sources.

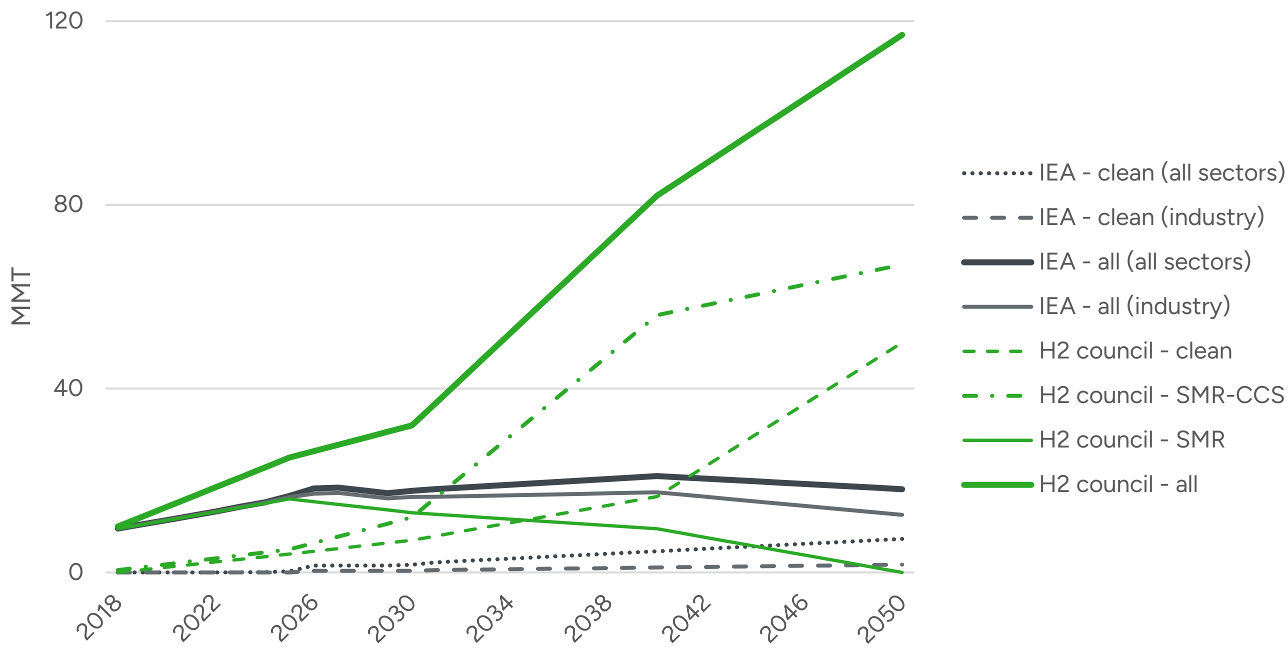

Figure B-2. Comparison of annual H_2 availability from different references (MMT)

Data sources: Hydrogen Council, Global Hydrogen Flows: Hydrogen trade as a key enabler for efficient decarbonization. prepared by McKinsey & Company, (2022), hydrogencouncil.com/wp-content/uploads/2022/10/Global-Hydrogen-Flows.pdf.; International Energy Agency, Global Hydrogen Review 2022 (2022), www.iea.org/reports/global-hydrogen-review-2022.

[594] U.S. Department of Energy, *U.S. National Clean Hydrogen Strategy and Roadmap* (2023), www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap.
[595] See Table 7.2 Electricity Net Generation in U.S. Energy Information Administration, “Monthly Energy Review,” October 2024, www.eia.gov/totalenergy/data/monthly/index.php.
[596] U.S. Department of Energy, *U.S. National Clean Hydrogen Strategy and Roadmap* (2023), www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap.
[597] Lea R. Winter et al., “Mining nontraditional water sources for a distributed hydrogen economy,” *Environmental Science & Technology* 56, 15 (July 2022): 10577-10585. doi.org/10.1021/acs.est.2c02439.
[598] Kiane de Kleijne et al., “The many greenhouse gas footprints of green hydrogen*,” Sustainable Energy & Fuels* 6, (August 2022): 4383-4387, doi.org/10.1039/D2SE00444E.
[599] Tom Terlouw et al., “Large-scale hydrogen production via water electrolysis: a techno-economic and environmental assessment,” *Energy & Environmental Science* 15, (July 2022): 3583-3602. doi.org/10.1039/D2EE01023B.
[600] Hydrogen Council, *Global Hydrogen Flows: Hydrogen trade as a key enabler for efficient decarbonization*. prepared by McKinsey & Company, (2022), hydrogencouncil.com/wp-content/uploads/2022/10/Global-Hydrogen-Flows.pdf.
[601] International Energy Agency, *Global Hydrogen Review 2022* (2022), www.iea.org/reports/global-hydrogen-review-2022.

Details of the assumptions and uses associated with H_2 use and demand can be found in detail for individual subsectors in Section 4. Cumulative comparison between H_2 supply and demand under various near zero scenarios shows that the projected H_2 supply should be able to satisfy most of the H_2 demand as feedstock. However, challenges in H_2 supply may occur when H_2 is considered as an alternative fuel in industrial subsectors (i.e., refining). Furthermore, the allocation of clean, SMR-CCS, and SMR H_2 to each subsector and application should be considered with care during decarbonization planning, as shown in all the scenarios that either source alone (SMR-CCS or clean) cannot meet the total industrial demand. Such consideration would need further modeling in terms of regional H_2 availability and the economics of H_2-based decarbonization methods.

Challenges and Outlook

The *Transformative Pathways* modeling considers the emissions of different H_2 sources, and the potential supply and demand across all the modeled subsectors. There are several key challenges of applying H_2 for industrial decarbonization that should be considered in future research, which are summarized below.

First, the comprehensive life cycle and economic performance of utilizing H_2 in various industrial subsectors should be a determining factor for adoption. For example, the cost target set by the *U.S. National Clean Hydrogen Strategy and Roadmap* is US$1/kg H_2.[602] Given current R&D efforts in electrolysis and CCS, this target could potentially be met by 2050. However, for non-essential H_2 use (i.e., as alternative fuel), the economic impacts of switching to H_2-based fuels should be analyzed and considered on a subsector-by-subsector basis.

Second, better predictions on the temporal-spatial influence on H_2-based decarbonization efforts would be highly beneficial. As discussed before, linear extrapolation was used for data points not reported in the literature. In the future, better metrics considering the technology deployment (i.e., learning rate) should be used for predicting the emissions and potential cost factors. For spatial influence, regionality considerations are recommended to also be incorporated. For example, transportation and storage costs associated with providing H_2 to the individual subsectors in different regions should be accounted for when evaluating cost and emissions factors.

Lastly, future work on optimizing the allocation for different H_2 sources across subsectors would be beneficial. Although the overall supply of clean H_2 should be able to meet the various demand scenarios from the *Transformative Pathways* modeling, industrial decarbonization will be a dynamic process. Therefore, it is important to properly allocate H_2 based on decarbonization needs, economic merits, and availability. Furthermore, regional productivity and the location of various industrial facilities, concerning potential pipeline transportation and underground storage infrastructure, should also be considered during the optimization and allocation of available clean H_2.

Fuels (Other Than Hydrogen) Emissions Factors

The method used for calculating combustion emissions is based upon the Tier 1 Calculation Methodology from Section 98.33 of EPA Reporting Rules. Combustion emissions are calculated by multiplying total energy consumption for a specific end use by the respective GHG emission factor for each energy type. Energy use data is specified as higher heating value. GHG emission factors for fuels other than hydrogen assumed in the *Transformative Pathways* modeling are displayed in Table B-2 below. Emissions factors in kilograms per million Btu (kg/MMBtu) for grid-purchased electricity are not held constant throughout the model and are discussed at the beginning of this appendix.

[602] U.S. Department of Energy, *U.S. National Clean Hydrogen Strategy and Roadmap* (2023), www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap.

Table B-2. Fuels (Other Than Hydrogen) Emissions Factors Used in the Transformative Pathways Models (kg/MMBtu)

Type	Emissions factors				Reference(s)
	CO_2	CH_4	N_2O	CO_2e	
Coal	94.67	0.011	0.0016	95.40	[1]
Distillate fuel oil and diesel fuel	73.96	0.003	0.0006	74.20	[1]
Natural gas	53.06	0.001	0.0001	53.11	[1]
Hydrocarbon gas liquids (HGLs)	61.71	0.003	0.0006	61.95	[1]
Purchased steam	71.71	0.0014	0.00	71.78	[2], [3]
Agricultural byproducts (e.g., bagasse)	N/A*	0.032	0.0042	2.01	[1]
Wood and wood residuals	N/A*	0.0072	0.0036	1.16	[1]
Waste gas**	66.72	0.003	0.0006	66.96	[1], [4]
Miscellaneous fuels***	74.54	0.003	0.0006	74.78	[1]

Note: CO_2e values were calculated using the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report 100-year global warming potentials (GWPs) of 1 for CO_2, 28 for CH_4, and 265 for N_2O (IPCC 2014, see Box 3.2, Table 1).

* Assumed as 0 for this modeling and analysis. Like all hydrocarbons, biomass combustion releases CO_2 as a chemical byproduct, however some portion of that CO2 was sequestered during the growth of the biomass, so the net emission of CO_2 is considered to be zero as per EPA GHG Reporting Rules.

** Waste gas is no longer provided in [1]; CO_2 factor is from [4] and CH_4, and N_2O factors assumed as "petroleum products" from Table C-2 in [1].

*** Assumed as "unfinished oil" emissions factors from [1].

[1] eCFR. 2024. Title 40 Part 98 Mandatory Greenhouse Gas Reports. www.ecfr.gov/current/title-40/chapter-I/subchapter-C/part-98#ap40.23.98_138.2. See Table C-1 (CO_2) and Table C-2 (CH_4, and N_2O).

[2] U.S. Environmental Protection Agency. Emissions Factors for Greenhouse Gas Inventories. March 26, 2020. www.epa.gov/sites/production/files/2020-04/documents/ghg-emission-factors-hub.pdf. See Table 7.

[3] U.S. Environmental Protection Agency. ENERGYSTAR Portfolio Manager Technical Reference: Source Energy. 2023. portfoliomanager.energystar.gov/pdf/reference/Source%20Energy.pdf?c8a6-69ad. Emissions factor from [2] for steam adjusted to include assumed 7.5% transmission and distribution loss per [3].

[4] The Climate Registry. 2023 default emissions factors. 2023. theclimateregistry.org/wp-content/uploads/2023/06/2023-Default-Emission-Factors-Final-1.pdf.

CCUS

CCUS is a process by which an impure CO_2 stream, is processed to obtain a pure CO_2 product suitable for utilization as a chemical feedstock or permanently stored at a geological site.[603] It has the potential to significantly help decarbonize the economy, especially when there are no alternatives to generating waste CO_2, such as in the case of industry process emissions or when combustion of hydrocarbon-based fuels cannot be easily avoided. Captured CO_2 varies in purity levels and scale between industrial subsectors and different plants within the same subsector, making it challenging to develop a nation-wide estimate of the capturable amount of CO_2 per subsector and the associated cost. The *Transformative Pathways* modeling effort considered four different CO_2 capture mechanisms: amine absorption, calcium looping, oxy-fuel combustion, and direct capture. Direct capture refers to the capturing of a pure CO_2 stream that only requires compression for transportation; it does not refer to direct air capture, a group of alternative CO_2 capture technologies. Amine absorption was the only technology applied in the modeling for the subsectors that utilized CCUS, but the other options are discussed below for reference.

In most cases, capturing CO_2 requires energy. These energy expenditures are generally referred to as the energy penalty and can vary significantly depending on the technology used and the CO_2 source purity. These energy penalties can also, in many cases, be reduced by waste heat integration. In the context of industrial CO_2

[603] Matthew E. Boot-Handford et al., "Carbon Capture and Storage Update," *Energy & Environmental Science* 7, 1 (September 2013): 130–89. doi.org/10.1039/C3EE42350F.

emissions, the energy penalty is the additional energy spent to capture CO_2 by keeping product output constant and is typically reported in GJ/MT CO_2 (or MJ/kg CO_2).

In this analysis, energy penalties were obtained from the average of values reported in the literature. The energy penalties, shown for each CO_2 capture technology, are shown in Table B-3 for cement and concrete, Table B-4 for iron and steel, and Table B-5 for other subsectors. Since the capture of industrial CO_2 emissions have received comparatively less attention compared to power plant CO_2 emissions, energy penalty values are generally not as available, save for a few well-studied subsectors (e.g., cement and concrete, iron and steel), especially for more than one CO_2 capture technology. For this reason, the energy penalties from power plants, which in general have low CO_2 concentrations,[604] are used as default values in Table B-5. A particular challenge, however, is that there is in general no distinction between heat and electricity penalties reported in the literature. To partially correct for this, it was assumed that at least 0.38 GJ/MT CO_2 of the energy penalty consisted of electricity, corresponding to CO_2 compression, and this was subtracted from the rest of the energy penalty, which was assumed to be heat.

Table B-3. Cement and Concrete Subsector Heat and Electricity Energy Penalties for CO_2 Capture Technologies

Technology	Heat Energy Penalty (GJ/MT CO_2)	Electricity Energy Penalty (GJ_e/MT CO_2)	References
Amine absorption	5.42	0.38	[1]-[5]
Calcium looping	2.65	0.38	[1], [4], [6]
Oxy-fuel combustion	0	1.28	[4]-[5]
Direct capture	0	0.38	[1]

[1] David L. McCollum and Joan M. Ogden. Techno-Economic Models for Carbon Dioxide Compression, Transport, and Storage & Correlations for Estimating Carbon Dioxide Density and Viscosity. University of California–Davis. 2006. escholarship.org/uc/item/1zg00532.

[2] M. M. Jaffar et al. "Comparative Techno-Economic Analysis of the Integration of MEA-Based Scrubbing and Silica PEI Adsorbent-Based CO_2 Capture Processes into Cement Plants." Journal of Cleaner Production 414 (August 2023). doi.org/10.1016/j.jclepro.2023.137666.

[3] Mar Pérez-Fortes et al. "CO_2 Capture and Utilization in Cement and Iron and Steel Industries." Energy Procedia 63 (2014): 6534–6543. doi.org/10.1016/j.egypro.2014.11.689.

[4] Konstantinos Vatopoulos and Evangelos Tzimas. "Assessment of CO_2 Capture Technologies in Cement Manufacturing Process." Journal of Cleaner Production 32 (September 2012): 251–261. doi.org/10.1016/j.jclepro.2012.03.013.

[5] Mari Voldsund et al. "Comparison of Technologies for CO_2 Capture from Cement Production—Part 1: Technical Evaluation." Energies 12, 3 (February 2019). doi.org/10.3390/en12030559.

[6] Edoardo De Lena et al. "Techno-Economic Analysis of Calcium Looping Processes for Low CO_2 Emission Cement Plants." International Journal of Greenhouse Gas Control 82 (March 2019): 244–260. doi.org/10.1016/j.ijggc.2019.01.005.

[604] Guiyan Zang et al., "Synthetic Methanol/Fischer–Tropsch Fuel Production Capacity, Cost, and Carbon Intensity Utilizing CO_2 from Industrial and Power Plants in the United States," *Environ. Sci. Technol.* 55, 11 (May 2021): 7595–7604. doi.org/10.1021/acs.est.0c08674.

Table B-4. Iron and Steel Subsector Heat and Electricity Energy Penalties for CO_2 Capture Technologies

Technology	Heat Energy Penalty ($GJ/MT\ CO_2$)	Electricity Energy Penalty ($GJ_e/MT\ CO_2$)	References
Amine absorption	3.3–4.0	0.28–0.38	[1]-[4]
Calcium looping	2.42	0.38	[1], [5]
Oxy-fuel combustion	0	0.97	[6]
Direct capture	0	0.38	[1]

[1] David L. McCollum and Joan M. Ogden. Techno-Economic Models for Carbon Dioxide Compression, Transport, and Storage & Correlations for Estimating Carbon Dioxide Density and Viscosity. University of California–Davis. 2006. escholarship.org/uc/item/1zg00532.

[2] Matteo Gazzani, Matteo C. Romano, and Giampaolo Manzolini. "CO_2 Capture in Integrated Steelworks by Commercial-Ready Technologies and SEWGS Process." International Journal of Greenhouse Gas Control 41 (October 2015): 249–267. doi.org/10.1016/j.ijggc.2015.07.012.

[3] Kunwoo Han, Chi Kyu Ahn, and Man Su Lee. "Performance of an Ammonia-Based CO_2 Capture Pilot Facility in Iron and Steel Industry." International Journal of Greenhouse Gas Control 27 (August 2014): 239–246. doi.org/10.1016/j.ijggc.2014.05.014.

[4] Jorge Perpiñán et al. "Integration of carbon capture technologies in blast furnace based steel making: A comprehensive and systematic review." Fuel 336 (March 2023). doi.org/10.1016/j.fuel.2022.127074.

[5] Sicong Tian et al. "Inherent Potential of Steelmaking to Contribute to Decarbonisation Targets via Industrial Carbon Capture and Storage." Nat Commun 9, 1 (October 2018). doi.org/10.1038/s41467-018-06886-8.

[6] Minh T. Ho, Andrea Bustamante, and Dianne E. Wiley. "Comparison of CO_2 Capture Economics for Iron and Steel Mills." International Journal of Greenhouse Gas Control 19 (November 2013): 145–159. doi.org/10.1016/j.ijggc.2013.08.003.

Table B-5. Other Subsectors Heat and Electricity Energy Penalties for CO2 Capture Technologies

Technology	Heat Energy Penalty (GJ/MT CO2)	Electricity Energy Penalty (GJe/MT CO2)	References
Amine absorption	3.26	0.38	[1]-[6]
Calcium looping	2.00	0.38	[1], [7]-[8]
Oxy-fuel combustion	0	1.84	[9]-[10]
Direct capture	0	0.38	[1]

[1] David L. McCollum and Joan M. Ogden. Techno-Economic Models for Carbon Dioxide Compression, Transport, and Storage & Correlations for Estimating Carbon Dioxide Density and Viscosity. University of California–Davis. 2006. escholarship.org/uc/item/1zg00532.

[2] Jacob N. Knudsen et al. "Experience with CO_2 Capture from Coal Flue Gas in Pilot-Scale: Testing of Different Amine Solvents." Energy Procedia 1, 1 (February 2009): 783-790. doi.org/10.1016/j.egypro.2009.01.104.

[3] No-Sang Kwak et al. "A Study of the CO_2 Capture Pilot Plant by Amine Absorption." Energy 47, 1 (November 2012): 41-46. doi.org/10.1016/j.energy.2012.07.016.

[4] Kangkang Li et al. "Systematic Study of Aqueous Monoethanolamine-based CO_2 Capture Process: Model Development and Process Improvement." Energy Sci. Eng. 4, 1 (January 2016): 23-39. doi.org/10.1002/ese3.101.

[5] E. Sanchez Fernandez et al. "Thermodynamic Assessment of Amine Based CO_2 Capture Technologies in Power Plants Based on European Benchmarking Task Force Methodology." Fuel 129 (August 2014): 318–329. doi.org/10.1016/j.fuel.2014.03.042.

[6] Inga von Harbou et al. "Pilot Plant Experiments for Two New Amine Solvents for Post-Combustion Carbon Dioxide Capture." International Journal of Greenhouse Gas Control 18 (October 2013): 305–314. doi.org/10.1016/j.ijggc.2013.08.002.

[7] Marco Astolfi et al. "Improved Flexibility and Economics of Calcium Looping Power Plants by Thermochemical Energy Storage." International Journal of Greenhouse Gas Control 83 (April 2019): 140–155. doi.org/10.1016/j.ijggc.2019.01.023.

[8] Carlos Ortiz et al. "Energy Consumption for CO_2 Capture by Means of the Calcium Looping Process: A Comparative Analysis Using Limestone, Dolomite, and Steel Slag." Energy Technol. 4, 10 (October 2016): 1317-1327. doi.org/10.1002/ente.201600390.

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APPENDIX C. SUBSECTOR DETAILS AND MODELING ASSUMPTIONS

Cement and Concrete

The analysis presented in this report and the underlying model build on several key studies published on the topic of cement and concrete decarbonization in both a global and a U.S.-specific context:

- Paul S. Fennell, Steven J. Davis, and Aseel Mohammed. "Decarbonizing Cement Production." *Joule* 5, 6 (June 2021): 1305–11. doi.org/10.1016/j.joule.2021.04.011.
- Steve Griffiths et al. "Decarbonizing the Cement and Concrete Industry: A Systematic Review of Socio-Technical Systems, Technological Innovations, and Policy Options." *Renewable and Sustainable Energy Reviews* 180 (July 2023): 113291. doi.org/10.1016/j.rser.2023.113291.
- G. Habert et al. "Environmental Impacts and Decarbonization Strategies in the Cement and Concrete Industries." *Nature Reviews Earth & Environment* 1, 11 (November 2020): 559–73. doi.org/10.1038/s43017-020-0093-3.
- Ali Hasanbeigi and Cecilia Springer. "Deep Decarbonization Roadmap for the Cement and Concrete Industries in California." San Francisco, CA: Global Efficiency Intelligence, 2019. www.climateworks.org/wp-content/uploads/2019/09/Decarbonization-Roadmap-CA-Cement-Final.pdf.
- Michel D. Obrist et al. "Decarbonization Pathways of the Swiss Cement Industry Towards Net Zero Emissions." *Journal of Cleaner Production* 288 (March 2021): 125413. doi.org/10.1016/j.jclepro.2020.125413.
- Sabbie A. Miller et al. "Achieving Net Zero Greenhouse Gas Emissions in the Cement Industry via Value Chain Mitigation Strategies." *One Earth* 4, 10 (October 2021): 1398–1411. doi.org/10.1016/j.oneear.2021.09.011.
- Pablo Busch et al. "Literature Review on Policies to Mitigate GHG Emissions for Cement and Concrete." *Resources, Conservation and Recycling* 182 (July 2022): 106278. doi.org/10.1016/j.resconrec.2022.106278.
- Sabbie A. Miller et al. "Carbon Dioxide Reduction Potential in the Global Cement Industry by 2050." Cement and Concrete Research, Report of UNEP SBCI Working Group on Low-CO_2 Eco-efficient cement-based Materials, 114 (December 2018): 115–24. doi.org/10.1016/j.cemconres.2017.08.026.
- International Energy Agency. "Technology Roadmap - Low-Carbon Transition in the Cement Industry." Paris, France, 2018. www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry.
- Sydney Hughes et al. *Analysis of Carbon Capture Retrofits for Cement Plants*. DOE/NETL-2023/3856. (National Energy Technology Laboratory, 2023). doi.org/10.2172/1970135.
- Thomas Hills et al. "Carbon Capture in the Cement Industry: Technologies, Progress, and Retrofitting." *Environmental Science & Technology* 50, 1 (January 2016): 368–77. doi.org/10/ghkp27.
- Maxwell Pisciotta et al. "Opportunities for Cement Decarbonization." *Cleaner Engineering and Technology* 15 (August 2023): 100667. doi.org/10.1016/j.clet.2023.100667.
- Ron M. Jacob and Lars-André Tokheim. "Electrified Calciner Concept for CO_2 Capture in Pyro-Processing of a Dry Process Cement Plant." *Energy* 268, (April 2023): 126673. doi.org/10.1016/j.energy.2023.126673.
- Sebastian Quevedo Parra and Matteo C. Romano. "Decarbonization of Cement Production by Electrification." *Journal of Cleaner Production* 425 (November 2023): 138913 doi.org/10.1016/j.jclepro.2023.138913.
- Izhar Hussain Shah et al. "Cement Substitution with Secondary Materials Can Reduce Annual Global CO_2 Emissions by up to 1.3 Gigatons." *Nature Communications* 13 (September 2022). doi.org/10.1038/s41467-022-33289-7.

Modeling Details

- Incumbent clinker production technologies and fuel share of coal and petroleum coke are assumed to follow a logistic decay function
- Different scenarios modeled assume different decay constants to allow for a more gradual or faster turnover of the incumbents.
- Clinker production technologies: relinquished market share by incumbents is distributed amongst the six next-generation technologies using a logit market share function based on a stylized aggregated parameter, which notionally represents various attributes such as cost and retrofittability based on literature data and expert judgement
- Fuels: relinquished market share from coal and petroleum coke is assumed to be distributed between natural gas and biomass at a fixed ratio over time depending on the scenario.

The clinker-to-cement ratio, which determines the total amount of SCMs in the final cement production in the model, is assumed to increase geometrically through 2050 at different rates depending on the scenario. The analysis conservatively assumes that all increase in SCM content would be due to increased usage of LC3 (i.e., amount of fly ash, blast furnace slag, natural pozzolans, etc. per kg of cement assumed to stay at current levels through 2050). The carbon intensity of LC3, which currently stands at about 0.25–0.3 kg CO_2e/kg,[168] is also assumed to geometrically decrease over time at different rates depending on the scenario to reflect expected improvements in efficiency and technology in a future with substantially increased use of LC3. Although identified as promising approaches to reducing cement emissions, alternative binders and electrochemical routes using silicates as feedstocks are not included in this study and will be part of future analysis. From the perspective of this model framework, inclusion of these approaches would be operationally similar to increased use of SCMs. This means that the increased use of alternative binders and chemistries will result in lower clinker production and need for rapid deployment of cleaner clinker production technologies with CCS, and the contribution to the overall emissions from cement production from these alternative binders and chemistries will be governed by the efficiency and carbon intensity of their respective production processes.

Representative Scenarios and Assumptions

The model is run to characterize GHG emissions and technology trajectories over time for six key scenarios. These scenarios and their salient features are described in Table C-1.

Table C-1. Key Assumptions for the Scenarios Explored in the Cement and Concrete Model

Scenario	Salient Features
BAU	• Demand increases as 0.5% p.a., resulting in about 28% increase in cement production in 2050 relative to 2018 • Clinker-to-cement ratio drops to 0.8 by 2050, with LC3 as the dominant SCM substituting clinker and carbon intensity of clinker drops to about 0.18 kg CO_2e/kg clinker by 2050 • Incumbent clinker technologies occupy over 80% market share by 2050 • Coal and petroleum coke comprise over 45%, natural gas provides over 40% of the fuel energy share for pyroprocessing with minimal increase in biomass share • Access to CCS limited to 50% of installed cement capacity
BAU, High SCM	• Same features as BAU, but clinker-to-cement ratio drops to 0.4 by 2050
CNZ	• Demand increases as 0.5% p.a., resulting in about 28% increase in cement production in 2050 relative to 2018 • Clinker-to-cement ratio drops to 0.6 by 2050, with LC3 as the dominant SCM substituting clinker

Scenario	Salient Features
	• Incumbent clinker technologies phased out by 2050, dry kiln with BAT preheater + precalciner with CCS is the dominant low-carbon clinker production technology (55% market share), with other technologies occupying relatively equal parts of the balance of the market share) • Coal and petroleum coke phased out by 2050, natural gas providing 75% and biomass providing 12% of the fuel energy share for pyroprocessing • Access to CCS available to 95% of installed cement capacity • Carbon intensity of electric grid falls to near zero by 2050
CNZ–Limited CCS	• Same features as CNZ, but access to CCS restricted to 50% of installed cement capacity and incumbent clinker technologies occupy about 20% of market share by 2050
CNZ–High SCM	• Same features as CNZ, but clinker-to-cement ratio drops to 0.4 by 2050 and incumbent clinker technologies occupy about 20% of market share by 2050
CNZ–High SCM (CCS on LC3)	• Same features as CNZ–High SCM, but carbon intensity of clinker drops to about 0.03 kg CO_2e/kg clinker by 2050

Table C-2. Energy Demand for Each Clinker Production Route Considered in the Analysis

Production Route	Heat Demand megajoules (thermal) (MJ_{th})/kg clinker	Electricity Demand megajoules (electric) (MJ_e)/kg clinker	References
Conventional wet kiln (incumbent)	6.19	0.20	[1]
Conventional dry kiln (incumbent)	3.67	0.17	[1]
Dry kiln with preheater + precalciner, best available technology (BAT)	2.86	0.13	[1]
Dry kiln with preheater + precalciner, BAT, CCS	2.86	0.13	[1]
Partial Electrification (electric precalciner, fuel kiln), CCS	1.92	2.26	[2]
Full Electrification (electric precalciner + kiln), CCS	0	3.40	[3]
Indirect heating (electric-based), partial-CCS	0	3.47	[4]
Indirect heating (fuel-based), partial-CCS	3.50	0.19	[4]

CCS-equipped routes have additional heat and electricity demand not shown here. The incumbent dry kiln technology represents a capacity-weighted average of the various types of dry kilns operational in the United States.

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[1] U.S. Department of Energy, Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Cement Manufacturing, (2017), www.osti.gov/biblio/1512370.

[2] Ron M. Jacob and Lars-André Tokheim, "Electrified calciner concept for CO2 capture in pyro-processing of a dry process cement plant," Energy 268 (2023): 126673.

[3] Wilhelmsson, Bodil, Claes Kollberg, Johan Larsson, Jan Eriksson, and Magnus Eriksson. "CemZero–A feasibility study evaluating ways to reach sustainable cement production via the use of electricity." Vattenfall Cem (2018).

[4] Leilac, A techno-economic analysis of the Leilac technology at full commercial scale, (2023), www.leilac.com/report/decarbonising-cement-leilac-full-commercial-scale-study/.

Figure C-1 illustrates the emissions reduction impact by decarbonization pillar for the High Clean Clinker Production, Moderate SCM Pathway. SCM usage falls within the Low-Carbon Feedstocks bar. The contribution of CCUS is due to the high rate of CCS adoption for clinker production that was assumed in the *Transformative*

Pathways modeling. As noted in the main text, alternative clean clinker production technologies or clinker alternatives can offset the need for and impact of CCS in a near zero cement and concrete subsector.

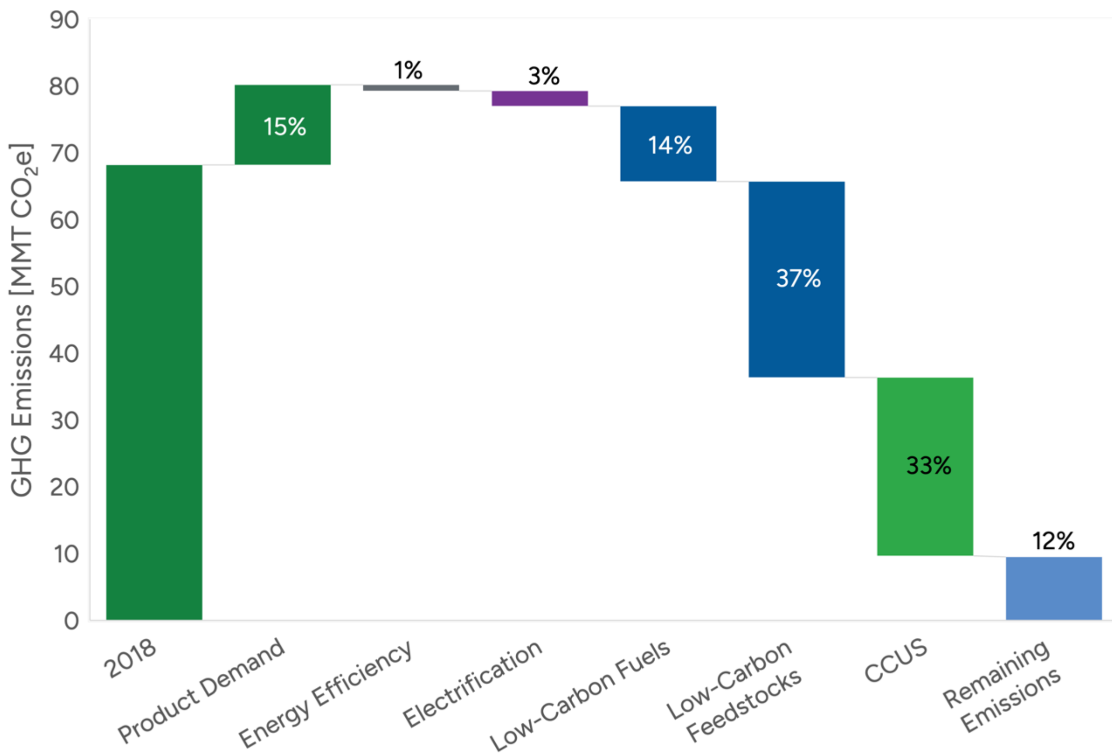


Figure C-1. Impact of decarbonization pillars on GHG emissions, U.S. cement and concrete manufacturing–High Clean Clinker Production, Moderate SCM pathway (MMT CO_2e), 2018–2050

This figure may differ from the associated Roadmap figure due to further modeling considerations. Source: Transformative Pathways modeling.

Table C-3. List of Major Cement and Concrete Decarbonization Measures with Key Technologies or Approaches

A (*) next to a technology or approach indicates that it is explicitly modeled in this analysis, a (†) indicates that the technology or approach was either indirectly or partially modeled in this analysis, and a (§) indicates that the technology or approach is not explicitly modeled in the analysis, although the model framework allows for its modeling in a future iteration.

Technology/Approach	Applicability to existing facilities	Barriers to accelerated RDD&D	Major uncertainties	Success drivers and decision points
Material Efficiency & Demand Reduction				
Efficient building design†	• Limited but can be applied in retrofits	• Availability of optimization tools, codes may not be adapted to lighter/alternative designs	• Trade-offs with both safety margins and service life	• Adoption of modeling tools and the regulatory shifts to accommodate while keeping safety and longevity at forefront
Longer service life†	• Maintenance practices, coatings for corrosion resistance	• Higher upfront costs and uncertainty over long term performance	• Verification of longevity, structure retirement before material end-of-life	• Clear economic benefits of longer service life
Clinker Substitution				
Fly ash*	• Common existing SCM	• N/A	• Limited supply with coal power phase-out • Cost and carbon intensity of fly ash beneficiation	• N/A
Blast furnace slag*	• Common existing SCM	• N/A	• Limited supply with possible phase-out of blast furnaces	• N/A
Calcined clay*	• Potential for reduced fuel consumption and electricity due to low processing temperature of clay calcination	• Clay supplies need to be dried • High CAPEX due to extra storage requirement	• Current focus is on Kaolin, impact of other clays may need to be developed • Supply uncertainty, access limited to certain locations in the U.S. • Cost and performance at higher levels of clinker substitution	• Cost of deployment based on where clay is calcined (at cement plant vs. grinding plant vs. greenfield site)
Natural pozzolans*	• Increasingly used in existing facilities	• Current standard limits amount of substitution	• Supply at scale • Cost and performance	• Modification of standards to allow increased usage
Alternative Binders				

Technology/Approach	Applicability to existing facilities	Barriers to accelerated RDD&D	Major uncertainties	Success drivers and decision points
Belite ferrite ye'elimite cement (BYF)§	• Less limestone à less CO_2 emissions and lower process temperature • Specialty applications	• Requires new norms • Needs aluminum-rich raw material which is expensive (from bauxite) and sulfur; potential for boron doping to enhance belite reactivity • Sensitive to temperature	• Raw material supply • Color • Compatibility with existing concrete admixtures • Cost	• Availability of multiple kilns as it cannot replace ordinary Portland cement/Portland limestone cement currently and one cannot switch between the two types without "cleaning"
Calcium sulfoaluminate-belite cement (CSAB)§	• Lower process temperature; no need to change anything in existing installation • Rapid setting, good for applications that need to be put back in service quickly or require a quick turnaround on site	• N/A	• Availability and proximity of bauxite	• Availability of multiple kilns as it cannot replace OPC/PLC currently and one cannot switch between the two types without "cleaning"
Carbonatable calcium silicate cement (CCSC)§	• Needs sealed curing chambers for precast applications • Otherwise, manufacturing process identical to regular ordinary Portland cement • Can be used to make carbonatable SCMs	• Requires new standards (ASTM 1905 and 1910 were created, not sure about adoption) • Limited to precast	• Cost premium may limit adoption • Quality of CO_2 (yield based on CO_2 purity)	• N/A
Replacing incumbent clinker production with low-carbon routes				
Wet kiln*	• Comprises about 3% of current capacity	• N/A	• N/A	• N/A
Long dry kiln*	• Comprises about 5% of current capacity	• N/A	• N/A	• N/A
Dry kiln with preheater*	• Comprises about 12% of current capacity	• N/A	• N/A	• N/A
Dry kiln with preheater & precalciner*	• Comprises about 80% of current capacity	• N/A	• N/A	• N/A

Technology/Approach	Applicability to existing facilities	Barriers to accelerated RDD&D	Major uncertainties	Success drivers and decision points
Dry kiln with preheater & precalciner + CCS*	• Only a few U.S. facilities currently piloting CCS with best available technology	• Access to CO_2 storage and transportation infrastructure • Significant increase in capital and operating costs and energy use from capture plant • Infeasible for smaller cement plants	• Incentives for CO_2 capture and low-carbon cement products • Community acceptance of CO_2 transport and storage infrastructure	• Significantly lower energy and cost penalty through breakthroughs in CO_2 capture technologies • Ability to modularize CO_2 capture technologies
Dry kiln with indirect fuel heating + partial CCS from calciner*	• Currently limited to demonstration scale plants	• Increased energy demand and cost due to higher energy loss posed by system configuration. • Cost of plant retrofit due to change in kiln design. • Access to CO_2 storage and transportation infrastructure	• Potential change in calcination efficiency which could impact energy use and CO_2 emissions. • Feasible chance of variation in clinker quality.	• Competitive cost for technology deployment at scale. • Prove of energy and emissions savings.
Dry kiln with indirect electric heating + partial CCS from calciner*	• Currently limited to demonstration scale plants	• Operational complexity associated with the integrated system. • High-cost barrier posed by electro-technology options. • Access to CO_2 storage and transportation infrastructure	• Limited knowledge of the electrified system configuration for large-scale deployment. • Feasible chance of variation in clinker quality.	• Competitive cost for technology deployment at scale. • Establishment of policy framework that supports decarbonization via electrification of systems.
Dry kiln with electric precalciner & electric kiln + CCS*	• NA	• Limitations related to temperatures, heat flux, heat transfer mechanisms, and material compatibility • Access to clean electricity infrastructure • Poor retrofittability	• Effects on product quality and characteristics • Access to CO_2 storage or merchant CO_2 markets	• Successful scaling from bench or pilot to demonstration scale
Fuel switching				

Technology/Approach	Applicability to existing facilities	Barriers to accelerated RDD&D	Major uncertainties	Success drivers and decision points
Biomass*	• Different bio-based fuels constitute a share of the current fuel mix in most facilities	• Limited availability of biomass dedicated for fuel. • Biomass supply and demand competition across sectors.	• Variability in composition of bio-based fuels delivered. • Seasonable variation in biomass leading to supply chain issues.	• Overcome solid waste regulatory which potentially restricts a higher share of waste biomass • Consensus on carbon neutrality of biomass.
Natural gas*	• Most facilities use some degree of natural gas as fuel	• Access to gas pipeline infrastructure and fluctuations in gas prices • Retrofits needed for higher • Contending with higher NOx emissions	• Supply and demand imbalance across subsectors and overall economy.	• Overcome regulatory challenges associated with higher emissions (e.g., NOx) caused by increased natural gas use.

Chemicals

The sections below provide additional detail on the chemicals subsector modelings assumptions.

Production Growth Rates

Table C-4. Assumptions for Annual Chemical Production Growth Rates, 2018–2050

Chemical	Assumed annual production growth rate (%)	References and remarks
Ethylene	2.0%	Extrapolated based on IEA projections [1] and a subscribed market assessment
Propylene	0.8%	Extrapolated based on IEA projections [1] and a subscribed market assessment
Butadiene	1.4%	Extrapolated based on a subscribed market assessment
BTX Aromatics	1.0%	Based on projected production growth for North America by IEA [1]
Chlorine	0.3%	Extrapolated from historic production volumes provided by the ACC's Guide to the Business of Chemistry [2]
Soda Ash	1.0%	Extrapolated from historic production volumes provided by the U.S. Geological Survey [3]
Ethanol	0.2%	Based on the EIA 2023 Annual Energy Outlook [4]
Methanol	3.0%	Based on projected global production growth by the International Renewable Energy Agency (IRENA) [5] and industry trends in the United States, as provided by EIA [6]

Ammonia	1.0% (in most scenarios) 3.0% (in ambitious ammonia demand scenario)	For most scenarios, growth in ammonia production is assumed based on U.S. Geological Survey projections, primarily for conventional end uses [7] For the ambitious ammonia demand scenario, which considers emerging end uses such as ammonia's role as a hydrogen carrier and shipping fuel, growth is projected based on IEA [8] and IRENA [9]
Rest of chemicals	0.3%	Extrapolated from production volumes for major chemicals provided by the ACC's Guide to the Business of Chemistry [2]

References:

[1] International Energy Agency, The Future of Petrochemicals: Towards a More Sustainable Chemical Industry (2018), www.iea.org/reports/the-future-of-petrochemicals.

[2] American Chemistry Council, 2023 Guide to the Business of Chemistry (2023), www.americanchemistry.com/chemistry-in-america/data-industry-statistics/resources/2023-guide-to-the-business-of-chemistry.

[3] U.S. Geological Survey, "Soda Ash Statistics and Information," accessed November 2023, www.usgs.gov/centers/national-minerals-information-center/soda-ash-statistics-and-information.

[4] U.S. Energy Information Administration, "Annual Energy Outlook 2023," 2023, www.eia.gov/outlooks/aeo/.

[5] IRENA and Methanol Institute, Innovation Outlook: Renewable Methanol, (Abu Dhabi: International Renewable Energy Agency, 2021), www.irena.org/publications/2021/Jan/Innovation-Outlook-Renewable-Methanol.

[6] U.S. Energy Information Administration, "New methanol plants expected to increase industrial natural gas use through 2020," February 21, 2019, www.eia.gov/todayinenergy/detail.php?id=38412.

[7] U.S. Geological Survey, Nitrogen (fixed)-Ammonia Mineral Commodity Summary (2022), pubs.usgs.gov/periodicals/mcs2022/mcs2022-nitrogen.pdf.

[8] International Energy Agency, Ammonia Technology Roadmap (2021), www.iea.org/reports/ammonia-technology-roadmap.

[9] International Renewable Energy Agency and Ammonia Energy Association, Innovation Outlook: Renewable Ammonia (2022), www.irena.org/publications/2022/May/Innovation-Outlook-Renewable-Ammonia.

Recycling Rates

Table C-5. Assumptions for Chemical Product Recycling Rates by 2050 in the Core Near Zero Pathway

Chemical	% of chemical used in recyclable products	Current recycling rate (%)	Assumed recycling target by 2050 in Core Near Zero Pathway (%)	Remarks
Ethylene	PET–3%	15%	50%	Increase in the recycling rate is expected to be feasible through improved collection systems, with a focus on mechanical recycling.
	HDPE–26%	10%	50%	Increase in the recycling rate is expected to be feasible through improved collection systems, with a focus on mechanical recycling.
	LDPE/LLDPE–33%	2%	50%	Increase in the recycling rate is expected to be feasible through improved collection systems, with a focus on mechanical recycling.
Propylene	PP–50%	3%	50%	Increase in the recycling rate is expected to be feasible through improved collection systems and primarily mechanical recycling, potentially coupled with solvent dissolution and purification.
Butadiene	Rubbers–55%	40%	-	Current recycling is largely open-loop, with an assumed negligible impact on chemical demand reduction.
Xylene	PET – 55%	15%	50%	Increase in the recycling rate is expected to be feasible through improved collection systems, with a focus on mechanical recycling.

Soda Ash	Container glass–9%	25%	50%	Increase in the recycling rate is expected to be feasible through improved collection systems and existing recycling processes.

Acronyms: HDPE (high-density polyethylene), LDPE (low-density polyethylene), LLDPE (linear low-density polyethylene), PET (polyethylene terephthalate), PP (polypropylene)

Ethylene

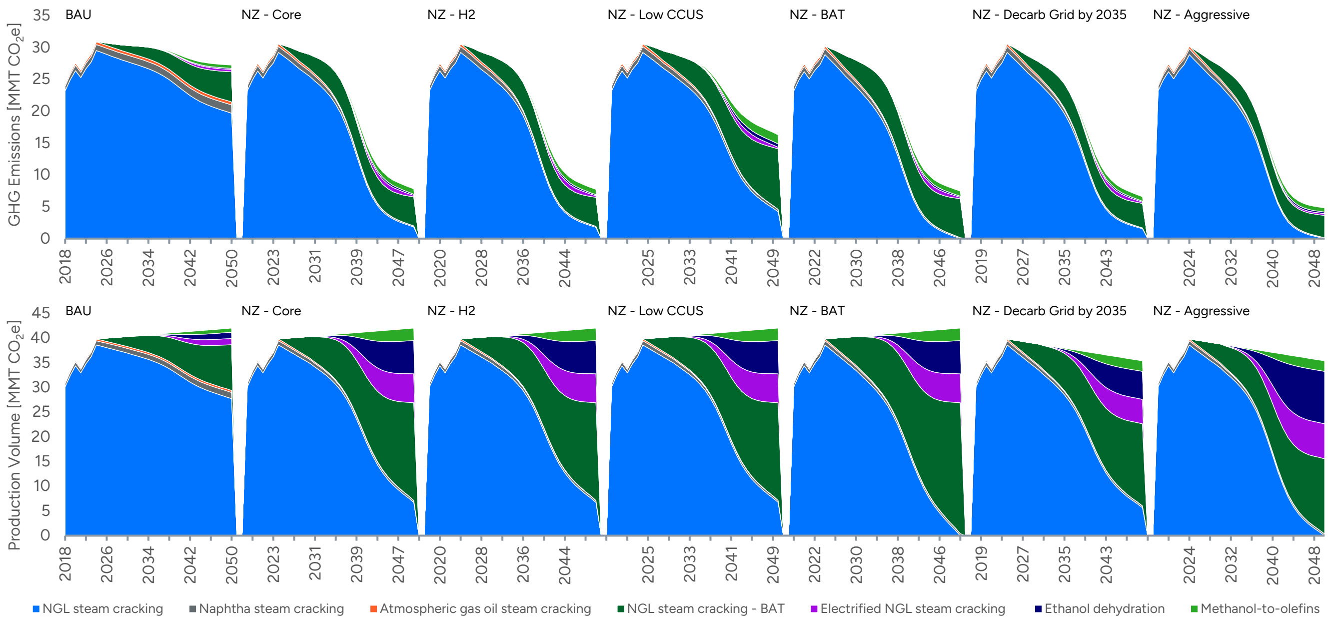


Figure C-2. U.S. ethylene production: (Top) Annual GHG emissions reductions–Core Near Zero pathway and sensitivities (MMT CO_2e/year), 2018–2050; (Bottom) Production route market share–Core Near Zero pathway and sensitivities (MMT/year), 2018–2050

Source: Transformative Pathways modeling.

Table C-6. Ethylene–Assumptions for Core Near Zero Pathway and Sensitivities

Scope	Production Route Market Share by 2050	Energy Efficiency	Electrification	LCFFES	CCUS
Core Near Zero (CNZ) Pathway	• Atmospheric gas oil steam cracking - AGO (0%) • Natural gas liquids steam cracking - NGL (63%) • Naphtha steam cracking (1%) • Electrified steam cracking (14%) • Methanol-to-olefins - MTO (6%) • Ethanol dehydration (16%)	• Up to 75% of NGL steam cracking to adopt BAT (optimal furnace heat balance, improved furnace coils, membrane separation, new column designs, etc.) by 2050. • Phase out AGO steam cracking by 2050. • 0.1-0.5% per annum autonomous improvement.	• 100% clean electric grid by 2050. • Transition 14% to electrified steam cracking by 2050, starting from 2030.	• Transition 16% to ethanol dehydration and 6% to MTO in 2050. • Increased use of tail gas. • 10% RNG blended with NG by 2050.	Capture 70% of all direct CO2 emissions by 2050.

Scope	Production Route Market Share by 2050	Energy Efficiency	Electrification	LCFFES	CCUS
CNZ–Increased Recycling	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ
CNZ–BAT	Same as CNZ	• 100% of NGL steam cracking to adopt BAT (optimal furnace heat balance, improved furnace coils, membrane separation, new column designs, etc.) by 2050. • Phase out AGO steam cracking by 2050. • 0.3-0.8% per annum autonomous improvement.	Same as CNZ	Same as CNZ	Same as CNZ
CNZ–Hydrogen	Same as CNZ	Same as CNZ	Same as CNZ	• Transition 16% to ethanol dehydration and 6% to MTO in 2050. • Increased use of tail gas. • 10% RNG blended with NG by 2050. • 20% by volume H_2 blended with NG by 2050.	Same as CNZ
CNZ–Low CCUS	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ	Capture 10% of all direct CO_2 emissions by 2050.
CNZ–Aggressive	• Atmospheric gas oil steam cracking - AGO (0%) • Natural gas liquids steam cracking - NGL (49%) • Naphtha steam cracking (1%) • Electrified steam cracking (20%) • Methanol-to-olefins - MTO (0%)	• 100% of NGL steam cracking to adopt BAT (optimal furnace heat balance, improved furnace coils, membrane separation, new column designs, etc.) by 2050.	• 100% clean electric grid by 2035. • Transition 20% to electrified steam cracking by 2050, starting from 2030.	• Transition 30% to ethanol dehydration in 2050. • Increased use of tail gas. • 10% RNG blended with NG by 2050. • 20% by volume H_2 blended with NG by 2050.	Same as CNZ

Scope	Production Route Market Share by 2050	Energy Efficiency	Electrification	LCFFES	CCUS
	• Ethanol dehydration (30%)	• Phase out AGO steam cracking by 2050. • 0.3-0.8% per annum autonomous improvement.			

Propylene

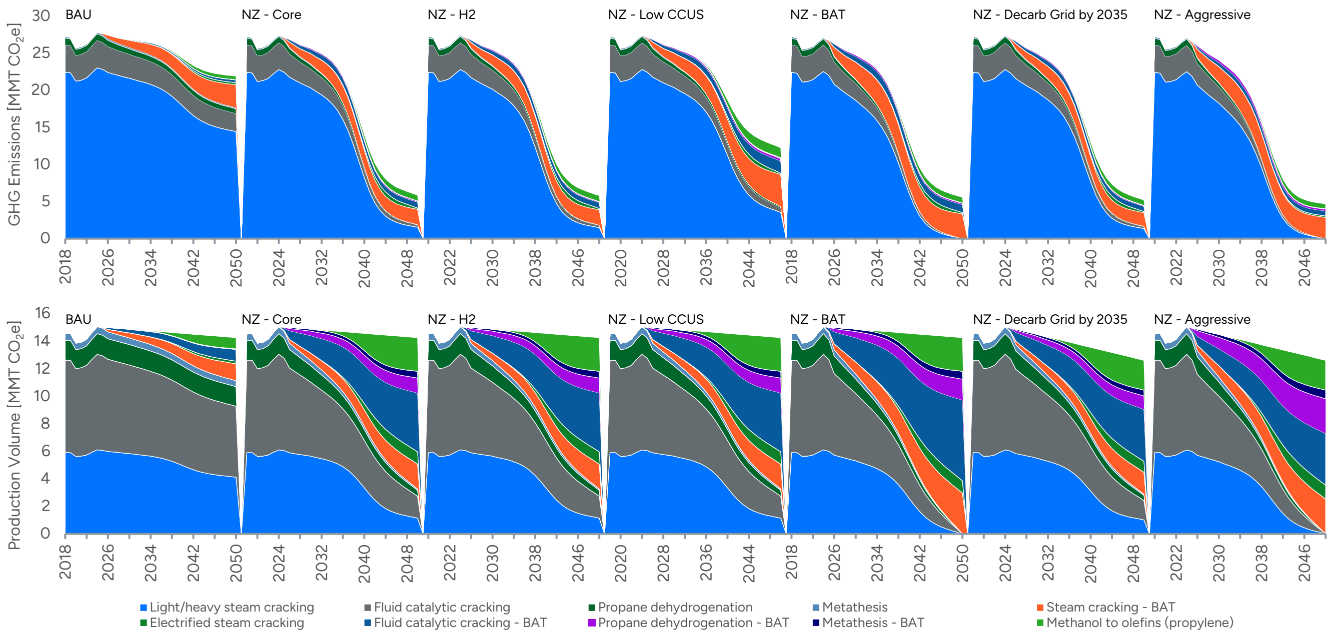


Figure C-3. U.S. propylene production: (Top) Annual GHG emissions reductions—Core Near Zero pathway and sensitivities (MMT CO_2e/year), 2018–2050; (Bottom) Production route market share—Core Near Zero pathway and sensitivities (MMT/year), 2018–2050

Source: Transformative Pathways modeling.

Table C-7. Propylene—Assumptions for Core Near Zero Pathway and Sensitivities

Scope	Production Route Market Share by 2050	Energy Efficiency	Electrification	LCFFES	CCUS
Core Near Zero (CNZ) Pathway	• Steam cracking (21%) • Electrified steam cracking (6%) • Fluid catalytic cracking - FCC (41%) • Propane dehydrogenation (11%) • Metathesis (4%)	• Up to 70% of conventional pathways adopt BAT (optimal furnace heat balance, structured packing, improved process control and optimization, etc.) by 2050.	• 100% clean electric grid by 2050. • Transition 6% to electrified steam cracking by 2050, starting from 2030. • Transition 17% to MTO in 2050.	• Transition 17% to MTO in 2050. • Increased use of tail gas. • 10% RNG blended with NG by 2050.	Capture 70% of all direct CO2 emissions by 2050.

Scope	Production Route Market Share by 2050	Energy Efficiency	Electrification	LCFFES	CCUS
	• Methanol-to-olefins - MTO (17%)	• Transition 11% to propane dehydrogenation, and 4% to metathesis in 2050. • 0.1-0.5% per annum autonomous improvement	• Increased use of tail gas. • 10% RNG blended with NG by 2050.		
CNZ–Increased Recycling	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ
CNZ–BAT	Same as CNZ	• 100% of conventional pathways adopt BAT (optimal furnace heat balance, structured packing, improved process control and optimization, etc.) by 2050. • Transition 11% to pro-pane dehydrogenation, and 4% to metathesis in 2050. • 0.3-0.8% per annum autonomous improvement.	Same as CNZ	Same as CNZ	Same as CNZ
CNZ–Hydrogen	Same as CNZ	Same as CNZ	Same as CNZ	• Transition 17% to MTO in 2050. • Increased use of tail gas. • 10% RNG blended with NG by 2050. • 20% by volume H_2 blended with NG by 2050.	Same as CNZ
CNZ–Low CCUS	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ	Capture 10% of all direct CO_2 emissions by 2050.

Scope	Production Route Market Share by 2050	Energy Efficiency	Electrification	LCFFES	CCUS
CNZ–Aggressive	• Steam cracking (20%) • Electrified steam cracking (8%) • Fluid catalytic cracking - FCC (30%) • Propane dehydrogenation (20%) • Metathesis (5%) • Methanol-to-olefins - MTO (17%)	• 100% of conventional pathways adopt BAT (optimal furnace heat balance, structured packing, improved process control and optimization, etc.) by 2050. • Transition 20% to propane dehydrogenation, and 5% to metathesis in 2050. • 0.3-0.8% per annum autonomous improvement.	• 100% clean electric grid by 2035. • Transition 8% to electrified steam cracking by 2050, starting from 2030.	• Transition 17% to MTO in 2050. • Increased use of tail gas. • 10% RNG blended with NG by 2050. • 20% by volume H_2 blended with NG by 2050.	Same as CNZ

Butadiene

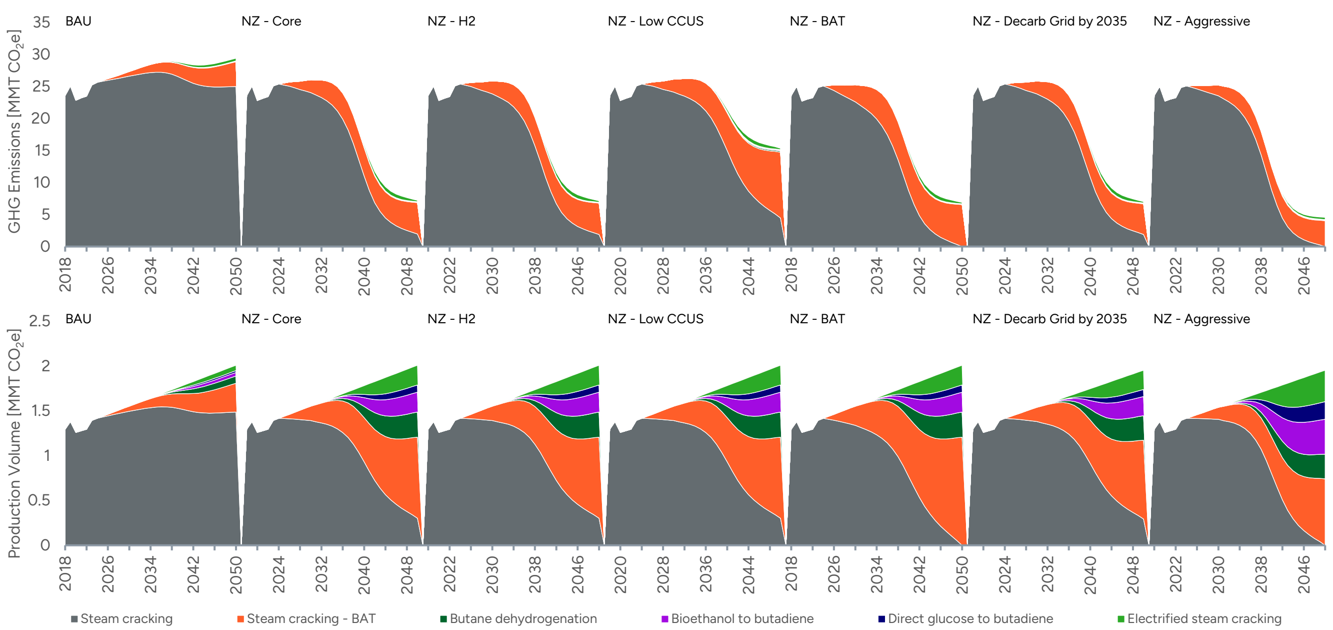


Figure C-4. U.S. butadiene production: (Top) Annual GHG emissions reductions—Core Near Zero pathway and sensitivities (MMT CO_2e/year), 2018–2050; (Bottom) Production route market share—Core Near Zero pathway and sensitivities (MMT/year), 2018–2050

Source: Transformative Pathways modeling.

Table C-8. Butadiene–Assumptions for Core Near Zero Pathway and Sensitivities

Scope	Production Route Market Share by 2050	Energy Efficiency	Electrification	LCFFES	CCUS
Core Near Zero (CNZ) Pathway	• Steam cracking (60%) • Electrified steam cracking (11%) • Direct glucose to butadiene (4%) • Bioethanol to butadiene (11%) • Butane dehydrogenation (14%)	• Up to 75% of conventional steam cracking adopt BAT (including NMP extraction) by 2050. • Transition 14% to butane dehydrogenation • 0.1-0.5% per annum autonomous improvement	• 100% clean electric grid by 2050. • Transition 11% to electrified steam cracking by 2050, starting from 2030.	• Transition 4% to direct glucose and 11% to bioethanol to butadiene in 2050. • Increased use of tail gas. • 10% RNG blended with NG by 2050.	Capture 70% of all direct CO2 emissions by 2050.
CNZ–Increased Recycling	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ
CNZ–BAT	Same as CNZ	• 100% of conventional steam cracking adopt BAT (including NMP extraction) by 2050. • Transition 14% to butane dehydrogenation • 0.3-0.8% per annum autonomous improvement	Same as CNZ	Same as CNZ	Same as CNZ
CNZ–Hydrogen	Same as CNZ	Same as CNZ	Same as CNZ	• Transition 4% to direct glucose and 11% to bioethanol to butadiene in 2050. • Increased use of tail gas. • 10% RNG blended with NG by 2050. • 20% by volume H_2 blended with NG by 2050.	Same as CNZ
CNZ–Low CCUS	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ	Capture 10% of all direct CO_2 emissions by 2050.

Scope	Production Route Market Share by 2050	Energy Efficiency	Electrification	LCFFES	CCUS
CNZ–Aggressive	• Steam cracking (47%) • Electrified steam cracking (18%) • Direct glucose to butadiene (10%) • Bioethanol to butadiene (25%) • Butane dehydrogenation (0%)	• 100% of conventional steam cracking adopt BAT (including NMP extraction) by 2050. • 0.3-0.8% per annum autonomous improvement	• 100% clean electric grid by 2035. • Transition 18% to electrified steam cracking by 2050, starting from 2030.	• Transition 10% to direct glucose and 25% to bioethanol to butadiene in 2050. • Increased use of tail gas. • 10% RNG blended with NG by 2050. • 20% by vol. H_2 blended with NG by 2050.	Same as CNZ

BTX Aromatics

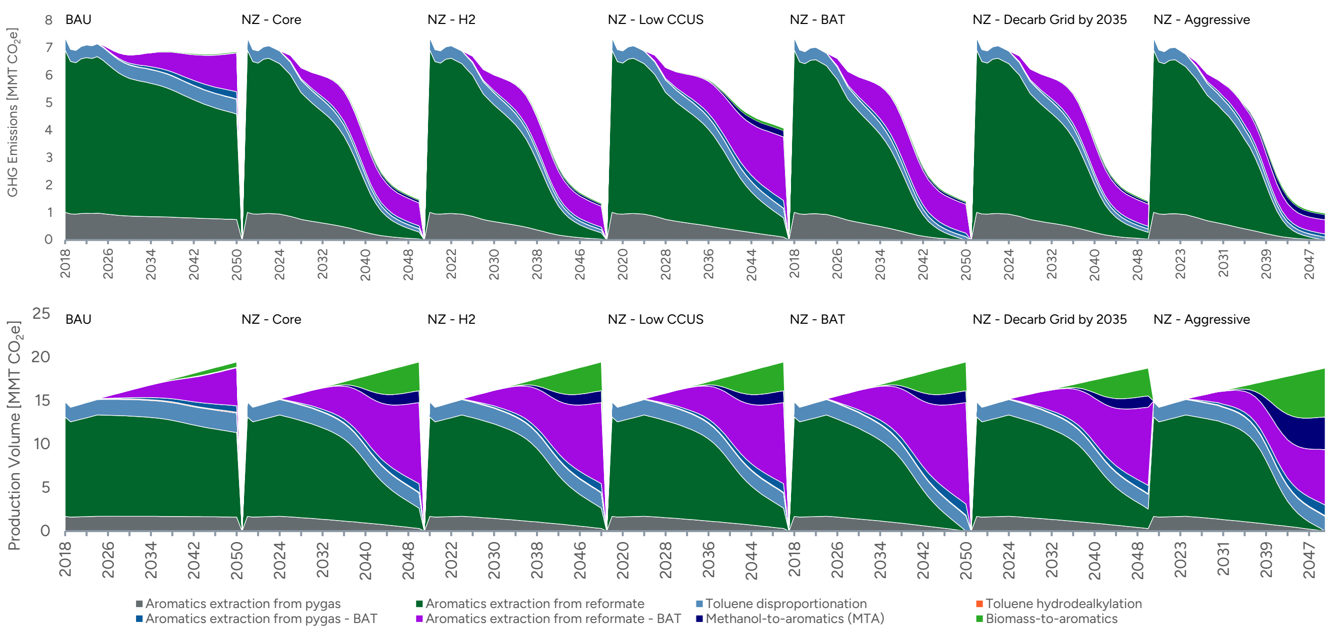


Figure C-5. U.S. BTX aromatics production: (Top) Annual GHG emissions reductions–Core Near Zero pathway and sensitivities (MMT CO_2e/year), 2018–2050; (Bottom) Production route market share–Core Near Zero pathway and sensitivities (MMT/year), 2018–2050

Source: Transformative Pathways modeling.

Table C-9. BTX Aromatics–Assumptions for Core Near Zero Pathway and Sensitivities

Scope	Production Route Market Share by 2050	Energy Efficiency	Electrification	LCFFES	CCUS
Core Near Zero (CNZ) Pathway	• Extraction from reformate (60%) • Extraction from pygas (7%)	• Up to 80% of conventional pathways adopt BAT (heat integration, process	100% clean electric grid by 2050.	• Transition 7% to MTA in 2050. • Transition 17% to Biomass-to-	Capture 70% of all direct CO2 emissions by 2050.

Scope	Production Route Market Share by 2050	Energy Efficiency	Electrification	LCFFES	CCUS
	• Toluene disproportionation (9%) • Toluene hydroalkylation (<1%) • Methanol-to-aromatics - MTA (7%) • Biomass-to-aromatics (17%)	intensification, advanced process control, and optimization, etc.) by 2050. • 0.1-0.5% per annum autonomous improvement.		aromatics in 2050. • 10% RNG blended with NG by 2050.	
CNZ–Increased Recycling	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ
CNZ–BAT	Same as CNZ	• 100% of conventional pathways adopt BAT (heat integration, process intensification, advanced process control, and optimization, etc.) by 2050. • 0.3-0.8% per annum autonomous improvement.	Same as CNZ	Same as CNZ	Same as CNZ
CNZ–Hydrogen	Same as CNZ	Same as CNZ	Same as CNZ	• Transition 7% to MTA in 2050. • Transition 17% to Biomass-to-aromatics in 2050. • 10% RNG blended with NG by 2050. • 20% by volume H_2 blended with NG by 2050.	Same as CNZ
CNZ–Low CCUS	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ	Capture 10% of all direct CO_2 emissions by 2050.
CNZ–Aggressive	• Extraction from reformate (34%)	• 100% of conventional pathways adopt	100% clean electric grid by 2035.	• Transition 20% to MTA in 2050.	Same as CNZ

Scope	Production Route Market Share by 2050	Energy Efficiency	Electrification	LCFFES	CCUS
	• Extraction from pygas (7%) • Toluene dis-proportionation (9%) • Toluene hy-droalkylation (<1%) • Methanol-to-aromatics - MTA (20%) • Biomass-to-aromatics (30%)	BAT (heat integration, process intensification, advanced process control, and optimization, etc.) by 2050. • 0.3-0.8% per annum autonomous improvement		• Transition 30% to Bio-mass-to-aromatics in 2050. • 10% RNG blended with NG by 2050. • 20% by volume H_2 blended with NG by 2050.	

Chlor-Alkali

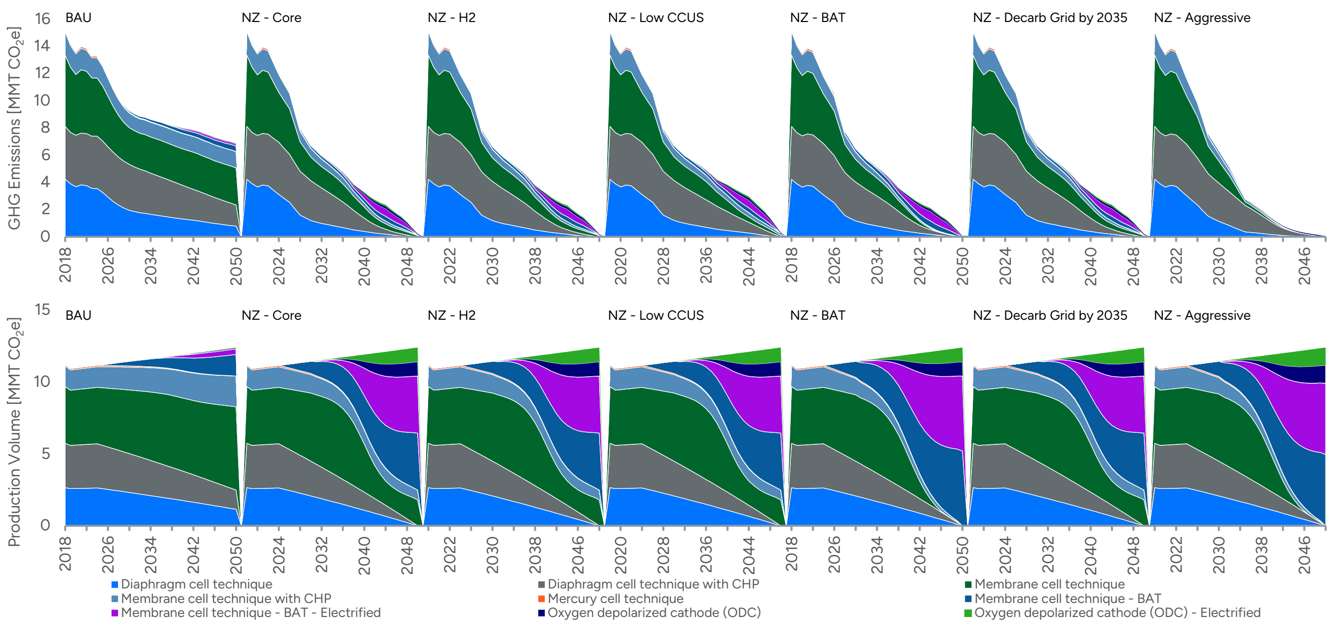


Figure C-6. U.S. chlor-alkali production: (Top) Annual GHG emissions reductions–Core Near Zero pathway and sensitivities ($MMT\ CO_2e$/year), 2018–2050; (Bottom) Production route market share–Core Near Zero pathway and sensitivities (MMT/year), 2018–2050

Source: Transformative Pathways modeling.

Table C-10. Chlor-Alkali–Assumptions for Core Near Zero Pathway and Sensitivities

Scope	Production Route Market Share by 2050	Energy Efficiency	Electrification	LCFFES	CCUS
Core Near Zero (CNZ) Pathway	• Mercury cell technique (0%) • Diaphragm cell technique (0%) • Membrane cell technique (84%)	• Phase out mercury and diaphragm cells at a constant rate, aiming for a 0% contribution from both by 2050.	• 100% clean electric grid by 2050. • By 2050, 50% of the steam generation for membrane cell technologies is	• Increased use of byproduct H2 in H2 fuel cell CHP within the context of the BAT assumption.	Capture 70% of all direct CO2 emissions by 2050.

Scope	Production Route Market Share by 2050	Energy Efficiency	Electrification	LCFFES	CCUS
	• Oxygen depolarized cathode - ODC (16%)	• Transition 64% to membrane cell (BAT) and 16% to ODC by 2050. • 0.1-0.5% per annum autonomous improvement.	projected to be electrified using HTHP.	• 10% RNG blended with NG by 2050.	
CNZ–Increased Recycling	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ
CNZ–BAT	Same as CNZ	• Phase out mercury and diaphragm cells at a constant rate, aiming for a 0% contribution from both by 2050. • Transition 84% to membrane cell (BAT) and 16% to ODC by 2050. • 0.3-0.8% per annum autonomous improvement.	Same as CNZ	Same as CNZ	Same as CNZ
CNZ–Hydrogen	Same as CNZ	Same as CNZ	Same as CNZ	• Increased use of byproduct H2 in H2 fuel cell CHP within the context of the BAT assumptions. • 10% RNG blended with NG by 2050. • 20% by volume H_2 blended with NG by 2050.	Same as CNZ
CNZ–Low CCUS	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ	Capture 10% of all direct CO_2 emissions by 2050.
CNZ–Aggressive	• Mercury cell technique (0%) • Diaphragm cell technique (0%)	• Phase out mercury and diaphragm cells at a constant	• 100% clean electric grid by 2035.	• Increased use of byproduct H2 in H2 fuel cell CHP within the	Same as CNZ

Scope	Production Route Market Share by 2050	Energy Efficiency	Electrification	LCFFES	CCUS
	• Membrane cell technique (84%) • Oxygen depolarized cathode - ODC (16%)	rate, aiming for a 0% contribution from both by 2050. • Transition 84% to membrane cell (BAT) and 16% to ODC by 2050. • 0.3-0.8% per annum autonomous improvement.	• By 2050, 40% of the steam generation for membrane cell technologies is projected to be electrified using HTHP.	context of the BAT assumptions. • 10% RNG blended with NG by 2050. • 20% by volume H_2 blended with NG by 2050.	

Soda Ash

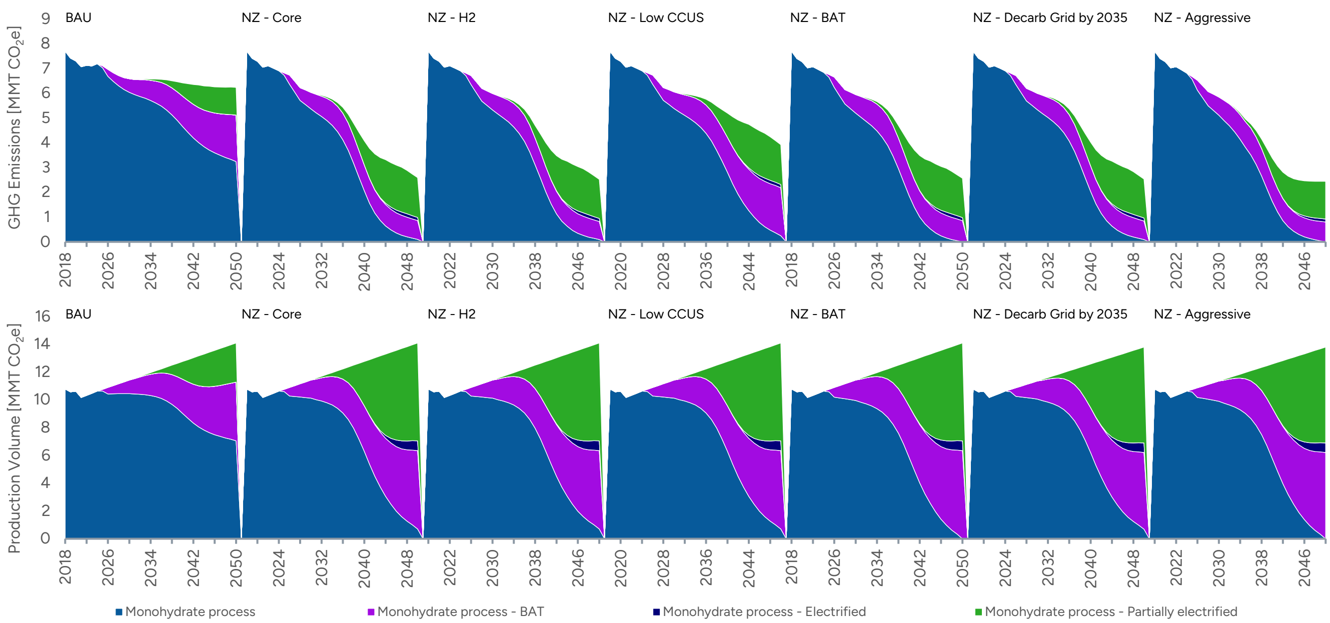


Figure C-7. U.S. soda ash production: (Top) Annual GHG emissions reductions–Core Near Zero pathway and sensitivities (MMT CO_2e/year), 2018–2050; (Bottom) Production route market share–Core Near Zero pathway and sensitivities (MMT/year), 2018–2050

Source: Transformative Pathways modeling.

Table C-11. Soda Ash–Assumptions for Core Near Zero Pathway and Sensitivities

Scope	Production Route Market Share by 2050	Energy Efficiency	Electrification	LCFFES	CCUS
Core Near Zero (CNZ) Pathway	• Monohydrate process (93%) • Direct carbonation (7%; assumed as carbon neutral	• Transition 95% to BAT (rotary steam dryers, heat integration, etc.) by 2050.	• 100% clean electric grid by 2050. • By 2050, 50% of the steam generation	• Switch entirely from coal to NG by 2050. • 10% RNG blended with NG by 2050.	Capture 70% of all direct CO2 emissions by 2050.

Scope	Production Route Market Share by 2050	Energy Efficiency	Electrification	LCFFES	CCUS
	already in the base year)	• 0.1-0.3% per annum autonomous improvement.	electrified using HTHP and electric boilers. • 5% electrified calcination by 2050 (market entry in 2040).		
CNZ–Increased Recycling	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ
CNZ–BAT	Same as CNZ	• Transition 95% to BAT (rotary steam dryers, heat integration, etc.) by 2050. • 0.3-0.5% per annum autonomous improvement.	Same as CNZ	Same as CNZ	Same as CNZ
CNZ–Hydrogen	Same as CNZ	Same as CNZ	Same as CNZ	• Switch entirely from coal to NG by 2050. • 10% RNG blended with NG by 2050. • 20% by volume H_2 blended with NG by 2050.	Same as CNZ
CNZ–Low CCUS	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ	Capture 10% of all direct CO_2 emissions by 2050.
CNZ–Aggressive	• Monohydrate process (93%) • Direct carbonation (7%; assumed as carbon neutral already in the base year)	• Transition 100% to BAT (rotary steam dryers, heat integration, etc.) by 2050. • 0.3-0.5% per an-num autonomous improvement.	• 100% clean electric grid by 2035. • By 2050, 50% of the steam generation electrified using HTHP and electric boilers. • 5% electrified calcination by 2050 (market entry in 2040).	• Switch entirely from coal to NG by 2050. • 10% RNG blended with NG by 2050. • 20% by volume H_2 blended with NG by 2050.	Same as CNZ

Methanol

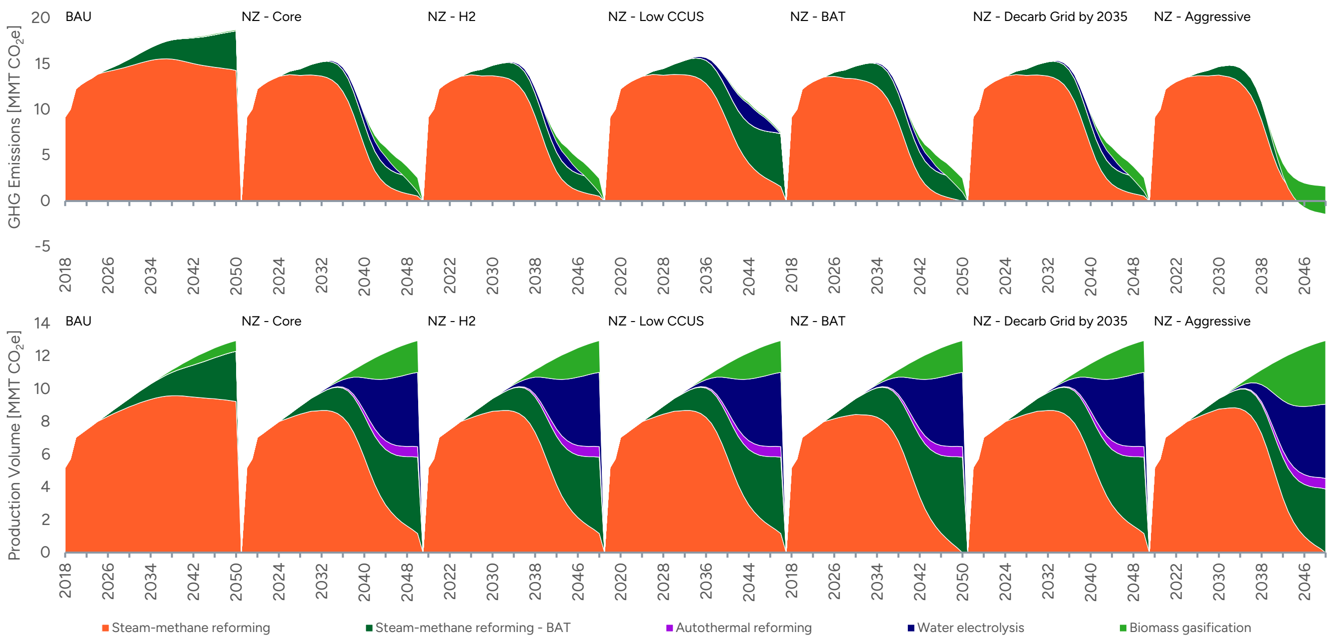


Figure C-8. U.S. methanol production: (Top) Annual GHG emissions reductions—Core Near Zero pathway and sensitivities (MMT CO_2e/year), 2018–2050; (Bottom) Production route market share—Core Near Zero pathway and sensitivities (MMT/year), 2018–2050

Source: Transformative Pathways modeling.

Table C-12. Methanol—Assumptions for Core Near Zero Pathway and Sensitivities

Scope	Production Route Market Share by 2050	Energy Efficiency	Electrification	LCFFES	CCUS
Core Near Zero (CNZ) Pathway	• Steam-methane reforming - SMR (45%) • Autothermal reforming - ATR (5%) • Water electrolysis (35%) • Biomass gasification (15%)	• 80% of SMR plants adopt BAT (improved heat integration, pre-reforming, etc.) by 2050. • Transition 5% to ATR in 2050. • 0.1-0.5% per annum autonomous improvement.	• 100% clean electric grid by 2050. • Transition 35% to water electrolysis (e-methanol) in 2050.	• Transition 15% to bio-methanol in 2050. • 10% RNG blended with NG by 2050.	Capture 70% of all direct CO2 emissions by 2050.
CNZ–Increased Recycling	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ
CNZ–BAT	Same as CNZ	• All conventional SMR adopt BAT (improved heat integration, pre-reforming, etc.) by 2050. • Transition 5% to ATR in 2050.	Same as CNZ	Same as CNZ	Same as CNZ

Scope	Production Route Market Share by 2050	Energy Efficiency	Electrification	LCFFES	CCUS
		• 0.3-0.8% per annum autonomous improvement.			
CNZ–Hydrogen	Same as CNZ	Same as CNZ	Same as CNZ	• Transition 15% to bio-methanol in 2050. • 10% RNG blended with NG by 2050. • 20% by volume H_2 blended with NG by 2050.	Same as CNZ
CNZ–Low CCUS	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ	Capture 10% of all direct CO_2 emissions by 2050.
CNZ–Aggressive	• Steam-methane reforming - SMR (30%) • Autothermal reforming - ATR (5%) • Water electrolysis (35%) • Biomass gasification (30%)	• All conventional SMR adopt BAT (improved heat integration, pre-reforming, etc.) by 2050. • Transition 5% to ATR in 2050. • 0.3-0.8% per annum autonomous improvement.	• 100% clean electric grid by 2035. • Transition 35% to water electrolysis (e-methanol) in 2050.	• Transition 30% to bio-methanol in 2050. • 10% RNG blended with NG by 2050. • 20% by volume H_2 blended with NG by 2050.	Same as CNZ

Ammonia

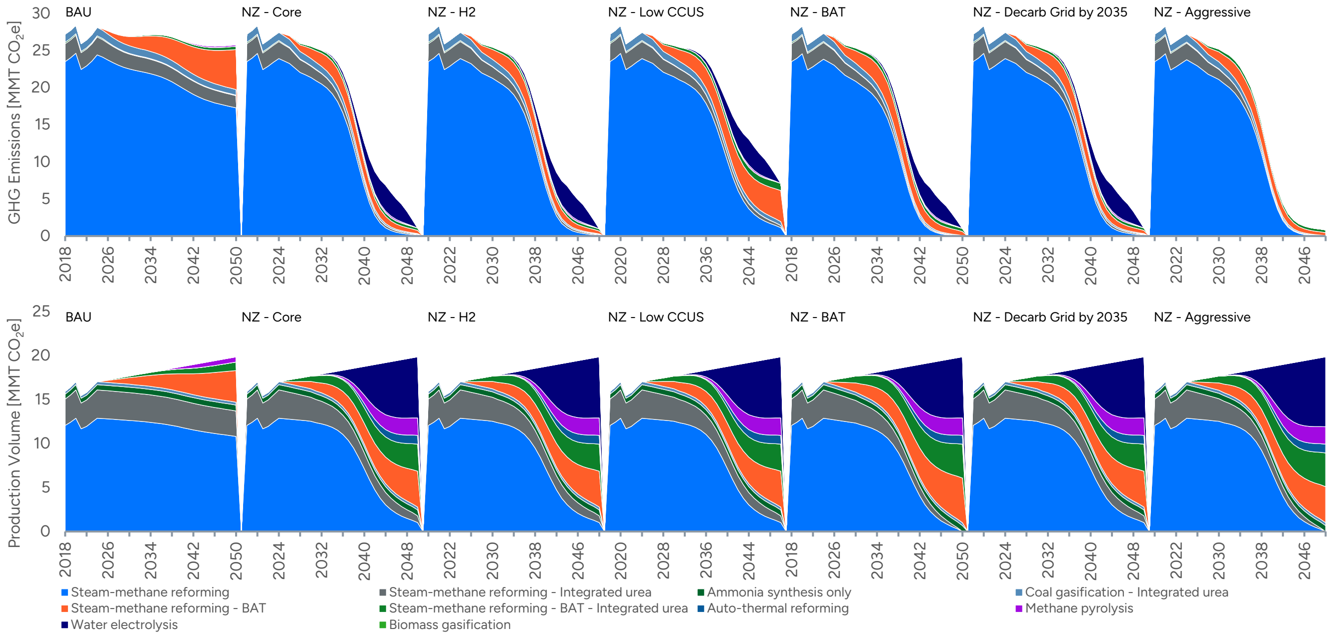


Figure C-9. U.S. ammonia production: (Top) Annual GHG emissions reductions–Core Near Zero pathway and sensitivities (MMT CO_2e/year), 2018–2050; (Bottom) Production route market share–Core Near Zero pathway and sensitivities (MMT/year), 2018–2050

Source: Transformative Pathways modeling.

Table C-13. Ammonia–Assumptions for Core Near Zero Pathway and Sensitivities

Scope	Production Route Market Share by 2050	Energy Efficiency	Electrification	LCFFES	CCUS
Core Near Zero (CNZ) Pathway	• Coal gasification - Integrated urea (2%) • Ammonia synthesis only (3%) • Steam-methane reforming - SMR (45%) • Autothermal reforming - ATR (5%) • Methane pyrolysis (10%) • Water electrolysis (35%) • Biomass gasification (inconclusive)	• Up to 80% of conventional SMR-HB adopt BAT (improved heat integration, pre-reforming, etc.) by 2050. • Transition 5% to ATR in 2050. • 0.1-0.3% p.a. autonomous improvement.	• 100% clean electric grid by 2050. • Transition 10% to methane pyrolysis and 35% to water electrolysis in 2050.	• Switch entirely to NG where clean energy alternatives are not applicable. • 10% RNG blended with NG by 2050.	Capture 90% of all direct CO2 emissions by 2050.
CNZ–Increased Recycling	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ
CNZ–BAT	Same as CNZ	• All conventional SMR-HB adopt BAT (improved heat integration, pre-	Same as CNZ	Same as CNZ	Same as CNZ

Scope	Production Route Market Share by 2050	Energy Efficiency	Electrification	LCFFES	CCUS
		reforming, etc.) by 2050. • Transition 5% to ATR in 2050. • 0.3-0.8% p.a. autonomous improvement.			
CNZ–Hydrogen	Same as CNZ	Same as CNZ	Same as CNZ	• Switch entirely to NG where clean energy alternatives are not applicable. • 10% RNG blended with NG by 2050. • 20% by volume H_2 blended with NG by 2050.	Same as CNZ
CNZ–Low CCUS	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ	Capture 40% of all direct CO2 emissions by 2050.
CNZ–Aggressive	• Coal gasification - Integrated urea (2%) • Ammonia synthesis only (3%) • Steam-methane reforming - SMR (40%) • Autothermal reforming - ATR (5%) • Methane pyrolysis (10%) • Water electrolysis (40%) • Biomass gasification (inconclusive)	• All conventional SMR-HB adopt BAT (improved heat integration, pre-reforming, etc.) by 2050. • Transition 5% to ATR in 2050. • 0.3-0.8% p.a. autonomous improvement.	• 100% clean electric grid by 2035. • Transition 10% to methane pyrolysis and 40% to water electrolysis in 2050.	• Switch entirely to NG where clean energy alternatives are not applicable. • 10% RNG blended with NG by 2050. • 20% by volume H_2 blended with NG by 2050.	Same as CNZ

Ethanol

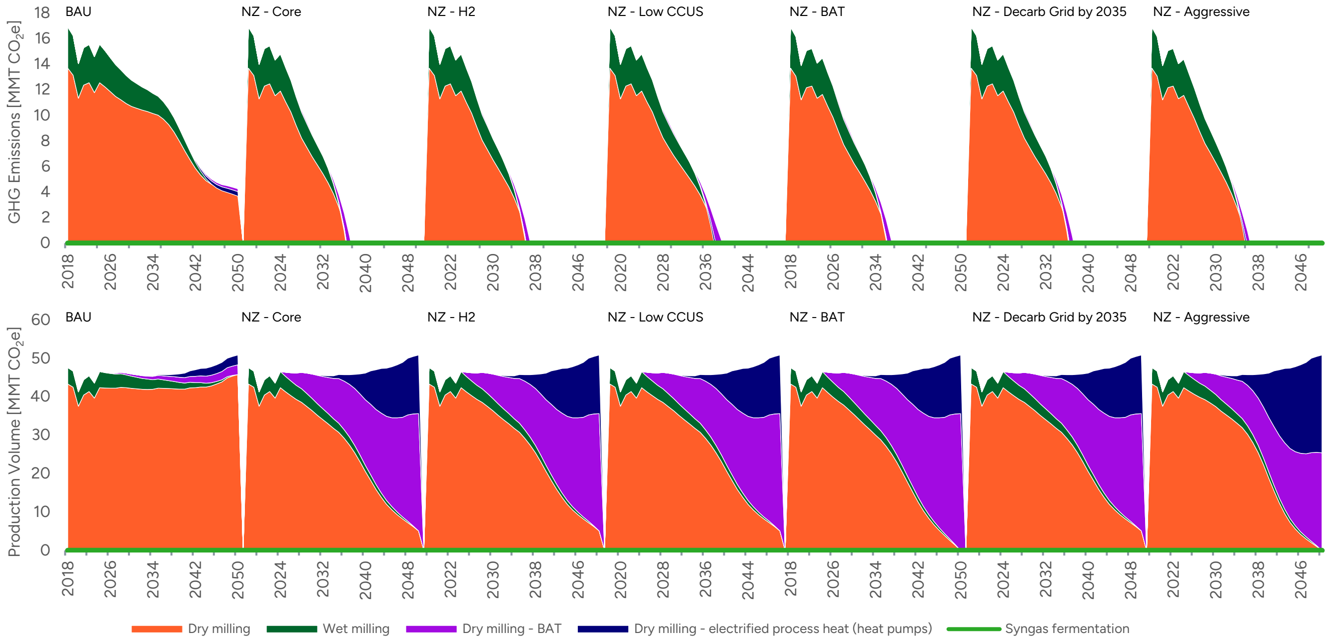


Figure C-10. U.S. ethanol production: (Top) Annual GHG emissions reductions—Core Near Zero pathway and sensitivities (MMT CO_2e/year), 2018–2050; (Bottom) Production route market share—Core Near Zero pathway and sensitivities (MMT/year), 2018–2050

Note: This figure does not account for the significant scope 3 emissions associated with ethanol production, such as those from corn farming, fertilizer and chemical application, land use change, transportation, and downstream combustion in vehicles. Including scope 3 emissions from ethanol production would prevent achieving net zero emissions, as shown in Table C-14 below. Therefore, the results in this figure should not be misinterpreted. See Section 4.2.3.9 for details. Source: Transformative Pathways modeling.

Table C-14. Ethanol–Assumptions for Core Near Zero Pathway and Sensitivities

Scope	Production Route Market Share by 2050	Energy Efficiency	Electrification	LCFFES	CCUS
Core Near Zero (CNZ) Pathway	• Dry milling (100%) • Wet milling (0%) • Syngas fermentation (inconclusive)	• Transition 60% to BAT (membrane separation, new enzymes, etc.) by 2050. • Phase out wet milling at a constant rate (0% by 2050). • 0.1-0.3% per annum autonomous improvement.	• 100% clean electric grid by 2050. • Assume 30% of mills implement HTHPs.	• Phase out coal. • 30% biogas/RNG by 2050. • 5% biomass (corn stover) by 2050.	• All fermentation emissions captured by 2050. • No capture of fuel emissions.
CNZ–Increased Recycling	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ
CNZ–BAT	Same as CNZ	• Transition 70% to BAT (membrane separation, new enzymes, etc.) by 2050.	Same as CNZ	Same as CNZ	Same as CNZ

Scope	Production Route Market Share by 2050	Energy Efficiency	Electrification	LCFFES	CCUS
		• Phase out wet milling at a constant rate (0% by 2050). • 0.3-0.5% per annum autonomous improvement.			
CNZ–Hydrogen	Same as CNZ	Same as CNZ	Same as CNZ	• Phase out coal. • 30% biogas/RNG by 2050. • 5% biomass (corn stover) by 2050. • 20% by volume H_2 blended with NG by 2050.	Same as CNZ
CNZ–Low CCUS	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ	60% of fermentation emissions captured by 2050. No capture of fuel emissions.
CNZ–Aggressive	• Dry milling (100%) • Wet milling (0%) • Syngas fermentation (inconclusive)	• Transition 70% to BAT (membrane separation, new enzymes, etc.) by 2050. • Phase out wet milling at a constant rate (0% by 2050). • 0.0.3-0.5% per annum autonomous improvement.	• 100% clean electric grid by 2035. • Assume 30% of mills implement HTHPs.	• Phase out coal. • 30% biogas/RNG by 2050. • 5% biomass (corn stover) by 2050. • 20% by volume H_2 blended with NG by 2050.	Same as CNZ

Remaining Chemicals

Table C-15. Remaining Chemicals–Assumptions for Core Near Zero Pathway and Sensitivities

Scope	Production Route Market Share by 2050	Energy Efficiency	Electrification	LCFFES	CCUS
Core Near Zero (CNZ) Pathway	Current production routes (100%)	0.5 % p.a. autonomous improvement.	• 100% clean electric grid by 2050. • 20% electrification of steam and hot water generation.	10% RNG blended with NG by 2050.	Capture 30% of all direct CO2 emissions by 2050
CNZ–Increased Recycling	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ
CNZ–BAT	Same as CNZ	0.8% p.a. autonomous improvement.	Same as CNZ	Same as CNZ	Same as CNZ
CNZ–Hydrogen	Same as CNZ	Same as CNZ	Same as CNZ	• 10% RNG blended with NG by 2050. • 20% by volume H_2 blended with NG by 2050.	Same as CNZ
CNZ–Low CCUS	Same as CNZ	Same as CNZ	Same as CNZ	Same as CNZ	Capture 5% of all direct CO2 emissions by 2050.
CNZ–Aggressive	Current production routes (100%)	0.8% p.a. autonomous improvement.	• 100% clean electric grid by 2035. • 20% electrification of steam and hot water generation.	• 10% RNG blended with NG by 2050. • 20% by volume H_2 blended with NG by 2050.	Same as CNZ

Aggregated Near Zero Pathways for Chemicals Manufacturing

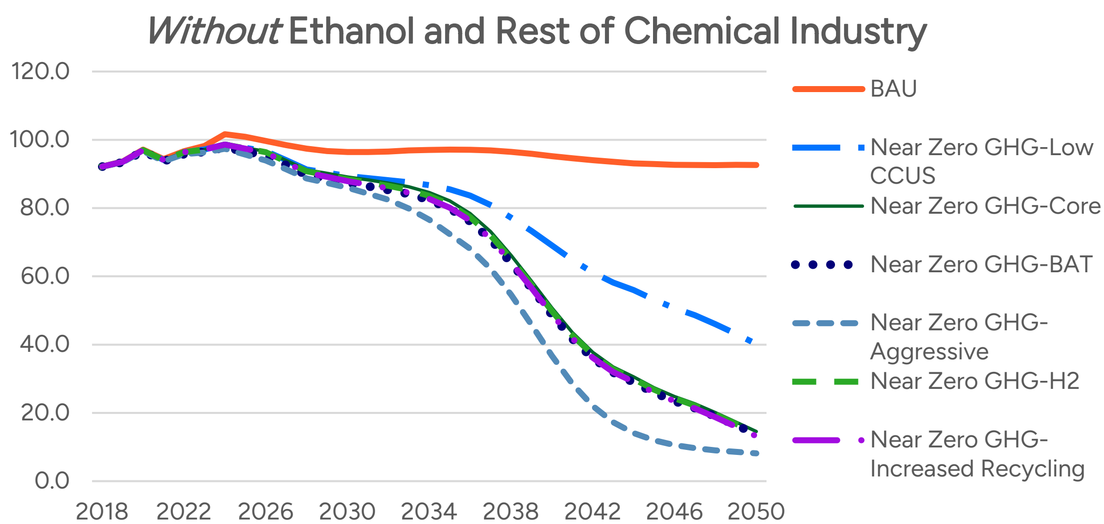
Figure C-11 summarizes the results for sensitivity analyses on the CNZ pathway compared to the BAU. The analysis, which focuses on only a small subset of material recycling, suggests that increased recycling rates could result in an additional cumulative CO_2e abatement of 38 MMT in the CNZ–Increased Recycling sensitivity, compared to the CNZ pathway. To enhance demand reduction in the chemicals subsector through material recycling, advanced recycling methods must be developed and demonstrated at scale for challenging polymers like polystyrene, polyvinyl chloride (PVC), and polyurethane.

Additionally, Figure C-11 illustrates the CNZ–BAT sensitivity, which has the potential to reduce an additional cumulative 196 MMT CO_2e emissions beyond the CNZ pathway. It is important to note that this sensitivity's goal is ambitious due to the significant techno-economic constraints associated with retrofitting existing facilities. These challenges are briefly discussed in Section 4.2.5.

In the CNZ–Hydrogen sensitivity, which assumes a 20% hydrogen blend with natural gas delivered through existing infrastructure, the subsector could achieve an additional cumulative CO_2e emissions reduction of approximately 95 MMT compared to the CNZ pathway.

Finally, in the CNZ–Low CCUS sensitivity, only about 55% of emissions could be reduced by 2050, compared to 75% in the CNZ pathway, relative to the projected annual emissions of 380 MMT CO_2e in the BAU scenario. Although this sensitivity still offers significant emissions reduction potential, it underscores the critical role of CCUS in achieving near zero emissions in the U.S. chemicals subsector.

Overall, the analysis of various decarbonization measures, including the ambitious alternative pathways, indicates that GHG emissions in the CNZ–Aggressive sensitivity could be reduced to 68 MMT CO_2e per annum, representing an approximate 82% reduction compared to the projected annual emissions of 380 MMT CO_2e in the BAU scenario.



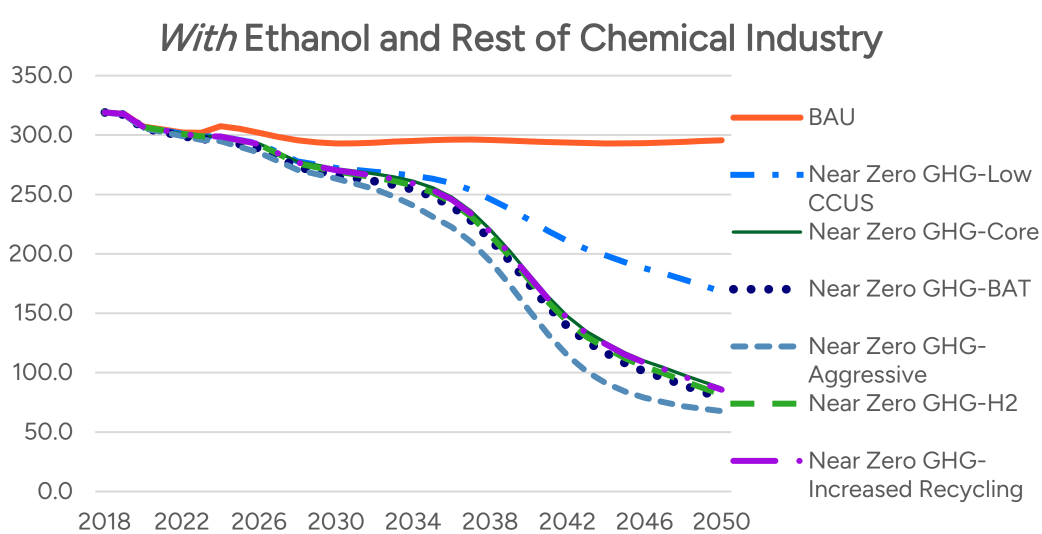


Figure C-11. Annual GHG emissions reductions, U.S. chemicals–Core Near Zero pathway and sensitivities (MMT CO_2e/year), 2018–2050: Without ethanol and remaining chemicals (left) and with ethanol and remaining chemicals (right)

Results are shown both with (right) and without (left) ethanol and the remaining chemicals. Source: Transformative Pathways modeling.

Food and Beverage

Additional details on calculations and assumptions used across the modeling effort and near zero pathways presented in Section 4.3 (as well as additional near zero pathways) are provided below.

Subsector Details

Grain and Oilseed Milling (NAICS 3112)

In 2018, the grain and oilseed milling subsector (NAICS 3112) consumed 246 TBtu of onsite energy and accounted for 10 MMT CO_2e of onsite emissions and 17 MMT CO_2e total emissions.[605,606] Most energy (61%) was provided by natural gas, followed by electricity (20%), coal (8%), purchased steam (7%), other fuel (wood chips/bark, waste gas, and miscellaneous fuels) (4%), and distillate fuel oil and diesel fuel (<1%). Figure C-12 provides a detailed breakdown of energy consumption by end use and energy type for the baseline year of 2018. Table C-16 shows the key thermal processes for the subsector, temperature ranges, heating mediums, and their assumed proportion of CHP/boiler and process heating use.

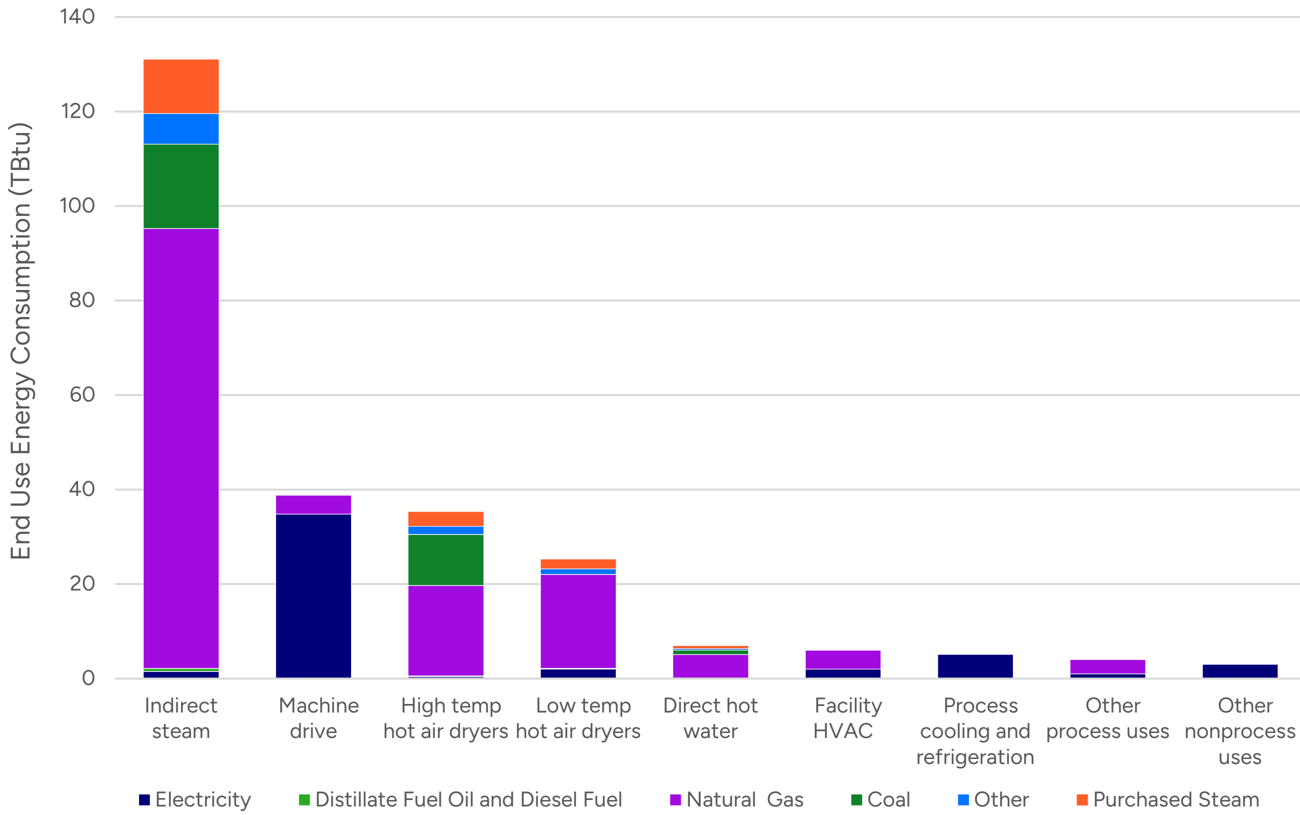


Figure C-12. U.S. grain and oilseed milling (NAICS 3112) energy consumption by end use and energy type, 2018

Data sources: U.S. Energy Information Administration, "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data," 2021, www.eia.gov/consumption/manufacturing/data/2018/; and sources provided in Table C-16.

[605] U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Food and Beverage," (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_food_beverage_energy_carbon_footprint.pdf.
[606] U.S. Energy Information Administration, "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data," 2021, www.eia.gov/consumption/manufacturing/data/2018/.

Table C-16. Grain and Oilseed Milling Baseline (2018) Thermal Unit Processes, Heating Mediums, and Temperature Ranges

Thermal Unit Processes	Typical Temperature Range (°F)	Temperature Range Reference(s)	Heating Medium	Subsector Share of Fuel for Boiler and CHP*	Subsector Share of Fuel for Process Heat*
Drying	130–250	[1]-[13]	Low temp hot air dryers	-	51%
Drying	400–625		High temp hot air dryers	-	49%
Evaporation	158–262		Indirect steam	62%	-
Extraction	113–149		Indirect steam	7%	-
Steeping	125		Direct hot water	5%	-
Dewatering	140		Indirect steam	6%	-
Cooking	149–365		Indirect steam	19%	-

* Reference for subsector shares: [6]

References:

[1] Charles R. Hurburgh Jr., M.K. Misra, and W.F. Wilcke. "Soybean Drying and Storage." Iowa State University Extension. 2008. www.extension.iastate.edu/grain/files/Migrated/soybeandryingandstorage.pdf.

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Sugar Manufacturing (NAICS 31131)

In 2018, the sugar manufacturing subsector (NAICS 31131) consumed 106 TBtu of onsite energy and accounted for 5 MMT CO_2e total emissions.[607,608] The largest portion of energy (36%) was provided by agricultural waste (bagasse), followed by natural gas (31%), coal (27%), electricity (4%), and purchased steam (2%). Figure C-13 provides a detailed breakdown of energy consumption by end use and energy type for the baseline year of 2018.

[607] U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Food and Beverage," (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_food_beverage_energy_carbon_footprint.pdf.
[608] U.S. Energy Information Administration, "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data," 2021, www.eia.gov/consumption/manufacturing/data/2018/.

Energy consumption in sugar manufacturing is concentrated across four end uses: low temperature indirect steam and convective hot air dryers, high temperature indirect steam, and machine drive.

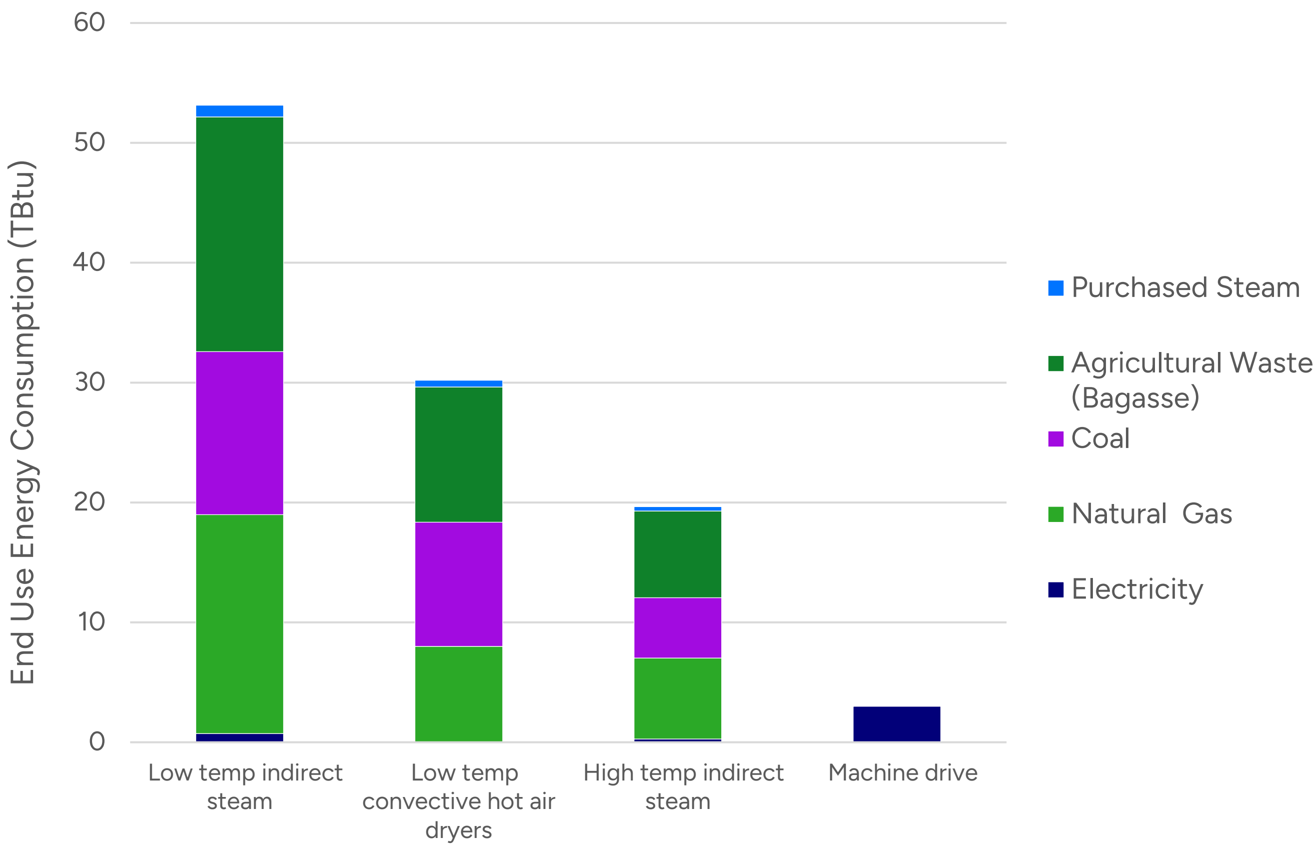

Figure C-13. U.S. sugar manufacturing (NAICS 31131) energy consumption by end use and energy type, 2018

Data sources: U.S. Energy Information Administration, "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data," 2021, www.eia.gov/consumption/manufacturing/data/2018/; and sources provided in Table C-17.

Table C-17. Sugar Manufacturing Baseline (2018) Thermal Unit Processes, Heating Mediums, and Temperature Ranges

Thermal Unit Processes	Typical Temperature Range (°F)	Temperature Range Reference(s)	Heating Medium	Subsector Share of Fuel for Boiler and CHP*	Subsector Share of Fuel for Process Heat*
Raw Juice Heating	158	[1]	Indirect steam	26%	-
Juice Evaporation	131–248	[2], [3]	Indirect steam	22%	-
Sugar Boiling (Vacuum Pans)	149–185	[4]	Indirect steam	14%	-
Drying	176–194	[5]	Hot air dryers	-	100%
Fermented Liquor Heating (ethanol production)	194	[6]	Indirect steam	11%	-

Thermal Unit Processes	Typical Temperature Range (°F)	Temperature Range Reference(s)	Heating Medium	Subsector Share of Fuel for Boiler and CHP*	Subsector Share of Fuel for Process Heat*
Distillation (Ethanol)	131–248	[3]	Indirect steam	27%	-

* Reference for subsector shares: [6]

References:

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[6] Adriano V. Ensinas et al. "Analysis of Process Steam Demand Reduction and Electricity Generation in Sugar and Ethanol Production from Sugarcane." Energy Conversion and Management 48, 11 (November 2007): 2978-87. doi.org/10.1016/j.enconman.2007.06.038.

Fruit and Vegetable Preserving and Specialty Food Manufacturing (NAICS 3114)

In 2018, the fruit and vegetable preserving and specialty food manufacturing subsector (NAICS 3114) consumed 129 TBtu of onsite energy and accounted for 5 MMT CO_2e of onsite emissions and 10 MMT CO_2e total emissions.[609,610] A majority of energy (71%) was provided by natural gas, followed by electricity (26%), hydrocarbon gas liquids (HGLs) (<1%), waste gas (<1%), miscellaneous fuel (<1%), and purchased steam (<1%). Figure C-14 provides a detailed breakdown of energy consumption by end use and energy type for the baseline year of 2018. Low temperature steam is by far the greatest energy (natural gas) demand for this subsector. The highest electricity demand end uses are process cooling and refrigeration and machine drive.

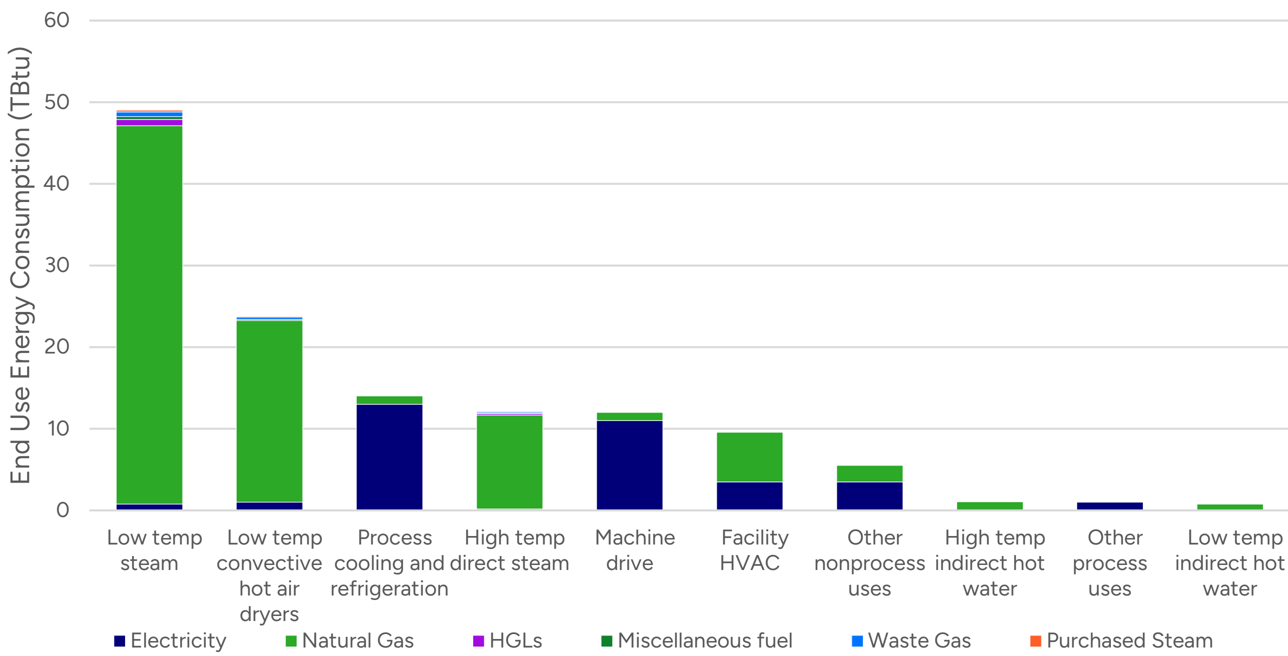

Figure C-14. U.S. fruit and vegetable preserving and specialty food manufacturing (NAICS 3114) energy consumption by end use and energy type, 2018

Data sources: U.S. Energy Information Administration, "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data," 2021, www.eia.gov/consumption/manufacturing/data/2018/; and sources provided in Table C-18.

[609] U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Food and Beverage," (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_food_beverage_energy_carbon_footprint.pdf.
[610] U.S. Energy Information Administration, "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data," 2021, www.eia.gov/consumption/manufacturing/data/2018/.

Table C-18. Fruit and Vegetable Preserving and Specialty Food Manufacturing Baseline (2018) Thermal Unit Processes, Heating Mediums, and Temperature Ranges

Thermal Unit Processes	Typical Temperature Range (°F)	Temperature Range Reference(s)	Heating Medium	Subsector Share of Fuel for Boiler and CHP*	Subsector Share of Fuel for Process Heat*
Pasteurization	212	[1]	Indirect hot water	2%	-
Sterilization	212–250	[2], [3]	Direct steam	19%	-
Blanching, cooking	158–212	[2]	Direct steam/ hot water	60%	-
Brine heating	149–158	[4]	Indirect hot water	1%	-
Evaporation	118–180	[5]	Indirect steam	12%	-
Drying/dehydration (Fruits)	77–158	[6]	Hot air dryers	-	100%
Exhausting (canning)	158–212	[5]	Direct steam	6%	-

* Reference for subsector shares: [1]

References:

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[3] U.S. Environmental Protection Agency. "9.8.1 Canned Fruits and Vegetables." Washington D.C., U.S.: U.S. Environmental Protection Agency (1995). www3.epa.gov/ttnchie1/ap42/ch09/final/c9s08-1.pdf.

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[5] Muhammad Siddiq and Mark A. Uebersax, eds. Handbook of Vegetables and Vegetable Processing. 1st ed. John Wiley & Sons Ltd. 2018. doi.org/10.1002/9781119098935.

[6] Sadat Kamal Amit et al. "A Review on Mechanisms and Commercial Aspects of Food Preservation and Processing." Agriculture & Food Security 6, 1 (December 2017): 51. doi.org/10.1186/s40066-017-0130-8.

Dairy Product Manufacturing (NAICS 3115)

In 2018, the dairy products manufacturing subsector (NAICS 3115) consumed 122 TBtu of onsite energy and accounted for 5 MMT CO_2e of onsite emissions and 10 MMT CO_2e total emissions.[611,612] Most of the energy (65%) was provided by natural gas, followed by electricity (32%), HGLs (2%), distillate fuel oil and diesel fuel (<1%), and purchased steam (<1%). Figure C-15 provides a detailed breakdown of energy consumption by end use and energy type for the baseline year of 2018.

[611] U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Food and Beverage," (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_food_beverage_energy_carbon_footprint.pdf.
[612] U.S. Energy Information Administration, "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data," 2021, www.eia.gov/consumption/manufacturing/data/2018/.

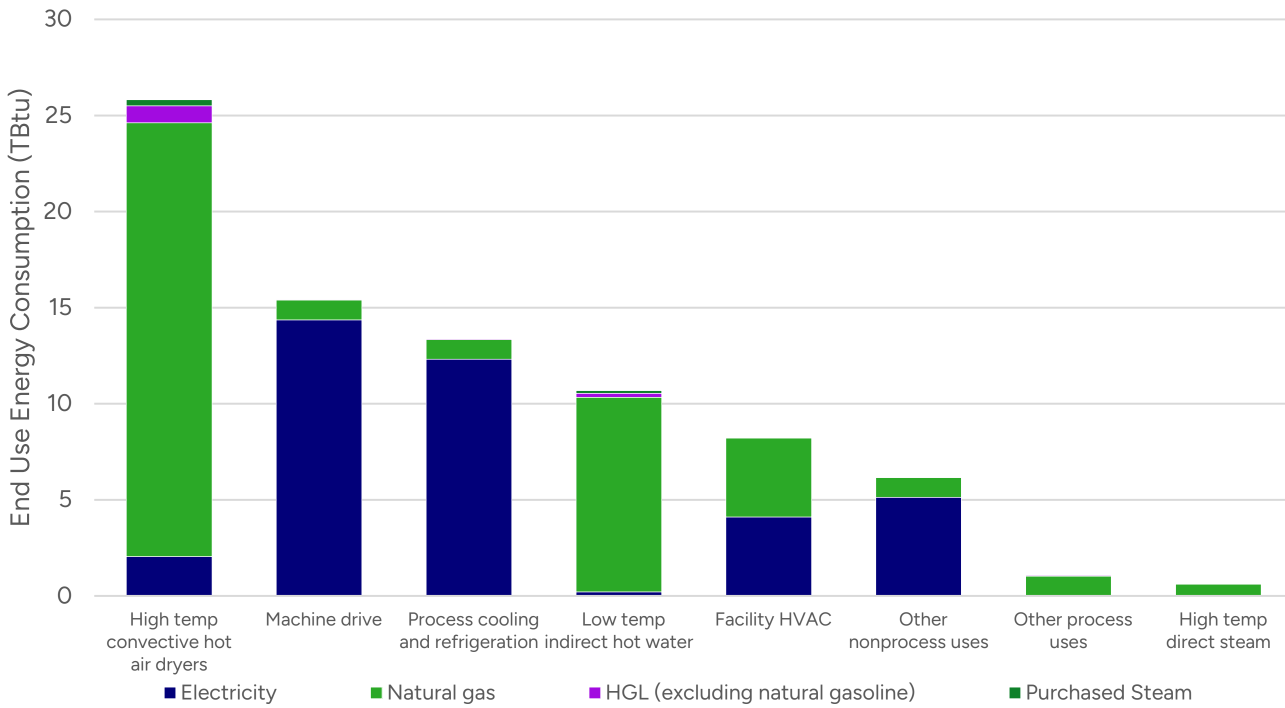

Figure C-15. U.S. dairy products manufacturing (NAICS 3115) energy consumption by end use and energy type, 2018

Data sources: U.S. Energy Information Administration, "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data," 2021, www.eia.gov/consumption/manufacturing/data/2018/; and sources provided in Table C-19.

Table C-19. Dairy Product Manufacturing Baseline (2018) Thermal Unit Processes, Heating Mediums, and Temperature Ranges

Thermal Unit Processes	Typical Temperature Range (°F)	Temperature Range Reference(s)	Heating Medium	Subsector Share of Fuel for Boiler and CHP*	Subsector Share of Fuel for Process Heat*
Pasteurization	145–162	[1]	Indirect hot water	16%	-
Sterilization	230–275	[2]	Direct steam	1%	-
Preheating (milk powder production)	167–248	[3]	Indirect steam	1%	-
Evaporation	162	[2]	Indirect steam	77%	-
Spray drying	482	[2]	Hot air dryers	-	100%
Make vats (cheese)	86–104	[2]	Indirect hot water	4%	-
Cooking or fermentation (fluid milk)	68–104	[2]	Indirect hot water	1%	-

* Reference for subsector shares: [4]

References:

[1] Safefood 360°. "Thermal Processing of Food - Whitepaper." Safefood 360°. 2014. www.tiselab.com/pdf/Thermal-Processing-of-Food.pdf.

[2] Germán Giner Santonja et al. "Best Available Techniques (BAT) Reference Document for the Food, Drink and Milk Industries: Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control)." Brussels, Belgium: Joint Research Center, European Commission. 2019. data.europa.eu/doi/10.2760/243911.

[3] Rotronic. "Milk Powder Production." Rotronic Humidity Fun Facts. Accessed October 5, 2023. www.rotronic.com/media/news/files/1466670855_FF-Milk-Powder.pdf.

[4] Adrian Brush, Eric Masanet, and Ernst Worrell. 2011. Energy Efficiency Improvement and Cost Saving Opportunities for the Dairy Processing Industry: An ENERGY STAR Guide for Energy and Plant Managers. LBNL-6261E. (Lawrence Berkeley National Laboratory, 2011). www.osti.gov/biblio/1171534.

Animal Slaughtering and Processing (NAICS 3116)

In 2018, the animal slaughtering subsector (NAICS 3116) consumed 278 TBtu of onsite energy and accounted for 9 MMT CO_2e of onsite emissions and 24 MMT CO_2e total emissions.[613,614] A majority of energy (54%) was provided by natural gas, followed by electricity (39%), purchased steam (4%), other fuel (waste gas, wood chips/bark, and miscellaneous fuels) (1%), distillate fuel oil and diesel fuel (1%), and HGLs (1%). Figure C-16 provides a detailed breakdown of energy consumption by end use and energy type for the baseline year of 2018. The highest energy consuming processes (and largest consumers of natural gas) are use of low temperature direct and indirect hot water. The highest consumers of electricity include process cooling and refrigeration and machine drive.

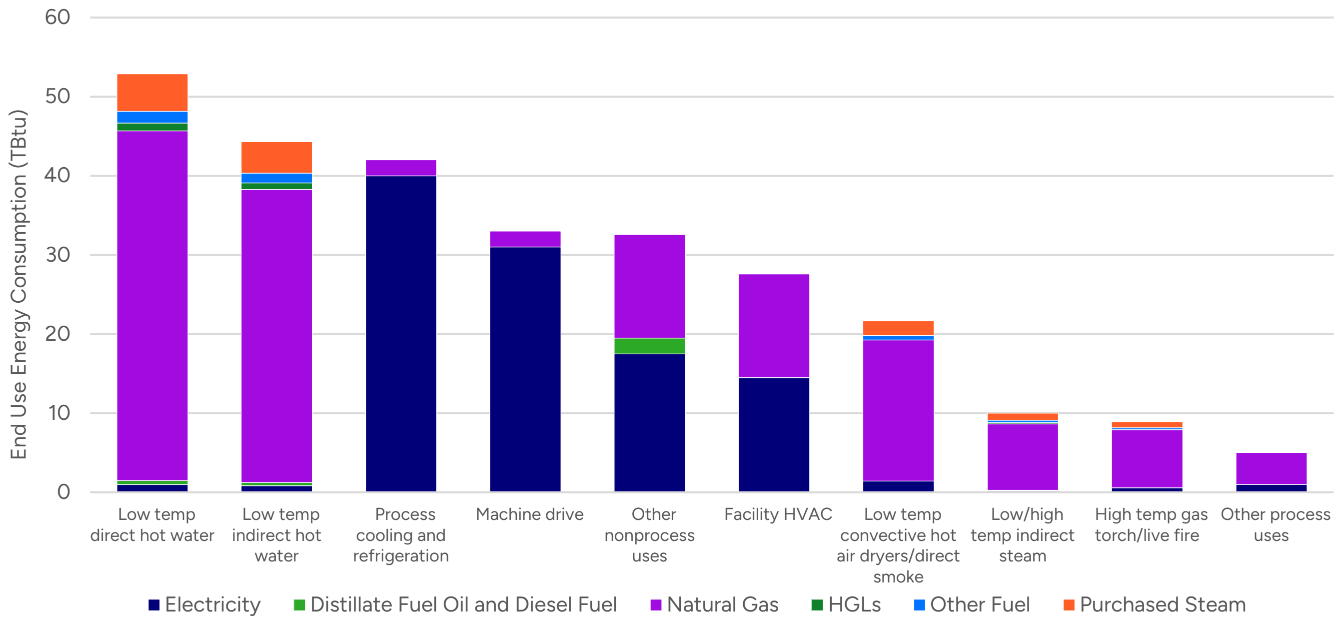

Figure C-16. U.S. animal slaughtering and processing (NAICS 3116) energy consumption by end use and energy type, 2018

Data sources: U.S. Energy Information Administration, "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data," 2021, www.eia.gov/consumption/manufacturing/data/2018/; and sources provided in Table C-16.

Table C-20. Animal Slaughtering and Processing Baseline (2018) Thermal Unit Processes, Heating Mediums, and Temperature Ranges

Thermal Unit Processes	Typical Temperature Range (°F)	Temperature Range Reference(s)	Heating Medium	Subsector Share of Fuel for Boiler and CHP*	Subsector Share of Fuel for Process Heat*
Curing, smoking, cooking	Cold smoking: 86–131 Hot smoking: 149–248	[1]	Direct smoke	-	33%
Blood processing–heating & drying	Heating: 158–194 Drying: 212–248	[2], [3]	Indirect steam	3%	-
Cleaning	140–180	[3]	Direct hot water	33%	-

[613] U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Food and Beverage," (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_food_beverage_energy_carbon_footprint.pdf.
[614] U.S. Energy Information Administration, "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data," 2021, www.eia.gov/consumption/manufacturing/data/2018/.

Thermal Unit Processes	Typical Temperature Range (°F)	Temperature Range Reference(s)	Heating Medium	Subsector Share of Fuel for Boiler and CHP*	Subsector Share of Fuel for Process Heat*
Drying	120–160	[3]	Hot air dryers	-	38%
Scalding	113–149	[4]	Direct hot water	16%	-
Other meat processing (pasteurization, sterilization, grilling)	176–185	[5]	Indirect hot water	41%	-
Edible rendering (Melting)	240–250	[2]	Indirect steam	7%	-
Singeing (exposed only for a few seconds)	Poultry: 230–248 Hogs: 750–1,110 Cattle: 1,110–1,470	[6]	Gas torch/ Live fire	-	29%

* Reference for subsector shares: [3], [7]

References:

[1] Germán Giner Santonja et al. "Best Available Techniques (BAT) Reference Document for the Food, Drink and Milk Industries: Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control)." Brussels, Belgium: Joint Research Center, European Commission. 2019. data.europa.eu/doi/10.2760/243911.

[2] John A. Clottey. Manual for the Slaughter of Small Ruminants in Developing Countries. FAO Animal Production and Health Paper 49. Rome: Food and Agriculture Organization of the United Nations. 1985. www.fao.org/3/X6552E/X6552E00.htm.

[3] C. A. Ramírez, M. Patel, and K. Blok. "How Much Energy to Process One Pound of Meat? A Comparison of Energy Use and Specific Energy Consumption in the Meat Industry of Four European Countries." Energy 31, 12 (September 2006): 2047-63. doi.org/10.1016/j.energy.2005.08.007.

[4] L. A. H. M. Verheijen. Management of Waste from Animal Product Processing. Livestock and the Environment: Finding a Balance. International Agriculture Centre. 1996. www.fao.org/4/x6114e/x6114e00.htm.

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[6] H. Maribo et al. "Comparison of Dehiding versus Scalding and Singeing: Effect on Temperature, pH and Meat Quality in Pigs." Meat Science 50, 2 (October 1998): 175-89. doi.org/10.1016/S0309-1740(98)00029-1.

[7] Joe Cresko et al. Thermal Process Intensification: Transforming the Way Industry Uses Thermal Process Energy. DOE/EE-2604. (U.S. Department of Energy, 2022). www.osti.gov/biblio/1871912.

Beverage Manufacturing (NAICS 3121)

In 2018, the beverage manufacturing subsector (NAICS 3121) consumed 111 TBtu of energy and with onsite emissions of 3 MMT CO_2e and total emissions of 9 MMT CO_2e.[615,616] A majority of energy (45%) was provided by natural gas, followed by electricity (41%), biomass (wood chips/bark) (11%), HGLs (1%), purchased steam (1%), and waste gas (1%). Figure C-17 provides a detailed breakdown of energy consumption by end use and energy type for the baseline year of 2018. The highest energy consumers are machine drive (top electricity use) and low temperature indirect hot water (top natural gas use).

615 U.S. Department of Energy, "Manufacturing Energy and Carbon Footprint: Food and Beverage," (2021), www.energy.gov/sites/default/files/2021-12/2018_mecs_food_beverage_energy_carbon_footprint.pdf.
616 U.S. Energy Information Administration, "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data," 2021, www.eia.gov/consumption/manufacturing/data/2018/.

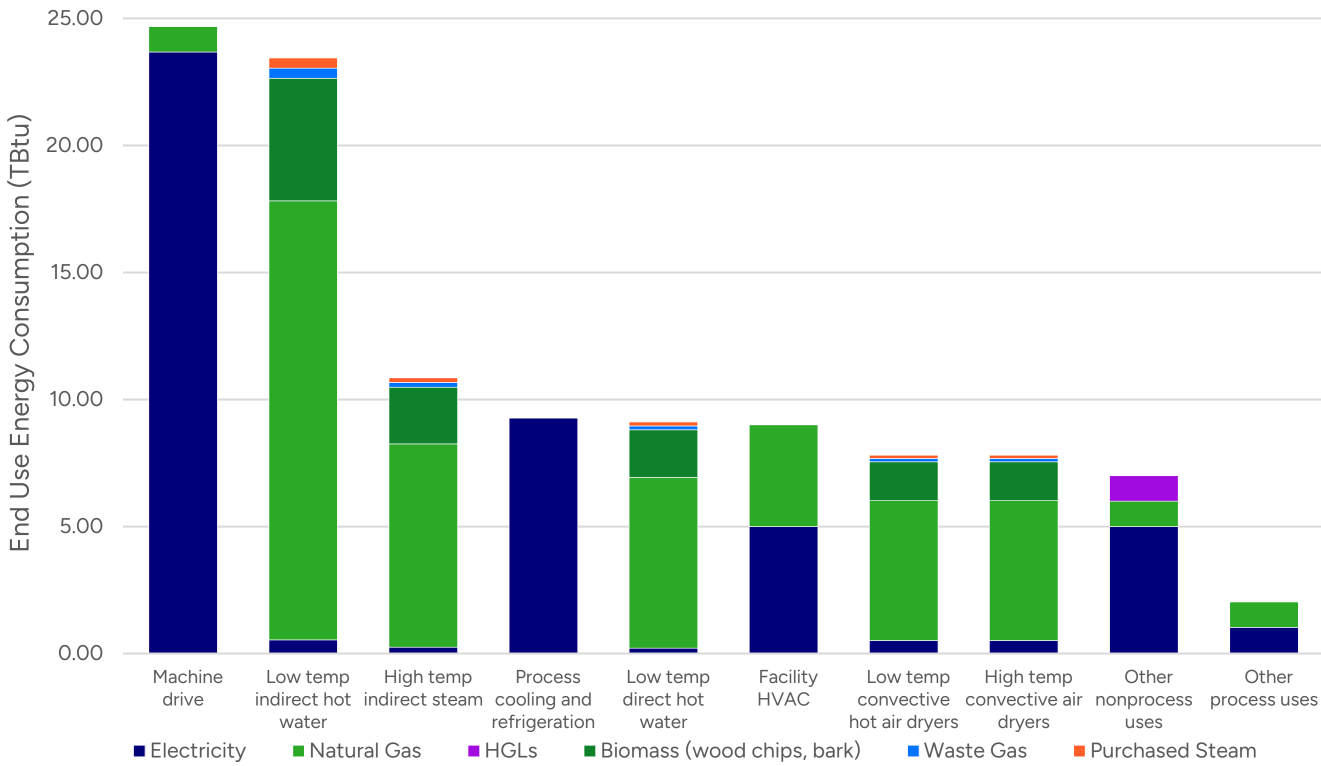

Figure C-17. U.S. beverage manufacturing (NAICS 3121) energy consumption by end use and energy type, 2018

Data sources: U.S. Energy Information Administration, "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data," 2021, www.eia.gov/consumption/manufacturing/data/2018/; and sources provided in Table C-21.

Table C-21. Beverage Manufacturing Baseline (2018) Thermal Unit Processes, Heating Mediums, and Temperature Ranges

Thermal Unit Processes	Typical Temperature Range (°F)	Temperature Range Reference(s)	Heating Medium	Subsector Share of Fuel for Boiler and CHP*	Subsector Share of Fuel for Process Heat*
Fermentation	Beer: 40–70 Wine: 77–86	[1], [2]	Indirect hot water	24%	-
Drying (malt)	Drum drying: 300	[3]	Hot air dryer	-	50%
Drying (malt)	Air drying: 120–170	[3]	Hot air dryer	-	50%
Mashing (wort)	143–162	[4]	Direct hot water	14%	-
Boiling (wort)	200–220	[5]	Indirect steam	25%	-
Pasteurizing	131–140 beer; 160–210 Fruit Juice	[5]	Indirect hot water	30%	-
Cleaning	140–176	[6]	Direct hot water	7%	-

* Reference for subsector shares: [7], [8]

References:

[1] Murli Dharmadhikari. "Red Wine Production." Iowa State University Extension and Outreach. 2016. www.extension.iastate.edu/wine/wp-content/uploads/2021/09/Red-Wine-Production-PDF.pdf.

[2] John Stika. "Controlling Fermentation Temperature." Brew Your Own. 2009. byo.com/article/controlling-fermentation-temperature-techniques/.

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[5] Craft Beer and Brewing. "The Oxford Companion to Beer Definition of Boiling." Craft Beer & Brewing. Accessed October 2023. beerandbrewing.com/dictionary/RZV7tB05MV/.

[6] Richard F. Stier. "The Basics of Cleaning and Sanitation in Food Plants." Food Engineering. January 7, 2020. www.foodengineeringmag.com/articles/98657-the-basics-of-cleaning-and-sanitation-in-food-plants.

[7] R. M. Bär and T. Voigt. "Analysis and Prediction Methods for Energy Efficiency and Media Demand in the Beverage Industry." Food Engineering Reviews 11, 3 (September 2019): 200-217. doi.org/10.1007/s12393-019-09195-y.

[8] Soteris Kalogirou. "The Potential of Solar Industrial Process Heat Applications." Applied Energy 76, 4 (December 2003): 337-61. doi.org/10.1016/S0306-2619(02)00176-9.

Production

Production values for U.S. food and beverage manufacturing were projected on an annual basis for use in the model. Estimating the flow of food through the manufacturing stage is difficult.[617] The U.S. Department of Agriculture (USDA) tracks food flows from agricultural stage ("On-farm"), as well as in the later stages through the loss-adjusted food availability (LAFA) data,[618] but nothing specifically for entering the manufacturing stage–leaving the food lost right before the manufacturing stage (unsold food) and lost during the manufacturing stage unclear. Projections for the food flow around the manufacturing stage for 2018 and beyond were estimated using USDA data projections for the agricultural output (specifically the entries like "Food, seed, & industrial", "Food", "Total disappearance", "Milk Production", "Total Ag Production") from 2020 to 2032 and the ratios of incoming and outgoing food from Dong et al. 2022.[619]

For projections from 2032 to 2050, simple linear regression models based on projected populations were created for each specific commodity produced within the agricultural stage, which were then aggregated into commodity groups corresponding to the North American Industry Classification System (NAICS) codes. Then, manufactured food was calculated using the estimated agricultural output (food into manufacturing) and ratio of manufactured food (food into distribution) to the input into manufacturing, derived for 2018 using the methodology from Dong et al. 2022[620] and USDA data.[621]

$$\boldsymbol{Manufactured\ Food\ =\ Food\ out\ of\ Agriculture \cdot \left(\frac{Food\ into\ Distribution}{Food\ into\ Manufacturing}\right)}$$

The $\left(\frac{\boldsymbol{Food\ into\ Distribution}}{\boldsymbol{Food\ into\ Manufacturing}}\right)$ factors by product are provided in Table C-22. For two commodities (seafood and peanuts), historic data was used instead of projections to create regressions, as they were not included the original projection modeling.

[617] Dong et al., "A framework to quantify mass flow and assess food loss and waste in the US food supply chain," *Communications Earth & Environment* 3, 1 (April 2022), doi.org/10.1038/s43247-022-00414-9.
[618] U.S. Department of Agriculture, "Loss-Adjusted Food Availability Documentation," November 12, 2020, www.ers.usda.gov/data-products/food-availability-per-capita-data-system/loss-adjusted-food-availability-documentation/.
[619] Dong et al., "A framework to quantify mass flow and assess food loss and waste in the US food supply chain," *Communications Earth & Environment* 3, 1 (April 2022), doi.org/10.1038/s43247-022-00414-9.
[620] Ibid.
[621] U.S. Department of Agriculture Economic Research Service, "Food and Beverage Manufacturing," October 9, 2024, www.ers.usda.gov/topics/food-markets-prices/processing-marketing/food-and-beverage-manufacturing/.

Table C-22. Fraction of Food Manufactured (Sent to Distribution) Out of the Total Food Into Manufacturing (Out of Agriculture)

Product Category	Product	% of Manufacturing Input Sent to Distribution
Grain & Oils	Barley	60%
	Oats	60%
	Sorghum	60%
	Soybeans	81%
	Wheat	70%
	Rice	70%
	Corn	58%
Animal Products	Meat & Poultry	69%
	Dairy	43%
	Egg	94%
	Seafood	44%
Fruit	All Fruit (citrus & non-citrus)	82%
Vegetables	Fresh market	92%
	Processing	44%
	Potatoes & Other Vegetables	67%
Sugar	All Sugar (Cane and Beet)	14%
Other Products	Tree Nuts & Peanuts	100%

Calculated from Dong et al. 2022. "A framework to quantify mass flow and assess food loss and waste in the US food supply chain." Communications Earth & Environment, 3, 1 (April). www.osti.gov/biblio/1861231. and USDA. 2023. "Food Availability (Per Capita) Data System." www.ers.usda.gov/data-products/food-availability-per-capita-data-system/.

From 2020 to 2030, most commodity groups are expected to increase production by a few percent per year, though fruit products manufactured in the United States are anticipated to decline slightly, despite rising consumer demand, due to increased imported fruit. Figure C-18 shows the change in food and beverages manufactured by subsector for 2010–2050. By 2050, an estimated 348 MMT of food and beverages will be manufactured in the United States, up from 293 MMT in 2018 (about a 19% increase).

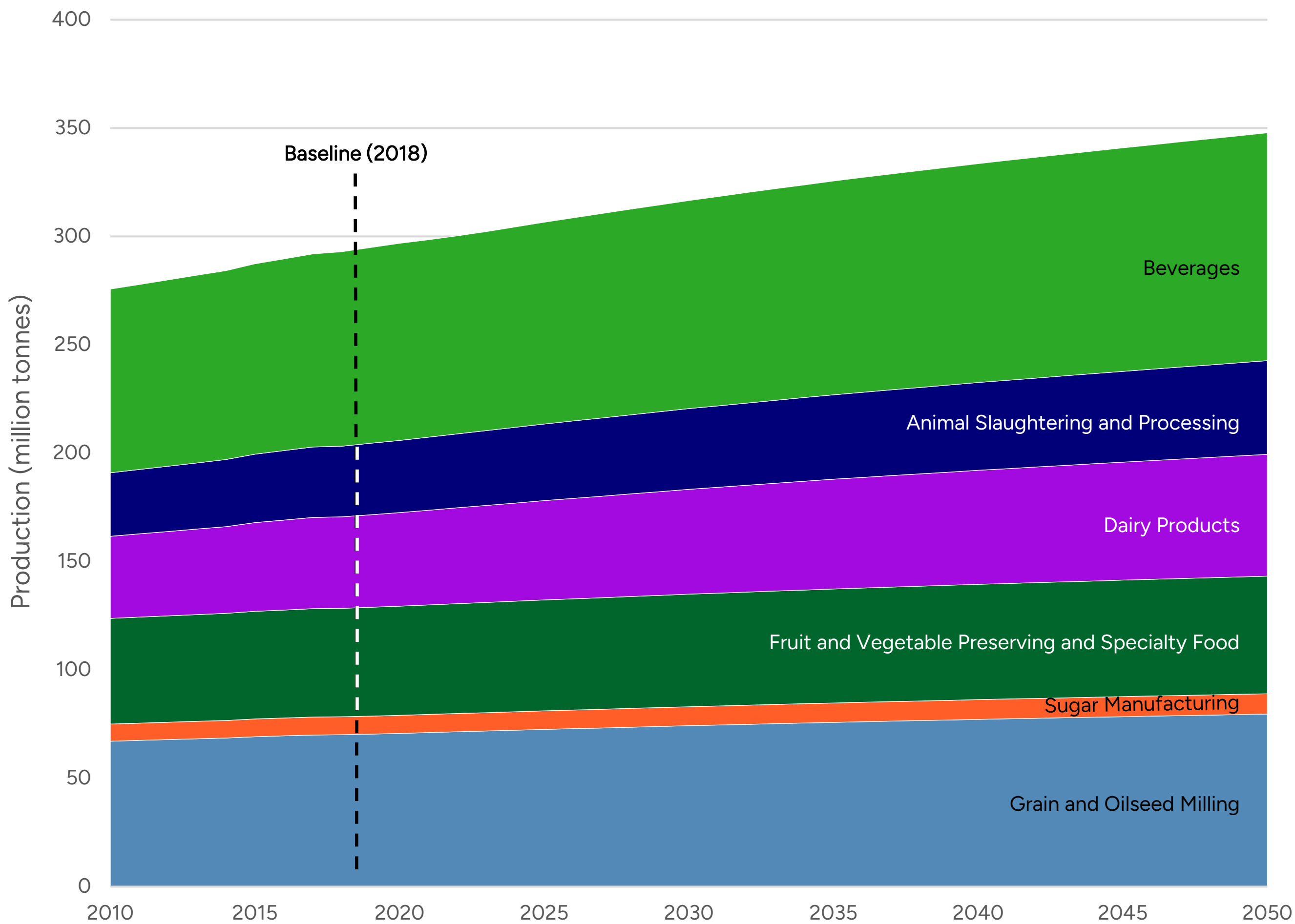

Figure C-18. Historical and estimated U.S. food and beverage manufacturing production, 2010–2050

BAU Assumptions

The BAU scenario leverages projections from the EIA's Annual Energy Outlook 2023 (AEO23).[622] It assumes an adoption rate of energy efficiency measures in line with AEO23's Technology Possibility Curve.[623] It also assumes a low rate of electrification, including slow heat pump adoption, again in line with AEO23's projections and no further increase in the use of LCFFES beyond MECS 2018 levels. No CCUS is assumed as implemented. AEO23 assumes 2022 as the baseline year and 2050 as the target year. To account for the MECS data that provides 2018 subsector energy consumption, the team employed insignificant technology adoption rates above BAU assumptions between 2018 and 2021. Within the BAU scenario, a comparison of electricity and fossil fuel consumption for the food and beverage subsector was conducted between the baseline year 2022 and the target year 2050. The subsector's total energy usage shifts from 28% electricity and 72% fuel in 2020 to 30% electricity and 70% fuel in 2050 respectively, with the 2% increase in the proportion of electricity usage attributed to electrification technologies, such as hot water and steam-generating heat pumps. The increase in electrification was applied against the share of fuels utilized to generate hot water, steam, and hot air in food and beverage manufacturing subsector; the fuels share is 25%, 50%, and 25% respectively. In short, for steam generating heat pumps, the fuel share of 50% was applied against the 2% increase in electricity usage, resulting in the final adoption rate of 1% for the said technology. For energy efficiency, average year-on-year improvements between 0.05% to 0.25% were assumed.

[622] U.S. Energy Information Administration, "Annual Energy Outlook 2023," 2023, www.eia.gov/outlooks/aeo/.
[623] Average year-on-year energy efficiency improvements between 0.05% and 0.25% were assumed.

Near Zero Pathways Overview

Section 4.3.4 provided an overview of the CNZ and CNZ–LCFFES pathways. As previously noted, an additional three pathways were explored and detailed in this Appendix. The following sections include modeling results and assumptions for the CNZ–LCFFES, CNZ–Max Eff, CNZ–Adv Elec, and CNZ–FLW pathways. The cumulative emissions and high-level characteristics by pillar for each pathway are summarized in Table C-23. Table C-25 provides an overview of key assumptions for the BAU scenario and CNZ pathways (more information on assumptions can be found in the rest of this appendix).

Table C-23. Food and Beverage Near Zero Pathways Summary

Pathway	Cumulative Emissions (2018–2050, MMT CO_2e)	Energy Efficiency	Electrification	LCFFES
CNZ	1,216	88%–92% adoption rates by 2050 for boilers, dryers, ovens, and machine drive energy efficiency measures	• Up to 88% adoption rates by 2050 for HWHPs and SGHPs • 3%–11% adoption rates for electric boilers and advanced electro-heating technologies by 2050 • Average share of electrification: 92%	• 100% LCFFES adoption for remaining fuel usage after maximum possible adoption of energy efficiency and electrification • Average share of LCFFES: 8%
CNZ–LCFFES	1,145	Equivalent to CNZ	• Lower adoption rates for electrification technologies because of higher LCFFES adoption (HWHPs and SGHPs–53% adoption rate by 2050) • Average share of LCFFES: 65%	• Higher LCFFES penetration as electrification is lower in this pathway • Average share of LCFFES: 35%
CNZ–Max Eff	1,135	Higher and earlier deployment of energy efficiency measures; hot water generation in lieu of steam, where applicable	• Waste heat integration used to increase SGHPs COPs • Earlier adoption of heat pump technologies because of higher waste heat integration uptake • Average share of electrification: 92%	• Equivalent to CNZ • Average share of LCFFES: 8%
CNZ–Adv Elec	1,213	Equivalent to CNZ	• Higher adoption rates of advanced electrification technologies–up to 83% by 2050; conversely, lower adoption of heat pumps (11% adoption rate by 2050) • Average share of electrification: 91%	• Equivalent to CNZ • Average share of LCFFES: 9%
CNZ–FLW*	1,085	Equivalent to CNZ	• Equivalent to CNZ	• Equivalent to CNZ

Table C-24. Food and Beverage Model Technology/Strategy Impact Assumptions

Decarbonization Technologies/Strategies Impacts	
Advanced electro-heating technologies	Infrared, microwave and ohmic heating: Reduction of baseline energy usage of up to 90% (57% on average)
Membrane pre-concentrators	Reduction in fossil fuel-based equipment energy usage of up to 75% (40% on average). Additional pump energy usage of 2%–5%
Electric boilers	95%–99% efficient
Hot water heat pumps	COPs between 1.9–5 with ambient source
Chillers energy efficiency measures	Electricity intensity reduction up to 17%
Pumps energy efficiency measures	Electricity intensity reduction up to 6%
Fans and blowers energy efficiency measures	Electricity intensity reduction up to 6%
Air compressors energy efficiency measures	Electricity intensity reduction up to 11%
Dryers/ovens energy efficiency measures	Fuel energy intensity reduction up to 15%
Process integration	Heating and cooling equipment: Fuel intensity reduced 23%–75% and electricity intensities reduced 19%–80% by 2050
Boilers energy efficiency measures	Fuel intensity reduction up to 20%

Table C-25. Food and Beverage Key Assumptions for the BAU Scenario and CNZ Pathways*

Key Assumption	BAU	CNZ	CNZ–LCFFES	CNZ–Max Eff	CNZ–Adv Elec
Energy efficiency measures (2050 adoption rates)	22%–44%	88%–92%	Same as CNZ	93%–95%	Same as CNZ
Process integration	1%	5%	Same as CNZ	10%	Same as CNZ
Electrification technologies (2050 adoption rates)					
SGHPs–hot air	8%	81%–87%	53%	Same as CNZ	11%
SGHPs–steam	8%	91%–94%	53%	Same as CNZ	Same as CNZ
Hot water heat pumps (HWHPs)	4%	91%–94%	52%	98%	Same as CNZ
Electric boilers	1%	6%–8%	3%	Same as CNZ	Same as CNZ
Advanced electro-heating technologies–hot air	3%	11%–17%	6%	Same as CNZ	83%
Membrane pre-concentrators–hot air	1%	3%–4%	2%	Same as CNZ	6%
SGHPs coefficient of performance (COP)	1.3–3.7 ($\bar{x}$= 2.2)	1.3–3.7 ($\bar{x}$= 2.2)	Same as CNZ	1.6–4.4 ($\bar{x}$= 3.2)	Same as CNZ
Share of 2050 energy consumption (averaged across the six modeled subsectors)					
LCFFES	6%	8%	35%	9%	9%
Electricity	33%	92%	65%	91%	91%
Other fuels (natural gas, coal, etc.)	60%	0%	Same as CNZ	Same as CNZ	Same as CNZ
Electric grid emissions factor (see Appendix B)	Reduced 67% 2018–2050	Reduced 100% 2018–2050	Same as CNZ	Same as CNZ	Same as CNZ

More details on assumptions across pathways can be found below in Appendix C. CCUS is not included in these pathways as it has less potential subsector-wide, although there could be opportunities for CCUS to be applied in facilities with large boilers. All pathways shown in table assume the same production values (see above in Appendix C) Some values shown as a range as they vary by subsector and/or end use. 2050 adoption rates are the portion of that technology's share across applicable end uses (e.g., in the CNZ SGHPs are deployed across 81%–94% of steam/hot air demand (varies by subsector and specific temperature range)).

*CNZ–FLW is the only pathway not shown as it has the same assumptions as CNZ except for production values (see below in Appendix C for details).

Figure C-19 shows the cumulative emissions for each pathway (the sum of emissions from 2018 to any given year). This metric is important because the impact of emissions added year upon year should be considered as well as annual emissions to slow the overall negative impacts to the environment. Pathways which reach near zero emissions in 2050 but emit a high magnitude of emissions along the way, could be harmful to the planet in the long term as the emitted GHGs stay in the atmosphere for decades. Therefore, reducing cumulative emissions is also a crucial part of decarbonization.

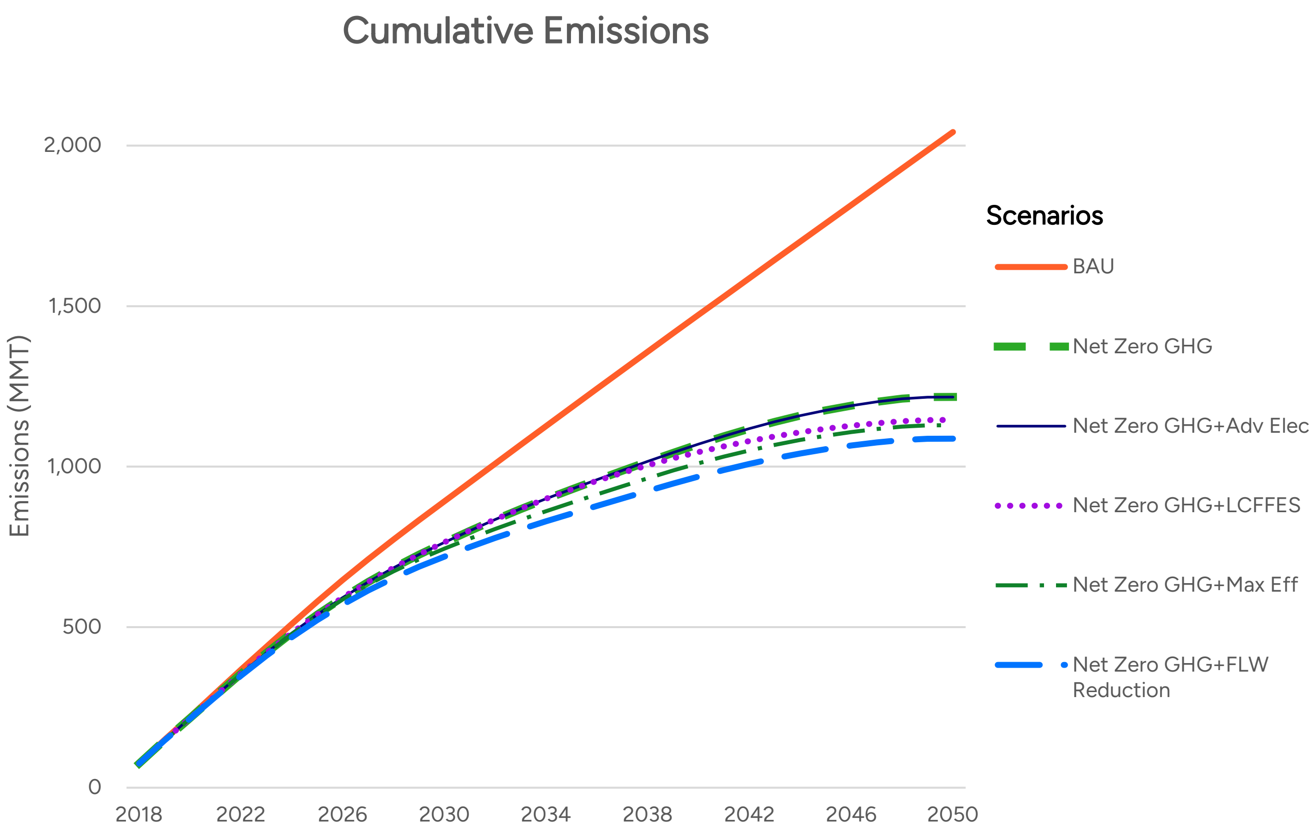

Figure C-19. Cumulative CO_2e emissions (MMT/year) for six U.S. food and beverage manufacturing subsectors for the BAU scenario, CNZ pathway, and alternate near zero pathways, 2018–2050

Acronyms/ abbreviations: BAU (business as usual), FLW (food loss and waste), GHG (greenhouse gas emissions), LCFFES (low-carbon fuels, feedstocks, and energy sources), MMT (million metric tons), CNZ–Adv Elec (impact of increased advanced electrification technologies beyond heat pumps), CNZ–7LCFFES (impact of increased LCFFES consumption), CNZ–Max Eff (impact of maximized energy efficiency and other efficiency measures uptake), CNZ–FLW (impact of reduced FLW). Source: Transformative Pathways modeling.

> *Cumulative emissions help understand emission impacts during the decarbonization transition period. For example, food loss and waste reduction results in lower overall cumulative emissions while higher efficiencies would show the greatest impact during the earlier years when the electric grid more reliant upon fossil fuels, and stall when the grid is cleaner in later years.*

In Figure C-20 for steam, the fuel intensity reduction by 2050 for the CNZ, CNZ–Adv Elec, and CNZ–Max Eff pathways mainly come from SGHPs (74% of fuel intensity reduction), with boiler energy efficiency accounting for 18% to 19% reduction, and electric boilers accounting for 6% reduction. The CNZ–Max. Eff. pathway sees earlier emissions reductions in 2030 and 2040 due to the increase in the COP of SGHPs. The CNZ–LCFFES pathway has lower comparative adoption of SGHPs and electric boilers, and instead has increased adoption of LCFFES to reduce emissions from steam production and consumption (37% reduction by 2050).

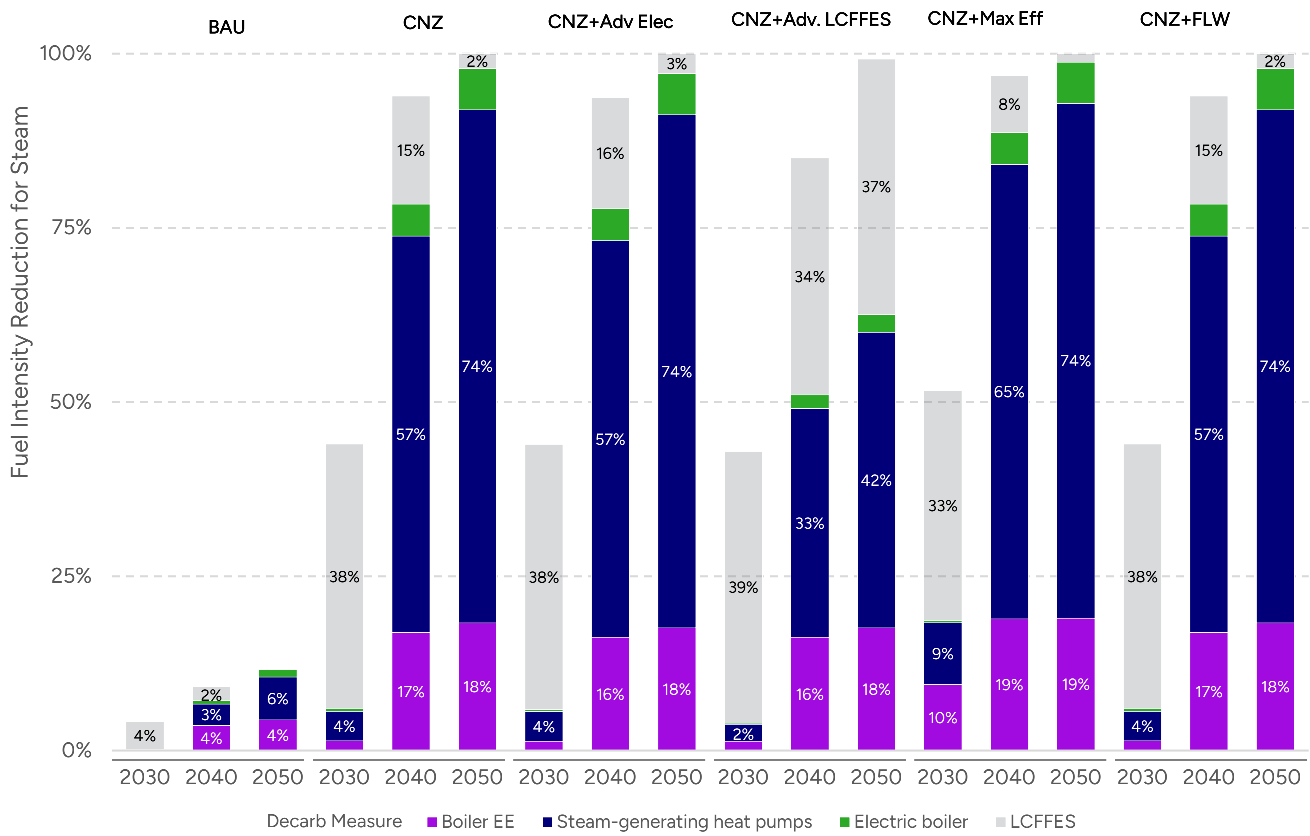

Figure C-20. Fuel intensity reductions by decarbonization measure for steam generation for six U.S. food and beverage manufacturing subsectors by decade and pathway, 2030–2050

Acronyms/abbreviations: BAU (business as usual), CNZ (Core Near Zero), EE (energy efficiency), LCFFES (low-carbon fuels, feedstocks, and energy sources), CNZ–Adv Elec (impact of increased advanced electrification technologies beyond heat pumps), CNZ–LCFFES (impact of increased LCFFES consumption), CNZ–Max Eff (impact of maximized energy efficiency and other efficiency measures uptake), CNZ–FLW (impact of FLW reduction). Source: Transformative Pathways modeling.

Figure C-21 provides an overview of the impact of decarbonization measures to reduce the fuel intensity of hot air generation by pathway. The intensity reduction by 2050 for the CNZ and CNZ–Max Eff pathways is mainly from SGHPs (76% reduction), followed by dryers and ovens energy efficiency measures (14% reduction), advanced electro-heating technologies (12% reduction), increased LCFFES consumption (11% reduction). The CNZ–Adv Elec is most significantly different than the other pathways for hot air fuel intensity reduction, given the higher adoption of advanced electro-heating technologies in this pathway. The CNZ–LCFFES pathway has the largest adoption of LCFFES by 2050 (accounting for 41% fuel intensity reduction). Process integration and membrane pre-concentrators both account for a small portion of fuel intensity reductions across the pathways.

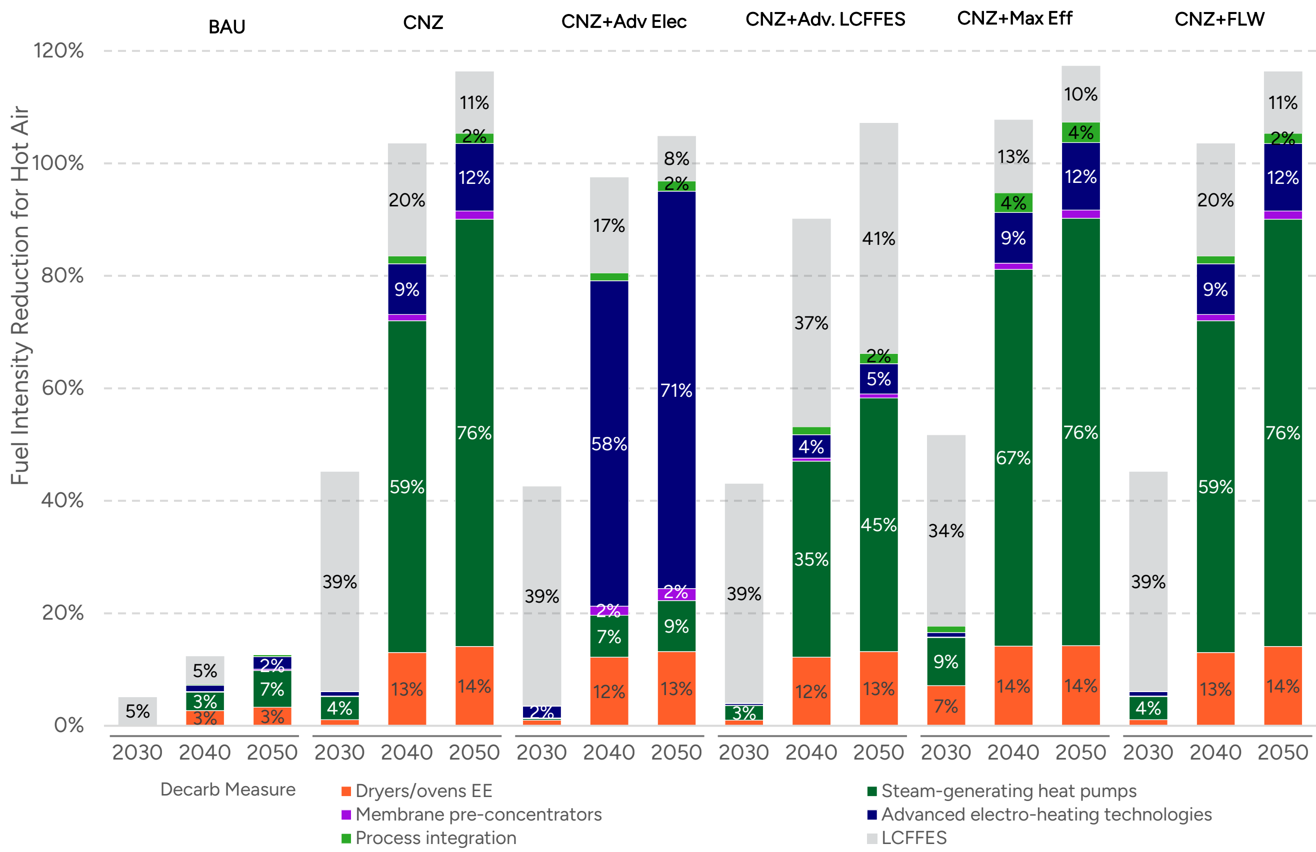

Figure C-21. Fuel intensity reductions by decarbonization measure for hot air generation for six U.S. food and beverage manufacturing subsectors by decade and pathway, 2030–2050

Acronyms/abbreviations: BAU (business as usual), CNZ (Core Near Zero), EE (energy efficiency), LCFFES (low-carbon fuels, feedstocks, and energy sources), CNZ–Adv Elec (impact of increased advanced electrification technologies beyond heat pumps), CNZ–LCFFES (impact of increased LCFFES consumption), CNZ–Max Eff (impact of maximized energy efficiency and other efficiency measures uptake), CNZ–FLW (impact of FLW reduction). Source: Transformative Pathways modeling.

Figure C-22 provides an overview of the impact of decarbonization measures to reduce the fuel intensity of hot water generation by pathway. HWHPs account for the majority of fuel intensity reduction (74% to 78%) for the CNZ, CNZ–Adv Elec, CNZ–Max Eff, and CNZ–FLW pathways. Similar to Figure C-20 and Figure C-21, the CNZ–Max Eff pathway will see earlier fuel intensity reductions in 2040 compared to other pathways due to increased heat pump COPs.

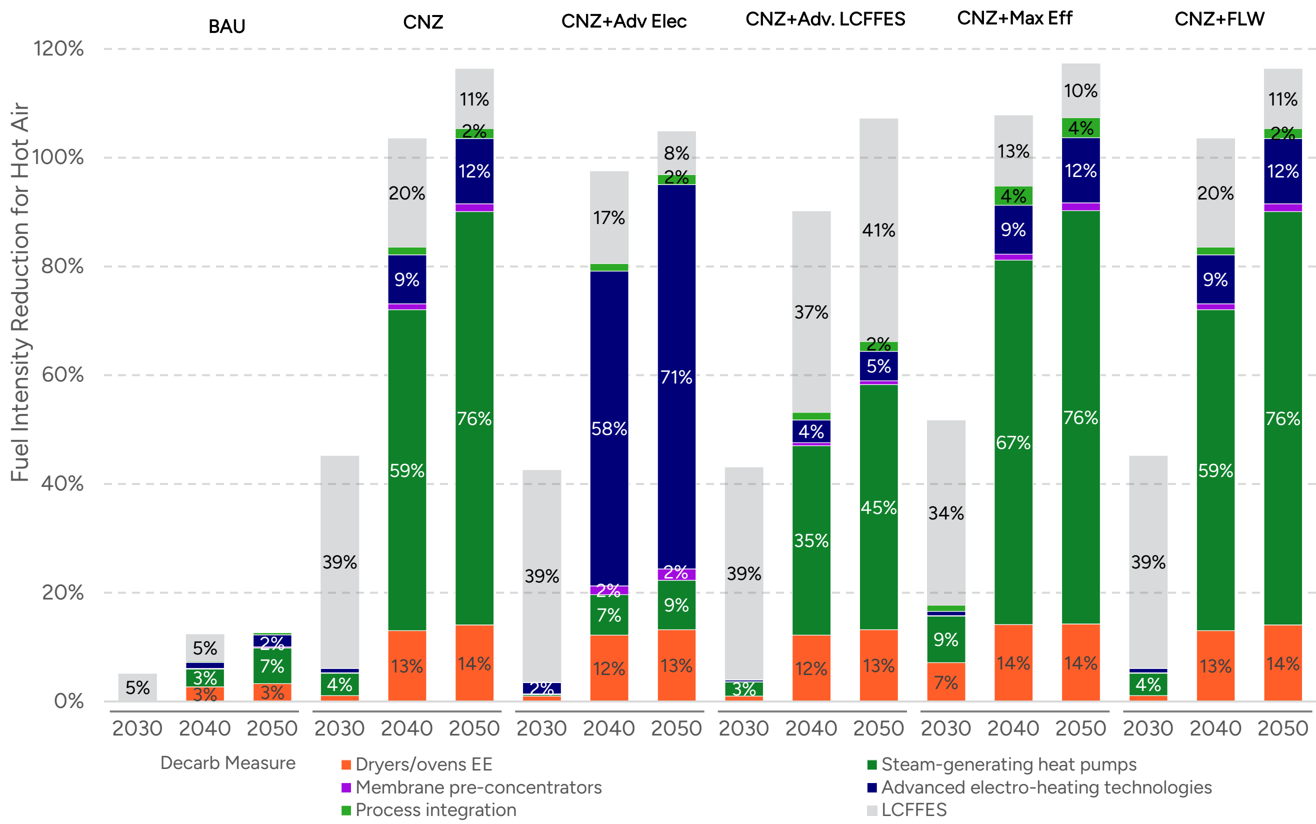

Figure C-22. Fuel intensity reductions by decarbonization measure for hot water generation for six U.S. food and beverage manufacturing subsectors by decade and pathway, 2030–2050

Acronyms/abbreviations: BAU (business as usual), CNZ (Core Near Zero), EE (energy efficiency), LCFFES (low-carbon fuels, feedstocks, and energy sources), CNZ–Adv Elec (impact of increased advanced electrification technologies beyond heat pumps), CNZ–LCFFES (impact of increased LCFFES consumption), CNZ–Max Eff (impact of maximized energy efficiency and other efficiency measures uptake), CNZ–FLW (impact of FLW reduction). Source: Transformative Pathways modeling.

Near Zero Pathway: Impact of Increased LCFFES Consumption (CNZ–LCFFES)

This pathway is centered around a substantial increase in the adoption of LCFFES opportunities involving biomass, biogas, hydrogen, and solar thermal applications within the food and beverage manufacturing subsector. In the CNZ pathway, LCFFES is utilized to help the subsector abate the last remaining emissions that cannot be achieved through energy efficiency, electrification, and where applicable, CCUS. In an accelerated LCFFES scenario, increase in LCFFES opportunities was modeled while the adoption of electrified technologies decreased. It should be noted that the adoption of LCFFES is heavily reliant on their availability at sufficient quality and generation, therefore, it will not be able to fully offset the electrification technologies.

Several recent industrial and economy-wide studies have made the following projections for industrial sector hydrogen utilization; the Hydrogen Council projects that hydrogen could account for 18% of total final energy consumption (TFEC) by 2050, while the IEA estimates 13% TFEC by 2070 under its Sustainable Development Scenario.[624] The International Gas Union predicts 7%–24% TFEC by 2050, depending on policy decisions. Meanwhile, the Energy Transitions Commission anticipates that hydrogen's share could reach 15%–20% of TFEC by 2050.[625] For biogas-related applications, the International Energy Agency (IEA) estimates that fully utilizing the sustainable potential of biogas could meet around 20% of global natural gas demand, based on 2018 production data.[626] The International Renewable Energy Agency (IRENA) estimated that solar technologies could

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[624] Steve Griffiths et al., "Industrial decarbonization via hydrogen: A critical and systematic review of developments, socio-technical systems and policy options," *Energy Research & Social Science* 80 (October 2021), doi.org/10.1016/j.erss.2021.102208.
[625] Ibid.
[626] International Energy Agency, *Outlook for Biogas and Biomethane: Prospects for Organic Growth* (2020), www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth.

supply almost 50% of the industrial sector's heat demand, depending on achievable temperature levels.[627] IRENA reports that solar thermal could cover up to 33% of the industrial sector's heat demand by 2030, with key application areas including the food and beverage, transport equipment, textile, machinery, and pulp and paper industries.[628]

Considering these estimates as well as the necessary demand for LCFFES sources, it was modeled that an average of 21% of overall energy consumption by 2050 would be attributed to LCFFES in the Core Near Zero scenario. In an accelerated LCFFES scenario, where the electrification of technologies is lower than that of the CNZ, the portion of LCFFES required for total energy consumption is estimated to have to be essentially double to 42%. The estimates are well aligned with the sources identified above. In fact, if there is an enough supply and availability of such LCFFES fuels, it could have an even higher impact in this subsector as most of the low heat demand can be electrified with heat pumps, whereas medium to high heat demand can be met with LCFFES-based process heat. Table C-25 provides the new adoption rates for electrification technologies that is a direct result of increased LCFFES energy up to 42% of total energy consumption. New electrification adoption rates are calculated as the Core Near Zero scenario assumptions multiplied by (1 – LCFFES%).

To further realize cost savings, biomass, and hydrogen-related costs should be comparable to natural gas while being substantially cheaper than electricity usage costs. In such scenarios, facilities will opt toward utilizing LCFFES to save costs and achieve significant carbon emissions reductions.

Near Zero Pathway: Impact of Maximized Energy Efficiency and Other Efficiency Measures Uptake (CNZ–Max Eff)

This near zero pathway includes assumptions around the impacts of better waste heat integration for steam generating heat pumps (SGHPs), efficient heating (utilizing hot water in lieu of steam, where applicable), and higher general energy efficiency estimates as compared to existing scenarios and assumptions. The subsector could maximize energy savings if the spark ratio (electricity to natural gas cost) decreases. With the increased adoption rate of HWHPs and improved COPs for SGHPs, a lower spark spread would make heat pumps more viable and decrease energy costs.

Many energy efficiency technologies and approaches are already being implemented in food and beverage manufacturing, but significant opportunities remain to expand their adoption. Also, many emerging technologies to improve efficiency could contribute significantly to emissions reductions and are nearing commercialization. Such measures include waste heat recovery, efficient oven burners, improvements to steam generation, and smart manufacturing principles and technologies. Key factors, assumptions, and impacts for this pathway are summarized in Table C-26. This pathway assumes the spark ratio (electricity to natural gas cost) would decrease by 2050, making heat pumps more economically viable.

Table C-26. Maximized Energy Efficiency and Other Efficiency Measures Uptake Near Zero Food and Beverage Manufacturing Pathway Key Factors, Assumptions, and Impacts

Key Factor	Assumptions and Impact
Better waste heat recovery/integration for steam generating heat pumps (SGHPs)	• Improved source heat would lower the lift required, thereby improving existing SGHP coefficient of performance (COP) • Higher COP increases installation costs exponentially for the same SGHP capacity, hence adoption rates would be same as the Core Near Zero Pathway (or in other words, not increase)
Efficient heating–utilize hot water in lieu of steam, where applicable	• Higher hot water heat pump (HWHP) and electric boiler adoption rates because of added energy demand through hot water

[627] International Renewable Energy Agency, *Solar Heat for Industrial Processes–Technology Brief*, ISBN: 978-92-95111-61-5 (2015), www.irena.org/publications/2015/Jan/Solar-Heat-for-Industrial-Processes.
[628] Ibid.

	• Replacing steam with hot water may require additional piping and storage related costs
Higher general energy efficiency estimates as compared to existing pathways and assumptions	• Investing in integration of waste heat would reduce overall energy intensity of processes • Maximize all general energy efficiency adoption rates • Maximize process integration uptake

Waste Heat Integration

The food and beverage subsector has many operations that generate waste heat that could be recovered as a thermal source for SGHPs. For example, common waste heat streams may include effluent, which carries heat away with liquid waste; sewage, where heat is lost through wastewater; and condenser heat from refrigeration plants. Waste heat from air compressors' heat of compression typically ranges between 77°F–140°F, whereas for refrigeration compressors, it is between 85°F–115°F, which is in a similar range as effluent cleaning water.[629,630] Even at lower waste heat availability, the food and beverage subsector still averages 113°F (45°C) waste heat temperatures across all sources which is recuperable for heat pumps.[631] It is assumed a limited amount of waste heat is available so it is only applied as source heat for SGHPs instead of hot water heat pumps (HWHPs) which already have favorable COPs and require relatively lower temperature lift. Due to a higher share of energy used to generate steam, having a higher COP is important in addition to decreasing the needed temperature lift for further improvement.

Table C-27 lists unique waste heat sources and their generalized temperature profiles for various subsectors within the subsector. For the animal slaughtering and processing, dairy, and sugar subsectors, a typical waste heat source of up to 190°F is possible on the higher end, whereas for grain, fruit and vegetable, and beverage manufacturing it is up to 176°F. The primary sources for the waste heat would be chillers, air compressors, and spent cleaning/heating water; these are robust sources for SGHPs are they will, in most cases, be available despite the rapid electrification of various other combustion processes such as boilers.

Table C-27. Waste Heat Source Temperature for SGHPs

Subsector	Product Type	Process	Temp. (°F)	References
Animal slaughtering and processing	Compressor oil	Cold storage cooling compressors	160	[1], [6], [8]
	Refrigerant desuperheater		140–190	
	Refrigeration phase change		82	
	Refrigeration subcooling		82	
	Hot water	Scalding	150	
	Cleaning water	Hot water cleaning	104–176	
Dairy products	Hot water/steam	Pasteurization	165	[3], [6]–[8]
	Refrigerant desuperheater	Cold storage cooling compressors	140–190	
	Exhaust air	Dryer exhaust	149–185	

[629] Richard Law, Adam Harvey, and David Reay, "Opportunities for Low-Grade Heat Recovery in the UK Food Processing Industry," *Applied Thermal Engineering* 53, 2 (May 2013): 188–96, doi.org/10.1016/j.applthermaleng.2012.03.024.
[630] Khattar Assaf et al., "Experimental Simulation of a Heat Recovery Heat Pump System in Food Industries," International Refrigeration and Air Conditioning Conference, 2010, docs.lib.purdue.edu/iracc/1087.
[631] Marina Dumont et al., "The Techno-Economic Integrability of High-Temperature Heat Pumps for Decarbonizing Process Heat in the Food and Beverages Industry," *Resources, Conservation and Recycling* 188 (January 2023): 106605, doi.org/10.1016/j.resconrec.2022.106605.

			140–176	
	Cleaning water	Hot water cleaning	104–176	
Grain and oilseed milling	Air compressors	Air compressor waste heat	77–140	[2], [8]
Sugar	Bagasse CHP flue gas waste heat after using it for other existing heat recovery processes	CHP exhaust	Up to 195	[4]
Fruit and vegetable processing	Hot water/steam	Pasteurization	131–158	[2], [8], [9]
	Cleaning water	Hot water cleaning	104–176	
	Air compressors	Air compressor waste heat	77–122; 86–140	
Beverages	Cleaning water	Hot water cleaning	104–176	
	Air compressors	Air compressor waste heat	77–122; 86–140	
Food and beverage subsector average waste heat			113	[5]

References:

[1] Omid Ashrafi et al. "Heat Recovery and Heat Pumping Opportunities in a Slaughterhouse." Energy 89 (September 2015):1–13. doi.org/10.1016/j.energy.2015.05.129.

[2] Khattar Assaf et al. "Experimental Simulation of a Heat Recovery Heat Pump System in Food Industries." International Refrigeration and Air Conditioning Conference. 2010. docs.lib.purdue.edu/iracc/1087.

[3] Atkins M. J. et al. "Minimising Energy Use in Milk Powder Production Using Process Integration Techniques." Chemical Engineering Transactions 29 (September 2012): 1507–12. doi.org/10.3303/CET1229252.

[4] Eunice Sefakor Dogbe, Mohsen Mandegari, and Johann F. Görgens. "Assessment of the Thermodynamic Performance Improvement of a Typical Sugar Mill through the Integration of Waste-Heat Recovery Technologies." Applied Thermal Engineering 158 (July 2019): 113768. doi.org/10.1016/j.applthermaleng.2019.113768.

[5] Marina Dumont et al. "The Techno-Economic Integrability of High-Temperature Heat Pumps for Decarbonizing Process Heat in the Food and Beverages Industry." Resources, Conservation and Recycling 188 (January 2023): 106605. doi.org/10.1016/j.resconrec.2022.106605

[6] Hussam Jouhara et al. "Waste Heat Recovery Technologies and Applications." Thermal Science and Engineering Progress 6 (June 2018): 268–89. doi.org/10.1016/j.tsep.2018.04.017.

[7] Kamil Kahveci and Ahmet Cihan. Drying of Food Materials: Transport Phenomena. ISBN 9781604562316. New York: Nova Science Publishers. 2008.

[8] Richard Law, Adam Harvey, and David Reay. "Opportunities for Low-Grade Heat Recovery in the UK Food Processing Industry." Applied Thermal Engineering 53, 2 (May 2013): 188–96. doi.org/10.1016/j.applthermaleng.2012.03.024.

[9] Jing Peng et al. "Thermal Pasteurization of Ready-to-Eat Foods and Vegetables: Critical Factors for Process Design and Effects on Quality." Critical Reviews in Food Science and Nutrition 57, 14 (May 2017): 2970–95. doi.org/10.1080/10408398.2015.1082126.

Identifying and utilizing such waste heat streams would require engineering and research into the facility's layout, processes, distribution systems, and heat exchangers. It is more favorable when processes are in continuous operations or at least operating during similar periods. For batch operations, which are prevalent in the subsector, short-duration thermal storage could reduce recuperable waste heat loss. Such in-depth analyses that are inherently different for most facilities are not analyzed in this report. Waste heat is assumed to be utilized with SGHPs with efficient piping, storage, and heat exchangers, whenever applicable. In doing so, the average COP for the subsector increased from an existing average of 2.2 to 3.2 (ranging from COPs between 1.6 and 4.4) when compared to using ambient air as the heat source. The real COP (considered as COP in this study) for heat pumps is calculated as:

$$COP = \left(1 - \frac{T_{Source}}{T_{Supply}}\right) x\, \eta_{isentropic}$$

Where: T_{Source} and T_{Supply} are waste heat sources (where heat is extracted) and sink (where heat is delivered) in °K, and $\eta_{isentropic}$ reflects the real performance of the compressor or other SGHP components relative to the ideal isentropic process ($\eta_{isentropic}$ = 0.45) – it is also significantly dependent on the heat pump working fluids. Based on the identified temperatures for waste heat, existing ambient source, and operating temperatures of various processes, the COPs are listed in Table C-28.

Table C-28. COPs with Better Heat Integration for CNZ–Max Eff Pathway

Subsector	COP with ambient air as sources	COP with waste heat as sources
Animal slaughtering and processing	1.8–3.2	3.0–4.3
Beverages	1.3–2.8	1.6–4.0
Dairy products	1.6–2.0	2.3–3.4
Fruit and vegetable processing	1.7–3.7	2.2–4.3
Grain and oilseed milling	1.9–3.0	2.6–4.4
Sugar	2.0–2.2	3.2–3.8

Efficient Heating (utilizing hot water in lieu of steam, where applicable)

Some processes utilize steam even though their required heat demand could be satiated with hot water, and further, reduce energy usage to generate this hot water through HWHPs. The subsector could leverage such opportunities and maximize them through independent or process integration methodologies. Doing so reduces energy costs and many steam-related risks. In the food and beverage subsector, a few unit processes that generally utilize steam for processes whose temperature requirements are below 212°F were identified. Specifically, processes such as cooking and heating that utilize steam jackets, and low-temperature extraction and dewatering utilize steam, even though their temperature requirements, in many cases, are well below 212°F.

The existing fuel usage to produce saturated steam at atmospheric pressure was estimated and compared to fuel usage to produce hot water at required temperatures (150°F–180°F). Ambient water is estimated to be 60°F. Logically, the fuel required to produce hot water is an order of magnitude lower than producing steam for the same mass flow rates because steam generation requires more energy to overcome the fluid's latent heat of vaporization. The new demand for hot water is estimated to be supplied by HWHPs which are significantly more efficient than fossil fuel-fired conventional or electric/electrode boilers. To evaluate this, we assumed an increased adoption rate in HWHPs of up to 98% as compared to the existing 94% in the CNZ. Table C-29 provides the relevant processes that were identified for replacement of incumbent steam to hot water. For simpler apprehension, the energy intensities are normalized to 1, thereby providing content for the percentage of energy intensity reduction when hot water is generated in lieu of steam. Between years 2018 and 2050, the energy intensities are linearly extrapolated to obtain energy intensity value for any given year. The 2018 energy intensity value decreases to reach 2050 value.

Table C-29. Energy Efficiency (EE) Technologies Adoption Rates Parameters for CNZ–Max Eff Pathway

Subsector	Unit Process	2018 Normalized Existing Energy Intensity	2050 Normalized Proposed Energy Intensity
Fruit and vegetable processing	Cooking	1	0.12
Grain and oilseed milling	Extraction	1	0.09
	Dewatering	1	0.08
Sugar manufacturing	Heating	1	0.10

Accelerated Adoption Rates

Additionally, we assumed accelerated adoption rates for various energy efficiency measures attributed to boilers, dryers, machine drives such as fans, pumps, blowers, air compressors, and process cooling and refrigeration. It was assumed that the adoption rates will accelerate based on logistic S-Curve adoption rates. For example, if half of the energy efficiency measures were to be adopted by 2035 in the Core Near Zero scenario, it was assumed to be 2030 in this scenario. The results are shown in Table C-30. The subsector could maximize energy savings if the spark ratio (electricity to natural gas cost) decreases. With the increased adoption rate of HWHPs and improved COPs for SGHPs, a lower spark spread would make heat pumps more viable and decrease energy costs.

Table C-30. Energy Efficiency (EE) Technologies 2050 Adoption Rates Parameters for CNZ–Max Eff Pathway

Technology	CNZ Adoption Rates	CNZ–Max Eff Adoption Rates	CNZ S-Curve 50% Adoption Year (Sigmoid Midpoint)	CNZ–Max Eff S-Curve 50% Adoption Year (Sigmoid Midpoint)
Dryers/ovens EE	88%	95%	2035	2030
Process Integration	5%	10%	2037	2032
Boiler EE	88%	95%	2035	2030
Chillers EE (Motors/variable frequency drives)	100%	100%	2035	2030
Pumps EE	92%	95%	2035	2030
Fans and Blowers EE	92%	95%	2035	2030
Air Compressors EE	92%	95%	2035	2030
Hot Water Heat Pump	94%	98%	2037	2032
Steam Generating Heat Pumps	88%	88%	2037	2035

Overall impact: For the CNZ–Max Eff pathway, there is a distinct emissions reduction during the earlier years than the other near zero pathways as can be seen in Figure C-20 through Figure C-22. Adoption rates for energy efficiency measures are accelerated (i.e., faster and higher adoption rates) compared to the Core Near Zero pathway. Further, increased SGHP COPs from waste heat integration would decrease the scope 2 emissions more in comparison to the other pathways. It is assumed that 80% of SGHPs uptake would occur between 2032 and 2043, with the highest uptake (58%) occurring between 2036 and 2039. Additionally, this pathway would have lower cumulative emissions compared to the others, due to lower energy demand from the uptake of more efficient distribution systems and machine drives as well as higher COPs of heat pumps. Table C-31 provides an overview of how this pathway impacts the six food and beverage manufacturing subsectors.

Table C-31. Food and Beverage Manufacturing CNZ–Max Eff Pathway Impact by Subsector

Subsector	BAU cumulative emissions (2018–2050) (MMT CO_2e)	CNZ cumulative emissions (2018–2050) (MMT CO_2e)	CNZ–Max Eff cumulative emissions (2018–2050) (MMT CO_2e)	CNZ–Max Eff Pathway Impact* (compared to CNZ)
Grain and Oilseed Milling	491	297	275	• 31% reduction in cumulative emissions through generating hot water in lieu of steam in extraction and dewatering processes • 26%–33% decrease in electricity intensity through higher COPs for SGHPs leading to a 12% reduction in cumulative emissions
Sugar	173	101	83	• 34% reduction in cumulative emissions through generating hot water in lieu of steam in the cooking process • 33%–40% decrease in electricity intensity through higher COPs for SGHPs leading to a 21% reduction in cumulative emissions
Fruit and Vegetable Preserving and Specialty Food	251	149	133	• 31% reduction in cumulative emissions through generating hot water in lieu of steam in the cooking process • Up to 32% decrease in electricity intensity through higher COPs for SGHPs leading to a 21% reduction in cumulative emissions
Dairy Products	271	161	149	• 29%–42% decrease in electricity intensity through higher COPs for SGHPs leading to a 15% reduction in cumulative emissions
Animal Slaughtering and Processing	630	374	365	• 25%–38% decrease in electricity intensity through higher COPs for SGHPs leading to a 14% reduction in cumulative emissions
Beverage	212	135	130	• 13%–30% decrease in electricity intensity through higher COPs for SGHPs leading to a 7% reduction in cumulative emissions

Note: Better waste heat integration for SGHPs will affect resulting emissions. For example, SGHPs with COPs <2 may increase net emissions in the short to medium term (and vice-versa) because the grid is still relatively fossil fuel-based. End-use steam temperature of 300°F will yield lower COP as compared to that of 212°F.

* Each subsector in this Pathway will also see lower energy and emissions from higher and earlier EE adoption for machine drives, boilers, and dryers.

Near Zero Pathway: Impact of Increased Advanced Electrification Technologies (Beyond Heat Pumps) (CNZ–Adv Elec)

This pathway investigates the impact of increasing the Core Near Zero pathway's assumptions around electrification technologies for hot air and drying applications that do not, primarily, involve heat pumps. This includes higher uptake of electro-heating technologies such as infrared drying and heating, microwave and ohmic heating, radio frequency drying and heating, and other non-heating methods such as pulsed electric fields and membrane pre-concentrators. Key factors, assumptions, and impacts for this pathway are summarized in Table C-32 and additional details can be found below.

Table C-32. Zero Food and Beverage Manufacturing CNZ–Adv Elec Pathway Key Factors, Assumptions, and Impacts

Key Factor	Assumptions and Impact
Higher adoption rates of electrification technologies (other than heat pumps)	• Increased adoption of electro-heating technologies such as infrared drying, microwaves, ohmic heating, etc. and reduced adoption of heat pumps • Increased membrane pre-concentrator applications
Energy costs favoring electrification	• Though energy costs are not explicitly modeled, assumes a higher cost of natural gas and hydrogen compared to electricity

This pathway assumes advanced electro-heating technologies such as infrared drying and heating, microwave and ohmic heating, radio frequency drying and heating, and other non-heating methods such as pulsed electric fields and membrane pre-concentrators are adopted at greater rates in place of SGHPs. These technologies and processes can reduce energy use substantially while also electrifying existing heating and drying applications. These could also improve food quality, safety, and shelf-life, specifically in canned and packaged fruits, vegetables, and dairy products.[632] For example, infrared and ultrasound heating provides more consistent and even heating, leading to improved quality attributes of dried products compared to other drying techniques.[633,634,635]

In the CNZ, a large uptake in SGHPs was estimated of up to 88% for steam and hybrid-drying applications. In this pathway, the assumed adoption rates for SGHPs-assisted heating specifically in the drying processes was reduced, while increasing adoption rates for advanced electro-heating technologies and membrane pre-concentrators. In short, the electro-heating technologies will share the larger load as they have more applications than those of the membrane-preconcentrates.

Also in this scenario, the adoption rate of membrane pre-concentrators is increased to 14%. Pre-concentrators could reduce the moisture and liquid content of the products before the application of existing evaporators and dryers or advanced electro-heating drying processes. Membranes could reduce the water content in manufacturing products by up to 15%, reducing the energy consumption of evaporators.636 Considering that increase, the remaining energy usage reductions are attributed to the advanced electro-heating technologies and steam-generating heat pumps. Table C-33 displays the final adoption rates for the technologies adjusted in this scenario.

Table C-33. Advanced Electrification Technologies 2050 Adoption Rates for CNZ–Adv Elec Pathway

Technology	CNZ Adoption Rates	CNZ–Adv Elec Adoption Rates
Advanced electro-heating technologies*	11%	83%
Steam generating heat pumps	88%	11%
Membrane pre-concentrators	2.8%	14%

* Includes infrared drying and heating, microwave and ohmic heating, radio frequency drying and heating, and other non-heating methods such as pulsed electric fields.

[632] Salam A. Aboud et al., "A Comprehensive Review on Infrared Heating Applications in Food Processing," *Molecules* 24, 22 (November 2019), doi.org/10.3390/molecules24224125.
[633] D. S. Delfiya et al., "Drying Kinetics of Food Materials in Infrared Radiation Drying: A Review," *Journal of Food Process Engineering* 45, 6 (July 2021), doi.org/10.1111/jfpe.13810.
[634] Fakhreddin Salehi, "Recent Applications and Potential of Infrared Dryer Systems for Drying Various Agricultural Products: A Review," *International Journal of Fruit Science* 20, 3 (2020): 586–602, doi.org/10.1080/15538362.2019.1616243.
[635] Cunshan Zhou et al., "Ultrasound, Infrared and Its Assisted Technology, a Promising Tool in Physical Food Processing: A Review of Recent Developments," *Critical Reviews in Food Science and Nutrition* 63, 11 (2023): 1587–1611, doi.org/10.1080/10408398.2021.1966379.
[636] Via Separations, *Black Liquor Concentration System: Solution Overview* (2020), viaseparations.com/wp-content/uploads/2020/11/via.pdf.

The subsector could only maximize energy and cost savings if the spark ratio (ratio of electricity to natural gas cost) decreases to less than 1.5. These technologies may be simpler to install, integrate, and operate, specifically at higher temperatures as compared to heat pumps, but they cannot compete with the efficiencies provided by electric heat pumps. Therefore, a very favorable spark ratio is required to obtain cost savings. Also, in this scenario, the hydrogen to natural gas cost ratio is assumed as higher, thereby pushing the subsector toward electrification.

Overall impact: This pathway results in a similar emissions reductions trajectory as the CNZ. Although there is an increase in the adoption of advanced electrification technologies, these are not as efficient as SGHPs. Therefore, the resulting emission reductions is smaller on a year-on-year basis. Due to the difference in equipment energy efficiencies, this pathway would have higher annual energy consumptions and cumulative emissions compared to the other near zero pathways. Table C-34 provides an overview of how this pathway impacts the six food and beverage manufacturing subsectors.

Table C-34. CNZ–Adv Elec Food and Beverage Manufacturing Pathway Impact by Subsector

Subsector	BAU cumulative emissions (2018–2050) (MMT CO_2e)	CNZ cumulative emissions (2018–2050) (MMT CO_2e)	CNZ–Adv Elec cumulative emissions (2018–2050) (MMT CO_2e)	CNZ–Adv Elec Pathway Impact (compared to CNZ)
Grain and Oilseed Milling	491	297	295	4% decrease in cumulative emissions
Sugar	173	101	102	5% increase in cumulative emissions
Fruit and Vegetable Preserving and Specialty Food	251	149	149	4% increase in cumulative emissions
Dairy Product	271	161	158	10% decrease in cumulative emissions
Animal Slaughtering and Processing	630	374	374	4% increase in cumulative emissions
Beverage	212	135	135	5% decrease in cumulative emissions

* Impact from higher adoption of advanced electro-heating and membrane pre-concentrator applications and lower adoption of high-temperature heat pump-assisted drying.

Near Zero Pathway: Impact of Reduced Food Loss and Waste (FLW) (CNZ–FLW)

This pathway informs the emissions reductions impact of food and beverage loss and waste reduction in downstream supply chain activities on energy usage and emissions in the manufacturing subsector. Key factors, assumptions, and impacts for this pathway are summarized in Table C-35.

Table C-35. CNZ–FLW Food and Beverage Manufacturing Pathway Key Factors, Assumptions, and Impacts

Key Factor	Assumptions and Impact
Reduction in downstream food loss/waste	Decrease in food waste during downstream supply-chain and end-use customers
Higher overall system-wide efficiencies	Improved and efficient production leading to longer products life
More sustainable packaging options	Reduce food waste during transit, warehouse storage

Although the impacts of upstream reduction in food waste could proportionally reduce energy usage during production, this pathway also aims to qualitatively inform other factors that may change production intensities in the subsector. Food waste reduction could be achieved through better and sustainable packaging as well. Though the cause and impacts of these possibilities were not quantitatively modeled as part of the *Transformative Pathways* effort, they are important and should be studied in future modeling work regarding food production and consumption pathways. Although not exactly a direct FLW reduction approach, it should be noted that opportunities such as a dietary shift to a vegetarian diet could increase production in other plant-based sectors while decreasing animal processing production; this could also be accompanied by lab-grown, alternative proteins, which could significantly reduce upstream scope 3 emissions. These are different approaches that are not modeled in this scenario; however, they could play a key role in this space in the future.

The FLW estimates for various food and beverage subsectors presented by Dong et al. in their study are utilized for production reduction estimates.[637] The study estimates FLW at various stages of the food manufacturing subsector supply chain, such as agriculture and farming, manufacturing, retail, distribution, and consumption. The estimates for the manufacturing and consumption stages of the supply chain are used and reduce their magnitude resulting in overall energy and emissions reduction in the subsector. USDA and EPA set a joint national goal in 2015 to reduce food loss and waste (FLW) sent to landfills and incinerators by 50% by 2030.[638] To support this goal, the Biden-Harris Administration released the first-ever Interagency National Strategy for Reducing Food Loss and Waste and Recycling Organics, investing over $200 million through the President's Investing in America agenda.[639] The strategy focuses on preventing food loss and waste, increasing the recycling rate for organic wastes, and promoting policies that encourage these practices.[640] As an enhanced productivity scenario with a 2050 timeline, we further assume a 25% reduction, resulting in an overall 75% reduction in FLW in the subsector. We assume the demand for food to be similar in both scenarios (CNZ and CNZ–FLW reduction) and change the amount of loss within the supply chain based on the 75% FLW reduction rate.

$$\text{Demand}_{\text{CNZ}} = F_p\ x\ (1 - L)$$
$$\text{Demand}_{\text{CNZ–FLW}} = F_p'\ x\ (1 - L')$$
$$L' = 75\%\ \text{of}\ L$$

Where: F_p and F_p' are the existing and proposed food production rate, respectively; and L and L' are existing and proposed food loss and waste rates. Assuming the demand in the two scenarios to be the same, the above equations estimate the new production rates, which could be written as:

$$F_p' = \frac{F_p\ x\ (1-L)}{1-0.75\ x\ L}$$

[637] Ibid.
[638] U.S. Environmental Protection Agency, "United States Food Loss and Waste 2030 Champions," August 24, 2024, www.epa.gov/sustainable-management-food/united-states-food-loss-and-waste-2030-champions.
[639] U.S. Department of Agriculture, "National Strategy for Reducing Food Loss and Waste and Recycling Organics," 2024, www.usda.gov/foodlossandwaste/national-strategy.
[640] The White House, "FACT SHEET: Biden-Harris Administration Releases First-Ever Interagency National Strategy for Reducing Food Loss and Waste and Recycling Organics," June 12, 2024, www.whitehouse.gov/briefing-room/statements-releases/2024/06/12/fact-sheet-biden-harris-administration-releases-first-ever-interagency-national-strategy-for-reducing-food-loss-and-waste-and-recycling-organics/.

Table C-36 provides the food production estimates for each of the subsectors. Dong et al carried out this analysis for only the food manufacturing subsector;[641] therefore, we utilize the average values of the food subsector and apply that to the beverage manufacturing subsector as well. The proposed food demand, is then, applied against the energy intensities (fuel and electricity) of each unit process to estimate their total energy consumption; thereafter, the energy consumption is applied against their respective emission factors to calculate the final GHG emissions (also shown in Figure C-23).

Figure C-23. Overall Emissions Estimation Framework

Table C-36. FLW Estimates Across Manufacturing and Consumption

Subsector	Average loss % at manufacturing	Average loss % at consumption	Overall average loss %	CNZ 2050 production (MMT)	CNZ–FLW 2050 production (MMT)
Animal Slaughtering and Processing	31%	25%	28%	43	33
Beverage Manufacturing	-	-	26%	105	83
Dairy Products	40%	22%	34%	56	41
Fruit and Vegetable Processing	21%	35%	26%	54	43
Grain and oilseed processing	35%	24%	30%	80	61
Sugar Manufacturing	8%	34%	11%	8	8

Overall impact: Table C-37 provides an overview of how this pathway impacts the six food and beverage manufacturing subsectors. Details on estimates for production reductions from FLW measures can be found below.

[641] Dong et al., "A framework to quantify mass flow and assess food loss and waste in the US food supply chain," *Communications Earth & Environment* 3, 1 (April 2022), doi.org/10.1038/s43247-022-00414-9.

Table C-37. Impact of Reduced Food Loss and Waste Near Zero Food and Beverage Manufacturing Pathway by Subsector

Subsector	BAU cumulative emissions (2018–2050) (MMT CO_2e)	CNZ cumulative emissions (2018–2050) (MMT CO_2e)	CNZ–FLW cumulative emissions (2018–2050) (MMT CO_2e)	CNZ–FLW Pathway Impact (compared to CNZ)
Grain and Oilseed Milling	491	297	266	10% reduction in cumulative emissions through 24% decrease in production quantity*
Sugar	173	101	90	11% reduction in cumulative emissions through 9% decrease in production quantity*
Fruit and Vegetable Preserving and Specialty Food	251	149	135	9% reduction in cumulative emissions through 21% decrease in production quantity*
Dairy Product	271	161	139	14% reduction in cumulative emissions through 28% decrease in production quantity*
Animal Slaughtering and Processing	630	374	332	11% reduction in cumulative emissions through 23% decrease in production quantity*
Beverage	212	135	123	9% reduction in cumulative emissions through 21% decrease in production quantity*

* Production quantity reduction assumptions have been adopted from Dong et al 2022.[642]

Iron and Steel

Figure C-24 illustrates how the model examines the carbon footprint of crude steel produced using an electric arc furnace (EAF), considering the source of iron, the source of electricity, and the percentage of scrap used in the process. It also compares the emissions footprint of EAF-produced crude steel with that of steel made in a blast furnace-basic oxygen furnace (BF-BOF) integrated mill. The findings highlight the potential for emissions reductions through optimized material and energy use. Note, these emissions intensities are before other interventions, such as energy efficiency and scope 2 emissions are addressed.

[642] Dong et al., "A framework to quantify mass flow and assess food loss and waste in the US food supply chain," *Communications Earth & Environment* 3, 1 (April 2022), doi.org/10.1038/s43247-022-00414-9.

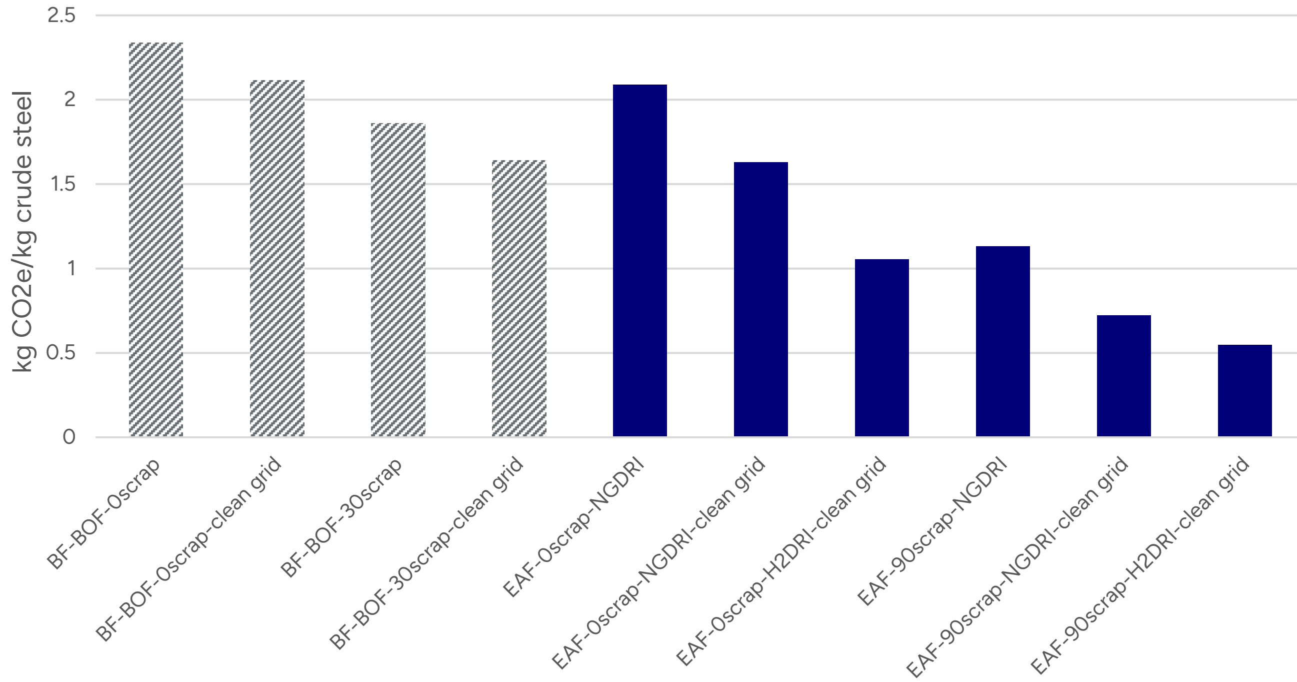

Figure C-24. GHG emissions intensity of crude steel with different production routes, assuming traditional finishing

See Table C-38.

Figure C-25 provides a geographical visualization of the locations of existing iron and steel mills across the United States. Each mill is represented by icons whose sizes correlate with their production volume, offering a spatial understanding of subsector distribution.

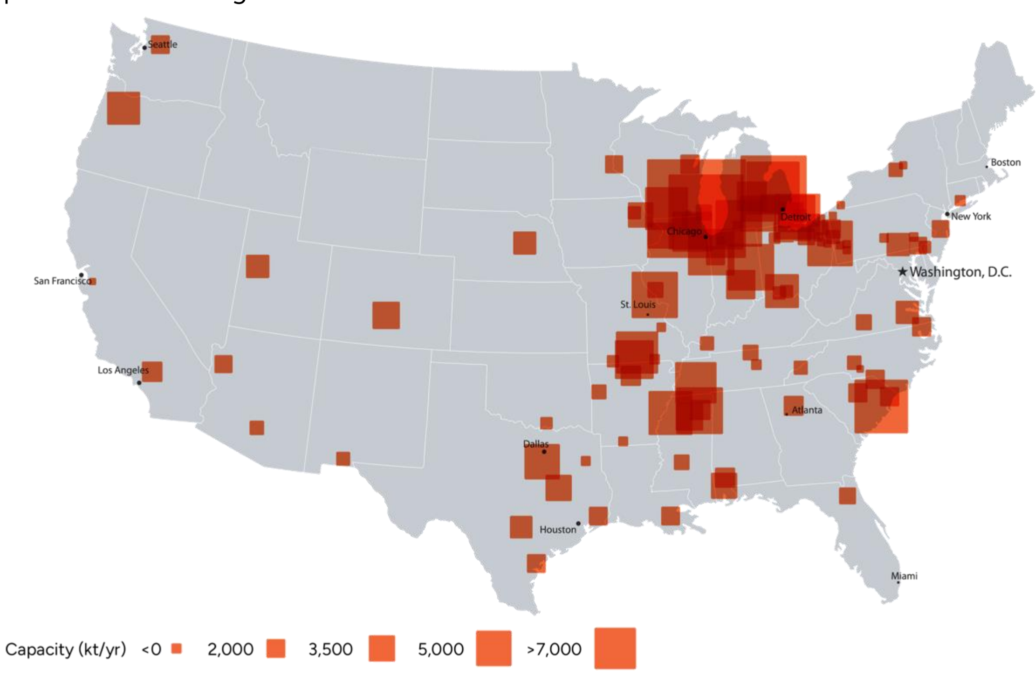

Figure C-25. Geographical distribution of U.S. iron and steel mills and their production volumes

Data source: Tianyang Lei et al. "Global iron and steel plant CO_2 emissions and carbon-neutrality pathways." Nature 622 (October 2023): 514-520. doi.org/10.1038/s41586-023-06486-7.

Figure C-26 and Figure C-27 present the production throughput and scrap usage scenarios in the model. These visuals enable a comprehensive understanding of potential future industry trends and strategies.

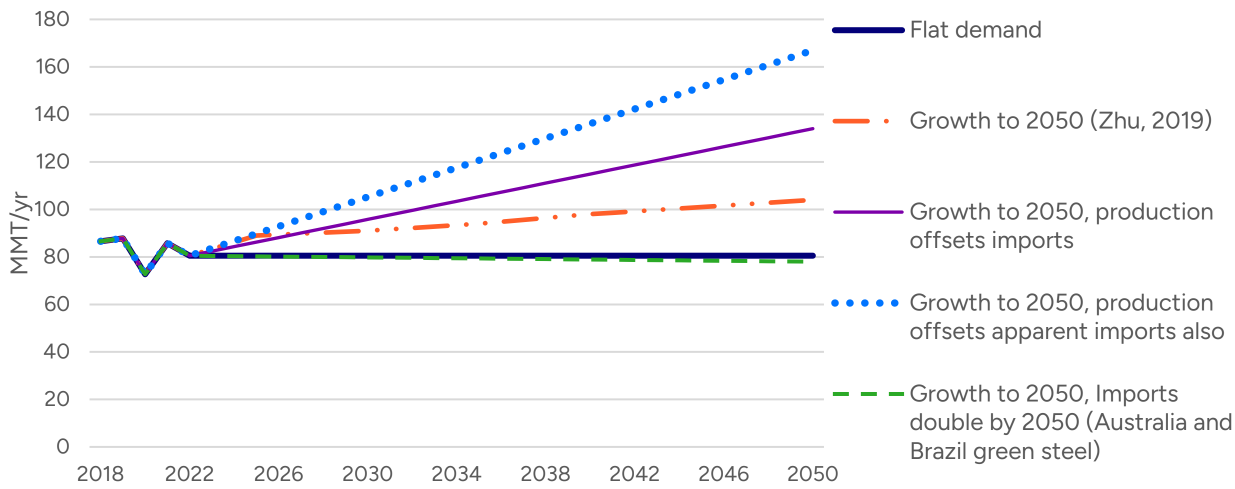

Figure C-26. Production throughput scenarios for crude steel, 2018

Source: Transformative Pathways modeling.

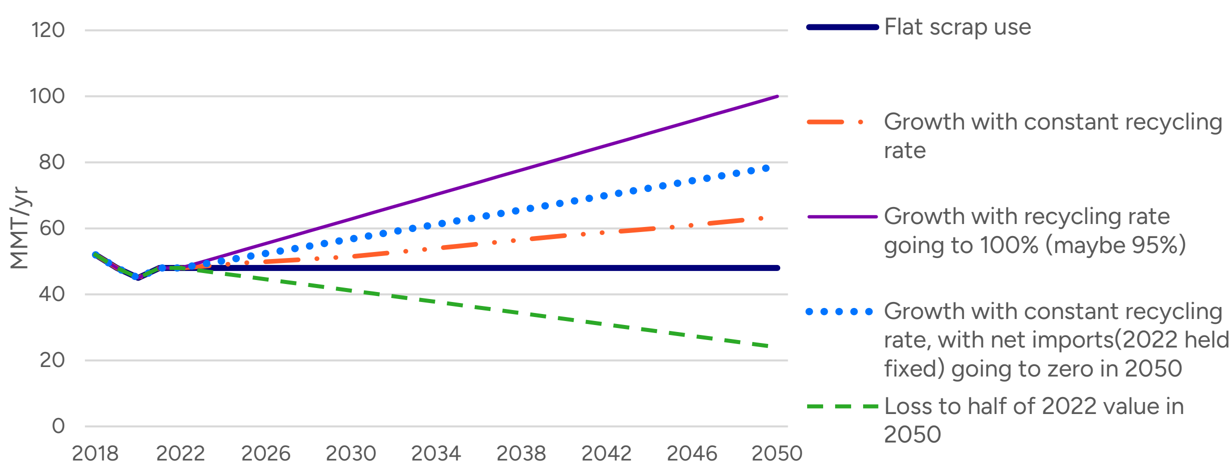

Figure C-27. Scrap usage scenarios in crude steel production, 2018–2050

Source: Transformative Pathways modeling.

Figure C-28 demonstrates the four scenarios of GHG intensity for hydrogen, reflecting the complexity and potential variability in emissions based on different production methods and technological advancements.

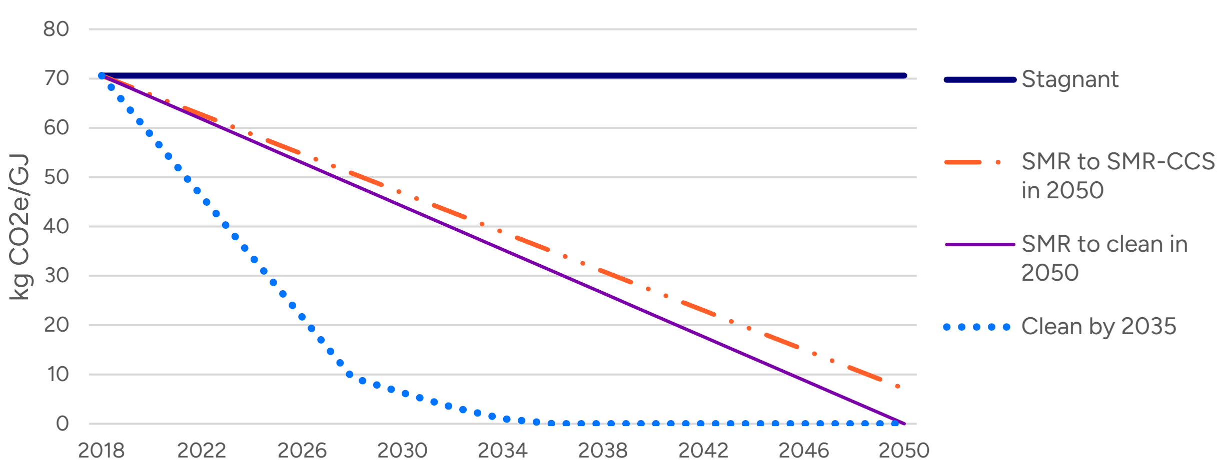

Figure C-28. GHG intensity scenarios for hydrogen in steel production, 2018–2050

Source: Transformative Pathways modeling.

Table C-38 lists the current and emerging technologies in iron and steel production, detailing their current and projected (2050) emissions intensity levels in a near zero emissions scenario. This table also identifies expected online timelines for each technology, providing insight into the subsector's transition to a more sustainable future.

Table C-38. Current and Emerging Technologies in Iron and Steel Production and Their Emissions Intensities

Technology Type	Process Name	Current Emissions Intensity (kg CO_2e/kg crude steel)	2050 Emissions Intensity in Near Zero Scenarios (kg CO_2e/kg crude steel)	Anticipated year brought online (not constrained for existing technologies)	Current Emissions Intensity Reference(s)
Ironmaking	BF	1.32	1.303	-	[1]
Ironmaking	NG-DRI	0.851	0.794	-	[2]
Ironmaking	NG-DRI-H2fuel	0.885	0.716	2026	[2]
Ironmaking	H2-DRI	1.079	0.519	2032	[2]-[4]
Ironmaking	H2-DRI-H2fuel	1.191	0.26	2032	[2]-[4]
Ironmaking	MOE	2.127	0.341	2032	[2]
Ironmaking	AqE	1.512	0.345	2032	[2]
Steelmaking	EAF-0scrap	0.421–0.693	0.172–0.364	-	[5]
Steelmaking	EAF-50scrap	0.402–0.540	0.131–0.265	-	[5]
Steelmaking	EAF-90scrap	0.345–0.525	0.116–0.231	-	[5]

References:

[1] U.S. Department of Energy. Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Iron and Steel Manufacturing (2015). www.osti.gov/biblio/1248755. Note coke was treated as a process emission.

[2] A. Keys, M. van Hout, and B. Daniëls. Decarbonisation options for the Dutch Steel Industry (PBL Netherlands Environmental Assessment Agency and ECN part of TNO, 2019). www.pbl.nl/sites/default/files/downloads/pbl-2019-decarbonisation-options-for-the-dutch-steel-industry_3723.pdf.

[3] C. Ravenscroft. "Building on core technology-creating flexibility and value." Direct from MIDREX 3rd Quarter 2017 (2017). www.midrex.com/wp-content/uploads/Midrex_2017_DFM3QTR_FinalPrint.pdf.

[4] R. Millner et al. "MIDREX H2 – The Road to CO2-free Direct Reduction." 2021 AISTech Conference Proceedings. (2021). www.primetals.com/fileadmin/user_upload/landing_pages/2021/Green_Steel/Publications/downloads/AISTech_2021_MIDREX_H2_Final.pdf.

[5] Calculations based on Marcus Kirschen et al. "Models for EAF energy efficiency." Steel Times International 44 (2017). www.steeltimesint.com/content-images/news/RHIPDF_1.pdf and Pablo E. Duarte and Carlos Lizcano. Latest Advancements in Direct Reduction Integrated to Meltshop: HYL High Carbon Iron (HCI) and the HYL Mini-Module. n.d.

Table C-39 provides an overview of the low, mid, and high sensitivities used in the iron and steel model.

Table C-39. Core Sensitivities Modeled for the Iron and Steel Subsector Model

Sensitivity	Low	Mid	High
Hydrogen: H_2-DRI:NG-DRI amount of hydrogen used as a fuel	1:6 0% H_2 as a fuel	1:1 10% for NG-DRI, 30% H_2-DRI	4:1 10, 30% for NG-DRI, 30, 100% for H_2-DRI
Electrified finishing in 2050 (e.g., reheat furnaces, annealing furnaces)	0%	50%	100%
CCS in 2050	0%	70%	100%
BF-BOF market share in 2050	~equal to 2022 value & 3% p.a. decrease out to 2050 for BAU	0%	0%
Low technology readiness ironmaking in 2050	0%	3%	6%
Production	Zero imports by 2050	104 MMT in 2050	Double imports by 2050
Total scrap used in 2050	24 MMT (half of 2022 value) in 2050	64 MMT in 2050	78 MMT in 2050 (no scrap exports)
Energy Efficiency	none & low (~0.1% p.a. for high maturity technologies)	high (~0.25% p.a. for high maturity technologies)	high (~0.25% p.a. for high maturity technologies)
Electric grid emission factor	BAU is AEO 2023 reference scenario	NZ by 2050 from 2023 standard scenarios – high hydrogen and high demand with modified 95% reduction by 2050	NZ by 2035 from 2023 standard scenarios – high hydrogen and high demand with 100% reduction by 2035
Hydrogen emission factor	SMR hydrogen in 2050 SMR-CCS hydrogen in 2050	Clean hydrogen by 2050	Clean hydrogen by 2035 from 2023 Standard Scenarios for high hydrogen and high demand and 100% reduction by 2035

Table C-40. Range of Iron and Steel Subsector Scenarios Modeled*

Core Scenario	Shorthand	Includes low-maturity ironmaking technology sensitivities?	Ratio of Nominal H_2-DRI to NG-DRI
Business as Usual	BAU	No	0.173
Low Hydrogen Adoption	lowH2	No	0.266
Mid Hydrogen Adoption	midH2	Yes	1.036
High Hydrogen Adoption (Nominal near zero)	highH2	Yes	3.934
Flat BF-BOF production	flatBF	No	0.406
High Hydrogen with increased scrap	highH2 + scrap	No	3.859
High Hydrogen with decreased scrap	highH2 - scrap	No	2.586
High Hydrogen with increased production	highH2 + prod	No	3.913
High Hydrogen with decreased production	highH2 - prod	No	1.784
High Hydrogen with increased production & scrap	highH2 + prod + scrap	No	3.955
High Hydrogen with flat production & scrap	highH2 flatprod flatscrap	No	3.933

* For all scenarios except BAU, CCS and electrified finishing are assumed to be 70%. BAU has no CCS or electrified finishing.

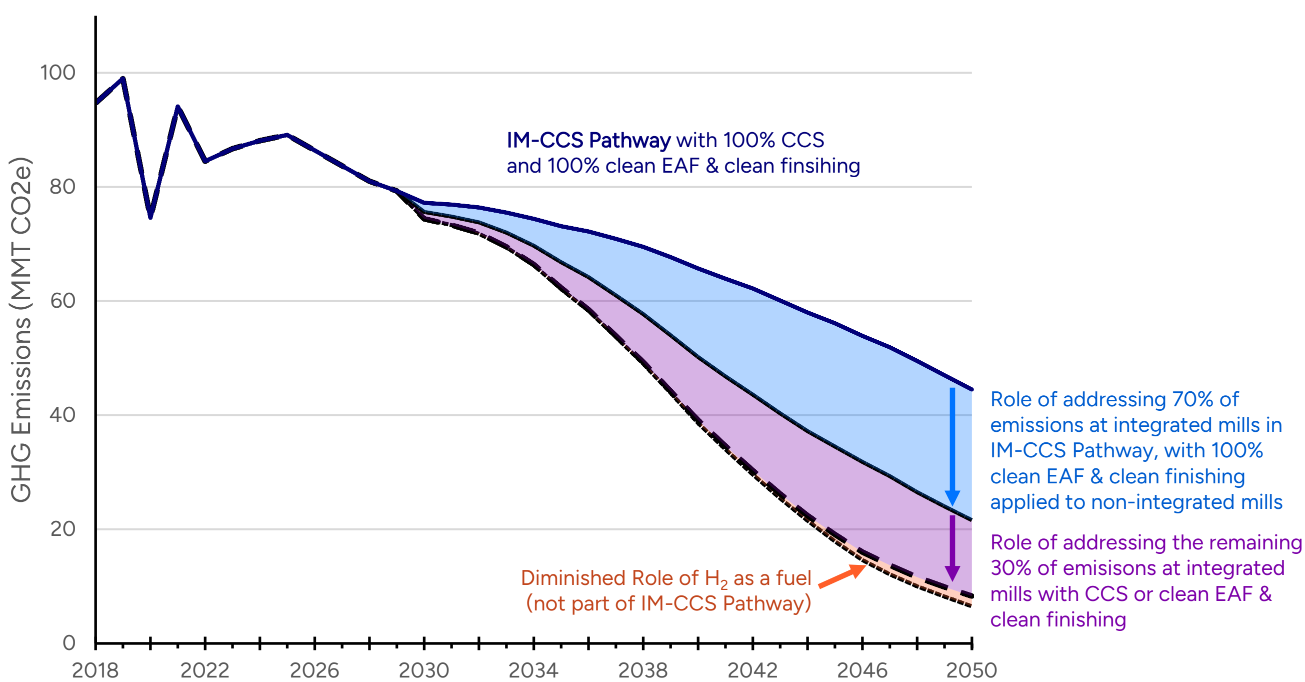

Figure C-29. Role of CCS and H_2 as a fuel in IM-CCS Pathway

Source: Transformative Pathways modeling.

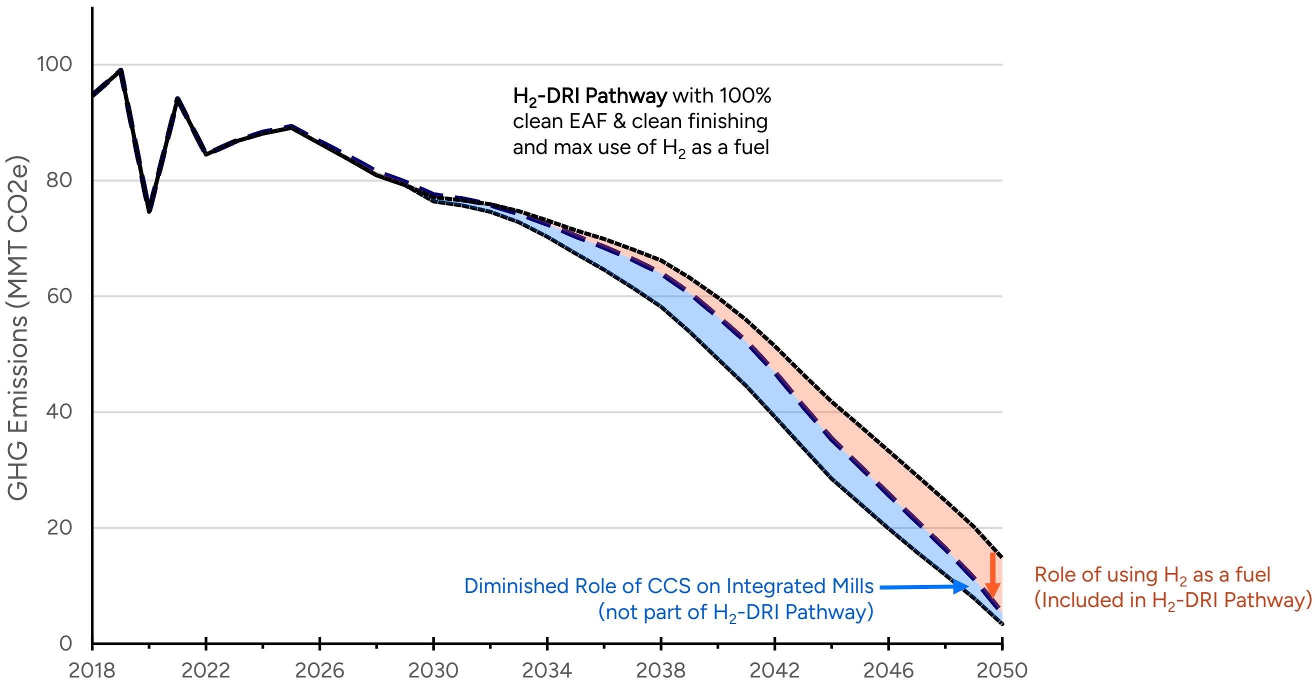

Figure C-30. Role of CCS and H_2 as a fuel in H_2-DRI Pathway

Source: Transformative Pathways modeling.

Petroleum Refining

Petroleum Trade and Economic Data

Although the United States produces more petroleum than it consumes on average, the domestic petroleum market is strongly linked to global trade of petroleum and petroleum-related products with imports totaling about 40% of domestic production, and this international trade strongly impacts U.S. refining capacity demand. In 2022, across just refined petroleum products, exports were 92 billion gallons and imports were 31 billion gallons, demonstrating that U.S. refining capacity is strongly connected with the global oil market for balancing refinery product slates and supporting both domestic and international demands.

Alongside their importance in energy supply changes, petroleum refineries are a critical subsector to decarbonize, not only as a measure of the volume of GHG emissions to be mitigated but also to maintain U.S. competitiveness in a low-carbon global economy. The American Petroleum Institute estimated that the oil and gas subsector supported 10.8 million direct and indirect jobs and contributed nearly $1.8 trillion to the economy in 2021 with 105,000 jobs and $350 billion attributed to petroleum refining and products specifically.[643]

Refining Production Routes

In this analysis, four production routes are considered, based on feedstock: petroleum crude, coprocessing bio-oils, FOGs, and advanced biofuel (using lignocellulosic and non-FOG waste feedstocks). Production routes are presented assuming two different levels of refining capacity forecasts, one with a relatively flat production capacity between now and 2050 reflecting a BAU projection and a second with a drastic reduction in production capacity reflecting a steep drop in global demand.

As a transition strategy, existing refinery infrastructure may be leveraged to process non-petroleum feedstocks and intermediates to reduce the emissions intensity of the resulting products and offer a negative emissions

[643] American Petroleum Institute, *Impacts of the Oil and Natural Gas Industry on the US Economy in 2021*, prepared by PricewaterhouseCoopers (2023), www.api.org/-/media/files/policy/american-energy/pwc/2023/api-pwc-economic-impact-report-2023.

pathway in combination with CCS. Today non-petroleum feedstocks include bio-oils that come from oil crops and waste oils (e.g., FOGs). These alternative feedstocks are typically refined in dedicated facilities, either conversions of existing petroleum refineries or new builds that are standalone or adjacent to existing facilities.

In recent years, production capacity for leveraging these alternative feedstocks has grown rapidly and expected to nearly double from 3 billion gallons per year at the end of 2022 to 5.9 billion gallons per year at the end of 2025,[644] surpassing relatively stagnant biodiesel production capacity of 2.1 billion gallons per year at the end of 2022.[645] Renewable diesel and biodiesel from waste oils offer 80% reduction in GHG emissions over petroleum diesel, and emissions reductions from oil crops are lower at around 50%.[646] However, further growth is likely to be limited by supply constraints.[647] Additionally, utilizing food crops for oil production may not be sustainable.[648]

To address the limitations and challenges of producing fuels from FOGs, expansion to lignocellulosic and non-FOG waste feedstocks could offer a more substantial emissions mitigation pathway. The 2023 Billion-Ton Report finds that more than 1 billion tons per year of biomass could be sustainably produced in the United States, excluding food-based energy crops, equating to over 60 billion gallons of sustainably produced liquid fuels.[649]

Although the refining subsector has largely bypassed co-processing FOG, a transitional period could be advantageous with these next generation biogenic feedstocks, given the more nascent state of technological development for both feedstock pre-processing and bio-oil refining. Co-processing non-FOG bio-oils could support a future bio-economy supply chain by creating a significant market demand for bio-oil production from lignocellulosic and waste feedstocks over the limited FOG refined today. Only a small fraction of bio-oil can be co-processed with petroleum, but blend constraints may decrease over time with operational experience and technological advancement.

Figure C-31 shows the modeled market growth potential for alternative feedstock routes to petroleum crude, assuming overall refining capacity is maintained at approximately 17 million bbl per day.[650] Any market penetration by an alternative feedstock route results in a demand reduction in the petroleum crude route to maintain the high refining capacity.

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[644] U.S. Energy Information Administration, "Annual Energy Outlook 2023," 2023, www.eia.gov/outlooks/aeo/.
[645] U.S. Energy Information Administration, "Monthly Energy Review," October 2024, www.eia.gov/totalenergy/data/monthly/index.php.
[646] Hui Xu et al., "Life Cycle Greenhouse Gas Emissions of Biodiesel and Renewable Diesel Production in the United States," *Environ. Sci. Technol.* 56, 12 (May 2022): 7512–7521, doi.org/10.1021/acs.est.2c00289.
[647] Tim Fitzgibbon, Khush Nariman, and Brian Roth, "Converting refineries to renewable fuels: No simple switch," McKinsey & Company, June 21, 2023, www.mckinsey.com/industries/oil-and-gas/our-insights/converting-refineries-to-renewable-fuels-no-simple-switch.
[648] Harish K. Jeswani, Andrew Chilvers, and Adisa Azapagic, "Environmental sustainability of biofuels: a review," *Proceedings of the Royal Society A* 476, 2243 (November 2020), doi.org/10.1098/rspa.2020.0351.
[649] U.S. Department of Energy, *2023 Billion-Ton Report*, ORNL/SPR-2024/3103 (2024), www.energy.gov/eere/bioenergy/2023-billion-ton-report-assessment-us-renewable-carbon-resources.
[650] Aligning with the AEO 2023 Reference case.

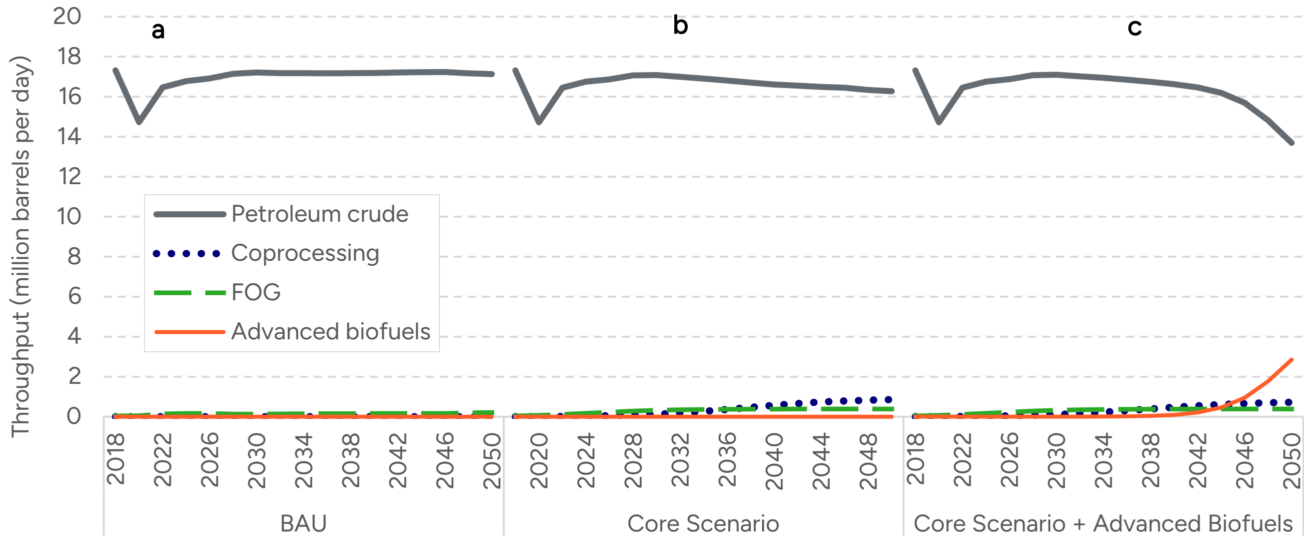

Figure C-31. Production rates for the four feedstock routes (petroleum crude, coprocessing, FOG, and advanced biofuel) in million barrels per day: (a) business as usual (BAU), (b) Core Scenario (CS), and (c) advanced biofuels sensitivity

(a) Aligns with the petroleum crude throughput in the EIA AEO 2023 reference case; (b) shows modest contributions from coprocessing and FOG; and (c) shows coprocessing, FOG, and the valorization of all sustainably-sourced feedstocks. Note: Any increase in throughput from alternative pathways results in an equal reduction in petroleum crude throughput to maintain the overall throughput in the EIA AEO 2023 reference case.

Figure C-31a illustrates the BAU scenario, which reflects the AEO 2023 reference case for projected refining throughput to 2050. Due to incentives for fuels with low life cycle emissions, products like renewable diesel, biodiesel, and synthetic paraffinic kerosene (SPK, a component of sustainable aviation fuel) represented the largest growth area for the refining subsector. Although the FOG feedstock production route has achieved some commercial success, this is supply limited as stated above. The market is projected to reach up to 0.4 million barrels per day by 2050 from its 2018 level of 0.04 million barrels per day, which is a significant increase but not substantial against the over 17 million barrels per day of crude throughput in the United States.[651] Note, this analysis does not include ethanol in the accounting of alternative fuels, as this compound is accounted for the chemicals subsector analysis.

A 2024 report, *The Role of Biofuels and Biomass Feedstocks for Decarbonizing the U.S. Economy by 2050*[652] examines how up to 60 billion gallons of renewable-carbon liquid fuels could be sustainably produced in the United States, excluding food-based energy crops (i.e., about 20% current refinery product volume). Figure C-31b shows modest increases in coprocessing of pyrolysis bio-oils in the fluid catalytic cracker (FCC) and utilization of FOG production routes. The bio-oil coprocessing output assumes that 15% of FCC feedstock is replaced with bio-oil. This is based on estimates of the total amount of pyrolysis oil that could be generated with existing feedstocks and the limits of processing bio-oil in existing FCC units without significant coking or degradation of product yields.[653] This 15% feed limit caps the overall impact of coprocessing at 5% of total petroleum crude throughput in 2050.

Figure C-31c includes impacts of advanced biofuels from standalone biorefineries for advanced biofuels, which represents the final production route considered in this analysis. Although biorefineries are considered a new industry and outside the traditional classification of petroleum refineries (NAICS 324110), the growth in biofuel throughput is represented in Figure C-31 as a direct demand reduction in petroleum crude throughput. A transitional period is expected for these next generation biogenic feedstocks, given the more nascent state of technological development for both feedstock pre-processing and bio-oil refining. Thus, this modeling effort assumes significant deployment of advanced biofuels will not be realized until the 2040s. Scaled across industry, advanced biofuels production could reach an estimated maximum market share of 15%–17%. However, Figure C-

[651] U.S. Energy Information Administration, "Petroleum & Other Liquids," accessed November 2024, www.eia.gov/petroleum/data.php.
[652] Troy R. Hawkins et al., *The Role of Biofuels and Biomass Feedstocks for Decarbonizing the U.S. Economy by 2050*, NREL/TP-5100-87279, ANL-23/56, PNNL-34336, INL/RPT-23-74427, ORNL/SPR-2023/3134 (2024), www.osti.gov/biblio/2337775.
[653] Michael Talmadge et al., "Techno-economic analysis for co-processing fast pyrolysis liquid with vacuum gasoil in FCC units for second-generation biofuel production," *Fuels* 293 (June 2021), doi.org/10.1016/j.fuel.2020.119960.

31 demonstrates that even with maximum commercialization of alternative feedstock routes, if demand for refinery products remains high, alternative feeds will not be sufficient to significantly offset or reduce petroleum crude throughput.

Figure C-32 presents similar deployments of alternative feedstock routes as Figure C-31 but uses more aggressive demand reduction projections which significantly lower the petroleum crude throughput from 2018 to 2050. Figure C-32a and b use a refining throughput that reflects the IEA APS, which projects that global oil demand will decline by around 2% per year on average by 2050. Figure C-32a applies low demand with alternative feedstock projections from the Core Scenario, which include modest impacts from bio-oil coprocessing and FOGs. Figure C-32b further applies maximum advanced biofuels production to the low demand and Core Scenario alternative feedstocks of Figure C-32a. Figure C-32b shows market parity between petroleum crude and alternative feedstock throughputs and represents the only pathway where the refining subsector emissions reach near zero. The petroleum crude remaining in the subsector by 2050 is decarbonized mostly through carbon capture and other decarbonization pillars. This pathway results in 8 million barrels per day throughput in 2050. For reference, the BAU scenario maintains a relatively steady 17 million barrels per day throughput from 2018 to 2050. The transition from BAU to Near Zero will result in a more than 50% reduction in overall demand for liquid fuels.

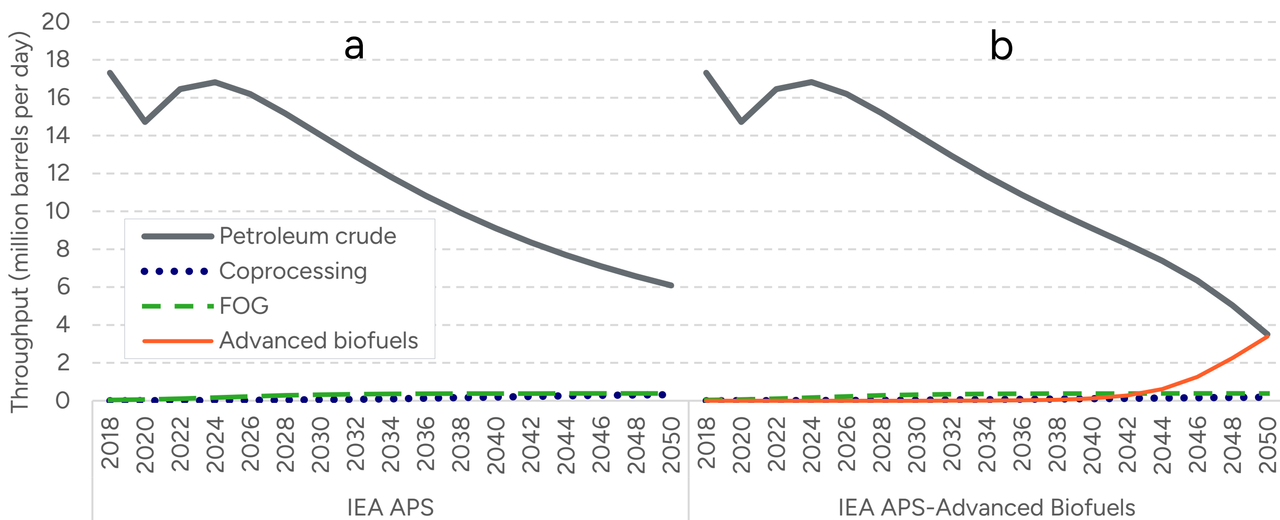

Figure C-32. Production rates for the four feedstock routes (petroleum crude, coprocessing, FOG, and advanced biofuels) in million barrels per day

Assumes a reduction in demand for liquid transportation fuels, which results in a decrease in overall refinery throughput to 2050.(a) IEA Announced Pledges Scenario (APS) with Core Scenario decarbonization conditions; and (b) IEA APS with Core Scenario decarbonization conditions and maximum deployment of advanced biofuels. For scenarios, see: International Energy Agency, World Energy Outlook 2023 (2023), www.iea.org/reports/world-energy-outlook-2023.

A global reduction in liquid transportation fuel demand will be necessary to realize true emissions reduction in the subsector. Otherwise, emissions abated from domestic decarbonization are at risk of being added to other regions in the world. Nevertheless, efforts to decarbonize domestic refining are still important to make the U.S. a low-carbon leader in transportation fuel production. Moreover, biogenic feedstocks generate biogenic fuels which result in significant life cycle emissions benefits for the transportation sector.

In summary, the analysis of alternative production routes demonstrates that these are feed resource limited. No single route will clearly equal or even replace crude refining as the dominant pathway in the 2050 timeframe. Although low demand, coupled with maximum deployment of alternative feedstocks, demonstrates a near zero pathway, this solution is not merely driven by subsector decarbonization measures, but rather is influenced by global economic and market factors that are difficult to forecast.

Analysis Boundary Conditions

Petroleum refineries are organized under the North American Industry Classification System (NAICS) code 324110. The subsector is comprised of establishments primarily engaged in refining crude petroleum into refined petroleum products and includes hydrogen production for refining feedstock and processing of fats, oils, and greases (FOG) feedstocks for renewable diesel and sustainable aviation fuel. Fuel ethanol plants and dedicated biorefineries (including biodiesel and advanced biofuels) are not included under NAICS 324110. These industries belong to the chemicals (NAICS 325) parent subsector.

The energy consumed in refining includes mainly natural gas, electrical power and self-generated fuels. A distinguishing element of petroleum refineries is that over half of the subsector's fuel is self-generated in the forms of refinery fuel gas and petroleum coke. This represents a fundamental challenge to decarbonizing petroleum refining, because decarbonization solutions must consider the energy balance within a given refinery, regardless of whether the facility processes petroleum or non-petroleum feedstocks.

At the plant-level, refineries are a composite of many individual process units (e.g., distillation columns, hydrotreaters, crackers, reformers, isomerization units, cokers), configured in specific and unique ways. Major emissions sources include furnaces, steam generation, and cogeneration and indirect emissions from purchased power. Within those, there are many opportunities to gain efficiency, reduce energy waste, and utilize fuels with low associated GHG emissions. Going beyond plant-level emissions, extraction and transport of crude oil can often generate emissions comparable to refinery direct emissions on a per barrel of crude oil basis, and the eventual combustion of refinery products may be several times more than scope 1 and scope 2 emissions. Although this report focuses on refinery scope 1 and scope 2 emissions, the decarbonization opportunities identified interact with the larger scope 3 supply chain emissions and will be a factor in all decarbonization strategies.

Subsector-specific Sensitivities

The CS for the refining subsector was created based on technologies evaluated across the four decarbonization pillars defined by DOE's Industrial Decarbonization Roadmap[654] and maximizes their adoption rates, while factoring in limited economic, regulatory, and infrastructure constraints to technology adoption. Low-carbon, fuels, feedstocks, and energy sources (LCFFES) were disaggregated to examine the relative impact of each sub-pillar. Reported low maturity technologies for advanced biofuels were also evaluated, with their addition to the market representing a replacement of traditional petroleum crude.[655] Finally, the impact of liquid transportation fuel demand reduction, based on IEA projections, was also considered. Table C-41 and Figure C-33 show the impact of these sensitivities on the CS. The table on the left lists the inputs, both more conservative and more aggressive, than the Core Scenario for each sensitivity. As shown on the chart on the right, the CS, illustrated by the dashed vertical line, estimates a reduction in subsector emissions of approximately 53% (about 130 MMT CO_2) from the 2018 baseline. Low deployment sensitivities show reduced emissions savings to the left of the CS line, and high deployment sensitivities show greater emissions savings to the right of the Core Scenario line. Some sensitivities show multiple outputs, such as high 'Changes in demand'. These inputs in the table are separated by a slash mark and are visualized as separate shades of blue in the chart.

Table C-41. Petroleum Refining Model Sensitivities

Sensitivity	Low	Core Scenario	High
Hydrogen	100% fossil-based	25% H_2 CCS Retrofit 25% Purchased H_2	50% H_2 CCS Retrofit 25% purchased H_2*
Grid	BAU Grid	~90% decarbonized in 2050	Net zero Grid / 50% electric boilers
Carbon Capture	No CCS / 20% decrease	25% H2, 25% Cogen, 5% FCC, 5% general	20% increase

[654] U.S. Department of Energy, *Industrial Decarbonization Roadmap*, DOE/EE-2635 (2022), www.energy.gov/industrial-technologies/doe-industrial-decarbonization-roadmap.
[655] Troy R. Hawkins et al., *The Role of Biofuels and Biomass Feedstocks for Decarbonizing the U.S. Economy by 2050*, NREL/TP-5100-87279, ANL-23/56, PNNL-34336, INL/RPT-23-74427,
ORNL/SPR-2023/3134 (2024), www.osti.gov/biblio/2337775.

Energy Efficiency	0.5% per year reduction in energy intensity	1.0% per year reduction in energy intensity	N/A
Advanced Biofuel	N/A	None	Max Deployment
Renewable Natural Gas	None	10% biogas blended in natural gas	20% biogas blended in natural gas
Changes in Demand	N/A	AEO 2023 Reference	IEA Stated Policies / IEA Announced Pledges
Coprocessing and FOGs	AEO 2023 Reference FOG	5% coprocessing IEA High FOG	7.5% coprocessing IEA High FOG

*Purchased H_2 assumed as 0.45 kg CO_2e/kg H_2

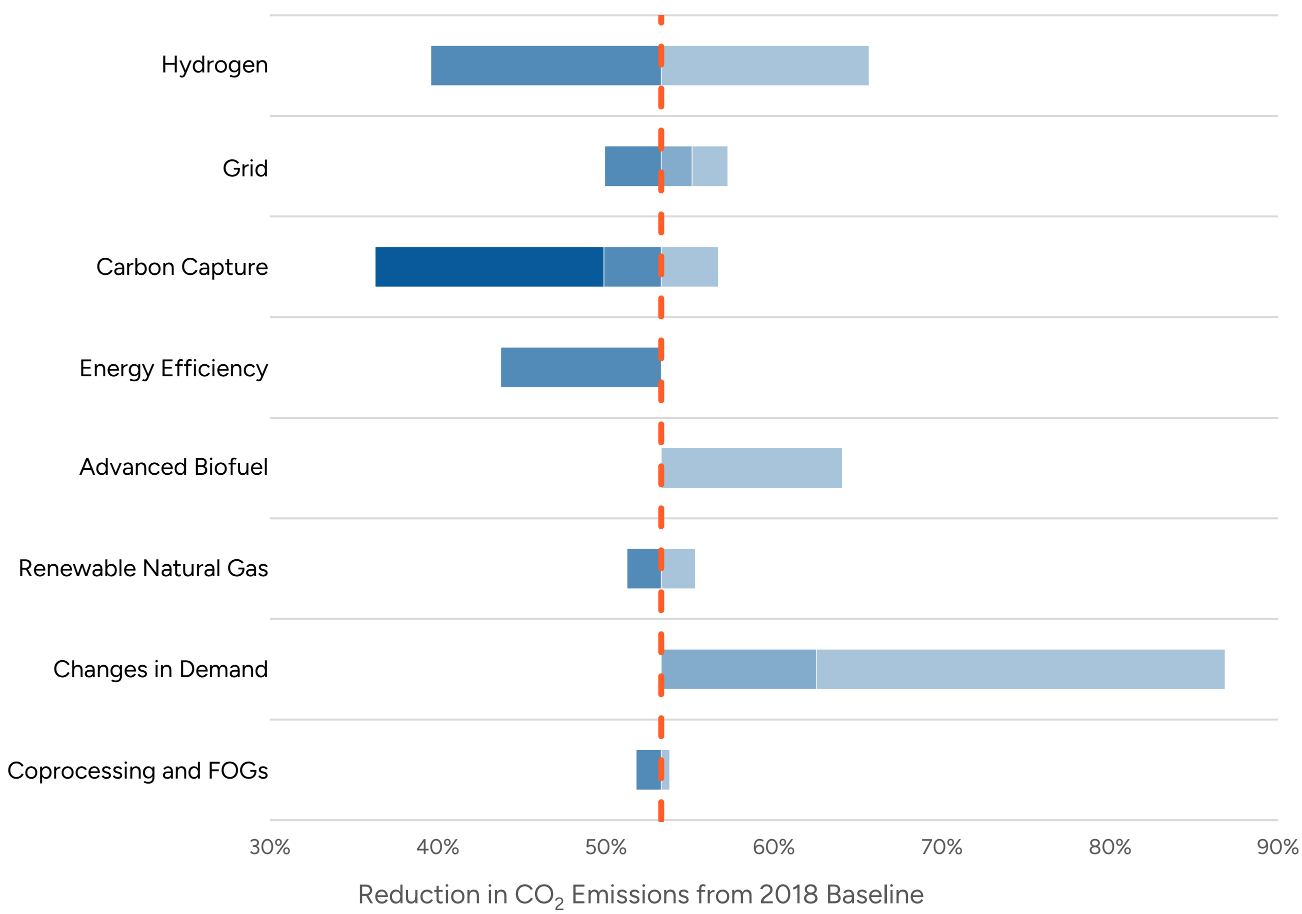

Figure C-33. Petroleum refining subsector sensitivity impact analysis

Note: Based on changing individual assumptions, as such, bars are not additive. Source: Transformative Pathways modeling.

Given the high utilization of hydrogen feedstock in petroleum refining, subsector decarbonization is highly sensitive to the carbon intensity (CI) and the relative amount of low CI hydrogen available to the subsector. Maintaining the status quo of 100% SMR hydrogen will reduce the 2050 decarbonization targets by up to 15%, while increasing the utilization of low CI hydrogen feedstock from 50% to 75% will increase maximum decarbonization potential of the CS by up to 15%. The analysis factors in both equipping existing onsite hydrogen production with carbon capture technology and the purchase of merchant low CI hydrogen. To note, this analysis does not expect significant amounts of electrolysis hydrogen to be available to the subsector in the 2050 timeframe. Moreover, this analysis does not consider fuel switching with hydrogen, because the subsector must balance the utilization of self-generated fuels. Fuel switching with hydrogen could possibly create a scenario of excess refinery fuel gas in the system, which is an unapproachable situation for refiners.

Carbon capture deployment also highly affects decarbonization outcomes in the refining subsector. Carbon capture is very attractive because it represents a sink for excess refinery fuel gas to generate the steam necessary to regenerate sorbents. The deployment of carbon capture technologies was based on cost of abated carbon estimates that are shown in the Appendix. In short, hydrogen and cogeneration units represent the most likely candidates for initial deployment of capture technology, due to the relative purity of the waste stream. FCCs and general combustion units are less likely due to the contamination of the waste stream with catalyst fines and capital burden of capturing distributed, lower volume emissions sources, respectively. To note, deployment of capture technology is highly dependent on access to CO_2 pipelines, and significant increases of CO_2 pipeline infrastructure will be needed to accommodate rates of capture reported herein.

Efficiency is also a very sensitive decarbonization lever. Should the 1% per year reduction of energy intensity reported in the CS be halved, this results in a nearly 10% reduction in maximum subsector decarbonization by 2050. The EIA AEO 2023 estimates reduction in energy intensity at a rate of 0.3% per year, while some major refiners surveyed in the analysis estimate annual energy intensity reductions of 0.3%–0.5% per year.[656,657] This further reinforces that investment in energy efficiency measures will be critical to achieving aggressive reductions in energy intensity rates.

Changes in demand represent the single most impactful sensitivity. Aggressive deployment of advanced biofuels may offset some petroleum crude throughput, increasing the maximum decarbonization of the subsector by up to an additional 10%.[658] Reduction in overall demand for liquid transportation fuel in conjunction with the other decarbonization pillars is, however, the only case that will push the subsector to greater than 90% decarbonization. As discussed in the previous section, this must be a global reduction in demand to prevent offshoring of emissions to other world regions.

Given that over half of the subsector's fuel consumption is provided by self-generated fuels, petroleum refining is not highly sensitive to grid decarbonization, as the subsector is a poor candidate for electrification. In addition, deployment of alternative energy sources, such as renewable natural gas, has little impact on subsector decarbonization. In short, hydrogen feedstock, carbon capture, efficiency, and demand reduction measures represent the decarbonization levers with the greatest influence over the petroleum refining subsector.

Figure C-34 shows the sensitivities range from 15% to 99% reduction with the CS of approximately 55%. This data includes only scope 1 and scope 2 emissions, and neither the downstream combustion of refinery products, nor the upstream feedstock production.

[656] Marathon Petroleum, "Sustainability," 2024, www.marathonpetroleum.com/Sustainability/.
[657] Shell, "Sustainability Report 2022," 2023, reports.shell.com/sustainability-report/2022/.
[658] Troy R. Hawkins et al., *The Role of Biofuels and Biomass Feedstocks for Decarbonizing the U.S. Economy by 2050*, NREL/TP-5100-87279, ANL-23/56, PNNL-34336, INL/RPT-23-74427, ORNL/SPR-2023/3134 (2024), www.osti.gov/biblio/2337775.

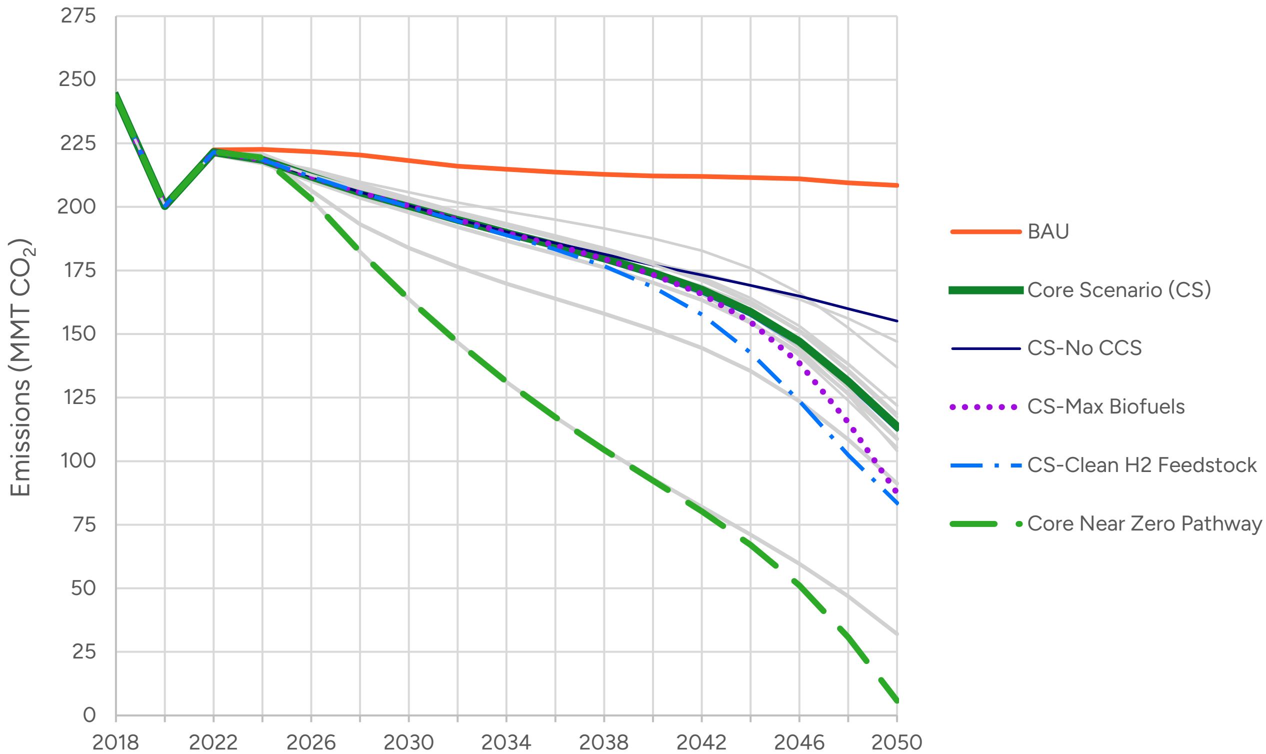

Figure C-34. Decarbonization potential within the petroleum refining subsector

The Core Scenario (CS) is shown in red. The BAU scenario is shown in purple. The Core Near Zero Pathways is shown in light blue. All other curves are the sensitivities with the colored curves representing sensitivities with significant influence over subsector decarbonization (see Figure C-33 and Table C-41). Source: Transformative Pathways modeling.

Business as Usual, Core Scenario, and Core Near Zero Pathway

Figure C-35 shows the breakdown of projected direct emissions impacts of each decarbonization pillar in the CS, which equates to approximately 130 MMT CO_2e (about 55%) reduction in emissions from the 2018 baseline. Energy efficiency plays a major role in refining decarbonization, and decarbonization outcomes in refining are highly sensitive to the durability of energy efficiency measures to 2050. The CS assumes an annual energy intensity reduction of 1.0% per year. Some major refiners surveyed in the analysis estimate annual energy intensity reductions of 0.3%–0.5% per year.[659,660] This further reinforces that investment in energy efficiency measures will be critical to achieving aggressive reductions in energy intensity rates. Given the high utilization of hydrogen as a feedstock in petroleum refining, subsector decarbonization is highly sensitive to the carbon intensity (CI) and the relative amount of low CI hydrogen available to the subsector. Maintaining the status quo of 100% SMR hydrogen versus increasing the utilization of low CI hydrogen feedstock from 75% may influence 2050 subsector decarbonization by up to 30%. The analysis factors in both equipping existing onsite hydrogen production with carbon capture technology and the purchase of merchant low CI hydrogen, thus the impacts of low CI hydrogen are captured across electrification, LCFFES, and CCUS pillars.

[659] Marathon Petroleum, "Sustainability," 2024, www.marathonpetroleum.com/Sustainability/.
[660] Shell, "Sustainability Report 2022," 2023, reports.shell.com/sustainability-report/2022/.

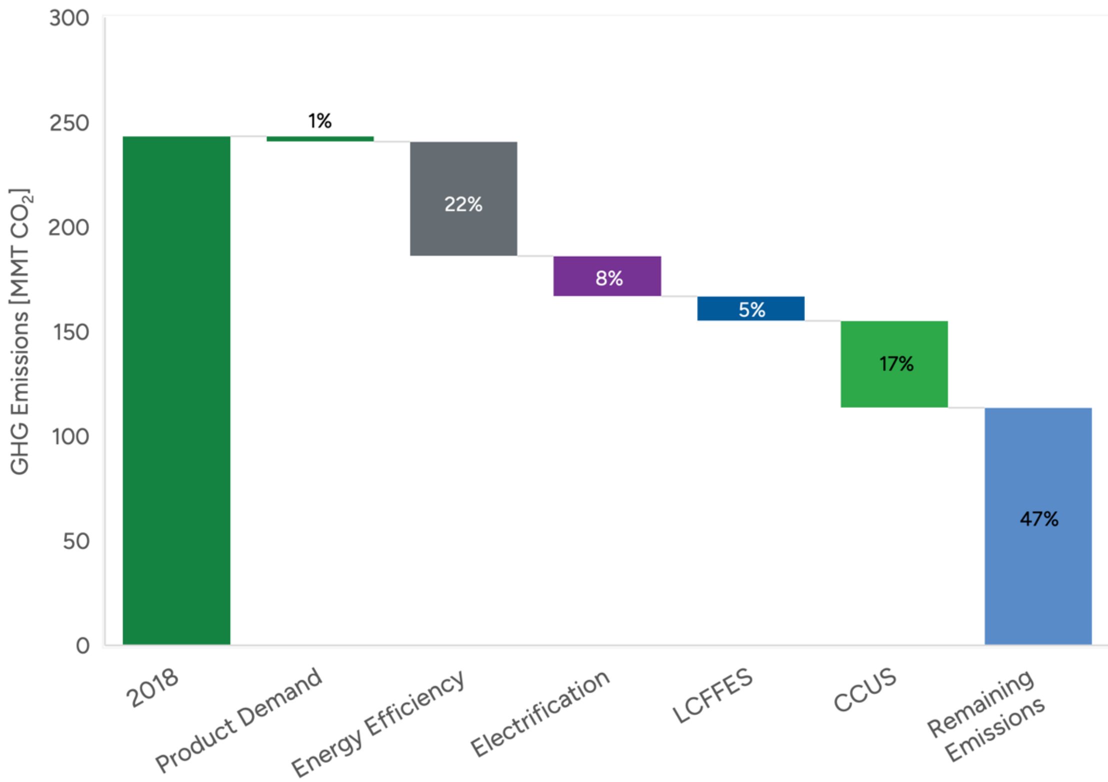

Figure C-35. Impact of decarbonization pillars on GHG emissions, U.S petroleum refining–Core Scenario (MMT CO_2e), 2018–2050

Source: Transformative Pathways modeling.

Decarbonization Strategy for Petroleum Refining Industry Leaders

The CS is a blend of multiple decarbonization measures that reflects the average decarbonization potential of the U.S. refining subsector, aggressively deploying a broad portfolio of decarbonization options. Actual decarbonization potential will be location specific and will depend on numerous factors. At the facility level, opportunities may be constrained by geography and depend on the size and complexity of individual refineries. Refiners must make strategic decisions, given that the portfolio of decarbonization strategies may be appropriate to different types of refiners and their individual circumstances.

Each refinery will need to develop a decarbonization strategy specific to their facility. In doing so, there are several key considerations that will influence the route each facility will take. Key variables include:

- General refinery location: Access to infrastructure will be critical for issues such as availability of CO_2 pipelines and distance to sequestration sites. In the near term, facilities that can access existing CO_2 pipelines and sequestration sites will likely advance carbon capture sooner than facilities located in other locations. Additionally, facilities located near the developing low CI hydrogen production facilities will have additional advantages. This analysis includes the geolocation of each operating refinery in the United States with an overlay of expected CO_2 and hydrogen infrastructure buildout, which allows the development of assumptions regarding access to decarbonization infrastructure. Finally, location will also be influenced by the logistical constraints of sustainably sourcing and delivering alterative feedstocks to the refinery.
- Facility size and ability to accommodate large CAPEX projects: larger facilities also have more process units, resources, and flexibility, likely giving a refiner more potential decarbonization opportunities.
- Regulatory drivers and regional incentives, such as California's Low Carbon Fuel Standard, which will drive technology replacement within existing markets to promote utilization of petroleum crude alternatives.
- Complexity and access to markets: Refiners with access to multiple markets and supply routes will likely have more flexibility to provide low-carbon products to the market.

The considerations above reveal three representative strategies that refineries may take to lower emissions (Table C-42). Refineries that are in more advantageous locations for hydrogen and CO_2 capture infrastructure, such as the Gulf Coast region, and/or those that have access to capital will likely focus on major projects that reduce onsite emissions (i.e., scope 1 focus). Refineries that are constrained by geography or the ability to pursue capital-intensive onsite decarbonization projects will likely focus on energy efficiency measures and purchase decarbonized fuels and feedstocks (i.e., scope 2 focus). Finally, refineries may opt to prioritize aggressive deployment of alternative feedstock production routes and the decarbonization of their products, rather than Scope 1 and 2 emissions reductions (i.e., scope 3 focus). Figure C-36 shows the profile of emissions reduction from 2018 to 2050 for the three distinct decarbonization strategies. Important to note in Figure C-36 is the three strategies result in very similar decarbonization outcomes for the petroleum refining subsector in 2050.

Table C-42. Refining Decarbonization Strategy Assumptions

Decarbonization Strategy	Assumptions
Refiners focus on onsite decarbonization projects (scope 1 emphasis)	• AEO 2023 Reference Demand • High renewable diesel (RD)/sustainable aviation fuel (SAF) from FOG • 0.7%/year efficiency improvements • 45% CCS • 25% Purchased low CI hydrogen • No biogas/renewable natural gas (RNG) • 25% steam system electrification • High (5%) FCC coprocessing • Net zero electric grid
Refiners focus on energy efficiency and supply decarbonization (scope 2 emphasis)	• AEO 2023 Reference Demand • High RD/SAF from FOG • 1.0%/year efficiency improvements • 25% CCS • 50% Purchased low CI hydrogen • 10% biogas/RNG • No electrification • Low (2.5%) FCC coprocessing • Net zero electric grid
Refiners focus on alternative feedstocks (scope 3)	• AEO 2023 Reference Demand • Maximum alternative production routes (coprocessing, FOGs, and advanced biofuels) • 0.5%/year efficiency improvements • Net zero electric grid

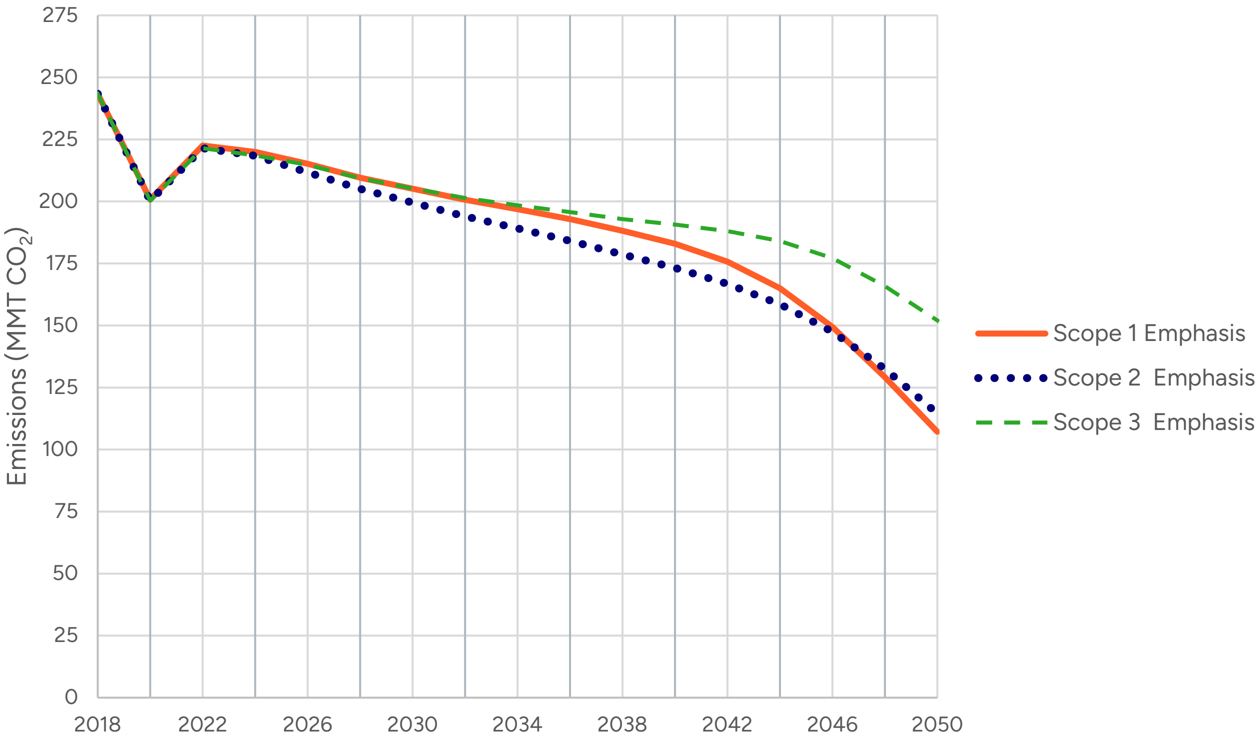

Figure C-36. Annual GHG emissions reductions, U.S. petroleum refining–Scopes 1, 2, and 3 emphases (MMT CO_2/year), 2018–2050 (capacity aligned with AEO 2023 Reference Case)

Refining capacity aligned with the EIA AEO 2023 Reference Case. Source: Transformative Pathways modeling.

Scope 1 emphasis refers to an approach that emphasizes decarbonization through a smaller number of large-scale projects across the refining subsector. This results in a slight deemphasis of energy efficiency measures and purchase of low CI fuels and feedstocks, with significantly more carbon capture deployment and electrification than the low CAPEX archetype. For larger facilities in refining-dense areas such as the Midwest and Gulf Coast regions, these facilities will likely have more options for decarbonization along with more access to supporting infrastructure. For clarification, the 40% CCS deployment is the subsector average, with refineries in the Gulf Coast and Midwest gaining CO_2 pipeline access at 75% and 25%, respectively. Additionally, larger facilities have the advantage of economy of scale benefits due to their relative size. As such, this archetype also realizes a degree of electrified steam generation and maximum amount of FCC co-processing. With more capital directed to major projects, there is expected to be a less aggressive rate of annual energy efficiency improvement.

Scope 2 emphasis refers to an approach that emphasizes decarbonization through many, smaller-scale energy efficiency projects across the refinery and the decarbonization of supply through purchase of low CI power, fuels, and hydrogen feedstock. This category includes refineries in locations with limited infrastructure access and/or those that seek lower capital, such as refiners outside of the Gulf Coast and/or smaller facilities in higher populated areas with limited access for growth, such as the Northeast. These refineries will seek to maximize energy efficiency and will invest little capital to engage in any high-risk replacement or modification of processes; hence the lower amount of co-processing, carbon capture, and electrification in 2050.

Scope 3 emphasis refers to a possible future that invests in feedstock replacement approaches and assume that refineries not only have access to appropriate feedstocks but also the logistics systems to deliver them to the refinery. This strategy emphasizes technology and process replacement and may favor regions with incentives that are well-aligned with product decarbonization, such as the Low Carbon Fuel Standard in California. This approach maintains a BAU annual energy efficiency improvement and does not include significant scope 1 or scope 2 decarbonization measures, since the subsector would take credit for downstream emissions reductions in the transportation sector via combustion of biogenically-derived fuels. The scope 3 curve in Figure C-36 only shows scope 1 and scope 2 emissions reductions in the refining subsector by 2050. These reductions arise from annual energy efficiency improvements, a net zero grid by 2050, and the modest onsite emissions reduction associated with processing alternative feedstocks. The downstream emissions impacts may be several times greater than those realized onsite.

In summary, pathways for the refining subsector's decarbonization are largely dependent on the rapid deployment of clean infrastructure (scope 1). Those that cannot access the infrastructure will aim to maximize efficiency and purchase low CI supply (scope 3). Refineries with favorable incentives and robust alternative feedstock supply chains may focus on production route replacement to supply the market with renewable fuels. Given the timeline of incentives from legislative actions, the subsector will need to make decisions in the late 2020's through early 2030's on whether to invest capital into any given pathway. Regardless of which pathway the subsector takes, the most important consideration to note is that the three strategies do not reach net zero emissions by 2050, and some pathways are expected to be more durable in a post-2050 timeframe than others. The scope 2 emphasis strategy will likely be the first to reach a decarbonization limit, with diminishing returns, as energy efficiency measures are applied to increasingly lower overall emissions over time. Scope 1 decarbonization measures could possibly reach greater decarbonization levels, assuming sustained buildout of carbon capture, power, and clean hydrogen infrastructure. However, continued processing of petroleum feedstocks at high refining capacities will inhibit the subsector from reaching absolute zero. Scope 3, assuming credit is taken for downstream emissions abatement, could reach highest overall emissions reduction. However, the maximum deployment of alternative pathways with sustainably sourced feedstocks will ultimately be insufficient to offset overall domestic demand, assuming the subsector maintains a high refining capacity in 2050.

Furthermore, the three strategies result in relatively similar decarbonization outcomes, yet the technological pathways taken for each are different and faces different barriers, uncertainties, and decision points. Table C-43 below summarizes many of these key elements for each strategy.

Table C-43. Petroleum Refining Decarbonization Strategy Details

Strategy	Scope 1 emphasis	Scope 2 emphasis	Scope 3 emphasis
Primary technologies (% deployment)	• Aggressive carbon capture (75% on Gulf Coast, 25% in Midwest) • Purchase of low carbon intensity (CI) hydrogen (25%) • Limited energy efficiency due to resource limitations (0.7% per year energy intensity reduction) • Primary boiler electrification (25%)	• Purchased fuels renewable natural gas (10%) and H2 as a feedstock (50%) • EE approaches (1% per year energy intensity reduction): advanced heat exchangers, digital controls, advanced furnace designs	• Maximum deployment of alternative feedstock production routes • Limited energy efficiency (0.5% per year energy intensity reduction) • Reduction of national refining capacity by more than 60%
Major barriers to developing and accelerating deployment of the key technologies and solutions	Higher risks projects that 1) are lower maturity and 2) are tied to incentives	• Requires multiple small projects implemented across several process technologies • Purchasing of lower CI fuels will increase OPEX	• Development of supply chains for maximum advanced biofuel deployment, given all available sustainable feedstocks are taken by the refining subsector • Lower efficiency at lower utilization for existing assets
Major uncertainties/ Primary drivers to determine this strategy	Aggressive deployment needed to leverage incentives, during allowable window based on legislation	• Clean energy infrastructure accessibility in the 2050 timeframe • Deployment of merchant clean H2 production	• Shrinking of the refining subsector • Major economic and market drivers that impact refining capacity and inhibit market from exporting products
Economic, environmental, and societal impacts	• Uncertainty with land acquisition for pipeline and CO2 sequestration site permitting, construction, and commissioning • Will likely come with significant public comment	• Largely avoids societal challenges related to buildout of CO2 infrastructure site permitting, construction, and commissioning • Follows subsector historical investment	• Possible reduction in economic contribution to U.S. gross domestic product • Impacts to direct and indirect jobs
Major decision points/timing between now and 2050 and needed info	Given infrastructure buildout scale, engineering, procurement of materials, and construction will need to be done efficiently, cost effectively, and on schedule for mega projects to reach target impact and achieve necessary incentives to offset financial risks	To allocate capital investment, refiners will need clear indication in the 2030s if clean energy infrastructure will be accessible. If not, they will likely divert capital to EE which will hamper possible investment in later decades	Regulatory, economic, or market developments that create conditions that limit refinery profitability

How much of subsector expected to choose strategy	Most likely adopters include large Gulf Coast refineries near pipelines, Midwest refineries that can integrate with ethanol pipelines, refineries with access to Regional H2 Hubs, refineries with favorable alternative feedstock logistics routes	Regions with limited clean infrastructure access, such as the East, Rocky Mountain, and parts of the Midwest regions	• Reduction of refining capacity, possibly favoring large, complex assets on Gulf Coast • Refiners in regulatory environments that promote generation of lower carbon products such as sustainable aviation fuel and renewable diesel

Potential Impact from Reduced Refining Capacity

Even greater levels of decarbonization by 2050 may be achieved with significant reduction in refining capacity, possibly due to a reduction in demand for transportation fuels. This would likely require market conditions that 1) reduce domestic fuel consumption, 2) make exports of domestic refinery products disadvantageous, and/or 3) result in a global reduction in refinery product demand. Figure C-37 presents the same strategic approaches from Figure C-36 (scope 1, scope 2, and scope 3 emphasis), but with the reduced refining capacity in the IEA APS. An important consideration to keep in mind is that forecasting the economic and society impacts of such a future is difficult, given the contribution of petroleum refineries to gross domestic product and both direct and indirect job creation.

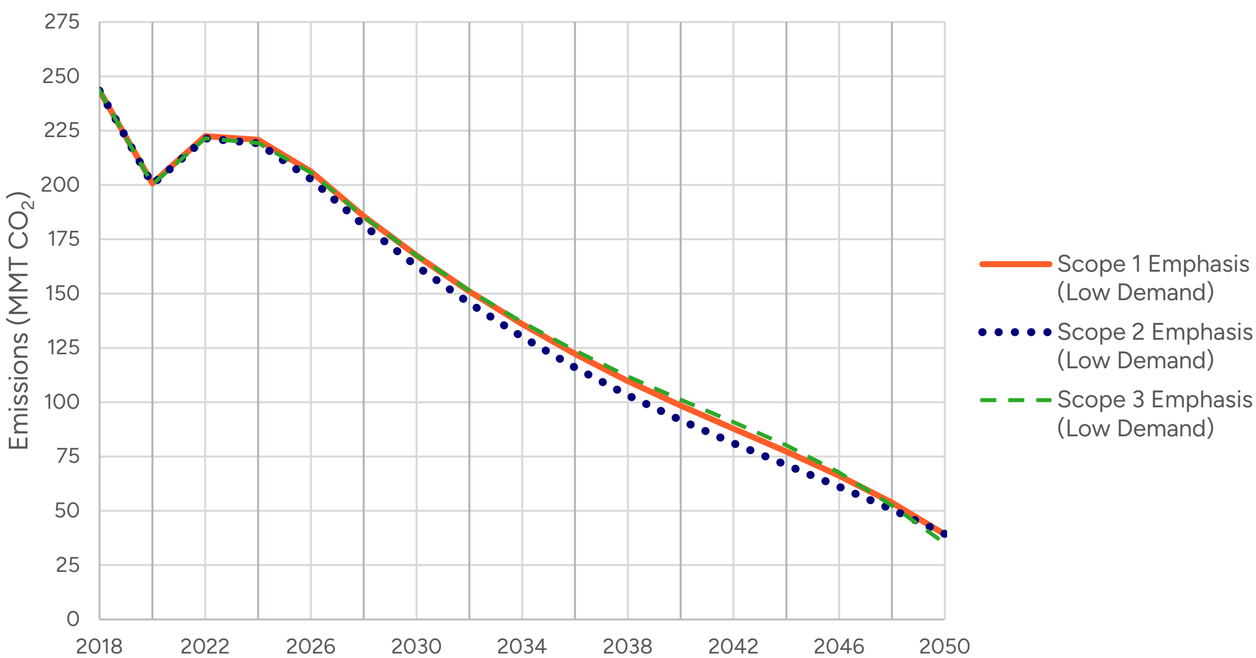

Figure C-37. Annual GHG emissions reductions, U.S. petroleum refining–Scopes 1, 2, and 3 emphases (MMT CO_2/year), 2018–2050 (capacity aligned with IEA APS)

Refining capacity aligned with the IEA APS. Source:Transformative Pathways modeling.

The scope 3 curve includes the low demand refining capacity reduction with maximum deployment of alternative feedstock production routes. The strategy represents the case with the maximum possible refining capacity in a low demand scenario. In this case, overall refining capacity decreases to 8 million barrels per day in 2050 (more than 50% capacity reduction from 2018 levels), with 50% of capacity coming from petroleum crude and 50% coming from alternative feedstocks, predominantly advanced biofuels. The approximately 4 million barrels per day of remaining petroleum crude capacity may then be effectively decarbonized by traditional decarbonization pillars: high energy efficiency, fully decarbonized hydrogen feedstock utilization, and high deployment of carbon capture on process units within the subsector; resulting in a true near zero scenario.

A promising economic impact of maximum deployment of alternative feedstock routes is the potential emergence of new industries, supply chains, and workforce across the market, including upstream feedstock collection, processing, and logistics; deployment of greenfield integrated biorefining assets; and potentially a shift in the downstream customer base (i.e., emphasis on renewable diesel and SAF product slates).

Pulp and Paper

The following tables and figures provide detailed methodology and assumptions considered in this analysis. The adoptions have been based on literature[661] and discussion with subsector experts.

Table C-44. Unit Operations and Energy Intensities for Each Product Type in the Pulp and Paper Subsector Model

Mill	Unit Process	Fuel Intensity (GJ/MT product)	Steam Intensity (GJ/ MT product)	Electricity Intensity (kWh/ MT product)	Energy Intensity (GJ/ MT product)
Market and specialty pulp	Woodyard	0	0	0.36	0.36
	Pulping/ Cooking	0	3.76	0.35	4.11
	Screening/ Refining	0	0	0.78	0.78
	Evaporation	0	4.01	0.15	4.16
	Chemical prep.	2.20	0	0	2.20
	Bleaching	0	4.46	0.45	4.92
	Repulping	*0.93*	*0*	*0.45*	*1.38*
	Total				**16.53**
Recycled paper and paperboard	Repulping	0	0.47	0.35	0.81
	Wet end (washing, screening, thickening, refining, cleaning)	0	0	0.55	0.55
	Forming and pressing, Drying	0	8.14	1.28	9.42
	Finishing (Calendaring, Winding, Cutting, Trimming)	0	0	0.2	0.2
	Total				**10.98**
Tissue and hygiene products	Stock preparation	0	0.34	0.35	0.69
	Wet end (washing, screening, thickening, refining, cleaning)	0	0	0.55	0.55
	Forming and pressing	0	0	1.05	1.05
	Drying	0	6.49	0.23	6.72
	Finishing (Calendaring, Winding, Cutting, Trimming)	0	0	0.20	0.20
	Through-Air Drying (TAD)	*27.0*	*0*	*5.4*	*32.4 (56% adoption)*
	Total				**9.22 (not including TAD)**
Specialty paper	Stock preparation	0	0.47	0.35	0.81
	Wet end (washing, screening, thickening, refining, cleaning)	0	0	0.55	0.55

[661] Such as Christophe G. Owttrim et al., "Energy efficiency as a critical resource to achieve carbon neutrality in the pulp and paper sector," *Journal of Cleaner Production* 360 (August 2022), doi.org/10.1016/j.jclepro.2022.132084.

Mill	Unit Process	Fuel Intensity (GJ/MT product)	Steam Intensity (GJ/ MT product)	Electricity Intensity (kWh/ MT product)	Energy Intensity (GJ/ MT product)
	Forming and pressing	0	0	1.05	1.05
	Drying	0	8.14	0.23	8.37
	Finishing (Calendaring, Winding, Cutting, Trimming)	0	0	0.20	0.2
	Total				**10.98**
Packaging paper and paperboard	Woodyard, Pulping/ Cooling, Screening/ Refining	0	4.4	1.36	5.76
	Evaporation	0	4.7	0.15	4.85
	Chemical prep.	2.2	0	0	2.2
	Bleaching	0	5.22	0.42	5.64 (only for bleached products)
	Wet end (stock prep, washing, screening, thickening, refining, cleaning)	0	0.47	0.90	1.37
	Forming and pressing, Drying	0	8.13	1.28	9.41
	Finishing (Calendaring, Winding, Cutting, Trimming)	0	0	0.2	0.2
	Total				**29.41**

References: U.S. Department of Energy, Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Pulp and Paper Manufacturing (2015), www.osti.gov/biblio/1248750; Jibran Zuberi, Ali Hasanbeigi, and William Morrow, Electrification of U.S. Manufacturing With Industrial Heat Pumps, LBNL-2001478, (Lawrence Berkely National Laboratory, 2022), eta.lbl.gov/publications/electrification-us-manufacturing; Brown, Hamel, and Hedman, Energy analysis of 108 industrial processes (1996), www.osti.gov/biblio/5576602; U.S. Department of Energy, Pulp and Paper Industry Energy Bandwidth Study (2006), www.osti.gov/biblio/1218635.

Note 1: Recovery and auxiliary boilers were assumed to match the steam generation requirement from the mill.

Note 2: Italicized processes are alternative processes, which change the throughput of other processes.

Table C-45. Summary of Sensitivity Cases Considered for the Pulp and Paper Model

Sensitivity	Sensitivity case	Net emissions in 2050 (MMT CO_2e) (excluding biogenic emissions, including captured carbon)	Net electricity demand in 2050 (MMBtu)	Net fuel demand in 2050 (MMBtu)	Net energy (fuel and electricity) demand in 2050 (MMBtu)
BAU	N/A	92,175	403	1,796	2,199
Core Near Zero scenario	N/A	5,584	440	1,632	2,072
Use of green H_2 as a fuel	Low potential H_2 (no adoption)	5,082	440	1,635	2,075
Increased electrification	High potential electrification adoption	3,175	1,002	928	1,930
Increased recycled content	With BAU	72,933	323	1,671	1,994
	With Core Near Zero	6,669	360	1,533	1,893
Impact of demand changes and demand reduction	Adoption of demand reduction strategies	4,086	322	1,149	1,471
Domestic production vs. Imports	Only domestic production, no imports	5,584	322	1,750	2,072
	Increased imports	4,369	390	1,426	1,816
	Increased imports with BAU	65,121	401	1,511	1,912

Table C-46. Decarbonization Technologies Considered by Mill Type and Product and Subsector Production and Emissions Impacts

Production values shown for medium demand growth scenario and emissions under the Core Near Zero pathway

Products	Energy Efficiency	Material Efficiency	Electrification	LCFFES	CCUS	Production in 2050 as % of 2018 (medium scenario)	Production in 2050 as % of 2050 total	Emission in 2050 as % of 2018
Market pulp	As applicable: Debarking upgrades, chip screening & conditioning, advanced digestion additives, waste heat recovery (debarking, pulp machine, digestor, bleach plant, recovery boiler, auxiliary boiler), high efficiency refiners, additional evaporation effects, lime kiln modification, recovery boiler temperature monitoring, batch stock optimization, high consistency forming, press section upgrades, turbulent bars, air supply optimization, improved drying technologies, paper machine vacuum system optimization	Increased recycled content, plan to add deep eutectic solvents and membrane separation once adoption is estimated	Electric boiler modification for auxiliary boiler;	Switch to 100% biomass in repulping and lime kiln, and 80% in auxiliary boiler	33% post combustion carbon capture in boilers and lime kiln	135%	12%	-78%
Specialty pulp						133%	1%	-86
Graphic paper		No imported pulp, but can include this and other alternative pulps				88%	10%	-99%
Tissue, hygiene products		No imported pulp, but can include this and other alternative pulps		Switch to 80% biomass for through-air drying, 70% in auxiliary boiler, 12% hydrogen	33% post combustion carbon capture in boiler	129%	8%	-92%
Specialty paper and others		None		Switch to 80% biomass in auxiliary boiler		95%	5%	-94%
Paper and paperboard		Considered imported pulp, potential for alternative pulp		Switch to 100% biomass in repulping and lime kiln, and 80% in auxiliary boiler	33% post combustion carbon capture in boilers and lime kiln	122%	48%	-99%
Recycled paper and paperboard		Considered imported pulp, potential for alternative pulp		Switch to 80% biomass in auxiliary boiler	33% post combustion carbon capture in boiler	161%	16%	-84%
Total Subsector						122%	100%	-95%

Table C-47. Market and Specialty Pulp Production Decarbonization Technologies Assumptions–BAU Scenario and Core Near Zero Pathway

Unit Process	Energy Intensity in 2018			Decarbonization Technologies	Pillar	Potential to Change Fuel Intensity if 100% Adopted (%)	Potential to Change Steam Intensity if 100% Adopted (%)	Potential to Change Electricity Intensity if 100% Adopted (%)	Assumed Adoption Rate by 2050 (% of U.S. Equipment)	
	Fuel (GJ/MT)	Electricity (kWh/MT)	Steam (GJ/MT)						BAU	Core Near Zero
Woodyard	0	99.40	0	Debarking upgrades (advanced ring or cradle debarkers)	EE	0%	0%	3%	0%	9%
				Debarking with waste heat recovery	EE	0%	0%	11%	14%	36%
				Chip screening and conditioning	EE	0%	0%	3%	5%	9%
Pulping/ Cooking	0	97.20	3.76	Pulp machine heat recovery	EE	0%	2%	3%	6%	14%
				Deep eutectic solvents	EE	0%	41%	0%	0%	0%
				Membrane separation of BL for lignin	EE	0%	-1%	12%	0%	0%
				Advanced digestion additives	EE	0%	1%	0%	10%	21%
				Digester heat recovery	EE	0%	9%	11%	6%	14%
Screening/ Refining	0	217.80	0	High efficiency refiners	EE	0%	0%	38%	7%	13%
Evaporation	0	41.70	4.01	Additional evaporation effects	EE	0%	7%	33%	0%	6%
				Membrane concentration of BL	EE	0%	32%	0%	0%	0%
Chemical Prep	2.20	0	0	Lime kiln modifications	EE	7%	0%	0%	5%	35%
Bleaching	0	127.90	4.46	Bleach plant heat recovery	EE	0%	17%	17%	11%	22%
Recovery Boiler	11.91	0	N/A	Recovery boiler flue gas heat recovery	EE	19%	N/A	0%	1%	31%
				Recovery boiler temperature monitoring	EE	1%	N/A	0%	11%	23%
Auxiliary Boiler	5.75	4.30	N/A	Electric boiler	Elec.	-100%	N/A	100%	3%	20%
				Auxiliary boiler flue gas heat recovery	EE	3%	N/A	0%	0%	12%
Repulping	0.93	126.00	N/A	Repulping	EE		N/A		16%	68%

Table C-48. Integrated Pulp and Papermaking Decarbonization Technologies Assumptions–BAU Scenario and Core Near Zero Pathway (Graphic Paper, Packaging Paper, and Paperboard)

Unit Process	Energy Intensity in 2018			Decarbonization Technologies	Pillar	Potential to Change Fuel Intensity if 100% Adopted (%)	Potential to Change Steam Intensity if 100% Adopted (%)	Potential to Change Electricity Intensity if 100% Adopted (%)	Predicted Adoption Rate by 2050 (% of U.S. Equipment)	
	Fuel (GJ/MT)	Electricity (kWh/MT)	Steam (GJ/MT)						BAU	Core Near Zero
Woodyard, Pulping/ Cooking, Screening/ Refining	0	376.76	4.40	Debarking with waste heat recovery	EE	0%	0%	3%	14%	36%
				Chip screening and conditioning	EE	0%	0%	1%	5%	9%
				Pulp machine heat recovery	EE	0%	2%	1%	6%	14%
				Advanced digestion additives	EE	0%	1%	0%	10%	21%
				Digester heat recovery	EE	0%	8%	3%	6%	14%
Evaporation	0	41.70	4.70	Additional evaporation effects	EE	0%	6%	33%	0%	6%
				Membrane concentration of BL	EE	0%	27%	0%	0%	0%
Chemical prep	2.20	0	0	Lime kiln modifications	EE	7%	0%	0%	5%	35%
Bleaching	0	116.30	5.22	Bleach plant heat recovery	EE	0%	14%	19%	11%	22%
Wet end (stock prep, washing, screening, thickening, refining, cleaning)	0	250.70	0.47	Batch stock optimization	EE	0%	14%	0%	4%	17%
Forming and Pressing, Drying	0	355.30	8.13	High consistency forming	EE	0%	0%	5%	0%	6%
				Press section upgrades	EE	0%	4%	-1%	0%	8%
				Turbulent bars	EE	0%	1%	0%	0%	16%
				Air supply optimization	EE	0%	3%	0%	1%	15%
				Improved drying technologies	EE	0%	6%	3%	0%	6%
Calendaring, Winding, Cutting, Trimming	0	55.60	0	Paper machine vacuum system optimization	EE	0%	0%	5%	12%	24%
Recovery Boiler	10.45	0	0	Recovery boiler flue gas heat recovery	EE	22%	N/A	0%	1%	31%
				Recovery boiler temperature monitoring	EE	1%	N/A	0%	11%	23%
Auxiliary Boiler	20.28	15.33	0	Electric boiler	Elec.	-100%	N/A	100%	3%	20%
				Auxiliary boiler flue gas heat recovery	EE	3%	N/A	0%	0%	12%

Table C-49. Non-Integrated Papermaking Decarbonization Technologies Assumptions—BAU Scenario and Core Near Zero Pathway (Tissue and Specialty Paper)

Unit Process	Energy Intensity in 2018			Decarbonization Technologies	Pillar	Potential to Change Fuel Intensity if 100% Adopted (%)	Potential to Change Steam Intensity if 100% Adopted (%)	Potential to Change Electricity Intensity if 100% Adopted (%)	Predicted Adoption Rate by 2050 (% of U.S. Equipment)	
	Fuel (GJ/MT)	Electricity (kWh/MT)	Steam (GJ/MT)						BAU	Core Near Zero
Stock Preparation	0	96.9	0.34	Batch stock optimization	EE	0%	19%	0%	4%	17%
Wet end (washing, screening, thickening, refining, cleaning)	0	153.0	0	Refining upgrades	EE	0%	0%	30%	7%	13%
Forming and Pressing	0	290.7	0	High consistency forming	EE	0%	0%	7%	0%	6%
Drying	0	64.6	6.49	Paper machine vacuum system optimization	EE	0%	0%	4%	12%	24%
				Turbulent bars	EE	0%	1%	0%	0%	16%
				Air supply optimization	EE	0%	4%	0%	1%	15%
				Improved drying technologies	EE	0%	7%	17%	0%	6%
Calendaring, Winding, Cutting, Trimming	0	55.6	0	Paper machine vacuum system optimization	EE	0%	0%	5%	12%	24%
Through-Air Drying (only for tissue, not at 100% adoption)	27	1,500	0	Through-Air Drying	EE		N/A		56%	56%
Auxiliary Boiler	6.49	6.5	0	Electric boiler	Elec.	-100%	N/A	100%	3%	20%
				Auxiliary boiler flue gas heat recovery	EE	3%	N/A	0%	0%	12%

Table C-50. Recycled Paper and Paperboard Production Decarbonization Technologies Assumptions–BAU Scenario and Core Near Zero Pathway

Unit Process	Energy Intensity in 2018			Decarbonization Technologies	Pillar	Potential to Change Fuel Intensity if 100% Adopted (%)	Potential to Change Steam Intensity if 100% Adopted (%)	Potential to Change Electricity Intensity if 100% Adopted (%)	Predicted Adoption Rate by 2050 (% of U.S. Equipment)	
	Fuel (GJ/MT)	Electricity (kWh/MT)	Steam (GJ/MT)						BAU	Core Near Zero
Repulping	0	96.90	0.47	Continuous repulping	EE	0%	10%	23%	4%	8%
				High consistency recovered fiber pulping	EE	0%	0%	3%	0%	3%
				Repulping rotor upgrades	EE	0%	0%	11%	2%	13%
				Batch stock optimization	EE	0%	14%	0%	4%	17%
				Deinking flotation optimization	EE	0%	0%	3%	5%	9%
Wet end (washing, screening, thickening, refining, cleaning)	0	153.80	0	Refining upgrades	EE	0%	0%	30%	7%	13%
Forming and Pressing, Drying	0	355.30	8.14	High consistency forming	EE	0%	0%	5%	0%	6%
				Press section upgrades	EE	0%	4%	-1%	0%	8%
				Turbulent bars	EE	0%	1%	0%	0%	16%
				Air supply optimization	EE	0%	3%	0%	1%	15%
				Improved drying technologies	EE	0%	6%	3%	0%	6%
Calendaring, Winding, Cutting, Trimming	0	55.60	0	Paper machine vacuum system optimization	EE	0%	0%	5%	12%	24%
Auxiliary Boiler	10.76	8.13	0	Electric boiler	Elec.	-100%	N/A	100%	1%	20%
				Auxiliary boiler heat recovery	EE	3%	N/A	0%	0%	75%

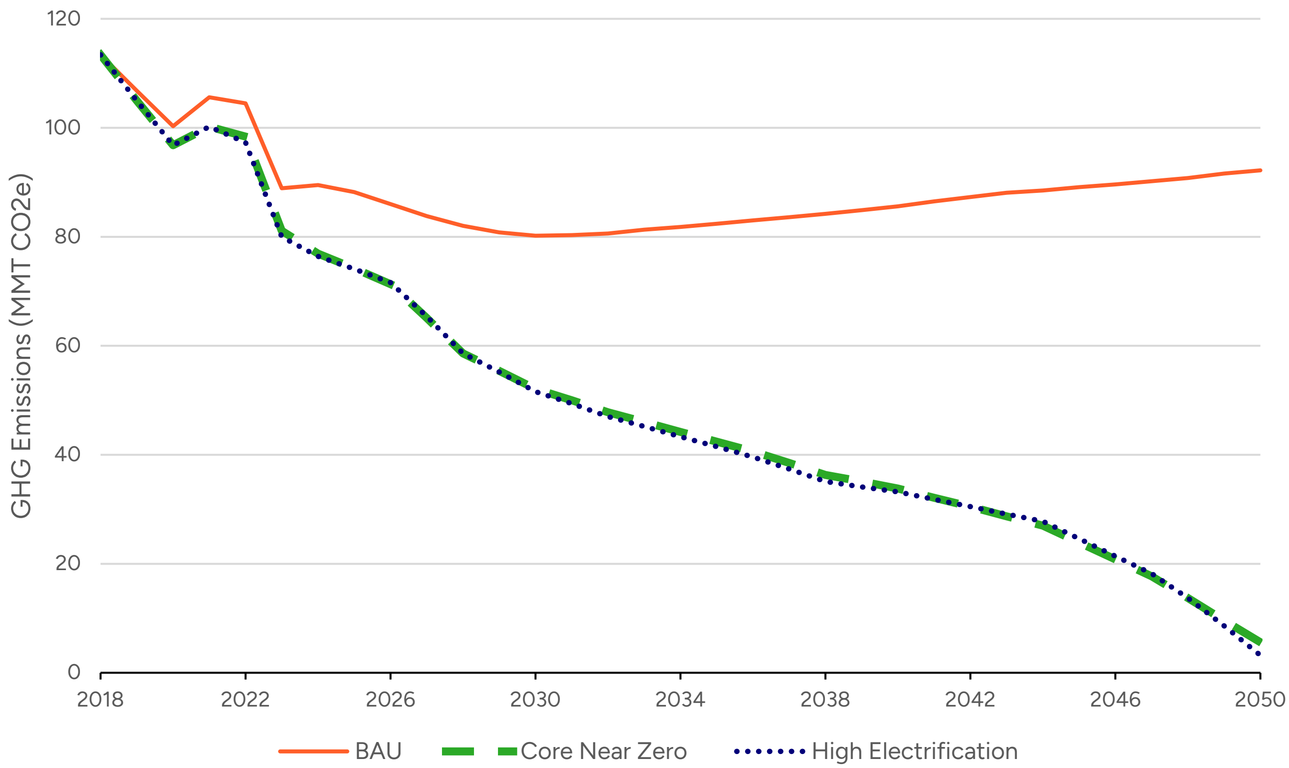

Figure C-38. Annual GHG emissions comparing the BAU, Core Near Zero pathway, and High Electrification sensitivity

Source: Transformative Pathways modeling.

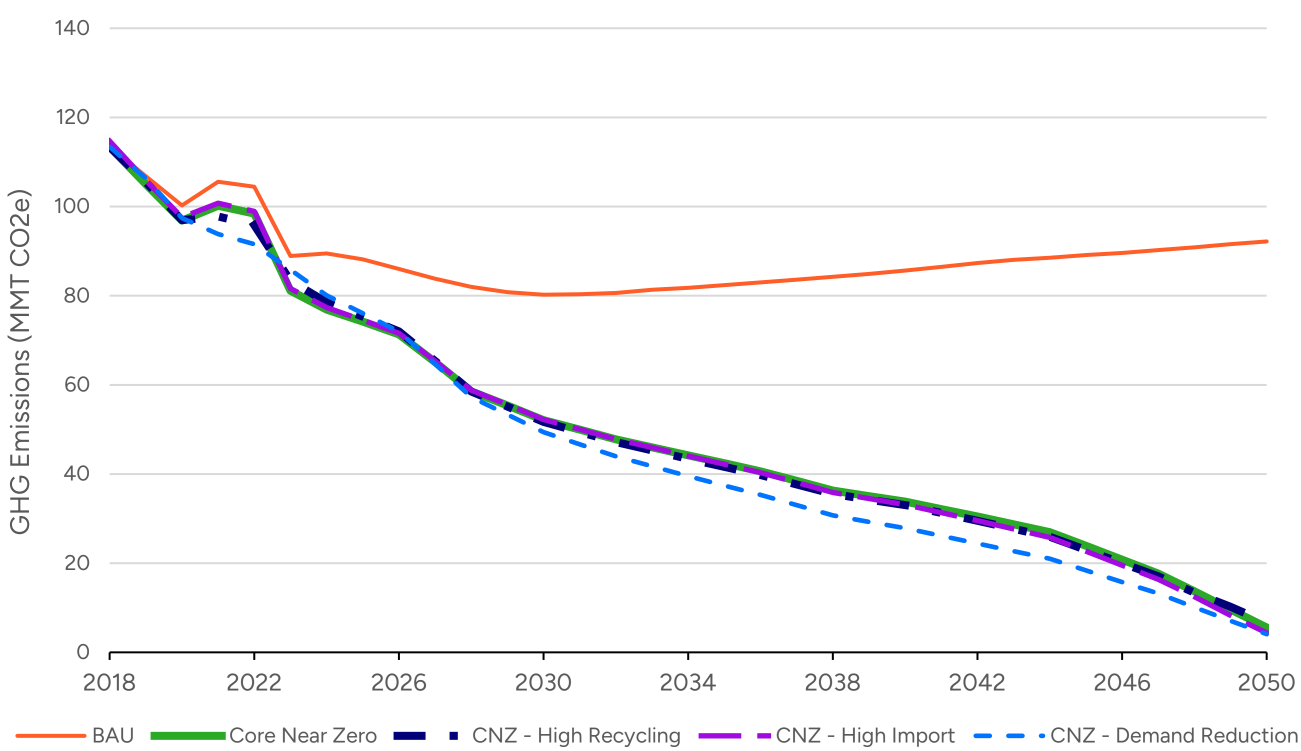

Figure C-39. Annual GHG emissions comparing BAU and Core Near Zero Pathway with high recycling, high import, and demand reduction sensitivities

Source: Transformative Pathways modeling.

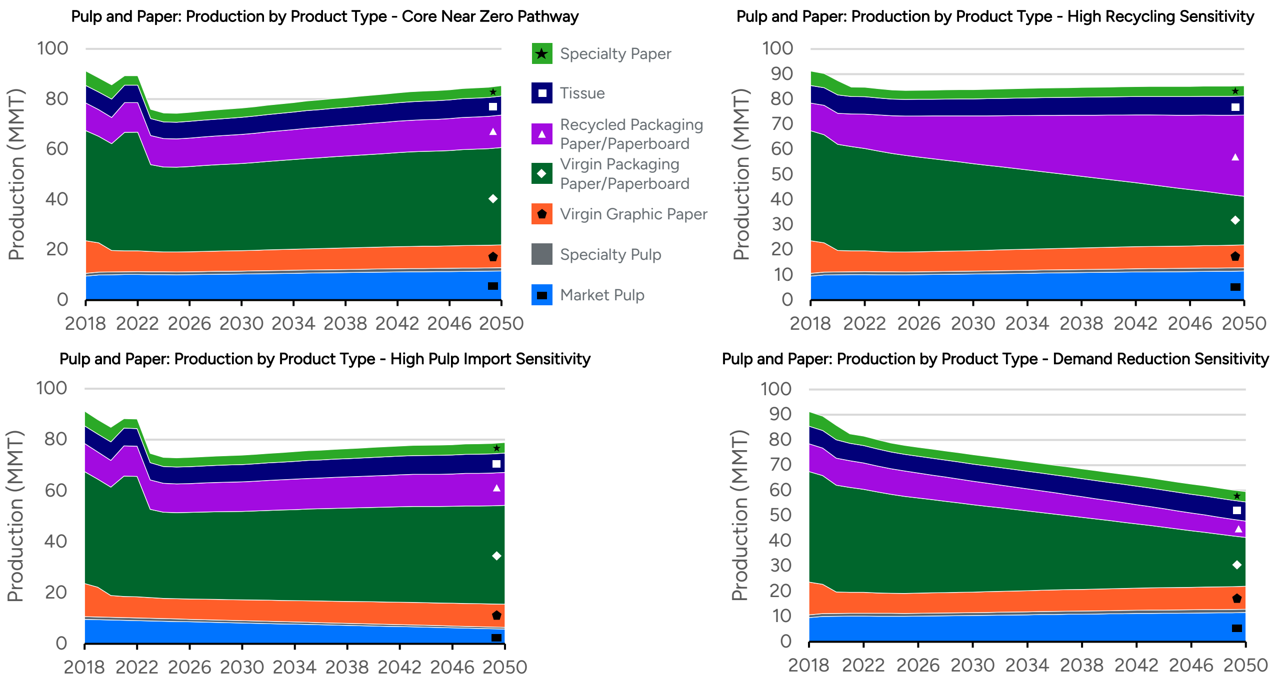

Figure C-40. Production volumes by product type for Core Near Zero Pathway (top left) and the High Recycling (top right), High Pulp Import (bottom left), and Demand Reduction (bottom right) sensitivities, 2018–2050

Source: Transformative Pathways modeling.

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