Industrial Decarbonization Roadmap

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U.S. Department of Energy's Industrial Decarbonization Roadmap

Table of Contents

List of Figures

List of Tables

Acronyms and Key Terms

ACC	American Chemistry Council
ACEEE	American Council for Energy Efficient Economy
AEO	Annual Energy Outlook
AMO	Advanced Manufacturing Office, DOE
ANL	Argonne National Laboratory
BAU	business as usual
BF	blast furnace
BF-BOF	blast furnace-basic oxygen furnace
BOTTLE	Bio-Optimized Technologies to keep Thermoplastics out of Landfills and the Environment (a DOE Consortium)
Btu	British thermal units
BTX	benzene, toluene, and xylenes
CCS	carbon capture and storage
CCUS	carbon capture, utilization, and storage
CDQ	coke dry quenching
CH_4	methane
CHP	combined heat and power
CO	carbon monoxide
CO_2	carbon dioxide
CO_2e	carbon dioxide equivalents
CSP	concentrating solar-thermal power
CST	concentrating solar-thermal energy
DAC	direct air capture
DOE	U.S. Department of Energy
DRI	direct reduced iron
EAF	electric arc furnace
EERE	Office of Energy Efficiency and Renewable Energy, DOE
EIA	U.S. Energy Information Administration
EU	European Union

FOA	funding opportunity announcement
GDP	gross domestic product
GHG	greenhouse gas
H_2	hydrogen gas
ICT	information and communications technology
IEA	International Energy Agency
IIOT	industrial internet of things
INL	Idaho National Laboratory
kg	kilogram
kton	kiloton or thousand metric tons
kWh	kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
LCA	life cycle assessment
LCFFES	low-carbon fuels, feedstocks, and energy sources
LHC	light hydrocarbons
LTS	U.S. Long-Term Strategy
MT	metric ton or tonne
MWh	megawatt-hour
N_2O	nitrous oxide
NAICS	North American Industry Classification System
NAS	National Academies of Sciences
NDC	nationally determined contribution
NG	natural gas
NPC	National Petroleum Council
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PE	polyethylene
PP	polypropylene
PV	photovoltaic
RAPID	Rapid Advancement in Process Intensification Deployment (a DOE Manufacturing USA Institute)
R&D	research and development
RD&D	research, development, and demonstration
REMADE	Reducing EMbodied-energy And Decreasing Emissions (a DOE Manufacturing USA Institute)
RNG	renewable natural gas
SCM	supplementary cementitious material
SEM	strategic energy management
SEWGS	sorption-enhanced water-gas shift
SMR	steam methane reforming
TBtu	trillion British thermal units
TEA	techno-economic analysis
TRT	top pressure recovery turbine
WGS	water gas shift
WHP	waste heat to power
WHR	waste heat recovery

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Executive Summary

The science is clear that significant greenhouse gas (GHG) emissions reductions are needed to moderate the severe impacts of ongoing climate change.[1] Bold action is needed, and the Biden Administration has set goals of 100% carbon pollution-free electricity by 2035 and net-zero GHG emissions by 2050.[2] The U.S. Long-Term Strategy (LTS)[3] presents multiple pathways to a net-zero economy by no later than 2050. Addressing environmental justice and energy equity will be integral to meeting these climate goals. The United States' overall industrial decarbonization strategy will support the Biden Administration's Justice40 Initiative, which pledges that at least 40% of overall benefits from federal investments in climate and clean energy will be delivered to disadvantaged communities.[4] The U.S. net-zero GHG 2050 goal, while ambitious, is achievable and will provide important benefits for all Americans in terms of public health, economic growth, reduced conflict from climate-related disasters, and quality of life. While this roadmap focuses on GHG emissions, other pollutant emissions will also need to be addressed as industry decarbonizes. Developing new technologies to reduce GHG emissions is an important opportunity to address other environmental issues and inequities. DOE is currently focusing on energy and environmental justice in complementary programs and initiatives.[5]

The U.S. industrial sector is considered a "difficult-to-decarbonize" sector of the energy economy,[6] in part because of the diversity of energy inputs that feed into a heterogenous array of industrial processes and operations. In 2020, the industrial sector accounted for 33% of the nation's primary energy use and 30% of energy-related carbon dioxide (CO_2) emissions.[7] Industrial sector emissions are attributed to a combination of sources, including:[8]

- **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

[1] Intergovernmental Panel on Climate Change, *Summary for Policymakers in Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. Masson-Delmotte, V. et al. (Cambridge University Press, 2021), https://www.ipcc.ch/report/ar6/wg1/#SPM.
[2] "Executive Order 14008 of January 27, 2021, Tackling the Climate Crisis at Home and Abroad," *Code of Federal Regulations,* Title 86 (2021): 7619–7633, https://www.federalregister.gov/documents/2021/02/01/2021-02177/tackling-the-climate-crisis-at-home-and-abroad.
[3] United States Department of State and the United States Executive Office of the President, *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050*, November 2021, https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf.
[4] Shalanda Young, Brenda Mallory, and Gina McCarthy, "The Path to Achieving Justice40," The White House Briefing Room (blog), July 20, 2021, https://www.whitehouse.gov/omb/briefing-room/2021/07/20/the-path-to-achieving-justice40/.
[5] For more information on DOE activity in energy and environmental justice, see: "Promoting Energy Justice," U.S. Department of Energy, accessed August 2022, https://www.energy.gov/promoting-energy-justice; "Justice40 Initiative," U.S. Department of Energy, accessed August 2022, https://www.energy.gov/diversity/justice40-initiative.
[6] National Academies of Sciences, Engineering, and Medicine, *Accelerating Decarbonization in the United States Energy Sector*, February 2021, https://www.nap.edu/catalog/25932/accelerating-decarbonization-of-the-us-energy-system.
[7] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 2. Energy Consumption by Sector and Source and Table 18. Energy-Related Carbon Dioxide Emissions by Sector and Source.
[8] The roadmap results include fuel-related, electricity generation, and select industrial process (cement and iron and steel) CO_2 emissions, which account for the largest portion of industrial GHG emissions.

- **Industrial Process Emissions:** non-energy-related process emissions from industrial activities (e.g., direct CO_2 emissions from chemical transformations in materials being processed)

- **Manufactured Product Life Cycle Emissions:** emissions generated from cradle-to-grave (or cradle-to-cradle) that include emissions generated both upstream of the manufacturing processes (supply chain) and downstream (during product use and end of life).

This roadmap frames the emerging and transformative technology pathways needed to achieve net-zero GHG emissions in the industrial sector by 2050. While the analysis focuses on the sector's fuel- and electricity-related emissions, the discussion also highlights the importance of reducing process and product life cycle emissions in a holistic decarbonization strategy. The analysis is scoping in nature and highlights the key technology needs and opportunities, while also considering the necessity of maintaining and enhancing U.S. industrial competitiveness. This roadmap fills a greater technical and strategic need by laying out a cohesive technical approach for U.S. industrial sector decarbonization.

The roadmap identifies four key "pillars" of industrial decarbonization: energy efficiency; industrial electrification;[9] low-carbon fuels, feedstocks, and energy sources (LCFFES); and carbon capture, utilization, and storage (CCUS). Each represents a high-level element of an industrial decarbonization action plan, and a cohesive strategy will require all four pillars to be pursued in parallel. This framework captures important crosscutting approaches, such as the need for improved thermal operations and material efficiency, as well as material substitution and circular economy approaches. For example, end of life materials have the potential to provide low-carbon feedstocks via the LCFFES pillar; however, this needs to be done in an energy-efficient manner. Some crosscutting topics need to be explored more thoroughly but are not covered in detail in this report. Such topics include bio-based options, material efficiency through product life cycles, circular economy approaches, and the interactions between multiple technology pathways; these needs are discussed briefly in Section 4.

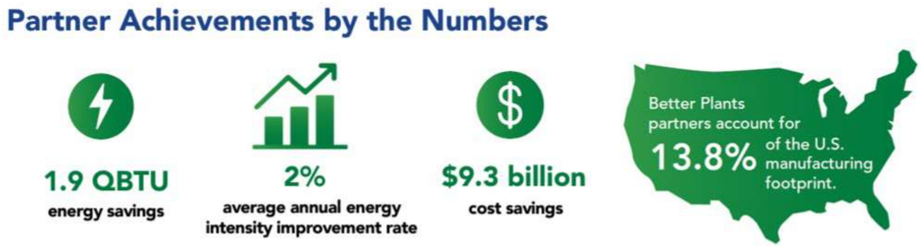
Decarbonization opportunities are explored and quantified in this roadmap by studying subsector-specific and crosscutting technologies, processes, and practices for five of the most carbon-intensive manufacturing subsectors: ***iron and steel***, ***chemicals***, ***food and beverage***, ***petroleum refining***, and ***cement***. These five subsectors together account for over 50% of the energy-related CO_2 emissions in the U.S. industrial sector.[10] Both geographically concentrated subsectors (chemicals, refining, iron and steel, and cement) and dispersed subsectors (food and beverage) are represented.

Scenario modeling undertaken in this roadmap shows that application of these pillars can enable the industrial sector to reach near-zero CO_2 emissions, with the balance of reductions required for an overall net-zero outcome achieved through the application of alternative strategies reaching beyond the four pillars (such as negative emissions technologies).

- **Energy efficiency:** This pillar offers the greatest opportunities for near-term decarbonization solutions. In many cases, it does not require major changes to industrial processes and can bring immediate reductions in emissions. Key energy efficiency goals include improvements in system efficiencies, process yield, and recovery of thermal energy; expansion of energy management practices; and increased implementation of smart manufacturing strategies designed to reduce energy consumption. Transitioning process-heat-related technologies and applications to low-

[9] The terms "industrial electrification" and "electrification" are used interchangeably throughout this roadmap.
[10] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 19. Energy-Related Carbon Dioxide Emissions by End Use.

carbon energy sources (electricity, hydrogen, biomass, etc.) is needed at scale. It is important that near-term energy efficiency improvements be done with longer-term decarbonization pathways in mind, to avoid lock-in to technologies that are harder to decarbonize.



DOE Better Plants Program Energy Impacts[12]

For example, in the Better Plants Program, the U.S. Department of Energy (DOE) partners with leading U.S. manufacturers and water and wastewater treatment agencies to improve their energy efficiency and sustainability. Partners pledge to meet the goal of reducing energy intensity by 25% over a 10-year period across all U.S. operations.[11] As of fall 2021, the 250+ Better Plants partners have saved a cumulative 1.9 quadrillion British thermal units (Btu) in energy and 116 million metric tons of CO_2 (see figure above).[12]

- **Industrial electrification**: Over 50% of all manufacturing energy is used for thermal processing, and less than 5% of these operations are electrified.[13] Electrification, particularly of thermal processes, provides an opportunity to leverage decarbonized and inexpensive electricity sources—including an electric grid that will undergo a clean energy transformation over the next decade—and reduce industrial emissions from onsite combustion of fossil fuels. The electrification pillar involves a) improving the energy efficiency of existing electrotechnologies or hybrid systems, b) innovating new electric or hybrid systems, and c) overcoming economic and technical barriers to implementing electrotechnologies in existing fossil-based processing systems.

Mechanical vapor recompressor

Industrial Heat Pump Technology

Industrial electrification technology includes electrification of process heat (e.g., heat pumps) or electrification of hydrogen production for industrial process use. Heat pumps can satisfy a range of thermal demands in low to medium temperatures across a range of industries. One example of electric heat pump technology, the mechanical vapor recompressor (depicted above), can replace hydrocarbon-based fuels used for chemical and refining industry process heat. Further, research,

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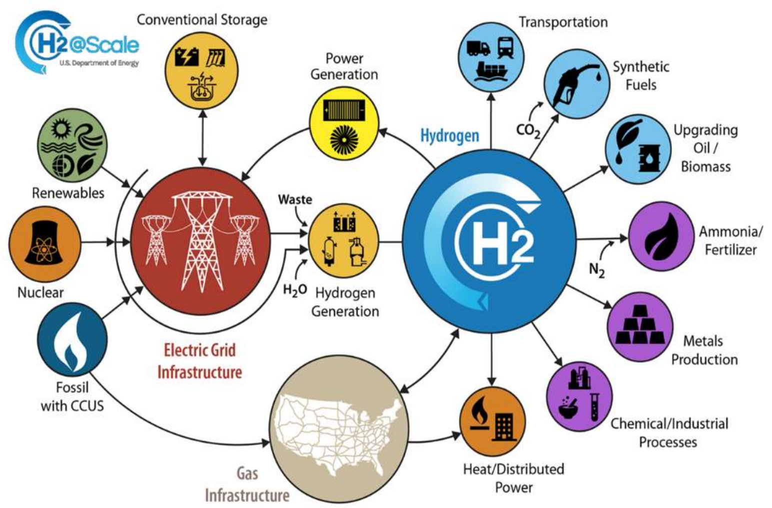
[11] "Better Plants," U.S. Department of Energy, accessed May 2022, https://betterbuildingssolutioncenter.energy.gov/better-plants.

[12] Savings are from the launch of the program in 2011 through fall 2021. U.S. Department of Energy, *Better Plants Progress Update Report*, Fall 2021, https://betterbuildingssolutioncenter.energy.gov/sites/default/files/attachments/2021_Better_Plants_Progress_Update.pdf.

[13] "Manufacturing Energy and Carbon Footprint: All Manufacturing (2018 MECS)," U.S. Department of Energy Advanced Manufacturing Office, December 2021, https://www.energy.gov/sites/default/files/2022-01/2018_mecs_all_manufacturing_energy_carbon_footprint.pdf.

development, and demonstration (RD&D) is needed to enable heat pump technology at higher temperatures and as an alternative to electrical power.

- **Low-carbon fuels, feedstocks, and energy sources (LCFFES)**:
  Adoption of clean energy technologies that do not release GHGs to the atmosphere from the production or use of energy sources will be critical for decarbonization; these approaches would include renewably sourced electricity, nuclear energy for electricity and heat, concentrating solar power, and geothermal energy. Developing low- or no-carbon energy sources, from clean hydrogen to synthetic fuels, will enable broader decarbonization, including in industries typically reliant on fossil fuels and non-industrial sectors (e.g., transportation). Some technologies from this pillar are advanced enough to be implemented early to meet initial emissions reduction goals, while others will require longer-term RD&D.

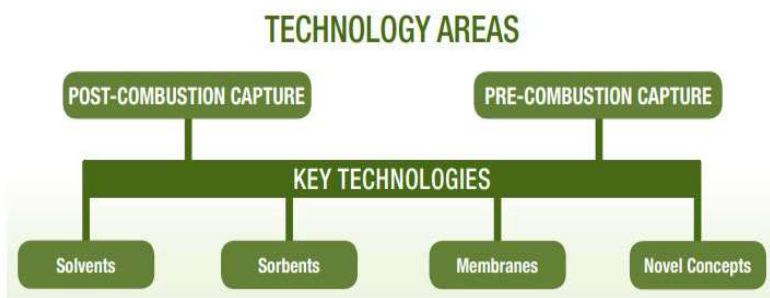


DOE's H2@Scale Opportunities[14]

LCFFES technology includes fuel-flexible processes, clean hydrogen fuels and feedstocks, biofuels and biofeedstocks, nuclear, concentrating solar power, and geothermal. For clean hydrogen, key needs include reducing cost to $1 per kilogram (kg) and improving efficiency and durability of low- and high-temperature electrolyzers. The figure to the right illustrates hydrogen applications and opportunities from the DOE H2@Scale initiative.[14] An example application involves decarbonizing primary steelmaking by using clean hydrogen to reduce iron ore, replacing carbon-based reductants that create CO_2 emissions. Hydrogen direct reduction with iron is also compatible with secondary steelmaking, where two-thirds of U.S. steel is produced in electric arc furnaces from steel scrap. For synthetic fuels, energy-efficient CO_2 reduction can enable captured CO_2 utilization as a feedstock, along with clean hydrogen, to produce synthetic hydrocarbon fuels with energy densities comparable to diesel, gasoline, and jet fuel.

[14] "H2@Scale," U.S. Department of Energy, accessed May 2022, https://www.energy.gov/eere/fuelcells/h2scale.

- **Carbon capture, utilization, and storage (CCUS)**: The pillars of energy efficiency, LCFFES, and electrification can be deployed sooner than CCUS and, collectively, can reduce 40% of the targeted emissions. However, these three approaches are not sufficient to reach net-zero emissions. In the roadmap modeling, CCUS was predicted to be the largest source of long-term emission reductions. Both carbon utilization and carbon storage will be critical to achieving the final carbon reductions—those not achievable through other decarbonization technologies and strategies. A specific example of CCUS application is in cement manufacturing, where nearly 60% of the CO_2 emissions are non-energy-related; they result from the chemical reduction of limestone to lime.[15]



CCUS Technology Approaches

  Key priorities for CCUS are improving efficiency, economic viability, and safety. Improvements to catalysts and process designs are critical to higher efficiency levels, lower costs, and lower material consumption or waste production. Examples of CCUS technology include post-combustion chemical absorption of CO_2 or construction of CO_2 pipelines and other CCUS-supportive infrastructure.

- **Alternate approaches, including negative emissions technologies:** Additional options are needed to address hard-to-abate emissions and reduce atmospheric presence of CO_2 (and in some cases, non-CO_2 GHGs) to achieve an industrial sector with net-zero emissions. Alternate approaches may include land use ecosystems management activities such as forestation/reforestation, use of biochar and soil carbon management, and others. Technological approaches may include biomass-energy with carbon capture and storage (BECCS) and capture of CO_2 from major emissions sources or from air (direct air capture). In all cases, an understanding of the time constants for which carbon is removed from the atmosphere is critical, with the goal of negative emissions technologies to durably remove and sequester CO_2. Technological breakthroughs in the other pillars could reduce the need for these approaches.

The coverage of emissions categories included in scenario modeling for each of the five subsectors is summarized in Table ES 1. Fuel-related CO_2 emissions and electricity generation CO_2 emissions were included for all focus subsectors, while process-related CO_2 emissions were included for the steel and cement subsectors only. Contributions of non-CO_2 GHG emissions, such as methane (CH_4) and nitrous oxide (N_2O), were not included for any subsector. For the food and beverage and chemicals industries (both of which comprise a large, diverse range of output products), roadmap analysis was bounded to a representative set of products (see Table ES 1 footnote, Section 2.2.3, and Section 2.3.2). These analysis boundaries allowed scenario modeling to consider a manageable scope of products and technologies, while still covering the breadth of industrial sector emissions in a representative way. For future

[15] For specific examples of carbon capture technology from various industrial point sources, see "Point Source Carbon Capture from Industrial Sources," National Energy Technology Laboratory, accessed May 2022, https://netl.doe.gov/carbon-capture/industrial.

research and analysis, scenario modeling will need to include additional subsectors and products, non-CO_2 GHGs, and further exploration of industrial process emissions (see Section 4).

TABLE ES 1. SCOPE OF EMISSIONS INCLUDED IN ROADMAP SCENARIO MODELING & ANALYSIS

Industry Subsector	Electricity Generation CO_2 Emissions	Fuel-Related CO_2 Emissions	Process-Related CO_2 Emissions	CH_4, N_2O, and Other Non-CO_2 GHG Emissions	Subsector Coverage in Analysis
Iron and steel	Included	Included	Included*	Not included	Full subsector coverage
Chemicals	Included	Included	Not included	Not included	Partial coverage**
Food and beverage	Included	Included	N/A ***	Not included	Partial coverage**
Petroleum refining	Included	Included	N/A ***	Not included	Full subsector coverage
Cement	Included	Included	Included	Not included	Full subsector coverage

* In the iron and steel industry, 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 this analysis.
** For the chemicals and food and beverage subsectors, a representative set of subsector products were selected for inclusion in scenario analysis. Representative products for the food and beverage subsector were wet corn milling, soybean oil, cane sugar, beet sugar, fluid milk, red meat product processing, and beer production. Representative products for the chemicals subsector were ammonia, methanol, ethylene, and benzene, toluene, and xylenes (BTX) aromatic.
*** No process-related emissions associated with food and beverage manufacturing or petroleum refining are reported by the U.S. Environmental Protection Agency. Fugitive emissions from the petroleum refining sector are not included.[16]

For each pillar, this roadmap identifies the primary barriers and opportunities, as well as the key RD&D needs. The result is an integrated RD&D action plan for the five energy-intensive focus industries to reach net-zero emissions by 2050 (Figure ES 1). Specifically, this roadmap highlights technology pathways to reduce emissions by 87%, or almost 400 million metric tons of CO_2 per year, by 2050 for the five subsectors studied.[17] With application of alternate approaches such as negative emissions technologies, a total of 457 million metric tons of annual CO_2 emissions can be avoided.

Additional decarbonization strategies in these five subsectors, beyond the representative set of products selected for analysis, need to be assessed further, as discussed in Section 4. Assuming the pillars and alternate approaches were applied to the entirety of the five subsectors, avoided emissions could reach approximately 700 million metric tons of CO_2 per year by 2050—about 50% of the industrial sector's 1,360 million metric tons of total energy-related CO_2 emissions in 2020.[18] Future work will

[16] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2019,* EPA Report No. 430-R-21-005, April 14, 2021, https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2019.
[17] These emissions reflect about one-third of the total industrial sector emissions. The roadmap scenario modeling covered a representative set of major commodity products in five subsectors, as identified in Table ES 1.
[18] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 18. Energy-Related Carbon Dioxide Emissions by Sector and Source.

prioritize further analysis to identify and quantify specific technological pathways to address the remaining 50% of the industrial emissions from subsectors not covered in this roadmap.

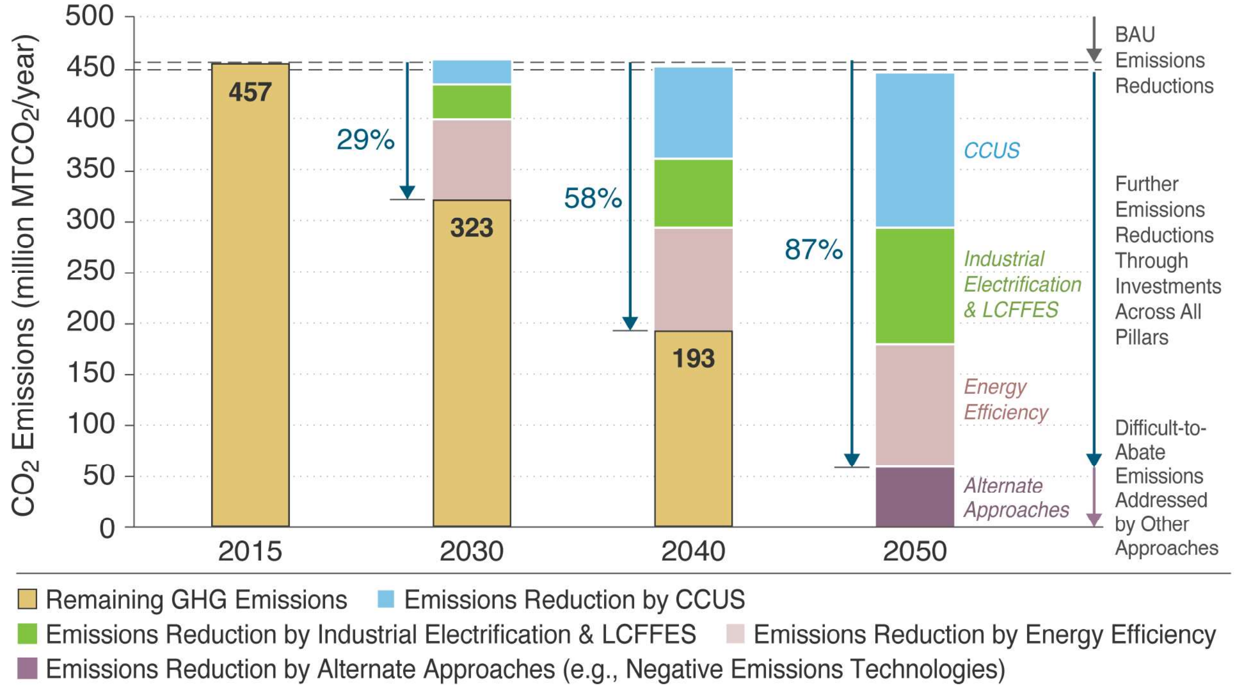


Figure ES 1. The path to net-zero industrial CO_2 emissions in the United States for five carbon-intensive industrial subsectors, with contributions from each decarbonization pillar: energy efficiency; industrial electrification; low-carbon fuels, feedstocks, and energy sources (LCFFES); and carbon capture, utilization, and storage (CCUS)). Emissions are in millions of metric tons (MT) per year.

Since industrial electrification and LCFFES technologies and strategies are strongly interconnected, these pillars were grouped for scenario modeling. The "alternate approaches" band shows further emissions reductions from approaches not specifically evaluated in scenario modeling for this roadmap, including negative emissions technologies. The powering of alternate approaches will also need clean energy sources (e.g., direct air capture could be powered by nuclear, renewable sources, solar, waste heat from industrial operations, etc.). The following Industrial subsectors were included in this analysis: Iron and steel, chemicals (only ammonia, methanol, ethylene, and BTX), food and beverage (only beer, beet sugar, cane sugar, fluid milk, red meat, soybean oil, and wet corn milling), petroleum refining, and cement manufacturing. Feedstocks and certain process-related emissions are excluded. Further details on assumptions can be found in the appendices. Source: this work.

> *Key message: Scenario modeling indicates that achieving net-zero CO_2 emissions in the top CO_2-emitting industrial subsectors by 2050 will require an "all of the above" strategy, including application of multiple decarbonization technologies and approaches in parallel.*

The roadmap report scenario projections include only CO_2 emissions from onsite fuel combustion and grid-purchased electricity for the five focus industries. It is important to recognize that this analysis does not comprise a full "cradle-to-gate" or "cradle-to-grave" life cycle assessment of CO_2 emissions associated with the manufactured products of the industries considered. Modeling did not include upstream and downstream CO_2 emissions, process CO_2 emissions (except for those involved in cement production), CO_2 emissions embodied into input materials (including imported materials), or non-CO_2 GHG emissions. In addition, the scenario analysis considered only representative samples for the refining, chemicals, and food and beverage subsectors, given the expansiveness of those industries' product outputs. As such, the actual GHG emissions reduction potential for the entire industrial sector is larger than what is reflected by the scenario modeling. Results of the scenario analysis shown in this report should be considered as a preliminary and representative assessment of CO_2 reduction potential. Ultimately, analyses for the full industrial sector (incorporating all GHG emissions) will be needed to provide a complete picture of the industrial decarbonization needs.

Along the road to net-zero emissions, many direct and indirect barriers will need to be addressed, and strong policy measures and incentives will be needed. The barriers can be seen as opportunities to increase U.S. competitiveness and establish leadership in industrial decarbonization. Subsector-specific barriers, opportunities, RD&D needs, and proposed RD&D action plans are presented for iron and steel, chemicals, food and beverage, petroleum refining, and cement.

Figure ES 2 illustrates the sector transformations needed to achieve industrial decarbonization. These transformations include contributions from the four key decarbonization pillars, which must be pursued concurrently to reach net-zero carbon emissions by 2050. While each pillar is shown separately, the pillars are not independent; cross-sectoral opportunities that provide synergies, address barriers, and accelerate progress can be pursued. Time bands by decade (excluding the first two bands, which are each five years) show how the state of the industrial sector must advance to realize early energy and GHG emissions reductions, advance and demonstrate technologies to improve economics and promote commercial adoption, and build the knowledge and capacity for transformative future technologies. Parallel investments in RD&D across pillars will be needed to realize the transformations to achieve net-zero.

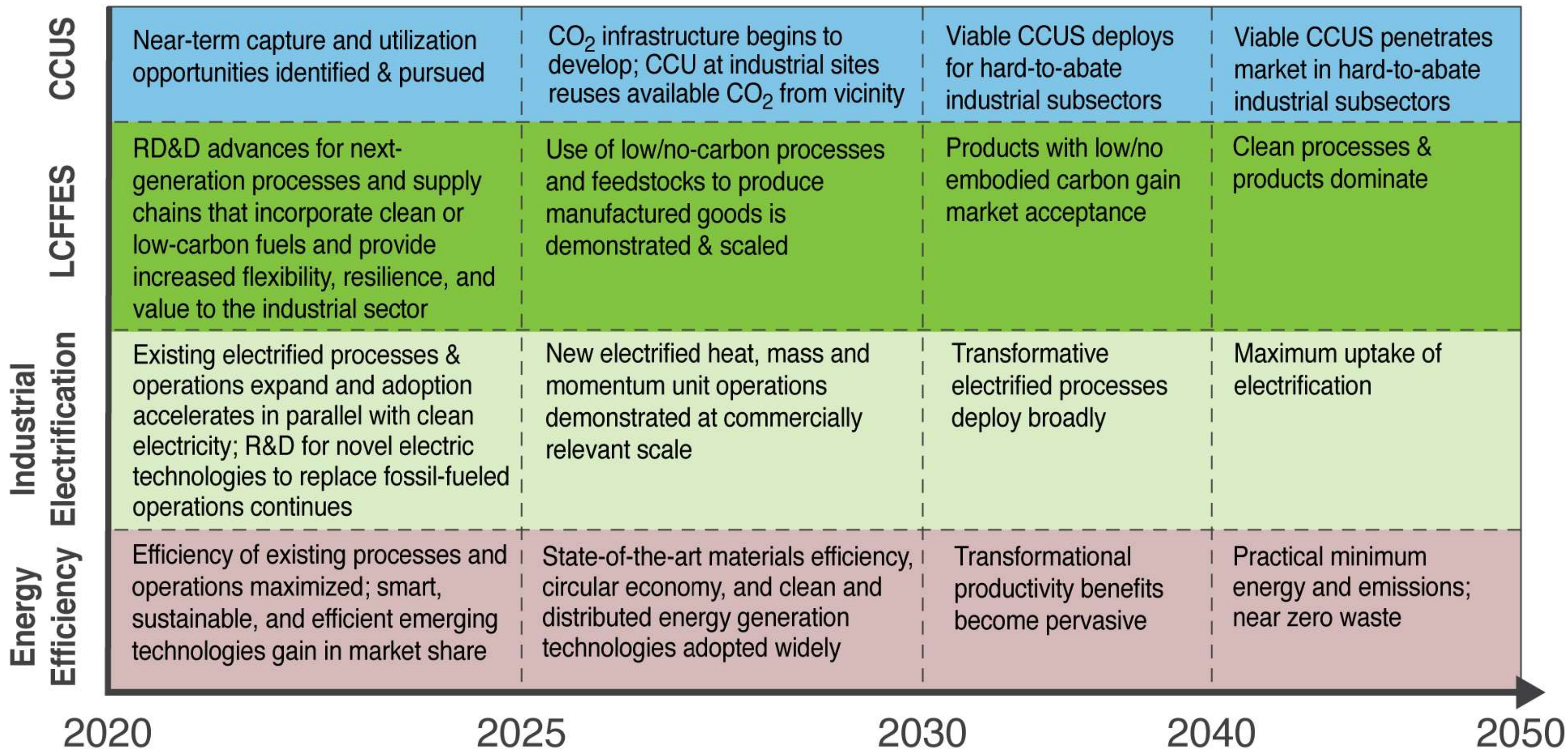


Figure ES 2. RD&D-enabled sector transformations to achieve industrial decarbonization, by decade and decarbonization pillar.

Early opportunities set the stage for later transformative advances and have crosscutting impacts in other pillars and sectors. CCUS: carbon capture, utilization, and storage; LCFFES: low-carbon fuels, feedstocks, and energy sources. Further definitions are available in the glossary. Source: this work.

Key message: RD&D investments are needed in near-term, mid-term, and longer timeframes to achieve the sector transformations necessary for industrial decarbonization. Strategies should leverage synergies within and across pillars and industrial subsectors.

Key Recommendations

Meeting industrial decarbonization emissions reduction targets will require rapid deployment of state-of-the-art technologies and development of new low- and no-carbon technology solutions. In addition to technology solutions, policy and other barriers must be overcome (these barriers are not the focus of this report). Key learnings and recommendations from the roadmap are discussed in Section 6 and summarized below.

- ***Advance early-stage RD&D.*** While technologies with high technical maturity levels will need to be deployed sector-wide, fundamental and applied RD&D to advance fundamental science and technologies with lower technical maturity levels must also proceed in parallel. Major advances in early-stage technologies across all decarbonization pillars will be needed in the coming decades to reach net-zero emissions by 2050.

- ***Invest in multiple process strategies.*** Investments in multiple low-carbon process technology strategies must be concurrently pursued to ensure viable pathways for industrial decarbonization. These investments can position the United States as a global leader in industrial modernization.

- ***Scale through demonstrations.*** In many cases, decarbonization technologies have been demonstrated through applied RD&D but have not yet been scaled for commercial use. Demonstrating technical and economic feasibility (leading to market adoption) of industrial technologies is particularly challenging, with a number of factors affecting adoption.[19] To accelerate deployment, testbeds and demonstration projects will be needed to catalyze and de-risk private sector investments. Low-capital approaches that maximize energy, material, and systems efficiency should be pursued throughout the transformation to lower hurdles and speed adoption of advanced technologies. Confidence from demonstrations at commercially relevant scales is needed for market adoption; however, other levers (deployment, procurement, etc.) can be used to drive the rate of uptake needed to meet the 2050 net-zero GHG emissions target.

- ***Address process heating efficiency and emissions across all sub-sectors.*** In the industrial sector, process heating consumes more energy than any other type of operation, and the majority of the energy used for process heating originates from fossil fuels. Efforts are needed to maximize efficiency and resource utilization associated with the thermal energy cascade (e.g., waste heat recovery, heat upgrading/reuse), while transitioning to electrified and low-carbon fuel and energy sources.

- ***Decarbonize electricity sources.*** Achieving net-zero GHG emissions in the industrial sector will require a fully decarbonized electric grid. The effectiveness (and speed) of electrification pathways in decarbonizing the industrial sector will depend on the rate of decarbonization of the U.S. electric grid. In parallel, the development of low-carbon electricity generation capabilities near industrial facilities could spur electrification near centers of concentrated industrial activities (e.g., through clusters or hubs).

- ***Integrate solutions.*** Focus is needed not just on new technologies but also on their integration into process systems and supply chains to reduce energy and emissions at the system level. Research will be needed to anticipate the changes in supply and value chains that will result from the transition to

[19] Rebecca Hanes et al., "Quantifying adoption rates and energy savings over time for advanced energy-efficient manufacturing technologies," Journal of Cleaner Production 232, (2019): 925-939. https://doi.org/10.1016/j.jclepro.2019.04.366.

a low-carbon economy, as well as to better understand how industrial infrastructure, technology, and services can work together to meet future needs while maximizing supply chain flexibility and resilience.

- ***Conduct modeling and system analysis.*** There is a need for advanced and integrating analysis approaches, including expanded use of life cycle assessments, techno-economic analyses, and related systems-level techniques for economic and environmental assessments, to ensure that low-carbon solutions have the positive impact desired and are commercially viable.
- ***Engage communities, develop a thriving workforce.*** The full range of the workforce needed across all industrial subsectors will require a spectrum of new skillsets to support successful implementation of decarbonization technologies and improved carbon accounting at a broad scale. Engaging state, local, and tribal communities and other stakeholders, with a particular focus on disadvantaged communities, will be critical to ensuring the benefits and impacts of industrial decarbonization are equitably distributed.

Decarbonization Pathways to Net-Zero Emissions by 2050 for the Five Energy-Intensive Industrial Subsectors Studied

Table ES 2 summarizes the key takeaways and decarbonization pathways (technologies, processes, and practices) to achieve net-zero CO_2 emissions by 2050 for the five subsectors analyzed. For each subsector, Section 2 also includes the analytical basis for the decarbonization pathways, detailed RD&D needs and opportunities, and a proposed RD&D action plan using the framework of the four pillars.

TABLE ES 2. KEY SUBSECTOR DECARBONIZATION PATHWAY TAKEAWAYS FOR SOLUTIONS TO NET-ZERO EMISSIONS IN INDUSTRY BY 2050

Industry Subsector	Key Takeaways
Iron and steel	• Under the near-zero GHG emissions scenario, U.S. steel industry GHG emissions can go down to almost zero in 2050, while steel production increases by 12%. • More than two-thirds of GHG emissions reduction comes from improvement in energy efficiency and switching to low- and no-carbon fuels and electrification. • Aggressive RD&D and procurement are needed for transformative technologies, such as hydrogen-based steel production, iron ore electrolysis, and CCUS. • Demand for clean hydrogen and low-carbon electricity use in steelmaking will increase significantly by 2050. RD&D efforts are needed to improve the efficiency of electrolyzers.
Chemicals	• Multiple crosscutting opportunities for subsector decarbonization include process heat; separations; use of hydrogen, biomass, and waste as fuel or feedstock; CCUS integration; thermal and electrical storage; and materials circularity and atom efficiency. • Process-specific opportunities include noncontact energy transfer (e.g., acoustic [such as thermoacoustics] and plasma), electrical transfer, and scaling of electrochemical processes. • Advancing the use of variable energy sources (e.g., solar and wind energy) effectively and economically to transition from current to low-carbon sources is an early opportunity. • Increasing electrolyzer efficiency is needed to advance electrochemical processes.

Industry Subsector	Key Takeaways
	• Systems efficiency and smart manufacturing research needs to be extended across multiple processes for integrated chemical facilities.
Food and beverage	• RD&D is needed in process heating electrification (especially for ovens and fryers), electric and hybrid boilers, and electrification of evaporation and pasteurization processes. • Issues with safety and quality concerns in food and beverage manufacturing need to be mitigated by supporting studies into the impacts of technology change on final products. • To reduce significant subsector waste, RD&D is needed in food and beverage processing practices and technologies to extend the shelf life of products. There is also a need for research that focuses on reduced volume of packaging waste, recycling opportunities, and supply chain visibility.
Petroleum refining	• Five energy-intensive refining processes (hydrocracking, atmospheric distillation, catalytic cracking, steam methane reforming, and regenerative catalytic reforming) account for the majority of U.S. refining CO_2 emissions and represent the most cost-effective RD&D opportunities to reduce refining emissions. • Refineries and transportation fuels markets are highly integrated, with 35% of total U.S. energy-related CO_2 emissions "passing through" refineries to become "vehicle tailpipe" CO_2 emissions.[20] • Producing low-net-GHG-emission liquid hydrocarbon fuels is an opportunity to build new, less carbon-intensive refinery processes while decarbonizing transportation and chemicals.
Cement	• Under the near-zero GHG emissions scenario, U.S. cement manufacturing GHG emissions can decrease to almost zero in 2050, while cement production increases by 46%. • Around 65% of total GHG emissions reduction needed to get to near-zero in 2050 comes from adoption of CCUS. • Aggressive RD&D, pilot, deployment, and procurement efforts are needed for CCUS and innovative chemistry (mainly replacing clinker with supplementary cementitious materials for cement production) to realize the net-zero GHG emissions goal by 2050.

Considerations for Reaching Net-Zero Carbon Emissions by 2050 for the Entire Industrial Sector

This roadmap provides detailed analysis of five subsectors; however, additional industrial subsectors should be examined for a more comprehensive evaluation of industrial decarbonization opportunities, as discussed in Section 4. For example, the pulp and paper industry is a large energy user (6.2% of U.S. industrial energy use in 2020) and also has a high thermal load.[21] Decarbonization technologies and strategies will vary for every subsector, and it will be important to be able to identify and leverage the crosscutting technologies that can be applied while also developing subsector-specific strategies and technologies to achieve the desired decarbonization levels.

[20] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 19. Energy-Related Carbon Dioxide Emissions by End Use.
[21] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 6. Industrial Sector Key Indicators and Consumption and Table 26. Paper Industry Energy Consumption.

Crosscutting barriers and opportunities that cut across many industrial subsectors are identified in Section 3. For example, digital manufacturing represents a crosscutting opportunity for facilitating decarbonization. The "Industry 4.0" concept seeks to improve industrial production efficiency by applying cutting-edge technologies, such as the Internet of Things, artificial intelligence, automation, robotics, and big data. These tools could assist with crosscutting efficiency measures by improving process controls, simulating industrial systems and scenarios (e.g., through digital twinning), improving sensor technology, better characterizing supply chains with big data tools, and optimizing facility siting.

The extraction and processing of materials from natural resources results in significant carbon emissions. Application of circular economy strategies, which include opportunities to reduce, re-use, and recycle products and materials, can reduce the environmental, economic, and social issues stemming from the depletion of earth's natural resources. Section 4 discusses additional scenarios that will need to be developed that incorporate materials efficiency and circular economy strategies. These scenarios can accurately account for the full life cycle energy consumption, GHG emissions, and other environmental impacts of technologies and products.

Comprehensive decarbonization approaches will also need to integrate consideration of the changing energy landscape, with expanding deployment of clean electricity generation (nuclear, renewable, fossil with CCUS, etc.) comprising an essential element of all net-zero paths. In addition to the opportunities for industrial GHG emissions reductions attributable to an increasingly decarbonized grid, there are also emerging opportunities for direct use of clean energy in the industrial sector, which will benefit from more detailed analysis. This includes nuclear power (fission and/or fusion); bioenergy deployed as fuels and feedstocks; and concentrating solar-thermal energy (CST), a source of emission-free high-temperature heat.

Policy needs and impacts (though out of scope in this roadmap) represent another critical area for further analysis. Enabling policies and incentives will be important in reaching the reductions described in this report.

To reach decarbonization goals, the United States needs to build a technology development pipeline and increase the technology commercialization rates. DOE investments – bolstered and accelerated by recent funding additions and expanded industry partnerships – will help to build confidence that technologies can be successfully deployed at commercially relevant scale. Besides its basic and applied RD&D activities, DOE has numerous capabilities such as analysis, modeling, tool development, and industrial partnerships to inform decision-making for the greatest impact on decarbonization. Section 5 discusses how DOE can utilize its existing suite of tools and resources to facilitate and catalyze industrial decarbonization. That section also discusses some specific RD&D activities with energy efficiency and embodied energy targets that also result in carbon intensity improvements.

Relevant DOE-industry partnerships (such as Better Plants[22] and the Better Climate Challenge[23]) can help develop and accelerate decarbonization pathways in manufacturing. DOE will continue to coordinate and collaborate across all offices to boost technology commercialization and adoption. DOE offices and federal agencies will also need to continue to collaborate to develop integrated approaches that advance not only the industrial sector but all sectors of the economy. There is a need for a coordinated

[22] "Better Plants," U.S. Department of Energy, accessed August 2022, https://betterbuildingssolutioncenter.energy.gov/better-plants.
[23] "About the Better Climate Challenge," U.S. Department of Energy, accessed August 2022, https://betterbuildingssolutioncenter.energy.gov/climate-challenge/about.

knowledge infrastructure that includes data analysis, evaluation tools, and methodology development to ensure that DOE investments are impactful, and this knowledge infrastructure should be shared across DOE offices and other federal and private partners.

In summary, decarbonizing the industrial sector will require rapid deployment and adoption of state-of-the-art technologies and development of new low- and no-carbon technology solutions across all the pillars identified. Even with rigorous pursuit of emissions reduction technologies across all pillars, industrial GHGs from hard-to-abate processes will remain, so there is a need for RD&D of alternative mitigation approaches, such as direct air capture or other negative emissions technologies, to advance the cost and performance of these technologies.

Considerations for Reaching Economy-Wide Net-Zero Carbon Emissions by 2050

The decarbonization pathways pursued by the non-industrial sectors (residential, commercial, and transportation) will also affect industrial sector decarbonization pathways and technology investments. For instance, considering that 97% of the transportation sector's CO_2 emissions "pass through" refineries, shifting to net-zero GHG transportation by 2050 is an opportunity for U.S. businesses to evolve refining and chemical manufacturing processes, business models, market structures, and markets. Producing low-net-GHG-emission liquid hydrocarbon fuels is an opportunity to build new, less carbon-intensive refinery and chemical process configurations, while decarbonizing transportation and chemicals—potentially creating new products, industries, and manufacturing subsectors by 2050. Refinery decarbonization RD&D should be pursued in synchronization with economy-wide decarbonization, and there will be a need for a robust, holistic life cycle-based "wells-to-wheels" governance structure that can account for these markets.

This integrated transportation–industry approach illustrates the greater need for economy-wide net-zero-carbon studies to identify tradeoffs between GHG emissions across all sectors and opportunities for acceleration. For example, a multi-sector integrated decarbonization analysis comprising the entire U.S. economy would provide a more comprehensive view of the key decarbonization opportunities for the industrial sector, including those that leverage advancements from other sectors.

The transformation to a net-zero carbon industrial sector will also require a spectrum of new skillsets that will support successful implementation of decarbonization technologies and improved carbon accounting at a broad scale. Engaging state, local, and tribal communities and other stakeholders, with a particular focus on disadvantaged communities, will be critical to ensuring the benefits and impacts of industrial decarbonization are equitably distributed. In addition to addressing carbon pollution and public health, investments in net-zero-carbon technologies and strategies can strengthen U.S. manufacturing competitiveness, which then creates new jobs and economic opportunities that improve quality of life.

1 Introduction

The Imperative to Reduce Greenhouse Gas Emissions

The global mean surface temperature (GMST) has already increased by almost 1°C over pre-industrial temperatures. Global temperature increases lead to increased frequency and intensity of weather events such as drought, heat waves, and flooding . Higher temperatures also impact the ecosystems that we rely on and are a part of. Overshooting the 1.5°C temperature rise target set out in the Paris Agreement could have dramatic, long-lasting, and irreversible impacts on the natural world. Potential impacts of overshooting 1.5°C include a two- to three-fold increase in the frequency of extreme weather, leading to 50% more of the population being impacted by water stress and scarcity, 420 million more people being impacted by extreme heatwaves, and a dramatic increase in melting of Arctic Sea ice.[24] To limit warming to 1.5°C, the world will need to cut emissions by 50% in the next decade and reach net-zero by 2050.[25]

The Biden Administration plans to achieve carbon-free electricity by 2035 and net-zero GHG emissions by 2050.[26] The 2021 Long-Term Strategy (LTS) presents pathways that include all aspects of federal action and supports broader non-federal and all-of-society efforts.[27] These efforts will require five key transformations, including U.S. actions to decarbonize electricity, electrify end uses and switch to clean fuels, cut energy waste, reduce methane and other non-CO_2 emissions, and scale up CO_2 removal.

The LTS approach puts the United States on a path to meet the 2030 nationally determined contribution (NDC) and achieve a 100% clean electric grid by 2035. The Biden Administration's goal of net-zero GHG emissions by 2050, while ambitious, is achievable and will provide benefits for all Americans in terms of public health, economic growth, reduced impacts of climate related disasters, and quality of life. Given the strong interdependence between economic sectors, policy and incentives will be critical as well as a sustained coordination between the public and private entities.

Addressing environmental justice and energy equity is integral to meeting these climate goals. The United States' overall industrial decarbonization strategy will support the Biden Administration's Justice40 Initiative, which pledges that at least 40% of overall benefits from federal investments in climate and clean energy be delivered to disadvantaged communities.[28] These benefits can come, for example, in the form of more affordable clean electric power; energy efficient homes with lower electric bills; reduced potential for climate related disasters (fires, tornadoes, floods, etc.) disrupting communities and families; pollution reductions that will improve air, water, and soil quality in

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[24] Intergovernmental Panel on Climate Change, *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty,* ed. Masson-Delmotte et al, 2018, https://www.ipcc.ch/sr15/.
[25] United Nations Climate Change Conference UK 2021, *COP26 Explained*, 2021, https://ukcop26.org/wp-content/uploads/2021/07/COP26-Explained.pdf.
[26] "Executive Order 14008 of January 27, 2021, Tackling the Climate Crisis at Home and Abroad," *Code of Federal Regulations,* title 86 (2021): 7619-7633, https://www.federalregister.gov/documents/2021/02/01/2021-02177/tackling-the-climate-crisis-at-home-and-abroad.
[27] United States Department of State and the United States Executive Office of the President, *The Long-term Strategy of the United States, Pathways to Net-Zero Greenhouse Gas Emissions by 2050*, November 2021, https://www.whitehouse.gov/wp-content/uploads/2021/10/US-Long-Term-Strategy.pdf.
[28] Shalanda Young, Brenda Mallory, and Gina McCarthy, "The Path to Achieving Justice40," The White House Briefing Room (blog), July 20, 2021, https://www.whitehouse.gov/omb/briefing-room/2021/07/20/the-path-to-achieving-justice40/.

communities near industrial facilities;[29] and participation in economic opportunities created by the clean energy transition. While this roadmap focuses on GHG emissions, other pollutant emissions will also need to be addressed as industry decarbonizes. Developing new technologies to reduce GHG emissions is an important opportunity to address other environmental issues and inequities. DOE is currently focusing on energy and environmental justice in complementary programs and initiatives.[30] There is an emerging body of knowledge and tools that can help assess the broad environmental and equity issues from emissions, including those from the industrial sector. Representative resources useful for evaluating impacts include DOE's Energy Justice Dashboard[31] and the Council on Environmental Quality's Climate and Economic Justice Screening Tool.[32]

The Industrial Decarbonization Challenge

In 2020, the industrial sector was responsible for 1,360 million metric tons of atmospheric CO_2 emissions—about 30% of the total U.S. energy-related CO_2 emissions.[33] Contributions from the manufacturing subsectors comprised 83% of the industrial total, while contributions from the three non-manufacturing industrial subsectors (mining, construction, and agriculture) made up the remaining 17% of industrial CO_2 emissions as shown in Figure 1.[34] For this report, decarbonization will refer to reducing atmospheric CO_2 emissions that can be attributed to industrial processes. Information on non-CO_2 GHG emissions can be found elsewhere,[35] and work on pathways for the reduction of these emissions could be the topic of additional research.

[29] A recent engineering-economic analysis conducted for Los Angeles quantifies multiple health benefits from reducing power plant pollution. These types of benefits can also be expected from industrial facilities that are electrifying their operations. The analysis results show monetized benefits from reducing pollution and negative health effects could amount to hundreds of millions to nearly $1.5 billion by 2045. For more information see: *LA100: The Los Angeles 100% Renewable Energy Study*, Jaquelin Cochran and Paul Denholm, eds., March 2021, https://maps.nrel.gov/la100/la100-study/report.
[30] For more information on DOE activity energy and environmental justice, see: "Promoting Energy Justice," U.S. Department of Energy, accessed August 2022, https://www.energy.gov/promoting-energy-justice; "Justice40 Initiative," U.S. Department of Energy, accessed August 2022, https://www.energy.gov/diversity/justice40-initiative.
[31] "Energy Justice Dashboard," U.S. Department of Energy, accessed August 2022, https://www.energy.gov/diversity/energy-justice-dashboard-beta.
[32] "Climate and Economic Justice Screening Tool," Council on Environmental Quality, accessed August 2022, https://screeningtool.geoplatform.gov/.
[33] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 18. Energy-Related Carbon Dioxide Emissions by Sector and Source.
[34] Manufacturing industrial subsectors include Petroleum Refining, Food Products, Paper Products, Chemicals, Glass, Cement and Lime, Iron and Steel, Aluminum, Fabricated Metal Products, Machinery, Computers and Electronics, Transportation Equipment, Electrical Equipment, Wood Products, Plastics, and Other Manufacturing. Non-manufacturing industrial subsectors are Mining, Construction, and Agriculture.
[35] "ADP Technical Expert Meetings: Non-CO_2 greenhouse gases," United Nations Framework Convention on Climate Change, October 22, 2014, https://unfccc.int/process-and-meetings/conferences/past-conferences/bonn-climate-change-conference-october-2014/events-and-programme/mandated-events/adp-technical-expert-meetings-non-co2-greenhouse-gases; "Inventory of U.S. Greenhouse Gas Emissions and Sinks," U.S. Environmental Protection Agency, last updated April 14, 2022, https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks.

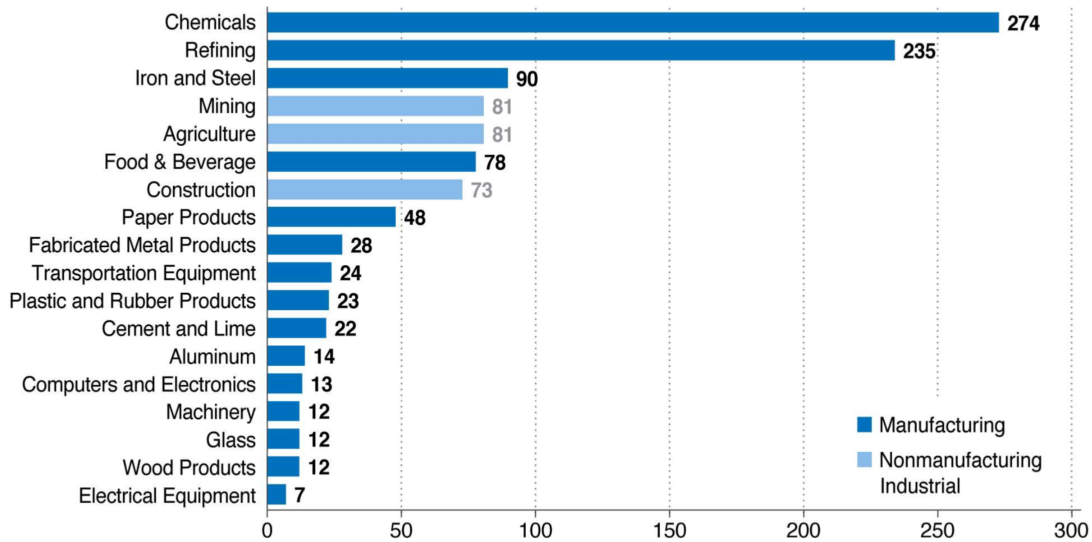

FIGURE 1. ENERGY-RELATED CO_2 EMISSIONS BREAKDOWN BY INDUSTRIAL SUBSECTOR IN 2020, MILLION MT CO_2.

FIGURE BASED ON 2020 DATA FROM AEO 2021.[36] NOTE THAT CEMENT AND LIME ARE SHOWN IN AGGREGATE IN THIS FIGURE, CONSISTENT WITH EIA AEO SECTOR DEFINITIONS; HOWEVER, CEMENT (WITHOUT LIME) IS ANALYZED AS AN INDEPENDENT SUBSECTOR IN THE SCENARIO ANALYSES OF THIS REPORT.

> *Key message: The U.S. industrial sector is made up of manufacturing and non-manufacturing subsectors, with the top three energy-related CO_2-emitting subsectors being chemicals, petroleum refining, and iron and steel.*

In 2020, CO_2 comprised 62% of CO_2 equivalent (CO_2e) industrial sector GHG emissions, with the balance attributed to methane (22%), nitrous oxide (15%), and fluorinated gases (2%).[37] However, a large fraction of the non-CO_2 industrial emissions arises in the agricultural sector[38] as a result of enteric fermentation in livestock, manure, and agricultural soil management practices. Excluding the agricultural sector from the industrial total,[39] in 2020 CO_2 made up 80% of the remaining industrial sector GHG emissions, with the balance attributed to methane (16%), nitrous oxide (2%), and fluorinated gases (3%).[40]

To decarbonize the industrial sector, the United States will face a range of structural and technical challenges. Considering the sheer magnitude of materials transformations undertaken in industry, from extraction of raw materials to the creation of intermediate and final products, decarbonization will

[36] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 19. Energy-Related Carbon Dioxide Emissions by End Use.
[37] EPA and EIA data for industrial CO_2 emissions do not align perfectly as they have different scopes and different definitions of what is covered under the industrial category. For this calculation, data from EPA's *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020* Table 2-12 are used and the agriculture subsector (separate in EPA's dataset) has been integrated into the industrial sector to improve consistency. See U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020,* EPA Report No. 430-R-22-003, April 14, 2022, https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2020.
[38] Greenhouse gas inventory convention (e.g., Intergovernmental Panel on Climate Change Guidelines for National Greenhouse Gas Inventories) categorizes agriculture as its own sector, separate from industry. The EIA definition of industry, used in this roadmap, includes both manufacturing and non-manufacturing (agriculture, construction, and mining).
[39] See previous footnote.
[40] U.S. Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020,* EPA Report No. 430-R-22-003, April 14, 2022, https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2020. See Table 2-12.

require a wide range of technology solutions that will have a ripple effect across increasingly complex supply chains. The emissions reductions needed will require approaches that are transformational rather than incremental, especially considering anticipated product demand growth of 58% by 2050[41] with an associated increase in energy-related CO_2 emissions of 18%[42] in a business as usual scenario. Despite these challenges to industrial decarbonization, the potential exists for the sector to improve manufacturing productivity and cost competitiveness at the global scale, develop innovative products, and meet expanding societal needs, while reducing its carbon dependence.[43]

This roadmap identifies technology approaches at a range of maturity levels that are needed to achieve net-zero CO_2 emissions in the industrial sector by 2050, while enhancing innovation and competitiveness. Adoption will occur as technologies mature and prove technically and economically feasible. It identifies opportunities for RD&D to guide federal agencies. This roadmap is scoping in nature and does not attempt to prioritize select technologies. Instead, it presents an integrated framework that can be updated as technologies advance.

Five energy-intensive industrial subsectors were selected for specific focus in this roadmap, enabling scenario-based decarbonization modeling under technology penetration assumptions specific to those subsectors. The focus subsectors (petroleum refining, chemicals, iron and steel, cement, and food and beverage products) accounted for over half of the total industrial sector energy consumption and CO_2 emissions in 2020, as shown in Figure 2 and Figure 3.[44] Four of the five subsectors are geographically concentrated (chemicals, petroleum refining, iron and steel, cement), while one is dispersed (food and beverage). Decarbonization efforts in other industrial subsectors are also important, and could be topics for additional research as noted in Section 4.

Key Definitions

Industrial Decarbonization

Industrial decarbonization refers to the phasing out of atmospheric greenhouse gas (GHG) emissions from the industrial sector. Globally, the most important gases contributing to the GHG effect are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and fluorinated gases. While emissions of all of these gases must be minimized to achieve U.S. industrial decarbonization, scenario modeling in this roadmap focuses primarily on energy-related CO_2 emissions attributable to industrial activity. In the United States, CO_2 emissions represent over 80% of U.S. manufacturing energy-related GHG emissions on a CO_2-equivalent basis.

Pillars

Pillars represent foundational elements of an overall industrial decarbonization strategy. In this roadmap, the pillars include improvements in the **energy efficiency** of industrial processes; **industrial electrification** approaches to leverage electricity generated from clean sources; expanded use of **low-carbon fuels, feedstocks, and energy sources (LCFFES)**; and the deployment of **carbon capture, utilization, and storage (CCUS) technologies** and **alternate approaches** to mitigate remaining emissions. In many cases, the boundaries between the pillars are indistinct as crosscutting actions, approaches, and infrastructure investments may accelerate progress and improvements across multiple pillars.

Pathways

Pathways are the specific actions the United States can pursue to achieve progress in and across the decarbonization pillars. These actions are informed and supplemented by RD&D to advance viable solutions (i.e., technologies, practices, approaches, and behaviors) that will need to be adopted at scale in the marketplace.

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[41] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 6. Industrial Sector Key Indicators and Consumption. Calculated as increase in Value of Shipments between 2020 and 2050.

[42] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 18. Energy-Related Carbon Dioxide Emissions by Sector and Source.

[43] International Energy Agency, *Clean Energy Innovation*, July 2020, https://www.iea.org/reports/clean-energy-innovation.

[44] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 2. Energy Consumption by Sector and Source and Table 19. Energy-Related Carbon Dioxide Emissions by End Use.

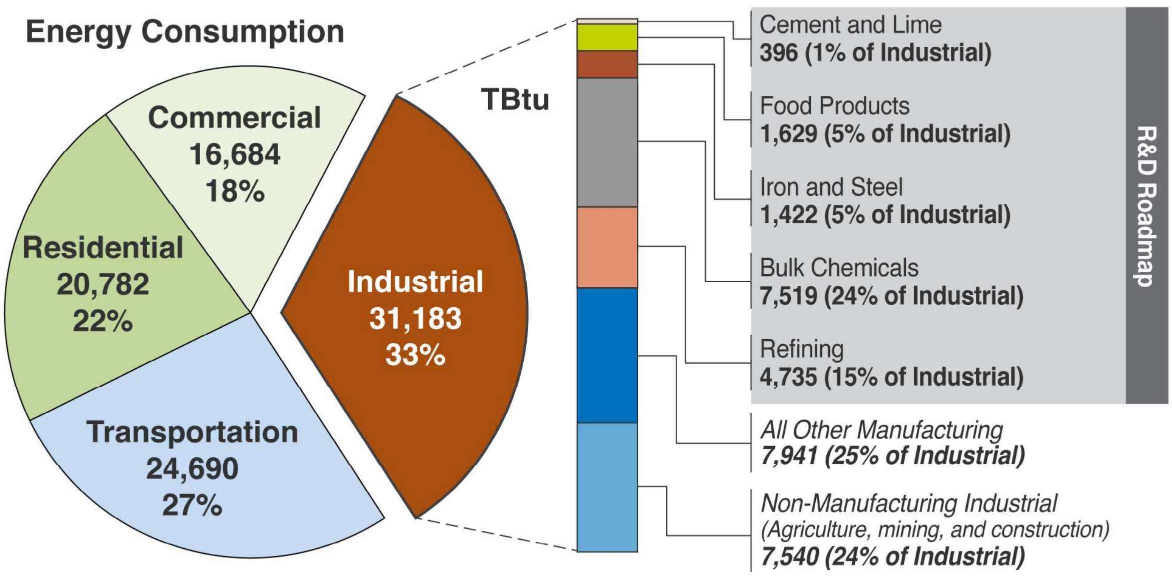

FIGURE 2. U.S. PRIMARY ENERGY CONSUMPTION BY END USE SECTOR (LEFT PIE CHART) AND A BREAKOUT BY INDUSTRIAL SUBSECTOR (RIGHT STACKED CHART) IN 2020. OFFSITE ELECTRICITY LOSSES (FOR THE POWER GENERATION SECTOR) ARE ALLOCATED TO END USE INDUSTRIES.

FIGURE DERIVED FROM 2020 DATA FROM EIA 2021.[45] NOTE THAT CEMENT AND LIME ARE SHOWN IN AGGREGATE IN THIS FIGURE, CONSISTENT WITH EIA AEO SECTOR DEFINITIONS; HOWEVER, CEMENT (WITHOUT LIME) IS ANALYZED AS AN INDEPENDENT SUBSECTOR IN THE SCENARIO ANALYSES OF THIS REPORT.

> *Key message: The U.S. industrial sector accounted for 33% of the nation's primary energy consumption in 2020, with the five industrial subsectors selected for focus in this roadmap responsible for over half of the industrial contribution.*

Figure 3 presents the energy-related atmospheric CO_2 emissions attributed to each economic sector, again breaking down industry by its subsectors. Although U.S. GHG emission intensities, as a percentage of gross domestic product, are projected to continue declining, the product demand that industry responds to is expected to rise more than 50% by 2050.[46] Total industrial GHG emissions are expected to rise more than 17% by 2050.[47] Considering the expected increases in production to meet societal demand, reducing GHG emissions to reach net-zero GHG emissions by 2050 will be even more challenging. This report primarily covers the energy-related emissions, yet it is recognized that there are also significant non-energy-related GHG emissions associated with manufacturing processes (e.g., CO_2 emitted during chemical transformations) and product use (e.g., high global warming potential (GWP) molecule emissions resulting from the use of refrigerants and blowing agents) that are not assessed here. There is a body of research for the latter, and studies specific to reductions of non-energy emissions in industry could be a topic for additional research.

[45] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 2. Energy Consumption by Sector and Source and Tables 24 – 34.
[46] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 6. Industrial Sector Key Indicators and Consumption. Calculated as increase in Value of Shipments between 2020 and 2050.
[47] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 18. Energy-Related Carbon Dioxide Emissions by Sector and Source.

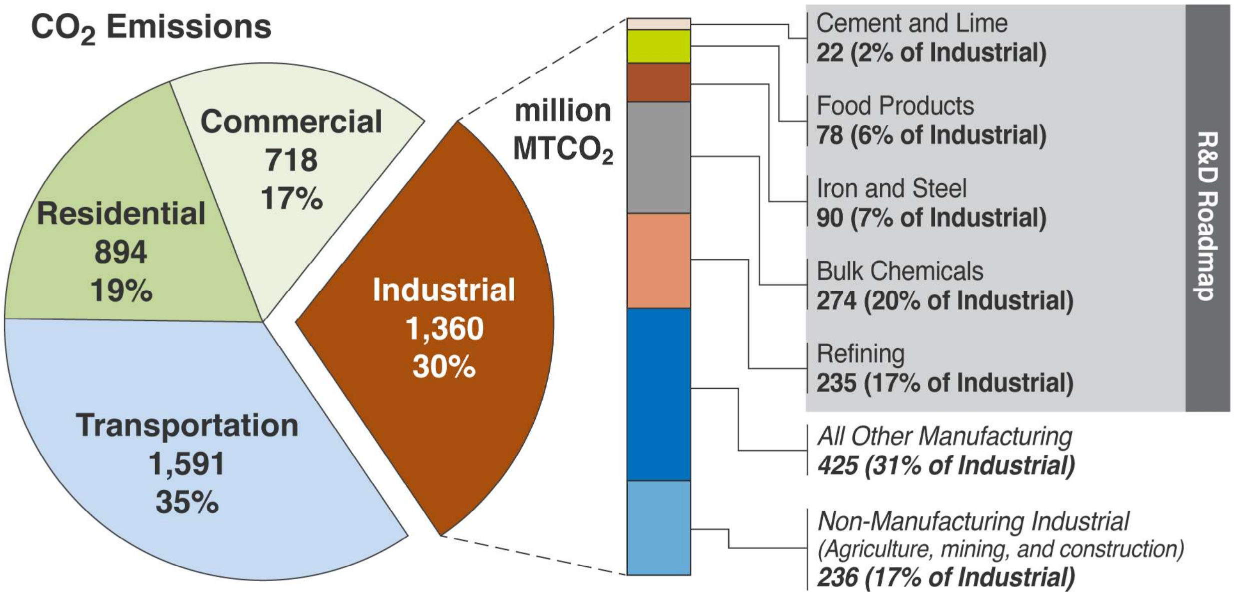

FIGURE 3. U.S. PRIMARY ENERGY-RELATED CO_2 EMISSIONS BY END USE SECTOR (LEFT PIE CHART) AND A BREAKOUT BY INDUSTRIAL SUBSECTOR (RIGHT STACKED CHART) IN 2020.

FIGURE DERIVED FROM 2020 DATA FROM AEO 2021.[48] NOTE THAT CEMENT AND LIME ARE SHOWN IN AGGREGATE IN THIS FIGURE, CONSISTENT WITH EIA AEO SECTOR DEFINITIONS; HOWEVER, CEMENT (WITHOUT LIME) IS ANALYZED AS AN INDEPENDENT SUBSECTOR IN THE SCENARIO ANALYSES OF THIS REPORT.

> *Key message: The U.S. industrial sector accounted for 30% of U.S. energy-related CO_2 emissions in 2020, with the five focus subsectors responsible for over half of the industrial contribution.*

In the United States, the variation of energy sources, energy uses, feedstock dependency, reductant usage,[49] product mix, products that rely on carbon, and GHG emission intensities for regional grids present challenges in reducing industrial emissions. To achieve the industrial net-zero GHG emissions goal, a range of strategies and approaches will need to be vigorously pursued in parallel across decades. Various strategies for decarbonization are described in the literature. For the purposes of this roadmap, DOE has simplified these to four "pillars" of decarbonization: energy efficiency; industrial electrification;[50] low-carbon fuels,[51] feedstocks, and energy sources (LCFFES); and carbon capture, utilization, and storage (CCUS). These pillars are defined in Table 1, with technology examples presented for each. The pillars will be described in more detail in Section 1.2. While this report focuses on these pillars, additional approaches will be needed for complete industrial decarbonization, as will detailed techno-economic analyses of candidate solutions.

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[48] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 19. Energy-Related Carbon Dioxide Emissions by End Use.
[49] Reducing agent; an element or compound that loses (or "donates") an electron to an electron recipient (oxidizing agent) in a redox chemical reaction. See "Reducing agent," Wikipedia, last modified May 3, 2022, https://en.wikipedia.org/wiki/Reducing_agent.
[50] The terms "industrial electrification" and "electrification" are used interchangeably throughout this roadmap.
[51] The term "low-carbon" refers to a technology, fuel, or process, with low net GHG emissions to the atmosphere, as opposed to the carbon content of the fuel or energy source being utilized. For example, by capturing CO_2 and by storing it underground, or utilizing it to prevent its release to the atmosphere can enable the use of high carbon content fuels like coal to generate low-carbon electricity, or low-carbon heat. In the case of a biogenic fuels such as biomass, CCUS can enable negative GHG emissions by capturing, storing, or utilizing the carbon absorbed from the atmosphere through photosynthesis.

TABLE 1. DECARBONIZATION PILLARS WITH EXAMPLES OF TECHNOLOGIES FOR INDUSTRY

Energy Efficiency	Industrial Electrification	Low-Carbon Fuels, Feedstocks, and Energy Sources (LCFFES)	Carbon Capture, Utilization, and Storage (CCUS)
Energy efficiency advancements minimize industrial energy demand, directly reducing the GHG emissions associated with fossil fuel combustion.	Industrial process technologies that utilize electricity for energy, rather than combusting fossil fuels directly, enable the sector to leverage advancements in low-carbon electricity from both grid and onsite generation sources.	Substitution of low- and no-carbon fuels and feedstocks for fossil fuels can further reduce combustion-associated emissions for industrial processes.	This multi-component strategy for mitigating difficult-to-abate emissions involves capturing generated CO_2 before it can enter the atmosphere; utilizing captured CO_2 whenever possible; and storing captured CO_2 long-term to avoid atmospheric release.
Energy efficiency technology examples: • Energy management approaches • Thermal integration of process heat • Smart manufacturing • Improved technologies and processes; system integration	Industrial electrification technology examples: • Electrification of process heat (e.g., heat pumps) • Electrification of hydrogen production for industrial process use	LCFFES technology examples: • Fuel-flexible processes • Clean hydrogen fuels and feedstocks • Biofuels and biofeedstocks • Concentrating solar power • Nuclear • Geothermal	CCUS technology examples: • Post-combustion chemical absorption of CO_2 • CO_2 pipelines and other CCUS-supportive infrastructure

The applicability and relative importance of decarbonization pillars will vary across the industrial subsectors, while tradeoffs in costs, local energy or carbon storage availability, and infrastructure will also influence strategy selection.[52] It will be necessary to invest in all four pillars in parallel to achieve the desired emissions reductions by mid-century.[53] For example, in the iron and steel industry, two competing technology pathways are under development in parallel to achieve the same high-level emission reduction outcomes: direct-reduction ironmaking using clean hydrogen (under the LCFFES pillar) and electrolytic ironmaking (under the electrification pillar). To maximize the probability of success, investment in multiple competing technologies is often warranted. The goal of this roadmap is to identify and guide RD&D for transformative technologies and address scale-up and adoption issues. It is a scoping study that identifies the opportunities for technology, RD&D, innovation, and competitiveness on the path to a decarbonized future.

[52] David Sandalow et al., *ICEF Industrial Heat Decarbonization Roadmap*, Innovation for Cool Earth Forum, December 2019, https://www.icef-forum.org/pdf/2019/roadmap/ICEF_Roadmap_201912.pdf; Arnout de Pee et al., Decarbonization of Industrial Sectors: The Next Frontier, McKinsey & Company, June 2018, https://www.mckinsey.com/business-functions/sustainability/our-insights/how-industry-can-move-toward-a-low-carbon-future.

[53] James H. Williams et al., *Pathways to deep decarbonization in the United States*, Sustainable Development Solutions Network and the Institute for Sustainable Development and International Relations, November 2015, https://irp.cdn-website.com/be6d1d56/files/uploaded/2014-technical-report.pdf.

1.1 The Roadmap Process

Multiple input sources and avenues informed the results of this work including an extensive literature review, a series of stakeholder meetings, a scoping analysis, and expert input during the review process. This process identified needs, opportunities, and barriers; technical areas where RD&D can accelerate progress; and the approach to pursue these advances. A small number of simple pillars are used to focus the decarbonization options, with the understanding that multiple technologies and approaches are within each pillar. Additionally, the roadmap evaluates the potential for CO_2 emissions reductions for each of the five industrial subsectors using four scenarios that implement specific technologies and strategies from these pillars over the coming decades. The scenarios are defined at the beginning of Section 1.3 (and in more detail in the Appendices: Scenario Methodology and Assumptions), which presents the roadmap's subsector-specific CO_2 emissions reducing technologies, processes, and practices.

1.1.1 Literature Review

In preparation for the stakeholder meetings, a literature review was conducted to identify opportunities for industrial decarbonization previously identified in articles, government reports, and other research material from national laboratories, industry, and academic institutions. The literature review results were synthesized into background documents that were shared with the meeting participants as a starting point for the discussions in the meetings. The overall process followed is shown in Figure 4.

FIGURE 4. DEVELOPMENT PROCESS FOR THE INDUSTRIAL DECARBONIZATION ROADMAP. SOURCE: THIS WORK.

The scale, scope, and the rate of changes needed for decarbonization is unprecedented, and multiple layers of challenges need to be addressed to achieve net-zero GHG emissions. Among the challenges are rapid development and deployment of emerging and transformative technologies with substantially lower-carbon footprints, connections to low-carbon energy sources (e.g., wind, solar, biofuels, and nuclear), and a transition to low-carbon feedstocks. RD&D is crucial to enabling this transition with step-change reductions in GHG emissions, improving competitiveness, and preparing the workforce to deliver on these challenges.

1.1.2 Stakeholder Meetings

To begin development of a roadmap for industrial decarbonization with stakeholder input, a series of virtual stakeholder meetings were held in May and June 2020.[54] The meetings were intended to bring together a range of stakeholders from the five identified subsectors (iron and steel, chemicals, food and beverages, petroleum refining, cement) to identify RD&D needs, the technical and market barriers

[54] In-person meetings were prohibited because of the coronavirus disease 2019 (COVID-19) pandemic.

industrial sector decarbonization, and the potential for existing and emerging technologies. The organizers reached out to stakeholders from industry, government, nongovernmental organizations, consultants, academia, and national laboratories to identify the appropriate experts to be included in the meetings, targeting experts around the industry subsectors being covered by the roadmap. These meetings were held to gain input on current and emerging technologies and RD&D needs, and no consensus advice was sought.

To facilitate conversation, a framing and background document describing a starting hypothesis on potential decarbonization pathways was developed and shared with meeting participants before the first meeting. The meetings were held using a webinar platform that allowed facilitators to break the groups into separate subsectors to hold detailed discussions with those subsector experts. Following an introductory session, subsector-specific breakout discussions were held to delve into decarbonization pathways for the five identified subsectors. Participants attended breakouts for their industrial sector of interest and provided input.

The discussions at these meetings included but were not limited to:

- **Gathering input:** What are the viable decarbonization pathways, technology adoption rates and timing?
- **Validating understanding:** Do the starting set of challenges, accelerators, potential enablers from the literature align with industry perspectives across the five identified subsectors (iron and steel, chemicals, food and beverages, petroleum refining, and cement)?
- **Exploring paths for RD&D:** Identify RD&D priorities for DOE to enable net-zero industrial GHG emissions by 2050. How could DOE facilitate the industrial transformation (across all technical maturity levels) with maximum value return and minimum elapsed time?
- **Gaining perspective:** What is the diversity of views across the five identified subsectors on pursuing the roadmap?

Following the third virtual meeting for the different subsectors, the meeting notes and comments from the collaboration platform were combined to summarize for the different subsectors. These summaries were then sent to the subsector participants to provide feedback and ensure proper capture of the discussions from the meetings. During the meetings, the organizers requested volunteers from the participants who would be willing to review the content for each subsector.

With the feedback on the summaries, the roadmap team used that information to draft the subsector content for the roadmap (i.e., Sections 2.1–2.5). The draft content for these sections was then sent to the volunteer reviewers and their feedback was incorporated in those sections. The feedback from one reviewer on the refining subsector suggested additional detail would be beneficial and that reviewer coordinated outreach to some members of the subsector to solicit additional feedback.

With the subsector-specific content reviewed and finalized, the full document was assembled and provided to several DOE experts for an internal review of the full document.

1.2 The Pillars of Decarbonization: Crosscutting Carbon-Reducing Technologies, Processes, and Practices

Technologies, approaches, knowledge management, and infrastructure that are developed or deeply used in one energy production or demand sector could benefit others, resulting in synergies that amplify benefits, leverage resources, reduce costs, speed adoption, improve system efficiency, and conserve resources. The crosscutting decarbonization pillars identified in this work are energy efficiency, industrial electrification,[55] LCFFES, and CCUS. These pillars were chosen amongst a range of options due to their ability to provide step-change reductions, applicability across all industrial subsectors, and the capability to deliver near-term and future reductions as the GHG emissions intensity of the electrical grid decreases, technologies develop (e.g., clean hydrogen), and hard-to-abate sources are addressed (by CCUS for example).

Roadmap Decarbonization Pillars

Energy Efficiency: Energy efficiency is a foundational, crosscutting decarbonization strategy. Reducing the energy consumption of the industrial sector directly reduces GHG emissions associated with fossil fuel combustion.

Industrial Electrification: As industry transitions from combustion fuels to electric power, it will be able to better leverage advancements in low-carbon electricity from both grid and onsite generation sources. For grid-purchased electricity, this strategy is predicated on the assumption of "greening of the grid" – i.e., parallel advancements made in the electric power sector to increase use of nuclear, renewable, and low-carbon fuel sources and reduce combustion emissions

Low-Carbon Fuels, Feedstocks, and Energy Sources (LCFFES): Substitution of low-carbon fuels, feedstocks, and energy sources such as hydrogen, biofuels, or solar thermal power, can further reduce combustion-associated GHG emissions for industrial processes.

Carbon Capture, Utilization, and Storage (CCUS): This multi-component strategy for mitigating hard-to-abate emissions sources involves capturing generated CO_2 before it can enter the atmosphere, utilizing captured CO_2 wherever possible, and storing captured CO_2 long-term.

The pillar framework can capture important crosscutting approaches, such as the need for improved material efficiency, material substitution, and circular economy approaches. For example, end of life materials have the potential to provide low carbon feedstocks via the LCFFES pillar; however, this needs to be done in an energy efficient manner. Crosscutting topics, such as material efficiency, circular economy, and bio-based options, need to be explored more thoroughly, but are not covered in detail in this report. These additional topics are discussed briefly in Section 4.

The interplay between pillars is also important to consider for the most effective GHG emissions reduction strategy. For example, the use of grid-based electrolysis to produce certain hydrogen-containing precursors (e.g., ammonia) can have energy intensity factors significantly higher than incumbent processes (e.g., Haber Bosch) resulting in increased emissions if a switch were made to electrolysis without a fully decarbonized source of electricity. This example highlights that advancement in one pillar may be necessary to achieve the full benefit of another, and that the application of pillars needs to be examined thoroughly to validate the magnitude of GHG emissions reductions.

Considerations for each pillar are discussed in the following sections.

[55] The terms "industrial electrification" and "electrification" are used interchangeably throughout this roadmap.

1.2.1 Energy Efficiency

Energy efficiency is a foundational crosscutting decarbonization strategy, and it remains the most cost-effective option for near term GHG emissions reductions. Energy efficiency impacts are delivered through energy-efficient technology development and deployment, combined with a continuing drive to implement strategic energy management (SEM) across all of industry. For example, a case study of 3M and Schneider Electric's SEM practices showed that sites that implemented such practices demonstrated energy performance improvements[56] that were up to 65% greater than sites without formal energy management systems.[57] Additional research also shows the effect of adopting SEM on a plant's efficiency, including a 6.4% realized energy savings after appointing an energy manager and 6.9% realized energy savings after undertaking an energy audit, with these values likely representing a lower bound.[58] The U.S. Department of Energy (DOE) recently highlighted the energy efficiency progress made by its more than 250 manufacturing partners in its 2021 Better Plants Annual Progress Update report. These organizations, which make up roughly 13.8% of the U.S. manufacturing energy footprint, have cumulatively saved $9.3 billion and 1.9 quadrillion British thermal units (Btu) of energy since inception of the program. Their annual energy intensity improvement rate is reported to be 2%.[59]

Energy end uses highlight focus areas for decarbonization through the energy efficiency pathway. The energy use distribution by end use for 2018 is shown in Figure 5. The generation and use of heat (e.g., process heating, boilers, and combined heat and power [CHP] systems) is the most significant end use of energy in the industrial sector (by a significant margin), followed by machine-driven systems. In U.S. manufacturing, steam accounts for 30% of process heat energy use.[60] The proportion of energy used for process heating varies by industry across broad ranges with the lower temperature ranges (below 150°C) offering the most significant energy reduction opportunities for current and emerging technologies.[61]

[56] Energy performance improvement is determined by accounting for energy consumption, normalizing for relevant variables through adjustment modeling, and calculating energy performance improvement. The determination and demonstration of energy performance improvement is based upon the comparison of two facility-wide approaches to calculating energy performance improvement (top-down and bottom-up). See Superior Energy Performance (SEP) 50001 for more details: "Certify and Get Recognized," Better Buildings Program, U.S. Department of Energy, accessed May 2022, https://betterbuildingssolutioncenter.energy.gov/iso-50001/sep-50001/certify-and-get-recognized.

[57] "Business case," Better Buildings Program, U.S. Department of Energy, accessed May 2022, https://betterbuildingssolutioncenter.energy.gov/iso-50001/business-case. See page 6.

[58] Gale Boyd, E. Mark Curtis, and Su Zhang. *Impact of Strategic Energy Management Practices on Energy Efficiency: Evidence from Plant-Level Data*, July 2021, https://www.aceee.org/sites/default/files/pdfs/ssi21/panel-3/Boyd.pdf.

[59] U.S. Department of Energy, *Better Plants Progress Update Report*, Fall 2021, https://betterbuildingssolutioncenter.energy.gov/sites/default/files/attachments/2021_Better_Plants_Progress_Update.pdf.

[60] "Manufacturing Energy and Carbon Footprint: All Manufacturing (2018 MECS)," U.S. Department of Energy Advanced Manufacturing Office, December 2021, https://www.energy.gov/sites/default/files/2022-01/2018_mecs_all_manufacturing_energy_carbon_footprint.pdf.

[61] Colin McMillan, "Manufacturing Thermal Energy Use in 2014," National Renewable Energy Laboratory, 10.7799/1570008, last updated December 18, 2020, https://data.nrel.gov/submissions/118.

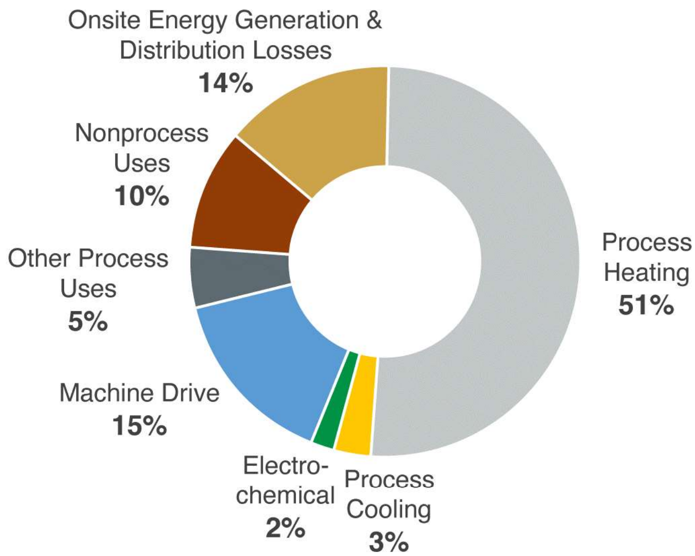

FIGURE 5. BREAKDOWN OF ENERGY USE ONSITE AT U.S. MANUFACTURING FACILITIES IN 2018 BY END USE.

FIGURE DERIVED FROM 2018 MANUFACTURING ENERGY CONSUMPTION SURVEY (MECS) DATA.[62]

> *Key message: Process heating accounts for over half of all onsite energy consumption at manufacturing facilities.*

Motor applications including pumps, fans, compressed air, materials handling, and others account for 91% of manufacturing electrical energy consumption[63] and 43%–46% of global electricity demand by end use[64] signaling another major opportunity for efficiency improvements. A systems-based approach, applied across entire motor systems, could result in much larger energy savings than individual efforts. For example, a United Nations Industrial Development Organization study showed that the system-level optimization of motor systems like compressed air, pump, and fan systems could result in a total technical electricity saving potential of 27%–57% of the total motor system energy use, depending on the efficiency baseline.[65]

Investments in energy efficiency technology development should be informed by the broad context of energy transitions underway in the United States, particularly when large capital investments are involved that might lock-in that technology over long periods. For example, an energy-efficient process heating system that relies on fossil fuel combustion may improve energy efficiency in the short term—but as the U.S. electric grid transitions to clean energy, electrified technologies may provide a greater emissions reduction in the long run. Careful consideration of such tradeoffs will be critical to a strategic and coordinated decarbonization approach.

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[62] "Manufacturing Energy and Carbon Footprint: All Manufacturing (2018 MECS)," U.S. Department of Energy Advanced Manufacturing Office, December 2021, https://www.energy.gov/sites/default/files/2022-01/2018_mecs_all_manufacturing_energy_carbon_footprint.pdf.

[63] Ibid.

[64] International Energy Agency, *Energy Efficiency Policy Opportunities for Electric Motor-Driven Systems*, May 2011, https://www.iea.org/reports/energy-efficiency-policy-opportunities-for-electric-motor-driven-systems.

[65] Aimee McKane and Ali Hasanbeigi, "Motor System Energy Efficiency Supply Curves: A Methodology for Assessing the Energy Efficiency Potential of Industrial Motor Systems," *Energy Policy* no. 39 (October 2011): 6595–6607. http://dx.doi.org/10.1016/j.enpol.2011.08.004.

To this end, RD&D is needed to advance tools and technologies for systems assessment and optimization in industrial plants, while considering factors stemming from the ongoing energy supply transition. While multiple capabilities have evolved in the last decade that allow faster and more accurate integrated optimization across systems, there is a need to quantify the energy and GHG reductions potential more comprehensively and transparently, supporting knowledge sharing, and dissemination of best practices.

Smart manufacturing and advanced data analytics could help the manufacturing sector unlock energy efficiency from the equipment level to the entire manufacturing facility and the whole supply chain. These technologies could make manufacturing industries more competitive, with intelligent communication systems, real-time energy savings, and increased energy productivity. A sophisticated energy impacts analysis and associated data and tools are needed to quantify energy and economic impacts on national, industry sector, facility, energy system and equipment levels.[66] Improved data analytics and effective use of advanced sensors can also improve workforce safety and limit failures leading to accidents.[67] RD&D is needed to better understand the cost of cyber-physical systems for different manufacturing plants and subsectors, including the cost of sensors, controllers, smart equipment, and information and communications technology (ICT) equipment.

RD&D could help both with big data challenges related to data quality, storage, and computing, and on developing advanced analytics tools to process the data. Because network infrastructure—both wired and wireless—are requirements of the Industrial Internet of Things (IIOT), the risk of network intrusion is increased. Novel cybersecurity counter measures are needed to protect intellectual property and digital clones' integrity. RD&D could also advance the newer generation of interfaces called dashboards, which attempt to convey pertinent information contextually to aid decision-making. Energy dashboards communicate energy information to workers, technicians, managers, and policymakers in ways that are instructive and actionable.

RD&D could lead to demonstrations of plant automation systems that provide real-time energy performance data, and eventually to utility efficiency programs that pay for energy saved, rather than equipment installed. This could also improve the flexibility, effectiveness, and impact of demand response programs. More research is needed to understand the specifics of not just how data analytics could be used to mine big data to facilitate efficiency gains within plants but also how external data can be harvested for the benefit of the supply chain. This new level of connectivity will likely soon integrate customers into product and service design processes. And it would be beneficial to further understand the broad implications for energy consumption of such a streamlined process, as it would likely have significant economic implications.[68]

All the opportunities for energy and productivity advancements aligned with an expanding IIOT will require additional data storage (e.g., cloud storage) and an expanding demand for information and communication technologies (ICT) hardware. The energy and GHG emissions implications of this expansion need to be assessed, and while there is an emerging understanding of the operational and

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[66] Sachin Nimbalkar et al., "Smart Manufacturing Technologies and Data Analytics for Improving Energy Efficiency in Industrial Energy Systems", (paper presented at the ACEEE Summer Study on Energy Efficiency in Industry, Denver, Colorado, 15-18 August 2017), https://www.osti.gov/biblio/1524315-smart-manufacturing-technologies-data-analytics-improving-energy-efficiency-industrial-energy-systems.

[67] U.S. Department of Energy Office of Nuclear Energy, *Advanced Sensors and Instrumentation Project Summaries*, June 2020, https://www.energy.gov/sites/prod/files/2020/09/f79/ne-asi-project-summaries-2020.pdf.

[68] Ethan A. Rogers et al., *Intelligent Efficiency: Opportunities, Barriers, and Solutions*, American Council for an Energy-Efficient Economy, Report No. E13J, October 2013, https://www.aceee.org/sites/default/files/publications/researchreports/e13j.pdf.

embodied carbon associated with an increasingly digitized industrial sector, more research is needed that spans the implications of rapidly increasing data usage and the required ICT infrastructure.[69]

1.2.1.1 Combined Heat and Power (CHP)

Industrial combined heat and power (CHP) technology has long been used by industry to provide reliable heat and power with high efficiency and lower emissions. The energy savings and GHG emissions reductions benefits of CHP are found in the aggregate reduction in overall energy consumption: CHP replaces both a separate onsite thermal system (furnace or boiler) and purchased power with a single, integrated system, efficiently producing both thermal energy and electricity at the point of use. Industrial CHP systems, through both topping and bottoming cycles, can provide needed energy services for some subsectors with overall energy efficiencies of 65%–85% compared to separate production of heat and power, which collectively averages 45%–55% system efficiency.[70] In particular, CHP is prevalent in chemicals, pulp and paper, refining, primary metals, and food industries, but can also be found in crop production, nonmetallic minerals, and other uses.[71]

Industrial CHP can provide significant GHG emissions reductions in the near- to mid-term as marginal grid emissions continue to be based on a mix of fossil fuels in most areas of the country. In order to prevent lock-in, CHP units installed today must have emissions below marginal grid emissions for the duration of their useful lifetime, including through retrofits to use clean sources of energy where possible. Furthermore, the use of nuclear energy for electricity and heat, renewable and synthetic fuels, and clean sources of energy as the prime movers for CHP systems can avoid the use of fossil fuels, which will support the integration of CHP into a fully decarbonized energy economy. Clean CHP systems can also enhance energy security and resilience for industrials and distributed microgrids.[72]

Converting some natural gas infrastructure over time to renewable natural gas (RNG), synthetic natural gas or hydrogen produced from nuclear energy, and hydrogen is one strategy to decarbonize CHP. CHP has long used digester and biogas as fuel sources,[73] and CHP systems deployed today can operate on increasing percentages of RNG as availability increases. In addition, engine and gas turbine manufacturers are currently testing and operating CHP systems on high percentage hydrogen fuels in preparation for increasing use of RNG and hydrogen in the future. RNG and hydrogen fueled CHP systems can be a long-term path to decarbonizing industrial thermal processes resistant to electrification because of technology or cost barriers, and for critical operations where dispatchable onsite power is needed for resilience and reliability. All major engine and gas turbine manufacturers are

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[69] John Patsavellas and Konstantinos Salonitis, "The Carbon Footprint of Manufacturing Digitalization: critical literature review and future research agenda," *Procedia CIRP* 81 (2019): 1354-1359, https://doi.org/10.1016/j.procir.2019.04.026; International Energy Agency, *Digitalisation and Energy*, November 2017, https://www.iea.org/reports/digitalisation-and-energy; GeSI, *Smarter 2030: ICT Solutions for 21st Century Challenges*, Accenture Strategy on behalf of the Global eSustainability Initiative, May 2015, http://smarter2030.gesi.org/downloads.php; Eric Masanet et al., "Recalibrating Global Data Center Energy-Use Estimates," *Science* 367, no. 6481 (February 2020): 984–86. https://doi.org/10.1126/science.aba3758; Nicola Jones, "How to stop data centres from gobbling up the world's electricity," *Nature* 561, no. 7722 (September 2018): 163-167. https://www.nature.com/articles/d41586-018-06610-y.

[70] U.S. Department of Energy Advanced Manufacturing Office, *Overview of CHP Technologies*, November 2017, https://betterbuildingssolutioncenter.energy.gov/sites/default/files/attachments/Overview_of_CHP_Technologies.pdf.

[71] "Many Industries use Combined Heat and Power to Improve Energy Efficiency," U.S. Energy Information Administration, July 27, 2016, https://www.eia.gov/todayinenergy/detail.php?id=27252.

[72] Net emissions for a CHP system are based on the fuel chargeable to power defined as the incremental fuel for the CHP system, relative to the fuel needs of a heat-only system divided by the net electrical power produced by the system.

[73] DOE's CHP Installation Database lists 608 CHP systems with a total of 538 megawatt operating on digester gas and landfill gas utilizing reciprocating engines, gas turbines, microturbines and fuels cells. "CHP Installations," U.S. Department of Energy, last modified October 31, 2021, https://doe.icfwebservices.com/chpdb/.

working on further improving performance with biogas and biofuels and developing the capability to operate efficiently and with low criteria air pollutant emissions at high levels of hydrogen. Challenges during the transformations to net-zero GHGs will include finding ways to maintain the benefits afforded by well-designed CHP systems (i.e., high utilization rates, reliability, efficiency, reliability, source flexibility), while moving to a higher proportion of lower carbon energy sources (i.e., H_2, biofuels, RNG, concentrating solar-thermal power (CSP), geothermal) and minimizing future obligations (i.e., capital, infrastructure, integration) to carbon intensive processes (e.g., inflexibility to future low-carbon technology adoption, or "lock-in") and exploring opportunities in thermal energy storage.

In addition to those above, RD&D needs for future CHP include prime mover development (e.g., reciprocating engines, gas turbines, and microturbines) to maintain high efficiency; high reliability and low criteria air pollutant emissions on biofuels and high levels of hydrogen; options for new cycles/working fluids; controls and control schemes for integrating with a dynamic smart grid and distributed microgrids; conversion of natural gas infrastructure to operate on high levels of RNG and hydrogen; heat exchangers to deal with "dirty" but hot streams; and considering solar/thermal integration for lower-grade heat.

1.2.2 Industrial Electrification and Low-Carbon Fuels, Feedstocks, and Energy Sources

A transformation in the way that energy is generated, stored, and used is central to climate change mitigation efforts.[74] For industry, a key opportunity is making cost competitive step-change reductions in the GHG emissions associated with process heat. This section will introduce several important approaches to achieve this transformation in process heat energy supply and GHG emissions mitigation. Application of electrification and transition to low-carbon fuels, feedstocks and energy sources to industrial processes are critical to achieving decarbonization. The low carbon-carbon fuels and energy sources include use of renewable energy sources, nuclear energy (from fission and/or future fusion reactors), CSP, geothermal and other low- and no-carbon emissions energy sources. The low-carbon feedstocks include biobased and end of life materials. Additionally, RD&D is necessary to assess additional infrastructure needs and associated costs for the electric grid to transmit and distribute power to meet the demand for future industrial electrification.

1.2.2.1 Electrification of Process Heat

In the United States, process heating consumes more energy than any other manufacturing end use. In 2018, a total of 7,576 trillion Btu (TBtu) of fuel, steam, and electric energy were consumed by U.S. manufacturers for this purpose, comprising 51% of total onsite manufacturing energy.[75] In the same year, process heating accounted for 360 million metric tons of CO_2e GHG emissions, representing 31% of the manufacturing sector's total energy-related emissions.[76] The magnitude of process heat energy use and its carbon footprint makes process heat a major opportunity for low-carbon solutions.

It is also important to consider the temperature ranges for process heat in individual subsectors, as they could provide insights into the technology applicability (see Figure 6 and Figure 7). About 30% of the

[74] National Academies of Sciences, Engineering, and Medicine, *Accelerating Decarbonization of the United States Energy System*, February 2021, https://www.nap.edu/catalog/25932/accelerating-decarbonization-of-the-us-energy-system.
[75] U.S. Department of Energy Advanced Manufacturing Office, *Manufacturing Energy and Carbon Footprint: All Manufacturing (2018 MECS)*, December 2021, https://www.energy.gov/sites/default/files/2022-01/2018_mecs_all_manufacturing_energy_carbon_footprint.pdf.
[76] Ibid.

process heat demand is at temperatures at or below 150°C,[77] making low-temperature process heating a prime candidate for electrification or implementation of other low- or no-carbon sources of heat. Electric technologies like heat pumps, microwave technologies, infrared technologies and other low- and no-carbon sources of process heat such as solar thermal[78] and nuclear[79] could be considered for use in this range.[80] Both solar thermal and nuclear can go far beyond 150°C. Current nuclear can go up to 300°C and in the near-term, advanced gas cooled very high temperature reactors (VHTR) can reach 900°C at scales appropriate for distributed applications.

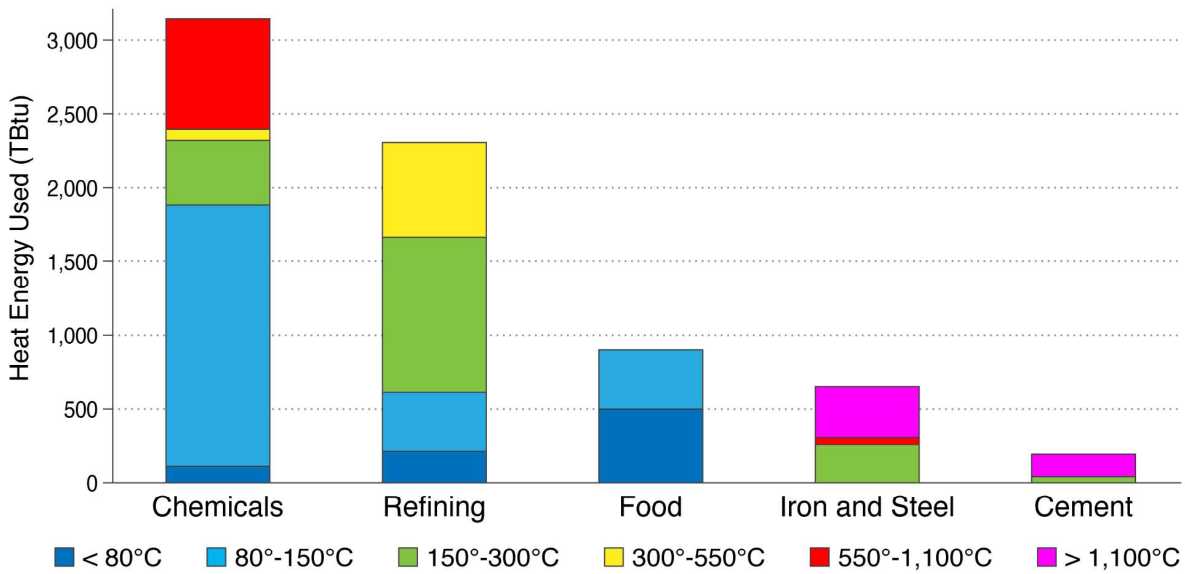

Figure 6. Distribution of process heat temperature ranges by industrial subsector in 2014.

Temperature ranges are in °C and heat use is in trillion Btu (TBtu). Data source: McMillan 2019[81]

Key message: Lower temperature (<300°C) process heat use is prevalent in chemicals, food, and refining subsectors.

[77] Colin McMillan, "Manufacturing Thermal Energy Use in 2014," National Renewable Energy Laboratory, 10.7799/1570008, last updated December 18, 2020, https://data.nrel.gov/submissions/118.
[78] Colin McMillan et al., *Opportunities for Solar Industrial Process Heat in the United States*, National Renewable Energy Laboratory, NREL/TP-6A20-77760, January 2021, https://www.nrel.gov/docs/fy21osti/77760.pdf.
[79] Richard D. Boardman et al., "Process Heat for Chemical Industries," *Encyclopedia of Nuclear Energy* 3, (2021): 49-60. https://doi.org/10.1016/B978-0-12-819725-7.00198-7.
[80] Ed Rightor, Andrew Whitlock, and R. Neal Elliott, *Beneficial Electrification in Industry*, American Council for an Energy-Efficient Economy, July 2020, https://www.aceee.org/research-report/ie2002.
[81] Colin McMillan, "Manufacturing Thermal Energy Use in 2014," National Renewable Energy Laboratory, 10.7799/1570008, last updated December 18, 2020, https://data.nrel.gov/submissions/118.

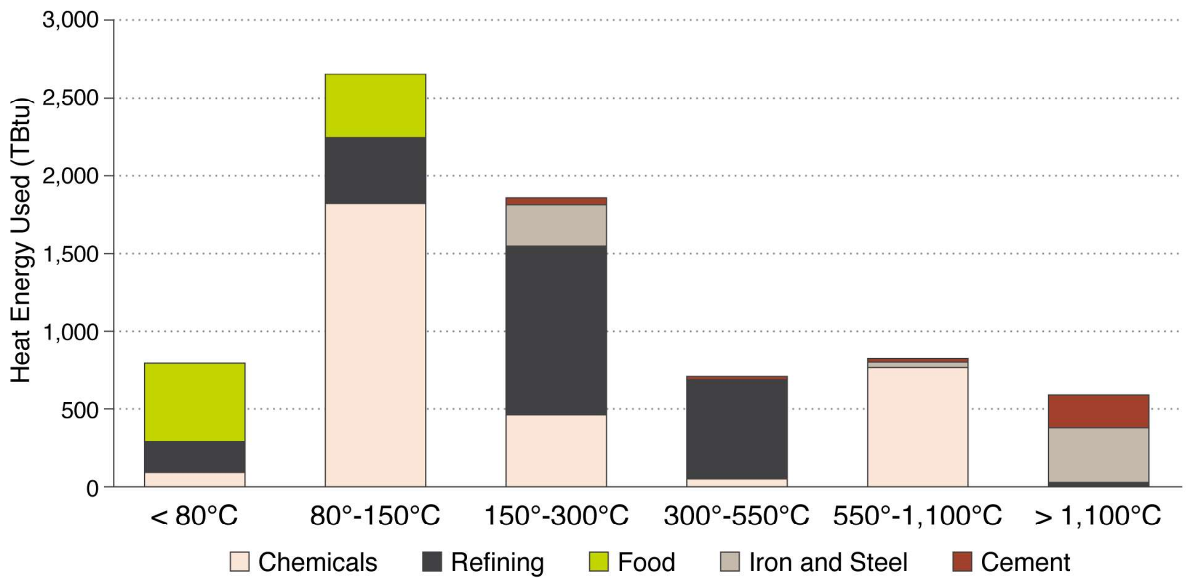

FIGURE 7. DISTRIBUTION OF PROCESS HEAT USE IN 2014 FOR KEY INDUSTRIAL SUBSECTORS BY TEMPERATURE RANGE. TEMPERATURE RANGES ARE IN °C AND HEAT USE IS IN TRILLION BTU (TBTU). DATA SOURCE: MCMILLAN 2019[82]

> *Key message: The quantity of lower temperature (<300°C) process heat in chemicals, food, and refining suggests there could be early opportunities for low-no carbon technologies that can supply heat in this range.*

Electrification represents a major opportunity for process heat decarbonization – for example, one study analyzing the manufacture of thirteen manufactured commodities showed a total opportunity of 134 million MT CO_2 saved per year in 2050 with the implementation of electrified technologies.[83] Electrified technologies (including induction, radiative heating, and advanced heat pumps) are particularly viable in the lower end of the medium-temperature range, but electrification is also feasible in the higher-temperature ranges (e.g., iron and steel or cement kiln advances). For process heating, hydrogen combustion could also provide an alternative low-carbon solution as hydrogen produces a 2,100°C flame when burned in air.[84] The next section (Section 1.2.2.2) examines the hydrogen option.

Following thermal processing, residual heat often remains as unused thermal energy, although such waste heat is often downgraded in temperature or working pressure. Waste heat represents a significant opportunity for recovery, considering its vast quantity across the industrial sector. Waste heat recovery technologies include systems-level solutions that enable reuse of the waste heat streams for other thermal processing and waste heat to power (WHP) electric technologies.[85] The waste heat can also be stored, which is an application of thermal storage where the main options are sensible, latent, or

[82] Ibid.
[83] Ali Hasanbeigi et al., *Electrifying U.S. Industry: Technology and Process-Based Approach to Decarbonization*, January 2021, https://www.globalefficiencyintel.com/electrifying-us-industry.
[84] David Sandalow et al., *ICEF Industrial Heat Decarbonization Roadmap*, Innovation for Cool Earth Forum, December 2019, https://www.icef-forum.org/pdf/2019/roadmap/ICEF_Roadmap_201912.pdf.
[85] U.S. Department of Energy, *Quadrennial Technology Review 2015, Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing: Technology Assessment for Process Heating*, September 2015, https://www.energy.gov/sites/prod/files/2016/06/f32/QTR2015-6I-Process-Heating.pdf.

thermochemical storage and which allows waste heat to be productively utilized when its generation does not directly match the timing or heat duty of potential uses.[86]

For industrial electrification, the key RD&D needs highlighted in stakeholder meetings and technical literature include:

- A portfolio of low- and no-carbon process heat solutions is needed as a starting point for industry to select options with the best fit in terms of application, economics, geography, and other factors.
- There is a need to overcome scaling issues for electric technologies. Although direct reduced iron (DRI) technologies work well at the pilot scale, systems that can process a million MT of steel a year or provide heat for a full-scale ethane cracker in chemicals are uneconomical.
- The production environments for several of the five industrial subsectors addressed in the stakeholder meetings require durable service in the presence of corrosive gases, so research to improve durability in intensive process conditions is needed.
- Further research is needed to improve the match between modular design sizing and its application (i.e., scale small enough to have a low investment hurdle yet large enough for good return on investment).
- Research is needed to explore the efficacy of electrification as a decarbonization measure and specifically examine the tradeoffs of energy source versus GHG emissions reduction through life cycle assessments (LCAs) and techno-economic analyses (TEAs).

1.2.2.2 Hydrogen as a Low-Carbon Fuel, Feedstock, and Energy Source

In the United States, about 10 million MT of hydrogen are produced yearly, primarily for use in petroleum refining and ammonia production, with smaller amounts used in industries such as metals production, methanol production, food processing, and electronics.[87] While most hydrogen is currently made from reforming of natural gas, hydrogen production from renewables, nuclear power, or fossil resources with carbon capture can reduce GHG emissions from these existing demand sectors. The development and advancement of novel technologies for clean hydrogen use, such as in medium- and heavy-duty vehicles, metals refining, synthetic fuel and biofuel production, and stationary fuel cells for power, can further enable nationwide GHG emissions reduction. Hydrogen production using electrolyzers can additionally supply grid services to increase grid resiliency, and hydrogen technologies can also be used for long duration energy storage. The DOE's Hydrogen and Fuel Cells Technologies Office (HFTO), in coordination with the DOE-wide Hydrogen Program, is addressing priority areas of RD&D to enable hydrogen use in these diverse sectors.[88] Beyond RD&D activities, deployment at scale to drive hydrogen market adoption and lower costs will be critical to achieve decarbonization targets; for example, the H2Hubs investment will create hydrogen networks and accelerate its innovative use in

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[86] Abby L. Harvey, "The Latest in Thermal Energy Storage," *Power Magazine,* June 30, 2017, https://www.powermag.com/the-latest-in-thermal-energy-storage/.
[87] U.S. Department of Energy, *Department of Energy Hydrogen Program Plan*, 2020, https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf.
[88] Ibid.

manufacturing.[89] These activities support the broader DOE priorities of its H2@Scale initiative as well as its Hydrogen Energy Earthshot.[90]

1.2.2.2.1 RD&D Needs and Opportunities

Hydrogen for industrial processes is usually produced at or close to the area of use. Reductions in the cost of large-scale hydrogen production technologies (e.g., electrolyzers and steam reforming and autothermal reforming with CCUS) are thus essential to enabling industrial hydrogen use. The cost of hydrogen produced from low-temperature electrolysis depends strongly on the electricity cost: it currently ranges from $5–$6/kg hydrogen for electricity prices in the $0.05–$0.07/kilowatt-hour (kWh) range.[91] The availability of lower-cost electricity—for example, in the $0.02–$0.03/kWh range from emerging wind and solar assets—coupled with ongoing advancements in electrolyzer technologies offers a pathway to cost-competitive hydrogen, at less than $2/kg.[92] Additional pathways to low-cost hydrogen production include the use of high-temperature electrolyzers. High-temperature electrolyzers can leverage both electricity and heat from generation sources such as nuclear, fossil with CCUS, or concentrating solar power plants to improve conversion efficiencies, further reducing cost.[93] Existing nuclear plants are working to reduce the cost of producing from approximately $30/megawatt-hour (MWh) at present to approximately $20/MWh or less through efforts to improve and modernize plants and improve efficiencies.[94]

Key RD&D needs enabling growth in clean hydrogen production includes:

- Reduction in cost and improvement in efficiency and durability of low- and high-temperature electrolyzers.
- Development of reversible fuel cells that combine the functionality of electrolyzers and fuel cells, using both electricity to split water into hydrogen and oxygen and using hydrogen and oxygen to produce electricity and water.
- Longer-term pathways for direct water-splitting, without the need for electricity. These include thermally driven chemical looping processes such as solar thermochemical systems, as well as light-driven photoelectrochemical processes. Ongoing RD&D—at the materials, component, and system levels—will be needed to address efficiency, durability, and cost challenges in all water-splitting processes.

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[89] "DOE Launches Bipartisan Infrastructure Law's $8 Billion Program for Clean Hydrogen Hubs Across U.S.," U.S. Department of Energy, June 6, 2022, https://www.energy.gov/articles/doe-launches-bipartisan-infrastructure-laws-8-billion-program-clean-hydrogen-hubs-across.

[90] "Hydrogen Shot," U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office, accessed May 2022, https://www.energy.gov/eere/fuelcells/hydrogen-shot.

[91] James Vickers, David Peterson, and Katie Rudolph, *Cost of Electrolytic Hydrogen Production with Existing Technology*, September 2020, https://www.hydrogen.energy.gov/pdfs/20004-cost-electrolytic-hydrogen-production.pdf.

[92] David Peterson, James Vickers, and Dan DeSantis, *Hydrogen Production Cost from PEM Electrolysis- 2019*, February 2020, https://www.hydrogen.energy.gov/pdfs/19009_h2_production_cost_pem_electrolysis_2019.pdf.

[93] Richard D. Boardman. "High Temperature Steam Electrolysis," *Encyclopedia of Nuclear Energy* 3, (2021): 82–93. https://doi.org/10.1016/B978-0-12-819725-7.00202-6.

[94] Nuclear Energy Institute, *Nuclear Costs in Context*, November 2021, https://www.nei.org/resources/reports-briefs/nuclear-costs-in-context; James Remer et al., *Light Water Reactor Sustainability Program: Process for Significant Nuclear Work Function Innovation Based on Integrated Operations Concepts,* U.S. Department of Energy Office of Nuclear Energy, INL/EXT-21-64134, August 2021, https://lwrs.inl.gov/Advanced%20IIC%20System%20Technologies/ProcessSignificantNuclearWorkFunctionInnovation.pdf.

- Discovery and control of novel materials, processes and predictive theories and computational methods to overcome fundamental barriers to achieving systems for hydrogen generation and use with high efficiency and long-term durability.[95]

Additional RD&D is also needed to lower the cost of large-scale hydrogen distribution infrastructure. Hydrogen is currently distributed at scale using pipelines, gaseous tube trailers, and liquid tankers. The United States currently has over 1,600 miles of hydrogen pipeline, eight liquefaction plants, and three geologic caverns for bulk hydrogen storage underground.[96]

RD&D needs to lower the cost of hydrogen infrastructure include:

- Materials RD&D to enhance the life of pressure vessels onboard tube trailers and reduce their cost.
- Compression concepts with increased capacity and high reliability, for use at tube trailer terminals and in pipeline systems.
- First-of-a-kind demonstrations of novel pipeline technologies, and assessment of the performance of pipeline materials in pure hydrogen and hydrogen blends.
- Novel, non-mechanical approaches to hydrogen liquefaction, such as the use of magnetocaloric materials
- Materials discovery and development to enable bulk hydrogen storage and transport in chemical carriers.

RD&D is also needed to enable the use of hydrogen in novel applications. Examples of emerging end uses of hydrogen include fuel cell vehicles (e.g., medium/heavy-duty trucks), iron refining (Section 2.1.3.2.2), synthetic fuel and biofuel production (Section 2.2.4.1.3), hydrogen blending in natural gas pipelines, stationary power, and long duration energy storage. RD&D needs in these areas include reductions in the costs of hydrogen storage and fuel cell technologies, systems engineering of iron reduction in hydrogen and foundational RD&D on process kinetics, energy efficient methods of synthetic fuel synthesis, assessment of the compatibility of materials and end uses with hydrogen blends, and innovations in manufacturing technologies for electrolyzers and fuel cells.

Depending on the production method, the energy and feedstock required to produce hydrogen can result in associated CO_2 emissions. For example, these emissions can run about 10 kg CO_2e/kg H_2 for hydrogen from natural gas to near zero for hydrogen made from electrolysis where the electricity comes from renewable energy or nuclear.[97] It is also possible to minimize emissions of fossil pathways by supplementing production with CCUS. The emissions intensity of these pathways will depend largely on the rate of CCUS, the efficiency of the system, and mitigation of upstream emissions (e.g., fugitive methane). Other routes to minimize associated emissions include the use of biomass or waste

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[95] U.S. Department of Energy Office of Science, *Basic Energy Sciences Roundtable: Foundational Science for Carbon-Neutral Hydrogen Technologies,* August 2021, https://science.osti.gov/-/media/bes/pdf/brochures/2021/Hydrogen_Roundtable_Report.pdf.

[96] U.S. Department of Energy, *Department of Energy Hydrogen Program Plan*, 2020, https://www.hydrogen.energy.gov/pdfs/hydrogen-program-plan-2020.pdf.

[97] Jay Bartlett and Alan Krupnick, *Decarbonized Hydrogen in the US Power and Industrial Sectors: Identifying and Incentivizing Opportunities to Lower Emissions*, Resources for the Future, Report 20-25, December 2020, https://media.rff.org/documents/RFF_Report_20-25_Decarbonized_Hydrogen.pdf; "GREET® Model: The Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model," Argonne National Laboratory, accessed May 2022, https://greet.es.anl.gov/index.php.

feedstock, which can also enable negative emissions, particularly when coupled with CCUS or methane pyrolysis, which has been identified as a position bridging technology.[98] Regardless of the source and process used to make hydrogen, the life cycle emissions footprint needs to be considered to understand overall process GHG emissions for a true assessment of the GHG reduction potential.

1.2.3 Carbon Capture, Utilization, and Storage

CCUS is the mitigation strategy for hard-to-abate sources that is the most developed, following decades of research and demonstration projects.[99] Demonstration projects across various sectors have provided a wealth of insight on how to face challenges and prospects for broad scale deployment of CCUS.[100] These include regulatory and economic challenges, with high-costs for industrial plants in terms of both capital and operating costs. There are several processes to a CCUS system, including the capture of CO_2 effluent from fossil fuel combustion or industrial processes, release from the capture media, so the CO_2 can be reused or sent to storage. The regeneration of adsorbents/absorbents typically incurs an energy penalty. Where utilization is employed, a large measure of energy is required to reactivate the CO_2, so the carbon can be used in chemical processes. However, some post-combustion CCUS technologies are closer to commercialization than others. Chemical absorption post-combustion carbon capture and oxy-fuel technology are already operating in some industrial plants, while post-combustion capture technologies using membranes for CO_2 separation, and calcium looping, are still in the RD&D stage. In general, the efficiency, economics, and safety of CCUS technology need to be demonstrated further.

CCUS technology could also benefit from more research on better catalysts and better process designs to bring higher efficiency levels, lower costs, and lower material consumption or waste production. RD&D could also identify optimization of the techno-economic performance of the technology and heat exchanger network, for example with calcium looping methodologies. RD&D could help with increasing pilot- and demonstration-scale for the emissions from the industries considered in this roadmap. Research could also address specific installation, operation, and maintenance requirements at the individual plant level to ensure continuous operation at a given level of CO_2 capture.

A comprehensive 2020 study[101] on transport infrastructure for decarbonization of the U.S. economy includes detailed analysis for industrial plants (Figure 8). A 2020 report[102] described how a national CO_2 pipeline network could evolve, starting with connecting major sources (such as industrial facilities) and sinks (storage locations) over the next 30 years. Currently in the U.S. CO_2 merchant market, production

[98] Mathilde Fajardy and Niall Mac Dowell, "Can BECCS Deliver Sustainable and Resource Efficient Negative Emissions?" *Energy & Environmental Science* 10, no. 6 (2017): 1389–1426, https://doi.org/10/gkdf5f; Nuria Sánchez-Bastardo, Robert Schlögl, and Holger Ruland, "Methane Pyrolysis for Zero-Emission Hydrogen Production: A Potential Bridge Technology from Fossil Fuels to a Renewable and Sustainable Hydrogen Economy," *Industrial Engineering Chemistry Research* 60, no. 32 (2021): 11855–11881, https://pubs.acs.org/doi/10.1021/acs.iecr.1c01679.
[99] Global CCS Institute, *Global Status of CCS*, 2020, https://www.globalccsinstitute.com/wp-content/uploads/2020/12/Global-Status-of-CCS-Report-2020_FINAL_December11.pdf.
[100] Howard Herzog, *Lessons Learned from CCS Demonstration and Large Pilot Projects*, Massachusetts Institute of Technology, May 2016, http://sequestration.mit.edu/bibliography/CCS%20Demos.pdf.
[101] Elizabeth Abramson, Dane McFarlane, and Jeff Brown, *Transportation Infrastructure for Carbon Capture and Storage: White Paper on Regional Infrastructure for Midcentury Decarbonization*, Great Plains Institute, June 2020, https://www.betterenergy.org/wp-content/uploads/2020/06/GPI_RegionalCO2Whitepaper.pdf.
[102] Eric Larson et al., *Net-Zero America: Potential Pathways, Infrastructure, and Impacts, interim report*, Princeton University, December 2020, https://environmenthalfcentury.princeton.edu/sites/g/files/toruqf331/files/2020-12/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf.

capacity of CO_2 is estimated to be about 14.3 million MT/year,[103] with ethanol, ammonia, and hydrogen production accounting for nearly three quarters of the capacity based on a 2014 study.[104] Industrial CO_2 capture capacity needs to increase substantially and at an unprecedented rate in a future with CCUS as a meaningful decarbonization approach. A 2017 journal article[105] identified the spatial distribution of U.S. industrial sites, their CO_2 output, and potential demand for storage sinks. A 2021 facility-level study[106] estimated a range of costs for the capture, compression, and transport of CO_2 from a select group of industrial and power generation point sources. Table 2 provides a summary of potential CO_2 point sources for CCUS in the United States along with estimated costs based on these studies.

[103] Although the data source for CO_2 merchant market referenced here is from a 2014 publication, that estimate is based on a plant-level inventory of capture units obtained from proprietary cryogenic gas industry data. A more recent estimate by Foust indicates that the installed capacity may in fact have shrunk to 12.8 million MT/year. This could be explained by the drop in gasoline demand and ethanol production (ethanol is the largest and the fastest growing supplier of industrial CO_2 in the U.S.) as a result of the COVID-19 pandemic and the 2020 Organization of the Petroleum Exporting Countries (OPEC)-Russia oil price war. Since it is expected that idled ethanol and CO_2 capture plants could be brought back online under the right market conditions, the authors propose that the 14.3 million MT/year value is a good upper-bound estimate for current installed capacity of merchant market CO_2. Thomas D. Foust, "Comparative Economics of Carbon Capture into Alternative Dispositions, Routes, and End Products," (Conference Presentation, Chapel Hill, NC, March 29, 2019), https://www.nrel.gov/docs/fy19osti/73573.pdf.

[104] Sarang D. Supekar and Steven J. Skerlos, "Market-Driven Emissions from Recovery of Carbon Dioxide Gas," 2014. Environmental Science and Technology 48, no. 24 (2014): 14615–23, https://doi.org/10.1021/es503485z. The authors note that in most of these merchant market applications, CO_2 is released into the atmosphere, thereby simply creating a delay in the emission of the CO_2 that was generated and captured elsewhere by an industrial facility. Installing CO_2 capture at additional industrial facilities presents a significant decarbonization opportunity of additional 50 million MT/year or more if the captured CO_2 is put into long-term storage.

[105] Peter C. Psarras et al., "Carbon Capture and Utilization in the Industrial Sector," *Environmental Science and Technology* 51, no. 19 (2017): 11440–4, https://doi.org/10.1021/acs.est.7b01723.

[106] 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 and Technology* 55, no. 11 (2021): 7595–7604, https://doi.org/10.1021/acs.est.0c08674

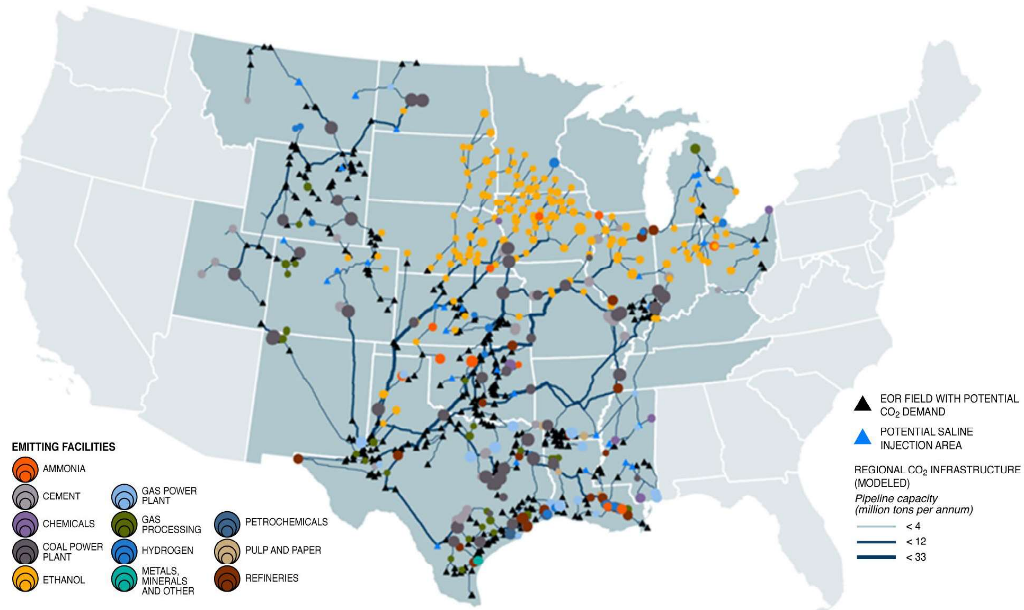

FIGURE 8. EXAMPLE OF OPTIMIZED TRANSPORT NETWORK FOR ECONOMY-WIDE CARBON CAPTURE AND STORAGE.

THE CIRCULAR DOTS SHOW THE TYPES OF CO_2 EMITTING SOURCES, INCLUDING SEVERAL INDUSTRIAL CATEGORIES, AND TRIANGLES SHOWING TWO CLASSES OF STORAGE LOCATIONS. SOURCE: ABRAMSON, MCFARLANE, AND BROWN 2020.[107]

> *Key message: To capture CO_2 emissions from hard-to-abate industrial sources connections will be needed to regional CO_2 pipelines that provide delivery to storage or reuse locations.*

[107] Elizabeth Abramson, Dane McFarlane, and Jeff Brown, *Transportation Infrastructure for Carbon Capture and Storage: White Paper on Regional Infrastructure for Midcentury Decarbonization*, Great Plains Institute, June 2020, https://www.betterenergy.org/wp-content/uploads/2020/06/GPI_RegionalCO2Whitepaper.pdf.

TABLE 2. NEAR- AND MEDIUM-TERM FACILITIES, CAPTURE TARGETS, AND COST ESTIMATES FOR U.S. INDUSTRIAL AND POWER PLANTS.[108]

Industry	Total Facilities	Total CO_2 Emissions (million MT/year)	Total Capturable CO_2 (million MT/year)^{A,B}	Estimated Cost ($/MT)^{C} [Min-Avg-Max]	Facilities Capturing Commercial CO_2
Coal Power Plant	272	1140	1594	33.6 – 55.0 – 124.0	2
Gas Power Plant	923	623	400	52.9 – 80.0 – 140.0	0
Iron and Steel	51	121	37	80.0 – 110.7 – 194.8	0
Cement	91	67	64	67.1 – 107.9 – 195.2	0
Refineries	123	57	56	*33.5 – NA – 70.4	18
Gas Processing	436	57	10	14.5 – 22.8 – 30.3	4
Hydrogen	112	44	40	56.9 – 81.9 – 156.8	15
Ethanol	210	32	27	17.6 – 27.0 – 33.4	41
Ammonia	29	21	20	12.2 – 20.5 – 42.8	21
Petrochemicals	68^{D}	18^{D}	10	*0^{E} – NA – 28.6	3

^{A} ONLY INCLUDES FACILITIES EMITTING GREATER THAN 100,000 MT CO_2/YEAR AND WHOSE CAPTURE COST IS LESS THAN $200/MT.

^{B} ONLY INCLUDES PROCESS CO_2 EMISSIONS EXCEPT IN THE CASE OF POWER PLANTS, WHICH INCLUDE ONLY COMBUSTION CO_2 EMISSIONS.

^{C} COST ESTIMATES DEVELOPED BASED ON ANALYSIS OF INDIVIDUAL U.S. PLANTS AND ACCOUNT FOR ECONOMIES OF SCALE OF CAPTURE UNITS UNLESS MARKED BY AN ASTERISK(*).

^{D} ESTIMATED USING EPA GHGRP DATASET.

^{E} ESTIMATE FOR NEAR PURE (99%+ PURITY) SOURCES AND DOES NOT INCLUDE COMPRESSION AND TRANSPORTATION COSTS.

These and other analyses[109] provide a good starting point for envisioning and planning a national-level CCUS network. However, additional work is needed on pairing and optimizing carbon capture technologies with industrial processes based on CO_2 purity and operational considerations of the industrial process (e.g., calcium looping is uniquely suited for CCS from clinker production). Research is also needed on CO_2 purity requirements and pipeline logistics for safe and economical transport when CO_2 is sourced from multiple industrial and/or power sources, each with differing species and concentrations of contaminants. Appropriate amendments to existing carbon accounting frameworks that concurrently address CO_2 capture, long-term storage, and reuse across multiple life cycles also are

[108] Sarang D. Supekar and Steven J. Skerlos, "Market-Driven Emissions from Recovery of Carbon Dioxide Gas," 2014. *Environmental Science and Technology* 48, no. 24 (2014): 14615–23, https://doi.org/10.1021/es503485z; Peter C. Psarras et al., "Carbon Capture and Utilization in the Industrial Sector," *Environmental Science and Technology* 51, no. 19 (2017): 11440–4, https://doi.org/10.1021/acs.est.7b01723; Guiyan Zang et al., "Synthetic Methanol/Fischer–Tropsch Fuel Production Capacity, Cost, and Carbon Intensity Utilizing CO2 from Industrial and Power Plants in the United States," *Environmental Science and Technology* 55, no. 11 (2021): 7595–7604, https://doi.org/10.1021/acs.est.0c08674; "Greenhouse Gas Reporting Program (GHGRP)," U.S. Environmental Protection Agency, last updated April 29, 2022, https://www.epa.gov/ghgreporting; Global CCS Institute, *Global Status of CCS 2021*, 2021, https://www.globalccsinstitute.com/wp-content/uploads/2021/10/2021-Global-Status-of-CCS-Report_Global_CCS_Institute.pdf.

[109] Daniel L. Sanchez, Nils Johnson, and Sean T. McCoy, "Near-Term Deployment of Carbon Capture and Sequestration from Biorefineries in the United States," *Proceedings of the National Academy of Sciences* 115, no. 19 (2018): 4875-4880, https://doi.org/10.1073/pnas.1719695115.

also needed to ensure that they do not create perverse incentives or disincentives for stakeholders in the CCUS value chain, lead to leakage, or double count emissions.

The efficient utilization of CO_2 is a long-term strategy to address carbon management through supply chains, across multiple U.S. economic sectors. Utilization options are possible for each subsector, and each has their own unique set of opportunities and RD&D challenges.[110] For example, in the petroleum refining subsector, if CO_2 can be recycled and utilized as a feedstock, then the liquid transportation fuel market would benefit from a closed loop carbon cycle. Developing CO_2 reduction technologies (such as artificial photosynthesis) and lowering the cost of converting CO_2 into syngas (e.g., the catalytic reverse water gas shift reaction) can enable CO_2 conversion to different final products, mainly high-quality carbon-neutral jet fuel, distillates, and chemical feedstocks. To deploy CO_2 reduction technologies at scales similar to current refinery units' capacities, RD&D is needed to lower energy input requirements, increase CO_2 reduction efficiency and yields, and integrate CO_2 reduction technologies into mature refinery operations. RD&D opportunities include reducing the total system capital and operating cost to a price point that is competitive with petroleum based liquid fuels plus the social cost of GHG emissions. The size of the transportation fuel market and the scientific challenges associated with CO_2 reduction and utilization warrant significantly more RD&D support.

1.3 Methodology for Development of Scenarios for GHG Emissions Reductions

Given the complexity of U.S. industry (diversity of material inputs, industrial processes, and manufactured products) and the timing, resources, scope, and expansiveness of the industrial sector, this roadmap focuses on five of the highest CO_2-emitting industries: petroleum refining, chemicals, iron and steel, cement, and food and beverage. As shown in Figure 3, the combined CO_2 emissions for these industries were 699 million MT CO_2 in 2020, accounting for 51% of industrial CO_2 emissions and 15% of U.S. economy-wide total CO_2 emissions.[111]

These subsectors were also chosen since they provide commodities, intermediaries, and products important to other manufacturing subsectors and the broader economy and are geographically dispersed across the United States. Considering these five industrial subsectors, representative RD&D opportunities were identified within the decarbonization pillars for each subsector and aggressive but realistic scenario modeling of GHG reductions through 2050 was undertaken.

1.3.1 Modeling Assumptions

To estimate the relative magnitude of CO_2 reductions possible for each pillar, the roadmap team used EIA's Annual Energy Outlook (AEO) 2021 Reference Case (called "AEO 2021" going forward in this report)[7] as a "business as usual" baseline for annual CO_2 emissions projections out to 2050. EIA develops an annual AEO using "an integrated model that captures interactions of economic changes and energy supply, demand, and prices."[112] The Reference Case includes only enacted laws and regulations that

[110] For specific discussion on carbon utilization within industrial subsectors, see Sections 2.1.3.3.2 (iron and steel), 2.2.4.2 (chemicals), 2.3.3.3 (food and beverage), 2.4.4.2.3.2 (petroleum refining), 2.5.3.3 (cement).
[111] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 19. Energy-Related Carbon Dioxide Emissions by End Use.
[112] "Documentation of the National Energy Modeling System (NEMS) Modules," U.S. Energy Information Administration, accessed May 2022, https://www.eia.gov/outlooks/aeo/nems/documentation/; U.S. Energy Information Administration, *Annual Energy Outlook 2021 Narrative*, February 2021, https://www.eia.gov/outlooks/aeo/pdf/AEO_Narrative_2021.pdf.

affect the energy sector. This assumption enables EIA to use the Reference Case as a benchmark to compare alternative policy-based cases.

By leveraging the AEO 2021 projections of annual energy consumption in the five identified industrial subsectors and the CO_2 emissions from the electric grid as a dataset, a CO_2 accounting model was developed to estimate the relative magnitude and timing of each pillar's potential CO_2 reductions on an annual basis out to 2050. Although process electrification reduces CO_2 emissions at industrial facilities, grid-purchased electricity can potentially temporarily increase CO_2 emissions in the power generation sector (until the U.S. electric grid is emissions-free). Therefore, the model includes annual electric grid CO_2 emissions factors based on AEO 2021 projections and alternative annual electric grid decarbonization CO_2 emissions factors.

The three industrial decarbonization scenarios in this report reflect a range of progressively more aggressive pathways to CO_2 reduction by 2050. However, the roadmap report scenario projections include only the CO_2 emissions from onsite fuel combustion and grid purchased electricity for the five sub-sectors considered and cement manufacturing process emissions;[113] non-CO_2 GHG emissions and emissions for other manufacturing subsectors were not included. Additionally, the scenarios do not evaluate full life cycle GHG emissions associated with manufactured products. Upstream and downstream GHG emissions, process GHG emissions, and GHG emissions embodied in imported materials were not modeled. In addition, for the refining, chemical, and food and beverage subsectors, a representative sample of those industries was chosen for scenario analysis given the expansiveness of product outputs from those industries.

Since only five industrial subsectors were modeled, the actual emissions reduction potential from the entire industrial sector is larger than what is reflected by the scenario modeling and actual emissions (and reductions potentials) for the refining, chemical, and food and beverage subsectors are larger than shown. In summary, the scenario analysis results shown in this report should be considered as a preliminary and representative assessment of CO_2 emissions reduction potential from the full industrial sector.

To better define the pathways for net-zero industrial sector CO_2 emissions by 2050, more comprehensive studies are needed for each of the five considered industrial subsectors; the other industrial manufacturing subsectors (such as paper, glass, aluminum, fabricated metal products, etc.) and industrial non-manufacturing subsectors (construction, mining, and agriculture) that were not modeled; and the full life cycle or cradle-to-gate GHG emissions of material flows through the industrial sector as a whole – including imports and exports.

1.3.2 Modeling and Scenario Limitations and Next Steps

Since non-industrial sectors' decarbonization pathways will affect industrial sector investments in decarbonization technologies, this report represents only a subset of a broader, all-of-economy integrated strategy towards industrial net-zero emissions by 2050. The scenarios presented in the report would be affected if the whole U.S. economy were included in a multisector integrated net-zero emissions by 2050 pathway analysis.

[113] Cement manufacturing process emissions are the byproduct of a chemical conversion process used in the production of clinker, a component of cement. In this process, limestone ($CaCO_3$) is converted to lime (CaO), resulting in CO_2 emissions that are independent of fuel type and/or use.

To better define pathways for economy-wide net-zero emissions by 2050, more comprehensive integrated studies are needed to identify tradeoffs between GHG emissions across all sectors. This requires models that integrate energy demands in all sectors of the U.S. economy, low-carbon emissions energy supplies, the flow of materials and manufactured products throughout the economy, and sector specific decarbonization technology options to better understand the interactions between the industrial sector and the rest of the economy regarding decarbonization options and tradeoffs.

For example, demand for low-carbon fuels and feedstocks for the transportation and other sectors will evolve depending upon factors, such as the rate of vehicle electrification and associated reductions in remaining fuel demand. Further, the residential and commercial building sectors will need to decarbonize construction and operations of urban and suburban building stocks, which will impact demand for fuels and feedstocks. The changes in these transportation and buildings systems will drive the development of low-carbon liquid fuels and feedstocks markets – which will in turn be affected by a complex interplay between diverse industrial sectors that will need to both:

- Produce low-carbon liquid fuels and feedstocks (including the production of agricultural fertilizers, growth of agriculture products, refining of low-carbon feedstocks, etc.); and
- Manufacture products that use the produced fuels and their derivatives (or alternatives), such as vehicles, construction materials, chemicals, commodities, and other intermediate and final end use products.

The future of the refining and chemical subsectors is dependent upon the evolution of these other sectors, highlighting the need for subsequent strategic analysis and more robust modeling to consider the role of the industrial sector in enabling emissions reductions in other sectors (transportation, buildings, and power generation sectors), as well as international markets and decarbonization at the global scale.

The discussions in the stakeholder meetings raised questions in all subsectors about the relative magnitude of GHG emissions reduction possible with the decarbonization pillars and the timing for when the reductions could occur. In an effort to respond to such questions, provide additional insights on priorities, and gauge how the pillars could help phase out net carbon emissions, the scenarios below were developed and used to evaluate CO_2 emissions reduction potential for each subsector:[114]

1. The **Business as Usual (BAU) Scenario** assumes a slow improvement in energy efficiency and adoption of commercially available electrification technologies.

2. The **Moderate Technology and Policy (Moderate) Scenario** assumes a higher rate of energy efficiency improvements, more switching to lower-carbon fuels, and a higher rate of electrification than the BAU scenario. It also assumes low adoption of CCUS.

3. The **Advanced Technology and Policy (Advanced) Scenario** assumes even higher energy efficiency improvement, more-aggressive switching to lower-carbon fuels, a higher rate of electrification, and CCUS adoption.

4. The **Near Zero GHG (Near Zero) Scenario** assumes aggressive energy efficiency improvement and more-aggressive electrification than the Advanced scenario. It also assumes that in 2050,

[114] Assumptions for the scenarios are described in more detail in the Appendices: Scenario Methodology and Assumptions.

70% of CO_2 from U.S. chemicals plants will be captured by CCUS following the maximum realistic energy efficiency and electrification adoption.

5. Finally, the **Net-Zero** results assumes sector- or subsector-wide achievement of net-zero CO_2 emissions. Note that this was not a modeled scenario, but rather reflects the quantity of difficult-to-abate emissions that must be mitigated through alternative means not specifically covered by the four industrial decarbonization pillars of this roadmap, such as negative emissions technologies.

For each progressively more aggressive scenario pathway, it was assumed that the electric grid would also decarbonize at rates similar to the five industrial subsectors included in the roadmap. As a result, every five years, grid purchased electricity CO_2 emissions factor declines by 15% in the BAU scenario, 17% in the Moderate scenario, 25% in the Advanced scenario, and 35% in the Near Zero scenario. Compared to 2015, in 2050 the grid-purchased electricity CO_2 emissions factors are lower by 71% in the BAU scenario, 76% in the Moderate scenario, 90% in the Advanced scenario, and 98% in the Near Zero scenario.

Additionally, the scenarios prompted discussion and input on the timing and sequence of RD&D investments for various technology and approaches that are subsets of the decarbonization pillars. These perspectives aided the development of RD&D action plans identifying what was needed to deliver significant early GHG emissions reductions as well as longer-term reductions via transformative process technologies. The relative impacts of the pillars across the decades vary among the subsectors. The scenarios in this report focused on the pillars described above. Pathways may include multiple crosscutting technologies, approaches, and infrastructure as noted earlier in the definition of pathways. For example, electrification and LCFFES have several shared factors (e.g., generation of electricity by low-carbon energy used to produce hydrogen and cases where hydrogen combustion is used to produce electricity). As it is difficult to separate the impacts of electrification and LCFFES at this early stage, the shared pathways were treated as one for the scenarios and their impacts are combined in the waterfall charts (e.g., Figure 15, Section 2.1.2). For the landscape figures (e.g., Figure 18, Section 2.1.4), the selection of technologies pertinent to the various pathways for the pillars was retained so that readers could see that strategic investments in multiple technologies for the pathways and pillars are needed across the course of the next 30 years. It is recognized that additional pillars and technology pathways may provide significant GHG emission reductions and are addressed outside this roadmap. Biomass and biofuels are some of these candidate technologies that are outside the scope of this report. Section 4.2 considers these technologies, providing references to materials for these approaches.

1.4 Getting to Net-Zero

Dramatic reductions in difficult-to-abate, energy-intensive industries, such as those examined in this report, are difficult to achieve in a short period of decades. In some subsectors, certain residual emissions may remain in 2050, even after applying all of the Industrial Decarbonization pillars described in this roadmap. Some industrial sector emissions, particularly those arising from process and combustion-related sources that are small and geographically dispersed, will be particularly difficult to mitigate cost-effectively. To fully reach the United States' goal of industrial net-zero emissions, targeted strategies will be needed to address those residual emissions through alternate approaches and aggressive technology deployment that stretch beyond the scenarios of this report. This will require more aggressive technology deployment, market mechanisms, mitigation, and negative emissions approaches as described below. Collectively, the more aggressive approaches needed to reach net-zero emissions (including those external to the industrial sector) are described here:

- **Accelerated shift to low-carbon process technologies:** More substantial emissions reductions could be realized if all or nearly all the existing stock of capital equipment used to make products were changed over to zero-carbon emitting processes by 2050 (which was not assumed in the existing roadmap scenarios). Such an accelerated transition would likely require policy drivers in addition to technology development and demonstration to de-risk capital investments. Also, processes designed to optimize low-carbon fuels and feedstocks, reuse carbon (which is accepted as zero-carbon), and produce near zero waste could be assumed to dominate across industries. Green chemistry and engineering principles, circular economy, new science, and technology, etc. would greatly reduce the need for mitigation. Step-changes in RD&D are needed in areas where zero-carbon processes are currently unknown.

- **100% clean electric grid:** For the most aggressive scenarios in this report, it was assumed that the grid emissions factor would go from 500 kg CO_2/MWh in 2015 to 11 kg CO_2/MWh in 2050 (a 97.8% reduction). This may be a conservative assumption, considering the Biden Administration's ambitious goals to achieve a 100% carbon pollution-free power sector by 2035.[115] If the grid mix is pollution-free, greater emissions reductions will be possible from the electrification pillar than those modeled in this report.

- **Ultra-low carbon energy carriers and feedstocks:** A 100% clean grid could increase the use of ultra-low carbon energy carriers (e.g., H_2) and feedstocks in industrial processes. Biomass, nuclear energy, renewable natural gas, and other low-carbon feedstocks were assumed to play a role in the current roadmap, but that role would need to be significantly expanded within the constraints of land use, transport, food supply, and other critical factors. CO_2 reduction and clean hydrogen is a low-carbon path for converting captured CO_2 into synthetic energy-dense hydrocarbon fuels. This path is an option for the refining subsector to offset petroleum-based fuel and associated CO_2 by providing low-carbon synthetic diesel, gasoline, and jet fuels for decarbonizing transportation modes, especially hard-to-electrify modes like aviation.

- **Procurement focus on embodied carbon:** Vastly increased demand-pull for low-carbon products is needed to drive the carbon intensity of products far below that of today. Public and private sector procurement and advanced market commitments are also needed and trade and border adjustments to address potential carbon leakage would complement this effort. To support this pathway, increased adoption, market acceptance, and ability to quantify and report Scope 1, 2 and 3 emissions are needed, along with expanded life cycle accounting for products' cumulative carbon impacts. One way to further assess and quantify embodied emissions and other environmental impacts of products is through Type III Environmental Product Declarations (EPDs), which are defined by Product Category Rules (PCRs) that provide more comprehensive and consistent reporting of environmental impacts.[116]

- **Improved material efficiency and a transition to a circular economy:** Manufacturers across all industrial subsectors would need to greatly increase material efficiency, including engagement in

[115] "Executive Order 14008 of January 27, 2021, Tackling the Climate Crisis at Home and Abroad," *Code of Federal Regulations,* title 86 (2021): 7619-7633, https://www.federalregister.gov/documents/2021/02/01/2021-02177/tackling-the-climate-crisis-at-home-and-abroad.

[116] International Organization for Standardization, *ISO 14025:2006 Environmental labels and declarations — Type III environmental declarations — Principles and procedures*, 2006, https://www.iso.org/standard/38131.html.

the process and supply-chain transformations needed to increase recycling and re-use of end of life materials for a circular economy.

- **Cost-effective and efficient carbon capture:** Industrial facilities are point sources of emissions that are in many cases technologically feasible to capture, but where existing CCUS technologies may not be commercially viable or cost effective. Further, current carbon capture technologies have a maximum capture rate of 85-95%.[117] RD&D to yield 100% capture, reduce the associated energy burden (with the energy supplied being from ultra-low-carbon sources), and improved process economics could yield greater reductions.

- **Negative emissions technologies and activities:** Ecosystem-based carbon management activities such as reforestation, biosystem protection, and soil carbon sequestration would need to be significantly expanded. Further, nascent technologies, such as direct air capture, are in early development stages and face the challenge of capturing species from very dilute streams. Capturing CO_2 from the atmosphere as a feedstock for synthetic fuels could result in fuels produced in a "closed-loop" with the atmosphere; this would enable refineries to produce net-neutral synthetic diesel, gasoline, and jet fuels – ideally reaching a steady-state balance in the long-term. Greatly improved efficiency and economics, along with abundant ultra-low carbon energy, are needed to meet societal needs while also powering these new technologies.

1.5 Application of the Decarbonization Pillars Across Subsectors

Because decarbonization across U.S. industries could take decades, it is important to start now to minimize cumulative effects of GHG emissions and to catalyze the learning needed to implement the transition across multiple subsectors and supply chains. The scenarios defined in Section 1.3 highlight both the CO_2 reduction potentials with these decarbonization pillars and the RD&D needs pertaining to the pillars. Combining the reductions across the subsectors evaluated in this roadmap (iron and steel, chemical manufacturing, food manufacturing, petroleum refining and cement) provides the composite plot of CO_2 emissions shown in Figure 9. The plot illustrates that aggressive pursuit of the decarbonization pillars (plus alternative strategies for difficult-to-abate emissions) can put the United States on a path to net-zero industrial emissions by 2050.

[117] Intergovernmental Panel on Climate Change, *Summary for Policymakers in Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. Masson-Delmotte, V. et al., (Cambridge University Press, 2021), https://www.ipcc.ch/report/ar6/wg1/#SPM.

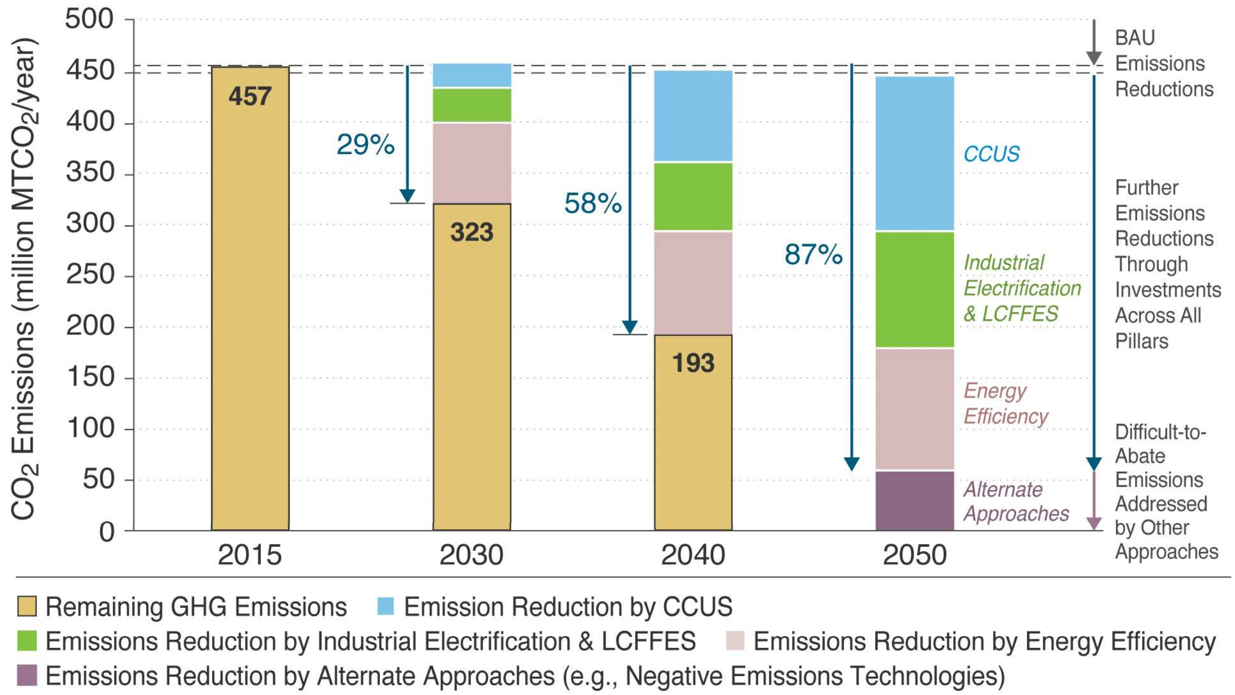

Figure 9. The path to net-zero industrial CO_2 emissions in the United States (million MT/year) for five carbon-intensive industrial subsectors, 2015–2050.

With contributions from each decarbonization pillar (energy efficiency; industrial electrification; low-carbon fuels, feedstocks, and energy sources (LCFFES); and carbon capture, utilization, and storage (CCUS)). Since industrial electrification and LCFFES technologies and strategies are strongly interconnected, these pillars were grouped for scenario modeling. Industrial subsectors included in this analysis were: Iron and steel, chemicals (only ammonia, methanol, ethylene, and benzene, toluene, and xylenes (BTX)), food and beverage (only beer, beet sugar, cane sugar, fluid milk, red meat, soybean oil, and wet corn milling), petroleum refining, and cement manufacturing. Feedstocks and certain process-related emissions are excluded. The "alternate approaches" band shows further emissions reductions from approaches not specifically evaluated in scenario modeling for this roadmap, including negative emissions technologies. Details on assumptions, parameters, and timing can be found in the appendix. Source: This work.

> *Key message: Scenario modeling indicates that achieving net-zero CO_2 emissions in the top CO_2 emitting industrial subsectors by 2050 will require an "all of the above" strategy including application of multiple decarbonization technologies and approaches in parallel.*

In the Executive Summary, Figure ES 2 illustrates the landscape of subsector transformations needed to achieve industrial decarbonization, including contributions from the four key decarbonization pillars that will need to be pursued concurrently to reach net-zero carbon emissions by 2050. While each pillar is shown separately, the pillars are not independent, since cross-sectoral opportunities that provide synergies, address barriers, and accelerate progress can be pursued. Time bands by decade (excluding the first two bands, which are each five years) show how the state of the industrial sector must advance to realize early energy and GHG emissions reductions, advance and demonstrate technologies to improve economics and promote commercial adoption, and build the knowledge and capacity for transformative future technologies.

Parallel investments in RD&D across pillars will be needed to realize the transformations to achieve net-zero. Building on the transformations described in Figure ES 2, Figure 10 shows the sequence of specific RD&D technology investment areas that are addressed by the roadmap. It shows the range of responses needed in the near term to get industry on the track for decarbonization in the first decade, pave the way for new technologies that need to be deployed in later decades, and enable the transformation with infrastructure that is multipurposed, flexible, and efficient. While Figure 10 provides a composite view of RD&D needs across all subsectors, specific RD&D needs – and specific landscape figures – for the five industrial subsectors covered by the roadmap will be presented in Section 2.

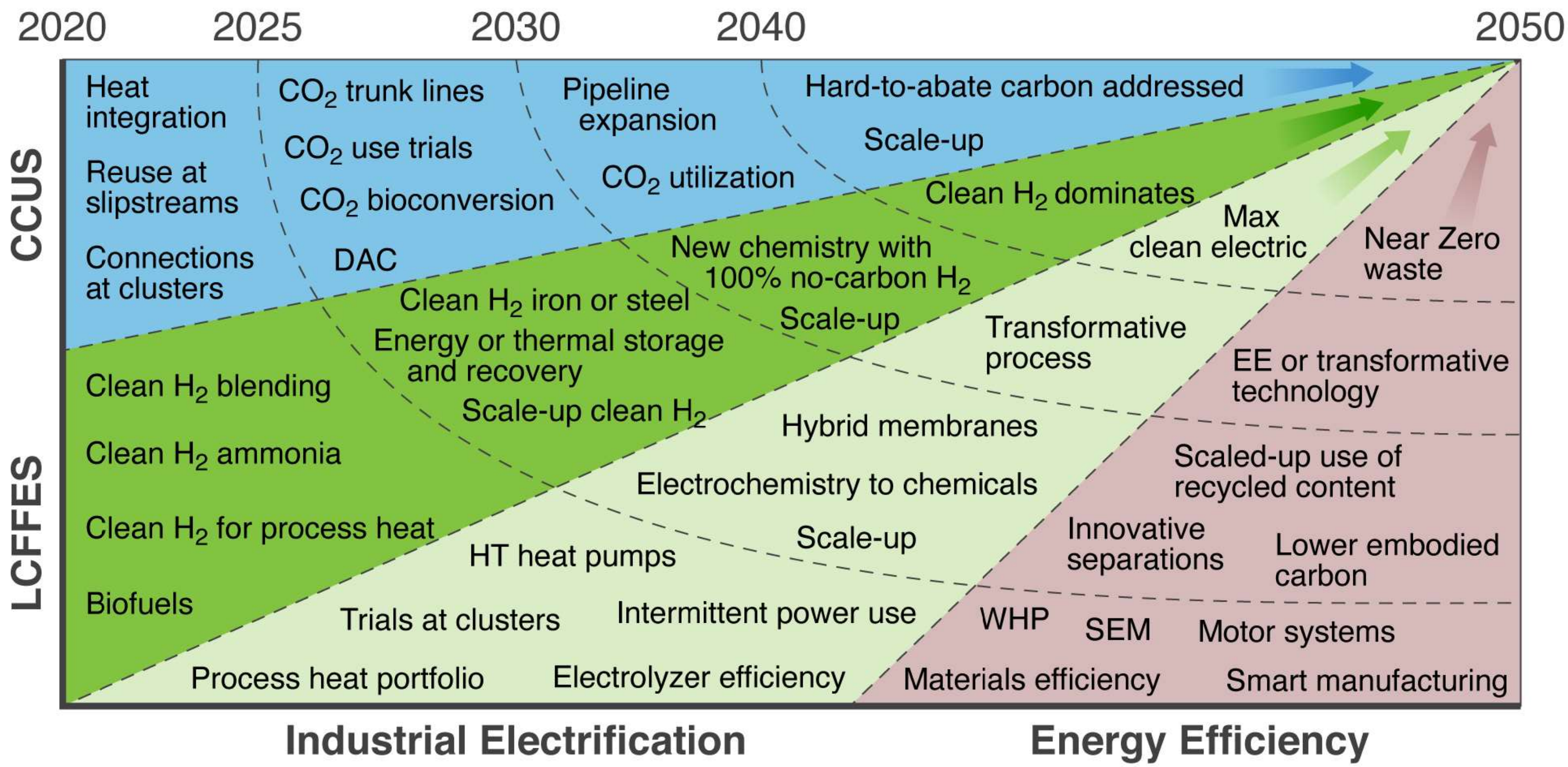

Figure 10. Landscape of major RD&D investment opportunities for industrial decarbonization across all subsectors by decade and decarbonization pillar.

Early opportunities (e.g., process heat solutions, or electrolyzer efficiency to produce hydrogen from low-carbon energy) may set the stage for later transformative and have crosscutting impacts in other pillars and subsectors. LCFFES includes clean technologies that do not release GHGs to the atmosphere from the production or use of energy sources, and include renewable sourced electricity, nuclear energy for electricity and heat, concentrating solar power, and geothermal energy. Further definitions are available in the glossary. Acronyms: DAC (direct air capture); EE (energy efficiency); HT (high temperature); SEM (strategic energy management); WHP (waste heat to power). Source: this work.

> *Key message: Investments are needed in near-, mid-, and longer timeframes to address numerous RD&D opportunities to accelerate industrial decarbonization by these top pillars. Strategies need to be pursued to realize synergies within and across pillars and industries.*

2 Subsector-Specific GHG Emissions Reducing Technologies, Processes, and Practices

The stakeholder meetings within individual subsectors provided input on the application of low-carbon technologies; adoption needs, challenges, and opportunities; and areas where RD&D could help lower costs, accelerate adoption, and improve efficiency. In each of the subsectors there were common discussion topics including the needs and opportunities, how the decarbonization pillars would apply, and specific technology needs and improvements for decarbonization. Across all these topics, the focus of this roadmap was to identify the RD&D needs and to gain perspective on the timing to address those needs. Crosscutting needs, in addition to those identified in Section 1.2, continue to be discussed in the subsector discussions and will be further discussed in Section 3.

2.1 Iron and Steel Manufacturing

2.1.1 Status of the U.S. Iron and Steel Industry

The crosscutting decarbonization pillars identified in this work are energy efficiency, industrial electrification, LCFFES from non-fossil fuel or low-carbon emitting sources, and CCUS, where electrification and LCFFES are highly connected and evaluated together for this roadmap. There is a range of iron and steel products and some adaptation of how the pillars are applied across the products and the facilities that are tailored to make them may be relevant. The amount of carbon and how it is used to attain the desired performance characteristics would be the focus of these adjustments. The source of the carbon and transitioning to lower-carbon sources would be an end goal. Improving technologies to recover the carbon as part of recycling or reuse efforts would also be part RD&D challenges that need to be considered. There are several approaches in various stages of development and commercialization that could be considered. While a review of those methodologies is outside the scope of this work, the reader is referred to the literature for additional information.[118] Managing the carbon and managing its GHG emissions impact is the goal, not eliminating the carbon, as it is vital to the performance of products.

The U.S. steel industry produced 87 million MT of crude steel in 2018, of which 33% was produced by primary steelmaking plants using blast furnace-basic oxygen furnace (BF-BOF) and 67% was produced by the electric arc furnace (EAF) production route (typically called secondary steelmaking), which mainly uses steel scrap but can also use direct reduced iron (DRI).[119] The United States also imported 31 million MT and exported 8 million MT of steel mill products in 2018.[120]

Iron and Steel Manufacturing Subsector: Key Takeaways

- The U.S. steel industry GHG emissions can go down to almost zero in 2050 under the Near Zero GHG emissions scenario while U.S. steel production increases by 12% during the same period.
- More than two-thirds of total GHG emissions reduction needed to get to near zero in 2050 comes from improvement in energy efficiency and switching to low- and no-carbon fuels and electrification.
- Aggressive RD&D and pilot and demonstration scale testing is needed for transformative technologies such as hydrogen-based steel production, electrolysis of iron ore, and CCUS to realize near zero GHG emissions goal by 2050.
- The demand for clean hydrogen and low-carbon electricity use in steel making will increase significantly by 2050. RD&D efforts will be needed to improve the efficiency of electrolyzers.
- Although not in the scope of this report, material efficiency strategies could help reduce industry GHG emissions for steel while delivering the same material services. This pathway needs to be explored further with defensible LCA and TEA analyses.

[118] Zhiyuan Fan and S. Julio Friedmann, "Low-carbon production of iron and steel: Technology options, economic assessment, and policy," *Joule* 5, no. 4 (April 2021): 829-862. https://www.sciencedirect.com/science/article/pii/S2542435121000957.
[119] Cris Candice Tuck, *2018 Minerals Yearbook: Iron and Steel [Advance Release],* U.S. Geological Survey, October 2021, https://pubs.usgs.gov/myb/vol1/2018/myb1-2018-iron-steel.pdf.
[120] Ibid.

The value of products produced by the U.S. iron and steel industry and ferrous foundries in 2018 was about $137 billion.[121] The U.S. BF-BOF plants that produced pig iron and crude steel as of 2018 were operated by three companies with integrated steel mills in nine locations.[122] Also in 2018, EAF steel plants were owned by 51 companies producing crude steel at 99 minimills.[123]

BF-BOF and EAF steel plants together employed around 81 thousand people, and iron and steel foundries employed an additional 64 thousand people in the United States in 2018.[124] Indiana accounted for 27% of total crude steel production, followed by Ohio (12%), Michigan (6%), and Pennsylvania (6%).[125] The construction subsector is the largest consumer of steel in the United States (43%) followed by transportation, predominantly the automotive industry (27%), machinery and equipment (10%), the energy sector (7%), appliances (5%), and other consumers (8%).[126] Overall, U.S. steel production has been declining in the past two decades (Figure 11).

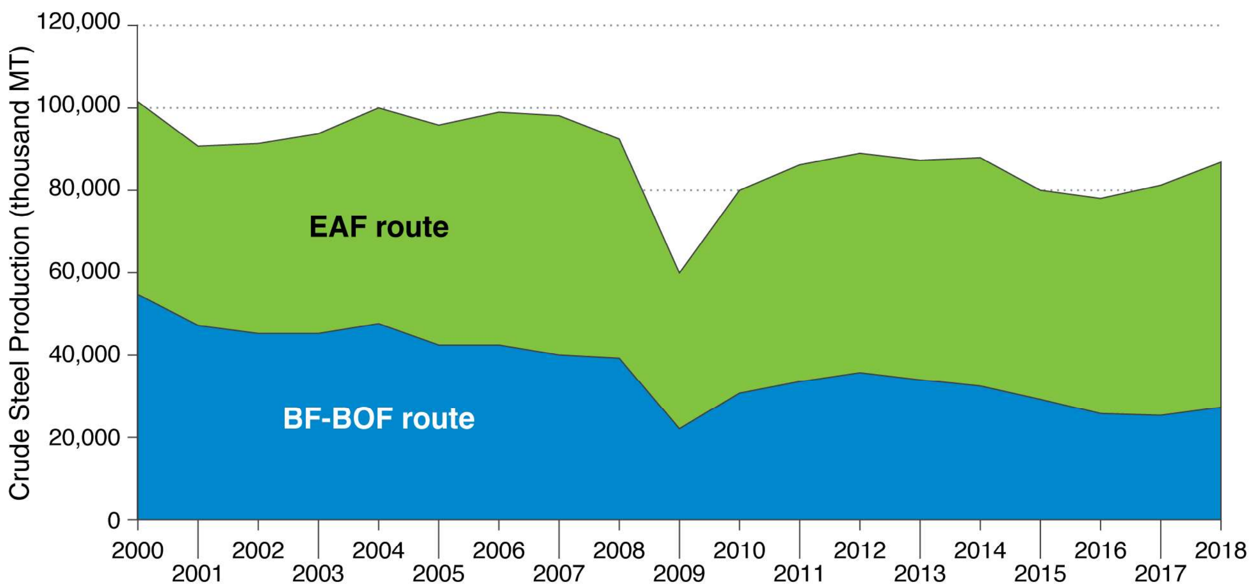

FIGURE 11. U.S. CRUDE STEEL PRODUCTION (IN THOUSAND MT) BY PRODUCTION ROUTE, 2000–2018[127]

Key message: EAF steel production has increased its share of U.S. steel production over the last couple of decades.

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[121] Christopher A. Tuck, *Iron and Steel Statistics and Information, Minerals Commodity Summaries*, U.S. Geological Survey, February 2019, https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/atoms/files/mcs-2019-feste.pdf.

[122] Cris Candice Tuck, *2018 Minerals Yearbook: Iron and Steel [Advance Release],* U.S. Geological Survey, October 2021, https://pubs.usgs.gov/myb/vol1/2018/myb1-2018-iron-steel.pdf.

[123] Ibid.

[124] Christopher A. Tuck, *Iron and Steel Statistics and Information, Minerals Commodity Summaries*, U.S. Geological Survey, February 2019, https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/atoms/files/mcs-2019-feste.pdf.

[125] Ibid.

[126] Ibid.

[127] "Global crude steel output increases by 3.4% in 2019," World Steel Association, January 27, 2020, https://worldsteel.org/media-centre/press-releases/2020/global-crude-steel-output-increases-by-3-4-in-2019; World Steel Association, *Steel Statistical Yearbook 2019*, November 2019, https://worldsteel.org/wp-content/uploads/Steel-Statistical-Yearbook-2019-concise-version.pdf.

2.1.1.1 Energy Use and GHG Emissions for the Iron and Steel Industry

Iron and steel manufacturing is one of the most energy-intensive industries worldwide. In addition, the use of coal as the primary fuel and feedstock for the chemical reduction of iron oxide, coupled with the sheer volume of iron and steel produced, means the industry has among the highest GHG emissions of any industry. The iron and steel industry accounts for around a fifth of industrial energy use and about a quarter of direct industrial GHG emissions in the world.[128] Iron and steel production accounts for over 7% of global GHG emissions.[129] Additionally, steel production generates significant air pollutants (such as sulfur dioxide, nitrous oxide, or non-methane volatile organic compounds), which contribute to adverse health effects and can negatively impact their local communities (typically in low-income, disadvantaged communities).[130] These air pollutants should be considered alongside GHG emissions as the steel industry decarbonizes.

The U.S. steel industry accounted for around 8% of total fuel used in the U.S. manufacturing sector in 2018.[131] Figure 12 shows the share of different energy types used in the U.S. steel industry. Natural gas had the largest share and accounted for 37% of the U.S. steel industry's final energy use in 2018.[132] This is significantly higher than many other countries where coal is the dominant fuel used in the steel industry. For example, in China, natural gas represented less than 1% of the fuel used in the steel industry in 2014.[133] Primary steel production using the BF-BOF production route (which requires a large amount of coal and coke) accounts for more than 90% of steel produced in China and only 30% of steel produced in the United States.[134] This helps to substantially lower the average carbon intensity of the U.S. steel industry compared to many other countries (Figure 13). It should be noted that as more steel scrap will be available in China, the share of EAF steel production will also increase in China in the coming decades. Figure 12 also shows the breakdown of final energy consumption by end use in the U.S. steel industry,[135] where process heating represents the highest share and accounts for 63% of total energy use in the steel industry.

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[128] International Energy Agency, *Iron and Steel Technology Roadmap*, October 2020, https://www.iea.org/reports/iron-and-steel-technology-roadmap.

[129] Ibid.

[130] Ali Hasanbeigi, Navdeep Bhadbhade, and Ahana Ghosh, *Air Pollution from Global Steel Industry: An International Benchmarking of Criteria Air Pollutants Intensities*, August 2022, https://www.globalefficiencyintel.com/air-pollution-from-global-steel-industry.

[131] "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data," U.S. Energy Information Administration, released 2021, https://www.eia.gov/consumption/manufacturing/data/2018/. See Table 3.2. Energy Consumption as a Fuel By Manufacturing Industry and Region.

[132] Ibid.

[133] Ali Hasanbeigi and Cecilia Springer, *How Clean is the U.S. Steel Industry? An International Benchmarking of Energy and CO_2 Intensities*, Global Efficiency Intelligence, November 2019, https://www.globalefficiencyintel.com/s/How-Clean-is-the-US-Steel-Industry.pdf.

[134] Ibid. See Figure 13.

[135] "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data," U.S. Energy Information Administration, released 2021, https://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.

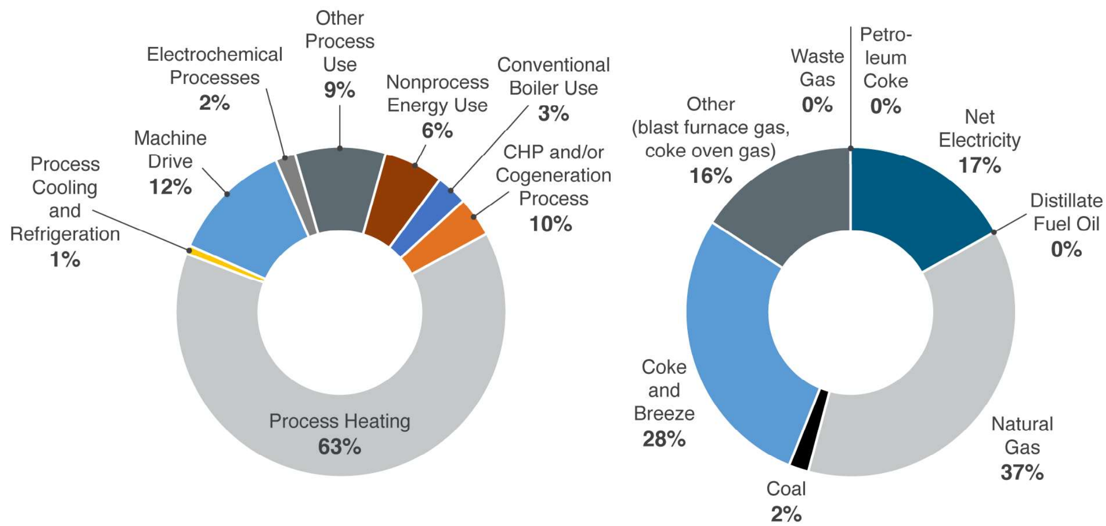

FIGURE 12. DISTRIBUTION OF ENERGY END USES (LEFT) AND SHARE OF DIFFERENT ENERGY TYPES USED (RIGHT) IN THE U.S. STEEL INDUSTRY IN 2018.[136]

THERMAL PROCESSES (PROCESSING HEATING, CHP, AND BOILERS) ACCOUNTED FOR AROUND 76% OF TOTAL ENERGY USED IN THE U.S. STEEL INDUSTRY.

> *Key message: In the United States, where the majority of steelmaking is electrified, electricity consumption represents about 17% of overall energy use. The dominant fossil fuel consumed in U.S. steelmaking is natural gas (not coal, the dominant fuel in most countries that predominantly use the BF-BOF steelmaking route). As a result of its focus on EAF steelmaking, the U.S. carbon footprint for steelmaking is lower than the global average (but still far from net-zero).*

A recent study[137] conducted benchmarking of the energy intensity and CO_2 emissions intensity of the U.S. iron and steel industry against that of the steel industry in 15 other major steel-producing countries/regions. Figure 13 shows the CO_2 emissions intensity of the steel industry in these countries/regions.[138]

[136] "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data," U.S. Energy Information Administration, released 2021, https://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.
[137] Ali Hasanbeigi, *Steel Climate Impact: An International Benchmarking of Energy and CO_2 Intensities*, Global Efficiency Intelligence, April 2022, https://www.globalefficiencyintel.com/s/Steel-climate-impact-benchmarking-report-7April2022.pdf.
[138] These values include Scope 1, Scope 2, and imported pig iron/DRI emissions. For more information on how the emissions intensity is defined, see: Ali Hasanbeigi, *Steel Climate Impact: An International Benchmarking of Energy and CO_2 Intensities*, Global Efficiency Intelligence, April 2022, https://www.globalefficiencyintel.com/s/Steel-climate-impact-benchmarking-report-7April2022.pdf.

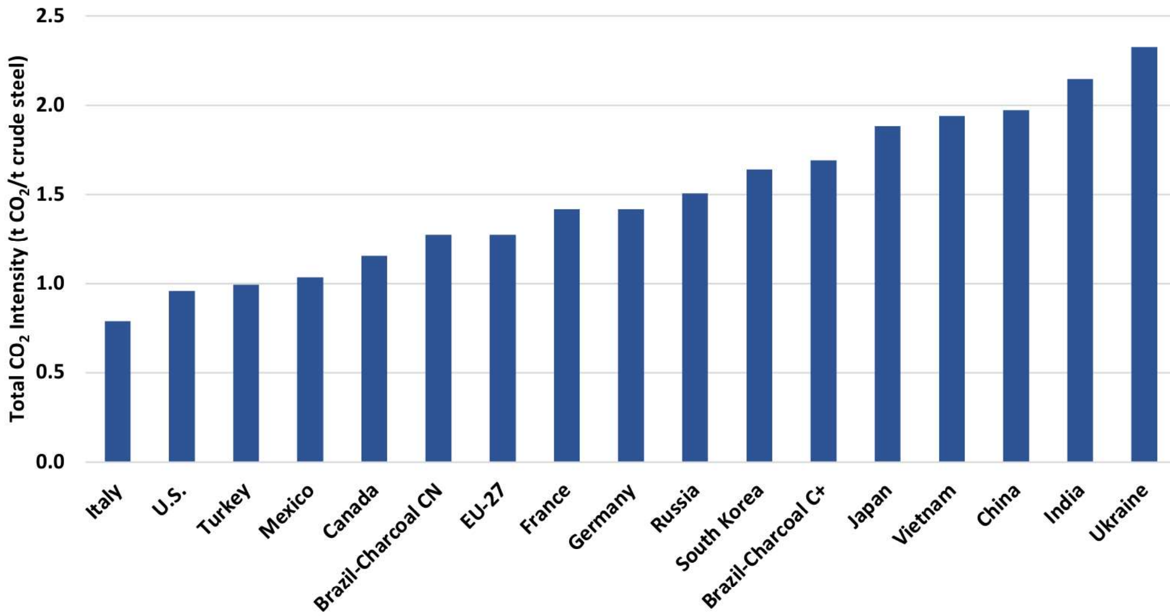

FIGURE 13. TOTAL CO_2 EMISSIONS INTENSITY OF THE STEEL INDUSTRY IN 16 COUNTRIES/REGIONS IN 2019.[139]

NOTE: BRAZIL-CHARCOAL CN REFERS TO WHEN CHARCOAL IS CONSIDERED CARBON NEUTRAL. BRAZIL-CHARCOAL C+ REFERS TO WHEN CHARCOAL IS NOT CONSIDERED CARBON NEUTRAL BECAUSE OF QUESTIONS AND CONCERNS REGARDING THE SUSTAINABILITY OF BIOMASS USED IN THE STEEL INDUSTRY IN BRAZIL. SEE SOURCE FOR MORE INFO.

Key message: U.S. steel industry has one of the lowest CO_2 emissions intensities among major steel producing countries. This is primarily because of the large share of U.S. EAF steel production (70%).

Some of the key factors influencing the energy and carbon intensity of the steel industry include:[140]

- *Share of EAF steel in total steel production*: The EAF process uses steel scrap to produce steel and is less energy and carbon intensive. A higher share of EAF steel production would lead to a lower overall steel industry energy intensity in a country.
- *Fuel shares in the iron and steel industry*: Natural gas has a significantly lower emissions factor per unit of energy compared to coal and coke which are the primary type of energy used in the steel industry in many countries (e.g., China and India). The higher share of natural gas used in the United States, Mexico, and Canada has helped to lower the CO_2 emissions of BF-BOF steel production in these three countries.
- *Electric grid GHG emissions factor*: The fuel mix for power generation in a country, and as a result the emissions factor of the grid (kg CO_2/kWh), plays an important role when comparing the CO_2 emissions of the iron and steel industry with other countries.
- *BF-BOF and EAF feedstock types*: The overall energy and carbon intensity of EAF steel production changes depending upon the type of feedstocks in EAFs (scrap steel vs. DRI vs. pig iron. The DRI

[139] Ibid.
[140] Some of these are discussed in detail by Ali Hasanbeigi, *Steel Climate Impact: An International Benchmarking of Energy and CO_2 Intensities*, Global Efficiency Intelligence, April 2022, https://www.globalefficiencyintel.com/s/Steel-climate-impact-benchmarking-report-7April2022.pdf.

(sponge iron) and pig iron production processes are highly energy and carbon intensive, which results in higher energy use and CO_2 emissions for EAF operations when used as feedstock materials in EAFs. In the case of BF-BOF, the quality of iron ore (iron content, impurities, etc.) influences the energy use and carbon intensity of steel production.

- *Penetration level of energy efficient technologies*: Energy efficiency technologies such as coke dry quenching (CDQ) for the coking process, top-pressure recovery turbines (TRTs) for blast furnaces, pulverized coal injection, and continuous casting help to reduce the energy and carbon intensities of BF-BOF steel production. The penetration of these technologies in different countries is different.
- *Each country's steel product mix:* Different steel products have different energy requirements in the rolling, casting, and finishing processes. Therefore, the product mix could influence the CO_2 intensities in different countries.
- *Steel manufacturing facility age in each country*: Even though BOF vessels in the United States have been relined and other upgrades have been made, they are overall older than most of the steel production facilities in China and therefore could be less energy-efficient than the Chinese facilities.
- *Capacity utilization:* Higher capacity utilization improves overall energy and carbon performance compared to lower capacity utilization if all other factors remain constant. Since it takes a long time and is costly to shut down and restart blast furnaces, operators avoid shutting down for short periods and instead reduce production rates so that the BFs continue to work at less than full capacity. This impacts their energy and carbon intensity.
- *Environmental regulations:* Environmental regulations can affect industry CO_2 emissions by incentivizing different operational and equipment choices. At the same time, the operation of some pollution control equipment requires additional energy, which can add CO_2 emissions.
- *Energy and raw materials cost:* Changing energy and materials sources to optimize costs can affect the CO_2 and energy intensities of a plant.
- *Steel industry boundary definitions* (i.e., which inputs and intermediary products are included in the analysis and whether the embodied energy and carbon in those products are included in the analysis): For example, some countries may report the energy use of the coke-making within the steel industry while some others may report it separately.

2.1.2 Decarbonization Pathways for the Iron and Steel Industry

To understand how the application of the decarbonization pillars (EE, industrial electrification, LCFFES, and CCUS) could help phase out net GHG emissions, the potential GHG emissions reductions possible for the steel industry were examined. This work was also pursued to provide guidance on where RD&D could significantly enable reductions. The topics of where to start on reductions, the relative impact of the decarbonization pillars, and priorities for RD&D were also of common interest across the stakeholder meetings. The scenarios used are described in Section 1.3.

For this work, DOE forecasted the CO_2 emissions of the U.S. steel industry to 2050 (Figure 14). For the BAU scenario, the CO_2 emissions of the U.S. steel industry decreases by 37% between 2015 and 2050, primarily driven by a decrease in the U.S. electric grid CO_2 emissions factors. As already mentioned, around 67% of U.S. steel is produced by EAF and most of the energy used in EAF is electricity. In the Advanced scenario, the CO_2 emissions of the steel industry decreases by 80% from 86 million MT CO_2 per year in 2015 to 17 million MT CO_2 per year in 2050. The drop is mainly because of the increased share of EAF steel production and substantial decarbonization of the U.S. electric grid in addition to the adoption of CCUS technologies. This decrease in emissions occurs while U.S. steel production increases by 12% during the same period to meet the needs of a growing population and expanding economy (see Appendix 1.1 for details). In the Near Zero GHG scenario, the most ambitious assumptions were made across all the decarbonization pillars (EE, industrial electrification, LCFFES, and CCUS) to get the U.S. steel industry's CO_2 emissions to near zero.

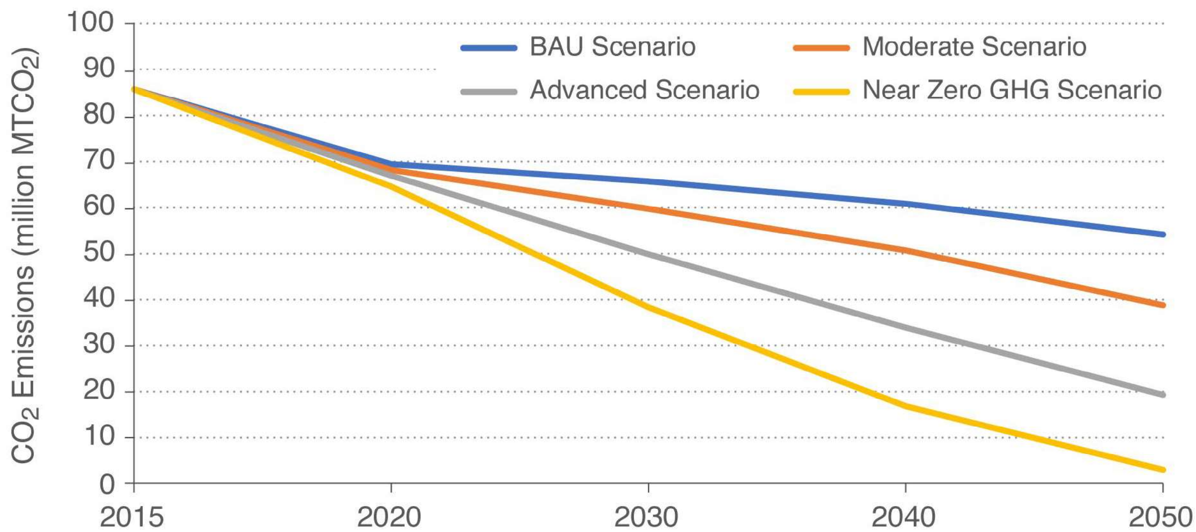

FIGURE 14. CO_2 EMISSIONS (MILLION MT/YEAR) FORECAST FOR THE U.S. STEEL INDUSTRY BY SCENARIO, 2015–2050.

AS DESCRIBED IN SECTION 1.3, THE BUSINESS AS USUAL (BAU) SCENARIO ASSUMES SLOW IMPROVEMENT, MODERATE ASSUMES HIGHER RATES OF ENERGY EFFICIENCY, SWITCHING TO LOWER-CARBON FUELS, ELECTRIFICATION ADOPTION, AND SOME CCUS, ADVANCED ASSUMES EVEN HIGHER RATES, AND NEAR ZERO ASSUMES THE MOST AGGRESSIVE IMPROVEMENT AND ADOPTION RATES. DETAILS ON ASSUMPTIONS, PARAMETERS, AND TIMING OF TRANSFORMATIVE TECHNOLOGY APPLICATION CAN BE FOUND IN APPENDIX 1.1. SOURCE: THIS WORK.

> *Key message: With aggressive adoption of energy efficiency, industrial electrification, LCFFES and CCUS, the CO_2 emissions of U.S. steel industry can reach near zero in 2050 while U.S. steel production increases by 12% during the same period.*

To achieve Near Zero GHG scenario results, in addition to ambitious deployment of current commercialized technologies, more-ambitious RD&D is needed by public and private sector entities, especially to make substantial adoption of transformative and CCUS technologies possible in the steel industry. These are discussed in detail in the following section (Section 2.1.3) on RD&D needs and opportunities.

Several factors contribute to the realization of significant CO_2 emissions reductions in the Near Zero GHG scenario. Figure 15 shows the contribution of each of the decarbonization pillars to the reduction of the U.S. steel industry's CO_2 emissions between 2015 and 2050. It should be noted that the impact of electrification includes the reduction in electric grid CO_2 emissions. DOE assumed less than 10% of the steel will be produced by BF-BOF process in 2050 under Near Zero GHG scenarios. In this scenario, most steel will be produced by scrap-based EAF and a small portion with hydrogen-based DRI-EAF process and electrolysis of iron ore process. Because all these processes are electricity-intensive, the U.S. electric grid CO_2 emissions and its projection to 2050 significantly influence the CO_2 emissions projection results under the electrification and LCFFES pillars. Further research is needed to understand how the transition to low-carbon energy generation in the electrical grid will impact industrial decarbonization.

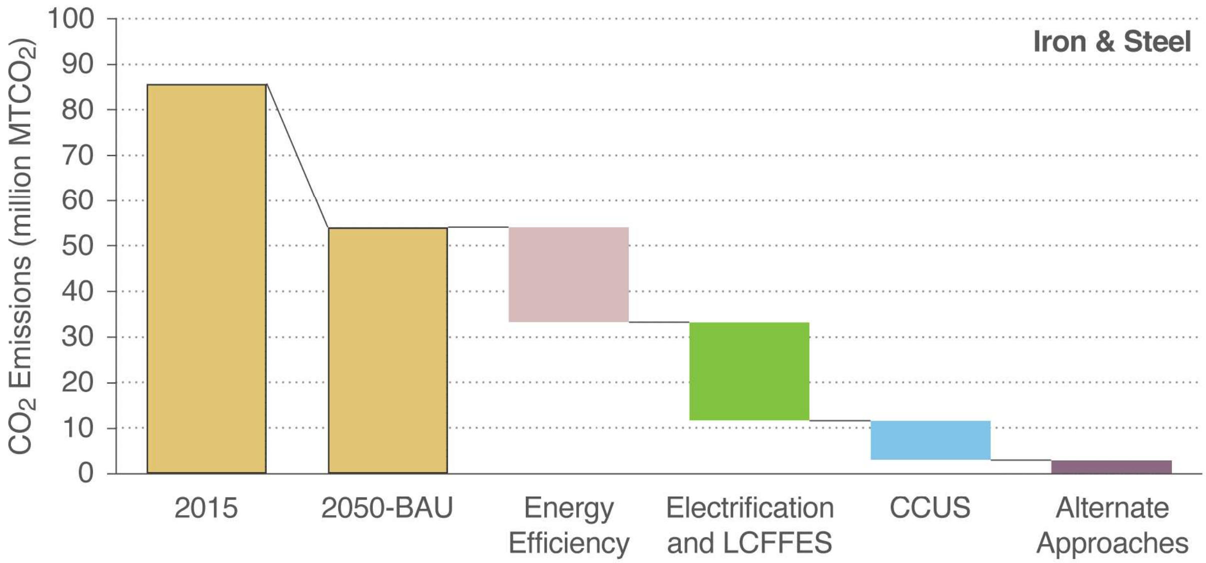

FIGURE 15. IMPACT OF THE DECARBONIZATION PILLARS ON CO_2 EMISSIONS (MILLION MT/YEAR) FOR THE U.S. IRON & STEEL INDUSTRY, 2015–2050.

SUBSECTOR EMISSIONS ARE ESTIMATED FOR BUSINESS AS USUAL (BAU) AND NEAR ZERO GHG SCENARIOS. SINCE INDUSTRIAL ELECTRIFICATION AND LCFFES TECHNOLOGIES AND STRATEGIES ARE STRONGLY INTERCONNECTED, THESE PILLARS WERE GROUPED FOR SCENARIO MODELING. THE "ALTERNATE APPROACHES" BAND SHOWS FURTHER EMISSIONS REDUCTIONS NECESSARY TO REACH NET-ZERO EMISSIONS FOR THE SUBSECTOR. THESE ALTERNATE APPROACHES, INCLUDING NEGATIVE EMISSIONS TECHNOLOGIES, ARE NOT SPECIFICALLY EVALUATED IN SCENARIO MODELING FOR THIS ROADMAP. THE POWERING OF ALTERNATE APPROACHES WILL ALSO NEED CLEAN ENERGY SOURCES (E.G., DIRECT AIR CAPTURE COULD BE POWERED BY NUCLEAR, RENEWABLE SOURCES, SOLAR, WASTE HEAT FROM INDUSTRIAL OPERATIONS, ETC.). DETAILS ON ASSUMPTIONS, PARAMETERS, AND TIMING OF TRANSFORMATIVE TECHNOLOGY APPLICATION CAN BE FOUND IN APPENDIX 1.5. SOURCE: THIS WORK.

> *Key message: The reduction in CO_2 emissions in the BAU scenario is primarily driven by a decrease in projected U.S. electric grid CO_2 emissions by 2050. Around 67% of U.S. steel is currently produced through the electrified process route, EAF. To achieve net-zero CO_2 emissions by 2050, major emissions reductions will be needed from further advancements in energy efficiency, electrification, and switching to hydrogen-based steel production; plus, smaller contributions from CCUS and alternate approaches.*

2.1.3 RD&D Needs and Opportunities for the Iron and Steel Industry

This section explores the RD&D challenges and opportunities of the decarbonization pillars (EE, industrial electrification, LCFFES, and CCUS) and what should be the priority approaches. The technologies covered in this section represent a wide range of technological maturity and market readiness. Figure 16 maps steel decarbonization technologies along these axes. The rest of this section discusses the specific challenges and opportunities for RD&D related to each of these decarbonization measures.

Iron and Steel Industry: Priority Approaches

Breakthroughs are needed in furnace gas recovery, implementation of low-carbon H_2 in DRI at scale, electrification of re-heat furnaces, production of iron by electrolysis, H_2 plasma smelting reduction, and top-gas recycling.

Technical assistance on developing mature strategic energy management systems in iron and steel facilities, technical assistance on deploying existing low-capital energy efficiency, waste heat recovery (including waste heat to power), and other decarbonization technologies.

Demonstration and rapid adoption of smart manufacturing and Internet of Things technologies to increase energy productivity.

Technology deployment activities that enable and accelerate the transition to lower-carbon fuels and process heat solutions, including demonstrations at scale and techno-economic analyses that show cost competitiveness (e.g., electric induction furnaces, use of clean hydrogen in blast furnaces).

Investments focused on reducing cost and improving efficiency of carbon capture and storage (CCS) technologies to decarbonize different routes of steel production, such as top-gas recycling in blast furnaces with CCS.

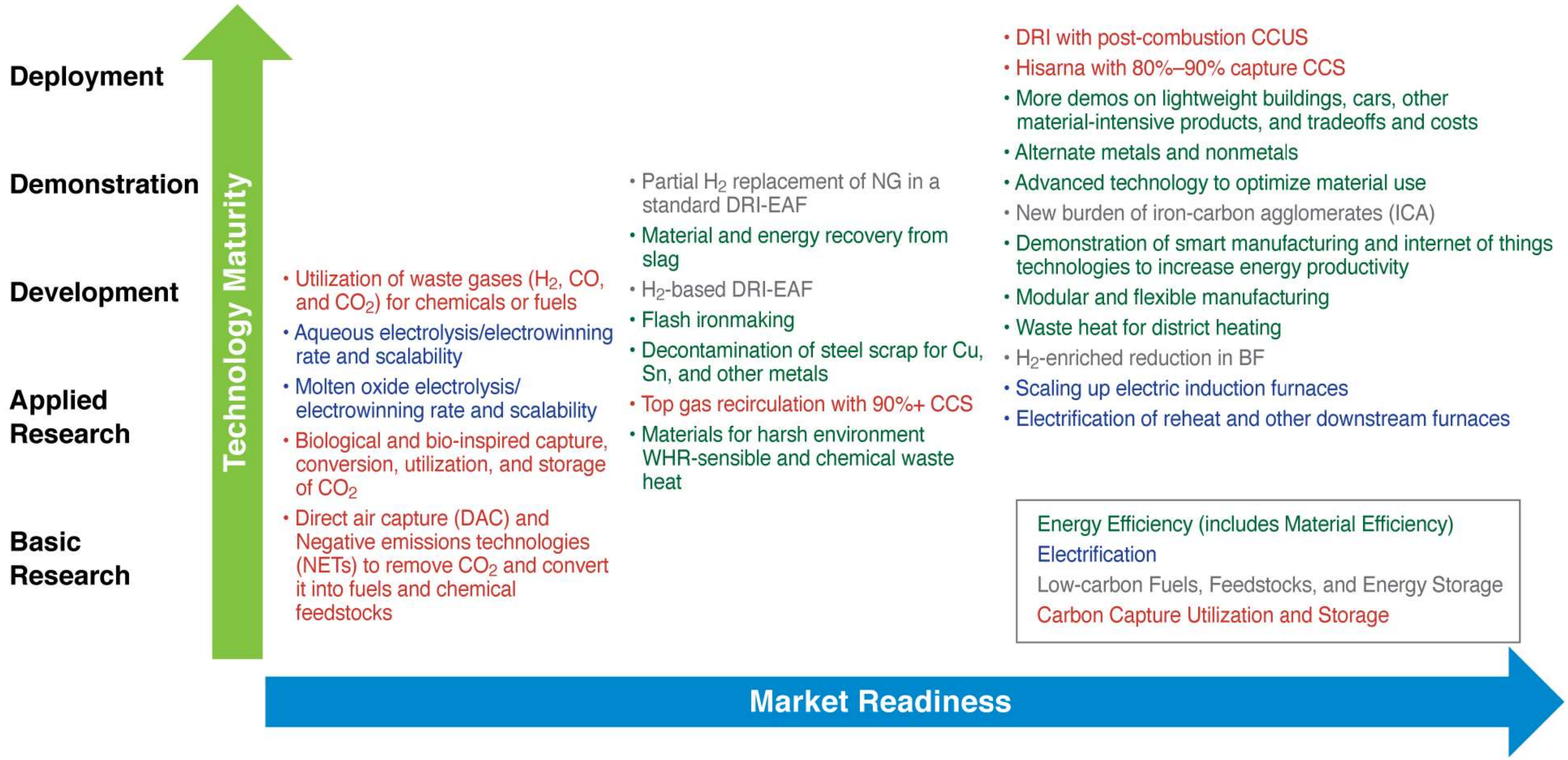

Figure 16. Technical maturity levels of select decarbonization technologies discussed during roadmap virtual meetings for the U.S. steel manufacturing industry.

Meeting participants provided input on the relative market readiness and technical maturing of these technologies during discussions. There is a distribution of technologies in several of these categories, which broaden the placement of items. Further definition of terms is provided in the glossary. Acronyms: BF: blast furnace; DRI: direct reduced iron; EAF: electric arc furnace; WHR: waste heat recovery. Source: this work.

> *Key message: Transformative technologies such as hydrogen based DRI, electrolysis of iron ore and CCUS are at the early or middle range of market readiness and need more RD&D support to become fully commercial and available for large scale deployment in mid- and long-term.*

2.1.3.1 Energy Efficiency for the Iron and Steel Industry

Because energy efficiency technologies could reduce—but not eliminate—GHG emissions, other decarbonization technologies and strategies are needed. There are many energy efficiency technologies and the World Steel Association estimates there is a significant potential for a further reduction in energy intensity for the global steel industry.[141] However, challenges with the deployment of these technologies remain, and RD&D could help address them. A 2010 energy efficiency and cost savings guide [142] describes a list of commercialized energy efficiency measures and technologies for the iron and steel industry and a 2013 report[143] describes 56 emerging technologies for energy efficiency improvement in the steel industry.

Energy efficiency technologies that are either already available or will be available in the next few years include various measures to optimize the blast furnace, such as reducing the coke rate through pulverized coal injection or using coke dry quenching to promote heat recovery. Alternative injection materials to pulverized coal could also be used, such as hydrogen. And the use of such alternatives would decrease the emissions associated with the coking process and improve the performance of conventional blast furnaces. For such technologies, the primary barriers are economic.

Waste heat and gas recovery (WHR) could also benefit from RD&D. Coke gas, blast furnace gas, and furnace gas can be recycled back into the process or be used to produce hot water, steam, and electricity. For commercialized WHR technologies, the primary challenge is economic viability. There is also room for technological advancement of WHR, such as developing materials for application in harsh environments. RD&D could drive innovation in phase-stable materials, functional surfaces, and embrittlement-resistant materials that can resist material aging effects. There could also be WHR from oxy-fired reheat furnaces. Also, RD&D is needed to reduce the initial investment cost for waste heat to power (WHP) systems, such as organic Rankine cycle and supercritical CO_2 power cycles.

Cutting-edge technologies could assist with energy management systems, drawing from smart manufacturing and the Internet of Things; such technologies include predictive maintenance and machine learning or digital twins to improve process control. More RD&D could scale-up and adapt these technologies for use by steel plants.

RD&D for energy efficiency should focus on the economic feasibility of these technologies by demonstrating potential costs and benefits to plant managers. Attention to systems efficiency and SEM is vital for continuous improvements in energy efficiency. RD&D could cover both analytical work, such as better characterizing the energy saving potential of different technologies and combinations of technologies, as well as practical tools that could help plant managers simulate and understand energy

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[141] ArcelorMittal, *Climate Action Report 1*, May 2019, https://corporate-media.arcelormittal.com/media/hs4nmyya/am_climateactionreport_1.pdf.
[142] Ernst Worrell et al., *Energy Efficiency Improvement and Cost Saving Opportunities for the U.S. Iron and Steel Industry: An ENERGY STAR Guide for Energy and Plant Managers*, Lawrence Berkeley National Laboratory, 2010, https://doi.org/10.2172/1026806.
[143] Ali Hasanbeigi, Lynn Price, and Marlene Arens, *Emerging Energy Efficiency and Carbon Dioxide Emissions-Reduction Technologies for the Iron and Steel Industry*, Lawrence Berkeley National Laboratory, BNL-6106E, January 2013, https://eta-publications.lbl.gov/sites/default/files/6106e-steel-tech.pdf.

efficiency opportunities. However, as noted earlier it is important that additional cutting-edge low-emissions technologies are developed to further reduce GHG emissions.[144]

2.1.3.2 Electrification and Low-Carbon Fuels, Feedstocks, and Energy Sources for the Iron and Steel Industry

Several fuels can replace coal or petroleum coke as a reducing agent in the smelting process. These alternative fuels include natural gas, biomass, or biogas, and on a longer time horizon, hydrogen. And the use of natural gas and charcoal already represents commercialized technologies for use in steel production.

RD&D could help map timelines for switching to fuels with lower-carbon footprints, such as using natural gas and biomass in the short-term as transition fuels to a longer-term option (i.e., hydrogen). And research could identify just how much hydrogen could be used in existing BF-BOF and DRI-EAF facilities.[145]

More RD&D on preparing agricultural waste for use in blast furnaces is also needed, including economic considerations, such as resource constraints and availability for different plants. Biomass may only be feasible for certain plants in specific locations, and more research needs to be done on the availability and life cycle impacts of local biomass resources. Also, there could be benefits of using biochar in a blast furnace, such as a reduction in harmful gases from the combustion that occurs in an incinerator.

2.1.3.2.1 Process Heat Electrification

Globally, the main pathway to the electrification of the steel industry is the use of EAF— not BF-BOF—steel production. In the United States, however, over 67% of the steel is already produced by EAFs and limited opportunity remains for increased use of EAF technology.[146] Another major pathway to electrification is the use of hydrogen that is produced from near zero emissions energy (e.g., renewable or nuclear), instead of natural gas in direct reduced iron (DRI) production and the electrolysis of iron ore; these two emerging technologies are discussed in Sections 2.1.3.2.2 (Hydrogen DRI-EAF) and 2.1.3.2.3 (Electrolysis of Iron Ore) respectively.

Several different process heating pathways in steel production could be decarbonized by switching to low-carbon electricity. Reheating furnaces could be electrified, and electric induction furnaces could be scaled up. Ladle and tundish heating could be switched to resistance, infrared, or plasma heating. There could also be reallocation or onsite generation of low-carbon electricity for secondary steel plants.

Electrification of these processes presents several technical challenges. For example, the production environment has many corrosive gases that could result in frequent failure of electrical heating equipment. For reheating equipment, switching from fuel-fired burners to an induction heater might only work for thin slabs or billets with current technologies, and plants might need some significant redesign to electrify this process, which requires temperatures over 2,000^{o}F (1100^{o}C).

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[144] Energy Transitions Commission, *Mission Possible: Achieving Net-Zero Carbon Emissions from Harder-to-Abate Sectors*, November 2018, https://www.energy-transitions.org/publications/mission-possible.

[145] Chris Bataille, *Low and Zero Emissions in the Steel and Cement Industries: Barriers, Technologies, and Policies,* (paper presented at OECD Green Growth and Sustainable Development Forum, Paris, November 26-27, 2019), https://www.oecd.org/greengrowth/GGSD2019_Steel%20and%20Cemement_Final.pdf.

[146] Cris Candice Tuck, *2018 Minerals Yearbook: Iron and Steel [Advance Release],* U.S. Geological Survey, October 2021, https://pubs.usgs.gov/myb/vol1/2018/myb1-2018-iron-steel.pdf.

Scale-up of technology to meet demand and the high capital cost involved are the biggest barriers to implementing electrotechnologies in the iron and steel industry. Though many of the technologies under consideration perform well for small-scale applications, systems that can process a million MT of steel per year using electrolysis of iron ore are not yet as economical as traditional systems, given the high capital cost. Large-scale testing and process optimization are needed to improve operational efficiency and bring down costs before such technologies could be adopted.[147] More RD&D is needed to improve furnace design so that resistance heating can be scaled up in batch and continuous furnaces. Given that electrification will increase electricity demand, RD&D could investigate the best ways to meet the capacity needs of industrial zones or clusters where high-voltage electricity transmission infrastructure can deliver electricity for steel production.[148] Also, some emerging technologies could save energy and materials for steel galvanizing and heat treatment, such as the Flash Bainite heat treatment process to replace the annealing of steel.[149] RD&D could help assess the mitigation potential of these technologies and assist with their increased uptake.

2.1.3.2.2 Hydrogen DRI-EAF

Hydrogen, especially low-carbon hydrogen, can be used in several ways to decarbonize steel production.[150] In addition to its potential to produce heat when burned as fuel, hydrogen can be used as an alternative reductant to produce iron that is then processed into steel in an EAF. One of the most advanced pathways to iron refining with hydrogen is known as direct reduction with iron (DRI) and is already commercial with natural gas and in demonstration stages with hydrogen internationally.

Key RD&D barriers to the use of hydrogen in iron refining include:

- Cost of hydrogen production (for more information, please see Section 1.2.2.2),
- Understanding of the kinetics of DRI, which influence the reliability and efficiency of DRI processes,
- Systems engineering of hydrogen-based processes to reduce capital cost and energy consumption and optimize iron quality,
- Foundational understanding of early-stage pathways to iron reduction, such as use of hydrogen plasmas.

2.1.3.2.3 Electrolysis of Iron Ore

The technical viability of iron electrolysis has been demonstrated in laboratory settings, and it could even use less electricity than is needed to synthesize hydrogen.[151] Direct electrolysis of iron would be a transformative technology in the long term, and it could be fully decarbonized if no-carbon electricity were used. Several routes for electrolysis are being investigated, including molten oxides at high

[147] Kiran Thirumaran et al., "Energy Implications of Electro-Technologies in Industrial Process Heating Systems," (paper presented at ACEEE Summer Study on Energy Efficiency in Industry, Portland, Oregon, August 12-14, 2019), https://www.osti.gov/servlets/purl/1564150.

[148] Chris Bataille, *Low and Zero Emissions in the Steel and Cement Industries: Barriers, Technologies, and Policies,* (paper presented at OECD Green Growth and Sustainable Development Forum, Paris, November 26-27, 2019), https://www.oecd.org/greengrowth/GGSD2019_Steel%20and%20Cemement_Final.pdf.

[149] Gary M. Cola, "Replacing Hot Stamped, Boron, And DP1000 with "Room Temperature Formable" Flash Bainite Advanced high strength steel," (presented at ASM Heat Treating Society Conference, October 20-25, 2015).

[150] International Energy Agency, *Iron and Steel Technology Roadmap*, October 2020, https://www.iea.org/reports/iron-and-steel-technology-roadmap.

[151] ArcelorMittal, *Climate Action Report 1*, May 2019, https://corporate-media.arcelormittal.com/media/hs4nmyya/am_climateactionreport_1.pdf.

temperatures (1,600°C) (Figure 17) and aqueous electrowinning at low temperatures (110℃). Aqueous electrolysis technology, such as Siderwin,[152] under a European Union (EU) Horizon2020-funded project, will be demonstrated as a prototype by 2022 and will then be ready for further scale-up.

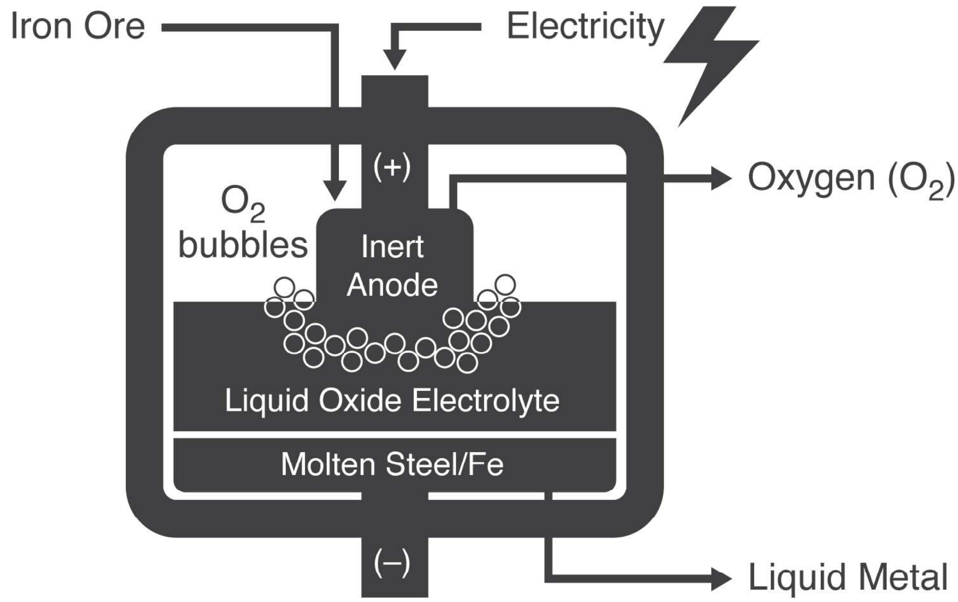

FIGURE 17. SCHEMATIC OF MOLTEN OXIDE ELECTROLYSIS[153]

The yield and scalability of electrolysis of iron ore are currently not at a commercial scale, and the technology is still in the basic RD&D stage. Fundamental questions about the energy footprint of this process remain, including whether the iron ore would need energy-intensive preprocessing before undergoing electrolysis. In addition, further research is needed on inexpensive, no-carbon inert anodes that can resist the corrosive conditions of high-temperature molten oxide electrolysis.[154]

RD&D could continue to promote technological development and increased efficiency as well as addressing economic challenges. For example, oxygen generated from electrolysis is a marketable by-product, and RD&D could investigate the comprehensive costs and benefits of electrolysis at scale, including both material and energy costs as well as the value of byproducts.

2.1.3.3 Carbon Capture, Utilization, and Storage for the Iron and Steel Industry

2.1.3.3.1 Carbon Capture and Storage

Carbon capture and storage (CCS) could decarbonize different processes of iron and steel production, such as top-gas recycling in blast furnaces, DRI, oxygen-rich smelt reduction, bath smelting reduction,

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[152] Siderwin project aims to develop a technology to produce steel by electrolysis of iron ore at low temperature. ArcelorMittal supported by 11 additional innovative European partners, aims at developing a 3-meter-long new experimental pilot to validate the technology at the demonstration level. See "Development of new methodologieS for InDustrial CO2-freE steel pRoduction by electrowinning," TECNALIA, accessed May 2022, https://www.siderwin-spire.eu/.
[153] "Transforming Metal Production," Boston Metal, accessed May 2022, https://www.bostonmetal.com/moe-technology/.
[154] Anne Carpenter, *CO_2 Abatement in the Iron and Steel Industry*, IEA Clean Coal Centre, ISBN 978-92-9029-513-6, 2012, https://www.sustainable-carbon.org/report/co2-abatement-in-the-iron-and-steel-industry-ccc-193/.

HIsarna, and direct smelting reduction.[155] These pathways vary greatly in their commercialization status, with blast furnace CCS being at the pilot stage, DRI CCS in the development stage, and smelting reduction CCS in the pilot stage. The top-gas recirculation blast furnace process with CCS could also reduce coal inputs and increase the percentage of CO_2 in the exhaust gas, which would also lower the cost of carbon capture. [156] Also, CCS could be combined with oxy-fuel combustion in reheat, sintering, or pelletizing furnaces, though this combination has not yet been demonstrated.

The main challenges for CCS technologies are achieving further reductions in costs and improving operational efficiencies. Building out the CO_2 transport and storage infrastructure near the iron and steel facilities which are dispersed across the United States is another challenge. Also, better materials and process designs are needed to improve carbon capture operations and lower costs.[157]

By helping to address these challenges, RD&D could help further develop the efficacy of CCS. RD&D could focus on design innovations, such as for BF-BOF, to increase the purity and concentration of the CO_2 stream, which would make capture more efficient and less costly. This would also decrease compression costs for liquification of the supercritical CO_2 for transport.

The DOE Office of Fossil Energy and Carbon Management recently funded an RD&D project by Cleveland Cliffs (formerly ArcelorMittal) in collaboration with Dastur Energy and ION Clean Energy to conduct the engineering feasibility research on an industrial-scale solution for CCS from blast furnace to capture 50-70% of CO_2 emissions from blast furnace (BF) gas.[158] Their proposed scheme includes a compositional shift of the BF gas by passing it through a series of water gas shift (WGS) reactors, which convert about 55% of the carbon monoxide (CO) in the BF gas to CO_2, thus enabling enhanced capture of up to 70% CO_2 from the available BF gas.[159] The STEPWISE project, funded through the European Horizon 2020 (H2020) Low Carbon Energy (LCE) program, is working on a similar technology called sorption-enhanced water-gas shift (SEWGS) for CO_2 capture from BF gas. It combines water-gas shift in the WGS section with CO_2 adsorption and separation steps in the SEWGS section using a selective solid adsorbent material.[160]

Also, RD&D could address economic challenges by focusing attention on CCS technologies with the greatest techno-economic potential. Some CCS technologies, such as calcium-looping lime production can capture CO_2 emissions at lower cost, and RD&D should further explore these opportunities.

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[155] Ali Hasanbeigi, Lynn Price, and Marlene Arens, *Emerging Energy Efficiency and Carbon Dioxide Emissions-Reduction Technologies for the Iron and Steel Industry*, Lawrence Berkeley National Laboratory, BNL-6106E, January 2013, https://eta-publications.lbl.gov/sites/default/files/6106e-steel-tech.pdf.
[156] Anne Carpenter, *CO_2 Abatement in the Iron and Steel Industry*, IEA Clean Coal Centre, ISBN 978-92-9029-513-6, 2012, https://www.sustainable-carbon.org/report/co2-abatement-in-the-iron-and-steel-industry-ccc-193/.
[157] Julio Friedmann, Zhiyuan Fan, and Ke Tang, *Low-Carbon Heat Solutions for Heavy Industry: Sources, Options, and Costs Today,* Columbia University Center on Global Energy Policy, October 2019, https://www.energypolicy.columbia.edu/sites/default/files/file-uploads/LowCarbonHeat-CGEP_Report_100219-2_0.pdf.
[158] "FOA 2187 and FOA 2188 Project Selections," U.S. Department of Energy Office of Fossil Energy and Carbon Management, September 1, 2020, https://www.energy.gov/fecm/articles/foa-2187-and-foa-2188-project-selections; Cleveland Cliffs and Dastur International Inc., 2021, personal communication.
[159] "Department of Energy Invests $72 Million in Carbon Capture Technologies," U.S. Department of Energy, September 1, 2020, https://www.energy.gov/articles/department-energy-invests-72-million-carbon-capture-technologies.
[160] Jurriaan Boon, et al., "Chapter One - Sorption-Enhanced Water–Gas Shift," *Advances in Chemical Engineering* 51, (2017): 1-96. https://doi.org/10.1016/bs.ache.2017.07.004.

2.1.3.3.2 Carbon Utilization

CO_2 emissions from iron and steel production can be captured and used for chemicals or fuel production (e.g., alcohol). Costs of doing this can vary widely depending on the product to be made and the site. Another utilization option, which is already commercialized, is carbonation of slag for use either in cement as a clinker substitute or in concrete as a cement substitute, which would displace the CO_2 emissions associated with cement production.

In general, carbon utilization technologies have not been demonstrated at scale, and there are technical barriers to developing carbon utilization, which RD&D could help address. More research is needed to characterize the utilization potential at steel plants and address whether carbon utilization technologies can utilize carbon on the scale at which it would be captured from a steel plant. In addition, RD&D should characterize the performance and durability of carbon utilization-based materials. There is also an opportunity for developing new carbon utilization technologies and applications.

Cost barriers for carbon utilization are significant because some of the materials carbon utilization technologies are trying to substitute for are already very inexpensive. RD&D could investigate specific standards and codes that could promote increased use of materials produced by carbon utilization technologies, and it could seek to understand policy options to incentivize uptake. The amount of energy needed could also be an issue because it could result in higher costs. Developing carbon utilization technologies that require lower temperatures can help reduce the cost. A better understanding of how the chemical manufacturing industry and the steel industry might work together for CO_2 utilized for chemicals production is also needed.

Waste gas recovery for utilization also has significant potential. Some waste gases that are currently incinerated could instead be captured and converted into useful products, such as bioethanol, which could have lower life cycle emissions. ArcelorMittal is building a pilot plant with waste gas recovery for ethanol production, and RD&D could encourage further piloting of this technology.[161] Also, high-pressure gas leaving the furnace could be captured and used to power other equipment.[162]

2.1.4 Proposed RD&D Action Plan for the Iron and Steel Industry

Because there is a large number of technologies—all of which vary in their maturity, deployment costs, mitigation potential, and other variables—developing guiding principles for an RD&D action plan would be useful.

RD&D investment could be guided by the balance of several factors. First, RD&D investment should cover both near- and long-term solutions in terms of technological maturity and manufacturing scale. One benefit of investment in near-term solutions is that they could potentially catalyze longer-term innovation. At the same time, long-term solutions may have trouble attracting investment today, and concerted RD&D support is thus needed.

RD&D investment for technologies that provide early, but modest gains, need to be balanced with "moonshot" technologies that might not deliver for more than a decade.

[161] "Capturing and utilising waste carbon from steelmaking," ArcelorMittal, accessed May 2022, https://corporate.arcelormittal.com/media/case-studies/capturing-and-utilising-waste-carbon-from-steelmaking.
[162] Anne Carpenter, *CO_2 Abatement in the Iron and Steel Industry*, IEA Clean Coal Centre, ISBN 978-92-9029-513-6, 2012, https://www.sustainable-carbon.org/report/co2-abatement-in-the-iron-and-steel-industry-ccc-193/.

In addition to a principle of balance, RD&D investment could also have a prioritization strategy. Given that RD&D is meant to catalyze innovation for technologies that have not yet received market support, technologies that do not have other significant near-term means of funding could be prioritized and a balanced approach could be taken as described earlier. Priority could be given to technologies with a high annual mitigation potential, namely energy efficiency, electrification and low- and no-carbon fuels, hydrogen-based reduction, and CCUS. Further, RD&D could improve the understanding of technologies' cross-sectoral benefits, which could provide options and synergies including both the actual technologies and the appropriate infrastructure (e.g., hydrogen or CCUS) across industries and demand sectors. Given such proposed guidelines, an RD&D action plan could cover several areas that cut across the technologies in the decarbonization pillars.

Figure 18 shows a "landscape" of needs and opportunities in the U.S. steel industry for RD&D investments organized by pillars (note industrial electrification and LCFFES are shown in separate wedges to spread out the needs) and decade through 2050. Inputs on the needs and opportunities came from participants in the virtual meetings. As noted in the principles above, needs and opportunities in the next five years should be pursued with targeted RD&D investments to lower technical hurdles, improve economic viability, accelerate adoption, and pave the way for even more transformative low-carbon technologies. The early opportunities also represent a means to achieve early GHG emissions reductions (e.g., energy efficiency, SEM, smart manufacturing, WHP) and initiate the transition to lower-carbon sources of energy (electrification, clean hydrogen, biofuels, and abatement of combustion related GHGs (e.g., top gas recycling with CCUS)). Also, there are crosscutting opportunities to pursue across the pillars (e.g., energy efficiency advancements that lower the energy burden for electrification and other technologies). For example, while a top pressure recovery turbine (TRT) is already a commercial technology, TRT with CCS still requires further development and demonstration. Also, while electrification of reheat furnaces is almost commercial, further RD&D is needed for H_2-based DRI EAF and electrolysis of iron ore technologies to shift towards electrified near zero carbon steelmaking.

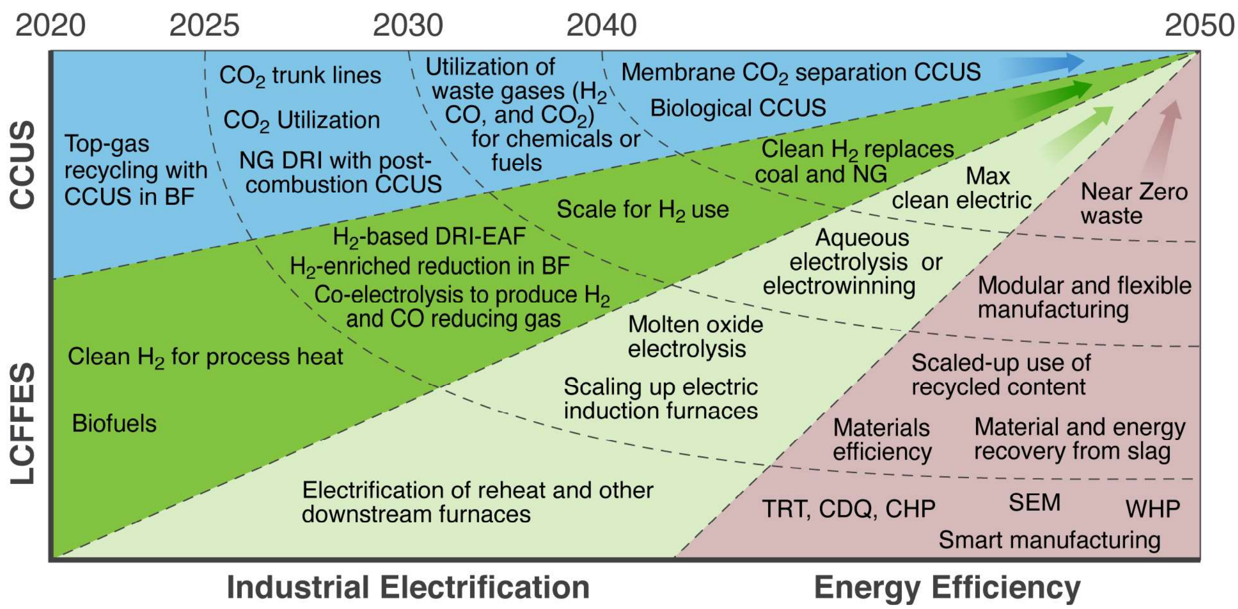

FIGURE 18. LANDSCAPE OF RD&D ADVANCEMENT OPPORTUNITIES BY DECADE AND DECARBONIZATION PILLAR FOR THE U.S. STEEL INDUSTRY

NEEDS AND OPPORTUNITIES CAPTURED IN THE FIGURE ARE AS NOTED BY ATTENDEES AT THE ROADMAP VIRTUAL SESSIONS. LCFFES INCLUDES CLEAN TECHNOLOGIES THAT DO NOT RELEASE GHGS TO THE ATMOSPHERE FROM THE PRODUCTION OR USE OF ENERGY SOURCES, AND INCLUDE RENEWABLE SOURCED ELECTRICITY, NUCLEAR ENERGY FOR ELECTRICITY AND HEAT, CONCENTRATING SOLAR POWER, AND GEOTHERMAL ENERGY. FURTHER DEFINITIONS ARE AVAILABLE IN THE GLOSSARY. ACRONYMS ARE DEFINED IN THE ACRONYMS LIST. SOURCE: THIS WORK.

> *Key message: RD&D investments are needed across a host of opportunities in the U.S. steel industry to lower technical hurdles, improve economic viability, accelerate adoption, and pave the way for even more transformative low-carbon technologies.*

This illustration also prompts thinking on how to balance RD&D investments across the near, mid, and longer-term horizons. Some investments are needed to lower hurdles and spur adoption of current low-carbon technologies, there needs to be an investment in mid-term technologies, approaches, and infrastructure to deliver on deeper reductions and while taking advantage of an electrical grid that is supplied with increasing levels of low-carbon generation, and longer-term investments are needed in parallel so that development of transformative technology can be accelerated. To subdivide the need for investments over this timeline into three categories:

RD&D needs with **near-term (2020–2025)** impacts include:

- Help leverage relatively low-capital solutions (energy efficiency, SEM, and waste heat reduction/recovery solutions (WHP, top pressure recovery turbine (TRT), coke dry quenching (CDQ)) that provide additional non-energy benefits
- Enable the transition to lower-carbon fuels and process heat solutions (e.g., electrification of reheat and downstream furnaces, clean hydrogen for process heat, biofuels),
- Continue advancing the integration of CCUS with hard-to-abate sources (e.g., top-gas recycling in BF furnaces).

RD&D needs with **mid-term (2025–2030)** impacts include:

- Probe routes to continue improving materials efficiency and flexibility including reuse, recycle and refurbishment (including materials and energy recovery from slag),
- Invest in lower-carbon process adaptations and routes (e.g., molten oxide electrolysis, scale-up of electric induction furnaces, clean hydrogen based direct reduction iron-electric arc furnace (DRI-EAF)),
- Expand the infrastructure and integration capabilities and knowledge to capture, transport, and reuse, where possible (in the steel process, or nearby uses), CO_2 from hard-to-abate sources with the highest efficiency and best economics possible.
- Explore innovative routes to produce carbon reductants using low-carbon, net-zero, or negative carbon methods, such as co-electrolysis of CO_2 and H_2O using clean electricity to provide a syngas that can be used for DRI production, potentially with the CO_2 coming from recycle or biomass.[163]

RD&D needs with **longer-term (2030–2050)** impacts include:

- Advance modular approaches for manufacturing to greater scale and proportion of the market,
- Lower technical and economic challenges for transformative approaches to making steel and accelerate development timeline (e.g., aqueous electrolysis and electrowinning),
- Develop additional routes for utilizing waste gases (hydrogen, CO, CO_2 etc.) onsite or in nearby facilities, improve the efficiency of separations of these and other gases so their energy and resource needs are significantly decreased and hurdles for implementation lowered.

These areas include information synthesis and analysis, laboratory testing, and pilot and demonstration projects.

2.1.4.1 Information Synthesis and Analysis for the Iron and Steel Industry

For many decarbonization technologies, even though they might be commercially available at a small scale, uptake is limited because of a lack of understanding of potential benefits. RD&D funding could be directed toward information synthesis and analysis that could help plant managers understand the specific benefits of a given technology for their plants. This includes regional and spatially detailed analysis, as well as cataloging of best practices and lessons learned from elsewhere in the world. For example, to promote lower-carbon fuels and electrification, more information on cost, availability, and performance tailored to each plant's production route could help steel producers understand potential benefits.

In addition, information synthesis and analysis could help pave the way for technologies still in the development phase by demonstrating their potential future benefits to encourage more attention and investment today. For example, for CCUS more research is needed to better characterize plant-level capture potentials and technology costs, especially given the many potential applications of carbon capture for different steel production routes. Although not in the scope of this report, material efficiency strategies could help reduce industry GHG emissions for steel while delivering the same

[163] Andries Krüger et al, "Integration of water electrolysis for fossil-free steel production," *International Journal of Hydrogen Energy* 45, no. 55 (November 2020): 29966-29977. https://doi.org/10.1016/j.ijhydene.2020.08.116.

material services. This pathway needs to be explored further with defensible LCA and TEA analyses and will be the subject of future work.

2.1.4.2 Laboratory Testing for the Iron and Steel Industry

RD&D could also be directed toward technologies that still require extensive in situ testing and development and have not reached the scale-up or production state. RD&D investment is particularly important for these types of technologies because at this stage, they may have difficulty attracting commercial finance and other sources of funding.

2.1.4.3 Pilot and Demonstration Projects for the Iron and Steel Industry

RD&D could also be directed toward technologies that are in the pilot and demonstration phase, but might not be ready for commercial use and might require more piloting for subsector-specific applications. At the same time, RD&D could help move development-stage technologies into the pilot and demonstration phase, which would be critical for convincing stakeholders of the potential benefits of adoption. A prime example of this is hydrogen DRI-EAF steel production or CCUS on blast furnaces.

2.2 Chemical Manufacturing

The diversity, complexity, and deep capital investment of the chemical manufacturing subsector leads to parallel RD&D needs for the decarbonization pillars (energy efficiency, industrial electrification, LCFFES, and CCUS). Electrification and LCFFES are highly connected and evaluated together for this roadmap. Key learnings and RD&D opportunities from the meetings include:

- Crosscutting RD&D opportunities include improving the application efficiency for chemical separations, the use of hydrogen as a fuel or feedstock, and the integration of CCUS to improve economics.
- A portfolio of low-carbon process heat solutions should be developed that industry could use as a starting point to select options with the best fit (e.g., application, economics, and geography).
- Subsector-specific RD&D opportunities include improving the effectiveness of thermal energy use (e.g., noncontact energy transfer), plasma, hydrogen fuel effectiveness, materials efficiency, electrical transfer (e.g., electrolyzers and electrochemistry), data science, and energy storage (e.g., thermal, chemical, and electrical storage) to improve the efficiency of whole system energy use.
- Advancing capabilities, such as battery storage, to use variable energy (e.g., variable solar and wind energy) to rapidly, effectively, and economically switch from current to low-carbon sources is an early-stage opportunity.
- To increase their deployment, the effectiveness of noncontact thermal heating and hydrogen combustion needs to be researched, improved, and deployed at an industrial scale.
- The diversity of needs and applications suggests a range of RD&D investments would be needed across a portfolio of solutions with active engagement with industrial companies in partnerships to test and scale-up the most promising technologies.
- Strategies that use existing capital and infrastructure will be crucial for near- and mid-term progress (e.g., energy efficiency, materials efficiency, LCFFES, and electrification).

Chemical Manufacturing Subsector: Key Takeaways

- There are multiple crosscutting opportunities to move toward subsector decarbonization, such as: process heat; separations; use of hydrogen, biomass, and waste as fuel or feedstock; CCUS integration; thermal and electrical storage; and materials efficiency.
- The subsector can also benefit from process-specific opportunities, including noncontact energy transfer (e.g., acoustic [such as thermoacoustics] and plasma), electrical transfer, and scaling of electrochemical processes.
- Advancing the use of variable energy (e.g., variable solar and wind energy) to rapidly, effectively, and economically switch from current to low-carbon sources is an early-stage opportunity.
- Advances in electrolyzer efficiency are needed to aid the prospects for electrochemical processes to replace incumbents and systems efficiency and smart manufacturing research needs to be extended across multiple processes for integrated chemical facilities.

2.2.1 Status of the U.S. Chemical Industry

2.2.1.1 U.S. Chemical Production

With more than 70 thousand products, 11 thousand manufacturing facilities, and deep supply chain interconnections, the U.S. chemical manufacturing industry is very diverse.[164] The dimensions of this subsector—which employs over half a million people[165]—signal a high potential for leveraged impact as the subsector transforms. Many contributions from the subsector are not highly visible, as many chemical companies are not directly involved in making consumer products. Numerous chemicals are precursors of other chemical products (about 24%), and downstream manufacturers use some 30% of production.[166] This last impact reflects that more than 96% of manufactured goods are directly touched by the business of chemistry.[167]

Overall chemical production has grown 13% since 2009 as shown in Figure 19.[168] The U.S. chemical manufacturing industry saw demand growth along with dropping feedstock and energy costs in recent years due to the increased availability of inexpensive shale gas. That competitive advantage has led to investments of $209 billion in new assets.[169] Energy intensity for the industry improved between 2001 and 2007 at an average rate of 5% per year, but the trend reversed with energy intensity going back up until 2016 as the industry recovered from the Great Recession (2007–2008) and low utilization rates.[170] Since 2016, energy efficiency again has been improving at an average rate of 2% per year.[171]

[164] "Chemical Sector Profile," Cybersecurity & Infrastructure Agency, May 2019, https://www.cisa.gov/publication/chemical-sector-profile.
[165] "The Business of Chemistry by the Numbers," American Chemistry Council, July 2021, https://www.americanchemistry.com/media/files/acc/chemistry-in-america/data-industry-statistics/the-business-of-chemistry-by-the-numbers/files/business-of-chemistry-by-the-numbers.
[166] U.S. Department of Energy Office of Industrial Technologies, *Energy and Environmental Profile of the U.S. Chemical Industry*, https://www.energy.gov/sites/prod/files/2013/11/f4/profile_full.pdf.
[167] "Chemical Sector Profile," Cybersecurity & Infrastructure Agency, May 2019, https://www.cisa.gov/publication/chemical-sector-profile.
[168] American Chemistry Council, *2020 Guide to the Business of Chemistry*, December 2020, https://www.americanchemistry.com/chemistry-in-america/data-industry-statistics/resources/2020-guide-to-the-business-of-chemistry.
[169] "U.S. Chemicals Trade by the Numbers," American Chemistry Council, June 2021, https://www.americanchemistry.com/media/files/acc/chemistry-in-america/data-industry-statistics/us-chemicals-trade-by-the-numbers/files/us-chemicals-trade-by-the-numbers.
[170] American Chemistry Council, *2020 Guide to the Business of Chemistry*, December 2020, https://www.americanchemistry.com/chemistry-in-america/data-industry-statistics/resources/2020-guide-to-the-business-of-chemistry.
[171] Ibid.

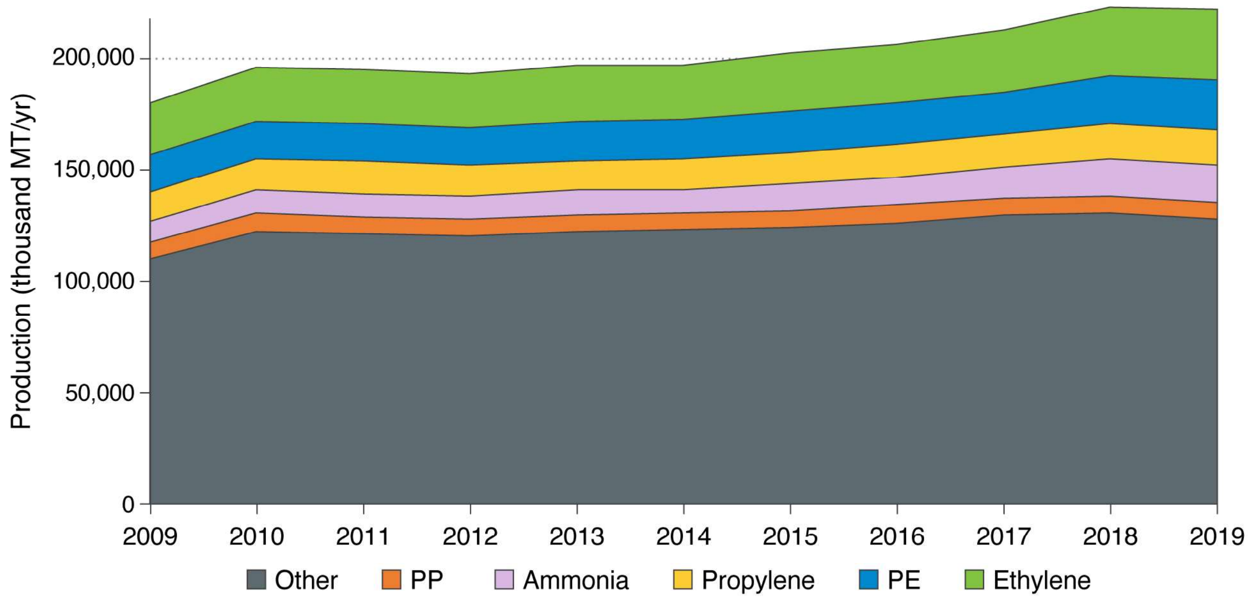

Figure 19. Production volumes for several high-volume U.S. chemicals 2009-2019 (thousand MT/year).

PP – polypropylene, PE – polyethylene. Data source: ACC. [172]

Key message: Demand for several major chemical products has been strong and production capacity has grown due to the availability of inexpensive feedstocks such as shale gas.

2.2.1.2 Energy Use and GHG Emissions for the Chemical Industry

When the energy use in feedstocks and heat and power are combined, the chemical industry is the largest energy user in the U.S. industrial sector (Figure 2). Natural gas and hydrocarbon gas liquids (HGLs) (which includes ethane, propane, propylene, and butanes), are the dominant energy sources used in manufacturing chemicals when considering both heat and power and feedstocks (Figure 20). For chemical manufacturing in 2018, natural gas accounted for 61% of the total heat and power consumption, electricity 13%, waste gas 11%, coal 3%, and other 12%.[173] Boilers, furnaces, and related systems combust those fuels to provide 90% of the thermal energy needs of industry.[174] This is evident in Figure 21 where the process heating, CHP, and boiler categories all connect with process heat.

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[172] American Chemistry Council, *2020 Guide to the Business of Chemistry*, December 2020, https://www.americanchemistry.com/chemistry-in-america/data-industry-statistics/resources/2020-guide-to-the-business-of-chemistry.

[173] "Manufacturing Energy and Carbon Footprint: Chemicals (2018 MECS)," U.S. Department of Energy Advanced Manufacturing Office, December 2021, https://www.energy.gov/sites/default/files/2021-12/2018_mecs_chemicals_energy_carbon_footprint_0.pdf; "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data, U.S. Energy Information Administration, released 2021, https://www.eia.gov/consumption/manufacturing/data/2018/.

[174] Ibid.

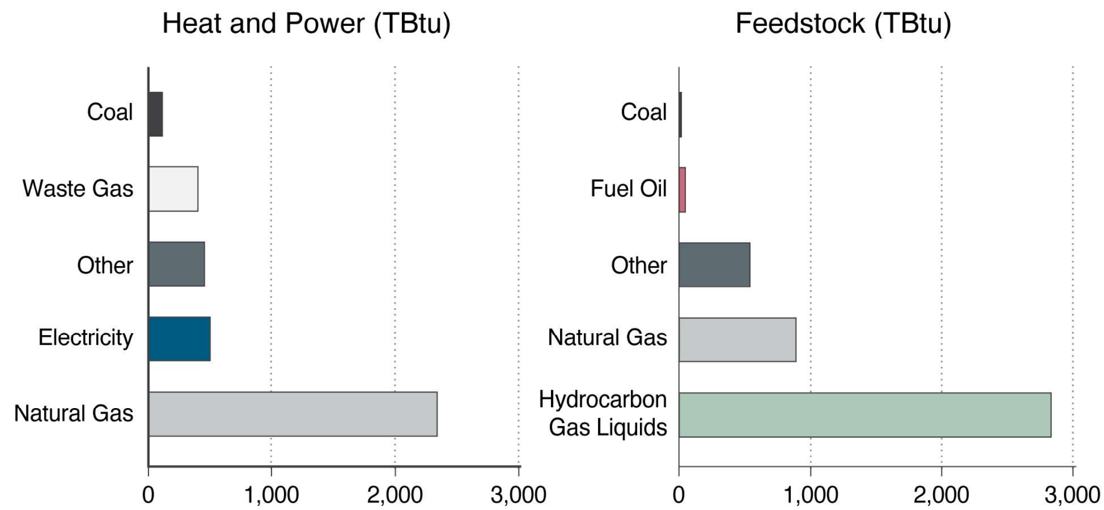

FIGURE 20. ENERGY SOURCES FOR THE U.S. CHEMICAL MANUFACTURING SUBSECTOR IN 2018.

ENERGY SOURCES ARE SEPARATED BY USE FOR HEAT AND POWER (LEFT), AND FEEDSTOCKS (RIGHT) IN TRILLION BTU (TBTU). HYDROCARBON GAS LIQUIDS INCLUDE BUTANES, PROPYLENE, AND PROPANE. DATA SOURCE: EIA MECS 2018 AND DOE FOOTPRINT 2021.[175]

> *Key message: Natural gas currently dominates the energy sources for heat and power in the chemical industry, and natural gas and hydrocarbon gas liquids account for the largest portion of feedstocks.*

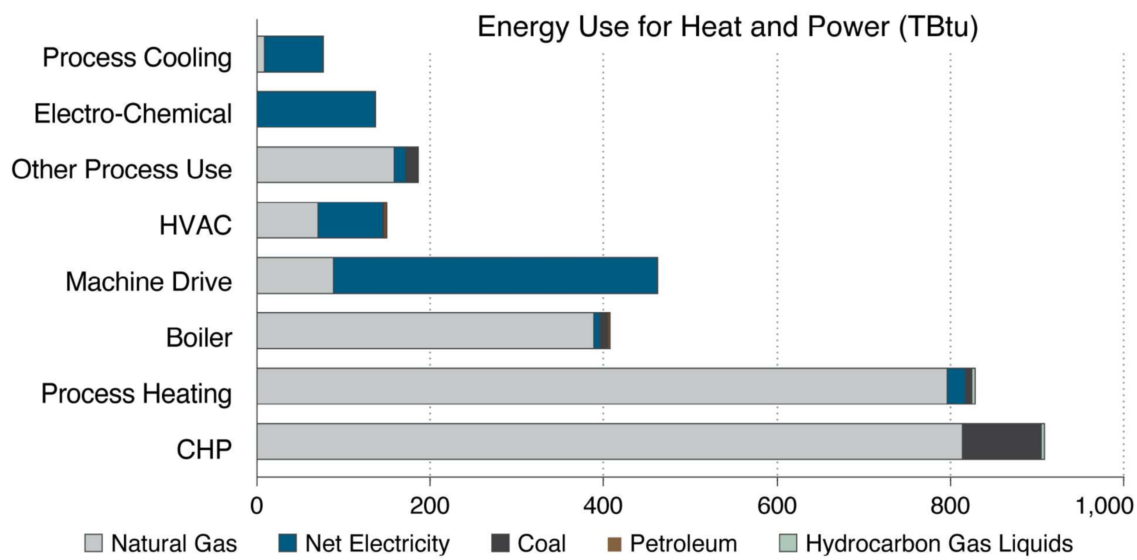

FIGURE 21. ENERGY USE FOR HEAT AND POWER IN THE U.S. CHEMICAL MANUFACTURING SUBSECTOR IN 2018.

DATA SOURCE: EIA MECS 2018.[176]

> *Key message: Natural gas supplies most of the energy for heat and power overall. Machine drive, process cooling, and electrochemical processes largely use electrical energy.*

[175] Ibid.

[176] "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data, U.S. Energy Information Administration, released 2021, https://www.eia.gov/consumption/manufacturing/data/2018/. See Table 5.2. Energy Consumed as a Fuel by End Use By Manufacturing Industry with Net Electricity.

Overall, the GHG emissions footprint of the U.S. chemical manufacturing industry was 274 million MT CO_2 in 2020 as shown in Figure 3.[177] The major classes of CO_2 emissions for 2018 shown in Figure 22 illustrate that about two-thirds comes from five major classes of products.

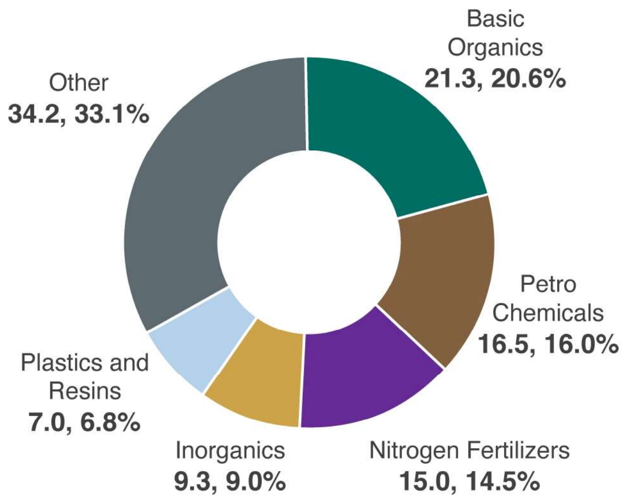

FIGURE 22. BREAKDOWN OF TOP U.S. CHEMICAL MANUFACTURING SUBSECTOR DIRECT CO_2 EMISSIONS (IN MILLION MT) IN 2018 BY NORTH AMERICAN INDUSTRY CLASSIFICATION SYSTEM (NAICS) CATEGORIES.

THE CLASSIFICATIONS ARE OTHER BASIC ORGANICS (NAICS 325199), PETROCHEMICALS (325110), NITROGEN FERTILIZERS (325311), INORGANICS (325180), AND PLASTICS AND RESINS (325211). DATA SOURCE: EPA.[178]

> *Key message: A large portion of chemical manufacturing subsector emissions are due to the production of a broad collection of organic chemicals, petrochemicals, and fertilizers.*

Across these basic product families, several chemicals dominate GHG emissions, including the large-volume chemicals (e.g., ammonia, ethylene, propylene, methanol, benzene, toluene, and xylenes (BTX), and polyethylene) that account for 80% of the subsector's energy demand and 75% of the industry's global GHG emissions.[179]

2.2.2 Barriers and Opportunities for the Chemical Industry

Several barriers and challenges specific to the chemical manufacturing industry were noted during the meetings. Those barriers with the strongest connections to RD&D needs are discussed here. Multiple connections to the general barriers and opportunities are discussed in Section 3.

[177] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 19. Energy-Related Carbon Dioxide Emissions by End Use.
[178] "Greenhouse Gas Reporting Program (GHGRP)," U.S. Environmental Protection Agency, last updated April 29, 2022, https://www.epa.gov/ghgreporting.
[179] International Energy Agency, International Council of Chemical Associations, and Dechema, *Technology Roadmap: Energy and GHG Reductions in the Chemical Industry via Catalytic Processes*, June 2013, https://www.iea.org/reports/technology-roadmap-energy-and-ghg-reductions-in-the-chemical-industry-via-catalytic-processes; Edward G. Rightor and Cathy L. Tway, "Global Energy and Emissions Reduction Potential of Chemical Process Improvements," *Catalysis Today* 258, no. 2 (December 2015): 226-229. https://doi.org/10.1016/j.cattod.2015.02.023.

Key barriers and opportunities highlighted include:

- The very low prices of energy and fuel sources (e.g., natural gas and natural gas liquids) in recent years is a particular challenge for justifying low-carbon alternatives as the economics of these sources are a key factor in the U.S. chemical industry's market advantage. This presents RD&D opportunities to make transformative technologies as economically viable as possible. For example, the cost of hydrogen from electrolysis can be five to ten times the cost of incumbent sources. RD&D at a scale that lowers the capital and operations costs are vital to the deployment of these and other low-carbon solutions. Additional underappreciated challenges in this space when it comes to using electrolysis-hydrogen as a chemical feedstock are that modern Haber-Bosch plants are highly integrated with their numerous steam methane reforming (SMR)/water gas shift/methanation reactors, and will not be compatible with electrolysis-hydrogen feedstocks without substantial retrofitting.

- The U.S. chemical industry has recently received an infusion of more than $200 billion in new capital investment connected with processing advantaged feedstocks from shale gas.[180] The new facilities made possible by such capital investment typically have the most energy efficient technologies available, are at large-scale, and could operate for 30–50 years making replacement with low-carbon technologies challenging. Research is needed on the best strategies (e.g., low-capital replacement approaches, transition to lower-carbon energy sources for heat and power, plug-in fuel replacements) to pursue considering the sunk capital and competitive economics of these newer facilities. The comparative benefits and drawbacks of CCUS versus retrofits, switching to low-carbon fuels or alternative carbon feedstocks such as CO_2, biomass, and waste should also be researched.

- Production facilities, such as ethane crackers, which are older than this new shale gas-inspired wave may be candidates for energy efficiency upgrades, trials of new low-carbon solutions, or retrofits. Strategies that use existing capital and infrastructure will be crucial for near- and mid-term progress (e.g., energy efficiency, plug-in low-carbon fuels, and electrification). At the opposite end of the efficiency distribution for production facilities from the new state-of-the-art facilities are the oldest, least efficient equipment, which could be considered for replacement by best available low-carbon technologies. There is a need to have low-carbon solutions and approaches across the distribution of process age and efficiency.

- Use of biomass, various waste streams (e.g., collected from municipalities, other industries, agriculture) holds a host of opportunities and RD&D challenges. These resources could serve as a source of low-net carbon emissions hydrocarbon feedstocks. RD&D to improve the quality of feedstock sources (e.g., separations), minimize carbon emissions associated with processing, and continued work to quantify the full life cycle impacts are some of the areas that need to be addressed. This topic is addressed also in Section 4.2 and is the topic of additional research reports.

- The value return for recycling and materials efficiency in the United States has seen increased uncertainty because of supply chain shifts such as China's plastics ban, which prevents the import

[180] "U.S. Chemicals Trade by the Numbers," American Chemistry Council, June 2021, https://www.americanchemistry.com/media/files/acc/chemistry-in-america/data-industry-statistics/us-chemicals-trade-by-the-numbers/files/us-chemicals-trade-by-the-numbers.

of all but the highest-quality plastics waste;[181] persistence of low disposal costs; and lack of customer willingness to pay more for products with higher recycled content. More efficient processes for recycling, materials separations, and improvement in physical properties of products with higher recycled content are needed to attain higher recycling rates.

- Supply and delivery of large quantities of competitively priced clean electricity are needed for chemical facilities to ramp up beneficial electrification, yet this electricity is not always available locally for the industry. The chemical manufacturing industry has not yet seen the advantage of using variable energy sources, current expertise is lacking, and process integration is not set up to tap into this resource. The RD&D opportunity is to enable opportunities where this resource could provide unique advantages, such as using onsite battery storage to ensure power quality and participate in wholesale markets.
- There is a paucity of quantitative information on the non-energy benefits of various electric technologies (which makes capital justification difficult) and a lack of technical information about the application for low-carbon solutions. Improved information availability, transparency, access, and shareability would aid justification arguments.[182]
- Unfavorable thermodynamics for CO_2 conversion to chemicals is a challenge in most paths to recycle or reuse captured CO_2. This does not exclude conversion, but it clarifies that the energy released when the CO_2 was formed during combustion must be added back to the process or material (and some more because of inefficiencies) to make products from CO_2. The CO_2 and energy burden will be part of the discussion even when the grid energy approaches a high level of clean electricity generation because of arguments that the low-carbon energy could be best used to displace high-carbon energy uses.[183]

2.2.3 Decarbonization Pathways for the Chemical Industry

To understand how the application of the decarbonization pillars could help phase out net GHG emissions, the potential GHG emissions reductions for several major chemical products (ammonia, methanol, ethylene, and BTX (benzene, toluene, and xylenes)) were examined. This work was also pursued to provide guidance on where RD&D could significantly enable reductions. The topic of where to start on reductions, relative impact of the pillars, and RD&D priorities were also of common interest across the meetings. Several scenarios were developed as described in Section 1.3.

The modeling results summarized in Figure 23 show that emissions could double in the BAU case considering the expected increase in demand for products and resulting emissions increases. Applications of the decarbonization pillars could level out the CO_2 emissions curve for the Moderate scenario and decrease emissions substantially by 2050 for the Advanced and Near Zero GHG scenarios. The Moderate scenario is largely achievable with commercially available technologies and current approaches, whereas the Advanced and Near Zero GHG scenarios assume ambitious application of transformative technologies and low-carbon approaches to the production of these major products. For the Moderate and Advanced scenarios, switching to electrification prior to decarbonizing the electric

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181 Marcus Lu, "How China's Plastics Ban Threw Global Recycling into Disarray," *Visual Capitalist,* July 7, 2020, https://www.visualcapitalist.com/china-plastic-ban-global-recycling-industry/.

182 U.S. Department of Energy Advanced Manufacturing Office, *Thermal Process Intensification: Transforming the Way Industry Uses Thermal Process Energy,* May 2022, https://www.energy.gov/eere/amo/articles/thermal-process-intensification-transforming-way-industry-uses-thermal-process.

183 Scott A. Stevenson, "Thermodynamic Considerations of CO_2 Utilization," *AIChE Journal* 65, no. 9 (June 2019). https://doi.org/10.1002/aic.16695.

grid could result in higher GHG emissions through 2030. Similarly, for the expansion of hydrogen use, GHG emissions could go up if increased amounts of hydrogen were made with higher-carbon processes (e.g., SMR without CCUS).

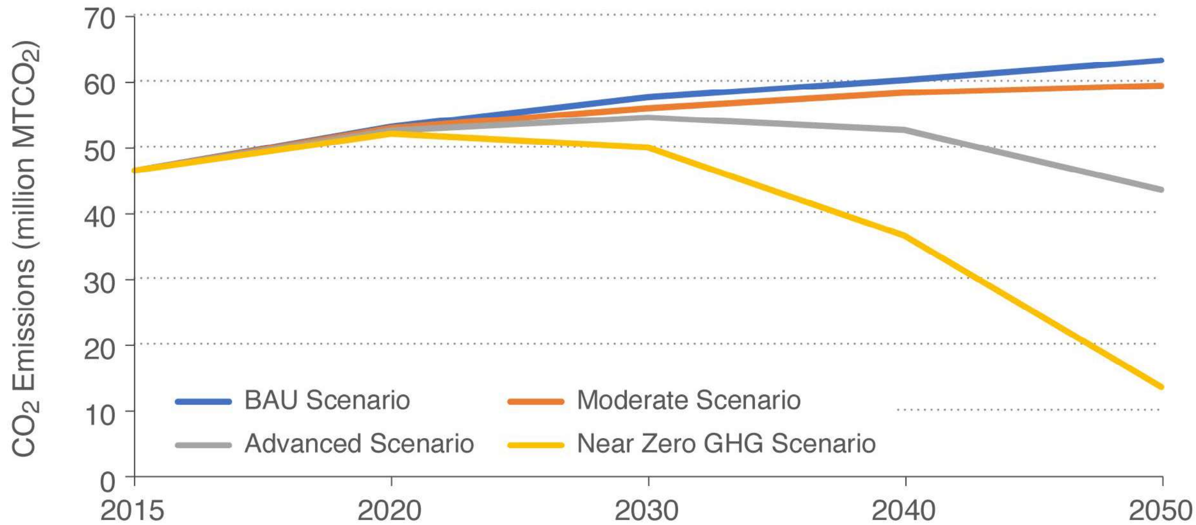

FIGURE 23. FORECASTED CO_2 EMISSIONS (MILLION MT/YEAR) FOR U.S. PRODUCTION OF AMMONIA, METHANOL, ETHYLENE, AND BTX BY DECARBONIZATION SCENARIO, 2015–2050.

AS DESCRIBED IN SECTION 1.3, THE BUSINESS AS USUAL (BAU) SCENARIO ASSUMES SLOW IMPROVEMENT; MODERATE ASSUMES HIGHER RATES OF ENERGY EFFICIENCY, SWITCHING TO LOWER-CARBON FUELS, ELECTRIFICATION ADOPTION, AND SOME CCUS; ADVANCED ASSUMES EVEN HIGHER RATES; AND NEAR ZERO ASSUMES THE MOST AGGRESSIVE IMPROVEMENT AND ADOPTION RATES. DETAILS ON ASSUMPTIONS, PARAMETERS, AND TIMING OF TRANSFORMATIVE TECHNOLOGY APPLICATION CAN BE FOUND IN APPENDIX 1.2. SOURCE: THIS WORK.

> *Key message: CO_2 emissions decline for the studied chemicals (ammonia, methanol, ethylene, and BTX) with the application of the decarbonization pillars with growing impact to 2050.*

The Moderate and Advanced scenarios show CO_2 emissions could increase which highlights the need for coordination on the timing of electrification and generation and use of low- or no- carbon electricity by the subsector. As discussed in Section 4.1, if industrial electrification occurs rapidly and locally supplied electricity has a relatively low proportion of low- or no-carbon electricity, the GHG emissions associated with the grid could cause increased emissions. This is due largely to the use of hydrogen made from electrolysis as a precursor for ammonia and methanol. If the locally supplied electricity has a relatively low proportion of clean electricity generation, the supplied hydrogen will have a higher carbon footprint than the incumbent process supplied by natural gas today. Hence, local generation of low- or no-carbon electricity that is reliable and suitable for industrial use (e.g., for hydrogen generation, process heat support, other) and increased adoption of electric technologies and processes needs to be coordinated and sequenced so that GHG emissions reductions are realized.

Even with the ambitious application of decarbonization technologies (i.e., under the Near Zero GHG scenario), some residual emissions would remain hard-to-abate (e.g., small dilute sources that are highly distributed across the chemical facility). Additionally, even if a significant portion of emissions were captured with CCUS, there would be some minor amount of residual CO_2 emissions because the capture efficiency likely would not be 100%. This suggests that there will need to be some intra-U.S. offsets or

GHG emissions reductions in other subsectors or positive reductions of GHG emissions from other means as discussed more fully in Section 1.4.

Different factors contribute to the realization of significant CO_2 emissions reductions in each scenario. Figure 24 shows the contribution of each of the decarbonization pillars to CO_2 reduction for producing the combined set of product examples. The shared electrification and LCFFES pathways make the largest contribution to CO_2 emissions reduction, a large portion of which is related to a shift from conventional production routes for ammonia, methanol, and ethylene to processes that use hydrogen produced from clean energy. Electrification of process heat and power also makes a substantial contribution.

These simulations also show that energy efficiency approaches could make a significant contribution to decarbonization. Energy efficiency will continue to be important throughout this 30-year transition, and RD&D is needed to increase its relative contribution to CO_2 reductions and application to lower the implementation costs of the other decarbonization pillars.

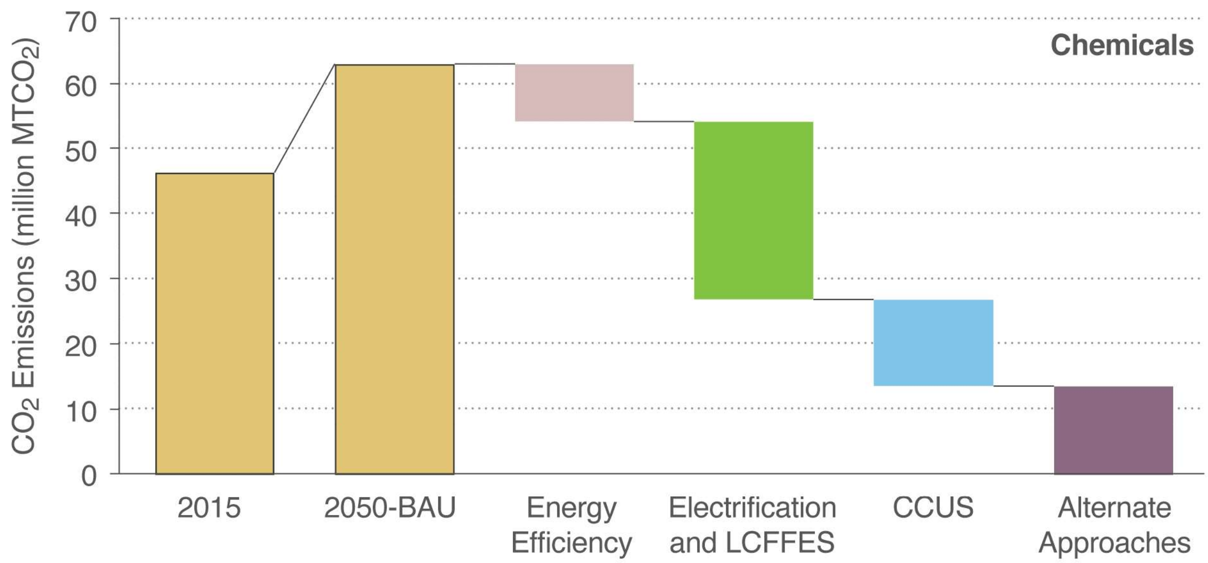

FIGURE 24. IMPACT OF THE DECARBONIZATION PILLARS ON CO_2 EMISSIONS (MILLION MT/YEAR) FOR U.S. PRODUCTION OF AMMONIA, METHANOL, ETHYLENE, AND BTX, 2015–2050.

EMISSIONS ARE ESTIMATED FOR BUSINESS AS USUAL (BAU) AND NEAR ZERO GHG SCENARIOS. SINCE INDUSTRIAL ELECTRIFICATION AND LCFFES TECHNOLOGIES AND STRATEGIES ARE STRONGLY INTERCONNECTED, THESE PILLARS WERE GROUPED FOR SCENARIO MODELING. THE "ALTERNATE APPROACHES" BAND SHOWS FURTHER EMISSIONS REDUCTIONS NECESSARY TO REACH NET-ZERO EMISSIONS FOR THE SUBSECTOR. THESE ALTERNATE APPROACHES, INCLUDING NEGATIVE EMISSIONS TECHNOLOGIES, ARE NOT SPECIFICALLY EVALUATED IN SCENARIO MODELING FOR THIS ROADMAP. THE POWERING OF ALTERNATE APPROACHES WILL ALSO NEED CLEAN ENERGY SOURCES (E.G., DIRECT AIR CAPTURE COULD BE POWERED BY NUCLEAR, RENEWABLE SOURCES, SOLAR, WASTE HEAT FROM INDUSTRIAL OPERATIONS). DETAILS ON ASSUMPTIONS, PARAMETERS, AND TIMING OF TRANSFORMATIVE TECHNOLOGY APPLICATION CAN BE FOUND IN APPENDIX 1.2. SOURCE: THIS WORK.

> *Key message: The application of the pillars could substantially reduce CO_2 emissions from the top volume and GHG emitting chemicals, but some residual process emissions will need to be addressed through alternate approaches.*

Figure 24 shows the combined impact approaches that can be considered "electrification" within these heavy industrial subsectors (including using electricity for process heat, generation of hydrogen that is used as a fuel, and use of hydrogen as a feedstock or precursor in chemical reactions). It is instructive to briefly explore the impacts and timing of these approaches.

Impacts of electrification of process heat: As noted in Section 1.2.2.1, process heat accounts for 7.6 quadrillion Btu or 51% of U.S. manufacturing's onsite energy consumption; about 30% of that amount is in the low-temperature range (at or below 150°C).[184] This temperature range and a growing portion of the medium-temperature range (150-300°C) are accessible by many commercial and electric technologies with the potential for both energy and non-energy benefits.[185] In general, electric technologies have a lower energy intensity than conventional technologies.[186] As the electric grid becomes decarbonized, this lower energy intensity will complement the lower-carbon impact of the energy source giving a lower CO_2 emissions factor as shown in Figure 25. The U.S. grid achieves emissions factor (kg CO_2/kWh) parity with coal between 2020 and 2030 in all scenarios[187] and with natural gas around 2030 in the Advanced and Near Zero scenarios. More aggressive assumptions on the rate of grid decarbonization from the BAU to Near Zero scenarios result in the emissions factor dropping more quickly below the emissions factors for coal or natural gas. For process heat applications, even if electrification occurs before the grid CO_2 emissions factor drops below the factor for natural gas and coal, there could be net reduction since electric technologies often have lower energy intensity (kWh/MT product) as shown in a recent study.[188] Electrification of process heat then is a highly efficient way to achieve early CO_2 reduction while providing many energy and non-energy benefits.[189]

[184] U.S. Department of Energy Advanced Manufacturing Office, *Manufacturing Energy and Carbon Footprint: All Manufacturing (2018 MECS)*, December 2021, https://www.energy.gov/sites/default/files/2022-01/2018_mecs_all_manufacturing_energy_carbon_footprint.pdf; Colin McMillan, "Manufacturing Thermal Energy Use in 2014," National Renewable Energy Laboratory, 10.7799/1570008, last updated December 18, 2020, https://data.nrel.gov/submissions/118.

[185] David Sandalow et al., *ICEF Industrial Heat Decarbonization Roadmap*, Innovation for Cool Earth Forum, December 2019, https://www.icef-forum.org/pdf/2019/roadmap/ICEF_Roadmap_201912.pdf; Abby L. Harvey, "The Latest in Thermal Energy Storage," *Power Magazine,* June 30, 2017, https://www.powermag.com/the-latest-in-thermal-energy-storage/.

[186] Abby L. Harvey, "The Latest in Thermal Energy Storage," *Power Magazine,* June 30, 2017, https://www.powermag.com/the-latest-in-thermal-energy-storage/.

[187] This pertains to the emissions factor per unit of energy (kg CO_2/MWh) of coal and natural gas when they are used as fuel for industrial heating as opposed to the emissions factor of electricity grid (under different scenarios) when electricity is used for industrial heating.

[188] Abby L. Harvey, "The Latest in Thermal Energy Storage," *Power Magazine,* June 30, 2017, https://www.powermag.com/the-latest-in-thermal-energy-storage/.

[189] David Sandalow et al., *ICEF Industrial Heat Decarbonization Roadmap*, Innovation for Cool Earth Forum, December 2019, https://www.icef-forum.org/pdf/2019/roadmap/ICEF_Roadmap_201912.pdf

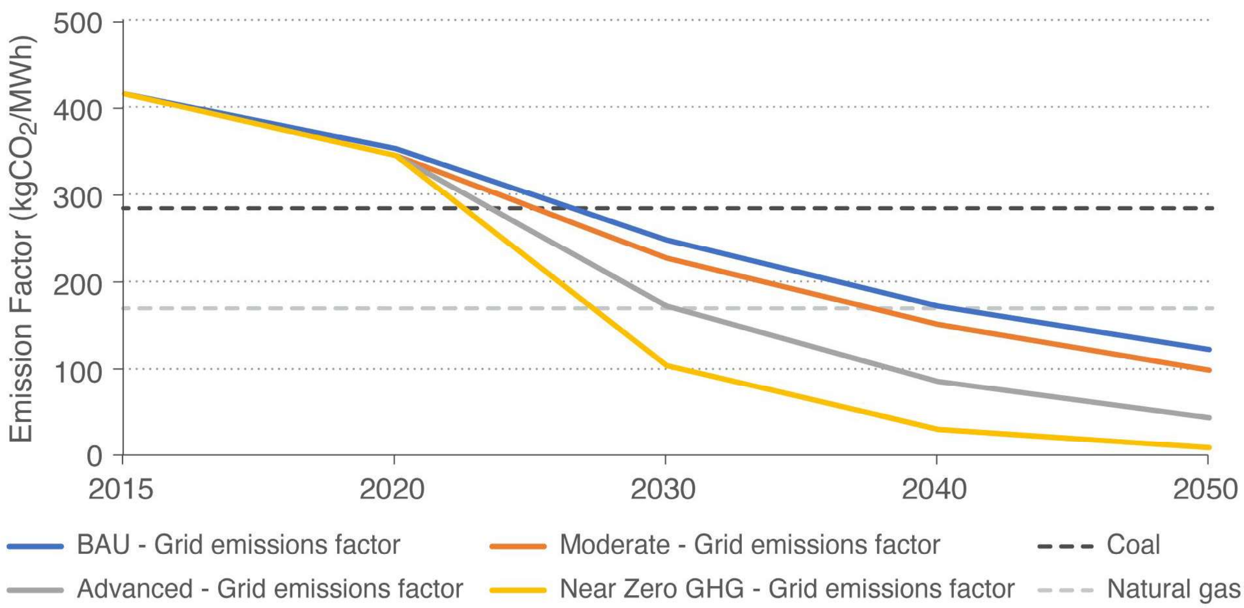

FIGURE 25. EMISSIONS FACTORS FOR SCENARIOS WHERE THE GRID IS DECARBONIZED COMPARED TO FUEL SOURCE EMISSIONS FACTORS FOR COAL AND NATURAL GAS (HORIZONTAL LINES).

THE RESULTS SHOW A DECLINE ACROSS THE DECADES. THIS FIGURE AIMS TO SHOW THE EMISSIONS FACTOR PER UNIT OF ENERGY (KG CO_2/MWH) OF COAL AND NATURAL GAS WHEN THEY ARE USED AS FUEL FOR INDUSTRIAL HEATING AS OPPOSED TO THE EMISSIONS FACTOR OF THE ELECTRICITY GRID (UNDER DIFFERENT SCENARIOS) WHEN ELECTRICITY IS USED FOR INDUSTRIAL HEATING. SOURCE: THIS WORK.

> *Key message: As the grid is decarbonized, CO_2 emissions factors for electricity decline so that CO_2 emissions are below that of coal and natural gas. The U.S. grid achieves emissions factor (kg CO_2/kWh) parity with coal between 2020 and 2030 in all scenarios, and with natural gas around 2030 in the Advanced and Near Zero scenarios. When the grid has a lower emissions factor than fossil fuel, switching from fossil fuel-based process heat to electrified process heat will result in reduced GHG emissions, assuming the same energy intensity for conventional and electrified processes. However, the electrified process often has a lower energy intensity than the conventional process resulting in even greater GHG reduction potential.*[190]

Impacts of electrification of hydrogen as a fuel: The use of hydrogen as a fuel to replace coal, natural gas, or other fossil fuels could provide GHG emissions reductions, depending on the emissions factor difference between the hydrogen (and the way it is generated) and the fuel that it could replace. For example, compared to coal the emissions factor difference versus hydrogen from clean energy would be the greatest, followed by hydrogen from steam methane reformers (SMR) with CCUS. This is illustrated in Table 3. Constant factors are assumed as we do not know the expected rate of improvement for the emissions factors for hydrogen with and without CCUS, but they will likely improve over time. RD&D that enables and lowers hurdles for the economic generation of clean hydrogen from low- or no-carbon-emitting processes at scale can help accelerate GHG emissions reduction via this approach. Also, RD&D that benefits implementing hydrogen as the replacement for fossil fuel sources with higher emissions factors would also be warranted.

[190] Ali Hasanbeigi et al., *Electrifying U.S. Industry: Technology and Process-Based Approach to Decarbonization*, Global Efficiency Intelligence, January 2021, https://www.globalefficiencyintel.com/electrifying-us-industry.

TABLE 3. EMISSIONS FACTORS FOR HYDROGEN PRODUCED USING STEAM METHANE REFORMING (SMR) WITH AND WITHOUT VARYING LEVELS OF CCUS AND ELECTROLYSIS USING RENEWABLE ENERGY COMPARED TO COAL AND NATURAL GAS.

Fuel Sources	Emissions Factors Used for Scenarios (kg CO_2/MWh)
Coal	341
Natural gas	202
Hydrogen SMR without CCUS	364
Hydrogen SMR 53% CCUS	169
Hydrogen SMR 64% CCUS	130
Hydrogen SMR 89% CCUS	40
Clean hydrogen (low-carbon energy electrolysis H_2)	-

NOTE: FOR THIS ROADMAP, THE EMISSIONS FACTORS ARE ASSUMED TO REMAIN THE SAME FROM 2015 THROUGH 2050.
SOURCE: THIS WORK.

Key message: Hydrogen produced by SMR with 53% or 89% carbon capture or by electrolysis (where electricity is 100% clean) has a lower CO_2 emissions factor than coal and natural gas. Switching from coal or natural gas-based process heat to hydrogen-based process heat will result in reduced CO_2 emissions, assuming the same energy intensity for conventional and hydrogen-based processes in the chemical subsector.

Impacts of electrification of hydrogen as a feedstock: Hydrogen is a key reactant in several chemical reactions where it is incorporated directly (e.g., ammonia) or indirectly (e.g., methanol where organic matter from natural gas, biomass, etc., is converted to synthesis gas containing hydrogen). Intermediates (e.g., methanol, ethanol) made with low-carbon hydrogen could be an approach to make major chemical building blocks such as ethylene or propylene – from which a host of polymers and other downstream chemicals can be made. For this roadmap, a key question is whether this approach is a viable route to GHG emissions reduction and whether it should be a prime area for RD&D in the near-term.

For the Moderate and Advanced scenarios, switching to hydrogen produced by electrolysis (referred to in this roadmap as "electrolysis-hydrogen") prior to decarbonizing the electric grid could result in higher GHG emission. For the expansion of hydrogen use, GHGs could possibly go up if increased amounts of hydrogen were made with higher-carbon processes (e.g., SMR without CCUS). Similarly, considering the generation of ammonia as an example, if electrolysis of hydrogen as a feedstock were to be pursued even modestly while produced using current projections for grid electricity, the scenarios show that CO_2 emissions could increase as shown in Figure 26. For clean electrolysis to be viable at scale, large-scale low-cost clean energy will be necessary as grid integrated electrolysis without a clean electricity grid will have more GHG emissions than hydrogen produced with SMR.

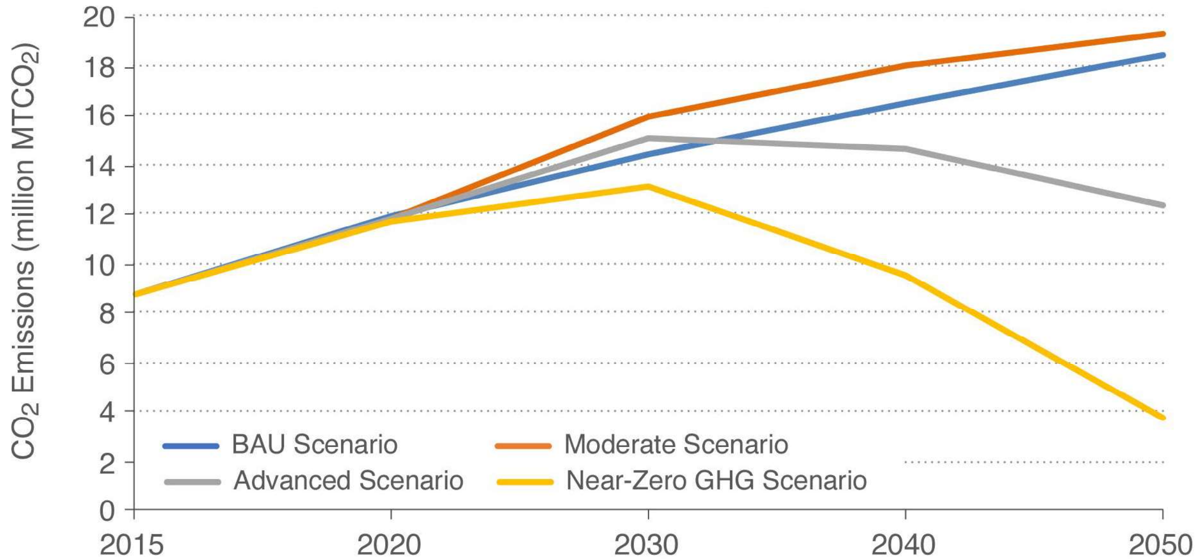

FIGURE 26. CO_2 EMISSIONS (MILLION MT/YEAR) FORECAST FOR THE U.S. AMMONIA INDUSTRY BY SCENARIO WHEN ELECTROLYSIS-HYDROGEN IS ADOPTED MODESTLY IN 2030–2050.

SOURCE: THIS WORK.

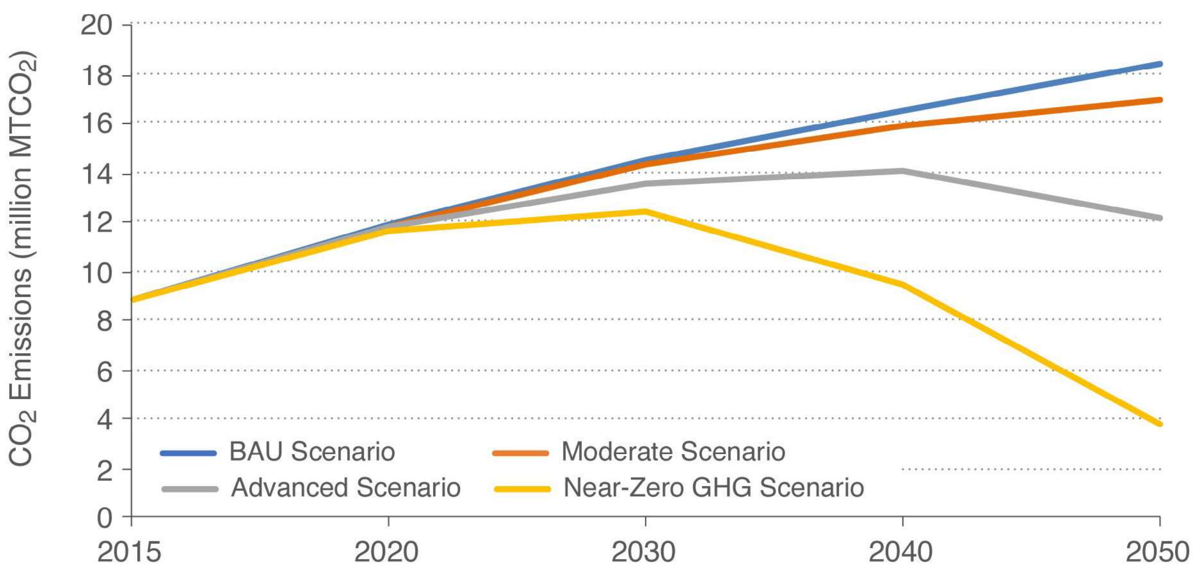

FIGURE 27. CO_2 EMISSIONS (MILLION MT/YEAR) FORECAST FOR THE U.S. AMMONIA INDUSTRY BY SCENARIO WHEN ADOPTION OF ELECTROLYSIS-HYDROGEN IS DELAYED UNTIL THE ELECTRIC GRID IS DECARBONIZED.

SOURCE: THIS WORK.

> *Key message: If electrolysis-hydrogen using grid-based electricity is applied too rapidly as a feedstock, by 2030 CO_2 emissions could increase above BAU (Figure 26), whereas if its use as a feedstock is delayed until the electric grid is highly decarbonized, the increased emissions above BAU could be avoided (Figure 27).*

This increase is due to the high electric intensity for ammonia produced from electrolysis-hydrogen (181 kWh/MT ammonia for natural gas-based process versus 9,500 kWh/MT ammonia for the electric process).[191] When using electrolysis-hydrogen as a feedstock instead of hydrogen produced from natural gas, DOE accounts for the emissions associated with the electricity used in electrolysis. However, there is no credit for displacing the natural gas because as a feedstock it is incorporated into the ammonia and does not result in direct emissions.

In the Moderate scenario, the balance point to keep CO_2 emissions from increasing above the BAU scenario (as shown in Figure 27) would limit U.S. ammonia production via the electrolysis-hydrogen pathway to about 1%, 3%, and 5% in 2030, 2040, and 2050, respectively. If the proportion of electrolysis-hydrogen is reduced in early years, this increase can be avoided (Figure 27).

This analysis showed that the use of electrolysis-hydrogen as a feedstock for major chemical products (e.g., methanol, polyethylene, polypropylene, ammonia) would require large-scale accessibility of clean electricity. Until the electric grid becomes 100% clean, the CO_2 emissions associated with grid-electricity generated hydrogen will hinder the use of electrolysis-hydrogen. Direct integration of non-carbon energy sources (such as wind or solar) with electrolysis could be an alternate route to clean-grid utilization and allow a higher level of production of chemicals via this pathway.

RD&D perspective learnings from this analysis include:

- Electrification of process heat is a top early opportunity. RD&D that lowers barriers, improves economics, accelerates adoption should be a top priority.
- Use of clean hydrogen can reduce GHG emissions from industry by displacing high-carbon incumbent feedstock.
- Use of electrolysis-hydrogen (generated via grid-based electricity) has several hurdles for use as a feedstock in chemicals, since the replacement electric processes have much higher energy intensity, and viability would require a low-carbon grid. Electrolysis-hydrogen could be used in chemical processes without increased CO_2 emissions if it is produced using electricity from 100% clean generation sources. RD&D should focus on routes to lower hurdles for direct use of no-carbon electricity at chemical facilities.
- RD&D that lowers hurdles and aids implementation for the economic generation of clean hydrogen at scale can help accelerate CO_2 reduction.

The combined electrification approaches—process electrification, switching to low-carbon energy sources, such as electrolytically produced hydrogen, hydrogen with CCUS, and transformative processes—could reduce emissions to 2015 levels. Abatement technologies and activities, such as CCUS, biofuels or biomass, and negative emissions approaches (such as soil carbon sequestration) could further reduce GHG emissions as described in Section 1.4. Although this simulation examines just a portion of the emissions for the subsector, by considering the three chemical products with the largest CO_2 emissions, it suggests a portion of CO_2 emissions from hard-to-abate sources would remain. Several

[191] Based on analysis conducted for this roadmap. Note: in addition to 181 kWh/MT ammonia, an additional 13 GJ/MT fuel (3600 kWh of NG) is used for NG-based ammonia. See U.S. Department of Energy Advanced Manufacturing Office, *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Chemical Manufacturing*, June 2015, https://www.energy.gov/sites/default/files/2015/08/f26/chemical_bandwidth_report.pdf.

other approaches and technologies could reduce GHG emissions further including carbon sinks (e.g., reforestation) and abatement technologies and activities (e.g., CCUS).

The relative contributions of the decarbonization pillars suggests additional RD&D in electrification would be crucial to realizing this impact. Also, the use of low-carbon hydrogen as a feedstock for the production of building block molecules (e.g., ethylene, propylene, and methanol), biomass (see Section 2.2.4.1.4), and other options are needed to further reduce CO_2. Efforts to accelerate the adoption and scaling of the cost-effective generation, transport, and use of renewably sourced hydrogen will be particularly important.

Understanding the best sources for CCUS application, combined with integration research to minimize costs and deployment hurdles, will also be important. Starting points for the capture of CO_2 from the highest-purity, highest-volume sources in industry have been studied, and those studies have shown that 123 facilities have the potential to avoid 68.5 million MT CO_2 per year at costs below $40 per MT CO_2 delivered.[192] There are RD&D needs associated with the connection to potential CO_2 transport and storage infrastructure. A build-out of trunk lines and an expanded national network would be needed to meet the CCUS needs of multiple industries.[193] This includes early expansion along the Gulf Coast, where several petrochemical complexes are located.

The RD&D needs and opportunities for each of the decarbonization pillars and technical requirements for their adoption in the U.S. chemical manufacturing industry are discussed in detail in the next section.

[192] Pilorgé, H., et al., Cost Analysis of Carbon Capture and Sequestration of Process Emissions from the U.S. Industrial Sector. 2020. Environmental Science & Technology 54, 12: 7524-7532. https://doi.org/10.1021/acs.est.9b07930.
[193] Greig, C., Net-Zero America Project, Andlinger Center for Energy and the Environment, Princeton University, personal communication, July 25, 2020.

2.2.4 RD&D Needs and Opportunities for the Chemical Industry

Chemical Industry: Priority Approaches

Technologies that support electrification (e.g., scaling of electrochemical processes) and the use of low-carbon fuels and feedstocks are needed. High volume, top energy consuming processes are a priority (e.g., ethylene, methanol). Additional opportunities are use of recovered CO_2, CO, and other off and flare gases and step-change improvements in efficiency and economics of chemical separations, catalysts, and process efficiency. For example, separation of ethane/ethylene, propane/propylene, CO_2/air, CH_4/air, and other separations could be made more efficient via use of hybrid membranes. Priority approaches include:

- Shift from conventional production routes for ammonia, methanol, and ethylene to processes that use hydrogen produced from low-carbon energy and/or steam methane reformers (SMR) with CCUS.
- Improve efficiency, cost, and durability for alternative, lower-energy separations methods (such as acoustic and electric field cryogenics); and develop nonequilibrium technologies to drive reactions or avoid need for separations (e.g., direct synthesis of polymers, high conversion technologies with high selectivity).
- Develop more efficient means of identifying, sorting, and recycling materials—while maintaining materials' properties.
- Invest in RD&D to improve catalysts for chemical conversion to reduce carbon footprints via improved yields.
- Improve chemical recycling (polymer to monomer or oligomer and back-to polymers) that can be incorporated into products.
- Explore opportunities for biomass and wastes to be used as feedstocks for chemicals production and as an energy source for process heat and power for chemical manufacturing; if combined with CCUS, increased use of biomass in the chemicals subsector could provide emission offsets.
- Develop processes for biosynthesis of fuels from waste gas and the conversion of CO_2 to high-value products (e.g., biopolymers and food protein).

This section explores the RD&D challenges and opportunities of the decarbonization pillars and what should be the priority approaches. Across RD&D for the decarbonization pillars and crosscutting areas, stakeholders noted that low-carbon technologies are in various development stages. Figure 28 summarizes the development stages of key technologies and approaches.

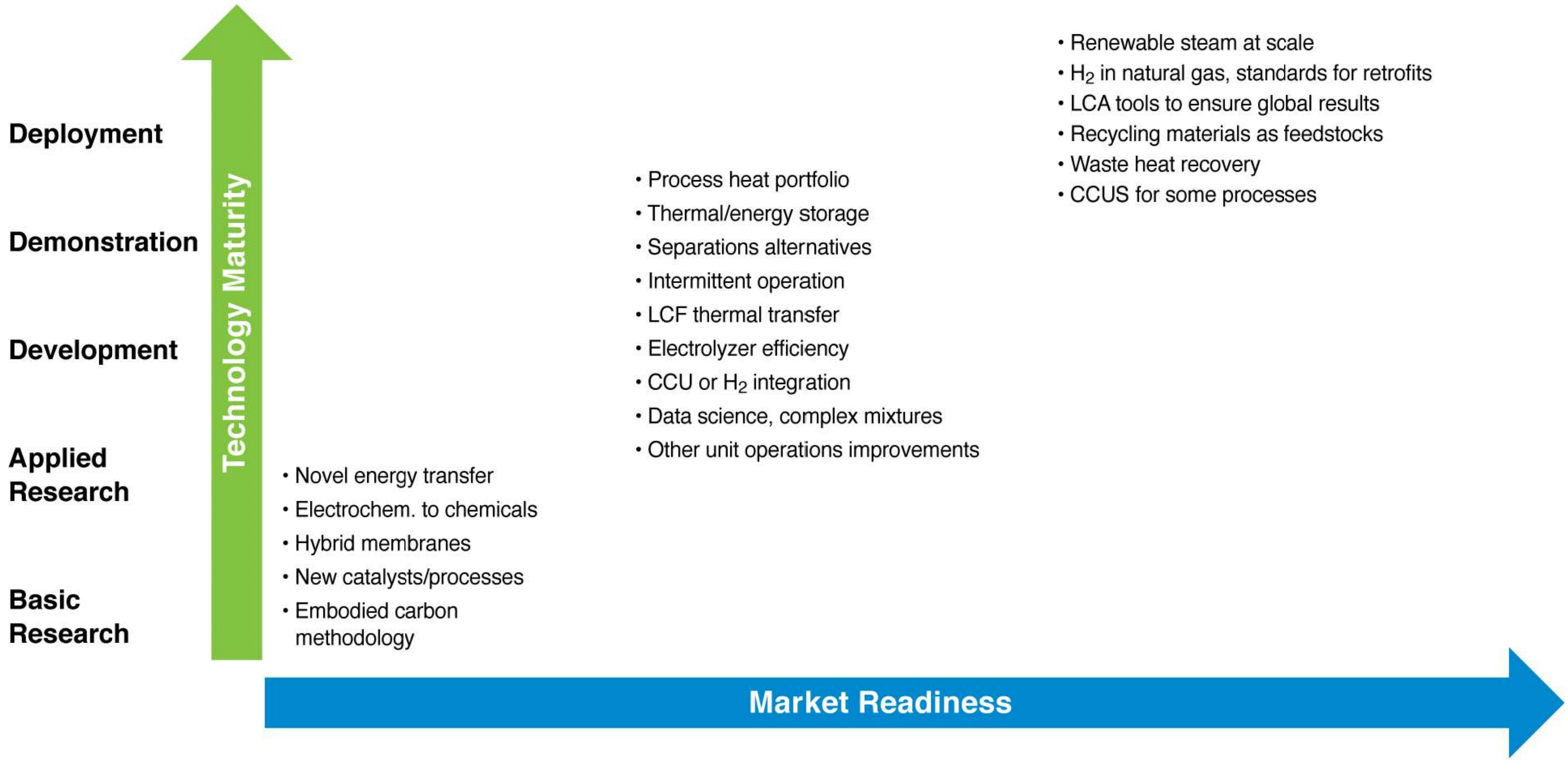

Figure 28. Technical maturity levels of select decarbonization technologies discussed during the roadmap virtual meetings for the U.S. chemical manufacturing industry.

Participants provided input on the relative market readiness and technical maturing of these technologies during discussions. There is a distribution of technologies in several of these categories which broaden the placement of items. For example, waste heat recovery represents several commercial technologies which are commercial and in earlier development stages. Further definition of terms is provided in the glossary. Source: This work.

> *Key message: Several technologies are at later stages of market and technical readiness and can be applied to lower energy use and GHG emissions in the U.S. chemical industry. There is a host of emerging technologies and approaches being developed with even greater promise for lowering energy use and GHG emissions in the future that need RD&D focus and industry engagement for implementation.*

The illustration in Figure 28 prompted further discussion of RD&D needs, including that:

- Scale-up of electrical heating to industrial scale needs to be de-risked (e.g., a commercial cracker). Electric crackers are currently used for laboratory and small pilot-scale studies, but a challenge for larger scale is decreasing the cost of both equipment and electricity on a delivered Btu basis.
- Numerous process heating options (e.g., nuclear heat and electricity, clean electricity, hydrogen, and renewable thermal) need further elucidation (e.g., a portfolio of solutions).
- RD&D is needed on membranes driven by electricity from low-carbon sources, as noted in a recent National Academies study.[194]
- LCA data and tools are needed to define the profile for intermediate and final products. Benchmarking studies are needed to enable more consistent assessment. Profiles for intermediate and final products are needed to form comparisons of new technologies. LCA and accounting methodologies and standardized, updated, trustworthy data sets are needed to apply those methodologies.

2.2.4.1 Cross Process Opportunities and RD&D Needs for the Chemical Industry

Four opportunities are presented here that extend across the breadth of chemical processes.

2.2.4.1.1 Process Heat

There are various temperature ranges to consider for process heat in the chemical industry, as shown in Figure 29. About 60% of the process heat demand is in the low-temperature range (the <80°C and 80–150°C categories), which is the best opportunity for several current technologies (e.g., electrification, solar heating, nuclear reactor heat and replacement of distributed steam generators).[195] An additional 15% of process heat is in the medium-temperature range (150–300°C), where emerging technologies such as high-temperature heat pumps are demonstrating capabilities.[196] Only 2% of the process heat is in the 300–550°C range, but an additional 24% is in the 550–1,100°C range.[197] The latter range could be accessible by advanced nuclear reactors including high temperature gas reactors (HTGR) and very high temperature reactors (VHTR) available in the near term, as well as molten salt reactors. Other technologies able to reach this range include electrolysis-hydrogen and electric heating.

[194] National Academies of Sciences, Engineering, and Medicine, *A Research Agenda for Transforming Separation Science*, The National Academies Press, Washington, DC, 2019, https://doi.org/10.17226/25421.
[195] Colin McMillan, "Manufacturing Thermal Energy Use in 2014," National Renewable Energy Laboratory, 10.7799/1570008, last updated December 18, 2020, https://data.nrel.gov/submissions/118.
[196] Ibid.
[197] Ibid.

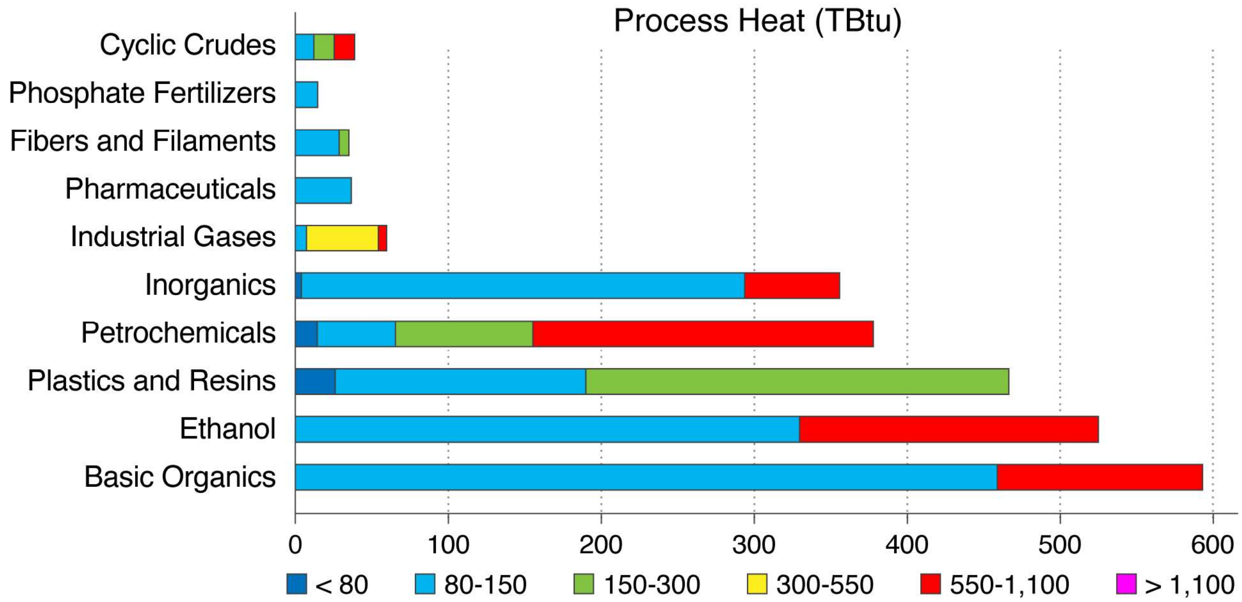

FIGURE 29. DISTRIBUTION OF PROCESS HEAT USE ACROSS TOP PRODUCT CATEGORIES IN THE U.S. CHEMICAL INDUSTRY BY TEMPERATURE RANGE (°C).[198]

Key message: Many chemical production categories use low- to medium-temperature process heat.

2.2.4.1.2 Separations and Other Unit Operations

Thermally driven separations account for some 40% of the energy consumption of 25 top chemicals, including ethylene, acetic acid, ethanol, methanol, and xylene.[199] In some cases, the introduction of alternative modes of energy transfer has shown promise for process enhancements. For example, electric fields applied to separations systems can control properties (e.g., transport and media structure), mitigate fouling, and help preconcentrate input flows.[200] The materials changes can extend porosity and the latter improvements could help with product cleanup, which is a route to waste reduction and energy savings. Retaining the performance of separations processes by minimizing degradation from unwanted chemical reactions is also vital. Research is needed on routes to minimize or control this degradation (e.g., reduced rates of change via operating conditions, additives, and chemical control to yield benign degradation products). A combination of electric and magnetic fields has been used in particle sorting and various triggers, including light, electric, and magnetic fields are being used to cycle separations materials.

Dewatering and electrically driven processes, such as ion separation or generating induced charges on compounds to aid separation, are low-carbon research targets. Opportunities to improve efficiency, provide the heat in ways that do not require fossil fuel combustion, use alternative separations methods (e.g., acoustic, electric field, replacement, and cryogenics), nonequilibrium technologies to drive reactions or avoid the need for separations (e.g., direct synthesis of polymers, very high selectivity

[198] Ibid.

[199] U.S. Department of Energy Advanced Manufacturing Office, *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Chemical Manufacturing*, June 2015, https://www.energy.gov/sites/default/files/2015/08/f26/chemical_bandwidth_report.pdf.

[200] National Academies of Sciences, Engineering, and Medicine, *A Research Agenda for Transforming Separation Science*, The National Academies Press, Washington, DC, 2019, https://doi.org/10.17226/25421.

processes) are also areas that could improve energy efficiency across the entire system. With some chemical products, drying and dewatering can be the largest energy consumer. Non-thermal drying processes should be investigated.

Several other unit operations are also large energy users in the chemical industry, including drying, calcining, curing, and forming for polymer production, and incineration. A systems-based approach to energy and materials efficiency examining where energy is used across multiple unit operations associated with a family of products and interactions across the chain of interconnected products and their utility needs could identify numerous opportunities for improvement.

2.2.4.1.3 Hydrogen in the Chemicals Industry

Hydrogen as a feedstock is an important option for decarbonizing industry. Clean hydrogen can serve as a precursor to chemicals production, providing a low-carbon route to methanol, ammonia, hydrazine, and other molecules that serve as feedstocks for other chemicals. Methanol is one of the most-produced commodity chemicals in the world, with a global demand in 2015 of 75 million MT.[201] Renewable methanol can be produced using the hydrogen from renewable or nuclear electricity (clean hydrogen) or from sustainable biomass. Methanol can be used in many ways, including as a feedstock, energy carrier, and transportation fuel.[202] Methanol can also be produced with CO_2, such as by the proprietary Methanex process, and used as an automotive fuel.[203]

In some chemical and metal production processes, syngas, a mixture of hydrogen and carbon monoxide, is a more efficient reactant than pure hydrogen. Decarbonized syngas could be produced by co-electrolysis of water and captured CO_2.

Ammonia is another candidate chemical for clean hydrogen use, given that it (1) is among the largest commodity chemicals (largely because of its use in fertilizers) and (2) accounts for the highest combined level of GHG emissions of any chemical produced.[204] Unlike other hydrogen carriers, it does not contain carbon. And it accounts for about 2% of worldwide fossil energy use and is responsible for 420 million MT CO_2 per year.[205] The manufacture of hydrogen, a key component of ammonia production, currently accounts for a significant portion of the energy spent and a large part of the GHG emissions in the making of ammonia. Hence, the use of hydrogen from electrolysis or other low-carbon methods is a route of interest for significantly lowering the carbon footprint of ammonia. Yara, a major ammonia producer, and Engie are pursuing this opportunity by piloting renewably produced hydrogen for

[201] "Smart, Sustainable, One-Stop Solution: Renewable Methanol to Mitigate Greenhouse Gases," Thyssenkrupp, last modified 2020, https://www.thyssenkrupp-industrial-solutions.com/power-to-x/en/green-methanol.
[202] Ibid.
[203] "About Methanol," Methanex, 2020, last modified 2020, https://www.methanex.com/about-methanol/how-methanol-made.
[204] International Energy Agency, International Council of Chemical Associations, and Dechema, *Technology Roadmap: Energy and GHG Reductions in the Chemical Industry via Catalytic Processes*, June 2013, https://www.iea.org/reports/technology-roadmap-energy-and-ghg-reductions-in-the-chemical-industry-via-catalytic-processes.
[205] Xinyu Liu, Amgad Elgowainy, and Michael Wang, "Life cycle energy use and greenhouse gas emissions of ammonia production from renewable resources and industrial by-products," *Green Chemistry* 22, (2021): 5751-5761. https://doi.org/10.1039/D0GC02301A.

ammonia synthesis at Yara's production facilities in Australia.[206] And in Norway, they are working with Nel to test a new electrolyzer technology.[207]

Production of ammonia using nuclear energy for heat, electricity, and hydrogen inputs has also been explored and appears to warrant further research.

Hydrogen combustion is another option to produce high-temperature heat for industrial applications. Combustion of hydrogen (in pure form or in blends with natural gas) can also significantly reduce GHG emissions. For example, a 30% blend of hydrogen by volume can reduce GHG emissions from combustion turbines by 10%.[208] A portion of the high-temperature heat used by some industries is a candidate for clean hydrogen as it can be burned in air producing a 2,100°C flame with special burners.[209] For example, in chemicals the portion of process heat provided above 550°C could be a candidate for the use of this hydrogen. That hydrogen could be made via electrolysis with electricity from low-carbon sources.

2.2.4.1.4 Biomass and Low-Carbon Emission Waste Streams as Fuels and Feedstocks for Clean Chemical Production

As noted in section 2.2.2, the prospect that a variety of biomass and waste streams could provide low-carbon emissions hydrocarbons for fuels and chemical feedstocks is an area of continued interest. Studies have noted that biological production methods can lower the GHG emissions of producing many chemicals by 39% to 86%[210] and a commercial partnership recently announced a joint venture to produced bio-based intermediates, with greater than 90%[211] lower GHG emissions.

The chemical industry has invested in multiple waves of RD&D and commercial projects using biomass over decades. For example, chemicals manufacturers have recently developed and commercialized processes to make bio-based polyethylene from sugarcane[212] and bio-based butadiene from the

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[206] "Yara and ENGIE to test green hydrogen technology in fertilizer production," Yara International ASA, February 13, 2019. https://www.yara.com/news-and-media/news/archive/2019/yara-and-engie-to-test-green-hydrogen-technology-in-fertilizer-production/.

[207] "Yara and Nel collaborate to produce carbon free hydrogen for fertilizer production," Yara International ASA, August 20, 2019, https://www.yara.com/news-and-media/news/archive/2019/yara-and-nel-carbon-free-hydrogen-for-fertilizer-production/.

[208] Jeffrey Goldmeer, "Gas Turbines: Hydrogen Capability and Experience - A presentation to the DOE Hydrogen and Fuel Cell Technologies Advisory Committee," March 9, 2020, https://www.hydrogen.energy.gov/pdfs/06-Goldmeer-Hydrogen%20Gas%20Turbines.pdf.

[209] David Sandalow et al., *ICEF Industrial Heat Decarbonization Roadmap*, Innovation for Cool Earth Forum, December 2019, https://www.icef-forum.org/pdf/2019/roadmap/ICEF_Roadmap_201912.pdf.

[210] Felix Adom et al., "Life-Cycle Fossil Energy Consumption and Greenhouse Gas Emissions of Bioderived Chemicals and Their Conventional Counterparts," *Environment, Science and Technology* 48, no. 24 (2014): 14624-14631. https://doi.org/10.1021/es503766e.

[211] "Cargill and HELM partner to build $300M commercial-scale, renewable BDO facility, first in the US, to meet growing customer demand," Cargill, June 8, 2021, https://www.cargill.com/2021/cargill-and-helm-partner-to-build-$300m-facility.

[212] Braskem, *I'm green™ polyethylene: innovation and differentiation for your product*, 2014, https://www.braskem.com.br/Portal/Principal/Arquivos/ModuloHTML/Documentos/846/AF_Catalogo_PE%20Verde_2014_ING_site.pdf.

fermentation of sugars.[213] These and many other RD&D and commercial ventures show the interest of chemical companies and their partners in tapping biobased routes to chemicals.[214]

A market assessment of chemicals from biomass examined several prospects with near-term potential and highlighted advantages of these green products, commercial involvement, and data and knowledge challenges.[215] The authors pointed out that although low natural gas prices present tough price challenges for biomass-based commodity chemicals like methanol, the increased dominance of light hydrocarbon production (e.g., natural gas-based ethylene production) diminishes production of C4 and C5 chemicals vs. heavier hydrocarbon production. Constrained production of chemicals in this category, including butadiene and isoprene, has led to price fluctuations and increased market potential for these products via bio-derived routes. One company has developed several commercial processes where waste gases are converted to ethanol using engineered bacteria.[216] A growth opportunity or foothold for bio-based products may be the production of chemicals and intermediates where there is limited production or reuse opportunities for wastes that are difficult to reuse by other means.

The use of biomass as a feedstock is not without barriers; a workshop held by the Chemical Sciences Roundtable explored challenges on scalability of sustainable fuels.[217] Among the challenges noted were associated with the supply chain (e.g., limited supply, challenges in harvesting and aggregating, transportation), the sparsely distributed nature of biomass products, seasonality, quality uniformity, etc. Potential solutions were also noted such as the concept of producing a uniform feedstock (e.g., converting biomass to uniform pellets that could be handled more readily at small depots, with aggregation at larger storage facilities). The "Billon Ton" study[218] summarized the status and prospects for biomass across multiple uses and noted that biomass already provided 3.9 quadrillion Btu of energy in 2015. The report illustrates that the U.S. has the resources to produce sufficient renewable biomass to meet the 2030 goal of producing one billion tons of biomass/year without impacting farm or forest products. And it noted that the woody portion of municipal solid waste can become a significant contributor to this resource.

The use of biomass as a decarbonization route has been included in the solution set for decarbonization of heavy industry, including a roadmap examining the chemical subsector where the authors envision global biomass use growing to 1.3 gigatons (25% of the energy mix).[219] It has been noted that methanol, a major chemical feedstock, is produced from biomass in Brazil (used primarily as a motor fuel and not a

[213] "INVISTA and Arzeda enter agreement to develop bio-derived raw materials," *BusinessWire*, February 6, 2013, https://www.businesswire.com/news/home/20130206006354/en/INVISTA-and-Arzeda-Enter-Agreement-to-Develop-Bio-Derived-Raw-Materials.
[214] Melody M. Bomgardner, "Biobased Chemicals and Fuels Face Growing Pains," *Chemical and Engineering News* 91, no. 26 (2013). https://cen.acs.org/articles/91/i26/Biobased-Chemicals-Fuels-Face-Growing.html.
[215] Mary J. Biddy, Christopher Scarlata, and Christopher Kinchin, *Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential*, National Renewable Energy Laboratory, NREL/TP-5100-65509, March 2016, https://www.nrel.gov/docs/fy16osti/65509.pdf.
[216] Arlene Karidis, "LanzaTech Makes Products from Carbon Dioxide," *Waste 360*, July 26, 2021, https://www.waste360.com/waste-energy/lanzatech-makes-products-carbon-dioxide.
[217] Sheena Siddiqui, Douglas Friedman, and Joe Alper, *Opportunities and Obstacles in Large-Scale Biomass Utilization: The Role of the Chemical Sciences and Engineering Communities: A Workshop Summary*, The National Academies Press, Washington, DC, 2012, https://www.ncbi.nlm.nih.gov/books/NBK115434/.
[218] U.S. Department of Energy Bioenergy Technologies Office, *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks*, July 2016, http://energy.gov/eere/bioenergy/2016-billion-ton-report.
[219] Deger Saygin and Dolf Gielen, "Zero-Emission Pathway for the Global Chemical and Petrochemical Sector," *Energies* 14, no. 13 (2021). https://www.mdpi.com/1996-1073/14/13/3772.

feedstock) and that European refiners are beginning to use renewable naphtha to make chemicals.[220] The use of biomass in chemicals was projected to account for 15-20% of the energy consumption in chemicals and other subsectors by 2030 in another study.[221]

Though not all chemicals are likely to have an economically viable path for replacement with biomass and waste feedstocks, RD&D advances in biomanufacturing have rapidly increased potentially viable routes. Biomass and waste product reuse and biomanufacturing processes can be an important contributor to decarbonization solutions. Section 2.5.3.2.2 provides additional discussion of biomass and alternative fuels and a starting illustration of RD&D needs.

2.2.4.2 Cross Process RD&D Needs and Opportunities for the Chemical Industry

- A portfolio of low-carbon solutions for process heat that connects with all the decarbonization pillars is needed. The portfolio needs to describe options, temperature ranges, efficiency, technical capabilities, and case study links.
- Research is needed to advance non-thermal separation approaches that withstand temporal changes (e.g., electrochemical potential, membrane longevity, materials, and the use of electricity to drive) instead of distillation. Dewatering also represents a research opportunity.
- RD&D is needed on clean or low-carbon hydrogen via electrolysis to lower costs and drive adoption at scale. There are also RD&D needs to address application needs, including avoiding materials embrittlement, unified standards for retrofits, applicability of furnaces with higher hydrogen content in blends, material safeguarding, and minimizing post-combustion moisture impacts. RD&D is also needed on low-carbon syngas production via co-electrolysis.
- RD&D is needed to help overcome scaling issues for electric technologies. It would be beneficial to have a better understanding of the match between modular design sizing and applications that are small enough to have a low investment hurdle for the first-of-a-kind technology, yet large enough to have a high return on investment.
- For CCUS, additional RD&D is needed to improve the effectiveness of capture and pulling multiple slip streams from a larger unit to enhance utilization, while addressing scale, process, and investment challenges. RD&D is also needed for process integration (e.g., process heat) to lower the cost of CCUS and tailoring of CCUS to medium-volume streams.
- Increased application of LCA methodologies is needed for the decarbonization pillars to ensure the best low-carbon paths are pursued and that the information is transparent and useful to consumers to aid market pull for low-carbon products.

The best options for RD&D between agencies, industry, technology developers, and others will continue to evolve, so it is important that there be regular input opportunities to increase the likelihood that industry adopts emerging and transformative technologies.

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[220] Samantha Gross, *The Challenge of Decarbonizing Heavy Industry*, Brookings Institution, June 2021, https://www.brookings.edu/wp-content/uploads/2021/06/FP_20210623_industrial_gross_v2.pdf.

[221] "Industrial Energy Efficiency Accelerator: Projects Selected for Phase 2," UK Department for Business, Energy and Industrial Strategy, last modified February 11, 2021, https://www.gov.uk/government/publications/industrial-energy-efficiency-accelerator-ieea/industrial-energy-efficiency-accelerator-projects-selected-for-phase-2

2.2.4.3 *Chemical Industry Subsector-Specific RD&D Needs and Opportunities*

Several RD&D needs noted during the meetings are specific to chemical manufacturing industry processes and products. The points presented in this section provide more information on discussions that were most relevant to RD&D needs. Energy efficiency was noted as a key approach, considering its multitude of benefits, value return potential, acceptance, ability to execute quickly, and lower cost of capital; the highest-priority energy efficiency needs are also listed here. Several topics here could also be coordination opportunities between the DOE Office of Science (SC), Office of Fossil Energy and Carbon Management (FECM), and Office of Energy Efficiency and Renewable Energy (EERE).

RD&D needs and opportunities related to **energy, materials, and process efficiency** include the following:

- There are opportunities to greatly improve efficiency, cost, and durability of alternative separations methods (e.g., acoustic technologies,[222] electric field cryogenics, non-thermal or hybrid processes), use nonequilibrium technologies to drive reactions, or reduce the need for separations (e.g., direct synthesis of polymers, high conversion technologies with high selectivity). Improved application of a systems-based approach to optimize separations and other unit operations across related processes and their use of resources is needed. A complex compromise of numerous factors (robustness, controllability, material cost, scalability, performance stability, process design) is often crucial for industrial adoption so an integrated systems-engineering approach can improve the performance and adaptability of innovative separations methodologies.[223]
- Needs include improved process efficiency and total system efficiency (e.g., improving thermal transfer efficiency, radiative transfer, process redesign).
- A systematic look at options for replacing legacy systems, with a portfolio of process heat options is needed.[224]
- More efficient means of identifying, sorting, and recycling materials—while maintaining materials' properties—are needed. There is a particular need to advance methods to separate contaminants in materials being recycled so that materials can be delivered with the quality and properties of virgin materials. Other areas of need include advances in industry standards, greater cooperation, transparency of key information to enable recycling, and LCAs leading to greater market acceptance.
- Scaling and integration RD&D are needed for the use of clean energy at the process level.

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[222] For example, leveraging acoustic microfluidic technologies that are being developed for biologic applications. See Yuan Gao et al., "Acoustic Microfluidic Separation Techniques and Bioapplications: A Review," *Micromachines* 11, no. 10 (2020): 921, https://pubmed.ncbi.nlm.nih.gov/33023173/.

[223] National Academies of Sciences, Engineering, and Medicine, *A Research Agenda for Transforming Separation Science*, The National Academies Press, Washington, DC, 2019, https://doi.org/10.17226/25421.

[224] Examples include the use of heat pumps, hybrid boilers, or other electric technologies in which the electricity comes from renewable energy. See Ed Rightor, Andrew Whitlock, and R. Neal Elliott, *Beneficial Electrification in Industry*, American Council for an Energy-Efficient Economy, July 2020, https://www.aceee.org/research-report/ie2002.

- Improved catalysts for chemical conversion remain an area of needed RD&D to reducing carbon footprints via improved yields.[225]

RD&D needs and opportunities related to **process electrification and transformative technologies** include the following:

- Advances are needed in the efficiency of electrolyzers to lower costs, improve reliability, and provide flexibility for replacing select chemical approaches with electrochemistry. Also, there is a need to scale up manufacturing to realize economies of scale and to accelerate learning that will lead to further performance, longevity, and economics advances.
- RD&D is needed in noncontact energy transfer methods (e.g., photonic, acoustic, plasma) to provide low-carbon ways to provide heat to reactions. More specificity is needed in energy delivery to effect the desired change (e.g., surface versus bulk heating of materials), decoupling bulk from localized heat.
- There are opportunities for increased use of variable power and learning on how to utilize variable energy sources. Storage and improved control technologies may enable solutions that ensure power quality for the industrial facility and present an opportunity to increase revenue through grid participation (not unlike CHP).
- There are needs for data science with complex mixtures and predictive exploration of reaction spaces with new and unknown conditions or materials and system performance. Inverse design (working backward from the final product desired to low-carbon feedstock with low-carbon, high energy efficiency, yield, sustainability, and other factors) is a related topic.
- Needs continue for improved chemical recycling, polymer to monomer or oligomer, and back-to polymers that can be incorporated into products.
- Opportunities in new processes or chemistries (e.g., sustainable chemistry or "green" chemistry[226]) were noted. Exemplary topic areas mentioned include sustainable design, including waste materials as substitutes for raw materials, and biosynthesis of fuels and chemicals from waste gas.

RD&D needs and opportunities related to **low-carbon energy and fuels** include the following:

- There are needs for modular and distributed processes for alternative sources of energy (e.g., renewable or nuclear electricity and hydrogen) and fuels (e.g., biofuels and synthetic natural gas) and allowing these approaches to meet the application demands in industry.
- The ability to switch from the current energy source or low-carbon fuel requires both integration research and support to scale and solutions.

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[225] U.S. Department of Energy Office of Science, *Basic Research Needs for Catalysis Science to Transform Energy Technologies, Report of Basic Energy Sciences Workshop*, May 2017, https://science.osti.gov/-/media/bes/pdf/reports/2017/BRN-Catalysis_factual_doc; International Energy Agency, International Council of Chemical Associations, and Dechema, *Technology Roadmap: Energy and GHG Reductions in the Chemical Industry via Catalytic Processes*, June 2013, https://www.iea.org/reports/technology-roadmap-energy-and-ghg-reductions-in-the-chemical-industry-via-catalytic-processes; Edward G. Rightor and Cathy L. Tway, "Global Energy and Emissions Reduction Potential of Chemical Process Improvements," *Catalysis Today* 258, no. 2 (December 2015): 226-229. https://doi.org/10.1016/j.cattod.2015.02.023.

[226] Green chemistry is the design of chemical products and processes that reduce or eliminate the generation of hazardous substances. See "Green Chemistry," U.S. Environmental Protection Agency, modified May 2, 2022, https://www.epa.gov/greenchemistry.

- There are RD&D opportunities for replacing (1) natural gas, fuel gas, or other higher-carbon sources with clean hydrogen or electricity or other alternatives such as solar or nuclear thermal for process heat and (2) thermochemical approaches with either electrochemical approaches, biofuels, or other low-carbon alternatives.
- Replacing traditional heat and power with small modular reactors is an RD&D opening. Nuclear power as a fuel source for decarbonizing a portion of the thermal and electrical needs of industry has been considered and the reader is referred elsewhere to find additional information.[227]
- There are opportunities for further integration of CHP with renewable energy and storage to backstop risk and variability and improve resilience.
- Additional opportunities exist for integrating waste-to-power or products (e.g., via gasification), in combination with CCUS, which could reduce fossil inputs and result in negative emissions.[228]
- For biomass, RD&D is needed to better quantify net GHG emissions reduction potential for bio-based pathways to chemicals, ensuring sustainability across multiple factors including land use change, recapture in biomass growth, and net GHG emissions reduction.
- RD&D is needed to better quantify net-GHG reduction potential for bio-based pathways to chemicals, ensuring sustainability across multiple factors including land use change.
- RD&D to enhance the rapid switching of hybrid approaches (e.g., dual boilers-gas/electric) should be explored.
- Biomass and wastes could be used as a feedstock for chemicals or process heat and power for chemical manufacturing; if combined with CCUS, it could provide emission offsets.[229]

RD&D needs and opportunities related to **CCUS** include the following:

- There are needs to further integrate CO_2 capture with process heat to improve prospects for CO_2 recycling where appropriate. Heat integration could also be used to aid the regeneration of alkanolamines, which is a currently dominant route to capture CO_2.
- Further systems analysis is needed to identify optimal approaches for (1) the use or capture of CO_2 and (2) integrations between heat, power, and chemical production including the use of landfill waste, plastics waste, and biomass as feedstocks. A range of studies[230] have been performed on CCUS applicability providing a foundation for more specific studies.

[227] Massachusetts Institute of Technology, *The Future of Nuclear Energy in a Carbon Constrained World*, 2018, https://energy.mit.edu/wp-content/uploads/2018/09/The-Future-of-Nuclear-Energy-in-a-Carbon-Constrained-World.pdf; Richard D. Boardman et al., "Process Heat for Chemical Industries," *Encyclopedia of Nuclear Energy* 3, (2021): 49-60. https://doi.org/10.1016/B978-0-12-819725-7.00198-7.
[228] Paulina Wienchol, Andrzej Szlęk, and Mario Ditaranto, "Waste-to-Energy Technology Integrated with Carbon Capture: Challenges and Opportunities," *Energy* 198, (2020): 117352. https://doi.org/10.1016/j.energy.2020.117352.
[229] Paolo Gabrielli, Matteo Gazzani, and Marco Mazzotti, "The Role of Carbon Capture and Utilization, Carbon Capture and Storage, and Biomass to Enable a Net-Zero-CO_2 Emissions Chemical Industry," *Industrial and Engineering Chemistry Research* 59 no. 15 (2020): 7033-7045. https://doi.org/10.1021/acs.iecr.9b06579; Ethan A. Rogers et al., *Intelligent Efficiency: Opportunities, Barriers, and Solutions*, American Council for an Energy-Efficient Economy, Report No. E13J, October 2013, https://www.aceee.org/sites/default/files/publications/researchreports/e13j.pdf.
[230] National Petroleum Council, *Meeting the Dual Challenge: A Roadmap to At-Scale Deployment of Carbon Capture, Use, and Storage*, *Volume I and II,* 2019, https://dualchallenge.npc.org/downloads.php.

- Integration across a chemical facility or industrial cluster requires an evaluation of lower energy and cost routes.
- There are also needs for the bioconversion of CO_2 to high-value products (e.g., biopolymers and food protein) where it provides economic and environmental benefits.

RD&D needs and opportunities related to **new chemistries** include the following:

- Waste materials as substitutes for raw materials that use carbon is an RD&D area. Circulating molecules (e.g., polymer to monomer, oligomer[231] back to polymer[232]).
- There are needs regarding the biosynthesis of fuels from waste gas and the conversion of CO_2 to high-value products (e.g., biopolymers, food protein).
- RD&D can help to grow and expand the use of bio-based feedstocks that will need to overcome the potential application challenges (e.g., complications that are due to impurities and other structural properties).

2.2.4.4 Timeline and Sequencing of RD&D Investments for the Chemical Industry

Stakeholders recognized that RD&D investments are needed for technologies with near-term impact, emerging technologies with mid-term impacts, and transformative technologies with longer-term impacts as illustrated in Figure 30. Key points made during the discussion included that:

- It would be useful to separate alternative fuels from the delivery of heat opportunities.
- Nuclear energy, natural gas substitution, and renewable steam should be added to the thermal portfolio.
- Application ranges need further definition for both hydrogen and electrification for process heating.
- Further elucidation of other thermal energy solutions is needed.

Figure 30 shows a selection of the near-, mid-, and longer-time frame opportunities grouped into bands for the decarbonization pillars and organized by the decade where a concerted effort is needed to further develop these solutions with focused RD&D efforts, trials, and a drive for deployment across the decades. Though the illustration is not exhaustive and different placement of these solutions could be suggested, the point is that RD&D, scaling, and investment need to be pursued in parallel across near-, mid-, and longer-range time frames. A strong focus on near-term solutions application is vital to realize early impacts, expand learning, and improve economics, mid-term investments are needed to develop the next-stage solutions, and at the same time resources need to be invested to develop the transformative technologies that will be crucial for larger GHG emissions reductions.

[231] Oligomers are polymers with fewer repeat units. They can be building blocks for longer, more-complex polymers.
[232] For oligomer-back-to-polymer impurities, both managing variation in the feed and meeting the performance characteristics of virgin materials have been challenging.

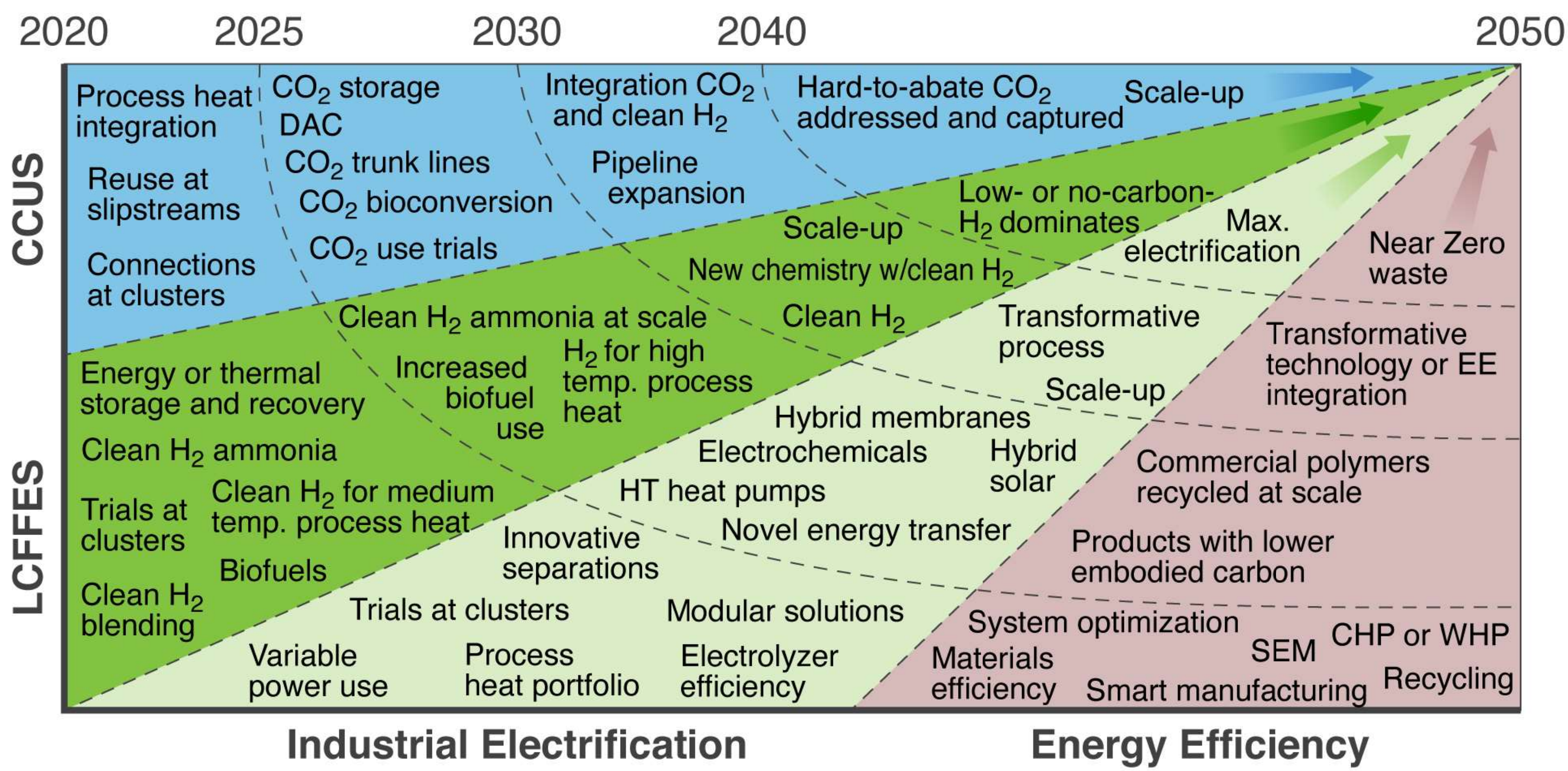

Figure 30. Landscape of RD&D advancement opportunities by decade and decarbonization pillar for the U.S. chemical manufacturing subsector noted by attendees at the Roadmap virtual sessions.

Early opportunities such as the portfolio of process heat solutions (heat pumps, boilers, microwave, infrared, solar thermal) and advances to improve electrolyzer efficiency (to produce hydrogen with low-carbon energy) are top areas for RD&D as they are enablers for later transformative technologies in electrification and have crosscutting impacts for other pillars and across industrial subsectors. LCFFES includes clean technologies that do not release GHGs into the atmosphere from the production or use of energy sources, and include renewable-sourced electricity, nuclear energy for electricity and heat, concentrating solar power, and geothermal energy. Further definitions are available in the glossary. HT – high-temperature. Source: This work.

Key message: RD&D investments are needed across a host of opportunities in the U.S. chemical manufacturing subsector to lower technical hurdles, improve economic viability, accelerate adoption, and pave the way for even more transformative low-carbon technologies. Across the time horizon to 2050 are RD&D needs associated with pillars and crosscutting opportunities.

2.2.5 Proposed RD&D Action Plan for the Chemical Industry

Given the complexity, heterogeneity, high degree of invested capital needed, integration required, and complicated supply chain interdependencies, the transformation to a low-carbon future for the chemical manufacturing industry will need to be pursued via several parallel paths, including the decarbonization pillars described in this work.

RD&D could play a crucial role over the next 30 years by lowering adoption hurdles, reducing implementation costs, and revealing synergies that provide benefits to society. Many factors can affect the adoption of a technology by industry, such as energy security, public health, environmental impacts, principal agent issues, asymmetric information (especially for small industry), finance and tax structure issues, regulatory issues, capital allocation issues, policy uncertainty, and market structure issues. Factors that fall into the policy space are out of scope for this report. DOE has considered technology adoption in the manufacturing space. The Advanced Manufacturing Office (AMO) Multi-Year Program Plan[233] discusses the range of barriers to technology adoption and the activities and strategies being deployed to overcome those barriers. A 2019 paper[234] evaluated in a semi-quantitative manner how the relative impacts (internal rate of return, payback period initial expenditure, and non-energy benefits), technical context (distance to core processes, type of modification, the scope of impact, and lifetime), and information context (transaction costs, necessary knowledge, and sectoral applicability) can affect the adoption of a technology by industry. The transformation would not be fast, but there are near-term opportunities that if pursued fervently could provide a fast start on GHG emissions reductions. There is strong interest in pursuing reductions now, but with very inexpensive fuels and feedstocks supporting current technologies and processes, the support for the transformation and the associated RD&D would need to be focused, durable, visionary, collaborative, and applied to drive low-carbon solutions to commercial scale. There are a multitude of RD&D needs and to make step-change GHG emissions reductions, the sorting of RD&D investments that follows could be considered. The needs below should be explored and pursued across a broad collaboration, including but not limited to industry, national laboratories, academia, and industry associations.

RD&D needs with **near-term (2020–2025)** impacts include:

- Enhance the impact of low-capital solutions, such as the following by pushing RD&D of applications:
    - Energy, materials, system efficiency
    - Innovations in separations and drying technologies
    - Thermal transfer efficiency
    - Plug-in exchange of high-carbon energy sources for lower ones
    - Smart manufacturing

[233] U.S. Department of Energy Advanced Manufacturing Office, *Multi-Year Program Plan For Fiscal Years 2017 Through 2021*, December 2016, https://www.energy.gov/eere/amo/downloads/advanced-manufacturing-office-amo-multi-year-program-plan-fiscal-years-2017.

[234] Rebecca Hanes et al., "Quantifying adoption rates and energy savings over time for advanced energy-efficient manufacturing technologies," *Journal of Cleaner Production* 232, (2019): 925-939. https://doi.org/10.1016/j.jclepro.2019.04.366.

  - Electrification where there are low hurdles (e.g., low-temperature process or waste heat)

- Pursue process heat opportunities starting with low-temperature openings and advancing to mid-temperature while aiming for high-temperature use where appropriate.
- Research how industry, with partners, might more effectively use variable energy and energy storage and develop and deploy routes to readily implement switching and blending intermediate solutions.
- Advance more effective electrolyzers for hydrogen, chemical processes, novel energy transfer, innovation separations (including those using electricity).
- Pursue trials at advantaged locations (e.g., industrial clusters) to lower adoption hurdles.
- Research on process integration to lower CCUS implementation costs.
- Further the storage, cataloging, and accessibility of data on the effectiveness of low-carbon solutions, LCA, systems efficiency, and other analytics to support evaluation of how effective technologies are in reducing energy usage, GHG emissions, and the presence of carbon in products.
- Pursue biomanufacturing of carbon-based chemicals to create products with significantly less need for process heat due to biological catalysts and fewer reactor vessels due to the ability to carry out multiple chemical transformations in a single tank.
- Incorporate biomass and waste feedstocks into carbon-based chemicals, lowering petroleum inputs and leading to potentially net-negative chemicals.

RD&D needs with **mid-term (2025–2030)** impacts include:

- Invest in RD&D now to provide impact in processes that will use hydrogen from low-carbon energy sources (e.g., electrolysis), including ammonia, methanol, and plastics.
- Invest in RD&D for use of electrification and low-carbon energy sources for processes and feedstock changes and for CO_2 utilization.
- Initiate RD&D supporting transformative process technologies (e.g., hybrid membranes).
- Develop capabilities for use of hydrogen for combustion use in high-temperature process heat.
- Research improved routes to rapidly scale-up transformative technologies (see Section 3.1).
- Provide RD&D support for a persistent push to improve the energy efficiency of processes, elimination of waste, and lowering of product-embodied carbon.
- Expand the variety of chemicals able to be produced cost effectively using biomanufacturing by pursuing new pathways and reactor designs as well as incorporation of additional feedstocks.

RD&D needs with **longer-term (2030–2050)** impacts include:

- Invest now in RD&D to discover fundamental science that will enable transformative chemical processes (new low-carbon ways of making products).

- Research interface strategies for transformative technologies so that connections to the infrastructure of the future is seamless.
- Anticipate tradeoffs in market availability for precursors, feedstocks, and materials.
- Deepen the understanding of what is critical to rapidly scale technologies and improve the efficacy of retrofits where other options are not viable (see Section 3.1).
- Research into performance advantaged bioproducts which can have improved performance attributes over petroleum-derived molecules leading to less overall material use and substantial GHG emissions reductions.
- Pursue more efficient and intensified process designs for biomanufacturing, including cell-free bioproduct production and enabling continuous biological chemical production processes.

2.3 Food and Beverage Manufacturing

The crosscutting decarbonization pillars identified in this work are energy efficiency, industrial electrification, LCFFES, and CCUS, where electrification and LCFFES are highly connected and evaluated together for this roadmap. Many food and beverage manufacturing subsectors are energy- and carbon-intensive, and mitigating the subsector's emissions presents a significant opportunity to further decarbonization in the industrial sector. The subsector faces many barriers and challenges, some of which are unique to food and beverage manufacturing and others that are common across industry. Unique obstacles include the fact that the subsector is particularly heterogeneous even within industry, manufacturing a highly diverse range of products using several different processes. Additionally, there is the need to maintain strict levels of product safety and quality compared to other industries. There are pressures on the subsector that come largely from increasing food and beverage demand, especially for products that are energy intensive in production, storage, or transport. Challenges common across industries include high capital costs, perceived risks, and the need to integrate new technologies into highly optimized processes. The stakeholder meetings helped connect members of the food and beverage manufacturing community with the government and nongovernmental organizations. The meetings also provided important insight into the nuances of the challenges facing the industry and its RD&D needs. Key learnings, needs, and RD&D opportunities from the meetings and the literature review include the following:

Food and Beverage Manufacturing Subsector: Key Takeaways

- RD&D is needed in process heating electrification, especially that of ovens and fryers. Electric and hybrid boilers and electrification of evaporation and pasteurization processes are other important opportunities to enable decarbonization.
- Issues with safety and quality concerns in food and beverage manufacturing need to be mitigated by supporting aggressive studies into technology change impacts on final products. The workforce must be adequately prepared to ensure products meet standards of safety and quality post-transition.
- To reduce significant subsector waste, RD&D is needed in food and beverage processing practices and technologies to extend the shelf life of products and reduce degradation. Research should also focus on reducing the volume of packaging waste, recycling opportunities, and supply chain visibility.

- Pursue crosscutting RD&D opportunities including building information infrastructure, deploying smart manufacturing technologies, and improving CCUS and CHP, energy intelligence, and scale-up assistance; these strategies are also relevant to the other subsectors in the roadmap effort.
- Focus on energy efficiency, electrification and CCUS: these categories capture many of the most promising decarbonization strategies in the food and beverage manufacturing, including efficient oven burners, electric and hybrid boilers, and reuse of waste CO_2 in packaging, among others.
- RD&D into lowering the barriers of incorporating transformative and more efficient technologies into manufacturing processes, and in expanding existing strategies and opportunities to reach more plants and achieve more energy savings and GHG emissions reductions.
- RD&D into processing practices and technologies to extend the shelf life of food products and reduce degradation.

- Develop a portfolio of options to respond to subsector diversity and laboratory-scale testing, demonstration, and commercialization of potentially transformative technologies.
- Adopt other means of reducing the waste of energy, ingredients, and other resources in food and beverage manufacturing: these strategies are essential to increasing energy productivity and mitigating subsector emissions. Each of these waste streams will require separate and distinct RD&D approaches.
- Strategies that use existing funding and infrastructure to both foster innovation and help manufacturers adopt best practices for emissions reductions will be crucial for near- and mid-term progress. Existing tools and infrastructure include things like DOE's Industrial Assessment Centers (IACs), Critical Materials Institute (CMI) RD&D grants, Industrial Materials for the Future, ARPA-E funding, and others.
- Address vendor continuity to support the implementation and integration of transformative technologies and achieve meaningful emissions reductions.
- Integrate of strategies in food and beverage manufacturing all along the supply chain from agriculture production through to distribution.
- Address subsector-specific and crosscutting opportunities together while addressing challenges brought up in the food and beverage manufacturing sessions of the stakeholder meetings will further efforts in the food and beverage industry toward their 2050 decarbonization goals.

2.3.1 Status of the U.S. Food and Beverage Manufacturing Industry

2.3.1.1 U.S. Food and Beverage Production

The food and beverage manufacturing industry is a critical component of the U.S. economy. In 2019, the subsector was responsible for adding $412 billion to the economy and employing more than 1.7 million workers.[235] Those workers comprised about 14.7% of all U.S. manufacturing employees and represented over 1% of all U.S. nonfarm employment.[236] In 2019, there were over 38 thousand food and beverage manufacturing plants in the U.S.[237] The states with the most food and beverage manufacturing plants in 2019 were California (6,041), followed by New York (2,611) and Texas (2,485).[238] Figure 31 presents the value added by food and beverage manufacturing subsectors. Meat processing, beverage manufacturing, and dairy production were the largest components of the industry group's total value added.

[235] "Annual Survey of Manufacturers (ASM)," U.S. Census Bureau, last modified April 21, 2022, https://www.census.gov/programs-surveys/asm.html.
[236] "Manufacturing: Food and Beverage Manufacturing," U.S. Department of Agriculture Economic Research Service, last modified December 22, 2021, https://www.ers.usda.gov/topics/food-markets-prices/processing-marketing/manufacturing/.
[237] Ibid.
[238] Ibid.

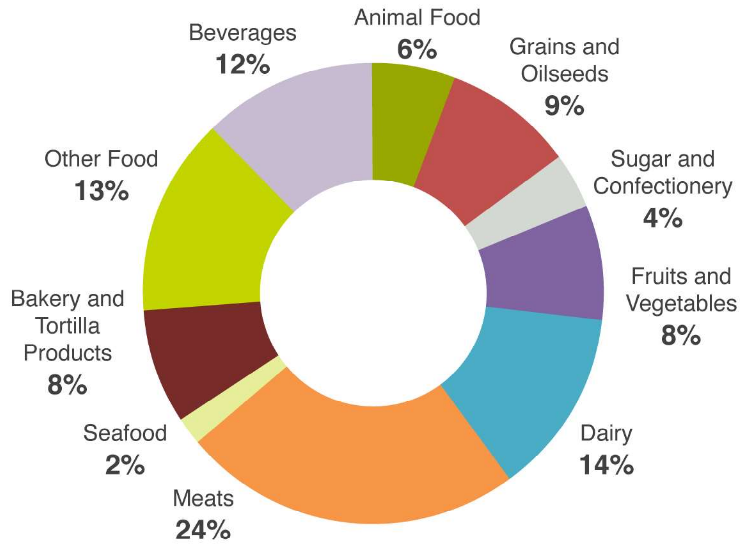

Figure 31. Food and beverage manufacturing subsectors' value added to industry in 2019.

This figure demonstrates the wide heterogeneity in the products of the food and beverage manufacturing subsector. Value added to industry is separated between ten large categories, each of which has its own opportunities and barriers for decarbonization. Data source: U.S. Department of Agriculture and U.S. Census 2019 Survey of Manufacturers.[239]

"Other food" refers to NAICS 3119, which includes snack food manufacturing, coffee and tea manufacturing, and spice manufacturing, among others.

> *Key message: Carbon impacts from the food and beverage manufacturing subsector are distributed across a wide range of heterogeneous and diverse products.*

2.3.1.2 Energy Use and CO_2 Emissions for Food and Beverage Manufacturing

Food manufacturing is one of the largest energy-consuming and GHG-emitting industries in the United States. The subsector is responsible for 6% of total industrial CO_2 emissions, with an estimated 78 million MT CO_2 emissions in 2020 (see Figure 3).[240] The food manufacturing subsector is critical in furthering industrial decarbonization efforts because of its role in the economy, projected rapid growth, and heterogeneity even within industry. Additionally, in contrast to other carbon-intensive manufacturing subsectors which are often concentrated in a few geographic locations, the food manufacturing subsector is widely dispersed throughout the country, meaning that emissions reductions benefit a larger number of communities. Natural gas accounted for the majority of the 1,185 TBtu energy consumption in the food manufacturing industry in 2020, followed by grid electricity and renewables (Figure 32).[241] Reducing the carbon-intensity of food and beverage manufacturing is important

[239] "Annual Survey of Manufacturers (ASM)," U.S. Census Bureau, last modified April 21, 2022, https://www.census.gov/programs-surveys/asm.html; "Manufacturing: Food and Beverage Manufacturing," U.S. Department of Agriculture Economic Research Service, last modified December 22, 2021, https://www.ers.usda.gov/topics/food-markets-prices/processing-marketing/manufacturing/.

[240] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 19. Energy-Related Carbon Dioxide Emissions by End Use.

[241] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 25. Food Industry Energy Consumption.

in mitigating emissions from the industrial sector as a whole, especially as industrial volume and resulting GHG emissions are projected to increase in most scenarios. Even though decarbonization of food and beverage manufacturing is challenging and unique because of diversity in the subsector, there is significant GHG emissions reduction potential.

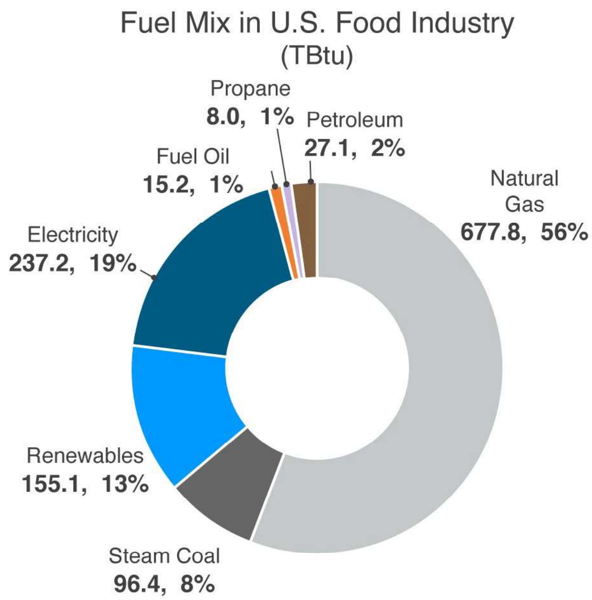

FIGURE 32. FUEL MIX (RIGHT) IN U.S. FOOD AND BEVERAGE MANUFACTURING INDUSTRY IN 2018

DATA SOURCE: U.S. DEPARTMENT OF AGRICULTURE AND U.S. CENSUS 2019 SURVEY OF MANUFACTURERS[242]

> *Key message: Consideration of renewable natural gas is an important industrial decarbonization step for the food and beverage manufacturing subsector since natural gas accounts for over half of the fuel mix.*

2.3.2 Decarbonization Pathways for Food and Beverage Manufacturing

DOE's estimation of the application of decarbonization pillars (energy efficiency, electrification and LCFFES, and CCUS) in U.S. food and beverage manufacturing focuses on seven major subsectors of the food and beverage manufacturing industry group. These energy-intensive subsectors account for around a third of total energy use overall in food and beverage manufacturing. They include wet corn milling, soybean oil, cane sugar, beet sugar, fluid milk, red meat product processing, and beer production. Figure 33 shows the estimated CO_2 emissions of U.S. food and beverage manufacturing from those subsectors under the four scenarios.

[242] "Annual Survey of Manufacturers (ASM)," U.S. Census Bureau, last modified April 21, 2022, https://www.census.gov/programs-surveys/asm.html; "Manufacturing: Food and Beverage Manufacturing," U.S. Department of Agriculture Economic Research Service, last modified December 22, 2021, https://www.ers.usda.gov/topics/food-markets-prices/processing-marketing/manufacturing/.

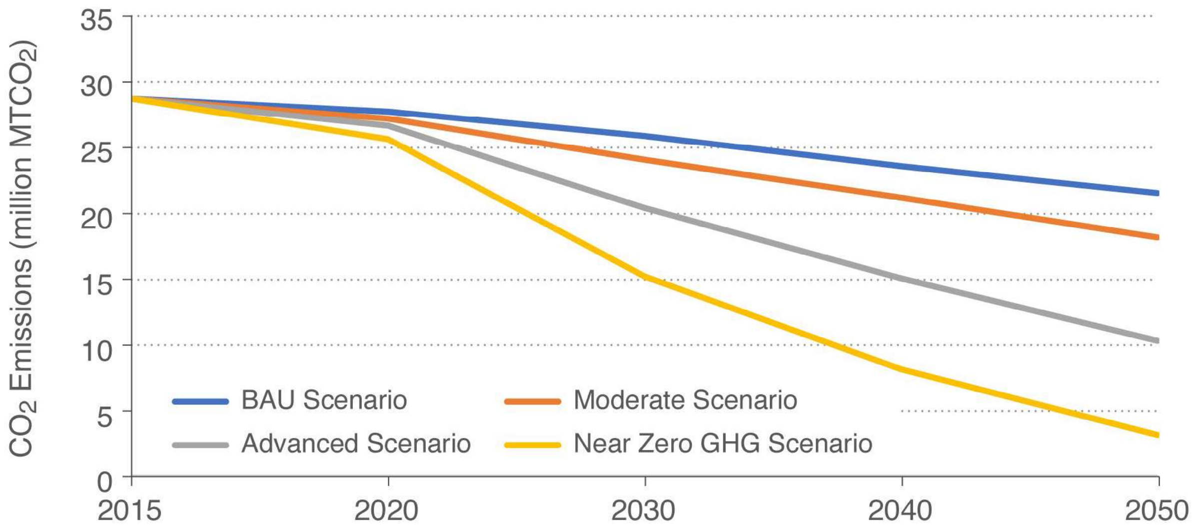

FIGURE 33. CO_2 EMISSIONS FORECAST FOR SELECTED SUBSECTORS OF THE U.S. FOOD AND BEVERAGE MANUFACTURING BY SCENARIO, 2015–2050.

THE INDUSTRIES COVERED ARE WET CORN MILLING, SOYBEAN OIL, CANE SUGAR, BEET SUGAR, FLUID MILK, RED MEAT PRODUCT PROCESSING, AND BEER PRODUCTION. SOURCE: THIS WORK.

In the BAU scenario, the CO_2 emissions of the seven selected subsectors decrease 25% between 2015 and 2050 due to both decarbonization of electricity and naturally occurring efficiency improvements. In the Advanced scenario, the annual CO_2 emissions of food and beverage manufacturing decreased by 65% from 29 million MT CO_2 in 2015 to 10 million MT CO_2 in 2050. During the same period, production in the covered industries increases by 25% to meet the needs of a growing population. In the Near Zero GHG scenario, more ambitious assumptions were made, especially for energy efficiency improvement and electrification of heat.

The Moderate and Advanced scenarios are achievable with commercially available technologies and measures. To achieve the Near Zero GHG scenario, more aggressive deployment of current commercialized technologies is needed, complemented by public and private sector RD&D. These actions are discussed in detail in the following section on RD&D needs and opportunities (Section 2.3.3).

Different factors contribute to the realization of significant CO_2 emissions reductions in each scenario. Figure 34 presents the contribution of each of the decarbonization pillars to the reduction in the food and beverage manufacturing's CO_2 emissions. Efficiency and electrification make the largest contribution to CO_2 emissions reduction. CCUS has limited potential in food and beverage manufacturing because of the high number of small-scale, dispersed production plants and lower concentration of point-source CO_2 emissions. The RD&D challenges and opportunities for each of the decarbonization pillars and technical requirements for their adoption in the U.S. food and beverage manufacturing are discussed in detail in the next section.

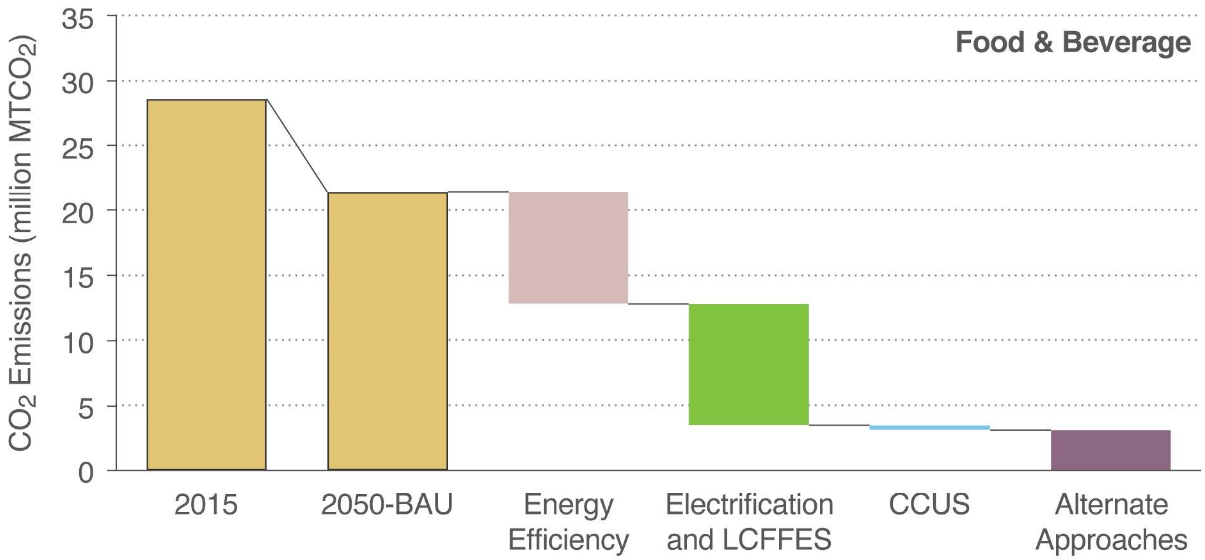

FIGURE 34. IMPACT OF THE DECARBONIZATION PILLARS ON CO_2 EMISSIONS (MILLION MT/YEAR) FOR SELECTED SUBSECTORS OF U.S. FOOD AND BEVERAGE MANUFACTURING, 2015–2050.

THE SUBSECTORS COVERED ARE WET CORN MILLING, SOYBEAN OIL, CANE SUGAR, BEET SUGAR, FLUID MILK, RED MEAT PRODUCT PROCESSING AND BEER PRODUCTION. SUBSECTOR EMISSIONS ARE ESTIMATED FOR BUSINESS AS USUAL (BAU) AND NEAR ZERO GHG SCENARIOS. SINCE INDUSTRIAL ELECTRIFICATION AND LCFFES TECHNOLOGIES AND STRATEGIES ARE STRONGLY INTERCONNECTED, THESE PILLARS WERE GROUPED FOR SCENARIO MODELING. THE "ALTERNATE APPROACHES" BAND SHOWS FURTHER EMISSIONS REDUCTIONS NECESSARY TO REACH NET-ZERO EMISSIONS FOR THE SUBSECTOR. THESE ALTERNATE APPROACHES, INCLUDING NEGATIVE EMISSIONS TECHNOLOGIES, ARE NOT SPECIFICALLY EVALUATED IN SCENARIO MODELING FOR THIS ROADMAP. THE POWERING OF ALTERNATE APPROACHES WILL ALSO NEED CLEAN ENERGY SOURCES (E.G., DIRECT AIR CAPTURE COULD BE POWERED BY NUCLEAR, RENEWABLE SOURCES, SOLAR, WASTE HEAT FROM INDUSTRIAL OPERATIONS, ETC.). DETAILS ON ASSUMPTIONS, PARAMETERS, AND TIMING OF TRANSFORMATIVE TECHNOLOGY APPLICATION CAN BE FOUND IN APPENDIX 1.3. SOURCE: THIS WORK.

2.3.3 RD&D Needs and Opportunities for Food and Beverage Manufacturing

This section explores the RD&D needs and opportunities of pillars for decarbonization in the food and beverage manufacturing industry (energy efficiency, industrial electrification and LCFFES, and CCUS). Pursuing opportunities in these three areas is the key to advancing the GHG emissions reduction scenarios of the previous section. Decarbonization of food and beverage manufacturing poses unique challenges that are due to the diversity and dispersion of processes in the subsector, which include energy-intensive processes such as wet corn milling; refrigeration in meat packing; washing, preservation and refrigeration in produce; and cooking and baking of prepared foods. Manufacturing sites vary from small family-run operations that are highly labor-intensive to larger capital-intensive and mechanized industrial processes. This diversity is reflected in differing energy and heat demands, as well as in variability in pathways to decarbonization. Despite this diversity, the three categories of mitigation strategies capture many of the crosscutting, cost-effective opportunities to decarbonize the industry. The technologies covered in this section represent a wide range of options in various levels of maturity and required RD&D investment. Figure 35 illustrates food and beverage manufacturing decarbonization technologies and opportunities along these axes.

Food and Beverage Manufacturing: Priority Approaches

Technology breakthroughs needed for the food and beverage manufacturing industry include step-changes in non-thermal drying and dewatering, innovative separations, efficient electrification of ovens, fryers, improved produce yields in indoor and outdoor agriculture, and waste reduction (including both food and packaging waste). Priority approaches include:

- Shift to electric ovens, fryers, boilers, and other electrified technologies where possible, especially as electric prices drop and the electric grid shifts towards generation from clean fuel sources.
- Reduce food waste throughout the supply chain through methods identified in LCAs and collaboration between manufacturers.
- Increase RD&D into heat pumps to recover and supply process heat in food and beverage manufacturing processes.
- Pursue recycling and material efficiency through methods like alternative packaging and packaging waste reduction.
- Invest in RD&D into transformative technologies such as cryogenic separation, advanced coatings to prevent ice buildup, advanced enzymes, and low ethanol producing yeast.

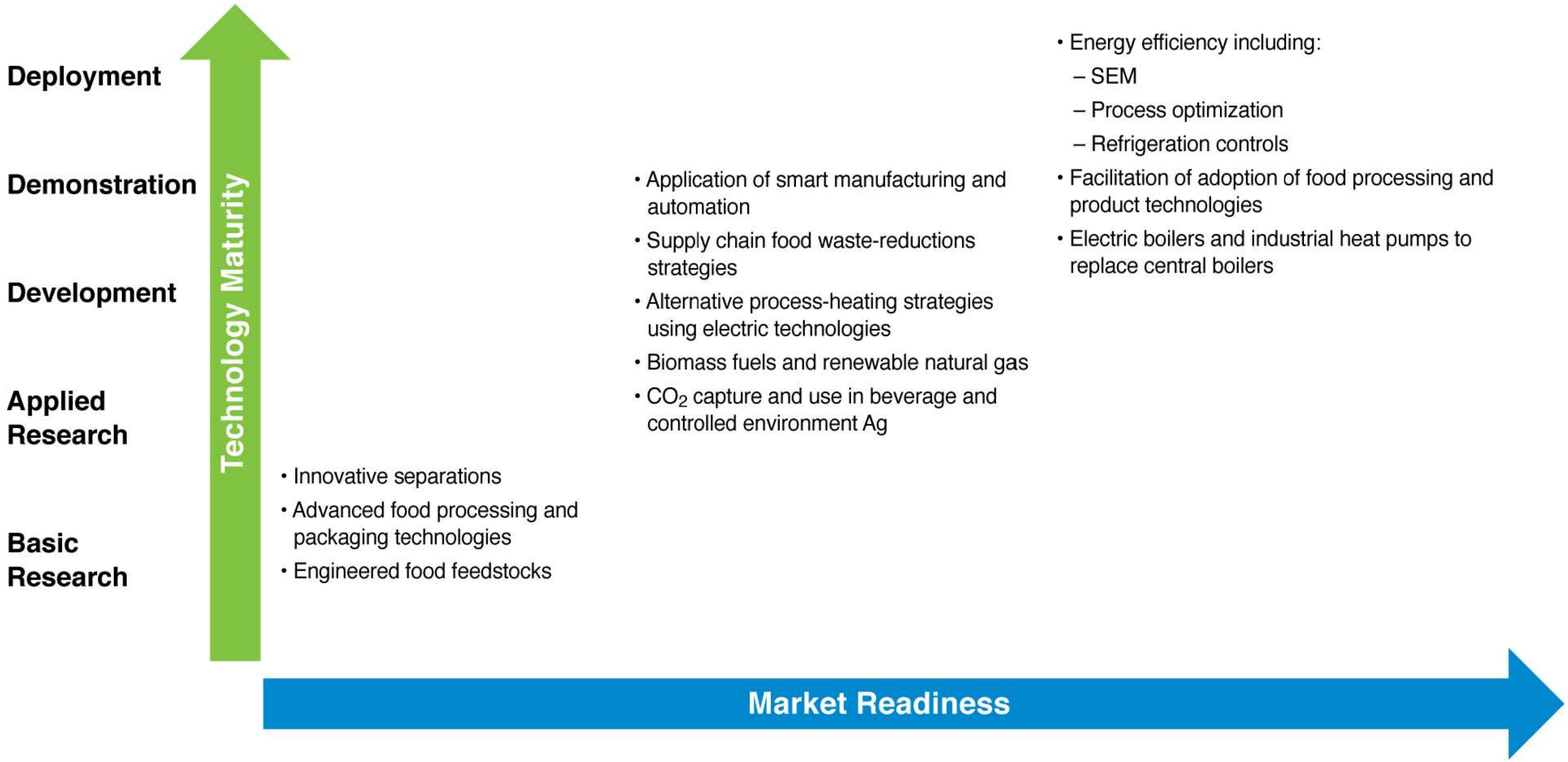

Figure 35. Technical maturity levels of the decarbonization technologies for the food and beverage manufacturing industry.

The curves depict necessary investment levels. Near-term solutions will require immediate investment, while long-term, more impactful strategies will need not only more and ongoing financial support, but also the prior learning and time afforded by early options. The strategic focal points are the development of meaningful transformative technologies in several pathways. Source: this work

2.3.3.1 Energy Efficiency for Food and Beverage Manufacturing

Many energy efficiency technologies and approaches are already being implemented on a commercial scale in food and beverage manufacturing, but significant opportunities remain to expand their adoption. Also, many emerging technologies to improve efficiency could contribute significantly to savings and are nearing readiness. Such emerging technologies include waste heat recovery (WHR), efficient oven burners, improvements to steam generation, and smart manufacturing principles and technologies. Smart manufacturing offers opportunities in this space in process optimization through the integration of thermal systems and in refrigeration and supply chain optimization. The supply chain can be optimized with the intent of both minimizing spoilage and waste and providing continuity for product safety as in traceability of products from farm to retail. However, there are still challenges with the deployment and proliferation of these technologies that RD&D could help address.

Some of the top challenges in the food and beverage manufacturing's efforts to decarbonization through energy efficiency are common among all industrial subsectors. Such barriers include long investment periods on incumbent technologies and processes, as well as incumbent workforces familiar with those existing technologies and processes. Transitions are capital- and time-intensive and often result in long returns on investments. In addition, the continued use, maintenance, and integration of more efficient technologies require vendor continuity and engagement that have not always existed in the market. In some cases, innovative technology has been deployed in a manufacturing facility only to become stranded when the vendor no longer supports the technology, resulting in a return to the legacy technology at a significant cost to the company with little, if any, benefit. Another significant issue is the lack of technical knowledge and familiarity with new technologies on the user side, which often increases reliance on vendor support, especially if engineering and maintenance staff are reduced to cut costs.

Increasing the efficiency of food and beverage manufacturing also comes with challenges that are unique to the subsector. First, the products of food and beverage manufacturing are typically held to a higher level of quality and safety scrutiny than the products of many other industrial subsectors. Food processing alterations are subject to multiple regulatory reviews on food quality, environmental impact, food health, and safety, as well as worker safety. These regulatory hurdles, while often necessary, typically result in additional costs to meet standards and additional workforce training that can impede the rapid implementation of energy efficiency measures. In addition, food and beverage products are subject to public perceptions of product safety and quality that can influence possibilities for the implementation of more efficient technologies at the process level as well as other transformative technologies. These concerns also increase food waste. Secondly, there are often few opportunities for financially feasible use of low-grade heat in-house, making WHR more challenging and often not cost-effective. This is compounded by the diversity of the subsector, especially in terms of geography, as there are few opportunities to share waste heat and other byproducts among facilities. New technologies, such as heat pipes, advanced air-to-air heat exchangers, and self-cleaning heat exchangers could expand WHR at some facilities. Additionally, heat pumps or booster heat could elevate temperatures of waste heat to a point of greater utility.

Despite challenges, many opportunities exist for further decarbonization through energy efficiency, as well as RD&D needs that would create or expedite new opportunities.

2.3.3.1.1 Efficient Oven Burners

Efficient oven burners are critical to improving energy efficiency in food processing. Oven burners can be optimized by minimizing several components of stack gases. Combustion efficiency can be furthered through such practices as oxygen trim and burner operations. Though it is still an emerging practice, determining the ideal combustion air/fuel ratio has significant potential for reducing energy use and resulting emissions.

2.3.3.1.2 Steam Generation Efficiency

Because hot water and steam are significant energy users, and sources of energy loss, in food processing plants, efficiency improvements in a steam generation are a critical opportunity that needs to be a focus. DOE estimates a typical industrial steam assessment can identify energy savings of 10%–15% per year.[243] One of the most significant barriers to improving steam generation efficiency in food and beverage manufacturing is the high pressures and large volumes at which steam is typically generated. RD&D is needed in how best to match production with demand and in recovering energy through technologies such as back-pressure steam turbines and turbo expanders. Other potential methods of pursuing energy efficiency in steam generation include improved process integration and energy management, and point-of-use heating versus heat loss and piping expenses for centralized supply of steam.

2.3.3.1.3 Food and Beverage Waste Reduction

Product degradation and spoilage are major problems in the food and beverage manufacturing. Estimates for waste average 31% of all food produced.[244] In many cases, the waste occurs not only at an individual processing plant, but also throughout the supply chain from the agricultural producer through to consumers. Opportunities exist to reduce this waste through improved processing, handling, and packaging practices that can significantly reduce the product that is not consumed, with a corresponding reduction in the energy, resources, and emissions that would otherwise be required. Reducing food waste is also a critical component in improving food security and lowering costs. RD&D on the processing practices and technologies to extend the shelf life of food and beverage products and reduce degradation is needed to identify new opportunities, achieve regulatory acceptance, and ensure consumers find products acceptable.[245] In addition, the packaging of food and beverage products is also an energy- and resource-intensive part of the industry; and research is needed to both improve performance and reduce the volume of packaging waste and where possible allow for recycling.

Other RD&D needs in this space include technologies and processes aimed toward reducing waste through beneficial reuse of waste streams, source reductions, and supply chain visibility. Food waste is lost revenue, so mitigating food waste is typically cost-effective. Processing changes can also mitigate waste, as wastage of processed fruit and vegetables is approximately 14% lower than that of fresh produce and 8% lower than that of seafood.[246] Another avenue to reducing food waste is the use of

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[243] U.S. Department of Energy, *Save Energy Now in Your Steam Systems*, January 2006, https://www.energy.gov/sites/prod/files/2014/05/f15/saveenergyinsteam.pdf.

[244] "Loss-Adjusted Food Availability Documentation," U.S. Department of Agriculture Economic Research Service, last modified November 12, 2020, https://www.ers.usda.gov/data-products/food-availability-per-capita-data-system/loss-adjusted-food-availability-documentation.

[245] Commission for Environmental Cooperation, *Characterization and Management of Food Loss and Waste in North America*, 2017, http://www3.cec.org/islandora/en/item/11774-characterization-and-management-food-waste-in-north-america-foundational-report-en.pdf.

[246] Hannah Ritchie, "Food Production is Responsible for One-Quarter of the World's Greenhouse Gas Emissions," *Our World in Data,* November 6, 2019, https://ourworldindata.org/food-ghg-emissions.

imperfect produce, which comprises approximately 40% of waste.[247] Supporting efforts to address negative public perceptions of such food as well as efforts to introduce new supply streams for unwanted produce (e.g., reuse in feed, soil health, and food service) could be another essential pathway to reducing waste and thereby mitigating emissions.

2.3.3.1.4 Other Technologies

Other potentially significant technologies that can improve efficiency in food and beverage manufacturing and should benefit from further RD&D include alternate drying technologies and advanced separations in processing and water treatment. There are also more efficient potato peeling and slicing technologies, in addition to opportunities in cryogenic separation, advanced coatings to prevent ice buildup, advanced enzymes, and low-ethanol producing yeast. The U.K. has also identified a low-temperature animal by-product processing technology that aims to demonstrate a 40% thermal energy reduction compared to traditional practices.[248]

2.3.3.2 Electrification and Process Electrification for Food and Beverage Manufacturing

Substantial near-term potential exists for energy and cost savings as well as emissions reductions through fostering electrification. Food and beverage manufacturing is well-suited for electrification because of low-temperature process-heating demands and high potential for modularization of heating to replace legacy central steam systems. However, challenges still exist with the deployment and proliferation of these technologies, which RD&D could help address.

Some of the top challenges to the food and beverage manufacturing's efforts to further decarbonization through electrification are common among all industrial subsectors. For example, as with efficiency upgrades, the costs of replacing existing equipment and process connections are likely to be much higher than those associated with maintaining incumbent equipment or like-for-like replacements. In other cases, there is a lack of electric technology demonstration at the site level. Additionally, the low cost of natural gas, which is the most frequently used fuel in the food and beverage manufacturing, has recently been much lower than the cost of electricity. However, EIA projects gas prices increasing faster than electricity prices in future years.

Electrifying the food and beverage manufacturing also comes with challenges that are unique to the subsector. Concerns and consumer perceptions persist that changes in energy sources could affect product quality. This uncertainty could result in implementation delays that would be needed to prove there is no adverse impact to the product from changes. In addition, production speeds could be slowed because of these technological changes. Despite these challenges, there are many opportunities to realize further decarbonization through electrification in the food and beverage manufacturing. And RD&D would play an important role in identifying or expediting new opportunities.

As the prices of clean electricity drop, electric boilers, hybrid boilers and the modularization of process heating in food and beverage manufacturing will become important decarbonization strategies. Through the electrification of process heating, ovens and fryers also represent a potential avenue of accelerating

[247] Brian Kateman, "The Time Is Ripe for Ugly Fruits and Vegetables," *Forbes,* March 2, 2020, https://www.forbes.com/sites/briankateman/2020/03/02/the-time-is-ripe-for-ugly-fruits-and-vegetables/#380724824a85.

[248] "Industrial Energy Efficiency Accelerator: Projects Selected for Phase 2," UK Department for Business, Energy and Industrial Strategy, last modified February 11, 2021, https://www.gov.uk/government/publications/industrial-energy-efficiency-accelerator-ieea/industrial-energy-efficiency-accelerator-projects-selected-for-phase-2.

decarbonization. Processes in food and beverages manufacturing, such as evaporation and pasteurization, mostly occur at temperatures below 200°C, as do processes in the pulp and paper subsector.[249] Therefore, decarbonization options for these subsectors largely involve replacing fuels in low- or medium-temperature heating applications. More RD&D would be needed on electrification as a decarbonization measure, including refining modeling assumptions, analyzing the impact of technology changes on products, integrating different modeling frameworks, and conducting sensitivity analysis on scenarios.

2.3.3.3 Carbon Capture, Utilization, and Storage for Food and Beverage Manufacturing

Some post-combustion CCUS technologies that are relevant to food and beverage manufacturing are closer to commercialization. No single CCUS commercial technology or process design can work for every food or beverage plant, especially given the diversity of the food and beverage manufacturing, varying CO_2 sources, geographical differences, and different emissions control designs at plants. Availability of CO_2 transport infrastructure varies by different potentials for capture efficiency at new food and beverage plants. Plant location also varies. Processing food-grade CO_2 for reuse is another potential challenge.

The opportunities for utilization of captured CO_2 in the food and beverage manufacturing include using CO_2 as a feedstock to improve the resiliency of the global food system. Captured CO_2 can be reused for meat packing, carbonated beverage production, sugar refining, and in the manufacturing of dry ice that is used to preserve food. CO_2 is also integral to the production, packaging, preservation, refrigeration, and marketing of products such as canned goods, alcoholic and carbonated beverages, cheese, and processed meats.[250] Other opportunities include pumping captured CO_2 into greenhouses, though there are concerns in some cases about nutritional content reductions and food quality. Finally, there is significant potential for reductions from fuel combustion and fermentation processes in food and beverage manufacturing. As with other technological innovations, the applications of CCUS need to be demonstrated and vetted to the food and beverage manufacturing industry for both product regulatory compliance and public perceptions of food quality.

2.3.4 Proposed RD&D Action Plan for Food and Beverage Manufacturing

Given the challenges, opportunities and needs identified earlier, a portfolio of low-carbon solutions for RD&D investment is needed to advance decarbonization of the food and beverage manufacturing. With the vast number of technologies, all of which vary in readiness level, timeline, and mitigation potential, it is essential to set out guiding principles for an RD&D action plan and lay out the specific RD&D needs of each of the decarbonization pillars.

The RD&D needs in the energy efficiency pillar include means to overcome the high initial costs of more efficient technologies and the long lifetimes of incumbent technologies. Transitions need to be facilitated and vendor continuity ensured. Additionally, regulatory burdens that are unique to the food

[249] Arnout de Pee et al., Decarbonization of Industrial Sectors: The Next Frontier, McKinsey & Company, June 2018, https://www.mckinsey.com/business-functions/sustainability/our-insights/how-industry-can-move-toward-a-low-carbon-future.
[250] Greg Williams, "How Reduced CO_2 in the Pandemic is Impacting the Food and Beverage Industry," Maryland Energy Administration, May 14, 2020, https://news.maryland.gov/mea/2020/05/14/how-reduced-co2-in-the-pandemic-is-impacting-the-food-and-beverage-industry/.

and beverage manufacturing must be altered to allow for more-efficient technologies to be sanctioned. Knowledge infrastructure and information gathering should be fostered to easily respond to any questions of food safety or quality. The energy efficiency opportunities identified in Section 2.3.3.1 should be funded further, and greater emphasis should be placed on RD&D into WHR in the subsector and how waste heat might be shared between facilities at which there are few uses of waste heat in-house, and those for which it might be a viable decarbonization strategy. There also needs to be RD&D into (1) processing practices and technologies to extend the shelf life of products to reduce food waste and (2) reduction of waste through beneficial reuse of waste streams, source reductions, and supply chain visibility.

The RD&D needs in the electrification and LCFFES pillar again include means to overcome issues of capital, energy, and operating costs. Demonstrations of readily available and high potential electrification technologies at the site level are also needed. And RD&D into product quality impacts from energy source changes is needed. Research into hybrid boilers, modularization, automation, and smart manufacturing would significantly advance decarbonization potential through this pillar.

The RD&D needs in the CCUS pillar include means to overcome high costs and the diversity of the food and beverage manufacturing. Research is needed on the demand, support, and cost-effectiveness of CCUS technologies and processes; how to make CCUS and associated technologies manageable within the existing workforce; and where CO_2 reuse can be the most effective. There also needs to be additional vetting and demonstration of the applications of CCUS to the food and beverage manufacturing in terms of safety and product quality.

Prioritization of investment should be determined by:

- **Crosscutting Strategies** (e.g., across industries, geography, and major processes): Strategies that can address multiple subsectors and regions simultaneously should be prioritized to lower costs. These include commercialization and scale-up needs.
- **Short-Term Strategies that Enable Meaningful Future Solutions**: Tying together short- and long-term options will be essential to determining the appropriate decarbonization steps to take and identify where additional RD&D and investment are needed.
- **Strategies with No Other Sources of Funding**: This area is especially important for critical strategies in the supply chain, or enablers of other strategies. There is already significant public discourse, exposure, and funding for several of the opportunities addressed in this roadmap. However, others lack the broad appeal and public knowledge that are essential to decarbonization progress. The options in the category with less public knowledge should be prioritized where possible. DOE could help such orphaned solutions, as the riskier solutions benefit from government support that the private sector cannot provide.
- **High Mitigation Potential**: RD&D investment should be balanced between support for low-hanging fruit and low-cost options with realized decarbonization potential and for “moonshot,” transformative-but-risky technologies and investments. Those opportunities with high mitigation potential should be the focus of further RD&D and long-term investment.
- **Capabilities within the Existing Workforce**: Supporting technologies that are within the capacity of the existing workforce will also minimize costs and the need for vendor continuity, technical assistance, and third-party maintenance.

The RD&D action plan, which cuts across the technologies in the CCUS pillar, should focus on:

- **Information Gathering:** Information and knowledge infrastructure could help expedite the development phase of transformative technologies by attracting attention and investment. CCUS and many of the technologies needed to improve energy efficiency and promote beneficial electrification require additional research and information gathering to characterize plant-level decarbonization potential and technology costs.
- **Portfolio of Options**: Developing a portfolio of options for industry, academia, and government would help overcome the barrier of diversity in the food and beverage manufacturing. Additional research into the costs and benefits of different strategies and technologies would ensure a robust portfolio of options and that the pathway toward decarbonization through those options would be clear.
- **Lab Testing**: RD&D should be focused especially on technologies that still require extensive lab testing and have not reached commercialization scale. This is essential because such technologies, despite having decarbonization potential, might have trouble attracting investments. Examples in this subsector include hybrid boilers and cryogenic separation.
- **Pilot Programs and Demonstration:** RD&D should also be focused on technologies that are in the pilot and demonstration phase but are not ready for use in the food and beverage manufacturing specifically. Such technologies require more piloting for subsector-specific applications. Those technologies may also require commercialization acceleration.

Through the strategies described here, namely energy efficiency, electrification, CCUS, waste reduction, and others, it is possible to pursue the ambitious GHG emissions reduction targets established in this roadmap, while ensuring the quality and safety of the products produced by this industry. Moderate-to-advanced emissions reductions are within the grasp of existing technological feasibility, short-term RD&D measures, and commercialization opportunities, while net-zero reductions are in the scope of the investments and the long-term RD&D opportunities identified here. By following the path of RD&D prioritization, balances, and action plan foci, and by establishing robust targets and opportunities, it is possible to achieve a cost-effective, market-stimulating, low-carbon future for the food and beverage manufacturing.

Figure 36 shows a selection of these opportunities grouped into bands for the decarbonization pillars and organized by the decade where new efforts are needed to further develop these solutions. Scaling, significant investment, and RD&D will be necessary to pursue these solutions and others. There will need to be a strong focus on near-term options that will yield early impacts, expand learning, and enable future strategies. However, there will also need to be resources committed to the medium- and long-term transformative technology opportunities that will be crucial for larger reductions in GHG emissions.

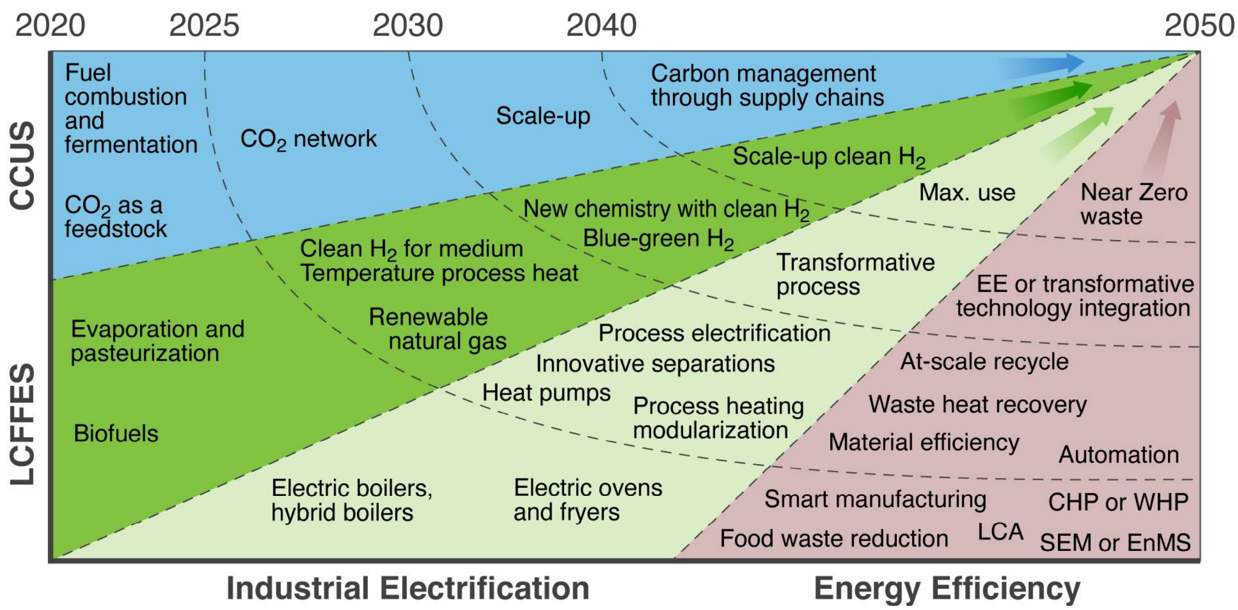

Figure 36. Landscape of RD&D advancement opportunities by decade and decarbonization pillar for the U.S. food and beverage manufacturing subsector noted by attendees at the roadmap virtual sessions.

Early opportunities such as advances in evaporation and pasteurization, smart manufacturing, waste heat recovery, and renewable natural gas are top areas for RD&D as they are enablers for later transformative technologies, and they have crosscutting impacts for other pillars and across industrial subsectors. LCFFES includes clean technologies that do not release GHGs to the atmosphere from the production or use of energy sources, and include renewable sourced electricity, nuclear energy for electricity and heat, concentrating solar power, and geothermal energy. EnMS: energy management system. Further definitions are available in the glossary. Source: This work.

To subdivide the need for RD&D investments over this timeline into three categories:

RD&D needs with **near-term (2020–2025)** impacts include:

- Develop electric ovens, fryers, boilers, and other technologies where possible, especially as electric prices drop.
- Reduce food waste throughout the supply chain through methods identified in LCAs and collaboration between manufacturers. Opportunities include:
    - Beneficial reuse of waste streams (e.g., explore anaerobic digestion of food waste to produce biogas),
    - Source reductions,
    - Supply chain visibility,
    - Processing and packaging improvements for increasing shelf life and stability.
- Invest in smart manufacturing strategies like system optimization, integration of thermal systems and refrigeration optimization.
- Invest in RD&D on low-carbon fuels and biofuels as feedstocks in food manufacturing to reduce emissions.

- Further the potential of CCUS in the subsector by advancing RD&D in CO_2 as a feedstock to improve resiliency and reduce emissions from fuel combustion and fermentation processes.

RD&D needs with **mid-term (2025–2030)** impacts include:

- Further the beneficial reuse of waste streams to include waste heat by advancing RD&D into ways to better share and store low grade waste heat for food manufacturers.
- Increase RD&D in automation and modularization.
- Increase RD&D into heat pumps to recover and supply process heat in food and beverage manufacturing processes.
- Pursue recycling and material efficiency through methods like alternative packaging and plastic waste reduction.
- Further RD&D into potentially transformative technologies such as cryogenic separation, advanced coatings to prevent ice buildup, advanced enzymes, and low ethanol producing yeast.
- Invest in renewable natural gas RD&D, synthetic natural gas produced using nuclear energy, and clean hydrogen for medium temperature process heat. Such investments will have to include funding for the infrastructure needed to integrate these low-carbon fuels into industrial processes.

RD&D needs with **longer-term (2030–2050)** impacts include:

- Develop clean hydrogen for use in food manufacturing processes.
- Deepen understanding of what is needed to rapidly scale transformative technologies.
- Incorporate new processes, fuels, and technologies at scale.

2.4 Petroleum Refining

The crosscutting decarbonization pillars identified in this work are energy efficiency, industrial electrification and LCFFES from non-fossil fuel or low-carbon emitting sources, and CCUS, where electrification and LCFFES are highly connected and evaluated together for this roadmap. The U.S. refining industry is the largest producer of liquid transportation fuels and refined petroleum products in the world; about 16.6 million barrels of oil per day (BPD) were refined in 2019 in the United States.[252] The subsector was comprised of 135 individual refineries in 2019[253] that refine raw materials, mostly crude oils supplemented by other natural or semi-processed hydrocarbon mixtures, into a range of petroleum products that includes transport fuels,[254] heating and

Petroleum Refining Subsector: Key Takeaways

- The majority of U.S. refinery CO_2 emissions are from five large energy-consuming processes (hydrocracking, atmospheric distillation, catalytic cracking, steam methane reforming, and regenerative catalytic reforming), representing the most cost-effective RD&D opportunities for refineries to reduce CO_2 emissions.
- Refineries and transportation fuels markets are highly integrated. In 2020, 97% of transportation's and 35% of total U.S. energy-related CO_2 emissions "passed through" refineries to become "vehicle tail-pipe" CO_2 emissions[251]

  Refining = 235 million MT CO_2 (5% of U.S. total)
  Transportation petroleum = 1,591 million MT CO_2 (35%)
  U.S. Total = 4,563 million MT CO_2 (100%)
- Producing low-net GHG emission liquid hydrocarbon fuels is an opportunity to build new, less carbon intensive refinery process configurations while decarbonizing transportation and chemicals. Decarbonizing U.S. transportation by 2050 requires a high level of integration with a decarbonizing electricity grid.
- To achieve cost-effective net-zero CO_2 emission solutions across the U.S. transportation sector and economy, refinery decarbonization RD&D should be pursued in harmony with broader decarbonization RD&D. A robust, holistic life cycle-based "wells-to-wheels" governance structure that accounts for these markets is likely required.
- The scale of shifting to net-zero GHG transportation by 2050 is an optimistic opportunity for U.S. business to evolve refining processes, business models, market structures, and markets – both U.S. and international – potentially creating new products, industries, and manufacturing sectors by 2050.

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251 "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 19. Energy-Related Carbon Dioxide Emissions by End Use.

252 "Petroleum and Other Liquids: Number and Capacity of Petroleum Refineries, Atmospheric Crude Oil Distillation Capacity," U.S. Energy Information Administration, last modified June 25, 2021, https://www.eia.gov/dnav/pet/pet_pnp_cap1_dcu_nus_a.htm. By comparison, in 2018 refineries in the European Union refined 12.7 million barrels per day, China refined 13.4 million barrels per day, and ~ 8.5 million barrels per day were refined in the Middle East (See page 30 of BP, *BP Statistical Review of World Energy 2021*, 2021, https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2021-full-report.pdf).

253 "Petroleum and Other Liquids: Number and Capacity of Petroleum Refineries, Number of Operable Refineries," U.S. Energy Information Administration, last modified June 25, 2021, https://www.eia.gov/dnav/pet/pet_pnp_cap1_dcu_nus_a.htm.

254 Transport fuels include gasoline, diesel fuel, jet fuel, and marine fuel.

industrial fuels, chemical feedstocks, lubricants base-stocks, and asphalts. Feedstock and product slate, process unit complexity, energy efficiency, and fuel carbon content are essential factors that govern the CO_2 intensity of a particular refinery.

Although engagement and feedback regarding the petroleum refining subsector was sparse in the stakeholder meetings, valuable feedback to guide RD&D needs across near-commercial, emerging, and transformative low-carbon technologies was provided. Key learnings and RD&D opportunities from the meetings include:

- In 2020, U.S. petroleum refining emissions accounted for 5% of the 4,563 million MT total U.S. energy-related CO_2 emissions, equivalent to 235 million MT CO_2; the U.S. transportation sector's energy-related CO_2 emissions were 1,591 million MT CO_2, 35% of total U.S. energy-related emissions.[255] Although refinery energy and material efficiency, electrification, and CO_2 capture (for sequestration or reuse) investments are within refiner's control, the maximum benefit of decarbonizing U.S. refineries towards the goal of net-zero CO_2 emissions is 5% of the total energy-related CO_2 emissions throughout the U.S. economy. Competing options for reducing the 35% of the U.S. economy's total petroleum-based transportation CO_2 emissions – such as vehicle technologies, electric vehicles fueled by decarbonized electricity (the most common transportation decarbonization pathway found in the literature)[256] as well as low-carbon feedstocks and supply chain alternative to crude oil – are outside refiners' control. Considering the capital-intensive investments required to revamp refineries, refinery decarbonization could be one of the least cost-effective options towards the goal of achieving net-zero CO_2 emissions.
- The refining subsector is integral to transportation sector decarbonization by providing options such as low-carbon fuels, and net-zero GHG aviation fuels.[257]
    - To viably achieve net-zero GHG emissions across the U.S economy, options to reduce refinery CO_2 emissions must be within refiners' control and harmonize with competing options across the U.S economy that are outside refiners' control.
    - Harmonizing cost-effective net-zero CO_2 emission solutions across the U.S economy requires a holistic life cycle-based "wells-to-wheels" governance structure that a) monitors and accounts for net CO_2 reductions, and b) rewards those making the necessary investments, such as refiners, manufacturers, or consumers. Moving forward without such mechanisms

[255] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 19. Energy-Related Carbon Dioxide Emissions by End Use.
[256] Frankfurt School-UNEP Collaborating Centre for Climate and Sustainable Energy Finance, *Global Trend in Renewable Energy Investment*, 2020, https://www.fs-unep-centre.org/wp-content/uploads/2020/06/GTR_2020.pdf; James H. Williams et al., "The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The Pivotal Role of Electricity," *Science* 335, no. 6064 (November 2011): 53-59. https://www.science.org/doi/10.1126/science.1208365; Sustainable Development Solutions Network and the Institute for Sustainable Development and International Relations, *Pathways to Deep Decarbonization,* December 2015. https://www.iddri.org/sites/default/files/import/publications/ddpp_2015synthetisreport.pdf.
[257] Thomas F. Stocker et al., *Fifth Assessment Report: Technical Summary*, Intergovernmental Panel on Climate Change, 2013, https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_TS_FINAL.pdf; Robert Lempert et al., *Pathways to 2050: Scenarios for Decarbonizing the U.S. Economy*, Center for Climate and Energy Solutions, May 2019, https://www.c2es.org/site/assets/uploads/2019/05/pathways-to-2050-scenarios-for-decarbonizing-the-us-economy-final.pdf; "Working Plan: The Low Carbon Pathways project: A holistic framework to explore the role of liquid fuels in future EU low-emission mobility (2050) – Work Plan," Concawe, April 17, 2018, https://www.concawe.eu/publication/low-carbon-pathways-project-holistic-framework-explore-role-liquid-fuels-future-eu-low-emission-mobility-2050/.

risks dwarfing, or even negating, the potential benefits of "siloed" refining subsector decarbonization investment decisions.

Key learnings and RD&D opportunities from the roadmap meetings include:

- The RD&D needed to reduce refinery CO_2 emissions range from early-stage RD&D to detailed development and deployment support. For example, carbon capture technologies are relatively mature, yet their deployment requires RD&D to develop cost-effective options to revamp current refinery configurations and complexities, whereas the use of captured carbon as feedstocks for producing low-carbon fuels requires earlier stage RD&D.
- Both government-supported RD&D and industry adoption of RD&D results require long-term active engagement and partnerships with industrial companies. This engagement and partnership will help identify cost-effective options, develop a strategic approach to the transition to net-zero CO_2 emissions across the U.S. economy, determine a strategic approach to private and public RD&D investments, and test and scale the most promising RD&D results and technologies.
    - Techno-economic studies are needed to understand the applicability of technologies (even at precommercial stages) and to provide cost-effectiveness targets, as well as timelines and milestones for RD&D results.
    - RD&D decisions for both refining and transportation decarbonization technologies should be pursued together. They should be informed by a holistic transportation decarbonization roadmap that compares CO_2 reduction potential and cost scenarios across multiple sectors of the U.S. economy and reflect the most cost-effective net-zero CO_2 reduction options.

Key learnings and RD&D opportunities from the literature include:

- Developing a uniform, impartial, transparent accounting system for measuring net GHG emissions reductions, as well as the time-to-market availability and sequencing of technology options toward a net-zero GHG emissions by 2050 requires the coordination of technology RD&D planning and the development of data analytics. An open-source database and knowledge network would be beneficial for accelerating deployment.
- All the technology that is needed to convert methane into hydrogen and to store CO_2 is already available, but it is costly and lacks incentives.
- Development of alternative low-carbon feedstocks requires a better understanding of the availability and reliability of supply chains, the scale of associated GHG emissions reductions, as well as the maturity level and feasibility of technology deployment. The EU has conducted studies that indicate clean hydrogen will be a crucial component of paths to reach net-zero GHG emissions by 2050,[258] along with second-generation biofuels and electric vehicles.[259]

[258] "Role of e-fuels in the European transport system (literature review)," Concawe, January 16, 2020, https://www.concawe.eu/publication/role-of-e-fuels-in-the-european-transport-system-literature-review/.

[259] "Impact Analysis of Mass EV Adoption and Low Carbon Intensity Fuels Scenarios," Concawe, September 21, 2018, https://www.concawe.eu/publication/impact-analysis-of-mass-ev-adoption-and-low-carbon-intensity-fuels-scenarios/; "Towards a Hydrogen Market for Europe: Council Adopts Conclusions," European Council, December 11, 2020, https://www.consilium.europa.eu/en/press/press-releases/2020/12/11/towards-a-hydrogen-market-for-europe-council-adopts-conclusions/.

  - For example, waste fats, oils, and grease-based bio-feedstocks are near-term but limited in volume compared to liquid transportation fuel demand. Algae-based fuels are a nearer-term possibility but have spatial constraints. Technologies that can enable an electrification of fuels are evolving rapidly but achieving a net reduction in CO_2 emissions depends on decarbonized electricity to avoid CO_2 "leakage" (transferring CO_2 emissions from inside the boundary to outside the boundary – refinery accounting to electric grid accounting). Whereas the substitution of clean hydrogen for fossil fuels depends on decarbonized electricity and hydrogen infrastructure.

- Producing low-carbon hydrocarbon-based fuels such as solar fuels[260] is a long-term vision for refineries, with opportunities for RD&D to improve or develop CO_2 reduction and utilization technologies. If successful, these technologies would present potentially game-changing opportunities for achieving net-zero GHG emissions solutions across multiple sectors in the U.S. economy. In the near-term, these technologies would displace fossil fuel CO_2 (that would otherwise be used) by recycling the carbon from fossil fuel combustion CO_2 waste streams. As the U.S. economy decarbonizes in the mid-term, these technologies could supply liquid aviation fuels derived from capture process CO_2 emissions (from the cement and iron and steel industries). Combined with direct air capture (DAC) in the long-term, CO_2 reduction can regulate global emissions by diverting captured carbon to sequestration or fuels as required. Across these time horizons, this option leverages the existing hydrocarbon-based infrastructure (e.g., refineries, pipelines, and fueling stations) and thus bypassing the need for new hydrogen dedicated infrastructure.

  - Diverse sources of renewable energy can be transmitted over long distances to refineries and demand markets.

  - Local sources of captured CO_2 could be found in refineries, other industrial subsectors, the power generation sector, or the atmosphere; reduced CO_2 can be combined with local sources of bioenergy and waste streams and refined into low-carbon liquid fuels.

  - The technology for converting CO_2 into a liquid hydrocarbon fuel currently exists.[261] Currently, the cost point for solar hydrocarbon-based fuels is much higher than it is for all other liquid hydrocarbon fuels. However, it is technically feasible for RD&D to lower the cost of both CO_2 capture and CO_2 reduction technologies.

  - The option of using renewable energy for fuels requires investor confidence in the stability of benefits and markets over an investment time horizon. Ensuring investor confidence requires an accounting system for: measuring net GHG emissions across upstream supply-chains, fuel production, and downstream fuel uses reduction; monetizing GHG emission reduction benefits and distributing benefits equitably.

[260] Solar fuels are hydrocarbon-based fuels derived from CO_2, water, and solar energy or carbon-free electricity.
[261] Solar fuels can be produced through photochemical, photobiological (i.e., artificial photosynthesis), thermochemical (i.e., using heat to drive a chemical reaction), and electrochemical reactions.

2.4.1 Status of U.S. Petroleum Refining

2.4.1.1 U.S. Refinery Production

Petroleum refining products are an essential part of the world economy, providing a large source of energy and other value-added products to key U.S. sectors such as chemical and transportation.[262] The United States consumed about 20.5 million barrels per day in 2019.[263] About 70% of petroleum is consumed in transportation, making that sector particularly vulnerable to changes in production and pricing.[264] In addition, manufacturing industries consume about 24% of petroleum as fuels and as feedstock in the production processes.[265]

Refinery activities have significant direct and indirect impacts on the U.S economy. For example, in 2020, the total value of U.S. petroleum refining products shipped amounted to $315 billion (6% of manufacturing value of shipments), and direct employment of the petroleum refining industry was approximately 63 thousand workers.[266]

Although refineries have similar processes, each is unique due to various aspects such as its evolution, accessibility of specific crude oils, product specification constraints, market demands and profitability. Furthermore, each refinery is subject to unique regional policies and regulations, such as regional air quality regulations. Thus, many U.S. refineries are configured for specific crude oils and U.S. regions as Figure 37 shows, reflecting unique historical policies, environmental performance regulations, and regionally specific vehicles stocks and product demands. Further, refining technology has changed over time, coevolving with vehicle technology. As a result, U.S. refineries often have one-of-kind equipment processing configurations.

To be competitive, most U.S. refineries' process units are highly optimized, operating at high-capacity utilization factors to produce high product volumes with low profit margins.[267] Within a refinery, process units are integrated by process flows; excess heat transferred between process flows and units; and shared steam, electric, cooling water, and wastewater treatment utilities. Refinery process and plant-level integration results in a highly efficient operation (85%–90+%) that is flexible in meeting incremental changes in product supply and demand.

[262] "Petroleum, Natural Gas, and Coal Continue to Dominate U.S. Energy Consumption," U.S. Energy Information Administration, July 1, 2019, https://www.eia.gov/todayinenergy/detail.php?id=40013.
[263] "Oil and Petroleum Products Explained," U.S. Energy Information Administration, last modified April 19, 2022, https://www.eia.gov/energyexplained/oil-and-petroleum-products/.
[264] "U.S. Energy Facts Explained," U.S. Energy Information Administration, last modified May 14, 2021, https://www.eia.gov/energyexplained/us-energy-facts/.
[265] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 6. Industrial Sector Key Indicators and Consumption.
[266] "Annual Survey of Manufacturers (ASM)," U.S. Census Bureau, last modified April 21, 2022, https://www.census.gov/programs-surveys/asm.html.
[267] "Changing Demand for Petroleum Products Has Led to Operational Changes at U.S. Refineries," U.S. Energy Information Administration, August 28, 2020, https://www.eia.gov/todayinenergy/detail.php?id=44936.

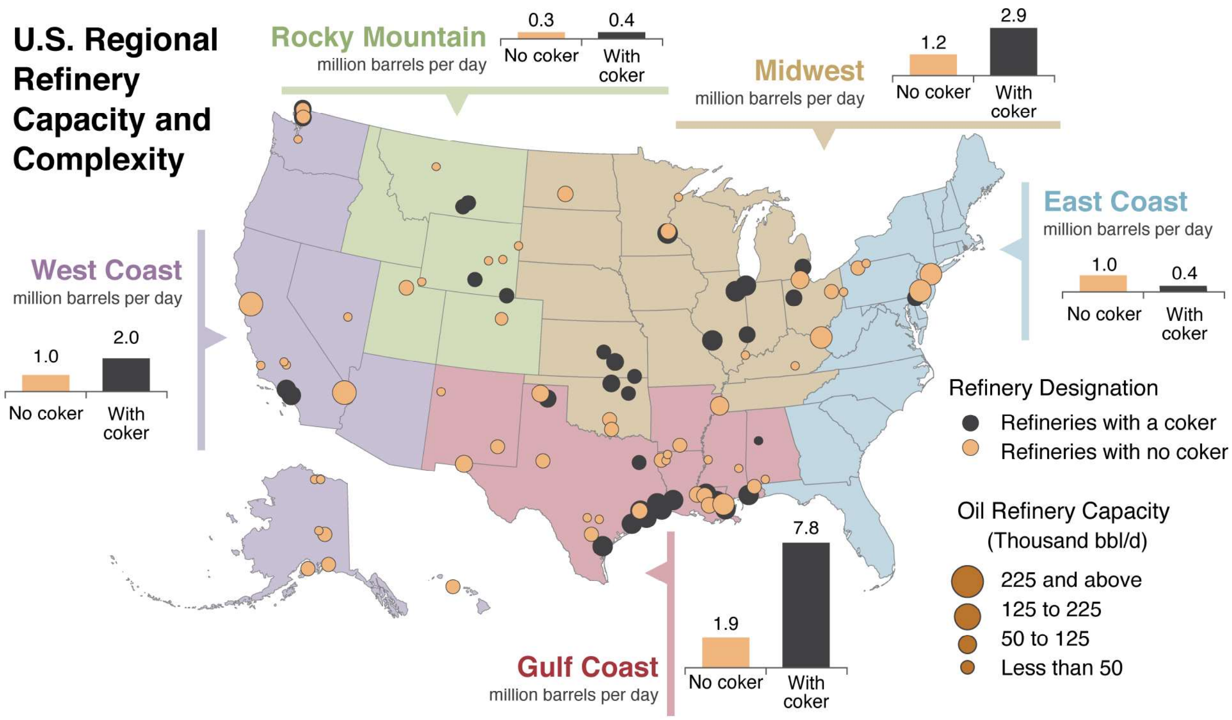

FIGURE 37. U.S. REGIONAL PETROLEUM REFINERY CAPACITY AND COMPLEXITY[268]

> *Key message: The combination of the level of capital investment required to revamp these highly connected refinery processes, and the raw material contributions to key U.S. sectors such as transportation and chemicals, makes the U.S. petroleum refining industry a strategic focal point in the transformation to net-zero GHG emissions. However, the adaptability of this complex system will be severely challenged by decarbonization of the U.S. industrial and transportation sectors.*

2.4.1.2 Energy Use and CO_2 Emissions for Petroleum Refining

Refinery feedstocks and refinery products are both comprised of a range of hydrocarbons with small quantities of other elements, such as sulfur and nitrogen. And most refineries have a similar array of process units that rearrange carbon and hydrogen atoms to obtain final products through:

- Physical separation of hydrocarbon fractions.
- Treatment of fractions (e.g., to remove undesirable compounds such as sulfur).
- Modification of molecular structure (e.g., cracking large molecules into smaller molecules, reformulating and hydrotreating branching molecules to address octane and enable more uniform combustion in vehicles).

The energy intensity of a refinery is a function of its complexity or configuration of the combination of processes operated, which in turn determines which crude oils can be processed as well as the type, yield, and quality of the refined products that can be manufactured. As a rule, more conversions of heavy streams into light products will lead to cleaner finished products and higher energy intensity; in

[268] "Regional Refinery Trends Evolve to Accommodate Increased Domestic Crude Oil Production," U.S. Energy Information Administration, January 25, 2015, https://www.eia.gov/todayinenergy/detail.php?id=19591#.

other words, a complex refinery will consume more energy than a simple refinery with the same crude throughput.

As a result of market developments, refineries have steadily become more complex, incorporating more process units dedicated to treating and converting heavy fractions into lighter ones. Further, the hydrogen-to-carbon ratio of combined refinery products has increased significantly beyond that of combined feedstocks, requiring a net addition of hydrogen, removal of carbon in the form of coke, or both. As Figure 38 shows, a simple refinery performing only distillation and treating, and no conversion, may consume 3%–4% of the energy content of its intake. In a very complex refinery with several conversion units and extensive treatment, for example, this figure is typically 7%–8%.

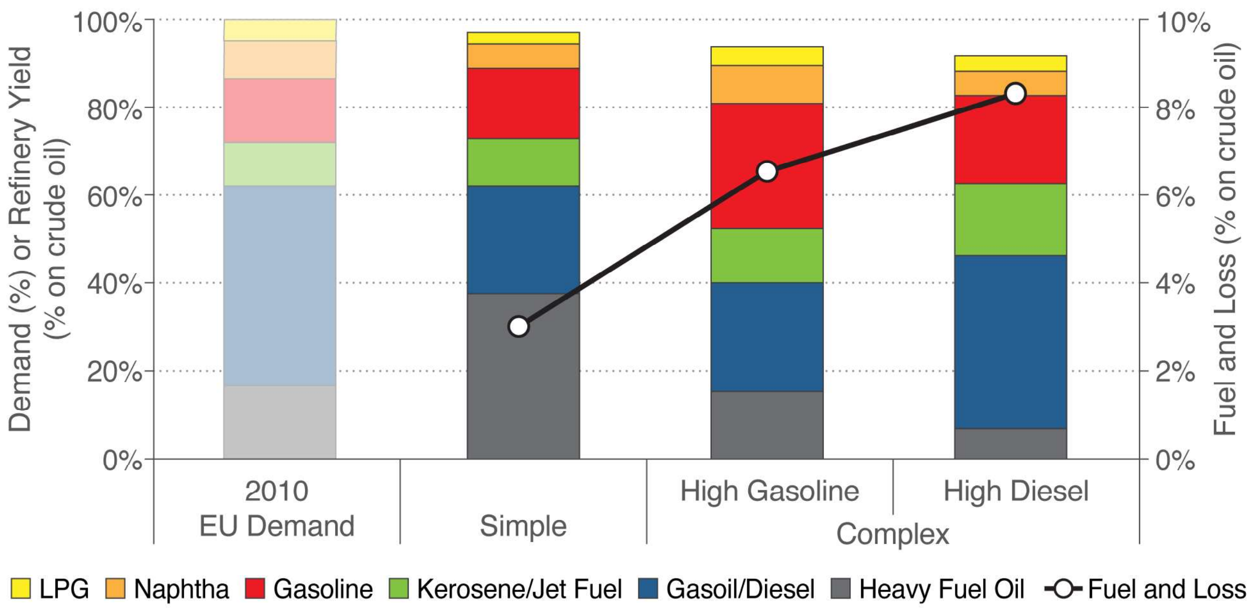

FIGURE 38. TYPICAL PRODUCT YIELD AND ENERGY INTENSITY FOR EU REFINERIES OF DIFFERENT COMPLEXITY[269]

> *Key message: Refining heavy fuel oil into cleaner burning gasoline and diesel transportation fuels reduces transportation sector criteria pollutant emissions, but increases refinery complexity, energy requirements, and associated CO_2 emissions regardless of location (EU and United States).*

Most refining process units produce undesirable hydrocarbons, such as waste gas (also referred to as refinery gas or still gas) and petroleum coke, as byproducts of crude oil refining. Most refineries capture and use these streams to avoid hazardous air emissions from flaring of the waste gases and costly waste treatment of petroleum coke, which represents avoided-cost sources of supplemental fuel, feedstocks, or both. Often, refinery process equipment (e.g., reactors and furnaces) and facility utility equipment (e.g., boilers and CHP units) are designed to enable the use of these byproducts as fuel. As a result, many refinery process operations represent a finely-tuned balance of heat and electricity—including direct heating (fired furnaces), indirect heating (steam from boilers or CHP), and electricity (from CHP). Fuel or electricity that have demands that cannot be met by these sources are supplied pipeline gas and electricity purchases, respectively.

[269] Concawe, *EU Refinery Energy Systems and Efficiency*, Concawe Report 3/12, March 2012, https://www.concawe.eu/wp-content/uploads/2017/01/rpt_12-03-2012-01520-01-e.pdf.

As Figure 39 shows, 68% of fuel energy used by the U.S. refining industry in 2018 was self-produced.[270] Most fuel gas is used for process heating or to generate steam and electricity in CHP units, while most electricity is used for machine drive. [271] Where hydrogen is required to achieve product specifications or to convert heavier fractions of the crude oil into suitable processing feedstocks, it is primarily obtained by removing the carbon from light hydrocarbons such as natural gas, which produces process CO_2 emissions in addition to CO_2 emissions from fuel consumption. Thus, the reduction of refinery facility CO_2 will require decarbonizing process heating, onsite power generation, and onsite hydrogen production.

Self-produced fuel gas use is the major source of CO_2 emissions from a refinery; however, the carbon content of these fossil-fuel derived emissions is less than that of natural gas because of the presence of residual hydrogen gas from some of the processing units.

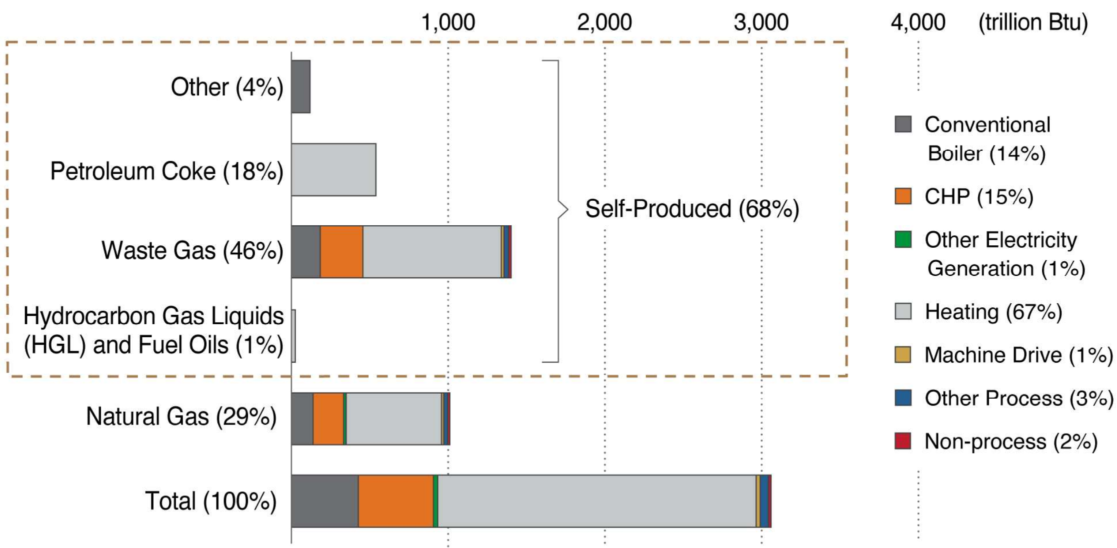

FIGURE 39. FUEL ENERGY CONSUMPTION AT U.S. PETROLEUM REFINERIES IN 2018, BROKEN OUT BY FUEL AND END USE[272]

Key message: Refineries self-supply most of their fuel demand, which places constraints on their fuel switching CO_2 reduction potential.

[270] "Manufacturing Energy and Carbon Footprint: Petroleum Refining (2018 MECS)," U.S. Department of Energy Advanced Manufacturing Office, December 2021, https://www.energy.gov/sites/default/files/2021-12/2018_mecs_petroleum_refining_energy_carbon_footprint.pdf; "Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data, U.S. Energy Information Administration, released 2021, https://www.eia.gov/consumption/manufacturing/data/2018/.
[271] Ibid.
[272] Ibid.

Figure 40 shows estimated energy consumption by the largest energy-consuming petroleum refining unit processes in 2019. The five largest energy-consuming refinery processes account for 85% of refinery energy consumption and associated CO_2 emissions.

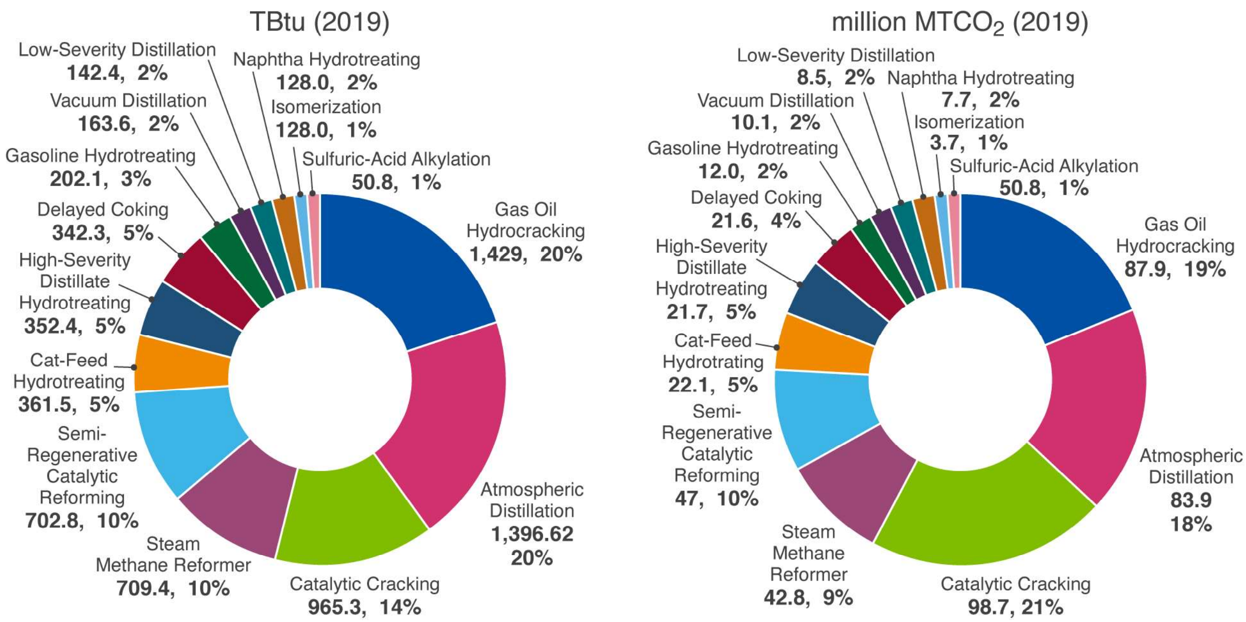

FIGURE 40. U.S. PETROLEUM REFINING ENERGY CONSUMPTION (LEFT) AND CO_2 EMISSIONS (RIGHT) BY PROCESS IN 2019[273]

> *Key message: Most refinery CO_2 emissions are from large point-sources where CO_2 reductions will be more cost-effective than from smaller refinery point-sources.*

[273] U.S. Department of Energy Advanced Manufacturing Office, *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Petroleum Refining*, DOE/EE-1230, June 2015, https://www.osti.gov/biblio/1248754-bandwidth-study-energy-use-potential-energy-savings-opportunities-petroleum-refining; "Manufacturing Energy and Carbon Footprint: Petroleum Refining (2018 MECS)," U.S. Department of Energy Advanced Manufacturing Office, December 2021, https://www.energy.gov/sites/default/files/2021-12/2018_mecs_petroleum_refining_energy_carbon_footprint.pdf; "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 24. Refining Industry Energy Consumption.

As Figure 41 shows, EIA's Annual Energy Outlook 2020 Reference Case projects U.S. petroleum refinery energy consumption and CO_2 emissions out to 2050. The total energy consumption is a function of demand for liquid transportation fuels, with both the ratio of energy source and associated CO_2 emissions remaining relatively constant.

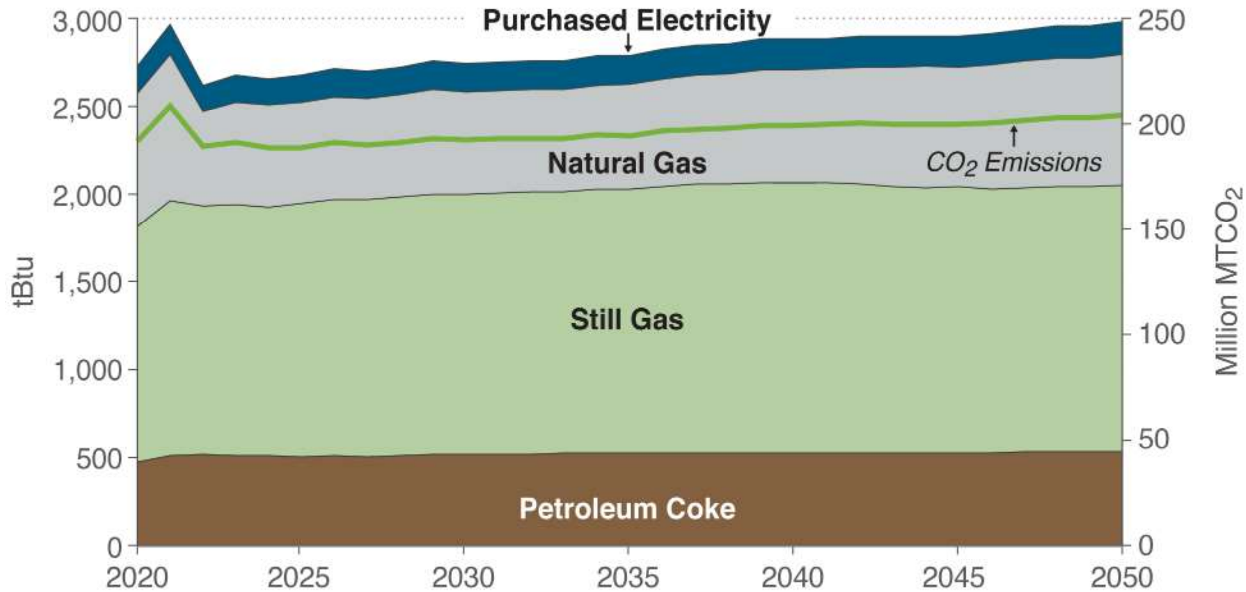

FIGURE 41. EIA ANNUAL ENERGY OUTLOOK 2020 REFERENCE CASE PROJECTION OF U.S. PETROLEUM REFINING ENERGY CONSUMPTION (IN TRILLION BTU) AND CO_2 EMISSIONS (IN MILLION MT) TO 2050.

SOURCE: AEO 2021.[274] NOTE: THE SCENARIOS IN THIS SECTION ARE BASED ON EIA AEO REFERENCE CASE WHICH ASSUMES BUSINESS AS USUAL, WHERE PETROLEUM PRODUCTION AND CONSUMPTION REMAINS CONSTANT. OTHER SCENARIOS NOT IN THIS ROADMAP INCLUDE DIFFERENT DEMAND SECTOR CHANGES WHICH NEED FURTHER ANALYSIS – SEE SECTION 4 FOR RECOMMENDED ADDITIONAL ANALYSIS NEEDS.

> *Key message: Projecting current energy markets and regulatory structures out to the year 2050, refinery CO_2 emissions remain consistent with transportation petroleum demand.*

2.4.2 Decarbonization Pathways for Petroleum Refining

Refineries will see similar opportunities; however, the range of decarbonization options will depend on each refinery's location, local policy, design, history, and technologies employed. The opportunities to reduce refinery GHG emissions can be grouped into the following areas:

- **Improve energy efficiency** both in processes and onsite steam and power generation.
- **Lower the carbon footprint of energy sources and feedstocks** by using lower-carbon fossil energy and introducing low-fossil carbon sources such as nuclear heat and electricity, clean electricity, clean hydrogen, or biofuels.
- **Capture CO_2** for either long-term storage or utilization.

[274] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 24. Refining Industry Energy Consumption.

Improving refinery energy efficiency is very much within refineries' control and builds on historical and ongoing efforts by the industry. For example, if efficiency measures were cost-effective, they could reduce GHG emissions from fuel use by 50%.[275] Even if major revamp or expansion projects were not specifically aimed at energy efficiency, they could provide decarbonization opportunities; however, drivers other than decarbonization may dictate the nature and timing of a potential implementation. Although the combustion of internally produced fuels generates GHGs, extracting useful energy from waste gases is significantly more efficient than the alternative, flaring; U.S. Environmental Protection Agency and state regulations limit routine flaring of gas. Furthermore, large changes to current refinery configurations often require new permitting which can discourage capital investments that are only marginally profitable. As a result, using waste gases is often the only available option. However, large integrated refineries also have the opportunity to change their product slate—through revamps—to more petrochemicals than fuels and use such revamps as a basis for decarbonization.

The other areas of opportunity relate to the industry's potential ability to take advantage of external opportunities (e.g., availability of affordable low-carbon feedstocks, technologies such as clean hydrogen, and carbon storage). Some of the potential technologies are not economic today, so the business case for them relies on cost reductions and regulatory or incentive frameworks. There are also uncertainties and tradeoffs between site potential (i.e., the degree to which a specific refinery could implement a specific option) and industry potential (i.e., the number of refineries that might have access to the external network or infrastructure supporting that option).

To understand how the application of the decarbonization pillars could help phase out net GHG emissions, the potential CO_2 reductions possible for refineries were examined, and several scenarios were developed and analyzed that were like those described for the other subsectors (see the introduction to this section). Figure 42 shows the results for scenarios in which energy intensity (gigajoules/barrel of oil) and potential CO_2 mitigation ranges found in the literature were applied to AEO 2021 projections of crude oil inputs to U.S. refinery distillation units and AEO 2021 projections petroleum fuel outputs quantities and mix of fuels do not change.[276]

[275] William R. Morrow III et al., "Efficiency Improvement and CO_2 Emission Reduction Potentials in the United States Petroleum Refining Industry," *Energy* 93, Part 1 (December 2015): 95-105. https://doi.org/10.1016/j.energy.2015.08.097.
[276] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 24. Refining Industry Energy Consumption.

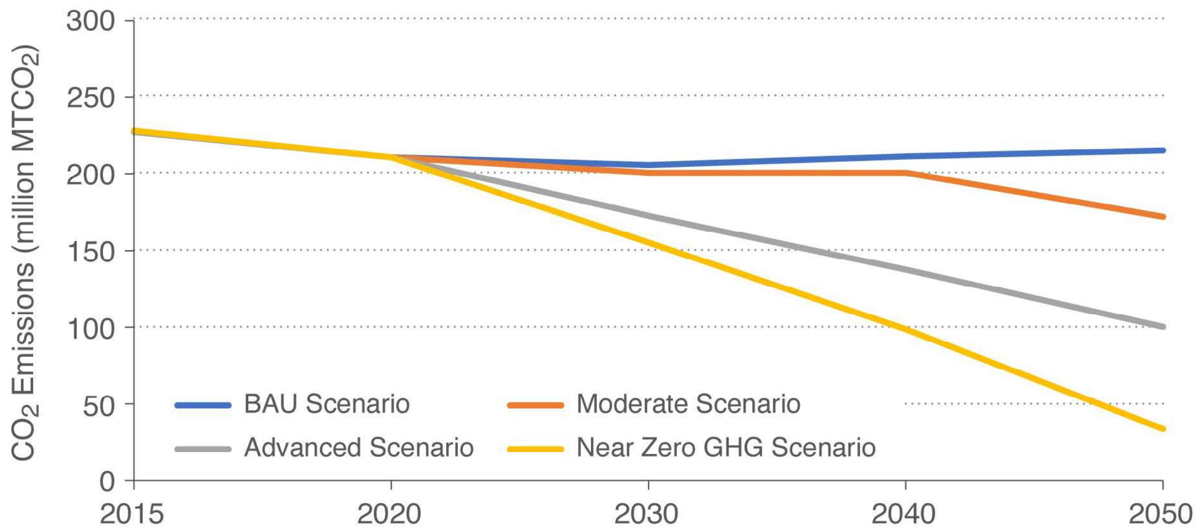

FIGURE 42. CO_2 EMISSIONS FORECAST THE U.S. PETROLEUM REFINING SUBSECTOR BY SCENARIO, 2015–2050.

SOURCE: THIS WORK.

> *Key message: Based on a recent in-depth analysis of EU refinery decarbonization RD&D options.*[277] *Similar U.S. technology RD&D has the potential to decarbonize roughly 80% of U.S. petroleum refining subsector CO_2 emissions by 2050.*

The BAU scenario assumes AEO 2021 projections of crude oil inputs are refined at the same energy intensity (GJ/barrel of oil) and carbon intensity (million MT CO_2/GJ) of U.S. refineries in 2015. The variation in BAU CO_2 emissions only reflects the variation in AEO 2021 projections of crude oil inputs between 2015 and 2050.

The Moderate Scenario applies AEO 2021 projections of refinery energy and carbon intensity through 2040, but it assumes the refining industry is 13% more energy efficient in 2050 than in 2015, based on the best available technology opportunities in a DOE refinery study.[278] The Advanced Scenario and the Near Zero GHG Scenario maintain the same efficiency improvements as the Moderate Scenario by 2020, but they ramp up to a more energy efficient refining industry by 2050 (relative to 2015) than the Moderate Scenario. Relative to 2015, the Advanced Scenario assumes a 28% more energy efficient refining industry by 2050. The 28% efficiency improvement is based on a recent EU refinery industry analysis for decarbonizing the EU refinery industry by 2050 that developed low, median, and maximum CO_2 mitigation scenarios through engagement with EU refiners.[279] For reference, EU refinery capacity is approximately 70% the size of U.S. refinery capacity.

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[277] Concawe, *CO_2 Reduction Technologies: Opportunities within the EU Refining System (2030/2050): Qualitative and Quantitative Assessment for the Production of Conventional Fossil Fuels (Scope 1 & 2)*, Concawe Report No. 8/19, July 2019, https://www.concawe.eu/wp-content/uploads/Rpt_19-8.pdf.

[278] U.S. Department of Energy Advanced Manufacturing Office, *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Petroleum Refining*, DOE/EE-1230, June 2015, https://www.osti.gov/biblio/1248754-bandwidth-study-energy-use-potential-energy-savings-opportunities-petroleum-refining.

[279] Concawe, *CO_2 Reduction Technologies: Opportunities within the EU Refining System (2030/2050): Qualitative and Quantitative Assessment for the Production of Conventional Fossil Fuels (Scope 1 & 2)*, Concawe Report No. 8/19, July 2019, https://www.concawe.eu/wp-content/uploads/Rpt_19-8.pdf.

The Near Zero GHG Scenario assumes a 38% more energy efficient refining industry by 2050 based on state-of-the-art technology opportunities in DOE's refinery energy bandwidth study.[280] A 38% more energy efficient refining industry in 2050 relative to 2015 represents an additional 33% efficiency improvement beyond the 4% improvement found in AEO 2021 projections for 2050.

The Advanced Scenario and the Near Zero GHG Scenario both assume electrification, fuel switching, and carbon capture can reduce U.S. refinery energy consumption and CO_2 emissions by an amount similar to levels anticipated to be possible in the EU refining industry. These levels are based on a recent EU refinery industry analysis for decarbonizing the EU refinery industry by 2050 that developed low, median, and maximum CO_2 mitigation scenarios through engagement with EU refiners.[281] In the EU mitigation scenarios, energy savings from electrification and fuel switching range from 18% to 28%, and carbon capture range from 21 to 87 million MT CO_2 in 2050. The Advanced Scenario assumes an 18% energy reduction from electrification and fuel switching by 2050 and that 35 million MT CO_2 are captured in 2050. The Near Zero GHG Scenario assumes a 21% energy reduction from electrification and fuel switching by 2050 and that 80 million MT CO_2 are captured in 2050.

Figure 43 shows the Near Zero GHG Scenario mitigation potential for the pillars in 2050 where a concerted effort is applied to further develop these solutions with focused RD&D efforts, trials, and a drive for deployment.

[280] U.S. Department of Energy Advanced Manufacturing Office, *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Petroleum Refining*, DOE/EE-1230, June 2015, https://www.osti.gov/biblio/1248754-bandwidth-study-energy-use-potential-energy-savings-opportunities-petroleum-refining.

[281] Concawe, *CO_2 Reduction Technologies: Opportunities within the EU Refining System (2030/2050): Qualitative and Quantitative Assessment for the Production of Conventional Fossil Fuels (Scope 1 & 2)*, Concawe Report No. 8/19, July 2019, https://www.concawe.eu/wp-content/uploads/Rpt_19-8.pdf.

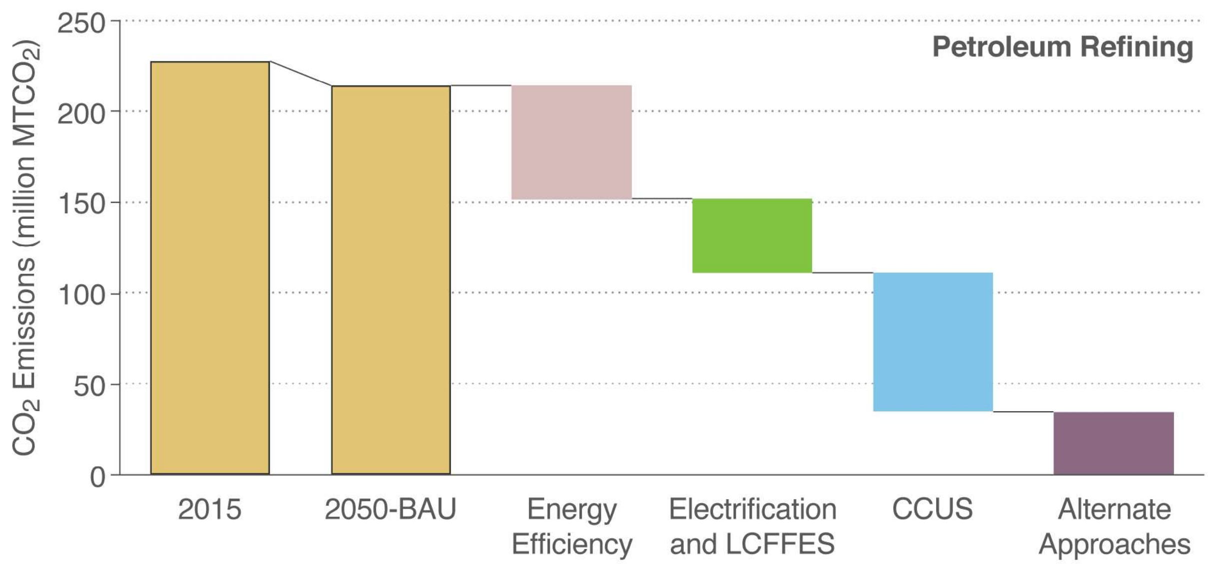

FIGURE 43. IMPACT OF THE DECARBONIZATION PILLARS ON CO_2 EMISSIONS (MILLION MT/YEAR) FOR THE U.S. PETROLEUM REFINING SUBSECTOR, 2015–2050.

THE SCENARIOS APPLY A PERCENT REDUCTION OF EU REFINERY CO_2 EMISSIONS FROM RECENT IN-DEPTH EU REFINERY DECARBONIZATION STUDIES[282] TO U.S. REFINERIES PETROLEUM REFINING CO_2 EMISSION PROJECTIONS (FIGURE 41) AS AN ESTIMATE OF U.S. REFINERY CO2 REDUCTION POTENTIALS BETWEEN 2020 AND 2050. SUBSECTOR EMISSIONS ARE ESTIMATED FOR BUSINESS AS USUAL (BAU) AND NEAR ZERO GHG SCENARIOS. SINCE INDUSTRIAL ELECTRIFICATION AND LCFFES TECHNOLOGIES AND STRATEGIES ARE STRONGLY INTERCONNECTED, THESE PILLARS WERE GROUPED FOR SCENARIO MODELING. THE "ALTERNATE APPROACHES" BAND SHOWS FURTHER EMISSIONS REDUCTIONS NECESSARY TO REACH NET-ZERO EMISSIONS FOR THE SUBSECTOR. THESE ALTERNATE APPROACHES, INCLUDING NEGATIVE EMISSIONS TECHNOLOGIES, ARE NOT SPECIFICALLY EVALUATED IN SCENARIO MODELING FOR THIS ROADMAP. THE POWERING OF ALTERNATE APPROACHES WILL ALSO NEED CLEAN ENERGY SOURCES (E.G., DIRECT AIR CAPTURE COULD BE POWERED BY NUCLEAR, RENEWABLE SOURCES, SOLAR, WASTE HEAT FROM INDUSTRIAL OPERATIONS, ETC.).DETAILS ON ASSUMPTIONS, PARAMETERS, AND TIMING OF TRANSFORMATIVE TECHNOLOGY APPLICATION CAN BE FOUND IN APPENDIX 1.4. SOURCE: THIS WORK.

> *Key message: Assuming the technologies identified in the EU studies and presented in this roadmap are deployed in U.S. refineries, U.S. petroleum refining CO_2 emission reductions between 2020 and 2050 are presented by decarbonization pillar and alternate approaches.*

These scenarios illustrate that the decarbonization pillars combined can dramatically reduce CO_2 emissions, yet even with CCUS, a small emissions footprint will need to be offset. Energy efficiency can play a significant role throughout the 30-year transformation with a proportionally large early impact. Hence, it is important to push early RD&D on ways to realize these reductions. Electrification of process heat, processes, motors, and other applications with the electricity coming from low-carbon sources can have contributed to CO_2 reductions across the decades. The generation of hydrogen from these sources (e.g., electrolysis) can substantially contribute to this reduction potential. As already noted, the levels of electrification and LCFFES assumed were moderate based on the literature. The level of CCUS reductions will depend on the successful capture of the remaining CO_2 from large emitters, as well as aggregation of some other sources. As with chemical manufacturing, petroleum refining can involve thousands of emissions sources and capture from all of them would unlikely be feasible or economic. Applying low-

[282] Concawe, *CO_2 Reduction Technologies: Opportunities within the EU Refining System (2030/2050): Qualitative and Quantitative Assessment for the Production of Conventional Fossil Fuels (Scope 1 & 2)*, Concawe Report No. 8/19, July 2019, https://www.concawe.eu/wp-content/uploads/Rpt_19-8.pdf.

net GHG emission feedstock alternatives to crude oil, including converting captured CO_2 into liquid fuels, requires sustained RD&D throughout the 30-year time frame to obtain their benefits by 2050.

2.4.3 Barriers and Opportunities for Petroleum Refining

Numerous barriers, many of which have connections to RD&D needs, were mentioned during the stakeholder meetings. For example, refineries rarely decommission an existing process unit unless it is no longer needed. And expansion is only driven by market expansion, refinery consolidation, or regulatory changes related to point sources emissions or fuel specifications. Considering the challenge of long equipment lifetimes and strategies that use existing capital and infrastructure (e.g., LCFFES, electrification, energy efficiency) will be crucial for near- and mid-term progress. Some low-net carbon resources like biomass are limited and or finite, and therefore must be used efficiently. The transition to transformative options will be challenged by capital intensity constraints, the interconnected footprint of refinery processes, market economics, and regulatory issues such as permitting—even if demonstrations prove that options are commercially viable.

Waste gas and petroleum coke are self-produced, captive sources of energy and therefore modifying current uses of waste gas and petroleum coke in refineries is limited by physical constraints – waste gas and petroleum coke will be produced due to the physics of refining crude oil. Subject to technological constraints – most refineries depend on waste gas and petroleum coke for process heating. And regulatory constraints –air quality flaring waste gas and permitting costs often exceed natural gas prices and international environmental laws increasingly restrict the use of petroleum coke in maritime shipping). These physical and technical constraints create unique microeconomics constraints which present a high hurdle for refinery capital investments.

Similarly, high capital investment makes it difficult to justify major investments at scale without significant performance and cost improvements (i.e., a high hurdle for newer technology). Smaller, modular, distributed production systems will have a hard time competing with the scale, integration, and high-capacity factors of current refineries, as all these elements are crucial to competitive economics. Likewise, the misconception of what low-carbon electricity can provide creates a barrier to electrification. For example, there is a misconception that the variable nature of some renewables is incompatible with current refinery processes and operations. Although the future costs for renewables might become competitive, grid-supplied electricity can be expensive on an equivalent Btu basis to less-expensive hydrocarbons such as self-produced waste gas. Many refineries export excess CHP-generated electricity to their local grid and recognize that they could become a net exporter of decarbonized electricity by adding carbon capture to their CHP capacity. While selling decarbonized electricity to the grid provides revenue (rather than the expenses of purchasing decarbonized electricity from the grid), being a net electricity supplier to the grid post-CCUS might not be cost-effective for refineries. If grid-scale, low-carbon, and or renewable electricity is inexpensive enough to displace refiner's waste gas fuels, then it is unlikely that the refiner's onsite CHP with CCS can generate low-carbon electricity inexpensive enough to be competitive in electric grid energy markets or capacity markets. Even if a refiner's low-carbon resource is competitive in an ancillary services market or spinning reserve market, a low return-on-investment might preclude the refiner's participation.

For many refinery capital investments, self-produced fuels frequently dominate cost-effectiveness metrics and capital investment decisions. Depending on the individual refinery operations, refinery cost-effectiveness price points can range from a) current natural gas spark spread prices, down to b) $0/kWh, or $0/therm if the refinery has excess CHP capacity, or c) a negative price point (e.g., -$30/MT NO_X

equivalent) if a refinery must incinerate self-produced fuels to purchase low-carbon and or renewable electricity from the grid.

Understanding the unique petroleum refining microeconomics will be crucial in improving refineries GHG emission reduction efforts. For example, energy efficiency measures that reduce both fuel and electricity end use demands without disrupting this energy ratio are the most viable strategies to implement.

By incorporating nuclear energy into a refinery, the low cost, high quality thermal energy can displace emissions produced by burning waste gas for heat. Instead of burning waste gas for heat, the waste gas may be recycled into refining processes for improving product yield or sequestering the carbon in material products. Nuclear plants produce electricity that is competitive on the grid, but nuclear plants produce heat first, at a much lower cost per Btu. The nuclear plant can produce very low cost, clean heat for the chemical processes, as well as electricity for production of large quantities of clean hydrogen used in refining, further reducing carbon emissions at the refinery. Finally, nuclear plants can provide clean electricity for the refinery as well.

The best strategy for overcoming a refiner's cost-effectiveness metric (which is dictated by self-produced fuels) is finding new markets for waste gas and petroleum coke as feedstock revenue value streams that stay above the cost of natural gas while sequestering carbon in products like plastics, resins, and carbon fibers. The RD&D opportunity is to expand material markets or develop new materials that can sequester the carbon content of the ethane, propane, propylene components of refinery waste gases into products, instead of fuels.

The misconception that thermodynamics—such as equilibrium constraints in reverse water gas shift and methanol synthesis—prohibits cost and energetically efficient chemical reduction of CO_2 to CO can be overcome through novel biological and photochemical strategies, commonly referred to as "artificial photosynthesis" and conversion to liquid fuels. As RD&D on chemical, electrochemical[283], and bio-electrochemical reduction of CO_2 to CO expands internationally, advancements in artificial photosynthesis and/or bio-electro catalysts are overcoming this misconception. Though CCUS requires national coordination, efforts to utilize CO_2 locally could reduce the larger cost burdens of CCUS while also providing useful carbon for feedstock purposes. The use of captured CO_2 as a low-carbon refinery feedstock could be a game changer across multiple U.S. sectors once efficient reduction and conversion processes are developed. However, CO_2 conversion to liquid fuels is a long-term strategy with a need for continuous RD&D over a range of time horizons.

[283] Stephanie Nitopi et al., "Progress and Perspectives of Electrochemical CO_2 Reduction on Copper in Aqueous Electrolyte," *Chemical Reviews* 119, no. 12 (2019): 7610-7672. https://doi.org/10.1021/acs.chemrev.8b00705.

2.4.4 RD&D Needs and Opportunities for Petroleum Refining

This section explores the RD&D challenges and opportunities of the decarbonization pillars (energy efficiency, electrification and LCFFES, and CCUS) for decarbonization of the petroleum refining industry as well as the priority approaches.

Petroleum Refining Industry: Priority Approaches

Technology breakthroughs needed in the petroleum refining industry include integration and control with variable power that can be implemented reliably 24/7, electrolyzer efficiency, and drop-in low-carbon processes. Transformative process innovations are needed to yield new low-carbon ways of making hydrocarbon liquid fuels (including enhanced reuse of CO_2), lubricants, and other products. Priority approaches include:

- RD&D to enhance the impact of low-capital solutions (energy, materials, system efficiency), distillation and separations innovations, and thermal transfer efficiency.
- Reduce fugitive methane emissions to near zero.
- Pursue zero-hydrogen desulfurization processes through RD&D for adsorbents, oxidative desulfurization, and electro-desulfurization.
- Provide RD&D support for a persistent push to improve the energy efficiency of processes, eliminate waste, and lower product-embodied carbon.
- Develop capabilities for produce low-net carbon emission liquid transportation fuels from low-net carbon feedstocks (such as CO_2 and clean hydrogen, biomass, and other wastes streams) at scales comparable to current refinery capacities.
- Develop capabilities for converting excess still gas into chemical feedstocks.
- Develop capabilities for centralized carbon capture.
- Develop capabilities for use of hydrogen for combustion in high-temperature process heat.

The next section synthesizes the discussion related to RD&D needs for the U.S. petroleum refining industry.

2.4.4.1 Crosscutting Opportunities and RD&D Needs for Petroleum Refining

- Hydrogen-related needs include embrittlement, unified standards for retrofits, applicability at furnaces with higher hydrogen in blends, material safeguarding and temperature control and management, and moisture post-combustion.
- CCUS could help meet multiple refinery decarbonization challenges by addressing scale and process, pulling multiple streams from smaller point sources, and tackling investment challenges.

- Non-thermal separation approaches continue to be a significant opportunity (e.g., using electrochemical potential or membranes to drive the process, instead of distillation). This could include dewatering, desulfurizing electrically driven processes such as ion separation, or generating induced charges on compounds to aid separation.
- Better analysis and metrics on carbon intensity across subsectors are needed, and consistency of metrics and assumptions is a key need for LCAs. For example, understandable, transparent, and generally accepted standardized metrics for GHG reporting would be beneficial to understanding the avoided carbon cost and would enable decarbonization. Such clarity could help aid market pull for low-carbon products.

2.4.4.2 Petroleum Refining Subsector-Specific RD&D Needs and Opportunities

- Continuous improvement through the implementation of a combination of measures and projects involving small to moderate capital expenditure is needed. Examples include catalyst improvements and hardware improvements such as new motors and heat exchangers, as well as energy management systems that combine equipment (e.g., energy measurement and control systems) with strategic planning, organization, and culture.
- Major capital projects are needed, including larger efficiency improvements reflecting changes to the technical configuration of individual refineries (e.g., extensive revamps of existing facilities and new process plants driven by changing refinery product output slates).
- Energy efficiency for distillation includes multicolumn progressive distillation, dividing wall columns (DWC), and heat-integrated distillation columns (HiDiC); these are mechanically complicated and better suited to fractionation of light products than crude. All are primarily new-build options.
- Separation technologies can achieve even greater energy efficiency improvements if RD&D overcomes membrane fouling and allows better separations of liquid streams (in addition to gaseous streams), including crude oil.
- Inter-unit heat integration and upgrading low-grade heat to higher temperatures have the potential to reduce GHG emissions if it reduces the need to produce heat through fuel fired furnaces and boilers. Mechanically driven heat pumps (e.g., vapor recompression) are currently suitable for upgrading low-grade heat. But RD&D is needed to extend heat pump technology to higher temperatures and alternatives to electrical power.
- Low- and zero-hydrogen desulfurization processes including adsorbents RD&D; specifically oxidative desulfurization processes that do not use hydrogen but may require high-energy feeds such as ozone or hydrogen peroxide.
    - Electro-desulfurization could be a disruptive concept for oil refining. RD&D activity is low, and it is barely beyond proof-of-concept using simple model feeds. Even if this were a research priority, it would take several decades to scale-up to practical application. It would also need large amounts of low-carbon electricity and its implications for product quality are not yet apparent.
- Reducing the combustion of petroleum coke and associated GHG emissions requires RD&D to commercialize new technologies. Examples include:

  - Advanced oxy-fueled fluidized catalytic cracker: a semicommercial technology capable of processing petroleum coke while mitigating GHG emissions.
  - Cold cracking: a laboratory-scale alternative technology using unconventional energies such as microwaves, ionizing radiation, photochemistry, or ultrasound.
  - Alternative uses for petroleum coke that allow refineries to switch to less carbon intensive gaseous fuels without petroleum coke combustion and GHG emissions leakage outside the refinery or industry net-zero GHG emissions framework.

- Developing a careful accounting of the diverted petroleum coke to ensure a reduction in refinery facility GHG emissions, because the current conversion of petroleum coke into other refinery products, such as diesel, jet fuel, and gasoline, is energy-intensive and might result in a net increase in refinery GHG emissions. Similarly, if petroleum coke is combusted outside refinery facilities it displaces a more carbon intensive fuel outside the refinery subsector to contribute to a net reduction in GHG emissions. Exporting petroleum coke outside the refining industry requires an even broader accounting system to prevent GHG emission leakage.

2.4.4.2.1 Efficient Use of Low-Carbon Energy

- Low-carbon energy can be refined into the current slate of refinery products (i.e., composition and energy density identical to petroleum-based gasoline, diesel, and aviation fuel) from non-fossil fuel feedstocks – such as biomass and or direct air captured CO_2 – using current conversion technologies. This is a realistic near-term option for lowering the carbon intensity of fuels. Especially some liquid transportation fuel markets that require energy dense fuels and or have limited options for fuel switching.[284]

- The supply of bio-feedstocks for low-carbon fuels and chemicals is limited by the quantity of biomass that can be grown. Traditional bio-energy crops like corn, soybeans, and other starch and oil seed crops produce both food and fuel: corn provides starch for ethanol and dried distiller grain for animal feed, and soybeans provide oil for renewable biodiesel and meal for animal feed. These crops have a limit on their ability to produce enough starch and vegetable oil, which often compete with food crops. The production of bio-energy crops can distort food production enough that their GHG mitigation benefits begin to diminish due to indirect land use changes as volumes of biofuel derived from traditional bio-energy crops approach roughly 10% of petroleum fuel volumes. To avoid GHG emission leakage and expand bio feedstocks beyond traditional bio-energy crops, the Bioenergy Technology Office (BETO) has been working with agricultural and forest residues, MSW, other organic wastes, and the development of dedicated energy crops – as well as developing transparent full life cycle accounting frameworks that includes supply chains validation measures and verification mechanisms for all of BETO's bio-feedstock pathways to fuels and chemicals. Even with these additional resources, biofuels cannot totally replace petroleum derived transportation fuels. Petroleum-based jet fuel accounts for about 9% of the current consumption of petroleum-based liquid transportation fuels.[285] BETO is focused primarily on the aviation subsector which requires energy dense fuels, has limited options for fuel switching, and the current volume of jet

[284] U.S. Department of Energy Bioenergy Technologies Office, *Sustainable Aviation Fuel: Review of Technical Pathways*, September 2020, https://doi.org/10.2172/1660415; Ralph Sims et al., *Fifth Assessment Report: Mitigation of Climate Change, Chapter 8 Transport*, Intergovernmental Panel on Climate Change, 2014, https://www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter8.pdf

[285] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 36. Transportation Sector Energy Use by Fuel Type Within a Mode.

fuel consumed in the U.S. can be displaced by bio-feedstock fuels. The demand for low-carbon transportation fuels can easily exceed the availability of bio-feedstocks, leaving very limited bio-feedstocks supply as a low-carbon energy resource for industrial decarbonization. Where liquid fuels are still used in refineries, switching to less carbon intensive gaseous fuels could reduce the demand for low-carbon feedstocks to liquid fuels, as well as reduce refinery facility GHG emissions.

- Looking beyond bio-feedstocks, other low-carbon energy feedstocks include hydrogen and captured CO_2.
    - Hydrogen can be used directly for heat and power. Improved recovery of hydrogen and liquid petroleum gas from fuel gas could reduce refinery GHG emissions, and/or the recovered products be sold as a petrochemical feedstock; however, this opportunity would be site-specific.
    - Captured CO_2 from point sources (e.g., cement process emissions), or from the atmosphere (e.g., direct air capture technologies), when combined with clean hydrogen, can be a feedstock for producing low-carbon hydrocarbon fuels with composition and energy density identical to the current slate of petroleum-based refinery products (e.g., gasoline, diesel, and aviation fuel) and utilized as low-carbon energy resources.
- All alternatives to petroleum feedstocks must compete with petroleum supply markets and highly variable petroleum prices. To be competitive in petroleum supply markets, lowering the cost of low-carbon energy conversion technologies and improving process conversion efficiencies will be required. Bio-feedstock life cycle accounting frameworks can help assess the net GHG emissions reduction potential across the life cycle for emerging, alternative bio-feedstocks used for low-carbon fuels. Consistent life cycle frameworks can also be used to apply lessons learned from existing biofuel production, which helps maintain public and private confidence in markets and investments. Significant public and private investment will be needed in refineries, supply chains, and end use technologies in manufacturing and other sectors like vehicles and aviation. The RD&D needs for developing life cycle and net-GHG accounting frameworks for alternative low-carbon feedstocks with new supply chains beyond bio-feedstock supply chains, include:
    - GHG accounting standards, metrics, and net-zero GHG accountability
    - Better information, sensors, and data processing, as well as coordination across multiple sectors, industries, and businesses.
- RD&D needs related to the conversion of alternative low-carbon feedstocks into fuels include:
    - Data science and process simulation RD&D for predictive modeling of alternative low-carbon energy resources, including reaction kinetics, complex mixtures with crude feedstocks, and predictive exploration of reaction space with new or unknown conditions, or materials/system performance; similarly, data science and simulation RD&D could identify reverse engineering solutions (e.g., working backwards from the final product desired to a low-carbon feedstock with low-carbon, high energy efficiency, yield, and sustainability).[286]

[286] U.S. Department of Energy Bioenergy Technologies Office, *Predictive Models and High-Performance Computing as Tools to Accelerate the Scaling-Up of New Bio-Based Fuels Workshop Summary Report,* 2020, https://www.energy.gov/sites/default/files/2020/11/f81/beto-scaleup-biofuels-wksp-report.pdf.

2.4.4.2.2 Electrification and Increased Use of Low-Carbon Electricity

- Using clean electricity to produce hydrogen with electrolyzers could lower GHG emissions from SMR that currently supplies refinery hydrogen.
- Increased use of electricity for general operations or offsetting current steam driven rotating machines could lower GHG emissions from refinery boilers. Displacement of a portion of the steam generation capacity at refineries by clean electricity could be a route to reduce refinery boiler loads and thus reduced GHG emissions. Substitution of fired boilers and heaters by electric heaters could reduce point source GHGs or other pollutants within refineries.
    - Medium- and high-pressure steam boilers compete with low-cost, self-produced refinery waste gases and would require RD&D to lower the capital cost enough to become cost-effective in the long-term.
    - A refinery in the right location could benefit from generating its supplemental energy from solar or wind assuming the variability of supply, need for firm capacity, and use of storage can be lowered enough for this option to be cost-effective. In many cases, direct solar thermal supplemented with fuels produced onsite can provide process heat and may be more cost-effective and easier to integrate with current refinery energy utility systems.
    - Embedded modular nuclear reactors that are customized for the temperature duties of distillation, fluid-catalyst-cracker regeneration, and reforming waste gases would significantly reduce the carbon footprint of refineries.
    - Displacement of a portion of the steam generation capacity at refineries by clean electricity could be a route to reduce refinery boiler loads and thus reduced GHG emissions, if advancements in clean electricity overcome the spark spread between natural gas and electricity prices.
- Plant wide energy storage of thermal energy and electricity could overcome the variability of imported renewable electricity or reliable nuclear generated electricity. In many cases, using direct solar thermal energy and available onsite fuels as supplements to provide process heat may be more cost-effective and easier to integrate with current refinery energy utility systems. A recent Energy Storage roadmap describing the technical, workforce, and policy advances will be a helpful starting point to spur implementation as well as additional RD&D.[287]
    - The large-scale adoption of electro-technologies and variable energy sources compete with continuous and reliable self-produced waste gases and their role in maintaining high unit operation capacity factors through refinery process integration.
    - Because generated waste gas is a natural by-product of petroleum refining, refiners must find a use for internally generated waste gas displaced by low-carbon electricity. If purchasing clean electricity from the grid is inexpensive enough to displace refinery waste gas fuels, then it is unlikely that an onsite refinery CHP and CCS unit can generate low-carbon electricity at prices low enough to sell back into any electric grid market (energy markets, capacity markets, ancillary service markets, spinning reserve markets,

[287] U.S. Department of Energy, *Energy Storage Grand Challenge Roadmap,* December 2020, https://www.energy.gov/sites/prod/files/2020/12/f81/Energy%20Storage%20Grand%20Challenge%20Roadmap.pdf.

etc.). But if it could, ensuring a net reduction in GHG emissions still requires careful accounting of onsite and offsite electricity generation, GHG emissions, and the energy and CO_2 displaced by refinery waste product fuels.

- Utilizing waste gas and petroleum coke as a feedstock for materials that can sequester carbon is a strategy for overcoming the dilemma of finding more efficient uses for self-produced refinery waste gases. RD&D can expand material markets beyond current refinery fuel uses and petrochemical feedstocks by identifying and developing new materials that sequester the carbon content of the ethane, propane, propylene components of refinery waste gases into products.

2.4.4.2.3 Carbon Capture, Utilization, and Storage

2.4.4.2.3.1 Carbon Capture

- Carbon capture could provide significant reductions in refinery subsector emissions. Refinery GHG emissions come from a combination of several point sources within refinery facilities; the larger refinery sources of GHG emissions are large-fired heaters, fluidized catalytic cracker units, hydrogen plants, and gas turbines in CHP plants.
- Although an individual refiner's GHG emissions can be large in aggregate, by power-industry standards, refinery point sources are quite small. Process fired heaters are individually smaller, with the flue gases being combined and ducted to a common stack in some cases.
- CO_2 concentration also varies significantly from concentrated streams from hydrogen plants (actual concentration depends on the technology) to low concentration combustion flue gases.
    - Candidates for cost-effective carbon capture revamp are the larger point sources units. The cost of capturing refinery CO_2 emissions increases as the CO_2 source (stream or concentration) decreases.
    - The most cost-effective approach to capturing refinery facility CO_2 emissions will likely be a large, centralized, point source utility plant providing energy to refinery processes (e.g., a large SMR unit with carbon capture that produces hydrogen supplied to process fired heaters).[288]
    - RD&D is needed to better understand refinery facility carbon capture: the technical challenges, optimal deployment strategies, and operational constraints.
- RD&D is needed to overcome the significant integration required to deploy carbon capture—with and without hydrogen options—and implement at a significant scale.

2.4.4.2.3.2 Carbon Utilization

- The liquid transportation fuel market is the largest market that currently exists – by volume and revenue. If CO_2 can be recycled to a cost-competitive liquid hydrocarbon fuel, the incentive for capturing and transporting CO_2 will come from the largest market that currently exists. The market demand for low-net-CO_2 emissions liquid transportation fuels will be the incentive for the refinery subsector to capture, transport, and utilize captured CO_2 as a feedstock pathway towards low-net-CO_2 emissions liquid transportation fuels. The efficient utilization of CO_2 is a long-term, potentially

[288] Yuan Yao, et al., "Quantifying Carbon Capture Potential and Cost of Carbon Capture Technology Application in the U.S. Refining Industry," *International Journal of Greenhouse Gas Control* 74, (2018): 87–98. https://doi.org/10.1016/j.ijggc.2018.04.020.

game-changing, strategy for achieving net-zero GHG emissions across multiple sectors in the U.S. economy.

  - For example, the U.S. industrial sector emitted 1,360 million MT CO_2 and the U.S. transportation sector emitted 1,591 million MT of petroleum-based CO_2 in 2020.[289] Hypothetically, if half of the CO_2 emissions could be captured and recycled into liquid hydrocarbon fuels using clean electricity, the U.S. industrial sector's GHG emissions would then displace about 40% of the U.S. transportation sector's petroleum-based GHG emissions.

- The concept involves the conversion of captured CO_2 into syngas using hydrogen. The hydrogen required is made from water by electrolysis using renewable electricity. The CO_2/hydrogen conversion process uses the catalytic reverse water gas shift reaction, with final conversion to different products, mainly high-quality carbon-neutral jet fuel and distillates.

  - There is interest in further integrating and intensifying CCUS throughout a single refinery or chemical facility, a cluster of industrial facilities, or even with electrical power systems. Such an approach could use carbon near the point of capture in combination with clean hydrogen to make a "recycled" fuel. Or it could involve regeneration of the captured molecule (e.g., alkanolamine) with process heat.

  - Develop CO_2 reduction technologies such as artificial photosynthesis and lowering the cost of processes for converting CO_2 into syngas from carbon captured with the refineries, or directly from the atmosphere.

  - The scientific challenges associated with CO_2 reduction and utilization warrant significantly more support than has been provided in the past decade. Although these sub-systems have been developed to pilot scale, or demonstrated in small commercial operations, RD&D is needed to continue lowering the energy requirements, increase CO_2 reduction efficiency by discovering new basic science breakthroughs, and integrate CO_2 reduction technologies with mature refinery operations.

  - To deploy CO_2 reduction technologies at scales similar to current refinery units' capacities, the RD&D target should be to reduce total system capital and operating cost to a price point that is competitive with petroleum based liquid fuels plus social cost of GHG emissions.

2.4.4.3 Technology Maturity and RD&D Needs for Petroleum Refining

Opportunities to reduce the carbon intensity of refinery products will require technological development to make the potential a reality at reasonable cost within necessary time horizons (2030 and 2050). The U.S. refining industry and its technology providers will continue to improve conventional refinery process technologies such as separation technologies, catalysts, and process additives, and refiners will invest in upgrades that phase out older technologies. Figure 44 shows the technology maturity and manufacturing scale of a select number of these opportunities.

[289] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 19. Energy-Related Carbon Dioxide Emissions by End Use.

In addition, in several areas, cross-sectoral and collaborative RD&D might accelerate the development and deployment of technologies such as low-grade heat-recovery, electrical process heating, clean hydrogen, and CCUS. Even with such collaborative RD&D, refineries would need to attract investment to revamp existing infrastructure or build new plants to integrate developing technologies. This would require the support of a regulatory framework and an economic environment that justifies such investments. If stakeholders do not see a future for an industry, they will not invest no matter what the incentives are.

2.4.4.4 Timeline and Sequencing of RD&D Investments for Petroleum Refining

There are multiple opportunities for RD&D to accelerate the adoption of low-carbon approaches and technologies, and to enable supporting infrastructure as already described. For each of the decarbonization pillars, there are near-, mid-, and longer-term solutions that need to be deployed, developed, envisioned, and supported through development stages (Figure 45).

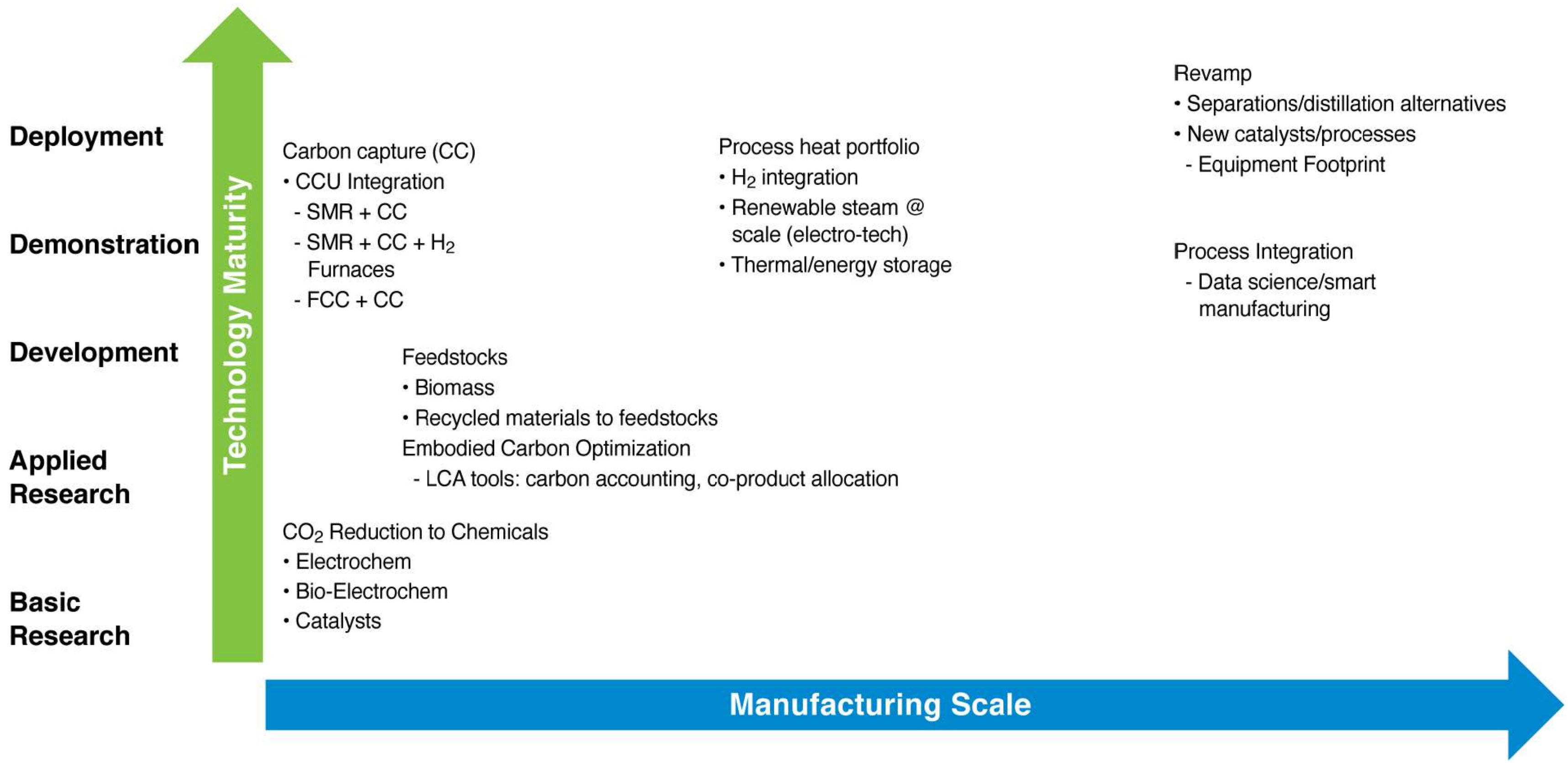

FIGURE 44. TECHNICAL MATURITY LEVELS OF DECARBONIZATION TECHNOLOGIES FOR THE PETROLEUM REFINING SUBSECTOR

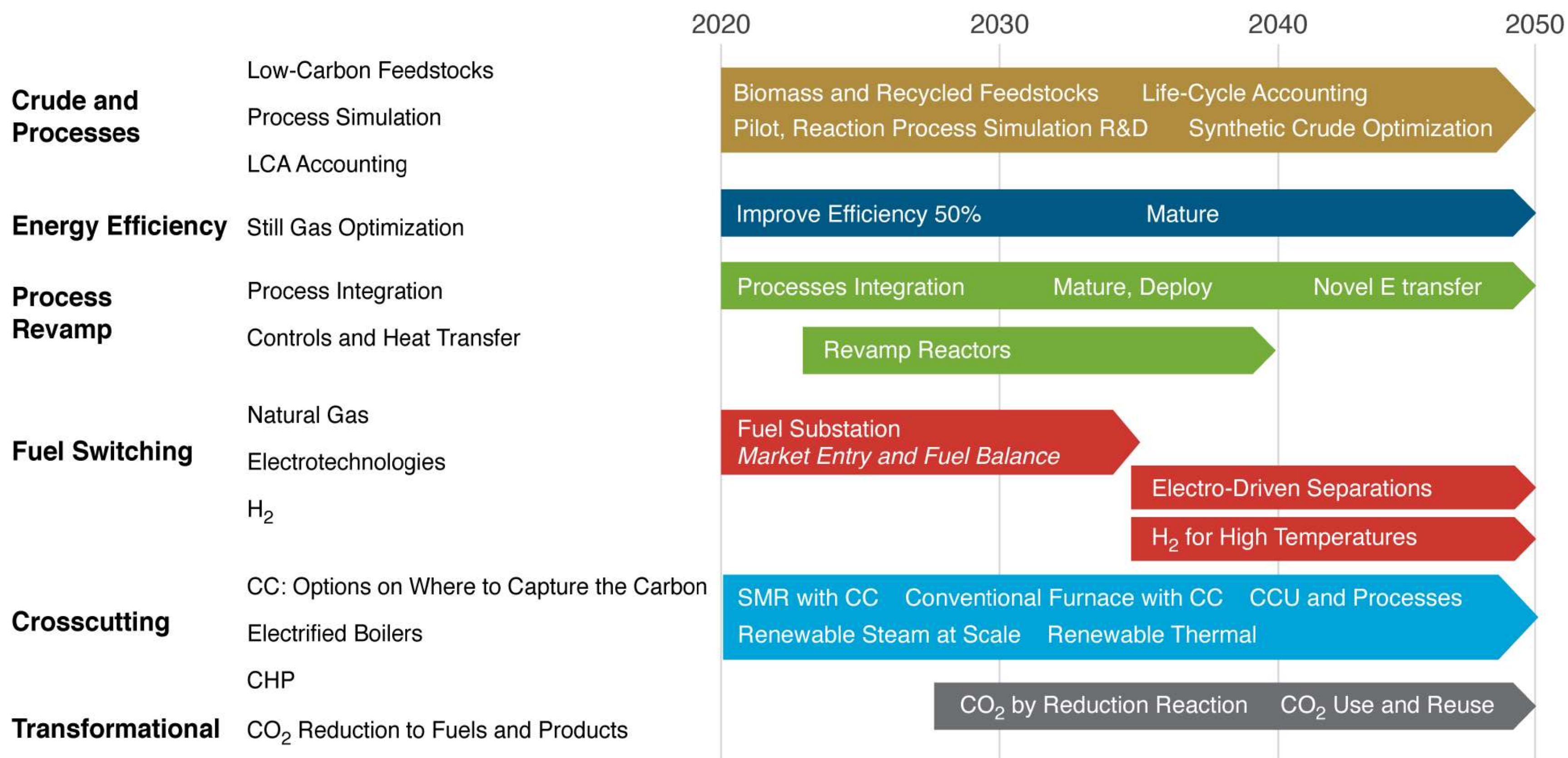

FIGURE 45. SEQUENCE OF RD&D INVESTMENTS OPPORTUNITIES BY DECADE FOR THE PETROLEUM REFINING SUBSECTOR

2.4.5 Proposed RD&D Action Plan for Petroleum Refining

A low-carbon petroleum refining industry requires the contemporaneous pursuit of several paths over the next few decades (Figure 46). Because of the high degree of already invested capital and the costs of reconfiguring refineries, action is required on many fronts to move the industry toward decarbonization. And RD&D can play a crucial role over the next 30 years by lowering adoption hurdles, reducing implementation costs, and revealing synergies that provide societal benefits. The transformation will not be fast, yet there are near-term opportunities that, if pursued fervently, could provide a fast start on GHG emissions reductions. There is strong interest in pursuing reductions now; however, with inexpensive fuels and feedstocks supporting current technologies and processes, the support for this transition—and the associated RD&D—will need to be focused, durable, visionary, collaborative, and applied to drive low-carbon solutions to commercial scale. There are myriad RD&D needs to make step-change GHG emissions reductions over the next 30 years, and many parallel activities to launch. An evolving RD&D strategy increases the likelihood of success given the complexity of refinery processes and facilities, the already efficient status of hydrocarbon-based fuels, and the complicated supply chain and market interdependencies in which refiners compete.

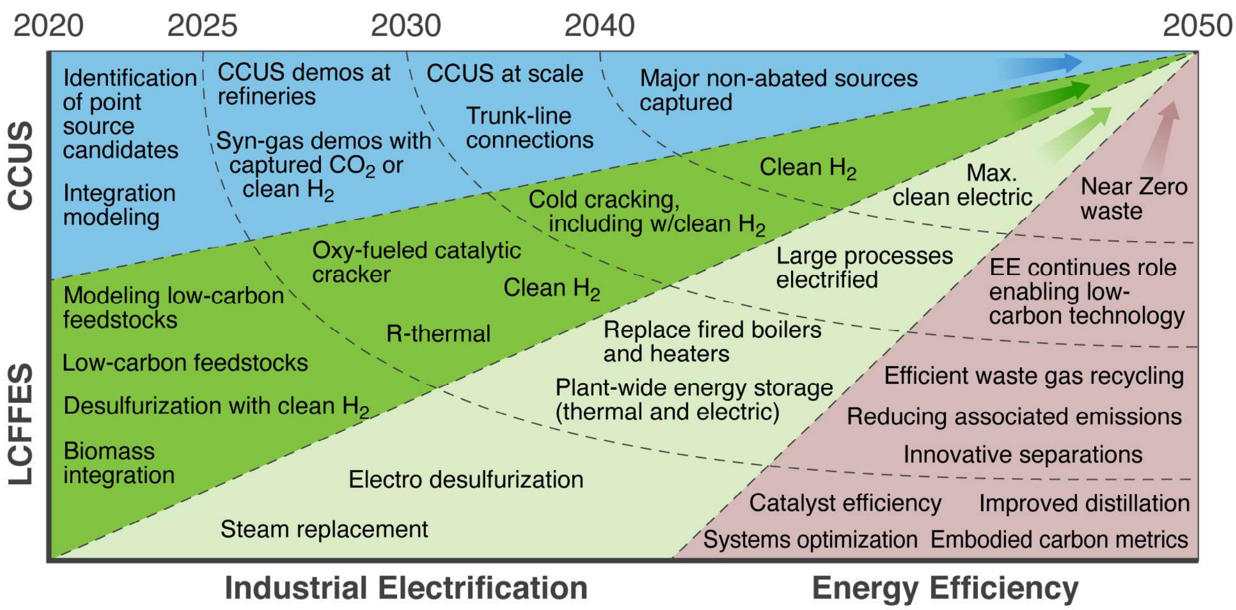

FIGURE 46. LANDSCAPE OF RD&D ADVANCEMENT OPPORTUNITIES BY DECADE AND DECARBONIZATION PILLAR FOR THE U.S. PETROLEUM REFINING SUBSECTOR NOTED BY ATTENDEES AT THE ROADMAP VIRTUAL SESSIONS.

LCFFES INCLUDES CLEAN TECHNOLOGIES THAT DO NOT RELEASE GHGS TO THE ATMOSPHERE FROM THE PRODUCTION OR USE OF ENERGY SOURCES, AND INCLUDE RENEWABLE SOURCED ELECTRICITY, NUCLEAR ENERGY FOR ELECTRICITY AND HEAT, CONCENTRATING SOLAR POWER, AND GEOTHERMAL ENERGY. SOURCE: THIS WORK.

As a starting point for decarbonization of the U.S. petroleum refining industry, the following are proposed RD&D actions, presented in order from near-term to longer-term impacts.

RD&D needs with **near-term (2020–2025)** impacts include:

- Enhance the impact of:
    - Low-capital solutions (energy, materials, system efficiency).
    - Distillation and separations innovations.
    - Thermal transfer efficiency.
    - Plug-in exchange of low-carbon energy sources for higher ones, and apply electrification where there are low hurdles (e.g., low temperature process heat) by advancing applications of RD&D.
- Pursue low-GHG emission alternative feedstock by:
    - Further advancing supply-chain data.
    - Supporting technology RD&D development/deployment.
    - Developing robust GHG accounting mechanisms (e.g., LCA) that increase the effectiveness low-carbon solutions and supply-chain systems efficiency to avoid GHG leakage.
- Pursue zero-hydrogen desulfurization processes through RD&D for adsorbents, oxidative desulfurization, and electro-desulfurization.
- Reduce fugitive methane emissions to near zero.
- Research how industry might more effectively use variable energy such as with storage and develop and deploy with partners routes to readily implement switching and blending intermediate solutions.
- Advance more effective electrolyzers for hydrogen, chemical processes, novel energy transfer, innovation separations (including those using electricity).
    - Water splitting is commercial but needs to be improved to lower costs.
- Pursue trials at advantaged locations (e.g., industrial clusters) to lower hurdles.
- Research, with industry, integration of heat to lower CCUS implementation costs.

RD&D needs with **mid-term (2025–2030)** impacts include:

- Invest in RD&D of electrification and low-carbon energy sources for processes and feedstock changes.
- Invest in RD&D of processes to produce hydrogen from renewable and nuclear sources (e.g., electrolysis) and RD&D of carbon capture for use as a feedstock for liquid fuels.
- Develop capabilities for use of hydrogen for combustion use in high-temperature process heat.
- Research improved routes to rapidly scale-up transformative technologies.

- Provide RD&D support for a persistent push to improve the energy efficiency of processes, eliminate waste, and lower product-embodied carbon.

RD&D needs with **longer-term (2030–2050)** impacts include:

- Invest in RD&D that will transform the refinery subsector with new low-carbon ways of making low-net-carbon hydrocarbon liquid fuels, lubricants, and other refinery products by 2050 such as:
    - An energy efficient and cost-effective reduction of CO_2 into a viable feedstock for conversion into hydrocarbon fuels and products that align with current infrastructure and end-product uses.
    - Application of high-grade heat produced by advanced nuclear reactors.
    - Research interface strategies for transformative technologies that can align with infrastructure of the future, including current hydrocarbon pipelines, future CO_2 pipelines, a decarbonized electric grid, and the availability of clean hydrogen.
    - Anticipate tradeoffs in market availability for precursors, feedstocks, and materials.
    - Deepen the understanding of what is critical to rapidly scale technologies; improve the efficacy of retrofits where other options are not viable.

2.5 Cement Manufacturing

2.5.1 Status of the U.S. Cement Industry

Cement Manufacturing Subsector: Key Takeaways

- U.S. cement manufacturing subsector GHG emissions can decrease to almost zero in 2050 under the Near Zero GHG emissions scenario, while U.S. cement production increases by 46% during the same period.
- Around 65% of total GHG emissions reduction needed to get to near zero in 2050 comes from adoption of CCUS.
- Aggressive RD&D, pilot, and demonstration are needed for CCUS and innovative chemistry (mainly replacing clinker with supplementary cementitious materials [SCMs] for cement production) to realize the net-zero GHG emissions goal by 2050.

In 2020, the United States produced 87 million MT of Portland cement and 2.3 million MT of masonry cement at 96 plants in 34 states.[290] Of those, 86 plants employed the dry kiln process and nine used the wet kiln process.[291] In 2020, sales of cement were around $12.7 billion and consumption was about 102 million MT.[292] Texas, Missouri, California, and Florida have the highest cement production, in that order, and they account for about 45% of U.S. cement production.[293]

In 2015, the U.S. cement industry used around 279 TBtu of heat from fuel combustion and 39 TBtu of electricity (see Figure 47), which represented a 19% decrease in fuel consumption and a 9% drop in electricity consumption from 2000.[294] The drops in energy use were primarily due to upgrades to more energy-efficient production technologies, retirement of a few older inefficient plants, construction of a few new state-of-the-art plants, and a slight (around 4%) reduction in U.S. clinker and cement production from 2000 to 2015.[295]

Coal is the primary fuel for the U.S. cement industry. Figure 47 shows the share of different energy types used in U.S. cement manufacturing in 2015. Heat from fuel combustion accounted for 88% of total final energy consumption and electricity use accounted for the remaining 12%. Lime and cement production can be broken into two major steps: the precalciner (600-700°C) and rotary kiln (1200-1400°C) for clinker production. The majority of the CO_2 emissions are from the precalciner where the CO_2 comes from decomposition of the calcium/magnesium carbonates.

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[290] Ashley K. Hatfield, *Mineral Commodity Summaries: Cement*, U.S. Geological Survey, January 2021, https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-cement.pdf.
[291] Ali Hasanbeigi, Dinah Shi, and Harshvardhan Khutal, *Federal Buy Clean Policy for Construction Material in the United States*, 2021, https://www.aceee.org/sites/default/files/pdfs/ssi21/panel-4/Shi.pdf.
[292] Ashley K. Hatfield, *Mineral Commodity Summaries: Cement*, U.S. Geological Survey, January 2021, https://pubs.usgs.gov/periodicals/mcs2021/mcs2021-cement.pdf.
[293] Ibid.
[294] Hendrik G. van Oss, *2015 Minerals Yearbook: Cement*, U.S. Geological Survey, September 2018, https://d9-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/atoms/files/myb1-2015-cemen.pdf.
[295] Ibid.

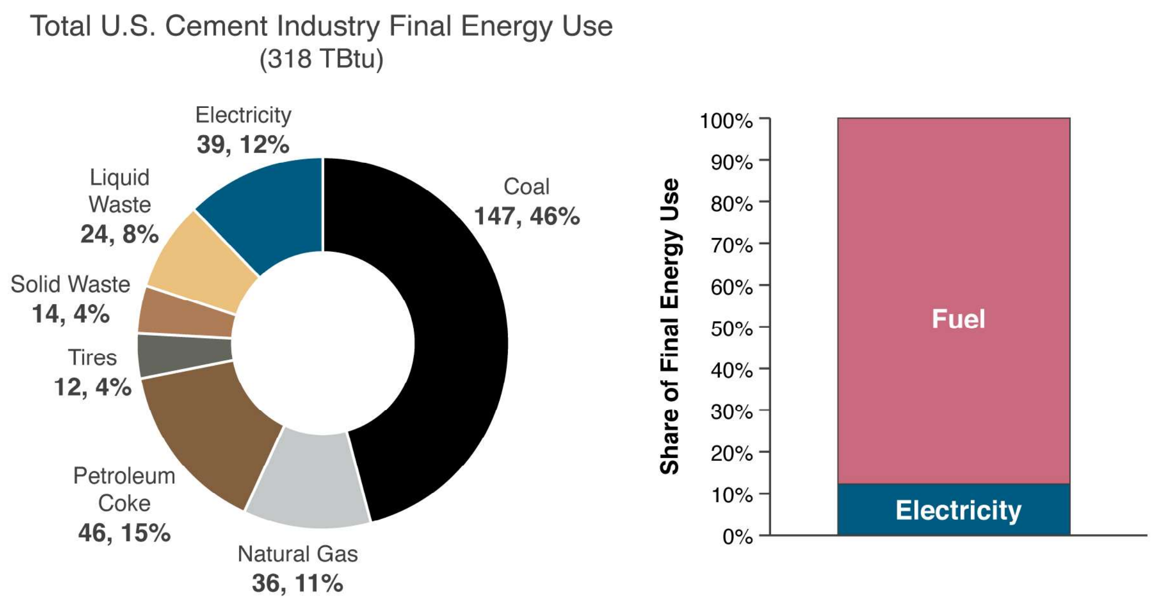

FIGURE 47. ENERGY MIX IN THE U.S. CEMENT INDUSTRY IN 2015.

NOTE: RECENT U.S. GEOLOGICAL SURVEY (USGS) DATA SHOW THAT THE SHARE OF NATURAL GAS CONSUMPTION BY THE CEMENT INDUSTRY INCREASED TO 46% AND COAL CONSUMPTION DECREASED TO 15% BETWEEN 2015 AND 2016 AND THAT BOTH REMAINED AT THESE LEVELS IN 2017. USGS DATA PROVIDES A BREAKDOWN OF FUEL SOURCES THAT ARE NOT AVAILABLE FROM OTHER PUBLIC DATA SOURCES. DATA SOURCE: USGS 2020[296]

> *Key message: A) Fossil fuels accounted for over 70% of the total energy used in the U.S. cement industry in 2015. B) Electricity only accounts for around 12% of total final energy use in the cement industry.*

In the U.S. cement industry in 2015, process-related CO_2 emissions from calcination accounted for 58% of total CO_2 emissions and energy-related CO_2 emissions accounted for 42% of total emissions. In other words, 58% of the CO_2 emissions from the U.S. cement industry were not associated with energy use (Figure 48).[297] Therefore, decarbonization in the cement industry cannot be achieved by the best available energy-efficient technologies or fuel switching alone. Deployment of technologies such as CCUS and innovative chemistry will be imperative to achieving near zero GHG emissions in cement production. Another key consideration is that electricity currently accounts for only 8% of total the U.S. cement industry's GHG emissions.

Additionally, cement manufacturing generates significant air pollutants (such as sulfur dioxide, nitrous oxide, or non-methane volatile organic compounds), which contribute to adverse health effects and can

[296] Clinker produced and fuel consumed by the U.S. cement industry by kiln process. Energy data from 2015 were used as the base line for the scenario analysis conducted as part of this decarbonization roadmap. See Table 7 of Hendrik G. van Oss, *2016 Minerals Yearbook: Cement*, U.S. Geological Survey, January 2020, https://d9-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/atoms/files/myb1-2016-cement.pdf.
[297] Ali Hasanbeigi and Cecilia Springer, *Deep Decarbonization Roadmap for California's Cement and Concrete Industry*, Global Efficiency Intelligence, September 2019, https://www.globalefficiencyintel.com/decarbonization-roadmap-california-cement-concrete.

negatively impact their local communities (typically in low-income, disadvantaged communities).[298] These air pollutants should be considered alongside GHG emissions as the cement industry decarbonizes.

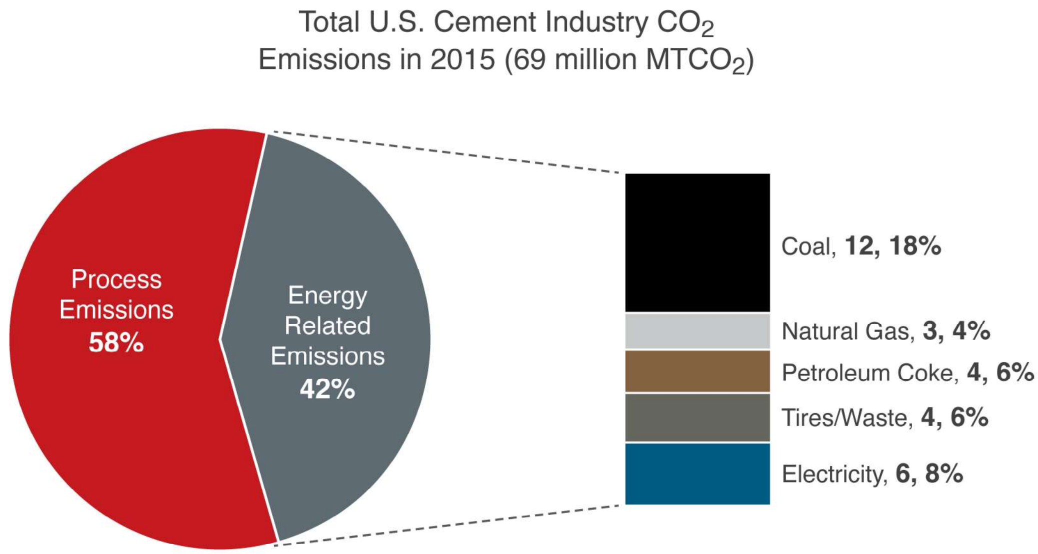

FIGURE 48. SOURCES OF CO_2 EMISSIONS IN THE U.S. CEMENT INDUSTRY IN 2015.

DATA SOURCE: ANALYSIS BASED ON USGS 2015 ENERGY USE DATA.[299]

> *Key message: A) Process-related emissions from calcination process account for 58% of total CO_2 emissions from the U.S. cement industry with the remainder of emissions coming from energy use. B) electricity only accounts for 8% of total CO_2 emissions from the U.S. cement industry.*

2.5.2 Decarbonization Pathways for the Cement Industry

To understand how application of the decarbonization pillars (energy efficiency, electrification and LCFFES, CCUS) could help phase out net GHG emissions, the potential CO_2 reductions for the cement industry were examined for each pillar. Electrification and LCFFES are highly connected and evaluated together for this roadmap. This roadmap also provides guidance on where RD&D could enable substantial reductions in GHG emissions. The topics of where to start on reductions, the relative impact of the decarbonization pillars, and priorities for RD&D were also of common interest across the stakeholder meetings.

Figure 49 shows a forecast of CO_2 emissions from the U.S. cement industry through 2050 for four scenarios: Business as Usual, Moderate Technology and Policy, Advanced Technology and Policy, and Near Zero GHG Emissions (see Appendix 1.5 for details).

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[298] Ali Hasanbeigi, Navdeep Bhadbhade, and Ahana Ghosh, *Air Pollution from Global Cement Industry: An International Benchmarking of Criteria Air Pollutants Intensities*, August 2022, https://www.globalefficiencyintel.com/air-pollution-from-global-cement-industry.

[299] Hendrik G. van Oss, *2016 Minerals Yearbook: Cement*, U.S. Geological Survey, January 2020, https://d9-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/atoms/files/myb1-2016-cement.pdf.

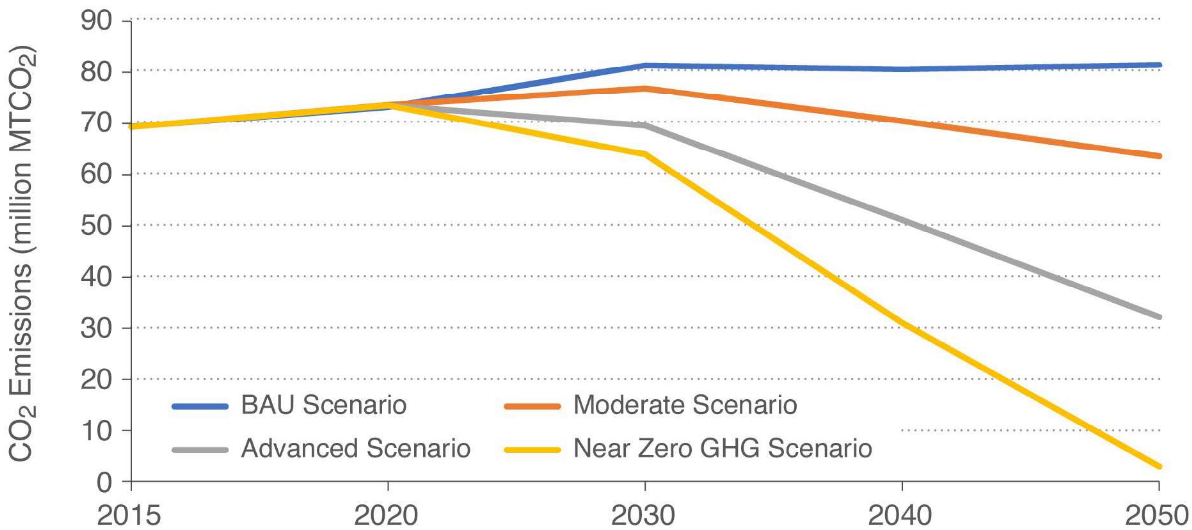

Figure 49. CO_2 emissions forecast for the U.S. cement industry by scenario, 2015–2050.

As described in Section 1.3, the business as usual (BAU) scenario assumes slow improvement; moderate assumes higher rates of energy efficiency, switching to lower-carbon fuels, electrification adoption, and some CCUS; Advanced assumes even higher rates; and near zero assumes the most aggressive improvement and adoption rates. Details on assumptions, parameters, and timing of transformative technology application can be found in appendix 1.5. Source: This work.

> *Key message: In the Near Zero GHG scenario, the CO_2 emissions for the cement industry decreases by 96% from 69 million MT CO_2 per year in 2015 to 3 million MT CO_2 per year in 2050, while cement production in the U.S. increases by 46% during the same period.*

The definition of scenarios, assumptions on forecasts for production, energy intensities, fuel mix and other variables used in the analysis are described in Appendix 1.5. In the Business as Usual (BAU) scenario, the CO_2 emissions of the U.S. cement industry increase by 17% between 2015 and 2050. In the Advanced Technology and Policy scenario, the CO_2 emissions decrease by 54% from 69 million MT CO_2 per year in 2015 to 32 million MT CO_2 per year in 2050. This decrease in emissions occurs while U.S. cement production increases by 46% during the same period to continuously meet the needs of a growing population and expanding economy. In the Near Zero GHG scenario, more ambitious technology advancement and deployment assumptions were used, especially for CCUS.

Various factors contribute to the realization of significant CO_2 emissions reductions in each scenario. Figure 50 shows the contribution of the decarbonization pillars (energy efficiency, industrial electrification and LCFFES, and CCUS) to reduction in the U.S. cement industry's CO_2 emissions between 2015 and 2050 for the Near Zero GHG scenario. CCUS makes the largest contribution to CO_2 emissions reduction, followed by energy efficiency which also includes innovative chemistry (mainly replacing clinker with supplementary cementitious materials (SCMs) for cement production and extending the use of lower-carbon binders instead of Portland cement). The RD&D challenges and opportunities for each of the decarbonization pillars and technical requirements for their adoption in the U.S. cement industry are discussed in detail in the next section.

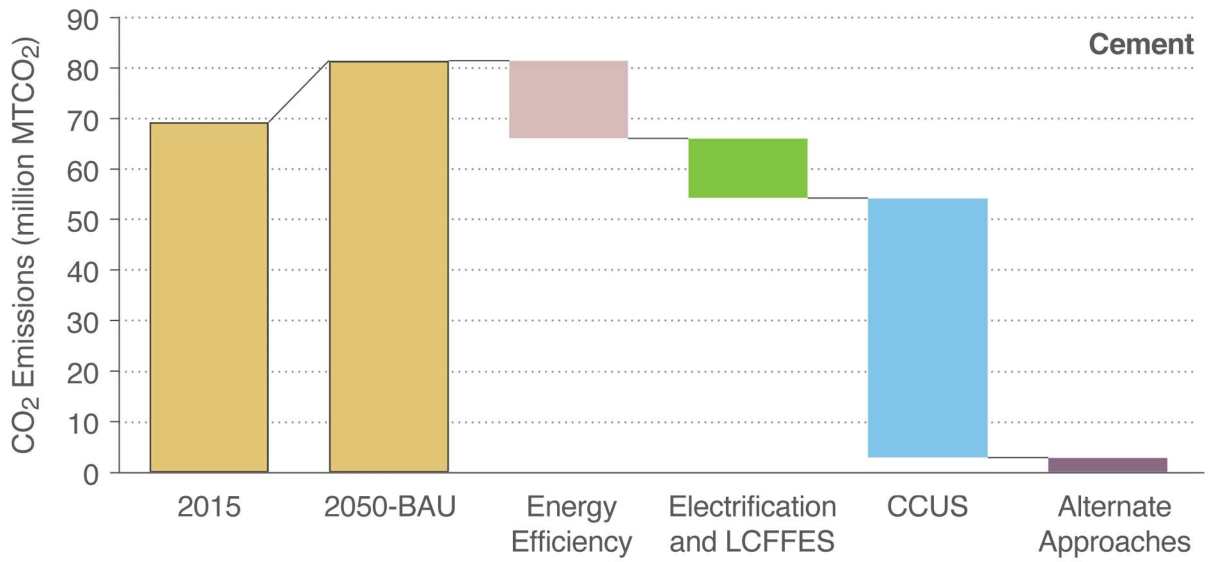

FIGURE 50. IMPACT OF THE DECARBONIZATION PILLARS ON CO_2 EMISSIONS (MILLION MT/YEAR) FOR THE U.S. CEMENT MANUFACTURING SUBSECTOR, 2015–2050.

SUBSECTOR EMISSIONS ARE ESTIMATED FOR BUSINESS AS USUAL (BAU) AND NEAR ZERO GHG SCENARIOS. SINCE INDUSTRIAL ELECTRIFICATION AND LCFFES TECHNOLOGIES AND STRATEGIES ARE STRONGLY INTERCONNECTED, THESE PILLARS WERE GROUPED FOR SCENARIO MODELING. THE "ALTERNATE APPROACHES" BAND SHOWS FURTHER EMISSIONS REDUCTIONS NECESSARY TO REACH NET-ZERO EMISSIONS FOR THE SUBSECTOR. THESE ALTERNATE APPROACHES, INCLUDING NEGATIVE EMISSIONS TECHNOLOGIES, ARE NOT SPECIFICALLY EVALUATED IN SCENARIO MODELING FOR THIS ROADMAP. THE POWERING OF ALTERNATE APPROACHES WILL ALSO NEED CLEAN ENERGY SOURCES (E.G., DIRECT AIR CAPTURE COULD BE POWERED BY NUCLEAR, RENEWABLE SOURCES, SOLAR, WASTE HEAT FROM INDUSTRIAL OPERATIONS, ETC.). DETAILS ON ASSUMPTIONS, PARAMETERS, AND TIMING OF TRANSFORMATIVE TECHNOLOGY APPLICATION CAN BE FOUND IN APPENDIX 1.5. SOURCE: THIS WORK.

> *Key message: CCUS makes the largest contribution to CO_2 emissions reduction (65% of total) followed by energy efficiency which also includes innovative chemistry (mainly replacing clinker with supplementary cementitious materials (SCMs) for cement production).*

2.5.3 RD&D Needs and Opportunities for the Cement Industry

This section explores the RD&D challenges and opportunities of the decarbonization pillars for the cement industry. RD&D could unlock new technologies for decarbonization and a DOE cement bandwidth study estimated that RD&D focused on energy efficiency, alternative raw materials, and other measures could lead to substantial energy intensity reduction for the U.S. cement industry.[300]

Cement Industry: Priority Approaches

To achieve the necessary decarbonization targets, the cement industry requires technology breakthroughs including new low-carbon manufacturing pathways, process electrification at scale, use of H_2, direct separation, carbon utilization and an enhanced circular economy approach for CO_2, and material reuse. Priority approaches include:

- Leverage relatively low-capital solutions (energy efficiency, SEM, and waste heat reduction/recovery solutions (WHP)).
- Probe routes to continue improving materials efficiency and flexibility including reuse, recycle, and refurbishment as well as innovative chemistry and blended cement with improved energy and emissions, CO_2 absorbing, and equivalent or better performance.
- Expand the infrastructure and integration capabilities and knowledge to capture, transport, and reuse CO_2 where possible (e.g., Oxy-combustion with CCUS, indirect calcination with CCUS, large scale carbon utilization for construction materials).
- Advance approaches to reduce waste, including the use of circular economy approaches for concrete construction.
- Increase use of low-carbon binding materials and natural SCMs.
- Develop additional routes for utilizing CO_2, including full scale deployment of carbon capture with innovative approaches such as calcium looping and use of membranes for CO_2 separation.

300 U.S. Department of Energy Advanced Manufacturing Office, *Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Cement Manufacturing*, September 2017, https://www.osti.gov/servlets/purl/1512370.

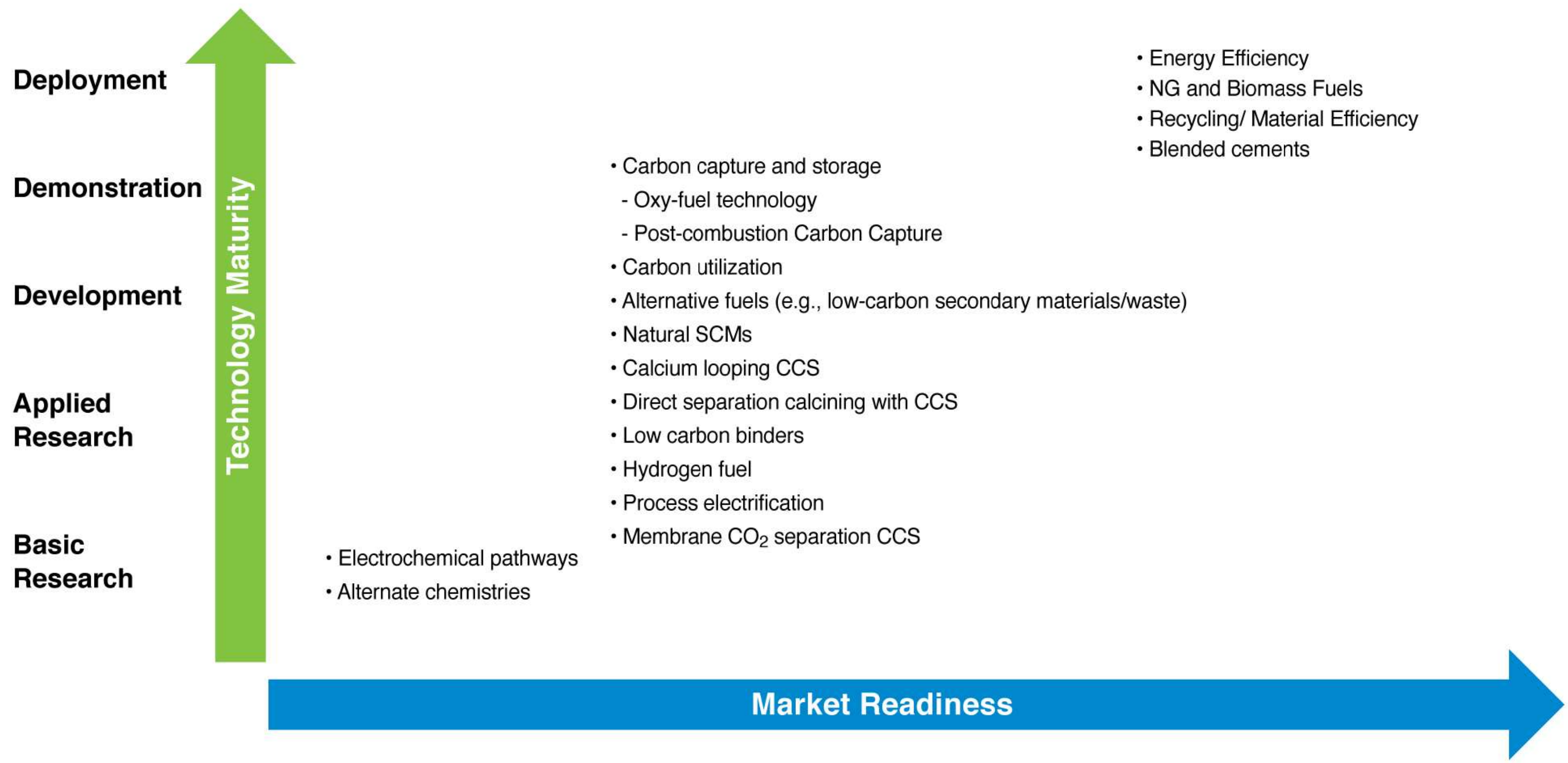

Figure 51. Technical maturity levels of select decarbonization technologies discussed during roadmap virtual meetings for the U.S. cement industry.

Participants provided input on the relative market readiness and technical maturing of these technologies during discussions. There is a distribution of technologies in several of these categories which broaden the placement of items. CCS: carbon capture and storage; SCM: supplementary cementitious material; NG: natural gas. Further definition of terms is provided in the glossary. Source: this work.

Key message: Energy efficiency, fuel switching to natural gas and biomass, and blended cement are at higher market readiness and have the highest potential for large scale deployment now. CCUS and process electrification need more RD&D support to become fully commercial and available for large scale deployment in mid- and long-term.

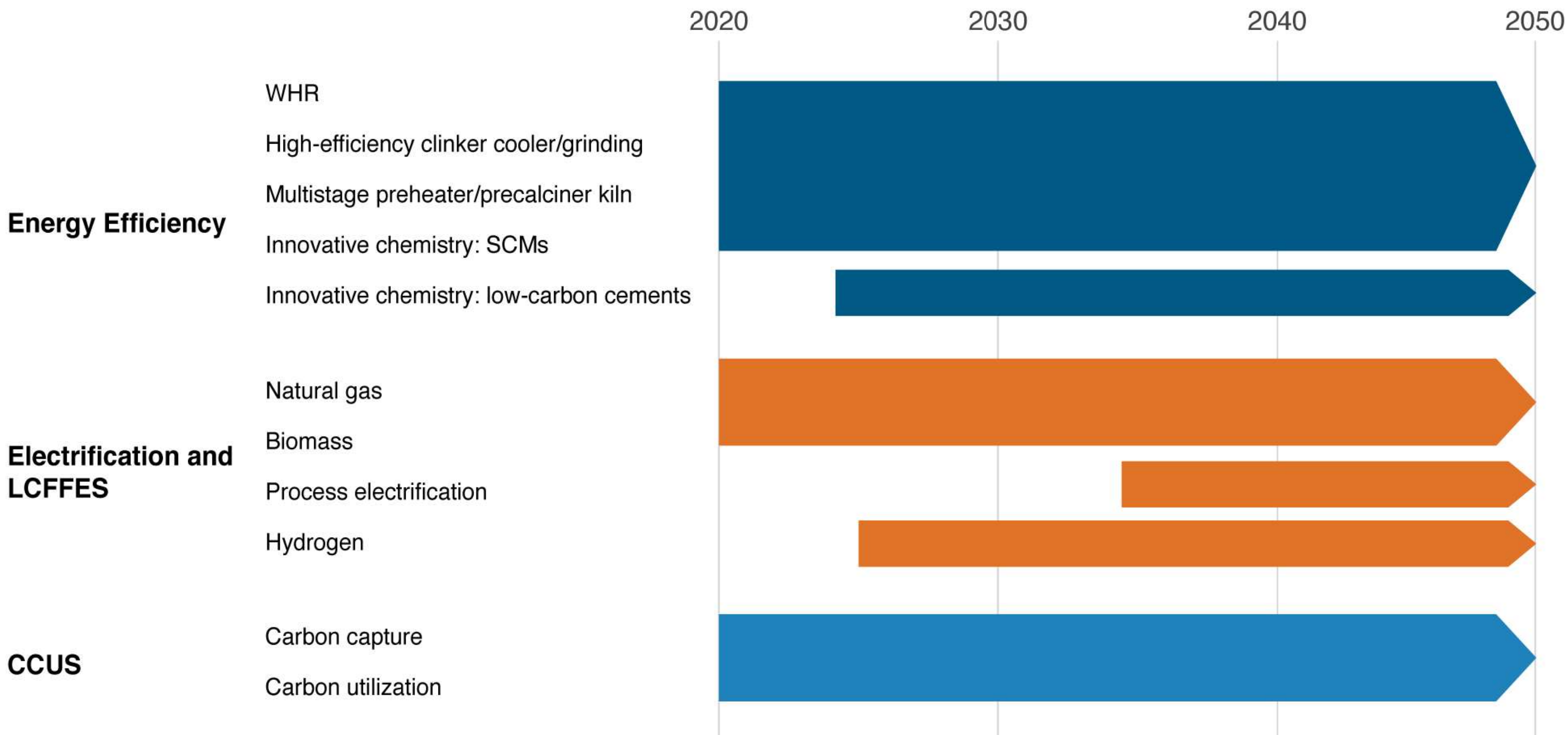

FIGURE 52. MARKET READINESS TIMELINE FOR LARGE-SCALE ADOPTION OF DECARBONIZATION TECHNOLOGIES IN THE U.S. CEMENT INDUSTRY.

PARTICIPANTS PROVIDED INPUT ON THE TIMELINE FOR MARKET READINESS AND TECHNICAL MATURITY OF THESE TECHNOLOGIES DURING DISCUSSIONS. THERE IS A DISTRIBUTION OF TECHNOLOGIES IN SEVERAL OF THESE CATEGORIES WHICH BROADEN THE PLACEMENT OF ITEMS. FURTHER DEFINITION OF TERMS IS PROVIDED IN THE GLOSSARY. SOURCE: THIS WORK.

Key message: Energy efficiency, switching to natural gas and biomass, and blended cement are at higher market readiness and have the highest potential for large scale deployment now. CCUS and process electrification need more RD&D support to become fully commercial and available for large scale deployment in mid- and long-term.

2.5.3.1 Energy Efficiency for the Cement Industry

Many energy efficiency technologies applicable to the cement industry are ready to be deployed on a commercial scale. These include WHR for power technologies, multistage preheater/precalciner kilns, high-efficiency clinker cooling, and more-efficient grinding processes. However, challenges with deployment of these technologies remain and RD&D could help address them.

Increasing the efficiency of multistage preheater/precalciner kilns and clinker coolers comes with unique challenges. For modern five-stage precalciner kilns, about 60% of the heat goes into the required chemical reactions. The preheater recuperates heat from the combustion products and the cooler recuperates heat from the hot clinker. The preheater exhaust gases (at around 300°C or 572°F) are used to dry raw materials. The amount of excess heat available in these gases depends on the amount of drying required and can be affected by seasonal variations. The cooler uses approximately two kilograms of air per kilogram of clinker, about half of which is used for combustion air in the kiln. The other half can be used for WHR. Currently, heat losses through radiation are about 10% or less and this can be reduced through better insulation. There are some technical tradeoffs for improving efficiency in the kiln and clinker cooler; for example, the number of preheating stages could be increased to improve heat recovery, but at the cost of increasing electricity consumption. Increases in preheater efficiency are partially neutralized by accompanying decreases in cooler heat recovery.

Some energy efficiency technologies, such as advanced grinding systems (e.g., contact-free grinding systems, ultrasonic or low-temperature comminution, high-voltage power-pulse fragmentation), are still in the research phase and require more RD&D.[301]

Economic challenges can be significant for deploying energy efficiency technologies. Some energy efficiency technologies are commercially available, such as WHR for power, but they have not been widely adopted in the United States because of cost barriers. The unpredictability of future regulations and uncertainty of permitting have a large impact on costs. And permitting adds cost and delays to any project.

To address technological challenges, RD&D opportunities could focus on improving the management of the preheating process using simulation models to optimize preheater design through such parameters as the number of stages, cyclone and duct design, and particle distribution in the gas stream. Also, simulation models could be used to assess different designs for clinker cooling and how to achieve optimal WHR. RD&D could help quantify the benefits of small energy efficiency measures, such as advanced mechanical seals and new insulation types. Better measurement capabilities for process control could help improve energy efficiency. RD&D could investigate how to adapt measurement devices to better withstand the harsh environment of pyroprocessing at a cement plant. As movement towards more emerging technologies occurs, there needs to be further RD&D on opportunities for WHR to generate electricity or other energy inputs using the Organic Rankine Cycle, the Kalina Cycle, or other technologies. RD&D could also investigate technologies for newer preheater designs or innovative heat exchange concepts.

To address economic and regulatory challenges, RD&D could demonstrate and document the economic benefits of energy efficiency investments, which could help plant managers make informed decisions.

[301] International Energy Agency, *Technology Roadmap: Low-Carbon Transition in the Cement Industry*, April 2018, https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry.

Another crosscutting RD&D measure would be to catalog best practices and results of energy management systems for cement operations.[302]

2.5.3.1.1 Innovative Chemistry

Innovative chemistry was identified during the stakeholder meetings and in subsequent written feedback from stakeholders as an important strategy to reduce GHG emissions from cement and concrete production. Innovative chemistry approaches include increasing the share of SCMs in cement (or concrete) production and using alternative binding materials. Substituting these materials for higher energy-consuming and CO_2-emitting clinker and Portland cement can reduce the energy and carbon footprint of cement and concrete. The Portland Cement Association notes that the common U.S. practice is adding less SCM during cement manufacturing and more SCM during the concrete batching process, whereas other countries tend to incorporate the SCMs during the cement manufacturing process. A variety of organic binders made from low-carbon materials that help to significantly reduce energy/GHGs of cement production may also be areas for RD&D.

In terms of technical challenges, for cement and concrete that incorporate a higher share of traditional SCMs, or use less common SCMs or alternative binders, questions remain about the ability of the final cement product to meet performance and durability requirements in certain construction applications. Market acceptance and economics are also major challenges for blended cements using SCMs. The use of SCMs largely depends on cost and regional availability of materials such as ground-granulated blast furnace slag (a waste product of primary steelmaking), fly ash (a waste product of coal-fired power plants), ground limestone, natural pozzolans, and calcined clay. While existing stockpiles of coal fly ash can continue to be mined for use in cement making, given the expected declining availability of ground-granulated blast furnace slag and fly ash (and potential regulations on fly ash storage that make it difficult to maintain adequate inventory onsite), natural SCMs such as ground limestone, pozzolans, and calcined clay are likely to be an upcoming focal point. Acceptance of different formulations will require (1) RD&D to build confidence in the performance and cost of new formulations, (2) alignment with global best practices for higher use of natural SCMs in cement and concrete production, and (3) incorporation in U.S. or states' standards to increase the allowable level of SCMs use.

There also needs to be safe transport, handling, and processing of SCMs given ecotoxicity concerns for some materials such as fly ash. In addition, the use of SCMs faces regulatory challenges, as performance requirements for SCM-blended cements vary regionally. To increase flexibility in their use, changes to current building codes, specifications, and standards will be needed in some cases and RD&D will be needed in other cases to help blended cement meet existing standards and overcome regulatory barriers. Performance-based standards rather than prescriptive-based standards are critical to increasing the use of SCMs in cement and concrete production. Finally, the mining of natural SCM materials such as pozzolans is subject to permitting and requirements, which could slow projects and increase the cost of extracting certain natural SCMs.

RD&D could focus on the technical aspects of increasing the share of SCMs in cement, especially natural SCMs. More research is needed on the structural performance of blended cement using novel ratios or SCM types, especially with regards to long-term durability for various applications. This includes

[302] For example, see: U.S. Environmental Protection Agency, *Energy Efficiency Improvement and Cost Saving Opportunities for Cement Making,* August 2013, https://www.energystar.gov/buildings/tools-and-resources/energy-efficiency-improvement-and-cost-saving-opportunities-cement-making.

research on optimizing particle size distribution in conjunction with porosity and reactivity for binders and inert fillers so the total binder content is minimized while achieving the desired performance.

To address regulatory and economic challenges, techno-economic analysis could help decision makers better understand opportunities for SCM use, especially on a regional basis and for upcoming natural materials. Adoption of LCA by professional services (e.g., architects and engineers) could identify opportunities for different applications of SCMs to reduce the overall carbon footprint. More broadly, modeling is needed to investigate mid- and long-term supply availability of SCMs to understand how plants might use them cost-effectively. The Portland Cement Association projects that SCM use in cement production will grow by 2040 (Figure 53), but a more fine-grained understanding of the supply limits for specific types of SCMs is needed to overcome economic challenges.

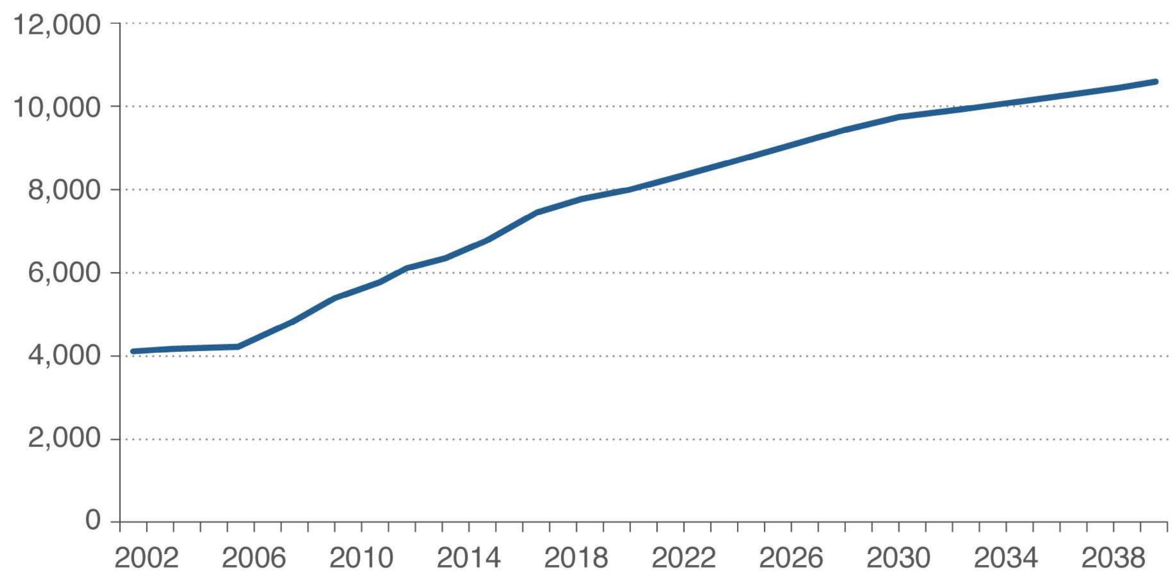

FIGURE 53. PORTLAND CEMENT ASSOCIATION PROJECTION OF SCM USE IN CEMENT PRODUCTION (THOUSAND MT).

SOURCE: PORTLAND CEMENT ASSOCIATION[303]

> *Key message: SCM use in the U.S. cement production is expected to increase by around 30% between 2020 and 2040.*

Alternative binding materials, which use different raw materials in place of Portland cement, face a similar set of challenges and opportunities. The technical performance of alternative binding materials is still not well-characterized, especially with regards to durability under different ambient conditions and long-term safety. Today, low-carbon chemistries can only be used for certain applications.

Economic challenges are also significant for alternative binding materials. Many such materials are currently high-cost and not yet produced at a large scale. Raw material availability is often limited, and some types of alternative binding materials compete as raw materials with other industries, such as the aluminum industry. Other alternative binding materials are already commercially available, such as belite clinker, calcium sulphoaluminate clinker, and alkali-activated binders. In the demonstration and pilot phases are materials like belite calcium sulphoaluminate clinker, cement based on carbonation of

303 Portland Cement Association, *Long-Term Cement Outlook*, November 2016, http://www2.cement.org/econ/pdf/long_term_report_2016f.pdf.

calcium silicates, and prehydrated calcium silicates. Magnesium oxides derived from magnesium silicates are still in the RD&D phase and face challenges in acquiring funding.

RD&D could address challenges with technical performance and seek to demonstrate the long-term safety of cement with alternative binding materials under different ambient conditions. Also, RD&D could provide information on the types of conditions under which alternate binding cements would be safe and appropriate to use. In addition, RD&D could assess the comparative carbon intensity of different cement binding materials (e.g., Figure 54) to demonstrate their decarbonization benefits for decision makers.

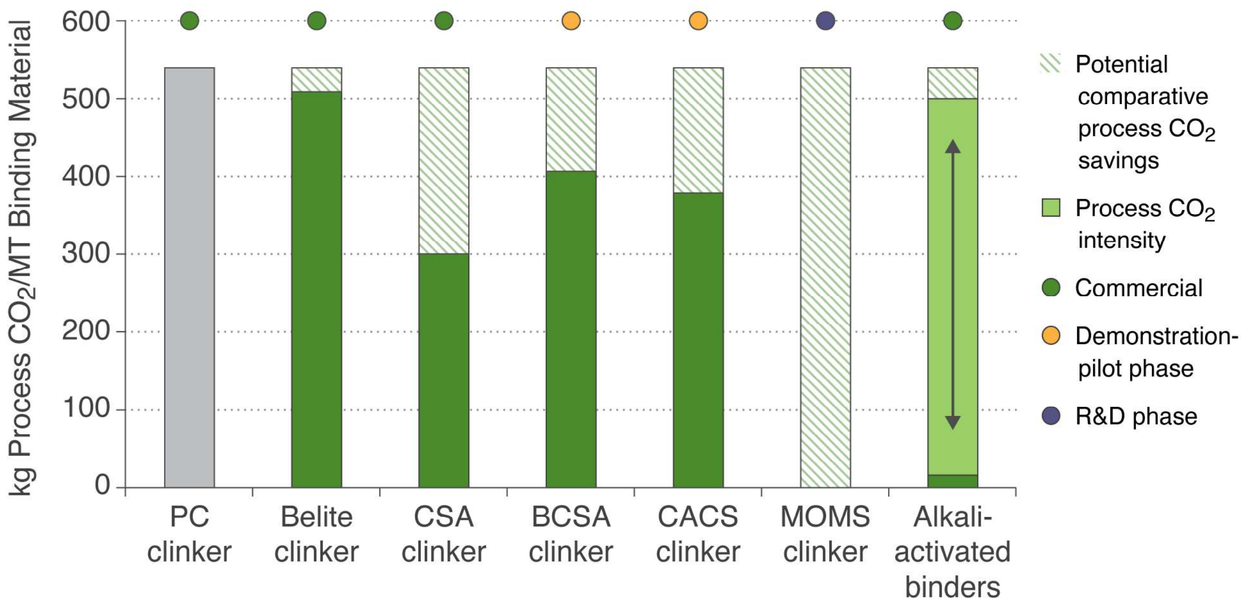

FIGURE 54. PROCESS CO_2 EMISSIONS INTENSITY FOR CEMENT BINDING MATERIALS.

THIS FIGURE SHOWS SHOW THE ALTERNATIVE BINDING MATERIALS TO PORTLAND CEMENT CLINKER. THESE ALTERNATIVE MATERIALS USE DIFFERENT CHEMISTRY TO LOWER THE ENERGY AND/OR PROCESS-RELATED EMISSIONS FROM CEMENT PRODUCTION. BCSA – BELITE CALCIUM SULPHOALUMINATE, CACS – CARBONATION OF CALCIUM SILICATES, CSA – CALCIUM SULPHOALUMINATE, MOMS – MAGNESIUM OXIDE DERIVED FROM MAGNESIUM SILICATES, PC – PORTLAND CEMENT. SOURCE: IEA[304]

> *Key message: Alternative binding materials using different chemistry can substantially reduce cement industry process-related CO_2 emissions.*

RD&D could also develop lower-cost production processes, given the economic challenges for alternative binding materials. Techno-economic analysis could identify regional cost and availability of raw materials and look at life cycle impact scenarios for different applications. There could also be educational, testing, pilot, and demonstration programs to promote acceptance and uptake.

[304] International Energy Agency, *Technology Roadmap: Low-Carbon Transition in the Cement Industry*, April 2018, https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry.

2.5.3.2 Electrification and Low-Carbon Fuels, Feedstocks, and Energy Sources for the Cement Industry

2.5.3.2.1 Natural Gas

Increased use of natural gas instead of coal and petroleum coke offers the potential to lower GHG emissions from cement plants in the near term. General challenges for increased natural gas use are related to infrastructure needs, as the basic technology is commercially available. Some cement plants are not near natural gas pipelines; even when pipelines are nearby, feeding off the main pipeline and bringing the gas to the plant can be difficult and costly. Utilities are often unwilling to take on the costs to build these connections. In urban areas, population density makes supply line connection a particular challenge. Uncertainty about consistency of supply, reliability, and cost can be a major barrier in some locations. In terms of the technology, some cement plants could require retrofits to the pyroprocessing system because of differences in retention time. Higher nitrogen oxide emissions, higher gas volumes per introduced energy unit, and reduced production efficiency can be caused by increased natural gas usage and can only be mitigated by permit changes that some plants might be reluctant to file. However, the technical challenges can be overcome by available technologies, and other countries (e.g., Russia and Qatar) have large natural gas resources and use natural gas as the primary fuel in their cement kilns.

RD&D could address infrastructure challenges by mapping the natural gas distribution infrastructure and identifying the optimal sites for fuel switching based on infrastructure and supply considerations. RD&D efforts to optimize kiln operations and burner design to minimize the effects of the different natural gas combustion characteristics could further accelerate the near-term adoption of natural gas. For example, research could focus on computational fluid dynamic modeling to address how to meet time-temperature requirements in new burners and redesigned calciner vessels. RD&D should also identify global best practices for using natural gas in cement plants and help transfer those lessons to the United States.

2.5.3.2.2 Biomass and Alternative Fuels

Increasing the use of biomass in cement kilns, which could lower GHG emissions from cement plants in the near and medium term, faces many similar challenges. For existing kilns, use of biomass is feasible up to a certain percentage. Increasing beyond that will require some RD&D. Transporting biomass to cement plants is often cost-prohibitive. In addition, biomass itself has significantly different combustion characteristics than coal and petroleum coke (e.g., a lower heating value), which means the calciners may require multichannel burners and careful monitoring of impurities.[305] Not all biomass is suitable for use in the kiln because of moisture content and high moisture content could require the use of more energy. Higher replacement rates of traditional fuel with biomass at the kiln would likely require drying and pyrolysis to achieve the necessary flame temperature.

Regulatory issues for alternative fuels, including nonhazardous secondary materials, are also challenging; they include solid waste regulations that might prohibit cement plants from using certain alternative fuels, including biomass, waste plastics, wastepaper, and municipal solid wastes. Insufficient financial incentives exist today for diverting large amounts of combustible wastes from landfills to use in cement kilns. The outputs from alternative fuels, such as the types of emissions and waste they produce, are less well-understood than they are for conventional fuels and additional research is needed to

[305] David Sandalow et al., *ICEF Industrial Heat Decarbonization Roadmap*, Innovation for Cool Earth Forum, December 2019, https://www.icef-forum.org/pdf/2019/roadmap/ICEF_Roadmap_201912.pdf.

improve the understanding of the public health implications for burning certain waste materials as fuel (e.g., plastics). In addition, there is still debate about whether biomass and some alternative fuels are low-carbon or carbon-neutral fuels.

Given the wide range of alternative fuel types and the various fuel mixes in use at cement plants, RD&D could help with cataloging what has already been done around the world (including collecting heating values for alternative fuels). For biomass, the BETO funded Feedstock Conversion Interface Consortium (FCIC)[306] has been researching fuel properties (e.g., heat values), life cycle impacts (e.g., GHG emissions), and techno-economic analysis of regional availability in the United States. The FCIC has also studied high moisture content biomass to identify efficient, cost-effective ways to use it under different torrefaction scenarios (i.e., producing the most biomass fuel with the least energy input and best particle size distribution). RD&D has also been done to assess the bulk flow characteristics of the biomass supply chain, thus helping identify efficient transport, storage, and preparation pathways for the U.S. cement industry.

The FCIC has also evaluated supply characteristics of other alternative fuels such as waste fuels. For example, other regions such as the EU use a much higher share of alternative fuels in their cement production fuel mix. And a key factor to the success of the EU in using alternative fuels in cement plants is the establishment of tipping fees for waste disposal, which provide economic incentives for cement plants to use these alternative waste fuels.

RD&D could focus on opportunities for economic scale-up of alternative fuel use in the U.S. cement subsector. This could include basic cataloging efforts on heating value, carbon content, and contaminant profiles for alternative fuels and developing case studies and best practices for safe use. Techno-economic analysis of alternative fuels could provide cost estimates for different combinations of alternative fuels that can optimize cost and emissions reduction based on availability.[307]

RD&D could also help demonstrate the economic and GHG benefits of using biomass and low-carbon alternative fuels for cement production. For example, the CEMCAP project[308] and subsequent analysis extensions compared the carbon intensity of clinker produced from different fuel mixes, including natural gas, biomass, different types of hydrogen, and electrification (the latter two technologies are discussed below). The project found that biomass and natural gas had lower carbon intensity than the coal baseline (Figure 55). Additional research is needed to further explore the GHG benefits of alternative fuels. Figure 55 shows that process-related emission from calcination accounts for a substantial share of GHG emissions from cement plants and cannot be reduced by switching fuel to natural gas, biomass, hydrogen, or electricity. CCS is required to capture process-related emissions. If clean hydrogen or renewably sourced electricity is used as fuel in the kiln and CCS is used to capture calcination-related CO_2 emissions, the GHG emissions intensity of clinker production can be brought down to zero or near zero.

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[306] "Feedstock-Conversion Interface Consortium," U.S. Department of Energy Bioenergy Technologies Office, accessed May 2022, https://www.energy.gov/eere/bioenergy/feedstock-conversion-interface-consortium.
[307] Julio Friedmann, Zhiyuan Fan, and Ke Tang, *Low-Carbon Heat Solutions for Heavy Industry: Sources, Options, and Costs Today,* Columbia University Center on Global Energy Policy, October 2019, https://www.energypolicy.columbia.edu/sites/default/files/file-uploads/LowCarbonHeat-CGEP_Report_100219-2_0.pdf.
[308] "CEMCAP," SINTEF, accessed 2021, https://www.sintef.no/projectweb/cemcap/.

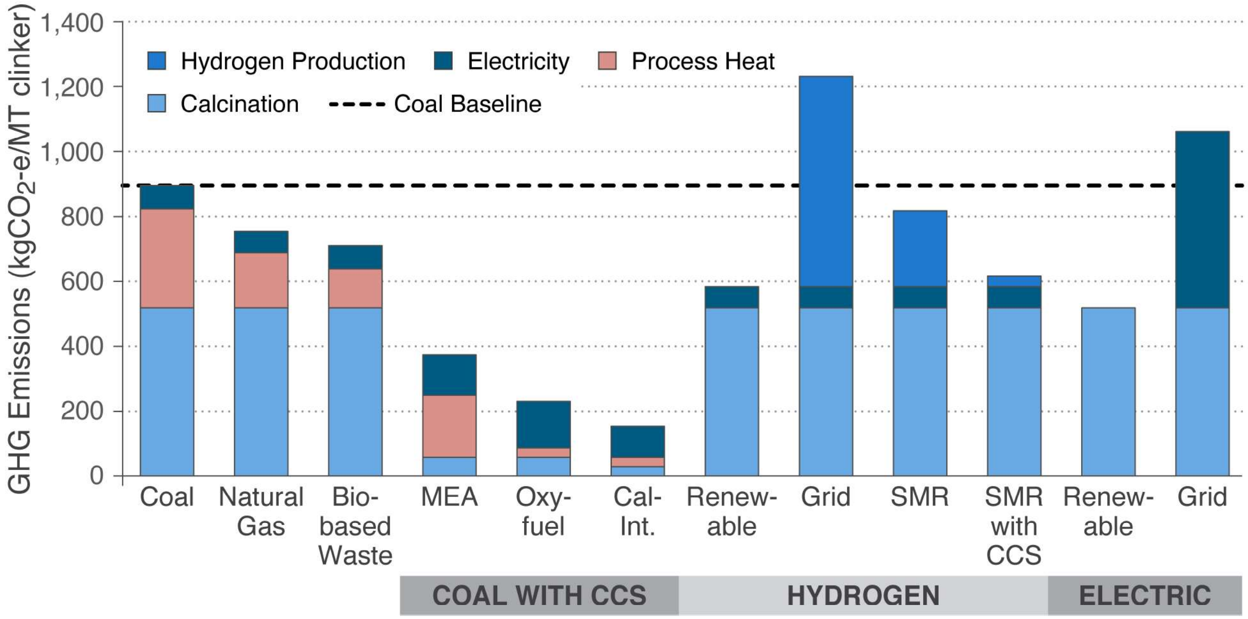

FIGURE 55. CARBON INTENSITY OF CLINKER PRODUCED BY DIFFERENT FUEL PATHWAYS.

THIS FIGURE SHOWS THE COMPARISON OF GHG EMISSIONS IN CEMENT PRODUCTION WHEN DIFFERENT TYPES OF FUELS ARE USED WITH OR WITHOUT CCS. MEA – MONOETHANOLAMINE, SMR – STEAM METHANE REFORMING. SOURCE: SANDALOW ET AL. 2019.[309]

> *Key message: Process-related emission from calcination accounts for a substantial share of GHG emissions from cement plants and cannot be reduced by switching fuel to natural gas, biomass, hydrogen, or electricity. CCS is required to capture process-related emissions. If clean hydrogen or renewably sourced electricity is used as fuel in the kiln and CCS is used to capture calcination-related CO_2 emissions, the GHG emissions intensity of clinker production can be brought down to zero or near zero.*

Few cement producers are also exploring other low-carbon energy sources like concentrating solar-thermal (CST) technology to generate temperatures at up to 1,500°C for industrial heat. For example, an innovative technology is under development that will undertake the elimination of the carbon footprint in cement using solar energy to drive the manufacturing process. The CO_2 emissions will be processed, captured, and subsequently converted into synthetic fuels using solar fuel technology.[310]

2.5.3.2.3 Process Electrification

Process electrification is in the early stages of development and still faces challenges in meeting the high temperatures and heat transfer required in cement production. Direct and indirect calcination using electric heating have different challenges.

For modern precalciner kilns, 40% of the fuel is fired in the kiln itself with flame temperatures reaching greater than 2,000°C. Clinkers, which form in a combination of viscous liquids and solids, coat the inside of the kiln, which protects the refractory. Attempts to produce Portland cement clinker in stationary (electric) vessels have often failed in the past because of the sticky nature of the clinker. Electrification is

[309] David Sandalow et al., *ICEF Industrial Heat Decarbonization Roadmap*, Innovation for Cool Earth Forum, December 2019, https://www.icef-forum.org/pdf/2019/roadmap/ICEF_Roadmap_201912.pdf.
[310] "CEMEX looks to use the sun to decarbonize cement," Synhelion, September 30, 2020, https://synhelion.com/news/cemex-looks-to-use-the-sun-to-decarbonize-cement.

possible, but because the full reaction of the clinker currently takes place in the combination of liquid and solids, new methods face technological challenges.

Around 60% of the fuel is fired in the precalciner with temperatures reaching around 850–900°C. Not all kilns have precalciners, but all kilns built in roughly the last three decades have precalciners. Indirect calcination, which drives the calcination reaction through indirect heating, provides a fairly clean CO_2 stream from the calcination reaction (which accounts for more than half the emissions of a modern precalciner plant). Indirect heating can be performed in many fashions and many suggestions for indirect heating have been made, including using heating oils, indirect firing, electric induction coils, and even concentrating solar power. Indirect calcination would be relatively easy to design and incorporate in new cement plants and may be retrofittable (with a loss of thermal efficiency) in existing precalciner kiln systems.

Though electric furnace technology for temperatures up to 1,000°C is in the early stages of commercialization for industrial-scale applications, much more RD&D is needed for higher temperatures.[311] Given the aforementioned technological challenges, more basic RD&D is needed for electrification of the full kiln via plasma arc or other technologies. The use of electric heating for indirect calcination could also be studied in combination with CCUS, given the concentrated process CO_2 emissions associated with this route. Other electrification options also exist. Initial lab tests have shown that sintering of cement can occur at a lower temperature in a microwave environment and studies have investigated a hybrid method combining conventional kilns and an electric furnace that indicated lower energy use than the fully conventional route.[312]

Given that electrification will increase electricity use and (depending on the electricity mix) could potentially increase GHG emissions, additional modeling of the energy and GHG impacts of different electrification options is needed to better understand the potential costs and benefits. For example, modeling done over the course of this work found that electrification technologies in the cement subsector would increase emissions over BAU in the near- to medium-term and would only reduce emissions after 2045 as the electric supply decarbonizes. In a more advanced scenario where the CO_2 emissions factor of the electricity were much lower in an earlier time frame, the result could be significantly different. In other words, the GHG impact of an electrified cement production process will depend on the source of electricity and its emissions factor.

2.5.3.2.4 Hydrogen in Cement Production

Hydrogen is another potentially transformative technology still in the research stage for application in cement kilns. Like other alternative fuels, using high levels of hydrogen in the fuel mix could affect physical aspects of the kiln such as the fuel mass flows, temperature profiles, heat transfer, exhaust gas moisture content, and safety considerations for the plant in ways that are not yet completely understood.[313] Some of the challenges of utilizing hydrogen for cement kilns are around the properties

[311] Arnout de Pee et al., Decarbonization of Industrial Sectors: The Next Frontier, McKinsey & Company, June 2018, https://www.mckinsey.com/business-functions/sustainability/our-insights/how-industry-can-move-toward-a-low-carbon-future.

[312] U.S. Department of Energy Advanced Manufacturing Office, *Sustainable Manufacturing: Opportunities, Trends, and Technoeconomic Analysis*, presented at the Advanced Manufacturing Office FY2020 Program Review Virtual Meeting, 2020, https://energy.gov/sites/prod/files/2020/05/f75/FY20%20AMO%20Peer%20Review%20-%20Sustainable%20Manufacturing%20Project%20Slides_Final_0.pptx.

[313] Volker Hoenig, *Carbon Dioxide Control Technologies for the Cement Industry*, presented at the GCEP Workshop: Carbon Management in Manufacturing Industries, Stanford, CA, April 15-16, 2008, https://gcep.stanford.edu/pdfs/2RK4ZjKBF2f71uM4uriP9g/Volker_Hoenig_Stanford_2008_upload.pdf.

of hydrogen, which require special handling and feeding and preclude use of pure hydrogen. For example, pure hydrogen flame has a lower heat transfer rate by radiation compared to natural gas which means the temperature profile of the kiln and the injection of the raw meal or clinker dust have to be modified.[314] Another potential problem is acidification—as the gas is cooled, nitrogen oxides, sulfur oxides, and chlorine may form, and higher moisture content in the exhaust gases going to the main baghouse may cause damage. The potential impact on refractory from high levels of hydrogen in the fuel mix is still unknown. However, there is the possibility of using low proportions of hydrogen in the fuel mix without needing substantial changes in operation.[315]

To address technological issues, RD&D could investigate how to optimize kilns and burners for low, medium, and high levels of hydrogen utilization, especially with regards to safety and efficient, effective combustion and heat transfer in the kiln fuel mix. Research is needed to better understand the impact of high levels of hydrogen and increased exhaust moisture on refractory and other materials in the kiln.

To address economic challenges, RD&D is needed to bring down the cost of hydrogen production and infrastructure. These RD&D requirements are discussed in Section 1.2.2.2.

2.5.3.3 Carbon Capture, Utilization, and Storage for the Cement Industry

Given that process-related CO_2 emissions from calcination accounted for 58%[316] of total CO_2 emissions from the U.S. cement industry in 2015, the adoption of CCUS technologies is key to achieving decarbonization in this subsector. There are technological challenges to storing CO_2 near cement kilns, which are often co-located with large limestone quarries, and each plant has its own unique geography with varying amounts of land area, water, power infrastructure, and other resources. No single off-the-shelf CCUS commercial design or technology will work for every cement plant, given the geographical variations and the varying emissions control technologies and designs at different plants. Transport infrastructure for CO_2 varies significantly from site to site. In addition, existing plants retrofitted for carbon capture and carbon capture integrated with new cement plants would have very different capture efficiencies.

CCUS is currently a very high-cost technology for cement plants in terms of both capital and operating costs, including an energy penalty (Figure 56). Calcium looping and oxy-combustion capture appear to be more cost effective than post combustion capture, likely because about 60% of CO_2 from clinker production is process CO_2 that is present in higher in concentration than CO_2 as a combustion byproduct. Avoiding the mixing of the large fraction of high purity process CO_2 stream with the smaller fraction of lower CO_2 concentration flue gas from fuel combustion for calcination and clinkering – by using oxygen instead of air for combustion (to produce high CO_2 concentration flue gas) and or using inexpensive lime sorbents in a regenerative calcium looping process to extract high purity CO_2 ($CaO + CO_2 \rightleftharpoons CaCO_3$) – appears to preclude the need for more capital-intensive amine-based post combustion capture process, leading to a more cost-effective carbon capture approach. A thorough techno-economic and energy analysis across capture technologies with a consistent set of assumptions is needed to verify this hypothesis.

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[314] Ibid.
[315] Ibid.
[316] Ali Hasanbeigi and Cecilia Springer, *Deep Decarbonization Roadmap for California's Cement and Concrete Industry*, Global Efficiency Intelligence, September 2019, https://www.globalefficiencyintel.com/decarbonization-roadmap-california-cement-concrete.

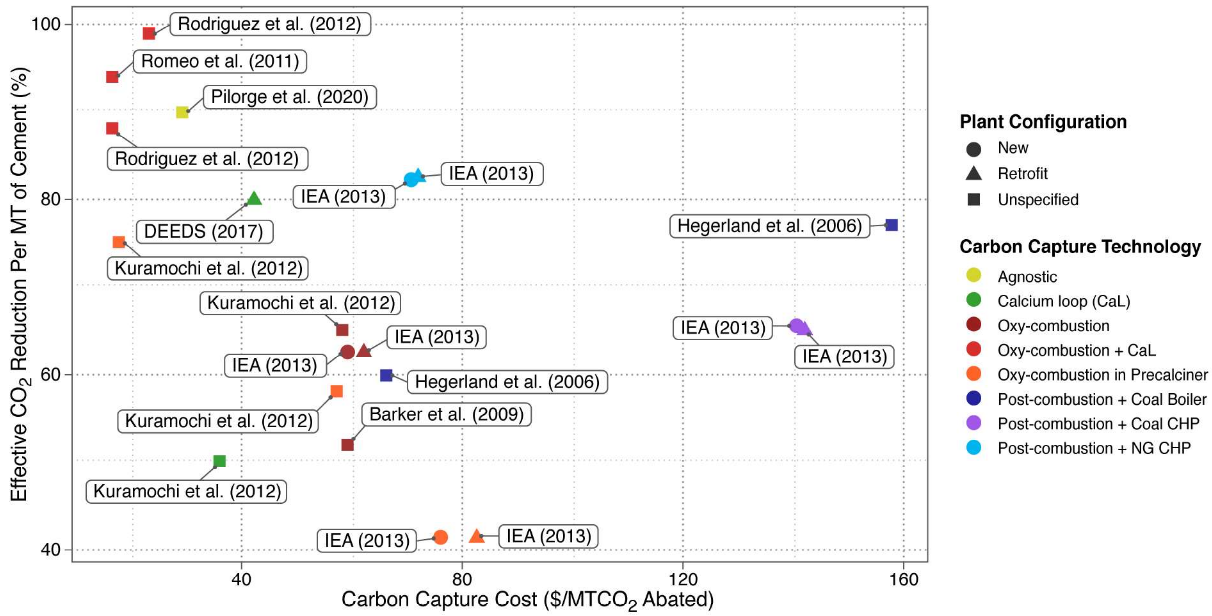

FIGURE 56. ESTIMATES OF COST OF CO_2 AVOIDED AND CORRESPONDING EFFECTIVE CO_2 REDUCTION RATE USING VARIOUS CARBON CAPTURE TECHNOLOGIES IN CEMENT PRODUCTION AS REPORTED IN LITERATURE.[317]

CAL = CALCIUM LOOP; CHP = COMBINED HEAT AND POWER PLANT. EACH DATA POINT CONTAINS BUILT-IN ASSUMPTIONS ABOUT A RANGE OF PARAMETERS INCLUDING PLANT LIFETIME, CAPITAL CHARGE FACTOR, DISCOUNT RATE, CAPTURE RATE, UNIT ENERGY DEMANDS, AND UNIT PROCESS CONDITIONS FOR A GIVEN CAPTURE TECHNOLOGY, MIX AND CARBON CONTENT OF CLINKER FEED, AND COST COMPONENTS (E.G., CO_2 TRANSPORTATION). CALCIUM LOOPING AND OXY-COMBUSTION APPEAR TO GENERALLY BE MORE COST EFFECTIVE THAN POST-COMBUSTION CARBON CAPTURE. HOWEVER, IN THE ABSENCE OF HARMONIZATION OF THESE ESTIMATES ACROSS TECHNOLOGIES AND TIMEFRAMES, WE CAUTION AGAINST DIRECT QUANTITATIVE COMPARISON OF COST VALUES, INCLUDING THOSE FOR IDENTICAL CAPTURE TECHNOLOGIES. FIGURE SOURCE: THIS WORK.

[317] D.J. Barker et al., "CO_2 Capture in the Cement Industry," *Energy Procedia* 1, no. 1 (February 2009): 87-94. https://doi.org/10.1016/j.egypro.2009.01.014; "DialoguE on European Decarbonization Strategies," EU CORDIS, last modified January 7, 2022, https://cordis.europa.eu/project/id/776646; Georg Hegerland et al., *Capture of CO_2 from a Cement Plant - Technical Possibilities and Economical Estimates*, presented at the International Conference on Greenhouse Gas Technologies, Trondheim, Norway, June 2006, https://www.researchgate.net/publication/262611768_Capture_of_CO2_from_a_cement_plant_-_technical_possibilities_and_economical_estimates; International Energy Agency, *Deployment of CCS in the Cement Industry*, December 2013, https://ieaghg.org/docs/General_Docs/Reports/2013-19.pdf; Takeshi Kuramochi et al., "Comparative Assessment of CO_2 Capture Technologies for Carbon-Intensive Industrial Processes," *Progress in Energy and Combustion Science* 38, no. 87 (January 2011): 87-112. https://www.researchgate.net/publication/284676629_Comparative_assessment_of_CO2_capture_technologies_for_carbon-intensive_industrial_processes; Hélène Pilorgé et al., "Cost Analysis of Carbon Capture and Sequestration of Process Emissions from the U.S. Industrial Sector," *Environmental Science & Technology* 54, no. 12 (2020): 7524-7532. https://doi.org/10.1021/acs.est.9b07930; Nuria Rodríguez, Ramón Murillo, and Carlos Abanades, "CO_2 Capture from Cement Plants Using Oxyfired Precalcination and or Calcium Looping," *Environ. Sci. Technol.* 46, no. 4 (2012): 2460-2466. https://doi.org/10.1021/es2030593; Luis M. Romeo et al., "Reduction of Greenhouse Gas Emissions by Integration of Cement Plants, Power Plants, and CO_2 Capture Systems," *Greenhouse Gasses: Science and Technology* 1, no. 1 (March 2011): 72-82. http://dx.doi.org/10.1002/ghg3.5; Cost and CO_2 reduction estimate derived from review by D. Leeson et al., "A Techno-Economic Analysis and Systematic Review of Carbon Capture and Storage (CCS) Applied to the Iron and Steel, Cement, Oil Refining and Pulp and Paper Industries, as Well as Other High Purity Sources," *International Journal of Greenhouse Gas Control* 61, (2017): 71-84, https://doi.org/10.1016/j.ijggc.2017.03.020.

It is also worth noting that regardless of the capture technology employed, a non-trivial amount of additional energy in the form of steam and electricity will be needed to power carbon capture unit processes, such as solvent/sorbent regeneration, air separation (for oxy-combustion only), and CO_2 compression; some of this additional energy could be available from WHR. The source of the rest of the additional energy must be carefully examined since the costs and carbon intensity of additional fuels and electricity can significantly influence the overall cost-effectiveness and net carbon abatement of a cement plant with carbon capture. A plant-level analysis of supplemental energy sources for carbon capture for cement plants in Norway[318] suggests that a natural gas-fired boiler is the least expensive and lowest GHG generating option for producing supplemental steam when compared against coal and biomass boilers. However, if a more electricity-intensive (as opposed to steam-intensive) carbon capture technology such as oxy-combustion is deployed, co-generation with an emphasis on meeting the additional electricity demand is likely to be more cost-effective than using a boiler primarily for steam generation.[319]

CCUS technology can also benefit from more research on catalysts for carbon capture and better process designs to bring higher efficiency levels, lower costs, and lower material consumption or waste production. RD&D could also identify optimization of the techno-economic performance of the technology and heat exchanger network for calcium looping. There also needs to be research on capturing CO_2 from indirect calcination processes. RD&D could also investigate the calcium looping in multiple industries, where spent sorbent (lime) is used as a cementitious material.

More research is needed on the technological potential of storage near cement plants, as well as on safe storage capacities, their geographical availability, and the environmental impacts of increased storage. Within plants, research should address specific installation, operation, and maintenance requirements for different plant and kiln types to ensure the continuous operation is possible at a given level of capture.

CCUS developers could benefit from a comprehensive model that allows cement producers to model different technologies for their specific situations. The model could include parameters such as availability of cogenerated waste products, flue gas impurities, or WHR availability as target output streams. New technologies should be included in the model as they are developed and feedback from pilot units and new installations could be constantly updated to refine the model. Such a model would need to be accompanied by training in its use. Also, RD&D is needed for pilot and demonstration-scale evaluation of different CCUS technologies in cement applications to assess the operational parameters and costs of CCUS technologies in U.S. cement plants.

RD&D could help lower the cost of CCUS and more directly address economic challenges. Computer models could be used to determine the cost of different processes for separating, compressing, and transporting CO_2 to and from industrial sites, thus identifying the most cost-efficient sinks. For example,

[318] Hassan Ali et al., "Steam Production Options for CO_2 Capture at a Cement Plant in Norway," presented at the 14th Greenhouse Gas Control Technologies Conference, Melbourne, Australia, October 21-26, 2018, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3366165.

[319] Nuria Rodríguez, Ramón Murillo, and Carlos Abanades, "CO_2 Capture from Cement Plants Using Oxyfired Precalcination and or Calcium Looping," *Environ. Sci. Technol.* 46, no. 4 (2012): 2460-2466. https://doi.org/10.1021/es2030593; Sarang Supekar and Steven J. Skerlos, "Sourcing of Steam and Electricity for Carbon Capture Retrofits," *Environmental Science and Technology* 51, no. 21 (2017): 12908–12917. https://pubs.acs.org/doi/10.1021/acs.est.7b01973.

one study identified the spatial distribution of U.S. industrial sites (including cement plants), their CO_2 output, and potential demand for storage sinks (Figure 57).[320]

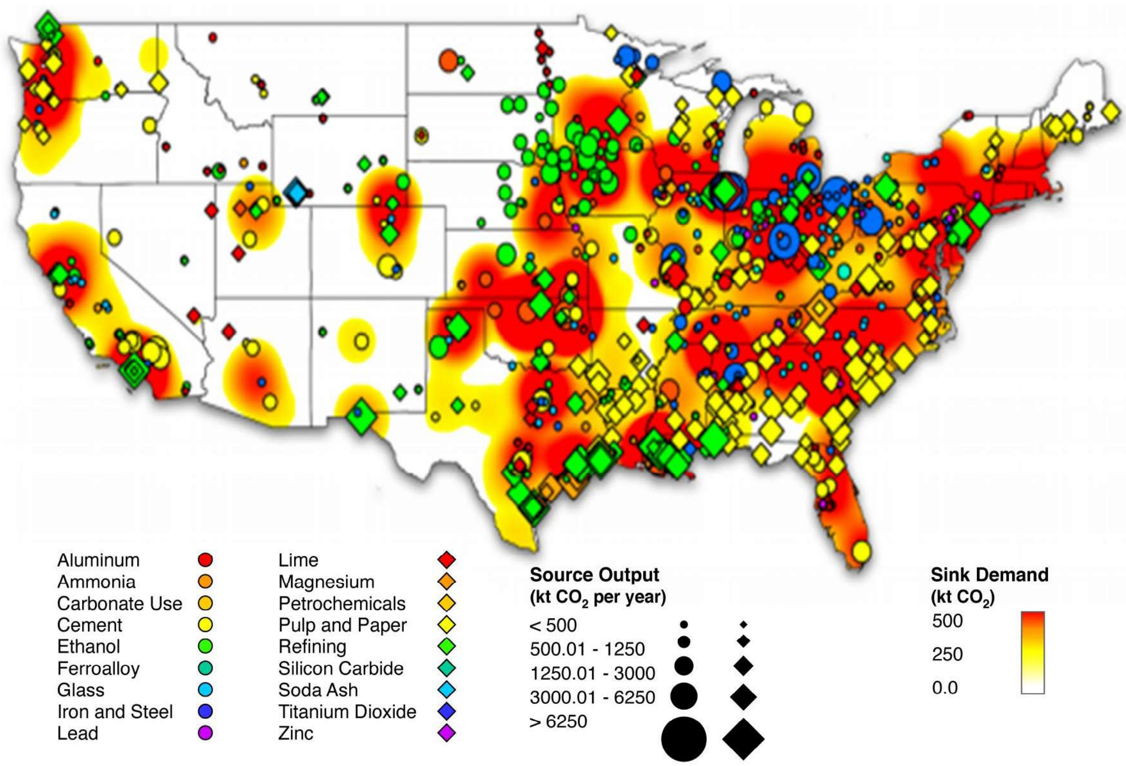

FIGURE 57. NATIONAL DISTRIBUTION OF INDUSTRIAL SITES, CO_2 OUTPUT, AND SINK DEMAND.

THIS FIGURE SHOWS THE LOCATION OF INDUSTRIAL SITES FOR ENERGY INTENSITY INDUSTRIAL SUBSECTORS ALONG WITH THE MAGNITUDE OF THEIR CO_2 EMISSIONS PER YEAR AS WELL AS THE AMOUNT OF CARBON SINK DEMAND. NOTE: CEMENT PLANTS ARE DENOTED BY YELLOW CIRCLES. SOURCE: PSARRAS ET AL. 2017[321]

> *Key message: A significant number of cement plants are in the South and Midwest region of the United States except for California, which is the second largest cement producing state after Texas.*

RD&D is also needed to understand the integration of post-combustion carbon capture equipment and its associated electricity demand and thermal energy use, which could increase the electricity intensity of cement production.[322] Finally, research could identify policy designs to maintain U.S. competitiveness if U.S. cement producers adopted CCUS technologies but overseas producers did not.

Carbon utilization is also a major opportunity for cement producers, and carbon utilization technologies vary in their commercialization status. Technologies such as CarbonCure[323] and Solidia[324] concrete are already available for commercial use in ready-mix plants and precast concrete plants, respectively.

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[320] Peter C. Psarras et al., "Carbon Capture and Utilization in the Industrial Sector," E*nvironmental Science and Technology* 51, no. 19 (2017): 11440–4.
[321] Ibid.
[322] International Energy Agency, *Technology Roadmap: Low-Carbon Transition in the Cement Industry*, April 2018, https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry.
[323] "CarbonCure," CarbonCure, accessed May 2022, https://www.carboncure.com/.
[324] "Solidia," Solidia, accessed May 2022, https://www.solidiatech.com/.

Carbon mineralization technologies such as Blue Planet[325] and Carbon8[326] are also being piloted. More than 20 organizations are working on commercialization of technologies to convert CO_2 to carbonate products for the construction subsector.[327] However, current challenges include ensuring final products will meet performance and durability requirements in some cases and could be addressed by adoption of performance-based standards. Unpurified CO_2 can also be a challenge in terms of utilization.[328]

Economic challenges are significant for carbon utilization technologies. The cost of these technologies is high especially in comparison to the low cost of alternative materials for which carbon utilization technologies can substitute. Cement producers have limited information on the potential economics of carbon utilization and the CO_2 market.

RD&D could help with both technological and economic barriers. More research is needed on materials produced with carbon utilization to verify and improve their performance. RD&D could identify innovative ways to use unpurified CO_2 to increase the range of applications.

For economic challenges, RD&D could identify ways to increase productivity, reduce processing costs, and find a wider range of low-cost waste materials that can currently be used as an input. In addition, cement companies could benefit from a well-maintained database of known and potential carbon utilization projects to help them understand market potential.

2.5.4 Proposed RD&D Action Plan for the Cement Industry

Given the challenges and opportunities identified earlier, the next step is to propose an action plan for potential investment in RD&D for cement subsector decarbonization. Given a large number of technologies—all of which vary in their technical maturity level, timeline for deployment, costs, mitigation potential, and other variables—it is useful to set out some guiding principles for an RD&D action plan.

RD&D investment could be guided by the balance of several factors. First, RD&D investment could cover both near-term and long-term solutions in terms of technological maturity. One benefit of investment in near-term solutions is that they can potentially catalyze longer-term innovation. At the same time, long-term solutions may have trouble attracting investment today so concerted RD&D support is needed.

RD&D investment could also balance support for "low-hanging fruit" with lower investment costs and certain, if small, decarbonization potential and support for "moonshot" technologies that are potentially transformative but also riskier.

In addition to a principle of balance, RD&D investment should also have a prioritization strategy. Given that RD&D is meant to catalyze innovation for technologies that have not yet received market support, priority should be given to technologies that do not have other significant, near-term means of funding, while also taking a balanced approach as described earlier. In addition, priority should be given to

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[325] "Blue Planet Systems," Blue Planet Systems, accessed May 2022, https://www.blueplanetsystems.com/.
[326] Carey, Paula, "Mineralisation: A CCUS Solution," Carbon8, July 20, 2021, https://c8s.co.uk/mineralisation-the-permanent-ccus-solution/.
[327] David Sandalow, *Carbon Dioxide Utilization: ICEF Roadmap 2.0*, Innovation for Cool Earth Forum, November 2017, https://www.icef-forum.org/pdf/2018/roadmap/CO2U_Roadmap_ICEF2017.pdf.
[328] Any reference to a specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply an endorsement, recommendation, or favoring by DOE and its partners in this roadmap. They are just case-study examples.

technologies with a high annual mitigation potential (e.g., CCUS for the cement industry) and high applicability across an industrial subsector.

Figure 58 shows a landscape of needs and opportunities in the U.S. cement industry for RD&D investments organized by pillar (note electrification and LCFFES are shown in separate wedges to spread out the needs) and decade through 2050. The needs/opportunities came from participants in the virtual meetings. For example, while energy efficiency technologies are fully commercialized, more RD&D is needed to develop and demonstrate CCUS, process electrification and use of hydrogen in the cement industry.

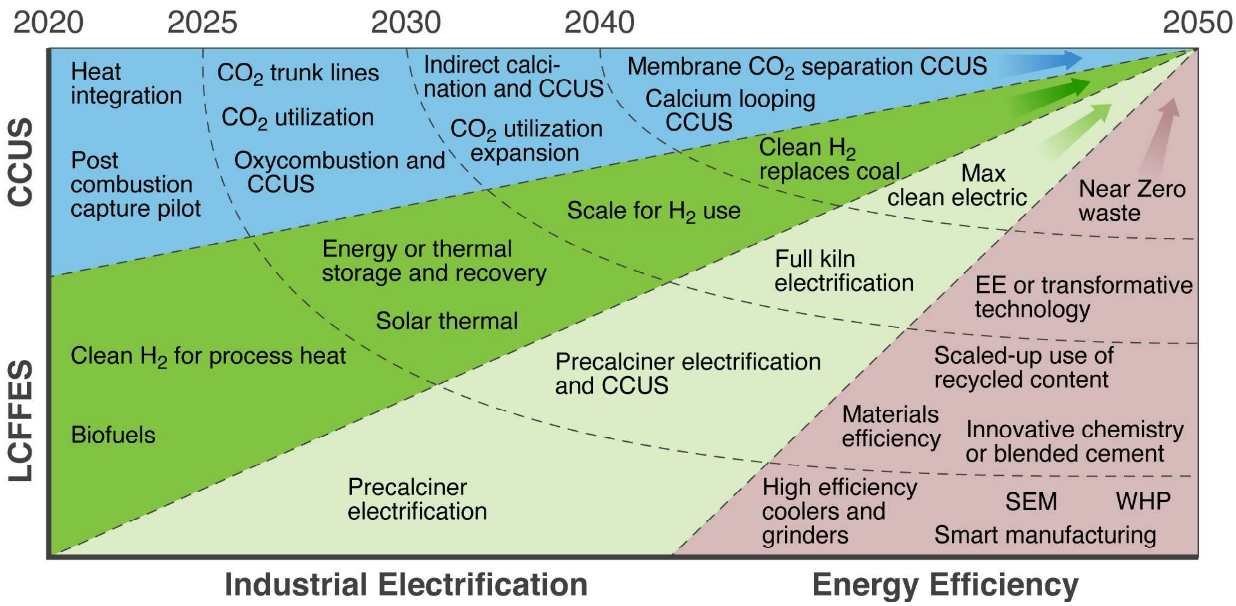

FIGURE 58. LANDSCAPE OF RD&D ADVANCEMENT OPPORTUNITIES BY DECADE AND DECARBONIZATION PILLAR FOR THE U.S. CEMENT INDUSTRY NOTED BY ATTENDEES AT THE ROADMAP VIRTUAL SESSIONS.

LCFFES INCLUDES CLEAN TECHNOLOGIES THAT DO NOT RELEASE GHGS TO THE ATMOSPHERE FROM THE PRODUCTION OR USE OF ENERGY SOURCES, AND INCLUDE RENEWABLE SOURCED ELECTRICITY, NUCLEAR ENERGY FOR ELECTRICITY AND HEAT, CONCENTRATING SOLAR POWER, AND GEOTHERMAL ENERGY. FURTHER DEFINITIONS ARE AVAILABLE IN THE GLOSSARY. SOURCE: THIS WORK.

> *Key message: RD&D investments are needed across a host of opportunities in the U.S. cement industry to lower technical hurdles, improve economic viability, accelerate adoption, and pave the way for even more transformative low-carbon technologies. Across the time horizon to 2050 are RD&D needs associated with pillars and crosscutting opportunities. For example, while energy efficiency technologies are fully commercialized, more RD&D is needed to develop and demonstrate CCUS, process electrification, and use of hydrogen in the cement industry.*

This illustration also prompts thinking on how to balance RD&D investments across the near, mid, and longer time horizons. Some investments are needed to lower hurdles and spur adoption of current low-carbon technologies, there needs to be investment in mid-term technologies, approaches, and infrastructure to deliver on deeper reductions and while taking advantage of an electrical grid that is supplied with increasing levels of low-carbon energy generation, and longer-term investments are needed in parallel so that development of transformative technology can be accelerated. The need for investments over this timeline are divided into three categories:

RD&D needs with **near-term (2020–2025)** impacts include:

- Help leverage relatively low-capital solutions (energy efficiency, SEM, and waste heat reduction/recovery solutions (WHP)).
- Enable the transition to lower-carbon fuels and process heat solutions (e.g., clean hydrogen for process heat, biofuels).
- Continue advancing the integration of CCUS with hard-to-abate sources (e.g., post-combustion CCS pilot in a cement plant).

RD&D needs with **mid-term (2025–2030)** impacts include:

- Probe routes to continue improving materials efficiency and flexibility including reuse/recycle/refurbishment including innovative chemistry and blended cement.
- Invest in lower-carbon process adaptations/ routes (e.g., precalciner electrification, solar or nuclear thermal heating, and large-scale use of hydrogen as fuel source).
- Expand the infrastructure and integration capabilities and knowledge to capture, transport, and reuse CO_2 where possible (e.g., Oxy-combustion with CCUS, indirect calcination with CCUS, large scale carbon utilization for construction materials.).

RD&D needs with **longer-term (2030–2050)** impacts include:

- Advance approaches to reduce waste and utilize a circular approach for concrete construction, low-carbon binding materials, and natural SCMs.
- Develop full kiln electrification with 100% clean energy as the power source or large-scale use of clean hydrogen as alternative fuels.
- Develop additional routes for utilizing CO_2; full scale deployment of carbon capture with innovative approaches such as calcium looping and use of membrane for CO_2 separation.

These areas include information synthesis and analysis, laboratory testing, pilot and demonstration projects, and policy designs and incentives as explained in the following sections.

Given these proposed guidelines, an actual RD&D action plan could cover several areas that cut across the technologies in the decarbonization pillars, including information synthesis and analysis, laboratory testing, and pilot and demonstration projects.

2.5.4.1 Information Synthesis and Analysis

For many decarbonization technologies, even if they are commercially available at a small scale, uptake is limited because of a lack of understanding of potential benefits. RD&D funding should be directed toward information synthesis and analysis that could help plant and company managers understand the specific benefits of a given technology for their plants. This includes regional and spatially detailed analysis and a cataloging of best practices and lessons learned from elsewhere in the world.

For example, to increase the use of alternative fuels, uptake of SCMs, and installation and operation of carbon capture equipment, more-tailored information on performance, cost, and availability could help regulators and cement users understand potential benefits. In addition, information synthesis and analysis could help pave the way for technologies still in the development phase by demonstrating their potential future benefits to encourage more attention and investment today. For example, CCUS, which is being developed on a timeline of the next five to ten years, needs more research to better characterize plant-level storage potentials and technology costs.

2.5.4.2 Laboratory Testing

RD&D could also be directed toward technologies that still require extensive in situ testing and development and have not reached the scale-up or production state. RD&D investment is particularly important for these types of technologies because at this stage, they may have trouble attracting commercial finance and other sources of funding. Examples include some advanced alternative binding materials, process electrification technologies, and how hydrogen use performs in the fuel mix of cement plants.

2.5.4.3 Pilot and Demonstration Projects

Finally, RD&D could also be directed toward technologies that are in the pilot and demonstration phase but may not be ready for use in the cement subsector specifically and may require more piloting for subsector-specific applications. A prime example of this is CCUS; the Portland Cement Association does suggest pilot and demonstration projects for technologies beyond solvents, sorbents, and membranes that are typically used for CCUS projects. At the same time, RD&D could help move development-stage technologies into the pilot and demonstration phase, which would be critical for convincing stakeholders about the potential benefits of adoption. Examples of this include innovative chemistries for cement production and the use of various biomass and alternative fuels in cement production.

3 Crosscutting Barriers and Opportunities

A critical step toward decarbonizing industry is elucidating the top barriers present in all five industrial subsectors studies that must be overcome to accelerate GHG mitigation. These barriers were gathered during the roadmap stakeholder meetings. Those meetings convened industry, government, academia, and nongovernmental organization representatives to deliver robust answers to questions of needs, challenges, and accelerators across subsectors. Table 4 summarizes these barriers grouped into four categories: industrial heterogeneity, incumbent technologies and practices, high costs, and scale-up. To accelerate U.S. industrial sector decarbonization, these RD&D and other needs must be addressed and opportunities must be seized. The high capital and operating costs that are typical of transformative low-carbon technologies is a recognized challenge to replacing incumbent technologies that cut across all subsectors.

Increased scrutiny on GHG emissions is changing the prioritization of factors involved in the making of industrial products. One of the forces driving transformation in industry is societal response to climate change. It is an externality that will not only spark change but also alter multiple types of barriers (structural, economic, information, etc.) and introduce new ones that need to be addressed.

There are multiple ways to segment the barriers associated with the application of these pillars. In a report on industrial energy efficiency, barrier analysis was divided into end use, demand response, and combined heat and power.[329] That work categorized barriers into economic and financial, regulatory, and informational groupings. The report went on to examine the economic benefits that help to pull projects across the barriers. It is also important to consider the impact of benefits. Maximizing benefits (energy or non-energy) while minimizing barriers can be important for encouraging adoption. In the case of crosscutting barriers and opportunities, the benefits can be amplified.

TABLE 4. SUMMARY OF BARRIERS AND RD&D OPPORTUNITIES FOR ALL FIVE INDUSTRIAL SUBSECTORS

	Barrier	RD&D Opportunities and Needs
Industrial Heterogeneity	A few industries account for the bulk of emissions, but the remaining distribution of emitters is very broad.	• Focus RD&D on industrial decarbonization. • Focus RD&D on carbon-intensive subsectors (starting with the five studied for this roadmap) and transformation routes to low-carbon processes (e.g., incorporating renewably generated hydrogen as a precursor in chemical processes).
	Adoption is slow given tailored implementation and integration is often needed.	• Develop a portfolio of crosscutting technologies that can be used in multiple subsectors (e.g., separations assisted by electricity from clean sources). • Spur technology transfer and provide technical assistance for low-carbon technology.
	Optimal decarbonization strategies are influenced by many variables (e.g.,	• Consider these variables when developing portfolios. • Harness synergies at industrial clusters to spur early action.

[329] U.S. Department of Energy, *Barriers to Industrial Energy Efficiency*, June 2015, https://www.energy.gov/sites/prod/files/2015/06/f23/EXEC-2014-005846_6%20Report_signed_0.pdf.

	Barrier	RD&D Opportunities and Needs
	subsector, location, and process).	• Share learnings across regions, industries, and manufacturer size.
	Material inputs and use vary widely.	• Develop low-carbon feedstock and material options across industries and supply chains. • Advance RD&D in recycling, reuse, refurbishment, and alternative materials. Develop paths to attain prime performance in recycled materials. • Develop solutions for varying levels of available resources, capabilities, sophistication, and ability to support solutions with limited number of personnel.
	Manufacturer needs vary with size, resources, and workforce capabilities.	• Develop approaches to adjust options in solution portfolios to subsector variables. • Harness synergies at industrial clusters to spur early action and gain experience uncovering and adjusting to implementation and other variables. • Share learnings across industries, manufacturer sizes, and regions to spur innovation.
Incumbent Technologies and Practices	Equipment can have a long service life and replacement requires years of planning.	• Provide technical assistance to help companies plan for a low-carbon transition. • Develop methods allowing energy and GHG estimation for low-carbon versus incumbent technologies to aid evaluations for replacement of long-lived equipment. • Provide a portfolio of low-carbon options for investment planning, including drop-in solutions for near-term and transformative mid- and longer-term solutions. • Support SEM to help companies lower transition costs.
	There is low penetration in crosscutting applications such as process heat.	• Develop a portfolio of process heat solutions flexible for needs across subsectors. • Define the minimum scale to demonstrate economic viability for multiple low-carbon technologies across industries. Address where modular approaches work. • Research more efficient heat exchange methods, thermal storage, and integration.
	Because of high integration, downstream impacts must be considered.	• Accelerate applied research on integration of low-carbon technology, modularization opportunities (where modular units are an option), and integration.

	Barrier	RD&D Opportunities and Needs
	Hesitancy to change is due to unvalidated performance of new equipment.	• Reduce risk with demonstrations, trials at scale, and performance metrics. • Research, build data warehouses, and publish case studies with implementation details to aid validation and communication.
	Availability of low-cost and reliable carbon-intensive materials is limited.	• Facilitate development of expertise in the field to support implementation and integration (building workforce capabilities). • Develop metrics for transparent tracking and reporting of product carbon intensity across the value chain, empowering customer choice. • Devise clear, simple labeling methods for key products. • Support RD&D including fundamental research to enable transformative low-carbon technologies, their adoption, and proof of low-carbon impact.
High Costs	Capital costs are typically upfront, which increases investment risk.	• Emphasize RD&D of scalable solutions, including modular solutions. • Advance research and support for low-capital solutions. • For early progress, provide RD&D for low-capital solutions (e.g., energy efficiency, some electrification technologies, lease-to-own and other flexible business models).
	Energy costs for low-carbon solutions start at high multiples of incumbent fossil fuel sources.	• Perform RD&D on new production methods of low-carbon fuels and feedstocks to improve economics (both capital and operating expenses). • Optimize efficiency of equipment designed to run on low-carbon fuels. • Quantify and publish energy and non-energy benefits during pilot and demonstration projects so improvement engineers can find information when evaluating incumbent technology replacement. • Advance options to reduce costs (e.g., energy efficiency, materials efficiency, and design, recycling).
Scale-Up	Reaching industrial scale, with competitive economics, is a challenge.	• Pursue RD&D on additional variables that hinder scaling in industry. • Perform precommercial techno-economic studies and improve them with information from commercial installations. • Perform RD&D on the lowest scale needed for modular systems to become economic and relevant.

	Barrier	RD&D Opportunities and Needs
	Vendor support for scaling, integration, and adaptation is lacking.	• Provide technical support and workforce training for newly deployed technologies. • Explore integration and adaptation needs. • Describe and document best practices.
	Interconnections for low-carbon solutions are new and need development.	• Perform RD&D for fast, reliable switching from current to low-carbon solutions. • Perform RD&D on modular approaches to lower integration hurdles.
	Potential gaps exist in clean energy supply chains.	• Establish RD&D into supply chain transparency.

3.1 Economies of Scale

In manufacturing, economies of scale reflect the experience that cost savings tend to occur when making more of a product. That is, the average cost of production tends to fall with an increasing volume of output. This is one of the factors that have led to companies striving for a larger production scale (other factors include increased ability to meet market demand and attain market share). There are multiple categories and factors associated with scale, including the experience that if scale gets too large it may overcome the organization's ability to support production and efficiency may suffer.[330]

This topic connects with decarbonization efforts in several ways. Emerging and transformational low-carbon technologies will need to compete in the marketplace with products made at facilities that are already at a huge scale (world-scale in many instances). It is hard for emerging technologies at small production volumes and high starting costs to compete with products made in production facilities that are at an immense scale. Newer technologies have had few improvement cycles, whereas the facilities at largescale have had years (in some cases, many decades) of efficiency improvement cycles that have propelled them down the learning curve. Entry technologies also tend to be single facilities, whereas world-scale production facilities often have highly integrated utilities (steam, fuel, by-products, etc.). Large-scale facilities tend to run product campaigns in large batch sizes (end point being continuous operation), so the costs and inefficiencies of set-up and winding down production are minor compared to new technologies.

Recent technological change and advancement of new capabilities (i.e., information technology, computer aided design, systems engineering, automated handling) have led to efforts to decouple manufacturing scale with efficiency and production cost (e.g., de-scaling).[331] Companies advancing innovative technology can meet market demand in new ways. Their flexibility to adjust to changing customer needs and more a nimble approach to addressing some of the disadvantages of small scale (e.g., computer aided efficiencies in product set up) can counter some of the disadvantages of scale. The RD&D need is to better understand how innovative technologies can be brought to market with

[330] "Achieving Economies of Scale: Understanding Why Bigger Can be Better," Mind Tools, accessed May 2022, https://www.mindtools.com/pages/article/newSTR_63.htm.

[331] Ludovico Alcorta, *The Impact of New Technologies on Scale in Manufacturing Industry: Issues and Evidence*, The United Nations University Institute for New Technologies, June 1992, https://archive.unu.edu/hq/library/Collection/PDF_files/INTECH/INTECHwp05.pdf.

improved efficiency and attributes that counter disadvantages of small-scale.[332] The USA Manufacturing Institute Rapid Advancement in Process Intensification Deployment (RAPID) is advancing capabilities in this area.[333] There is some evidence that offsite manufacturing of modular units and numbering up as opposed to scaling up could have capital expenditure advantages and reduce the risk in deploying novel technology.[334] The Clean Energy Smart Manufacturing Innovation Institute (CESMII) is advancing capabilities to rapidly share instrument control and analytics securely, which will also aid smaller manufacturers and innovative technologies.[335]

An associated topic is improving retrofit efficacy. When to implement a retrofit versus purchase of new equipment is a frequent debate in industry. Limited capital budgets and the need to prioritize reductions for the largest emitting sources may mean that retrofits may be a worthy option for other process improvements. Recent advances in smart manufacturing and the drive to Industry 4.0 may provide complementary benefits for retrofits.[336] The strategy for deep retrofits in buildings has been studied[337] and there may be useful learnings for energy intensive industries to leverage. Research on economies of scale and process improvement efficiency should be connected to retrofits as it is common for scale expansions to be considered at the same time as retrofits.

Emerging and transformative technologies face many challenges from concept to full commercialization to adoption at scale. In addition to those mentioned above, there are those challenges associated with product development, market validation, and establishing a track record.[338] There are also challenges with process integration, the interaction with increased variables and the need for flexibility to meet changing customer needs, and financing and capital as the process is scaled up to commercial scale in industry. The Advanced Manufacturing Office (AMO) collaborates with end users to help industry with technological issues to bridge these challenges.[339]

3.2 Digital Manufacturing

The rise of the Industry 4.0 concept seeks to apply cutting-edge technologies such as the Internet of Things, artificial intelligence, automation, robotics, and big data to improve industrial production efficiency. These tools could assist with crosscutting efficiency measures, such as improving process controls, simulating industrial systems and scenarios (i.e., through digital twinning), improving sensor technology, better characterizing supply chains with big data tools, and optimizing facility siting. Some

[332] Arvind S. Raman, et al., "Economic Risk Analysis for the Capture of a Distributed Energy Resource using Modular Chemical Process Intensification," *Journal of Advanced Manufacturing and Processing* 3, no. 4 (October 2021). https://doi.org/10.1002/amp2.10096.
[333] "RAPID (Rapid Advancement in Process Intensification Deployment Institute)," Manufacturing USA, accessed May 2022, https://www.manufacturingusa.com/institutes/rapid.
[334] James T. O'Connor et al., "Specialty Chemicals Production Case Study: Economic Analysis of Modular Chemical Process Intensification versus Conventional Stick-Built Approaches," *Journal of Advanced Manufacturing and Processing*, 3, no. 3 (July 2021), http://dx.doi.org/10.1002/amp2.10102.
[335] "CESMII," CESMII, accessed May 2022, https://www.cesmii.org/.
[336] Jon Lawson, "Retrofit your Way to Industry 4.0," *EngineerLive*, November 3, 2016, https://www.engineerlive.com/content/retrofit-your-way-industry-40.
[337] Eric Bloom and Clint Wheelock, *Retrofit Industry Needs Assessment Study: Public White Paper*, Rocky Mountain Institute, 2010, https://rmi.org/insight/retrofit-industry-needs-assessment-study/.
[338] Hara Wang and Cyril Yee, "Climate Tech's Four Valleys of Death and Why We Must Build a Bridge," Third Derivative (D3), June 17, 2020, https://www.third-derivative.org/blog/climate-techs-four-valleys-of-death-and-why-we-must-build-a-bridge.
[339] Rebecca Hanes et al., "Quantifying adoption rates and energy savings over time for advanced energy-efficient manufacturing technologies," *Journal of Cleaner Production* 232, (2019): 925-939. https://doi.org/10.1016/j.jclepro.2019.04.366.

companies are working on new technologies that could use these tools to reduce energy inputs and increase yield for the cement industry. The Alliance for Manufacturing Foresight (MForesight) works to inform the public and private sectors and federal decisionmakers on nascent opportunities and priorities in manufacturing such as those emerging through Industry 4.0.[340]

For example, a partnership between Argos, DOE, and the University of Louisville aims to use sensors, artificial intelligence, and data analytics to reduce the energy intensity of clinker production in cement.[341] There is also a link here as well to smart manufacturing capabilities, such as those being developed at CESMII provide digitization and knowledge generation enabling step-change improvements in manufacturing energy and materials efficiency while ensuring security and retention of intellectual property.[342]

[340] "Alliance for Manufacturing Foresight (MForesight)," MForesight, accessed May 2022, http://mforesight.org/.
[341] "Smart Manufacturing of Cement," CESMII, March 10, 2021, https://www.cesmii.org/smart-manufacturing-of-cement/.
[342] "CESMII," CESMII, accessed May 2022, https://www.cesmii.org/.

4 Further Strategic Analysis Needs

While this Roadmap lays a preliminary foundation for an overall U.S. industrial decarbonization strategy, the underlying scenario modeling was limited to five subsectors, with additional scope-limiting assumptions, to allow for a manageable scope. Additional analysis—including scenario modeling for additional industrial subsectors, inclusion of non-CO_2 GHGs and additional process emissions, and examination of other aspects of decarbonization not yet covered in this roadmap—will be needed to develop a comprehensive and holistic strategy for the entire industrial sector. Examples of those analysis needs are detailed in this section.

4.1 The Changing Energy Landscape

Deployment of state-of-the-art energy efficient industrial technologies provides energy and economic benefits to manufacturers and emissions intensity reductions. However – as identified in this roadmap – energy intensity improvements alone are insufficient achieve the large step-change reductions needed to reach U.S. emissions reductions targets, especially in context with an evolving background of primary energy production and delivery. A more comprehensive approach is required to assess industrial sector opportunities to use low- or no-GHG emissions fuels, feedstocks, and energy sources; transition to low-carbon process technology; cost-effectively capture remaining CO_2 bound for the atmosphere; etc. as outlined in this roadmap. Expanding renewable and nuclear electricity deployment will be an essential element of net-zero paths and today's clean electricity production capacity may need to grow four times by 2030 to be on track to achieve emissions reduction goals.[343] Within that context, there are several connections that need to be more explicitly evaluated in order to assess intra- and inter-dependencies amongst the four pillars outlined in this roadmap, including:

- **The connection between industrial productivity and clean electricity generation**. If the industrial productivity improvement rate of 3% per year (the highest multi-decade rate observed) could be achieved, the wind, solar, and nuclear capacity generation needed by 2050 could be reduced 10% for some scenarios, carbon capture needs would drop, and the economic hit to total energy/supply system cost would decline 5% (net present value).[344] Industrial productivity clearly has a key role to play. An increase in energy productivity that outpaces industry growth could reduce future infrastructure capacity requirements and reduce total energy-related GHG emissions.
- **The connection between industrial electrification and delivery of clean electricity**. The scenarios in Section 2.2.3 (Figure 26) show that if hydrogen is used as a feedstock for processes such as ammonia production when the hydrogen comes from grid-supplied electricity that has a relatively low proportion of low- or no-carbon electricity, the CO_2 emissions can increase by 2030 for the Moderate and Advanced scenarios. Hence, local generation of low- or no-carbon electricity that is reliable and suitable for industrial use (e.g., for generation of hydrogen, support of process heat, other) and increased adoption of electric technologies and processes for industrial operations needs to be coordinated and sequenced so that GHG emissions reductions are realized.
- **The connection between increased use of low-, no-, or negative-carbon feedstocks and energy sources used in the industrial sector**. Technological and supply chain breakthroughs are needed to

[343] Eric Larson et al., *Net-Zero America: Potential Pathways, Infrastructure, and Impacts, interim report*, Princeton University, December 2020, https://environmenthalfcentury.princeton.edu/sites/g/files/toruqf331/files/2020-12/Princeton_NZA_Interim_Report_15_Dec_2020_FINAL.pdf.
[344] Ibid.

decouple the source of energy and feedstocks from GHG emissions within the industrial sector, and the decoupling of energy sources and GHG emissions from GDP growth. The availability and effective use of biofuels, nuclear, renewable or low- or no-carbon natural gas, etc. needs to expand without conflicts with the food supply at a rate that will contribute to this transition.

- **The connections between materials efficiency, energy, and GHG emissions**. Sustainable manufacturing methods that pursue a cradle-to-cradle approach to production (circular economy) were not addressed in the scenario analyses for this roadmap, nor were substitution or development of new materials that could provide the same or greater service with reduced energy and emissions. Scenarios need to be developed that can accurately account for the full life cycle energy consumption, GHG emissions, and other environmental impacts of these approaches. Additionally, implementing and adopting such strategies, technologies, and thinking in industry can provide new opportunities for U.S manufacturers in an increasingly competitive global marketplace. These opportunities also need to be assessed, given that manufacturing accounts for 11.4 million jobs and contributes $2.38 trillion per year to the U.S. economy.[345]
- **The connections to other sectors of the economy**. The industrial sector's centrality to supply and value chains for a vast array of products and services highlights the importance of industrial production to other sectors (e.g., transportation; residential and commercial buildings; electricity production and distribution). As these sectors adopt new, low-carbon products and strategies, those interrelationships must be accounted for within industrial emissions reductions scenarios.

Given these important and evolving connections, integrating analyses are needed to fully map out pathways to net-zero emissions by 2050. The following sections highlight specific areas of emerging interest and opportunity that need to be included in integrated analyses.

4.2 Bioenergy, Biofuels, and Bio-feedstocks

The use of bioenergy for multiple purposes (process heat, feedstock, fuel, precursor for chemical reactions, RNG steam reforming to clean hydrogen) is a broad and important topic. Although a deep dive into this topic was not included in the roadmap's scope, it is important to note the opportunities for bioenergy use within industry.[346] Biomass has the potential to provide a portion of industrial heat demand, and if electricity prices exceed $20/MWh biomass could compete with electrification.

Opportunities for bioenergy to reduce GHG emissions have been studied for steel[347] but the potential reduction impacts for other subsectors is an opportunity area for further research.

[345] "Annual Survey of Manufacturers (ASM)," U.S. Census Bureau, last modified April 21, 2022, https://www.census.gov/programs-surveys/asm.html.

[346] Research from DOE, ORNL, and NREL continue to explore the opportunities in this area. See the following for more information: U.S. Department of Energy Bioenergy Technologies Office, *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks*, July 2016, http://energy.gov/eere/bioenergy/2016-billion-ton-report; "National Transportation Research Center: Bioenergy Technologies," Oak Ridge National Laboratory, accessed May 2022, https://www.ornl.gov/facility/ntrc/research-areas/bioenergy-technologies; U.S. Department of Energy Office of Transportation Technologies, *Biofuels, a Solution for Climate Change: Our Changing Earth, Our Changing Climate*, September 1999, https://www.nrel.gov/docs/fy99osti/24052.pdf

[347] Mandova, H., et al., Possibilities for CO_2 emission reduction using biomass in European integrated steel plants. 2018. Biomass and Bioenergy, 115, 231-243. https://www.sciencedirect.com/science/article/pii/S0961953418301107.

4.3 Other Low-Carbon Energy Sources

In addition to the opportunities for industrial GHG emissions reductions attributable to an increasingly decarbonized grid, there are also emerging opportunities for direct use of clean energy in the industrial sector, which will benefit from more detailed analysis. This includes nuclear power which is concentrated, high quality, dispatchable, and produces no carbon emissions. The greatest thermodynamic efficiencies are ultimately attained by direct application of the thermal energy produced by nuclear reactors, needs to be aligned with industrial process heating demands (e.g., amount and quality of heat) by industrial subsector (see Figure 6)), and could be a strong candidate for providing process heat for the chemical subsector.[348] A 2018 study on the future of nuclear energy[349] provides some findings and recommendations on how nuclear energy can be deployed to help with national decarbonization goals noting that cost, heat range, and location dependence are factors to be considered. That analysis estimated that approximately 16.5% of the domestic industrial heat market could be supplied using nuclear energy.[350]

Additionally, concentrating solar-thermal energy (CST) is a source of emission-free high-temperature heat. CST uses a field of mirrors that track the sun to focus its rays onto a receiver, where a heat-transfer medium is heated to a high temperature. Currently, CST is primarily commercially deployed to produce electricity, in the form of CSP plants. There are nearly 100 CSP plants producing electricity in commercial operation worldwide, representing almost 7 GW of capacity. Many CSP plants in operation today utilize thermal energy storage (TES) systems, which store solar energy as heat for use when it is needed. This heat can be used for a variety of industrial processes or power generation. By incorporating thermal energy storage, CST has the potential to offer dispatchable renewable heat at a wide range of temperatures for difficult-to-decarbonize industries. CST technologies can directly produce steam or high-temperature fluids by concentrating sunlight. This solar-generated heat can then be directly integrated with thermally driven industrial processes. Solar-thermal processes could also generate energy-dense chemicals or fuels that could deliver stored solar energy. Developing pathways for solar-derived chemicals or fuels can help reduce the carbon intensities of numerous industries. However, significant technological challenges remain, including the design and equipment for integrated solar-thermal processes that can address the variability challenges inherent in using sunlight as fuel.

4.4 Additional Industrial Subsectors

Several additional industrial subsectors could be examined for the application of these pillars and pathways. For example, pulp and paper manufacturing is a large energy user that also has a high thermal load (much of it at relatively low temperature) and accounts for 4% of U.S. industrial energy-related CO_2 emissions.[351] Opportunities for significant GHG emissions reduction in other global regions have suggested that the adoption of a number of technologies including energy efficiency, heat recovery, bioenergy, electrification, and decarbonization of the electrical supply will need to be

[348] Richard D. Boardman et al., "Process Heat for Chemical Industries," *Encyclopedia of Nuclear Energy* 3, (2021): 49-60. https://doi.org/10.1016/B978-0-12-819725-7.00198-7.
[349] Massachusetts Institute of Technology, *The Future of Nuclear Energy in a Carbon Constrained World*, 2018, https://energy.mit.edu/wp-content/uploads/2018/09/The-Future-of-Nuclear-Energy-in-a-Carbon-Constrained-World.pdf.
[350] Ibid.
[351] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 19. Energy-Related Carbon Dioxide Emissions by End Use and Table 26. Paper Industry Energy Consumption.

pursued.[352] Decarbonizing fertilizer is connected to the generation of hydrogen from low-carbon energy as a significant portion of the energy consumed in fertilizer production is typically associated with hydrogen generation. The opportunity to decarbonize hydrogen has recently been analyzed.[353] Glass manufacturing is another subsector with potential for future research, and there has been some analysis on decarbonization opportunities in Europe.[354]

4.5 Competitiveness

Many energy intensive industries have large portions of their product portfolios that are mature with relatively low margins. Most companies and their products face fierce global competition. In this environment, companies are faced with the challenges described in this report, to transform their energy usage, feedstocks, and process technology to achieve dramatically lower GHG emissions. The companies must balance stakeholder and societal demands for decarbonization while maintaining or growing market share amidst that competitive landscape, meeting increased demand for products, and addressing a host of risks. Policies incentivizing decarbonization may play an important role in accelerating the transformation.

The clean energy technology market size has been estimated at over $60 trillion by 2040 (including $8 trillion for renewable energy supply and $23 trillion for energy efficiency).[355] While that would suggest a lucrative market attracting a wide range of investors, the portion of the market developing low-carbon process technologies is relatively small and underdeveloped. Companies developing clean energy technologies have been challenged to tap this market as early offerings have tied up capital for longer than expected, solutions are expensive to scale, there is little room for error given the exposure of these companies to commodity margins, and the target customers such as large industrial companies are averse to risk and paying a premium for unproven growth prospects.[356] Considering these challenges, it is important to understand how to more effectively apply the resources of venture capital and other supporting partners.

Research at DOE analyzing clean energy manufacturing competitiveness (including several case studies) emphasizes the central role of shared information in the industrial commons, mature supply chain interactions, and access to capital to scale up the technology. These components help reduce risk and provide resources to allow expanded participation in scale-up activities. Also, the research notes the need for a skilled, robust workforce, attention to materials supply chain development, and advanced

[352] Paul W. Griffin, Geoffrey P. Hammond, and Jonathan B. Norman, "Industrial Decarbonization of the Pulp and Paper Sector: a UK Perspective," *Applied Thermal Engineering* 134, (April 2018): 152-162. https://doi.org/10.1016/j.applthermaleng.2018.01.126.

[353] Jay Bartlett and Alan Krupnick, *Decarbonized Hydrogen in the US Power and Industrial Sectors: Identifying and Incentivizing Opportunities to Lower Emissions*, Resources for the Future, Report 20-25, December 2020, https://media.rff.org/documents/RFF_Report_20-25_Decarbonized_Hydrogen.pdf.

[354] UK Department for Business Energy and Industrial Strategy and British Glass, *Glass Sector: Industrial Decarbonization and Energy Efficiency Roadmap and Action Plan*, October 2017, https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/652080/glass-decarbonisation-action-plan.pdf.

[355] International Energy Agency, *World Energy Outlook 2016*, 2016, https://iea.blob.core.windows.net/assets/680c05c8-1d6e-42ae-b953-68e0420d46d5/WEO2016.pdf. See Page 22.

[356] Benjamin Gaddy, Varun Sivaram, and Francis O'Sullivan, *Venture Capital and Cleantech: The Wrong Model for Clean Energy Innovation, An MIT Energy Initiative Working Paper*, MIT Energy Initiative, 2016, https://energy.mit.edu/wp-content/uploads/2016/07/MITEI-WP-2016-06.pdf.

manufacturing capabilities to ramp up scale while driving down production costs.[357] For the rapid development, and in particular accelerated adoption, of emerging and transformative technology it is important that these factors are addressed. Consortia and other partnerships with industry that engage in the development, demonstration, and commercialization of these technologies are vital to success for low-carbon technologies.

4.6 Material Efficiency

The extraction of natural resources and subsequent processing into manufactured goods account for almost 50% of total global GHG emissions.[358] The circular economy is viewed as an alternative economic model capable of reducing environmental, economic, and social issues stemming from the depletion of earth's natural resources. In a circular economy, resources are circulated rather than dispersed, looking to maintain materials' value within the economy and minimizing waste. Through strategies such as redesigning, reusing, repurposing, or recycling, the circular economy could benefit the economy – potentially generating an additional $1 trillion per year globally.[359]

Materials efficiency, circular economy, and resource conservation approaches can help lessen energy demand and GHG emissions and can provide up to 30% of global targeted emissions reductions for cement, steel, and aluminum.[360] The 2021 Circularity Gap Report[361] estimates how nationally determined contributions (NDCs) and circular economy strategies can keep global warming below 2°C. These strategies can also result in more moderate deployment needs for low-GHG emissions process technologies. This can also lower the cumulative capital investment, such as a 4% lower capital investment for steel, cement, and aluminum by 2060.[362]

Besides directly contributing to the circular economy and decarbonization, materials efficiency and recycling strategies can be applied to renewable technologies to further enhance their contribution to decarbonization. A 2018 paper[363] for instance, estimated that recycling end of life wind turbines saves about 123 tons of CO_2e/MW. In another example, the repurposing of electric vehicles' old batteries to store energy from photovoltaics (PV) in homes reduces GHG emissions by 58% compared to the use of a new lithium-ion battery.[364] Regarding PV, a recent study[365] shows that applying the circular economy concept of industrial symbiosis to enhance material recovery from end of life PV modules could save up

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[357] U.S. Department of Energy, *Quadrennial Technology Review 2015, Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing: Supplemental Information, Competitiveness Case Studies*, September 2015, https://www.energy.gov/sites/prod/files/2017/01/f34/Ch6-SI-Competitiveness-Case-Studies_0.pdf.
[358] Ellen MacArthur Foundation, *Completing the Picture: How the Circular Economy Tackles Climate Change*, 2021 reprint, https://www.ellenmacarthurfoundation.org/publications/completing-the-picture-climate-change; International Resources Panel, *Global Resources Outlook 2019: Natural Resources for the Future We Want*, 2019, https://www.resourcepanel.org/reports/global-resources-outlook.
[359] Jouni Korhonen, Antero Honkasalo, and Jyri Seppälä, "Circular Economy: The Concept and its Limitations," *Ecological Economics* 143, (January 2018): 37-46. https://doi.org/10.1016/j.ecolecon.2017.06.041.
[360] International Energy Agency, *Material Efficiency in Clean Energy Transitions*, March 2019, https://www.iea.org/reports/material-efficiency-in-clean-energy-transitions.
[361] The Platform for Accelerating the Circular Economy, "The Circularity Gap Report 2021," 2021, https://www.circularity-gap.world/2021.
[362] Ibid.
[363] Jonas Pagh Jensen, "Evaluating the environmental impacts of recycling wind turbines," *Wind Energy* 22, no. 2 (September 2018): 316-326. https://doi.org/10.1002/we.2287.
[364] Silvia Bobba et al., "Life Cycle Assessment of repurposed electric vehicle batteries: an adapted method based on modelling energy flows," *Journal of Energy Storage* 19, (October 2018): 213-225. https://doi.org/10.1016/j.est.2018.07.008.
[365] N. Mathur, S. Singh, and J.W. Sutherland, "Promoting a circular economy in the solar photovoltaic industry using life cycle symbiosis," *Resources, Conservation and Recycling* 155, (April 2020): 104649. https://doi.org/10.1016/j.resconrec.2019.104649.

to 2.75 MT GHG emissions per MT of recycled PV. Other circularity strategies such as reuse, new module designs, and improved PV module durability could lower PV's carbon footprint.[366]

Overall, transitioning to a more circular economy could be a fundamental step towards achieving decarbonization. The Ellen MacArthur foundation argues that when circular strategies are applied to four critical industrial materials (cement, steel, plastic, and aluminum), GHG emissions from their respective industries could be cut by 40%.[367]

Although literature review has revealed significant progress in circular economy, there are some research gaps. Tradeoffs and unintended consequences of circular economy strategies can dim their contribution to decarbonization. There are examples where materials efficiency strategies can reduce GHG emissions from the use of materials, but also increase GHG emissions from the operational phase.[368]

To enable greater uptake of materials efficiency, several actions are needed including benchmarking, data collection, increased use of LCA methodology, and promoting circular economy strategies (i.e., longer lifetimes, reuse, repurposing, recycling). The multi-material decisions and competitive marketplace interactions associated with other aspects of this topic are not simple as considering additional supply chain impacts and more research is needed to weigh the impact of several factors.[369]

The supply chain contributions to the embodied carbon of products and raw materials and opportunities to decrease the product carbon intensity are related aspects of materials efficiency. More granular research is needed on the impacts, interconnections, and routes to reduce embodied carbon. RD&D is needed to better characterize the supply chain contributions and GHG emissions reduction opportunities for all subsectors.

4.7 Addressing Residual GHG and Other Emissions

Even with application of these pillars and others to deliver dramatic GHG emissions reductions, it is probable that other mechanisms will be needed to reduce or negate the residual GHG emissions from hard-to-abate processes and small emitters that are impractical to abate. This raises the question of where those reductions will come from and how they can be verified, tracked, and counted. Various options have been described for technologies and activities (e.g., reforestation[370]), negative emissions strategies, and for the role of GHG markets in developing and tracking credits generated by these

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[366] Garvin A. Heath et al., "Research and development priorities for silicon photovoltaic module recycling to support a circular economy," *Nature Energy* 5, (2020): 502-510. https://www.nature.com/articles/s41560-020-0645-2.; Hengky K. Salim et al., "Drivers, barriers and enablers to end-of-life management of solar photovoltaic and battery energy storage systems: A systematic literature review," *Journal of Cleaner Production* 211, (February 2019): 537-554. https://doi.org/10.1016/j.jclepro.2018.11.229.

[367] Ellen MacArthur Foundation, *Completing the Picture: How the Circular Economy Tackles Climate Change*, 2021 reprint, https://www.ellenmacarthurfoundation.org/publications/completing-the-picture-climate-change.

[368] Edgar G. Hertwich et al., "Material efficiency strategies to reducing greenhouse gas emissions associated with buildings, vehicles, and electronics—a review," *Environmental Research Letters* 14, no. 4 (April 2019): 043004. https://doi.org/10.1088/1748-9326/ab0fe3.

[369] Reid Lifset and Matthew Eckelman, "Material Efficiency in a Multi-Material World," *Phil. Trans. R. Soc. A.* 371, no. 1986 (March 2013). https://doi.org/10.1098/rsta.2012.0002.

[370] Ross W. Gorte and Jonathan L. Ramseur, *Forest Carbon Market: Potential and Drawbacks*, Congressional Research Service, July 3, 2008, https://fas.org/sgp/crs/misc/RL34560.pdf.

technologies and activities (e.g., sectoral approaches,[371] clean development mechanisms, subsequent United Nations Framework Convention on Climate Change programs[372]).

Experience to date with reforestation suggests that while there are opportunities for negative emissions to slow the rate of deforestation, there can also be additionality, verification, and leakage challenges. The list of emerging negative emissions strategies continues to grow, and early experimentation with methods such DAC are providing information on life cycle GHG emissions reductions, economics, resource needs, and input on future research strategies.[373] The energy and materials resource requirements continue to be issues that raise uncertainty on large scale application of negative emissions technologies and raise topics for additional research.[374] Other approaches such as bioenergy with CCS,[375] soil carbon sequestration, etc. are in early stages of research. These topics are further RD&D opportunities to understand the quantities of CO_2 that can be sequestered, tradeoffs, and their value in addressing hard-to-abate industrial emissions.

In addition to abating residual GHG emissions, it is also important to consider reductions of non-GHG emissions (e.g., carbon monoxide, sulfur oxides (SOx), nitrogen oxides (NOx)). New technologies should be developed with the goal of being fully sustainable, considering the full range of possible emissions, in addition to addressing GHG emissions. Sustainable manufacturing (or circular economy) approaches, which consider the full life cycle of a product from material extraction to reuse, are essential to ensuring sustainability of technologies.[376]

4.8 Policy Implications and Impacts

The ability of the RD&D developments described in the roadmap to achieve GHG reductions will depend on enabling policies and support. As the technical challenges in decarbonizing the industrial sector are complex, so too are the required policy responses. There are a range of policies that will have an impact on the eventual uptake of industrial decarbonization technologies.

Although policies are not assessed or evaluated in this roadmap and no recommendations of policies are included, several groups have recently explored policies and programs to support industrial decarbonization. The Aspen Global Change Institute and a National Academies panel, among other entities, have identified the technologies and policies needed to decarbonize industry worldwide.

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[371] Richard Baron, Barbara Buchner, and Jane Ellis, *Sectoral Approaches and the Carbon Market,* OECD/ IEA, May 2009 https://www.oecd.org/env/cc/42875080.pdf.

[372] Michale Gillenwater and Stephen Seres, *The Clean Development Mechanism: A Review of the First international Offset Program*, Pew Center, March 2011, https://www.c2es.org/site/assets/uploads/2011/03/clean-development-mechanism-review-of-first-international-offset-program.pdf; "Ten options for negative emissions technologies," CarbonBrief, April 11, 2016, https://www.carbonbrief.org/explainer-10-ways-negative-emissions-could-slow-climate-change.

[373] National Academies of Science, Engineering and Medicine*, Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*, The National Academies Press, Washington, DC, 2019, https://www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda.

[374] Kevin Anderson and Glen Peters, "The Trouble with Negative Emissions," *Science* 354, no. 6309 (October 2016): 182-183. https://doi.org/10.1126/science.aah4567.

[375] International Energy Agency, *Combining Bioenergy with CCS*, December 2011, https://www.iea.org/reports/combining-bioenergy-with-ccs.

[376] U.S. Department of Energy, *Quadrennial Technology Review 2015 Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing Technology Assessments, Sustainable Manufacturing - Flow of Materials through Industry*, September 2015, https://www.energy.gov/sites/default/files/2016/05/f31/QTR2015-6L-Sustainable-Manufacturing.pdf.

5 Department of Energy Approaches to Catalyze Industrial Decarbonization

Earlier sections of this document outlined both industry-specific and broad challenges to decarbonizing the industrial sector. The broad range of RD&D needs, magnitude of change, and accelerated timeframe signal that multiple partners across the public and private sectors will need to proactively engage in this challenge over decades. DOE plays a key role in advancing decarbonization by catalyzing technology development and accelerating new technology deployment through programs and funding opportunities and helping to meet the Biden administration's 2050 net-zero emissions goal. Since 2021, EERE offices have announced or awarded over $10 billion of investments in industrial decarbonization efforts. DOE and its various offices are well-positioned to address many of the industrial decarbonization barriers identified in this roadmap. This section describes DOE office activities, collaborations, and capabilities that can be leveraged and potential pathways that could address many of the challenges identified above.

DOE has numerous mechanisms to impact industrial decarbonization. Analysis, modeling, and tool development serves to guide DOE offices and inform decision-making for the greatest impact on decarbonization. DOE offices use this information and input from stakeholders, solicited through workshops and Requests for Information (RFIs), to shape Funding Opportunity Announcements (FOAs) and Laboratory Calls,[377] which solicit proposals for research, development, demonstration, deployment, and technical assistance from industry, academia, national laboratories, consortia, and other entities. These are competitive solicitations reviewed by subject matter experts, resulting in the selection of the most meritorious projects. For technology scale up, loans and other financing programs facilitate the commercialization and use of energy-saving technology.

As DOE receives more congressional direction to focus on emissions reduction, the offices and their programs provide a framework that could be built upon to include RD&D, industry partnerships, and education and workforce development that targets industrial decarbonization.

5.1 DOE Office Activities in Industrial Decarbonization

Significant work addressing the four decarbonization pillars occurs in multiple DOE offices as shown in Table 5. Involvement by each office may occur anywhere from the basic science level (early technical maturity level) through the Office of Science (SC) or the Advanced Research Projects Agency – Energy (ARPA-E) to support of large-scale demonstrations through the newly established Office of Clean Energy Demonstrations (OCED).

The next section reviews select recent and past collaborations between the offices.

[377] This process is similar to what is described in U.S. Department of Energy, *Quadrennial Technology Review 2015, Chapter 10: Concepts in Integrated Analysis*, September 2015, https://www.energy.gov/sites/prod/files/2017/03/f34/qtr-2015-chapter10.pdf.

TABLE 5. INDUSTRIAL DECARBONIZATION SUPPORT BY DOE OFFICE

DOE Office	Role in Supporting Industrial Decarbonization
U.S. DEPARTMENT OF ENERGY Energy Efficiency & Renewable Energy ADVANCED MANUFACTURING OFFICE	EERE's Advanced Manufacturing Office (AMO) supports development of new manufacturing processes and products and is dedicated to improving the energy efficiency, material efficiency, productivity, and competitiveness of manufacturers across the industrial sector.
U.S. DEPARTMENT OF ENERGY Energy Efficiency & Renewable Energy BIOENERGY TECHNOLOGIES OFFICE	EERE's Bioenergy Technology Office (BETO) supports development of low-carbon fuels and energy through focus on alternative feedstocks (e.g., biomass, waste, CO_2) and process improvements through biomanufacturing.
U.S. DEPARTMENT OF ENERGY Energy Efficiency & Renewable Energy FUEL CELL TECHNOLOGIES OFFICE	EERE's Hydrogen and Fuel Cell Technologies Office (HFTO) works to advance the development of hydrogen and fuel cell technologies for multiple decarbonization opportunities across industrial sectors and applications.
U.S. DEPARTMENT OF ENERGY Energy Efficiency & Renewable Energy SOLAR ENERGY TECHNOLOGIES OFFICE	EERE's Solar Energy Technology Office (SETO) supports development of solar processes. For decarbonization, a main focus includes solar thermal industrial process heat for thermally-driven processes across multiple manufacturing subsectors.
U.S. DEPARTMENT OF ENERGY Energy Efficiency & Renewable Energy **Strategic Analysis**	EERE's Strategic Analysis team (SA) sponsors crosscutting analysis and model development across multiple technology areas relevant to the key strategies for industrial decarbonization.
arpa·e	The Advanced Research Projects Agency – Energy (ARPA-E) supports development of low-maturity technologies and processes across the four decarbonization pillars. Recent supported topic areas include zero-emissions iron and steel making, cement production emissions reduction, and industrial process heating decarbonization.
U.S. DEPARTMENT OF ENERGY Fossil Energy and Carbon Management	DOE's Office of Fossil Energy and Carbon Management (FECM) supports all areas of the CCUS value chain/system and is a leader in CCUS life cycle assessment and techno-economic analysis.
U.S. DEPARTMENT OF ENERGY Office of Nuclear Energy	DOE's Office of Nuclear Energy (NE) supports development of new applications of nuclear beyond electricity (e.g., small modular, flexible, advanced reactors) to help decarbonize the economy and develop the potential future energy system
U.S. DEPARTMENT OF ENERGY Office of Electricity	DOE's Office of Electricity (OE) R&D focuses on technologies leading to a reliable and resilient electric grid that can safely integrate the technologies pursued by other DOE applied offices.

DOE Office	Role in Supporting Industrial Decarbonization
U.S. DEPARTMENT OF ENERGY Office of Science	DOE's Office of Science (SC) supports development of discovery and use-inspired fundamental science (low-maturity technologies and processes) to decarbonize industry and transform advanced manufacturing. SC helps define priority research directions to transform advanced manufacturing and decarbonize industry.

5.2 Advancing Enabling Technologies and Practices through RD&D

RD&D is central to how DOE achieves its mission. Although RD&D is based on congressional direction and authorization, most of the research has been guided by energy efficiency and embodied energy targets; carbon intensity improvement is often also a result. DOE offices have had prior and ongoing research efforts targeting many of the areas discussed throughout Section 1.5 and are well-positioned to leverage existing programs and partnerships to address other key opportunity areas to advance decarbonization. RD&D may be focused on addressing specific pillars, industries, or crosscutting technologies or topics.

Most DOE funding for RD&D takes the form of competitively awarded projects and programs, national laboratory research and public-private partnerships(such as Manufacturing USA Institutes and research hubs), and user facilities. Ongoing RD&D addresses many of the barriers identified in this roadmap in two ways: directly through RD&D areas that reduce GHG emissions and by providing a framework that can be leveraged and or built upon to more explicitly target emissions reduction. To guide funding opportunities, all DOE offices conduct analysis to identify capability gaps and assess the opportunity for energy efficiency improvement across many sectors and in crosscutting areas.

Within DOE, several crosscutting activities are agency-wide initiatives. Such collaboration enables integration across complex systems. Typically, the goal is to focus on energy impacts; however, decarbonization is more frequently an objective that is being included in the goals and targets. Moreover, these strategic collaborations could be leveraged to make systematic changes. For example, building a more resilient electric grid would enable higher levels of electrification in industry. As identified in this roadmap, industrial electrification, use of clean hydrogen, and the integration of carbon capture and utilization in manufacturing are opportunities to decarbonize the industrial sector, but these are not achievable without broader, more integrated efforts. All these technologies stem from basic science discovery and development. Close collaboration between the Office of Science (SC) and applied offices will accelerate progression through the technology development pipeline and is critical to addressing the urgent climate crisis.

5.3 DOE Interoffice Collaboration

Decarbonization of the industrial sector will require not only innovation of specific technologies but also system-level changes. The industrial sector is part of a larger system and will benefit from developments in other sectors, such as electrification, nuclear energy, renewable energy and hydrogen generation, and energy storage. DOE offices must collaborate to develop integrated approaches that advance not only the industrial sector but also other sectors. Figure 59 highlights just a few existing collaborations for DOE by office. The next sections briefly discuss these activities, though full information can be found by visiting the DOE website.[378]

[378] U.S. Department of Energy, https://www.energy.gov/.

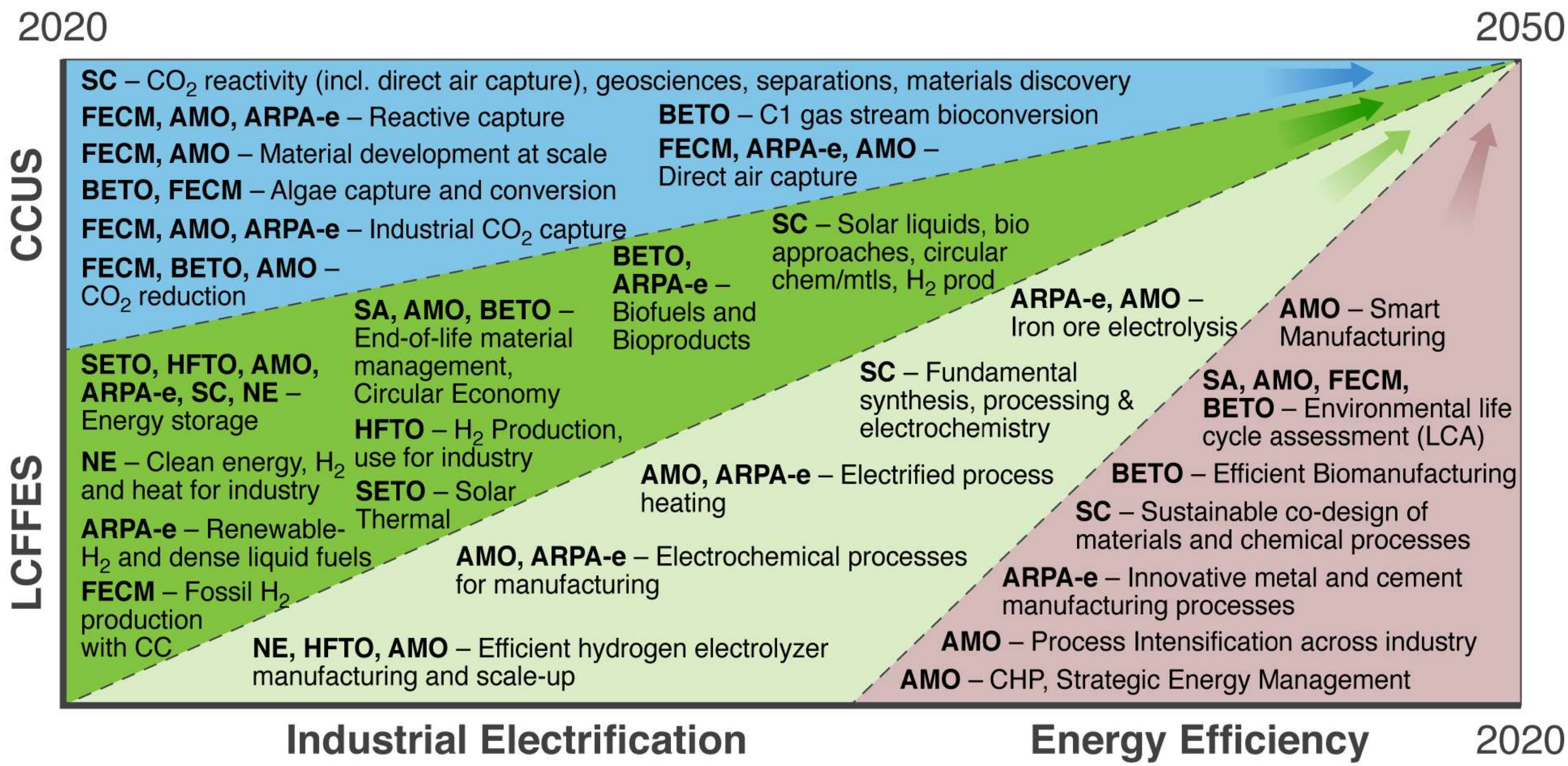

Figure 59. Landscape of DOE office activities across the four decarbonization pillars to achieve net-zero emissions by 2050.

AMO: Advanced Manufacturing Office; ARPA-e: Advanced Research Projects Agency – Energy; BETO: Bioenergy Technologies Office; FECM: Office of Fossil Energy and Carbon Management; HFTO: Hydrogen and Fuel Cell Technologies Office; NE: Office of Nuclear Energy; SA: EERE Strategy Analysis; SC: Office of Science; SETO: Solar Energy Technologies Office.

Key message: Each office has individual and collaborative work occurring across the four decarbonization pillars, to help reach the net-zero emissions by 2050 goal.

5.3.1 Energy Efficiency

Some examples of DOE office activities and collaboration within the energy efficiency pillar include:

Process Intensification (AMO, ARPA-e): AMO funds RD&D in chemical manufacturing through individual projects led by industry, academia, and the national laboratories and through the Rapid Advancement in Process Intensification Deployment Institute (RAPID),[379] which focuses on process improvements to chemical processes. The RAPID Institute is working to improve the efficiency of chemical processes through intensified processes and includes a body of work on refinery processes. RAPID's focus areas include chemical commodity processes, natural gas upgrading, and intensified process fundamentals, all of which include projects that improve refinery processes. An example of a refining-related RAPID project is one in which a membrane is being developed that can separate propylene from propane[380] and which would eliminate the need for costly and energy-intensive thermal separations. Process intensification to redefine and shorten the steelmaking value chain is also an area of interest for ARPA-E, including a recent award demonstrating a novel membrane to significantly reduce energy in pulp and paper recovery boilers.[381]

Innovative Chemistry (AMO, BETO, SC): SC supports fundamental science to understand and overcome the barriers to achieving superior energy efficiency in chemical and materials manufacturing. These advances include new upcycled polymers; catalysts for low-temperature chemical synthesis; materials for extreme environments; isotope production, purification, and use; advanced nuclear fuels; and innovative accelerator technology for materials and chemical process characterization under operando conditions.

Combined Heat and Power (AMO): As discussed in Section 1.2.1.1, CHP can play a key role in industrial decarbonization efforts through energy efficiency improvements and GHG reductions. AMO continues to support further development and utilization of CHP through R&D projects[382] and its CHP Deployment Program.[383]

Life Cycle and Techno-Economic Assessments (SA, AMO, FECM): For some industries and manufacturers, investment in cutting-edge technologies is limited by the inherent challenge in making a business case for premature replacement of existing capital assets. This is particularly true for industries that make low-margin commodity products that rely on high volume production to make a profit due to the high capital cost of process changes. The development and updating of TEA throughout RD&D projects are also encouraged for DOE funded projects to ensure the technology being developed has a solid value proposition. SA also focuses on conducting LCA and TEA in coordination with other DOE offices. FECM conducts power generation technologies LCA.

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[379] "RAPID (Rapid Advancement in Process Intensification Deployment Institute)," RAPID, accessed May 2022, https://www.aiche.org/rapid.

[380] "Energy Efficient Separations of Olefins and Paraffins through a Membrane," RAPID, accessed May 2022, https://www.aiche.org/rapid/projects/energy-efficient-separations-olefins-and-paraffins-through-membrane.

[381] "Scalable Graphene Oxide Membranes for Energy-Efficient Chemical Separations," ARPA-E, last modified November 15, 2018, https://arpa-e.energy.gov/technologies/projects/scalable-graphene-oxide-membranes-energy-efficient-chemical-separations.

[382] "Combined Heat and Power (CHP) and District Energy," U.S. Department of Energy Advanced Manufacturing Office, accessed May 2022, https://www.energy.gov/eere/amo/combined-heat-and-power-chp-and-district-energy.

[383] "Combined Heat and Power Deployment," U.S. Department of Energy Better Buildings, accessed May 2022, https://betterbuildingssolutioncenter.energy.gov/chp.

Material Efficiency (AMO): Research on composites through the Institute for Advanced Composite Manufacturing Innovation (IACMI)[384] and the Carbon Fiber Test Facility (CFTF)[385] enable reduction of transportation emissions and could potentially provide material efficiency and switching benefits. Similarly, work on additive manufacturing at the Manufacturing Demonstration Facility (MDF)[386] enables material efficiency in manufacturing.

5.3.2 Industrial Electrification

Some examples of DOE office activities and collaboration within the industrial electrification pillar include:

Electrolyzer Manufacturing (HFTO, AMO): To enable electrification, continued electrolyzer RD&D is needed. HFTO and AMO jointly fund R&D to reduce the cost of electrolyzer components, scale-up, and manufacturing.[387] HFTO's recently launched H2NEW consortium targets enabling a modeled hydrogen cost of $2/kg (at scale) by 2025.[388]

Electrified Process Heating (AMO, ARPA-e): Section 1.2.2.1 discusses the importance of process heat electrification to reduce emissions in the industrial sector. In Fiscal Year 2019, AMO began funding research that could enable electrified process heating and would couple CHP systems with clean energy sources; both topics were meant to increase the use of low-carbon energy sources in manufacturing. ARPA-E also has an interest in electrified process heat for both crosscutting and industry-specific opportunities (e.g., petroleum refining, chemicals, pulp and paper, ironmaking, and metal fabrication). Numerous projects have already been funded by ARPA-E,[389] with an interest in funding future technologies that may dramatically reduce heat, entirely eliminate heat use, or dramatically reduce the cost of electrifying heat.

Iron Ore Reduction (AMO, ARPA-e, HFTO, NE): As noted in Section 2.1.3.2, electrolysis of iron ore is a key RD&D opportunity for reaching the Near Zero GHG Scenario. In 2021, ARPA-E released a Request for Information on steel made via emissions-less technologies[390] and held a workshop on zero-emission iron

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[384] IACMI is a Manufacturing USA institute focused on developing advanced composites. "IACMI," IACMI, accessed May 2022, https://iacmi.org/.

[385] The Carbon Fiber Test Facility is a user facility that conducts research on carbon fiber manufacturing. For more information, see "Carbon Fiber Technology Facility," Oak Ridge National Laboratory, accessed May 2022, https://www.ornl.gov/facility/cftf.

[386] The Manufacturing Demonstration Facility is a user facility focused on R&D of additive manufacturing. For more information see "Manufacturing Demonstration Facility," Oak Ridge National Laboratory, accessed May 2022, https://www.ornl.gov/facility/mdf.

[387] "Energy Department Announces Approximately $64M in Funding for 18 Projects to Advance H2@Scale," U.S. Department of Energy, July 20, 2020, https://www.energy.gov/articles/energy-department-announces-approximately-64m-funding-18-projects-advance-h2scale.

[388] "H2NEW (Hydrogen from Next-generation Electrolyzers of Water)," U.S. Department of Energy, accessed May 2022, https://h2new.energy.gov/.

[389] "Innovating Through Unconventional Ideas," ARPA-E, January 9, 2020, https://arpa-e.energy.gov/news-and-media/blog-posts/arpa-e-innovating-through-unconventional-ideas; "High Value Energy Saving Carbon Products and Clean Hydrogen Gas from Methane," ARPA-E, last modified November 15, 2018, https://arpa-e.energy.gov/technologies/projects/high-value-energy-saving-carbon-products-and-clean-hydrogen-gas-methane; "Carbon Dioxide-Free Hydrogen and Solid Carbon from Natural Gas via Metal Salt Intermediates," ARPA-E, last modified November 15, 2018, https://arpa-e.energy.gov/technologies/projects/carbon-dioxide-free-hydrogen-and-solid-carbon-natural-gas-metal-salt.

[390] ARPA-E, *Request for Information (RFI) DE-FOA-002536 on Steel Made Via Emissions-less Technologies (SMELT)*, May 2021, https://arpa-e-foa.energy.gov/Default.aspx?foaId=f1ed4287-118f-49b0-9d27-2f7ce530907a.

and steelmaking.[391] AMO and HFTO have both recently funded R&D projects advancing the use of hydrogen in iron reduction.

Electrochemical Synthesis (SC, AMO, FECM, BETO, HFTO): Increased development of catalysts, materials, methods, understanding of synthetic mechanisms, in-situ spectroscopy techniques, and multi-scale modeling have advanced electrochemical processes and, in addition to declining electricity costs, have opened new opportunities for the economic electrolytic manufacturing of chemicals, fuels, and materials.

Electrified Process Scale-up (AMO, HFTO): Electricity in U.S. industry is predominantly consumed for motor-driven systems, but relatively little is used for thermal processes (e.g., process heating, electrolysis other than for select applications such as primary aluminum production). Dramatically expanded use of electrification for process heating, process intensification, electrochemical synthesis, etc. will require innovations for unit operations, processes, components, and technologies to operate at commercially relevant scale.

5.3.3 Low-Carbon Fuels, Feedstocks, and Energy Sources

Some examples of DOE office activities and collaboration within the LCFFES pillar include**:**

End of Life Materials (AMO, BETO, SC): In recent years, DOE has strengthened its focus on sustainable manufacturing to include circular economy approaches. This not only reduces the embedded energy of the materials used, but it also lowers the carbon footprint by keeping materials "in play," reducing the need to extract virgin materials. Significant energy savings and emissions reductions could be derived by the increased use of secondary, or recycled, materials.[392] The Reducing EMbodied-energy And Decreasing Emissions (REMADE) Institute[393] funds work to advance the use of secondary metals, fibers, plastics, and e-waste. Its broad mandate includes the analysis and development of supply chains for reliable, cost-effective, secondary materials for remanufacturing. DOE has also made more-targeted investments to promote circular material life cycles, including the ReCELL center,[394] which enables recycling of batteries; the BOTTLE (Bio-Optimized Technologies to keep Thermoplastics out of Landfills and the Environment) Consortium,[395] which will develop recycling pathways for plastics; and the Critical Materials Institute (CMI),[396] which aims to provide the metals and other materials to implement

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391 "Zero-emission Iron & Steelmaking Workshop," ARPA-E, accessed May 2022, https://arpa-e.energy.gov/events/zero-emission-iron-steelmaking-workshop.

392 U.S. Department of Energy Advanced Manufacturing Office, *Sustainable Manufacturing Workshop: Workshop Summary Report*, DOE/EE-1415, May 2016, https://www.energy.gov/sites/prod/files/2016/07/f33/AMO_Sustainable%20Manufacturing%20Workshop%20Report_compliant_0.pdf; U.S. Department of Energy, *Quadrennial Technology Review 2015, Chapter 6: Innovating Clean Energy Technologies in Advanced Manufacturing: Technology Assessment of Sustainable Manufacturing*, September 2015, https://www.energy.gov/sites/prod/files/2019/06/f63/Advanced%20Manufacturing%20Technology%20Assessment%20-%20Sustainable%20Manufacturing_0.pdf.

393 REMADE Institute is a Manufacturing USA institute focused on reducing embodied energy of manufactured products through the increased use of secondary materials. "REMADE Institute," REMADE, https://remadeinstitute.org/.

394 "ReCell Advanced Battery Recycling," U.S. Department of Energy Vehicle Technologies Office, accessed May 2022, https://recellcenter.org/.

395 "BOTTLE (Bio-Optimized Technologies to keep Thermoplastics out of Landfills and the Environment) consortium," U.S. Department of Energy, accessed May 2022, https://www.bottle.org/; See also the "Joint FY20 Bioenergy and Advanced Manufacturing FOA BOTTLE: Bio-Optimized Technologies to Keep Thermoplastics out of Landfills and the Environment," U.S. Department of Energy Bioenergy Technologies Office, accessed May 2022, https://www.energy.gov/eere/bioenergy/joint-fy20-bioenergy-and-advanced-manufacturing-foa-bottle-bio-optimized-technologies.

396 "Critical Materials Institute," Ames Laboratory, accessed May 2022, https://www.ameslab.gov/cmi.

renewable energy and energy efficiency. DOE continues to invest in basic science targeting new concepts for upcycling plastics and designing de novo circular-use polymers.[397]

Thermal Process Heating (AMO, SETO): SETO's industrial decarbonization work is focused on solar thermal industrial process heat for processes such as desalination, enhanced oil recovery, agriculture and food processing, petroleum refining, chemicals manufacturing, and mining and metals processing. By 2025 SETO aims to have the following defined: system concepts and key components for solar process heat (for carbon emissions intensive and high heat demand industries) and fuel production from CSP. Priority research areas for SETO include reducing the levelized cost of heat with thermal energy storage (for relevant industrial process temperature ranges), improving solar-thermal coupled processes thermal efficiency, and developing long-duration, thermochemical storage of solar energy (i.e., solar fuels and chemical commodities).[398] Recently, SETO released a funding opportunity to initiate RD&D projects to de-risk integrated industrial processes driven by solar thermal energy.[399]

Hydrogen Generation (HFTO, FECM, AMO, SC) and Industrial Use (AMO, HFTO, ARPA-E, NE, SC): Key opportunity areas for hydrogen use include hard to decarbonize subsectors (iron and steel, cement, ammonia, etc.), energy storage and blending, and export potential. More detail on hydrogen as a LCFFES is detailed in Section 1.2.2.2. HFTO coordinates DOE's hydrogen program, through which Offices are collaborating on RD&D in support of H2@Scale, and in support of the DOE Hydrogen Energy Earthshot's targets to achieve affordable clean hydrogen within one decade.[400] For example, AMO and HFTO have co-funded RD&D to reduce the cost of carbon fiber used in hydrogen storage, manufacturing technologies to enable scale-up of electrolyzers and fuel cells, and processes for hydrogen use in steelmaking. HFTO, FECM, and AMO have collaboratively funded R&D to enable hydrogen blending in natural gas pipelines through the HyBlend initiative.[401] HFTO and NE have co-funded R&D, analysis, and demonstrations of hydrogen production at nuclear power plants. ARPA-E has funded numerous projects on hydrogen and carbon production from methane.[402] SC has long supported fundamental research needed to advance this field, leading to innovations in atomic-level design of components such as catalysts, membranes, and electrolytes for hydrogen generation, and electrochemical cells for hydrogen

[397] U.S. Department of Energy Office of Science, *Chemical Upcycling of Polymers, Report of Basic Energy Sciences Roundtable*, May 2019, https://science.osti.gov/-/media/bes/pdf/reports/2020/Chemical_Upcycling_Polymers.pdf.
[398] U.S. Department of Energy Solar Energy Technologies Office, *Solar Energy Technologies Office Multi-Year Program Plan*, May 2021, https://www.energy.gov/eere/solar/articles/solar-energy-technologies-office-multi-year-program-plan.
[399] "Funding Notice: Concentrating Solar-Thermal Power Fiscal Year 2022 Research, Development, and Demonstration," U.S. Department of Energy Solar Energy Technologies Office, February 8, 2022, https://www.energy.gov/eere/solar/articles/funding-notice-concentrating-solar-thermal-power-fiscal-year-2022-research.
[400] "Hydrogen Shot," U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office, accessed May 2022, https://www.energy.gov/eere/fuelcells/hydrogen-shot.
[401] "HyBlend: Opportunities for Hydrogen Blending in Natural Gas Pipelines," U.S. Department of Energy Hydrogen and Fuel Cell Technologies Office, accessed May 2022, https://www.energy.gov/eere/fuelcells/hyblend-opportunities-hydrogen-blending-natural-gas-pipelines.
[402] "High Value Energy Saving Carbon Products and Clean Hydrogen Gas from Methane," ARPA-E, last modified November 15, 2018, https://arpa-e.energy.gov/technologies/projects/high-value-energy-saving-carbon-products-and-clean-hydrogen-gas-methane; "Carbon Dioxide-Free Hydrogen and Solid Carbon from Natural Gas via Metal Salt Intermediates," ARPA-E, last modified November 15, 2018, https://arpa-e.energy.gov/technologies/projects/carbon-dioxide-free-hydrogen-and-solid-carbon-natural-gas-metal-salt; "Molten-Salt Methane Pyrolysis Optimization Through in-situ Carbon Characterization and Reactor Design," ARPA-E, last modified January 9, 2020, https://arpa-e.energy.gov/technologies/projects/molten-salt-methane-pyrolysis-optimization-through-situ-carbon; "Ammonia Cracking Membrane Reactor," ARPA-E, last modified December 15, 2016, https://arpa-e.energy.gov/technologies/projects/ammonia-cracking-membrane-reactor.

use. SC, in collaboration with EERE, FECM, and NE, held a roundtable to identify challenges and new research opportunities to advance carbon-neutral hydrogen generation and use.[403]

Energy and Thermal Storage (HFTO, AMO, SETO, SC): A key interoffice collaboration is the DOE Energy Storage Grand Challenge.[404] Through this coordinated effort, DOE aims to make the United States the global leader in energy storage utilization and exports. The Grand Challenge brought together several offices across DOE to develop a roadmap[405] that will guide activities in this area to achieve the Grand Challenge's goals. Many of the efforts coming out of the roadmap will be collaborative by nature. For example, AMO has collaborated with the Office of Electricity to address manufacturing and related supply chain issues through technology development.[406]

5.3.4 Carbon Capture, Utilization, and Storage

Some examples of DOE office activities and collaboration within the CCUS pillar include:

Carbon Capture from Industry and Utilization (FECM, AMO, BETO, SC): AMO, FECM, BETO, and SC are working closely to coordinate research efforts on industrial carbon utilization. FECM is coordinating the offices' ongoing work in carbon capture, DAC, and industrial decarbonization. Other offices including AMO are able to leverage FECM's deep expertise from years of funding CCUS work. For example, AMO worked closely with FECM and BETO before issuing a 2020 Advanced Manufacturing Multitopic FOA[407] aimed at increasing use of carbon capture in industry through the integration of carbon capture and utilization into manufacturing plants. BETO areas of research include on CO_2 feedstock, CO_2 reduction to one-carbon (C1) intermediates, and microbial intermediate upgrading to chemicals. FECM has numerous projects and activities related to industrial carbon capture, including supporting TEA of capture R&D pathway studies including analyses on BECCS and DAC; innovative R&D through FOAs; and the National Carbon Capture Center.[408] Based on a recent ARPA-E workshop on recycling carbon, reactive carbon capture could reduce the cost for carbon utilization processes by directly reacting absorbed/adsorbed carbon, eliminating the capital and operating expenditures for solvent/sorbent regeneration and carbon purification.[409]

[403] U.S. Department of Energy Office of Science, *Basic Energy Sciences Roundtable: Foundational Science for Carbon-Neutral Hydrogen Technologies,* August 2021, https://science.osti.gov/-/media/bes/pdf/brochures/2021/Hydrogen_Roundtable_Report.pdf.

[404] The DOE Energy Storage Grand Challenge (ESGC) was launched in January 2020. "Energy Storage Grand Challenge," U.S. Department of Energy, accessed January 2022, https://www.energy.gov/energy-storage-grand-challenge.

[405] U.S. Department of Energy, *Energy Storage Grand Challenge Roadmap,* December 2020, https://www.energy.gov/sites/prod/files/2020/12/f81/Energy%20Storage%20Grand%20Challenge%20Roadmap.pdf.

[406] " Department of Energy Invests $17.9 Million in Long-Duration Energy Storage Technologies," U.S. Department of Energy, September 24, 2021, https://www.energy.gov/eere/amo/articles/department-energy-invests-179-million-long-duration-energy-storage-technologies; "Energy Department Announces $20 Million to Advance Manufacturability of Grid-Scale Energy Storage Technologies," U.S. Department of Energy, March 20, 2021, https://www.energy.gov/eere/amo/articles/energy-department-announces-20-million-advance-manufacturability-grid-scale.

[407] DE-FOA-002252: FY20 Advanced Manufacturing Office Multi-topic FOA included a subtopic on "Integrating Carbon Capture and Utilization into Industrial Processes". See " DE-FOA-0002252: FY20 ADVANCED MANUFACTURING OFFICE MULTI-TOPIC FOA," U.S. Department of Energy, accessed May 2022, https://eere-exchange.energy.gov/Default.aspx?foaId=96fd81da-41e6-4d21-b5b9-06252b707825.

[408] "National Carbon Capture Center," National Carbon Capture Center, accessed May 2022, https://www.nationalcarboncapturecenter.com/.

[409] "Reactive Carbon Capture Workshop," ARPA-E, accessed May 2022, https://arpa-e.energy.gov/events/reactive-carbon-capture-workshop.

5.3.5 Crosscutting RD&D Opportunities

To amplify the impact of its funded projects, DOE funds crosscutting research that could improve efficiency in multiple subsectors.

5.3.5.1 Computational Tools and Artificial Intelligence:

High-performance computing and artificial intelligence hold the promise of solving many challenging and complex problems. When applied to manufacturing systems and challenges, they could reduce energy and material consumption by optimizing numerous parameters, including operations, process design, and material selection. The High-Performance Computing for Manufacturing program allows industrial partners to use DOE's high-performance computing capabilities at the national laboratories through collaborations with national laboratory researchers.[410] This program has been broadly applied to improve energy efficiency of numerous industries. For example, Agenda 2020, Lawrence Livermore National Laboratory, and Lawrence Berkeley National Laboratory partnered on a project to use advanced simulation and high-performance computing to optimize wet pulp drying, one of the most energy-intensive steps in papermaking.[411] In addition, DOE has established the Clean Energy Smart Manufacturing Innovation Institute (CESMII), a Manufacturing USA Institute, which aims to advance the development and use of smart manufacturing.[412]

SC develops computational tools coupled with a system-based co-design approach to integration of experiments, predictive theory, and artificial intelligence and machine learning which are central to the discovery and application of transformative science.

5.3.5.2 Education and Workforce Development

Another crosscutting barrier identified in this roadmap is developing a skilled workforce that can use technology to minimize emissions and energy use. Many DOE offices are involved in developing a workforce that is ready for the next generation of energy technologies. If directed, these programs could be leveraged and replicated for technology and practices needed to reduce the carbon footprint of U.S. industry. For example, programs such as DOE's Industrial Assessment Centers (IACs),[413] which train college students to conduct energy assessments at local manufacturing sites, could be enhanced to develop training and assessments for carbon intensity. Another initiative that could be leveraged is expanded use of competency models, such as the Renewable Energy Competency Model, which the U.S. Department of Labor (DOL) developed with the assistance of EERE, NREL, and several industry

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[410] "High Performance Computing for Energy Innovation," Lawrence Livermore National Laboratory, accessed May 2022, https://hpc4energyinnovation.llnl.gov/; "High Performance Computing for Advanced Manufacturing," U.S. Department of Energy, accessed May 2022, https://www.energy.gov/eere/amo/high-performance-computing-advanced-manufacturing.
[411] "Computation Helps Boost Energy Efficiency in Paper Processing," Lawrence Livermore National Laboratory, n.d., https://hpc4energyinnovation.llnl.gov/sites/hpc4energyinnovation/files/2021-09/Agenda2020_BR_735129_042019.pdf. See other examples of success stories at https://hpc4energyinnovation.llnl.gov/success-stories.
[412] "CESMII," CESMII, accessed May 2022, https://www.cesmii.org/.
[413] "Industrial Assessment Centers," U.S. Department of Energy, accessed May 2022, https://iac.university/.

associations.[414] All of the DOL competency models are available online and as open-linked data that can be used in public and private workforce applications for training, recruiting, and hiring.[415]

Manufacturing USA Institutes[416] have requirements to include education and workforce development in their mission. Although not mandated, other public-private partnerships such as hubs and user facilities also have education and workforce development efforts to enable an educated and capable workforce that can support emerging technology in these areas. Programs offered by institutes and hubs span the full range of elementary education through post-graduate and even to the current workforce.

HFTO also supports the Hydrogen Education for a Decarbonized Global Economy (H_2EDGE)[417] program which will provide training, education, and recruiting to build skills needed in the hydrogen industry.

5.3.5.3 Coordination of Knowledge Infrastructure

Technology development and RD&D priorities should be science- and data-driven. Data analysis, evaluation tools, and methodology development, collectively referred to here as knowledge infrastructure, are critical to ensuring DOE investments are impactful. As technology is developed in multiple subsectors, knowledge infrastructure should be shared across these offices. Coordination in decarbonization has been seeded in the narrow space of DAC between FECM, SC, BETO, and AMO. These connections could be built upon and expanded to include additional offices and even across agencies, where appropriate. Alignment of GHG accounting methods and estimates across federal agencies will be critical to consistent assessments of progress towards Biden Administration goals. Additionally, current development of platforms for shared knowledge and information are priorities in all the Energy Earthshots[418] addressing the climate crisis; expanded access and coordination are critical.

5.3.5.4 Technology Demonstration, Commercialization, and Adoption through Industry Partnerships

Novel technology is often slow to be adopted, particularly in well-established industries. The time to adoption increases with the complexity of the technology and with the uncertainty of benefits that it could provide. DOE uses several approaches to overcome these challenges and accelerate the adoption of energy efficient technologies. To address barriers and challenges identified in this roadmap, existing programs within or outside DOE could be leveraged or expanded to include a focus on decarbonization technologies.

DOE promotes the commercialization and deployment of novel, energy-efficient technologies in various ways. One route is through the funding of research at the pilot and field validation stages. Research at the Manufacturing USA institutes which extends beyond DOE includes technology demonstrations, including field trials that lend further credibility to the technology. The Manufacturing USA and similar consortia models provide a good example of a platform for robust public private partnerships that can

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[414] "Renewable Energy Competency Model," U.S. Department of Labor, Employment and Training Administration (ETA), accessed July 2022, https://www.careeronestop.org/CompetencyModel/competency-models/renewable-energy.aspx. ETA also developed an Advanced Manufacturing Competency Model with leading industry organizations (https://www.careeronestop.org/CompetencyModel/competency-models/advanced-manufacturing.aspx). There are also three models outlining the competencies needed to support more energy-efficient commercial and residential buildings.
[415] "Competency Model Clearinghouse," DOL, ETA, accessed July 2022, https://www.careeronestop.org/CompetencyModel/.
[416] "Institutes," Manufacturing USA, accessed May 2022, https://www.manufacturingusa.com/institutes.
[417] "H2EDGE," EPRI, accessed May 2022, https://grided.epri.com/H2EDGE.html.
[418] "Energy Earthshots Initiative," U.S. Department of Energy, accessed May 2022, https://www.energy.gov/policy/energy-earthshots-initiative.

lead to broad stakeholder engagement. These public-private partnerships bring together the industrial, academic, and national laboratory communities to accelerate development of technology in key areas. Technology development is accelerated through the interactions and collaborations fostered by these partnerships, and the inclusion of industrial partners provide a more facile pathway to commercialization. In fact, industrial participation is encouraged on all projects and required by many, even those outside the consortia for that reason. DOE also funds Small Business Innovation Research grants which could be used by small businesses for demonstrations leading up commercialization of their technologies. While these efforts have been successful, large-scale demonstration and deployment efforts have long been a gap in DOE's industrial sector efforts. Addressing this gap could further accelerate demonstration and adoption of industrial sector strategies across the pillars.

A technical partnerships group within AMO develops industrial partnerships and conducts outreach to manufacturers interested in improving their energy efficiency. This group facilitates the adoption and efficient operation of energy efficient technologies through various approaches. One approach that has been successful is to provide technical assistance partnerships[419] to educate potential adopters on the benefits of complex technology, such as CHP systems, and how to implement that technology for their sites. The CHP technical assistance partnerships have completed more than 500 technical assistance activities with an estimated capacity of 800 megawatts.

Another approach is through the energy assessments provided by DOE's Industrial Assessment Centers (IACs),[420] which help quantify the benefits of energy efficient technologies and practices by training college students to conduct energy assessments. These assessments provide small and medium-sized manufacturers with specific energy-saving recommendations and include estimates of costs, performance, and payback times. It is estimated that the IACs saved 54 trillion Btu, avoided 6 million MT of gross CO_2 emissions, and provided a net energy savings of 21 trillion Btu from FY2009-2013.[421]

The Better Plants Program (BPP),[422] led by AMO, establishes partnerships with industry to improve their energy efficiency. As of Fall 2021, the 250+ BPP partners have reported savings of $9.3 billion in cumulative energy costs and saved 1.9 quadrillion Btu.[423] The program requires industry partners to set energy savings goals and provides advice and tools that help them reach those goals. Program partners also participate in best practice sharing and advertise improvement projects that delivered energy savings to their manufacturing sites. Recently, the BPP kicked off a waste reduction program[424] aimed at reducing waste materials in various forms at partner sites.

[419] Better Buildings Program CHP technical assistance partnerships are regional partnerships that promote CHP, waste heat to power, and district energy technologies. For more information, see "CHP Technical Assistance Partnerships (CHP TAPS)," U.S. Department of Energy Better Buildings Program, accessed May 2022, https://betterbuildingssolutioncenter.energy.gov/chp/chp-taps.
[420] "Industrial Assessment Centers," U.S. Department of Energy, accessed May 2022, https://iac.university/.
[421] SRI International, *Saving Energy, Building Skills: Industrial Assessment Centers Impact*, March 2015, https://iac.university/technicalDocs/Industrial%20Assessment%20Centers%20Impacts%20SRI%20International.pdf.
[422] "About Better Plants," U.S. Department of Energy Better Buildings, accessed May 2022, https://betterbuildingssolutioncenter.energy.gov/better-plants/program-information.
[423] Savings are from the launch of the program in 2011 through Fall 2021. U.S. Department of Energy, *Better Plants Progress Update Report*, Fall 2021, https://betterbuildingssolutioncenter.energy.gov/sites/default/files/attachments/2021_Better_Plants_Progress_Update.pdf.
[424] "Waste Reduction Network," U.S. Department of Energy Better Buildings, accessed May 2022, https://betterbuildingssolutioncenter.energy.gov/special-initiatives/waste-reduction-pilot.

6 Summary and Conclusions

This report discusses a roadmap for industrial decarbonization, including major pillars of energy efficiency, industrial electrification and LCFFES, and CCUS. In the development of this roadmap, industry stakeholders identified needs and opportunities connected with decarbonization and application of these decarbonization pillars.

As part of the roadmap development, the following crosscutting RD&D needs were identified as having potential to leverage learnings across multiple subsectors (see Section 3). These include rapid deployment of state-of-the-art technologies to drive near-term emissions reductions; development of new low- and no-carbon technology solutions to reach full decarbonization of the industrial sector; and overcoming deployment barriers, including demonstration activities and techno-economic analyses to show commercial viability. Key learnings and recommendations from the roadmap include:

- ***Advance early-stage RD&D.*** While technologies with high technical maturity levels will need to be deployed sector-wide, fundamental and applied RD&D to advance fundamental science and technologies with lower technical maturity levels must also proceed in parallel. Major advances in early-stage technologies across all decarbonization pillars will be needed in the coming decades to reach net-zero emissions by 2050.
- ***Invest in multiple process strategies.*** Investments in multiple low-carbon process technology strategies must be concurrently pursued to ensure viable pathways for industrial decarbonization. These investments can position the United States as a global leader in industrial modernization.
- ***Scale through demonstrations.*** In many cases, decarbonization technologies have been demonstrated through applied RD&D, but have not yet been scaled for commercial use. Demonstrating technical and economic feasibility (leading to market adoption) of industrial technologies is particularly challenging, with a number of factors affecting adoption.[425] To accelerate deployment, testbeds and demonstration projects will be needed to catalyze and de-risk private sector investments. Low-capital approaches that maximize energy, material, and systems efficiency should be pursued throughout the transformation to lower hurdles and speed adoption of advanced technologies. Confidence from demonstrations at commercially relevant scales is needed for market adoption; however, other levers (deployment, procurement, etc.) can be used to drive the rate of uptake needed to meet the 2050 net-zero GHG emissions target.
- ***Address process heating efficiency and emissions across all sub-sectors.*** In the industrial sector, process heating consumes more energy than any other type of operation, and the majority of the energy used for process heating originates from fossil fuels. Efforts are needed to maximize efficiency and resource utilization associated with the thermal energy cascade (e.g., waste heat recovery, heat upgrading/reuse), while transitioning to electrified and low-carbon fuel and energy sources.
- ***Decarbonize electricity sources.*** Achieving net-zero GHG emissions in the industrial sector will require a fully decarbonized electric grid. The effectiveness (and speed) of electrification pathways in decarbonizing the industrial sector will depend on the rate of decarbonization of the U.S. electric grid. In parallel, the development of low-carbon electricity generation capabilities near industrial

[425] Rebecca Hanes et al., "Quantifying adoption rates and energy savings over time for advanced energy-efficient manufacturing technologies," Journal of Cleaner Production 232, (2019): 925-939. https://doi.org/10.1016/j.jclepro.2019.04.366.

facilities could spur electrification near centers of concentrated industrial activities (e.g., through clusters or hubs).

- ***Integrate solutions.*** Focus is needed not just on new technologies, but also on their integration into process systems and supply chains to reduce energy and emissions at the system level. Research will be needed to anticipate the changes in supply and value chains that will result from the transition to a low-carbon economy, and to better understand how industrial infrastructure, technology, and services can work together to meet future needs while maximizing supply chain flexibility and resilience.
- ***Conduct modeling and system analysis.*** There is a need for advanced and integrating analysis approaches, including expanded use of LCA, TEA, and related systems-level techniques for economic and environmental assessments, to ensure that low-carbon solutions have the positive impact desired and are commercially viable.
- ***Engage communities, develop a thriving workforce.*** The full range of the workforce needed across all industrial subsectors will require a spectrum of new skillsets to support successful implementation of decarbonization technologies and improved broad scale carbon accounting. Engaging state, local, and tribal communities and other stakeholders, with a particular focus on disadvantaged communities, will be critical to ensuring the benefits and impacts of industrial decarbonization are equitably distributed.

Additionally, subsector-specific needs were also identified (introduced in Section 1.5 and detailed in Section 2), as were programmatic responses that DOE could provide (Section 5). For each of the five industrial subsectors, the results of the scenario analyses were shown to help provide perspective on the sequence of RD&D initiatives across near-, mid-, and longer-term horizons. A figure that combines the results across the subsectors analyzed (Figure 60) illustrates the need to initiate RD&D that will help extract the most energy and result in the largest GHG emissions reductions from the pillars.

As nuclear and renewables supply a higher proportion of low-carbon energy to the grid, electrification and low-carbon fuels and energy carriers (such as hydrogen) can have an increasing impact in lowering the carbon footprint of industry. It is crucial for RD&D to advance technologies that would enable the use of clean electricity and low-carbon fuels, and the energy carriers and low-carbon feedstocks provided by that electricity (e.g., by electrolysis)—and to enable their deployment by advancing demonstrations at scale.

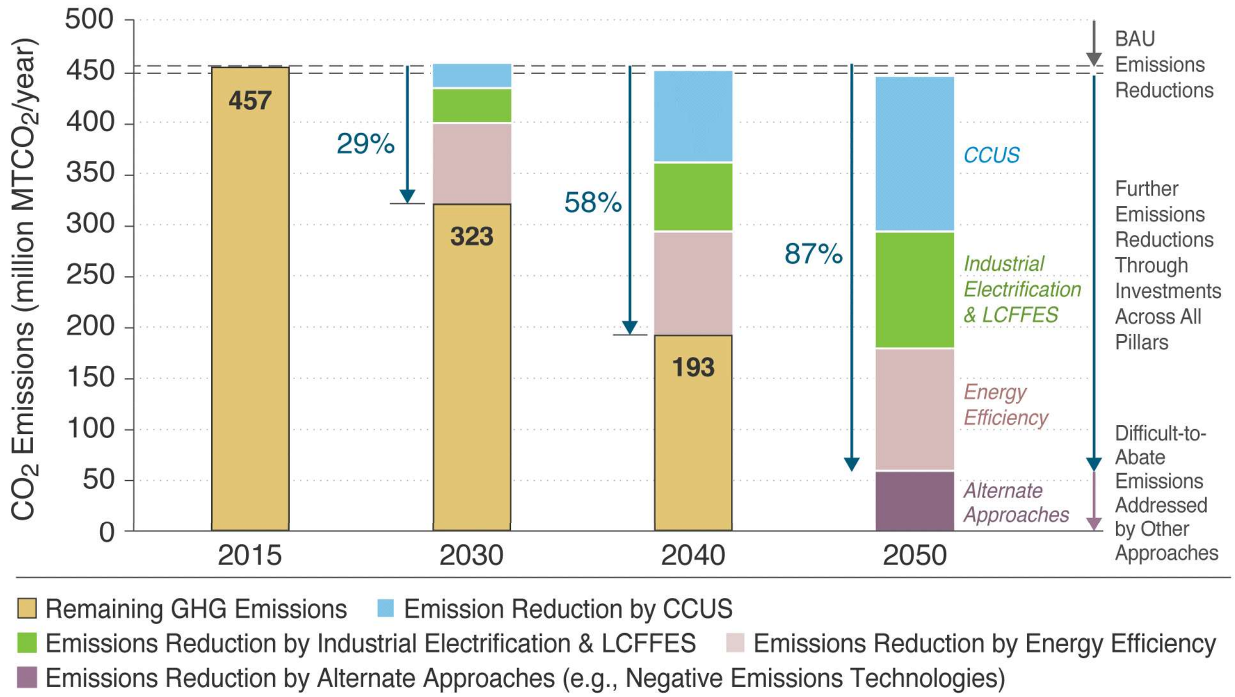

FIGURE 60. CO_2 EMISSIONS REDUCTION POTENTIAL (MILLION MT) THROUGH THE APPLICATION OF THE DECARBONIZATION PILLARS FOR THE U.S. IRON AND STEEL, CHEMICAL, FOOD, PETROLEUM REFINING, AND CEMENT MANUFACTURING SUBSECTORS (EXCLUDING FEEDSTOCKS).

WITH CONTRIBUTIONS FROM EACH DECARBONIZATION PILLAR (ENERGY EFFICIENCY; INDUSTRIAL ELECTRIFICATION AND LOW-CARBON FUELS, FEEDSTOCKS, AND ENERGY SOURCES (LCFFES); AND CARBON CAPTURE, UTILIZATION, AND STORAGE (CCUS)). SINCE INDUSTRIAL ELECTRIFICATION AND LCFFES TECHNOLOGIES AND STRATEGIES ARE STRONGLY INTERCONNECTED, THESE PILLARS WERE GROUPED FOR SCENARIO MODELING. INDUSTRIAL SUBSECTORS INCLUDED IN THIS ANALYSIS WERE: IRON AND STEEL, CHEMICALS (ONLY AMMONIA, METHANOL, ETHYLENE, AND BENZENE, TOLUENE, AND XYLENES (BTX)), FOOD AND BEVERAGE (ONLY BEER, BEET SUGAR, CANE SUGAR, FLUID MILK, RED MEAT, SOYBEAN OIL, AND WET CORN MILLING), PETROLEUM REFINING, AND CEMENT MANUFACTURING. FEEDSTOCKS AND CERTAIN PROCESS-RELATED EMISSIONS ARE EXCLUDED. THE "ALTERNATE APPROACHES" BAND SHOWS FURTHER EMISSIONS REDUCTIONS FROM APPROACHES NOT SPECIFICALLY EVALUATED IN SCENARIO MODELING FOR THIS ROADMAP, INCLUDING NEGATIVE EMISSIONS TECHNOLOGIES. THE POWERING OF ALTERNATE APPROACHES WILL ALSO NEED CLEAN ENERGY SOURCES (E.G., DIRECT AIR CAPTURE COULD BE POWERED BY NUCLEAR, RENEWABLE SOURCES, SOLAR, WASTE HEAT FROM INDUSTRIAL OPERATIONS, ETC.). DETAILS ON ASSUMPTIONS, PARAMETERS, AND TIMING CAN BE FOUND IN THE APPENDIX. SOURCE: THIS WORK.

> *Key message: Application of the decarbonization pillars in the top CO_2 emitting industrial subsectors could reduce emissions by about 400 million MT per year by 2050 according to these scenarios.*

Even with rigorous pursuit of both energy efficiency *and* accelerated, innovative deployment of electrification, LCFFES, and carbon capture, substantial GHGs from hard-to-abate processes will remain. Alternative mitigation approaches such as DAC or other negative emissions technologies that can address hard-to-abate GHG emissions in industry will be needed to economically achieve net-zero carbon emissions. RD&D is needed to advance these technologies and bring their economics and technical capabilities within feasible ranges. The sequence of RD&D investment areas that are addressed by the roadmap are illustrated—across the five industrial subsectors and four decarbonization pillars—in Figure 61. It shows the range of responses needed in the near-term to get industry on the track for decarbonization in the first decade, pave the way for new technologies that need to be deployed in later decades, and enable the transformation with infrastructure that is multipurposed, flexible, and efficient.

Ultimately, a host of technology opportunities need to be pursued in parallel over the next five to 30 years.

In this roadmap, representative RD&D opportunities for industrial decarbonization of five key subsectors were explored. While this provides a solid understanding of the pathways to decarbonize industry more broadly, additional work is needed to fully characterize the entire industrial sector and connections to the other sectors of the economy. The industrial sector plays an essential role as the producer of goods for other sectors of the economy, including developing and manufacturing clean energy technologies. To achieve a fully decarbonized economy, focus is needed not only on direct efforts to decarbonize the industrial sector and its supply chains, but also to leverage and integrate those efforts with decarbonization activities in other economic sectors.

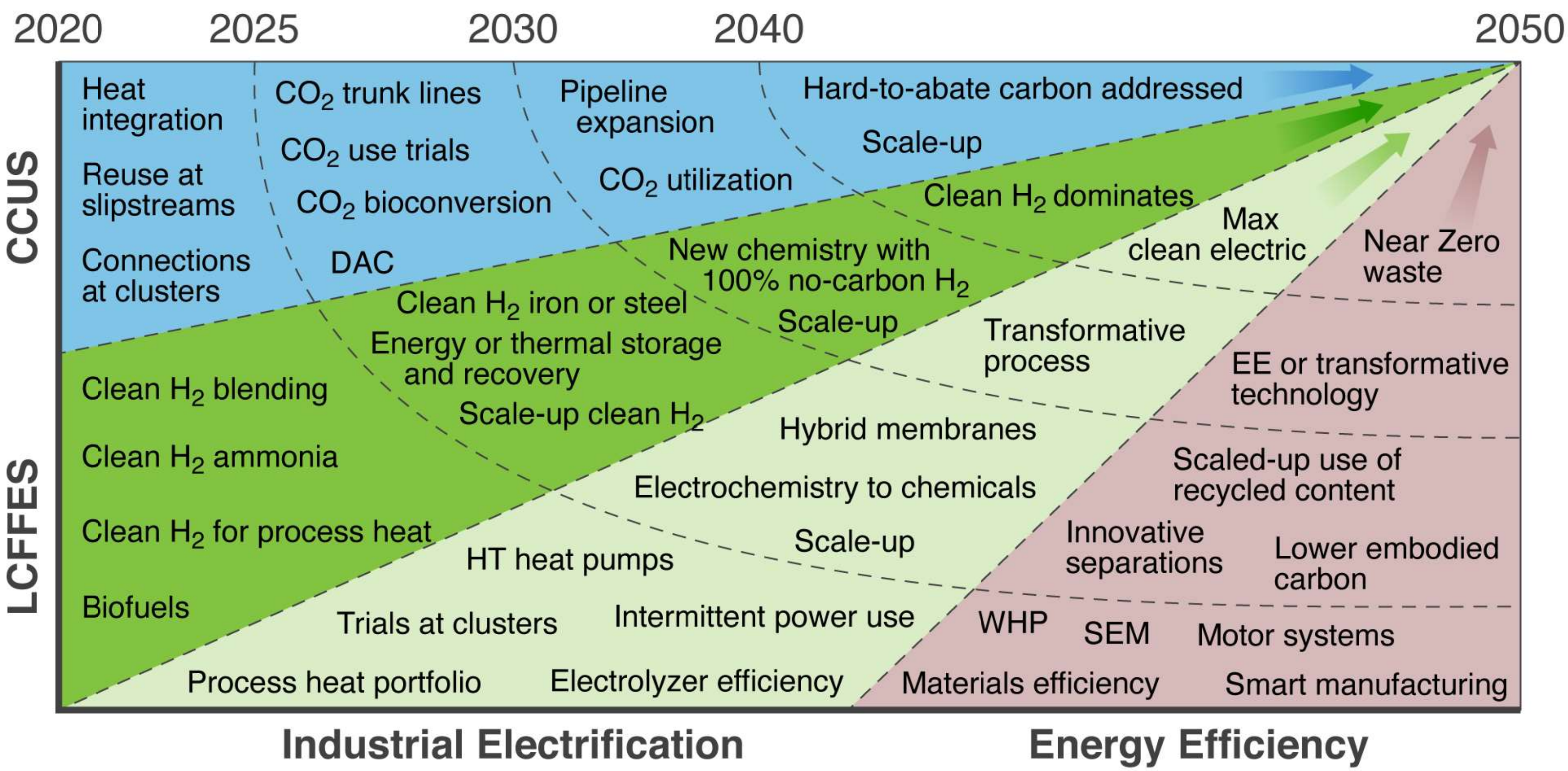

Figure 61. Landscape of major RD&D Investment opportunities for industrial decarbonization across all five subsectors by decade and decarbonization pillar.

Early opportunities (e.g., process heat solutions, or electrolyzer efficiency to produce hydrogen from low-carbon energy) may set the stage for later transformative and have crosscutting impacts in other pillars and subsectors. LCFFES includes clean technologies that do not release GHGs to the atmosphere from the production or use of energy sources, and include renewable sourced electricity, nuclear energy for electricity and heat, concentrating solar power, and geothermal energy. Acronyms: DAC (direct air capture); HT (high temperature); SEM (strategic energy management); WHP (waste heat to power). Further definitions are available in the glossary. Source: this work.

Key message: Investments are needed in near-, mid-, and longer timeframes to address numerous RD&D opportunities to accelerate industrial decarbonization by these top pillars. Strategies need to be pursued to realize synergies within and across pillars and subsectors.

7 Appendices: Scenario Methodology and Assumptions

To develop GHG emissions scenario pathways for the five industries, DOE started by conducting an extensive literature review to collect information and related data needed for this analysis. DOE used 2015-2050 as the study period. DOE defined four scenarios: 1. Business as Usual (BAU), 2. Moderate Technology and Policy (Moderate), 3. Advanced Technology and Policy (Advanced), and 4. Near Zero GHG. More detailed explanations of scenarios are presented in industry methodology subsections below. DOE defined the decarbonization pillars: energy efficiency, electrification and LCFFES, and CCUS. DOE aimed to quantify the impact of each of these pillars on GHG emissions pathways of industries under each scenario.

DOE then collected data for the base year for the key modeling variables such as production, energy intensities, fuel mix, CCUS, etc. DOE made assumptions for projections of each variable under each scenario based on the analysis and literature review. Projections for each of these key variables used in the analysis are presented in detail in the following subsections under each industry methodology section.

DOE also identified key transformative technologies and alternative production technologies for each industry and made assumptions for the penetration of those technologies in the U.S. industry under each scenario. Having these data, assumptions, and projections of key variables, DOE calculated the energy use and GHG emissions of each industry under each of the four scenarios. The results are depicted in both line charts and waterfall charts showing the trajectory of GHG emissions in each subsector during 2015-2050 under each scenario as well as the impact of each decarbonization pillar. The results were investigated and discussed in detail and a few sensitivity analyses were conducted to better understand the impact of some key variables on the final results. Figure A 1 shows a flow diagram of the methodology used for scenario analysis. More detailed explanations of methodology and assumptions for each industrial subsector studied are presented in the subsections below.

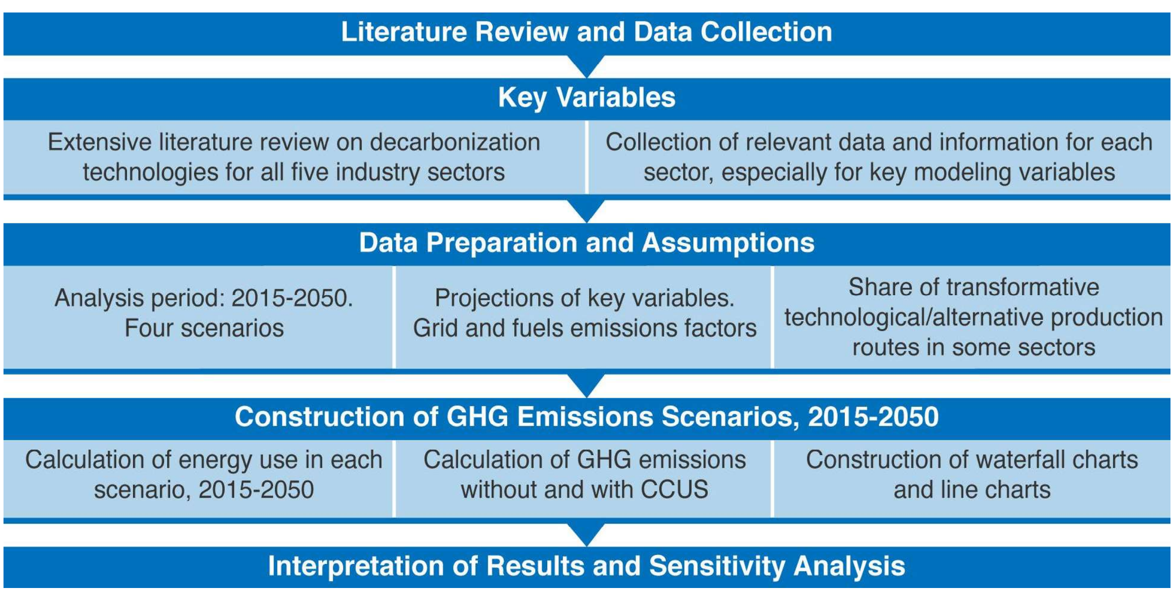

FIGURE A 1. SCENARIO ANALYSIS METHODOLOGY. SOURCE: THIS WORK.

Appendix 1.1. Iron and Steel Industry Analysis: Methodology and Assumptions

After analyzing the current status of the U.S. steel industry and its energy and carbon intensity, DOE developed a decarbonization roadmap for the U.S. steel industry. In this subsection, DOE presents some of the key assumptions and indicators used in the roadmap development. DOE developed four main scenarios:

1. **Business as Usual (BAU) scenario**: The BAU scenario assumes slow improvement in energy efficiency and fuel switching and slow adoption of CCUS technologies, and reflects current business practices and current policies and regulations.

2. **Moderate Technology and Policy (Moderate) scenario**: This scenario assumes higher energy efficiency improvement, more fuel switching to lower-carbon fuels, and a slightly higher rate of shift to EAF steel production. It also assumes low adoption of CCUS technologies.

3. **Advanced Technology and Policy (Advanced) scenario**: This scenario assumes significantly higher energy efficiency improvement using commercially available technologies, more aggressive fuel switching to lower-carbon fuels, and a small adoption of transformative technologies such as hydrogen-based DRI-EAF. It also assumes, in 2050, 40% of CO_2 emitted from U.S. steel plants will be captured by CCS technologies.

4. **Near Zero GHG (Near Zero) scenario**: This scenario assumes the most aggressive energy efficiency improvement using commercially available technologies, more aggressive fuel switching to lower-carbon fuels, and higher rate of shift to EAF steelmaking and small adoption of hydrogen-based DRI-EAF and electrolysis of iron ore technologies after 2040. It also assumes, in 2050, 85% of CO_2 emitted from U.S. steel plants will be captured by CCS technologies.

The first step in developing the pathways was to project U.S. steel production and demand from 2015 to 2050 (Figure A 2). The steel demand projection to 2050 is based on historical steel demand per capita, population growth, current steel production capacity, average capacity utilization, expectation of any future steel production expansion, etc. DOE assumed a 15%-18% difference between U.S. steel production and demand, which is in line with the recent U.S. net import of steel.[426] Based on these, DOE calculated the U.S. steel demand and production up to 2050. DOE assumed similar steel production across all four scenarios.[427]

[426] The assumption of 15-18% of steel demand provided from imports (or 82-85% of steel demand met by U.S. production) was based on latest available data from U.S. Geological Survey (See Christopher A. Tuck, *Iron and Steel Statistics and Information, Minerals Commodity Summaries*, U.S. Geological Survey, January 2020, https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-iron-steel.pdf).

[427] Note that materials efficiency and demand management is out of scope of this quantitative analysis. The materials efficiency could change the demand outlook.

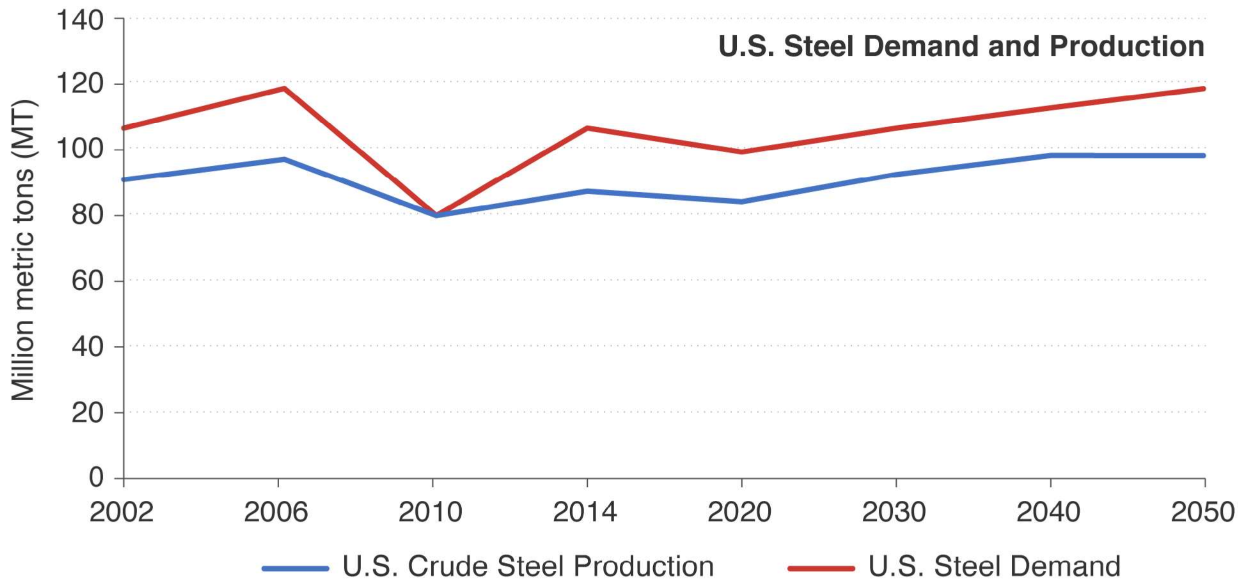

FIGURE A 2. ANNUAL U.S. STEEL DEMAND AND PRODUCTION FORECAST, 2002-2050

SOURCE: VALUES FOR 2002-2014 ARE FROM U.S. GEOLOGICAL SURVEY MINERAL COMMODITY SUMMARIES FOR IRON AND STEEL[428]; 2020-2050 PRODUCTION AND DEMAND WERE CALCULATED USING EXPERT JUDGEMENT, HISTORICAL TRENDS, AND U.S. CENSUS BUREAU POPULATION PROJECTIONS. ASSUMPTIONS INCLUDED 0.3 TON/PERSON STEEL DEMAND AND 82-85% OF TOTAL STEEL DEMAND MET BY DOMESTIC PRODUCTION.

Table A 1 shows some of the key parameters and indicators for the U.S. steel industry and their projections up to 2050 under all scenarios.

[428] See 2003-2020 versions at "Iron and Steel Statistics and Information," U.S. Geological Survey, accessed May 2022, https://www.usgs.gov/centers/national-minerals-information-center/iron-and-steel-statistics-and-information.

Table A 1. Key parameters used for the U.S. steel industry under each scenario, 2015-2050

Parameter	Unit	Base Year	BAU Scenario			Moderate Scenario			Advanced Scenario			Near Zero GHG Scenario		
		2015	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Steel demand[429]	kt	107,000	107,500	113,800	119,800	107,500	113,800	119,800	107,500	113,800	119,800	107,500	113,800	119,800
Fuel intensity[430]	GJ/t steel	8.5	7.1	6.9	6.7	6.7	6.3	5.8	6.3	5.4	4.6	5.7	4.0	2.5
Electricity intensity[431]	kWh/t steel	678	665	653	641	647	623	601	610	622	638	543	664	864
Fuel-related CO_2 emissions intensity*[432]	kg CO_2/t steel	634	510	494	478	476	433	375	432	346	267	382	239	131
Electricity-related CO_2 emissions intensity*[433]	kg CO_2/t steel	338	197	136	93	177	112	71	126	64	33	67	25	10
Total CO_2 emissions intensity*	kg CO_2/t steel	972	708	629	571	653	545	446	558	410	300	450	264	141

*These intensities are before application of CCUS.

[429] 2015-2019 values from U.S. Geological Survey Mineral Commodity Summaries for Iron and Steel (See "Iron and Steel Statistics and Information," U.S. Geological Survey, accessed May 2020, https://www.usgs.gov/centers/national-minerals-information-center/iron-and-steel-statistics-and-information); 2020-2050 production and demand were calculated using expert judgement, historical trends, and U.S. Census Bureau population projections. Assumptions included 0.3 ton/person steel demand and 82-85% of total steel demand met by domestic production.

[430] Base year (2015) intensity values from Ali Hasanbeigi and Cecilia Springer, *How Clean is the U.S. Steel Industry? An International Benchmarking of Energy and CO_2 Intensities*, Global Efficiency Intelligence, November 2019, https://www.globalefficiencyintel.com/s/How-Clean-is-the-US-Steel-Industry.pdf; projected intensities are based on expert judgements for each scenario.

[431] Ibid.

[432] Base year (2015) intensity values from "Documentation of California's 2000-2019 GHG Inventory," California Air Resources Board (CARB), last modified October 8, 2021, https://ww2.arb.ca.gov/applications/california-ghg-inventory-documentation and Institute for Global Environmental Strategies (IGES), *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, 2006, https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html; projected intensities based on assumed scenario fuel mixes.

[433] Base year (2015) intensity from "State Electricity Profiles: United States Electricity Profile 2015," U.S. Energy Information Administration, last modified January 17, 2017, https://www.eia.gov/electricity/state/archive/2015/unitedstates/; projected intensity for all scenarios up to 2050 based on historical trends of the U.S. grid's CO_2 emissions factor in the past 20 years, future projections for the share of renewables in the U.S. grid, and scenario definitions.

In addition, DOE assumed various adoption rates of CCS technologies in the U.S. steel industry across scenarios (Table A 2). It should be noted that post-combustion carbon capture technologies can reach up to 95% capture efficiency, but because of the structure of steel plants and different emissions point sources in production and the leakage that happens during carbon capture, it is hard to reach that high capture efficiency in steel plants.

TABLE A 2. CCS ADOPTION RATE IN THE U.S. STEEL INDUSTRY (AS % OF TOTAL CO_2 EMISSIONS AFTER ADOPTION OF OTHER DECARBONIZATION PILLARS)[434]

Scenario	2014	2020	2030	2040	2050
BAU	0%	0%	0%	3%	5%
Moderate	0%	0%	2%	8%	15%
Advanced	0%	0%	5%	20%	40%
Near Zero GHG	0%	0%	10%	40%	85%

Another important assumption that influences GHG emissions projections is the share of each steel production route from total U.S. steel production up to 2050. Figure A 3 shows the share of each production route under all scenarios in 2050.

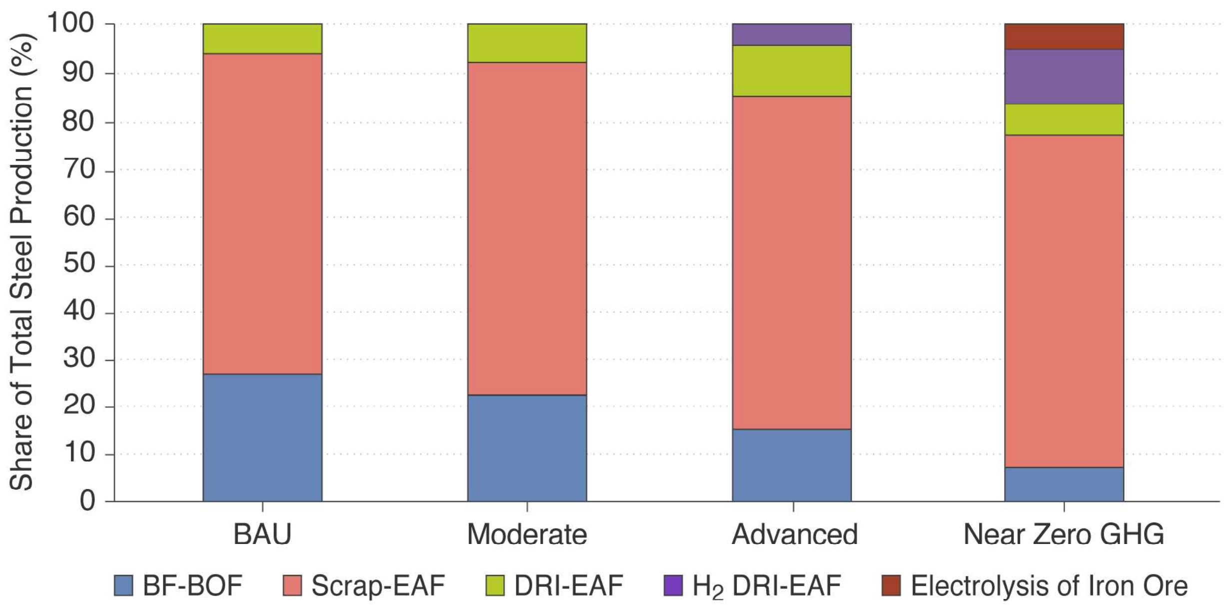

FIGURE A 3. SHARE OF STEEL PRODUCTION ROUTES UNDER EACH SCENARIO IN 2050

SOURCE: BASED ON EXPERT ASSUMPTIONS.

Finally, DOE projected the fuel mix used in the U.S. steel industry (Figure A 4) by shifting to lower-carbon fuels. For example, in the Near Zero GHG scenario, DOE assumed the coal and coke consumption in the

[434] Based on expert assumptions and International Energy Agency, *Iron and Steel Technology Roadmap*, October 2020, https://www.iea.org/reports/iron-and-steel-technology-roadmap.

U.S. steel industry will be reduced substantially by 2050, and the share of electricity will increase because of the shift in production process routes shown in Figure A 3. DOE also assumed a small use of biomass in 2050, which combined with CCS will provide carbon sink in this industry. DOE also assumed small amount of hydrogen will be used in the fuel mix for process heating.

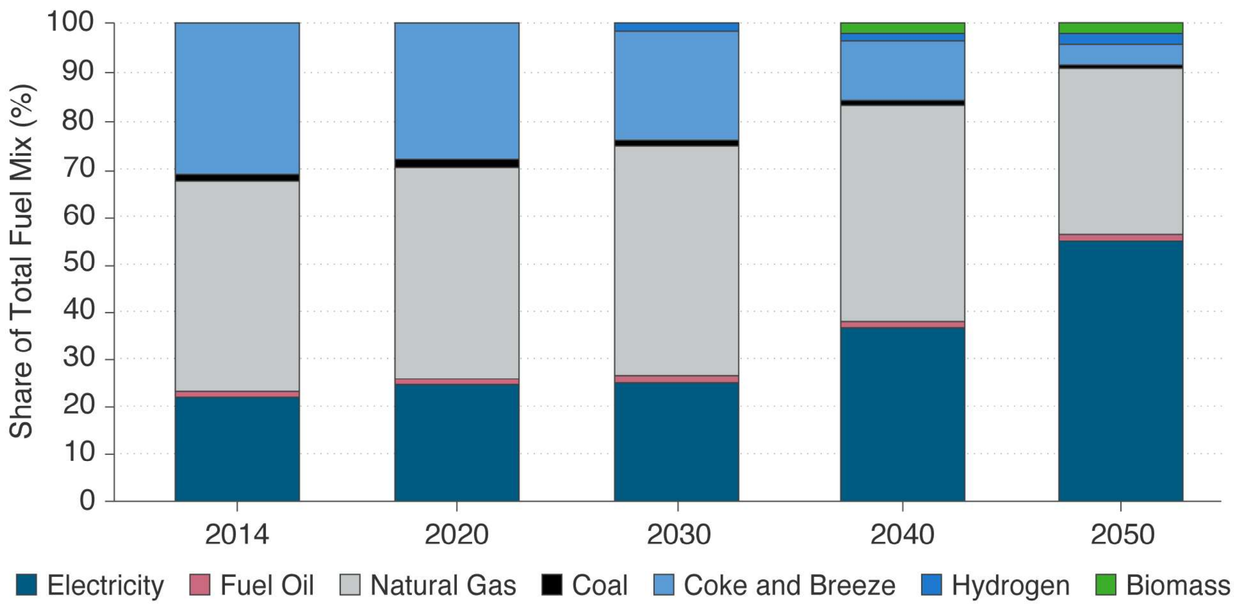

FIGURE A 4. FUEL MIX PROJECTIONS FOR THE U.S. STEEL INDUSTRY UNDER NEAR ZERO GHG SCENARIO, 2014-2050

SOURCE: 2014 VALUES FROM EIA MECS.[435] 2020-2050 VALUES BASED ON EXPERT ASSUMPTIONS.

Breakdown of pillar contributions for steel. A breakdown of the contribution of the pillars to reductions in steel is shown in Figure A 5. Here steel production is increasing in 2015-2050, but the CO_2 emissions decreases readily even in the BAU as over 70% of steel is already produced by EAF (electric arc furnace) which is electricity based. Hence the grid emissions factor will decrease even in the BAU scenario. The other scenarios show that the contribution of energy efficiency can make a large impact on CO_2 reduction that helps to mitigate the rising CO_2 from small production demand growth and yielding a net CO_2 reduction. Electrification strategies have a strong influence on reducing CO_2 with the impact growing significantly by 2050. CCUS plays a role for steel that is significant by 2050, but as the process technology for steel can largely be transitioned to electrified processes (e.g., EAF) by 2050 only a small amount of CO_2 remains to be mitigated after pursuit of the other pillars.

[435] "Manufacturing Energy Consumption Survey (MECS): 2014 MECS Survey Data, U.S. Energy Information Administration, released 2018, https://www.eia.gov/consumption/manufacturing/data/2014/.

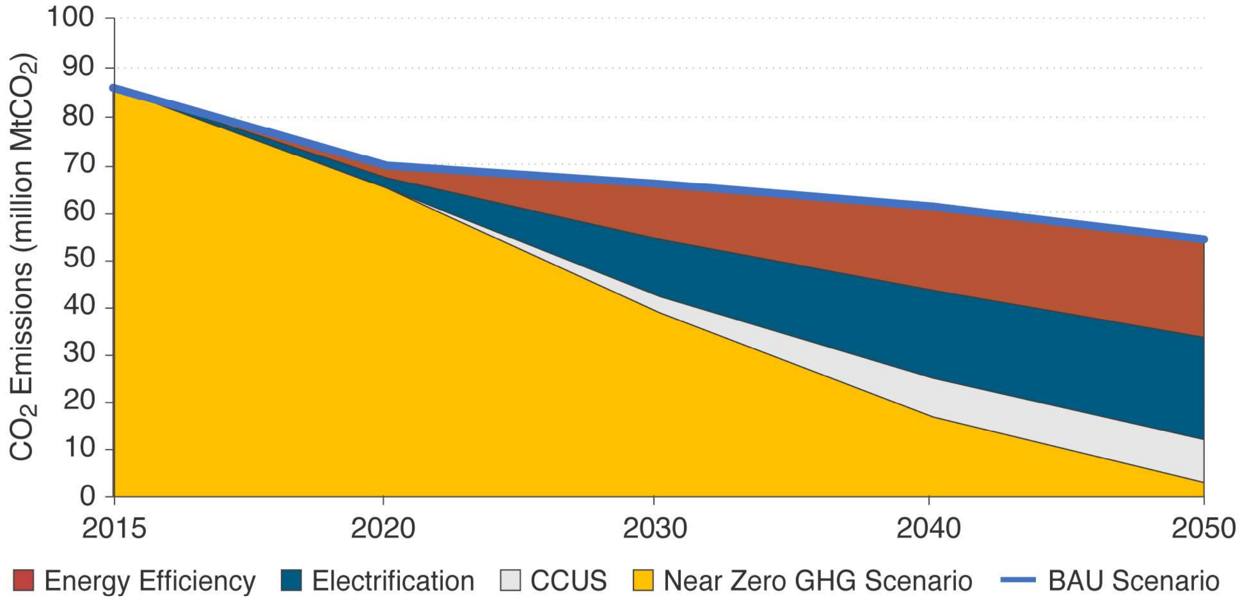

FIGURE A 5. AREA PLOT OF PILLAR CONTRIBUTIONS TO CO_2 REDUCTION FOR THE STEEL INDUSTRY.

SOURCE: THIS WORK.

Appendix 1.2. Chemical Industry Analysis: Methodology and Assumptions

To understand how application of the decarbonization pillars could help to reach net GHG emissions, the potential CO_2 reductions possible for several major chemical products (i.e., ammonia, methanol, ethylene, and benzene, toluene, and xylenes (BTX)) were examined. This work was also pursued to provide guidance on where RD&D could significantly enable reductions. The topic of where to start on reductions, the relative impact of the pillars, and priorities for RD&D were also of common interest across the meetings. Several scenarios were developed as described earlier. In this subsection, DOE presents some of the key assumptions and indicators used in the roadmap development. DOE developed four main scenarios:

1. **Business as Usual (BAU) scenario**: The BAU scenario assumes a slow improvement in energy efficiency and slow adoption of commercially available CCUS technologies, and reflects current business practices and current policies and regulations.

2. **Moderate Technology and Policy (Moderate) scenario**: This scenario assumes higher energy efficiency improvement, more fuel switching to lower-carbon fuels compared to BAU. It also assumes low adoption of CCUS technologies, up to 10% in 2050.

3. **Advanced Technology and Policy (Advanced) scenario**: This scenario assumes significantly higher energy efficiency improvement using commercially available technologies, more aggressive fuel switching to lower-carbon fuels. It also assumes, in 2050, 30% of CO_2 emitted after the adoption of energy efficiency and fuel switching technologies from U.S. chemical plants within the subsectors studied will be captured by CCUS technologies.

4. **Near Zero GHG (Near Zero) scenario**: This scenario assumes the most aggressive energy efficiency improvement using commercially available technologies, more aggressive fuel switching to lower-carbon fuels compared to the Advanced scenario. It also assumes, in 2050, 70% of CO_2 emitted after the adoption of energy efficiency and fuel switching technologies from U.S. chemical plants within the subsectors studied will be captured by CCUS technologies.

The first step in developing the pathways was to project selected U.S. chemicals production and demand for 2015 to 2050.

It should be noted that feedstocks are crucial building blocks for a wide range of products in the chemical industry. The vast majority are currently based on fossil fuels (predominately hydrocarbon gas liquids as shown in Figure 20). As the calculations for the scenarios primarily examined the overall carbon intensity of the key products selected, the carbon contribution of feedstocks was included with the total emissions of the products. Some products may be used later in other economic sectors (e.g., automobiles), and some relatively small amount of chemicals may end up in fuels that are combusted, but these emissions were outside the boundary of this work. Similarly, hydrocarbon by-products (such as hydrogen and methane) are already accounted for on a carbon basis in fuel usage. These by-products are often used to heat the cracking furnace, so counting the stream as both feedstock energy and fuel would result in double counting.

To provide input for the above scenarios on the potential impact of the decarbonization pillars on reducing carbon intensity for chemical products, five key, high volume products were chosen as mentioned above. The CO_2 related emissions intensity of production was evaluated using these scenarios to 2050 starting with baseline data from 2015. For example, Table A 3 shows some of the key parameters and indicators for the U.S. ammonia industry and their projections up to 2050 under all scenarios. The same type of projections was made for other selected chemicals studied in this analysis. In addition, parameters for emissions factors, conversion factors, and production volumes were taken from the literature.

TABLE A 3. KEY PARAMETERS USED FOR THE U.S. AMMONIA INDUSTRY UNDER EACH SCENARIO, 2015-2050

Parameter	Unit	Base year	BAU Scenario			Moderate Scenario			Advanced Scenario			Near Zero Scenario		
		2015	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Ammonia production[436]	kt	11,800	21,100	25,800	30,500	21,100	25,800	30,500	21,100	25,800	30,500	21,100	25,800	30,500
Fuel intensity[437]	GJ/t ammonia	13.0	12.6	12.3	12.1	11.8	10.9	9.5	11.3	10.1	8.1	10.4	8.5	5.6
Electricity intensity[438]	kWh/t ammonia	181	175	172	168	617	1,030	1,837	827	1,425	2,579	1,226	2,150	3,897
Fuel-related CO_2 emissions intensity*[439]	kg CO_2/t ammonia	651	631	619	606	593	537	459	559	487	385	505	405	259
Electricity-related CO_2 emissions intensity*[440]	kg CO_2/t ammonia	89.95	52	36	24	169	186	218	171	147	133	152	80	44
Total CO_2 emissions intensity*	kg CO_2/t ammonia	741	683	654	631	762	723	677	730	635	518	657	485	302

*These intensities are before application of CCUS.

[436] Base year (2015) data from American Chemistry Council, *2020 Guide to the Business of Chemistry*, December 2020, https://www.americanchemistry.com/chemistry-in-america/data-industry-statistics/resources/2020-guide-to-the-business-of-chemistry. Production data up to 2050 based on expert assumptions and anticipated growth rate for ammonia production.

[437] Base year (2015) data from Beyond Zero Emissions Inc., *Zero Carbon Industry Plan: Electrifying Industry,* September 2018, https://bze.org.au/wp-content/uploads/2020/12/electrifying-industry-bze-report-2018.pdf. Projected intensities based on expert assumptions, scenario definitions, and analysis within U.S. Department of Energy Advanced Manufacturing Office, *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Chemical Manufacturing*, June 2015, https://www.energy.gov/eere/amo/downloads/bandwidth-study-us-chemical-manufacturing.

[438] Ibid.

[439] Base year (2015) intensity values from "Documentation of California's 2000-2019 GHG Inventory," California Air Resources Board (CARB), last modified October 8, 2021, https://ww2.arb.ca.gov/applications/california-ghg-inventory-documentation and Institute for Global Environmental Strategies (IGES), *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, 2006, https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html; projected intensities based on assumed scenario fuel mixes.

[440] Base year (2015) intensity from "State Electricity Profiles: United States Electricity Profile 2015," U.S. Energy Information Administration, last modified January 17, 2017, https://www.eia.gov/electricity/state/archive/2015/unitedstates/; projected intensity for all scenarios up to 2050 based on historical trends of the U.S. grid's CO_2 emissions factor in the past 20 years, future projections for the share of renewables in the U.S. grid, and scenario definitions.

The reason for the substantial increase in electricity intensity projections is that DOE assumed a substantial amount of hydrogen needed as feedstock for ammonia production, which currently is produced from natural gas, will be produced by electrolysis process using nuclear or renewable energy (electrolysis-hydrogen). Figure A 6 shows DOE's assumptions on the share of electrolysis-hydrogen from total hydrogen used as feedstock in the U.S. ammonia industry.

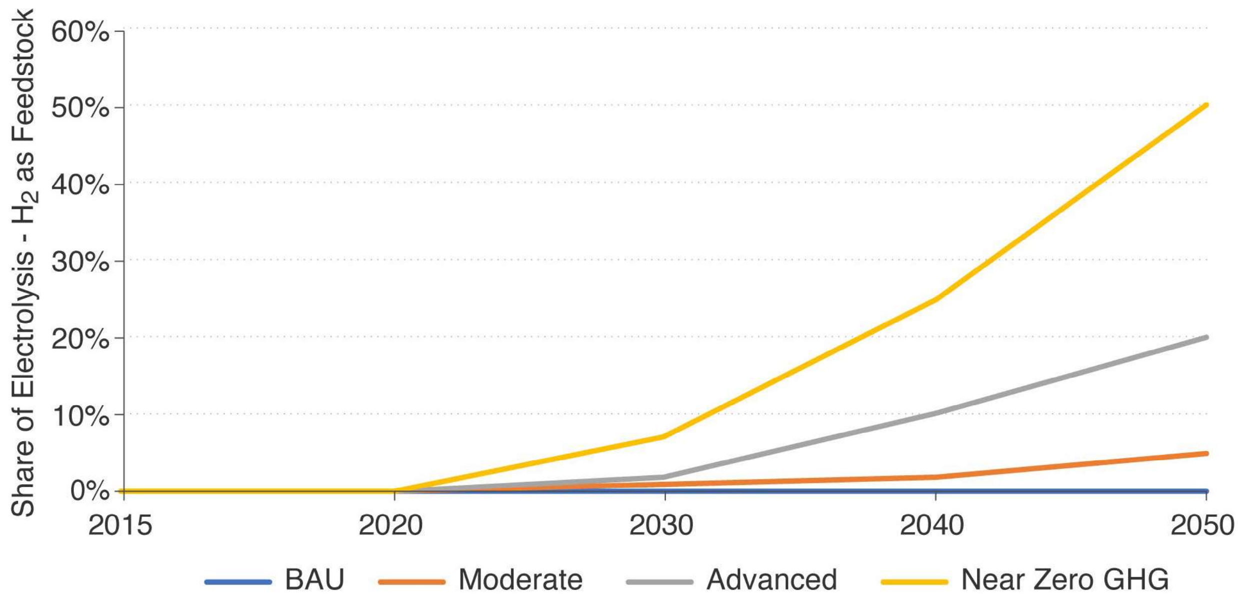

FIGURE A 6 SHARE OF ELECTROLYSIS-HYDROGEN FROM TOTAL HYDROGEN USED AS FEEDSTOCK IN U.S. AMMONIA INDUSTRY

SOURCE: THIS WORK.

In addition, DOE assumed various adoption rates of CCS technologies in the U.S. chemical industry across scenarios (Table A 4). It should be noted that post-combustion carbon capture technologies can reach up to 95% capture efficiency, but because of the nature of emissions in the chemical industry and several point sources for emissions, it is hard to reach that high capture efficiency in chemical plants.

TABLE A 4. CCS ADOPTION RATE IN THE U.S. CHEMICAL INDUSTRY (AS % OF TOTAL CO_2 EMISSIONS AFTER ADOPTION OF OTHER DECARBONIZATION PILLARS)[441]

Scenario	2015	2020	2030	2040	2050
BAU	0%	0%	0%	3%	5%
Moderate	0%	0%	2%	5%	10%
Advanced	0%	0%	4%	15%	30%
Near Zero	0%	0%	8%	30%	70%

[441] Based on expert assumptions and Figure 4.10 of International Energy Agency, *Energy Technology Perspectives 2017,* June 2017, https://www.iea.org/reports/energy-technology-perspectives-2017.

Finally, DOE projected the fuel mix used in the U.S. chemical industry by shifting to lower-carbon fuels. For example, in the Net-Zero GHG scenario, DOE assumed the share of natural gas consumption will go down while the share of biomass and hydrogen in fuel mix increases. Figure A 7 shows an example of fuel mix assumption under Near Zero GHG scenario for the ammonia industry.

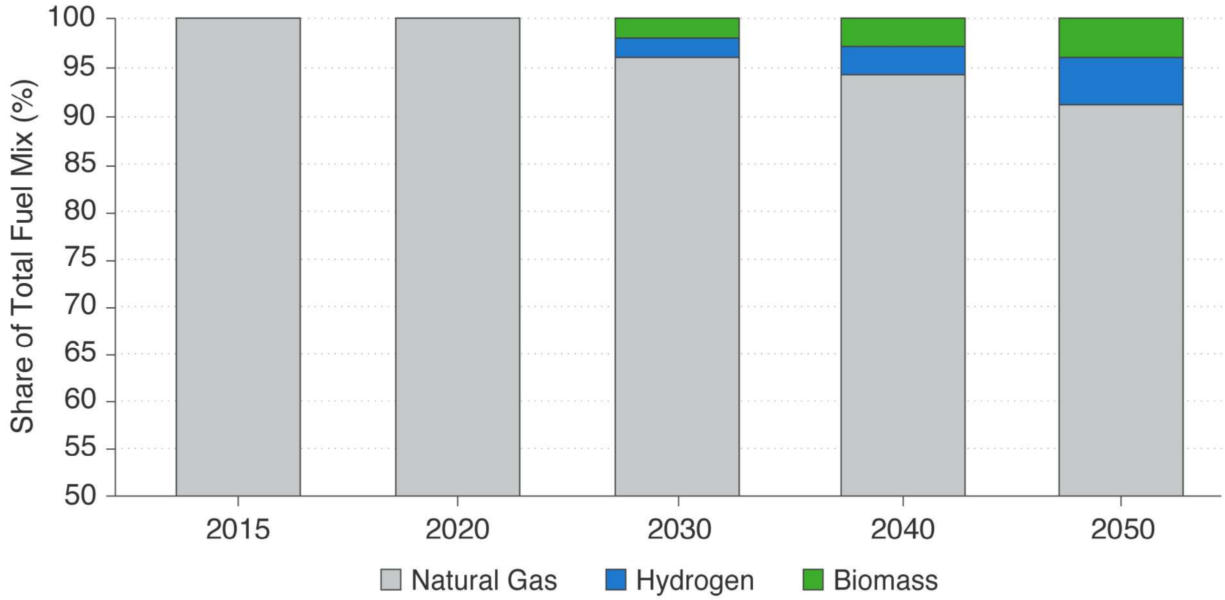

Figure A 7. Fuel mix for heat (excluding feedstock) projections for the U.S. ammonia industry under Near Zero GHG scenario, 2015-2050

Source: Fuel mix for 2015 from USGS 2016 and IEA 2021.[442] Projections based on expert assumptions.

Breakdown of pillar contributions for ammonia. The contributions of the pillars to the CO_2 reduction in the subsectors can also be viewed across the time horizon as shown in Figure A 8 for ammonia in the near zero scenario. This plot reflects the expected strong growth in product demand increases across all scenarios which results in the steady increase in CO_2 emissions for the BAU. The scenarios suggest that energy efficiency can make an increasing contribution to CO_2 reduction through 2050 which blunts the CO_2 expected from the product demand growth. The contribution from combined electrification strategies (including process heat, hydrogen and other low-carbon fuels as a fuel or feedstock) makes the dominant contribution in later years as the electric grid is decarbonized. The CCUS contribution also grows as infrastructure is added to mitigate hard-to-abate sources. An amount of CO_2 remains in 2050 largely due to the challenges with transitioning the entire distribution of process technologies to transformative approaches given the long lifetime of capital assets and the vast number of sources at chemical facilities that are difficult to economically collect and capture.

[442] Lori E. Apodaca, *Nitrogen (Fixed) – Ammonia*, U.S. Geological Survey, January 2016, https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/mineral-pubs/nitrogen/mcs-2016-nitro.pdf; International Energy Agency, *Ammonia Technology Roadmap,* October 2021, https://www.iea.org/reports/ammonia-technology-roadmap.

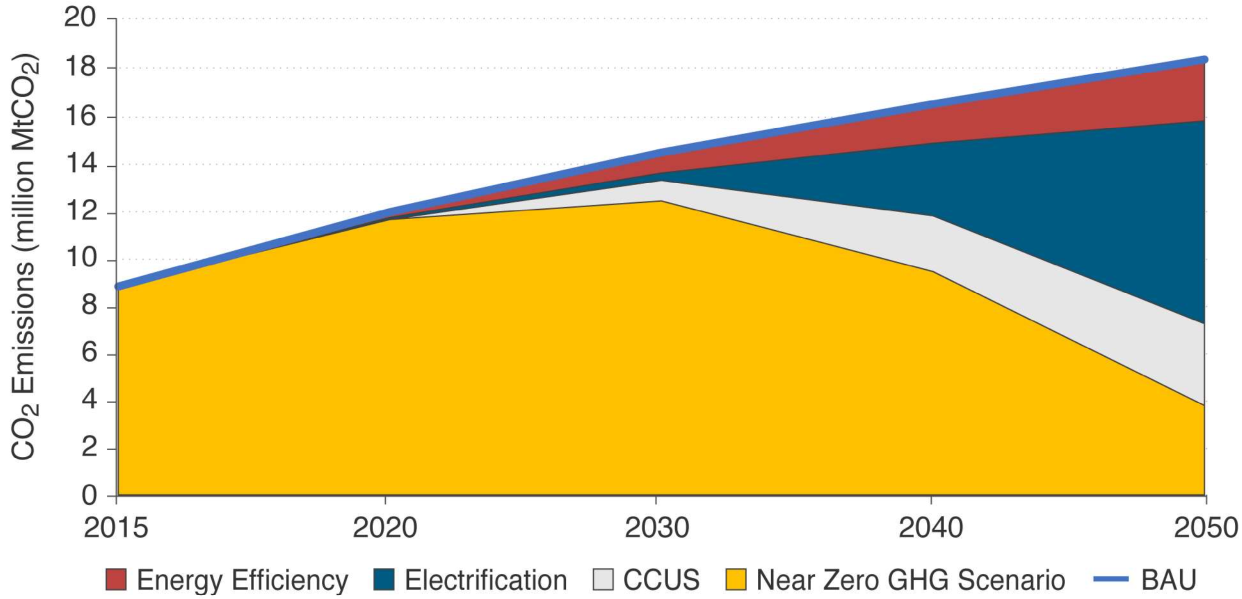

FIGURE A 8. AREA PLOT OF PILLAR CONTRIBUTIONS TO CO_2 REDUCTION FOR THE AMMONIA INDUSTRY.

SOURCE: THIS WORK.

Appendix 1.3. Food and Beverage Industry Analysis: Methodology and Assumptions

DOE's estimation of the application of the decarbonization pillars in the U.S. food and beverage manufacturing subsector includes seven major subsectors. These energy-intensive subsectors account for around a third of total food and beverage manufacturing energy use. They include wet corn milling, soybean oil, cane sugar, beet sugar, fluid milk, red meat product processing, and beer production. Several scenarios were developed as described earlier. In this subsection, DOE presents some of the key assumptions and indicators used in the roadmap development. DOE developed four main scenarios:

1. **Business as Usual (BAU) scenario**: The BAU scenario assumes a slow improvement in energy efficiency and slow adoption of commercially available CCUS technologies, and reflects current business practices and current policies and regulations.

2. **Moderate Technology and Policy (Moderate) scenario**: This scenario assumes higher energy efficiency improvement, more fuel switching to lower-carbon fuels compared to BAU. It also assumes low adoption of CCUS technologies, up to 6% in 2050.

3. **Advanced Technology and Policy (Advanced) scenario**: This scenario assumes significantly higher energy efficiency improvement using commercially available technologies, more aggressive fuel switching to lower-carbon fuels. It also assumes, in 2050, 15% of CO_2 emitted after the adoption of energy efficiency and fuel switching technologies from U.S. food and beverage plants within the subsectors studied will be captured by CCUS technologies.

4. **Near Zero GHG (Near Zero) scenario**: This scenario assumes the most aggressive energy efficiency improvement using commercially available technologies, more aggressive fuel switching to lower-carbon fuels compared to the Advanced scenario. It also assumes, in 2050, 30% of CO_2 emitted after the adoption of energy efficiency and fuel switching technologies from U.S. food and beverage plants within the subsectors studied will be captured by CCUS technologies.

The first step in developing the pathways was to project selected U.S. food and beverages production and demand during the period 2015 to 2050.

To provide input for the above scenarios on the potential impact of the decarbonization pillars on reducing carbon intensity for food and beverage products, seven key, high volume and high energy consuming food and beverage subsectors were chosen as mentioned above. The carbon intensity of production was evaluated using these scenarios to 2050 starting with baseline data from 2015. For example, Table A 5 shows some of the key parameters and indicators for U.S. wet corn milling industry and their projections up to 2050 under all scenarios. The same type of projections was made for other selected food and beverages studied in this analysis.

Table A 5. Key parameters used for the U.S. wet corn milling industry under each scenario, 2015-2050

Parameter	Unit	Base year	BAU Scenario			Moderate Scenario			Advanced Scenario			Near Zero Scenario		
		2015	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Production[443]	kt product	28,800	32,300	34,200	36,000	32,300	34,200	36,000	32,300	34,200	36,000	32,300	34,200	36,000
Fuel intensity[444]	GJ/t product	3.2	3.0	2.9	2.8	3.0	2.8	2.6	2.8	2.3	1.8	2.4	1.7	0.9
Electricity Intensity[445]	kWh/t product	195	206	219	231	212	230	255	218	281	372	239	345	485
Fuel-related CO_2 Emissions intensity *[446]	kg CO_2/t product	201	188	179	169	179	168	147	161	126	93	137	84	36
Electricity-related CO_2 Emissions intensity *[447]	kg CO_2/t product	97	61	45	34	58	41	30	45	29	19	30	13	5
Total CO_2 Emissions intensity *	kg CO_2/t product	298	250	224	203	236	210	178	207	155	112	167	97	42

*These intensities are before the application of CCUS.

[443] Base year (2015) production from U.S. Department of Energy Advanced Manufacturing Office, *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Food and Beverage Manufacturing*, DOE/EE-1571, September 2017, https://www.energy.gov/eere/amo/downloads/bandwidth-study-us-food-and-beverage-manufacturing. Projected production estimated based on expert assumption calculated using expert judgement, historical trends, and U.S. Census Bureau population projections.

[444] Base year (2015) intensity from U.S. Department of Energy Advanced Manufacturing Office, *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Food and Beverage Manufacturing*, DOE/EE-1571, September 2017, https://www.energy.gov/eere/amo/downloads/bandwidth-study-us-food-and-beverage-manufacturing. Projected intensities based on expert assumptions and scenario definitions.

[445] Ibid.

[446] Base year (2015) intensity values from "Documentation of California's 2000-2019 GHG Inventory," California Air Resources Board (CARB), last modified October 8, 2021, https://ww2.arb.ca.gov/applications/california-ghg-inventory-documentation and Institute for Global Environmental Strategies (IGES), *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, 2006, https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html; projected intensities based on assumed scenario fuel mixes.

[447] Base year (2015) intensity from "State Electricity Profiles: United States Electricity Profile 2015," U.S. Energy Information Administration, last modified January 17, 2017, https://www.eia.gov/electricity/state/archive/2015/unitedstates/; projected intensity for all scenarios up to 2050 based on historical trends of the U.S. grid's CO_2 emissions factor in the past 20 years, future projections for the share of renewables in the U.S. grid, and scenario definitions.

In addition, DOE assumed various adoption rates of CCS technologies in the U.S. food and beverage industry across scenarios (Table A 6). It should be noted that post-combustion carbon capture technologies can reach up to 95% capture efficiency, but because of the nature of emissions in the food and beverage industry and many point sources for emissions that will be too small and or not suitable for CCUS, it is hard to reach that high capture efficiency in food and beverage plants.

TABLE A 6. CCS ADOPTION RATE IN THE U.S. FOOD AND BEVERAGE INDUSTRY (AS % OF TOTAL CO_2 EMISSIONS AFTER ADOPTION OF OTHER DECARBONIZATION PILLARS)[448]

Scenario	2015	2020	2030	2040	2050
BAU	0%	0%	0%	2%	4%
Moderate	0%	0%	1%	3%	6%
Advanced	0%	0%	2%	7%	15%
Net-Zero GHG	0%	0%	4%	15%	30%

Finally, DOE projected the fuel mix used in the U.S. food and beverage industry by shifting to lower-carbon fuels. For example, in the Net-Zero GHG scenario, DOE assumed the share of coal consumption will go down from 39% in 2015 to 4% in 2050 while the share of biomass and hydrogen in the fuel mix increases (Figure A 9).

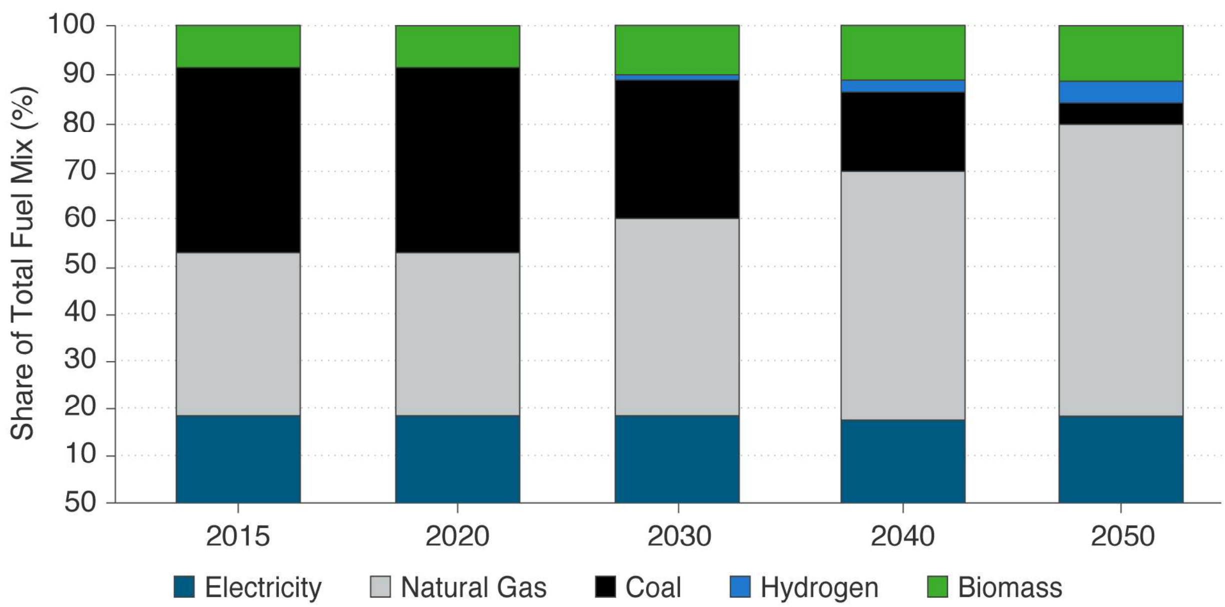

FIGURE A 9. FUEL MIX PROJECTIONS FOR THE U.S. WET CORN MILLING INDUSTRY UNDER NEAR ZERO GHG SCENARIO, 2015-2050

SOURCE: FUEL MIX FOR 2015 FROM EIA MECS.[449] PROJECTIONS BASED ON EXPERT ASSUMPTIONS.

[448] Based on expert assumptions.
[449] "Manufacturing Energy Consumption Survey (MECS): 2014 MECS Survey Data, U.S. Energy Information Administration, released 2018, https://www.eia.gov/consumption/manufacturing/data/2014/.

Appendix 1.4. Petroleum Refining Industry Analysis: Methodology and Assumptions

DOE's estimation of the application of the decarbonization pillars in the U.S. petroleum refining subsector starts with EIA's AEO 2021 Reference Case projections of crude oil "Inputs to Distillation Units" and refinery "Energy Related to Refining Activity Only"[450], which accounted for 63% of the total energy consumed in the refinery industry and EIA projects to fall to 58% by 2050. Several scenarios were developed as described earlier. In this subsection, DOE presents some of the key assumptions and indicators used in the roadmap development.

To estimate the application of the decarbonization pillars in the U.S. petroleum refining subsector, DOE assume the crude oil "Inputs to Distillation Units" in the AEO 2021 Reference Case projections are refined to produce the slate of product outputs in the Reference Case projections.[451] From this assumption, DOE developed four main scenarios:

1. **Business as Usual (BAU) scenario**: The petroleum refining BAU scenario assumes that the crude oil inputs and slate of product outputs in the AEO 2021 Reference Case projections are refined at the same energy intensity (GJ/barrel of oil) and carbon intensity (million MT CO_2/GJ) of U.S. refineries in 2015. The AEO 2021 Reference Case projections reflect BAU energy efficiency improvements associated with technology adoption between 2015 and 2050, and reflects current business practices and current policies and regulations.

   The variation in BAU CO_2 emissions only reflect the variation in AEO 2021 projections of crude oil inputs between 2015 and 2050. The refinery BAU CO_2 emission projection are independent of variation in AEO 2021 projections of refining subsector energy efficiency improvement and/or fuel switching assumptions.

2. **Moderate Technology and Policy (Moderate) scenario**: This scenario assumes higher energy efficiency improvement and more fuel switching to lower-carbon fuels compared to BAU. It also assumes low adoption of CCUS technologies, up to 10% in 2050. The Moderate Scenario applies AEO 2021 projections of refinery energy and carbon intensity through 2040, but also assumes the refining industry is 13% more energy efficient in 2050 than in 2015 based on the best available technology opportunities in a DOE refining study.[452]

3. **Advanced Technology and Policy (Advanced) scenario**: This scenario assumes significantly higher energy efficiency improvement using commercially available technologies and more aggressive fuel switching to lower-carbon fuels. It also assumes in 2050, 30% of CO_2 emitted after adoption of energy efficiency and fuel switching technologies from U.S. petroleum refineries will be captured by CCUS technologies.

[450] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 24. Refining Industry Energy Consumption.
[451] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 11. Petroleum and Other Liquids Supply and Disposition.
[452] U.S. Department of Energy Advanced Manufacturing Office, *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Petroleum Refining*, DOE/EE-1230, June 2015, https://www.osti.gov/biblio/1248754-bandwidth-study-energy-use-potential-energy-savings-opportunities-petroleum-refining.

The Advanced scenario and the Near Zero GHG scenario maintain the same efficiency improvements as the Moderate scenario by 2020, but they ramp up to a more energy efficient refining industry by 2050 (relative to 2015) than the Moderate scenario assumes.

4. **Near Zero GHG (Near Zero) scenario**: This scenario assumes the most aggressive energy efficiency improvement using commercially available technologies and more aggressive fuel switching to lower-carbon fuels compared to the Advanced scenario. It also assumes, in 2050, 70% of CO_2 emitted after adoption of energy efficiency and fuel switching technologies from U.S. petroleum refineries be captured by CCUS technologies. Relative to 2015, the Advanced scenario assumes a 28% more energy efficient refining industry by 2050 (based on a recent EU refinery industry analysis for decarbonizing the EU refinery industry by 2050 that developed low, median, and maximum CO_2 mitigation scenarios through engagement with EU refiners).[453] For reference, EU refinery capacity is approximately 70% the size of U.S. refinery capacity.

To understand how application of the decarbonization pillars could help phase out net GHG, the potential CO_2 reductions for refineries were examined, and several scenarios were developed and analyzed that were like those described for the other subsectors (see the introduction to these Appendices: Scenario Methodology and Assumptions). Table A 7 shows some of the key parameters and indicators for U.S. refineries and their projections out to 2050 under all scenarios.

[453] Concawe, *CO_2 Reduction Technologies: Opportunities within the EU Refining System (2030/2050): Qualitative and Quantitative Assessment for the Production of Conventional Fossil Fuels (Scope 1 & 2)*, Concawe Report No. 8/19, July 2019, https://www.concawe.eu/wp-content/uploads/Rpt_19-8.pdf.

TABLE A 7. KEY PARAMETERS USED FOR THE U.S. PETROLEUM REFINING INDUSTRY UNDER EACH SCENARIO, 2015-2050

Parameter	Unit	Base year	BAU Scenario			Moderate Scenario			Advanced Scenario			Near Zero Scenario		
		2015	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Production: Crude Oil Inputs to Distillation Units[454]	Million Barrels per day	17.23	18.28	18.43	18.54	18.28	18.43	18.54	18.28	18.43	18.54	18.28	18.43	18.54
Production: Crude Oil Inputs to Distillation Units[455]	Million Barrels per year	6,290	6,674	6,726	6,766	6,674	6,726	6,766	6,674	6,726	6,766	6,674	6,726	6,766
Production: Crude Oil Inputs to Distillation Units[456]	Mt crude oil	880	934	942	947	934	942	947	934	942	947	934	942	947
Fuel intensity[457]	GJ/t crude oil	3.2	3.2	3.2	3.2	2.8	2.9	2.8	2.5	2.4	2.3	2.4	2.2	2.0
Electricity Intensity[458]	kWh/t crude oil	74.9	88.5	91.8	99.5	63.3	70.9	64.0	58.9	118.7	173.4	66.6	115.9	161.6
Fuel-related CO_2 emissions intensity*[459]	kg CO_2/t crude oil	231.7	202.7	206.8	209.1	202.9	206.9	201.3	182.0	162.4	143.7	174.1	146.7	120.0
Electricity-related CO_2 emissions intensity*[460]	kg CO_2/t crude oil	37.3	26.2	19.0	13.7	17.3	12.8	7.6	12.2	12.3	9.0	8.3	4.3	1.8
Total CO_2 emissions intensity*	kg CO_2/t crude oil	269.0	228.9	225.9	222.7	220.1	219.7	208.9	194.2	174.6	152.7	182.3	151.0	121.8

*These intensities are before application of CCUS.

[454] "Annual Energy Outlook 2021 with Projections to 2050," U.S. Energy Information Administration, February 3, 2021, https://www.eia.gov/outlooks/archive/aeo21/. See Table 11. Petroleum and Other Liquids Supply and Disposition and Table 24. Refining Industry Energy Consumption.
[455] Ibid.
[456] Ibid.
[457] Concawe, *CO_2 Reduction Technologies: Opportunities within the EU Refining System (2030/2050): Qualitative and Quantitative Assessment for the Production of Conventional Fossil Fuels (Scope 1 & 2)*, Concawe Report No. 8/19, July 2019, https://www.concawe.eu/wp-content/uploads/Rpt_19-8.pdf; U.S. Department of Energy Advanced Manufacturing Office, *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Petroleum Refining*, DOE/EE-1230, June 2015, https://www.osti.gov/biblio/1248754-bandwidth-study-energy-use-potential-energy-savings-opportunities-petroleum-refining
[458] Ibid.
[459] Base year (2015) intensity values from "Documentation of California's 2000-2019 GHG Inventory," California Air Resources Board (CARB), last modified October 8, 2021, https://ww2.arb.ca.gov/applications/california-ghg-inventory-documentation and Institute for Global Environmental Strategies (IGES), *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, 2006, https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html; projected intensities based on assumed scenario fuel mixes.
[460] Base year (2015) intensity from "State Electricity Profiles: United States Electricity Profile 2015," U.S. Energy Information Administration, last modified January 17, 2017, https://www.eia.gov/electricity/state/archive/2015/unitedstates/; projected intensity for all scenarios up to 2050 based on historical trends of the U.S. grid's CO_2 emissions factor in the past 20 years, future projections for the share of renewables in the U.S. grid, and scenario definitions.

In addition, DOE assumed various adoption rates of CCS technologies in the U.S. petroleum refining industry across scenarios (Table A 8).

TABLE A 8. CCS ADOPTION RATE IN THE U.S. PETROLEUM REFINING INDUSTRY (AS % OF TOTAL CO_2 EMISSIONS AFTER ADOPTION OF OTHER DECARBONIZATION PILLARS)[461]

Scenario	2015	2020	2030	2040	2050
BAU	0%	0%	0%	2%	4%
Moderate	0%	0%	2%	5%	10%
Advanced	0%	0%	4%	15%	30%
Net-Zero GHG	0%	0%	8%	30%	70%

The Advanced Scenario and the Near Zero Scenario both assume electrification, fuel switching, and carbon capture can reduce U.S. refinery energy consumption and CO_2 emissions by an amount similar to levels anticipated to be possible in the EU refining industry. These levels are based on a recent EU refinery industry analysis[462] for decarbonizing the EU refinery industry by 2050 that developed low, median, and maximum CO_2 mitigation scenarios through engagement with EU refiners. In the EU mitigation scenarios, energy savings from electrification and fuel switching range from 18% to 28%, and carbon capture ranges from 21 to 87 million MT CO_2 in 2050.[463]

The Near Zero Scenario assumes a 38% more energy efficient refining industry by 2050 based on state-of-the-art technology opportunities in DOE's refinery energy bandwidth study.[464] A 38% more energy efficient refining industry in 2050 relative to 2015 represents an additional 34% efficiency improvement beyond the 4% improvement found in AEO 2021 projections in 2050.

These scenarios illustrate that the decarbonization pillars combined can dramatically reduce CO_2 emissions, yet even with CCUS, a small emissions footprint will need to be offset. Energy efficiency can play a significant role throughout the 30-year transformation with a proportionally large early impact. Hence, it is important to push early RD&D on ways to realize these reductions. Electrification of process heat, processes, motors, and other applications with the electricity coming from low-carbon sources have contributed to CO_2 reductions across the decades. The generation of hydrogen from these sources (e.g., electrolysis) can substantially contribute to this reduction potential. As already noted, the levels of electrification and LCFFES assumed were moderate based on the literature. The level of CCUS reductions will depend on successful capture of the remaining CO_2 from large emitters, as well as aggregation of some other sources. As with chemical manufacturing, petroleum refining can involve thousands of emissions sources and capture from all of them would unlikely be feasible or economic. Applying low-net GHG emission feedstock alternatives to crude oil, including converting captured CO_2 into liquid fuels, requires sustained RD&D throughout the 30-year time frame to obtain their benefits by 2050.

[461] Based on expert assumptions and Figure 4.10 of International Energy Agency, *Energy Technology Perspectives 2017,* June 2017, https://www.iea.org/reports/energy-technology-perspectives-2017.

[462] Concawe, *CO_2 Reduction Technologies: Opportunities within the EU Refining System (2030/2050): Qualitative and Quantitative Assessment for the Production of Conventional Fossil Fuels (Scope 1 & 2)*, Concawe Report No. 8/19, July 2019, https://www.concawe.eu/wp-content/uploads/Rpt_19-8.pdf

[463] Ibid.

[464] U.S. Department of Energy Advanced Manufacturing Office, *Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Petroleum Refining*, DOE/EE-1230, June 2015, https://www.osti.gov/biblio/1248754-bandwidth-study-energy-use-potential-energy-savings-opportunities-petroleum-refining.

Appendix 1.5. Cement Industry Analysis: Methodology and Assumptions

After analyzing the current status of the U.S. cement industry and its energy and carbon intensity, DOE developed a decarbonization roadmap for the U.S. cement industry. In this subsection, DOE presents some of the key assumptions and indicators used in the roadmap development. DOE developed four main scenarios:

1. **Business as Usual (BAU) scenario**: The BAU scenario assumes slow improvement in energy efficiency and slow adoption of commercially available CCUS technologies, and reflects current business practices and current policies and regulations.

2. **Moderate Technology and Policy (Moderate) scenario**: This scenario assumes higher energy efficiency improvement, more fuel switching to lower-carbon fuels, and a higher rate of clinker substitution compared to BAU. It also assumes low adoption of CCUS technologies.

3. **Advanced Technology and Policy (Advanced) scenario**: This scenario assumes significantly higher energy efficiency improvement using commercially available technologies, more aggressive fuel switching to lower-carbon fuels, and a higher rate of clinker substitution. It also assumes, in 2050, 50% of CO_2 emitted from U.S. cement plants will be captured by CCS technologies.

4. **Near Zero GHG (Near Zero) scenario**: This scenario assumes the most aggressive energy efficiency improvement using commercially available technologies, more aggressive fuel switching to lower-carbon fuels, and higher rate of clinker substitution compared to the Advanced scenario. It also assumes, in 2050, 95% of CO_2 emitted from U.S. cement plants will be captured by CCS technologies.

The first step in developing the pathways was to project cement and clinker production and demand in the U.S. during the period 2015 to 2050 (Figure A 10). The cement demand projection to 2050 is based on expert assumptions and a 2016 report.[465] DOE assumed 15%-18% share of cement import from total U.S. cement demand and based on that calculated U.S. cement production for 2015-2050. The difference in clinker production between the scenarios is because of different clinker-to-cement ratio assumptions in these scenarios with a lower ratio in the Near Zero GHG scenario.[466]

[465] Portland Cement Association, *Long-Term Cement Outlook*, November 2016, http://www2.cement.org/econ/pdf/long_term_report_2016f.pdf.
[466] Note that materials efficiency (e.g., optimized concrete elements, reduced mass elements, element reuse, etc.) is out of scope of this work, since materials efficiency could change the demand outlook. In this work, the cement demand outlook is fixed between all scenarios.

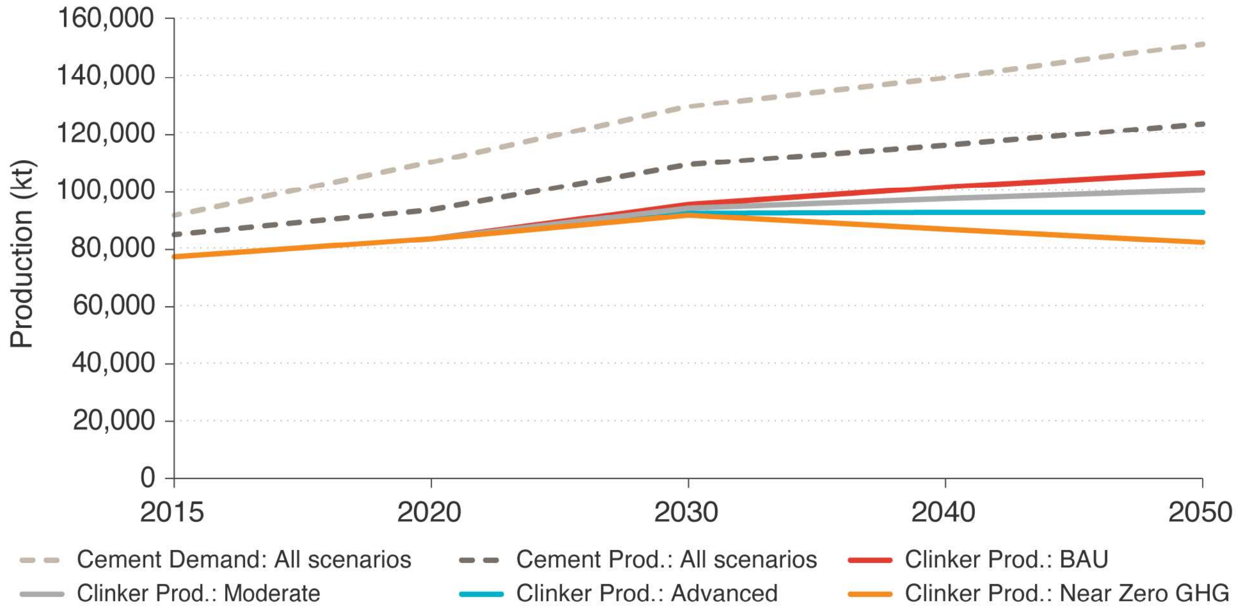

FIGURE A 10. ANNUAL CEMENT AND CLINKER PRODUCTION FORECAST FOR THE U.S., 2015-2050.

SOURCE: VALUES FOR 2015-2019 ARE FROM THE U.S. GEOLOGICAL SURVEY MINERAL COMMODITY SUMMARIES FOR CEMENT.[467] PROJECTIONS FOR PRODUCTION THROUGH 2050 BASED ON EXPERT ASSUMPTIONS AND PORTLAND CEMENT ASSOCIATION 2016.[468]

Table A 9 shows some of the key parameters and indicators for U.S. cement industry and their projections up to 2050 under all scenarios.

In addition, DOE assumed various adoption rates of CCS technologies in the U.S. cement industry across scenarios (Table A 10). It should be noted that post-combustion carbon capture technologies can reach up to 95% capture efficiency, but because of the structure of cement kiln systems and the leakage that happens during carbon capture, it is hard to reach that high capture efficiency in cement plants.

[467] See 2015-2020 versions at "Cement Statistics and Information," U.S. Geological Survey, accessed May 2022, https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information.
[468] Portland Cement Association, *Long-Term Cement Outlook*, November 2016, http://www2.cement.org/econ/pdf/long_term_report_2016f.pdf.

Table A 9. Key parameters used for the U.S. cement industry under each scenario, 2015-2050

Parameter	Unit	Base year	BAU Scenario			Moderate Scenario			Advanced Scenario			Near Zero Scenario		
		2015	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Cement production[469]	kt	84,400	109,200	116,200	123,630	109,200	116,200	123,630	109,200	116,200	123,630	109,200	116,200	123,630
Clinker production[470]	kt	76,920	96,100	101,100	106,330	95,010	97,610	100,150	92,820	92,960	92,730	91,730	85,990	81,600
Clinker-to-cement ratio	-	0.91	0.88	0.87	0.86	0.87	0.84	0.81	0.85	0.80	0.75	0.84	0.74	0.66
Fuel intensity[471]	GJ/t clinker	3.83	3.6	3.5	3.5	3.6	3.4	3.3	3.5	3.2	3.0	3.5	3.2	2.9
Electricity intensity[472]	kWh/t cement	135	122	115	115	110	100	91	106	88	79	106	88	75
Process-related CO_2 emissions intensity*	kg CO_2/t cement	474	458	452	447	452	435	418	442	413	385	435	380	335
Fuel-related CO_2 emissions intensity*[473]	kg CO_2/t cement	281	252	236	227	234	202	170	204	156	119	199	141	93
Electricity-related CO_2 emissions intensity*[474]	kg CO_2/t cement	67	36	24	17	30	18	11	22	9	4	13	3	1

*These intensities are before application of CCUS.

[469] 2015 production values from Hendrik G. van Oss, *Cement,* U.S. Geological Survey, January 2017, https://d9-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/atoms/files/myb1-2017-cemen.pdf. Projections for production through 2050 based on expert assumptions and Portland Cement Association, *Long-Term Cement Outlook*, November 2016, http://www2.cement.org/econ/pdf/long_term_report_2016f.pdf.
[470] Ibid.
[471] Intensities for the base year (2015) are calculated from data in Hendrik G. van Oss, *2016 Minerals Yearbook: Cement [Advance Release]*, U.S. Geological Survey, January 2020, https://d9-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/atoms/files/myb1-2016-cement.pdf. Projected energy intensities through 2050 based on expert assumptions.
[472] Ibid.
[473] Base year (2015) intensity values from "Documentation of California's 2000-2019 GHG Inventory," California Air Resources Board (CARB), last modified October 8, 2021, https://ww2.arb.ca.gov/applications/california-ghg-inventory-documentation and Institute for Global Environmental Strategies (IGES), *2006 IPCC Guidelines for National Greenhouse Gas Inventories*, 2006, https://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html; projected intensities based on assumed scenario fuel mixes.
[474] Base year (2015) intensity from "State Electricity Profiles: United States Electricity Profile 2015," U.S. Energy Information Administration, last modified January 17, 2017, https://www.eia.gov/electricity/state/archive/2015/unitedstates/; projected intensity for all scenarios up to 2050 based on historical trends of the U.S. grid's CO_2 emissions factor in the past 20 years, future projections for the share of renewables in the U.S. grid, and scenario definitions.

TABLE A 10. CCS ADOPTION RATE IN THE U.S. CEMENT INDUSTRY (AS % OF TOTAL CO_2 EMISSIONS AFTER ADOPTION OF OTHER DECARBONIZATION PILLARS)[475]

Scenario	2015	2020	2030	2040	2050
BAU	0%	0%	0%	3%	5%
Moderate	0%	0%	2%	8%	15%
Advanced	0%	0%	5%	25%	50%
Near Zero GHG	0%	0%	10%	50%	95%

Finally, DOE projected the fuel mix used in the U.S. cement industry (Figure A 11) by shifting to lower-carbon fuels. For example, in the Near Zero GHG scenario, DOE assumed the coal consumption in the U.S. cement industry will be reduced from 52% of fuel share to 2%, and petroleum coke use will be reduced to zero between 2015 and 2050, and natural gas, which has a much lower CO_2 emissions factor, will substitute these two fuels. DOE also assumed increased use of solid waste (mainly biomass) in 2050, which combined with CCS will provide a carbon sink in this industry. DOE also assumed a small amount of hydrogen will be used in the fuel mix.

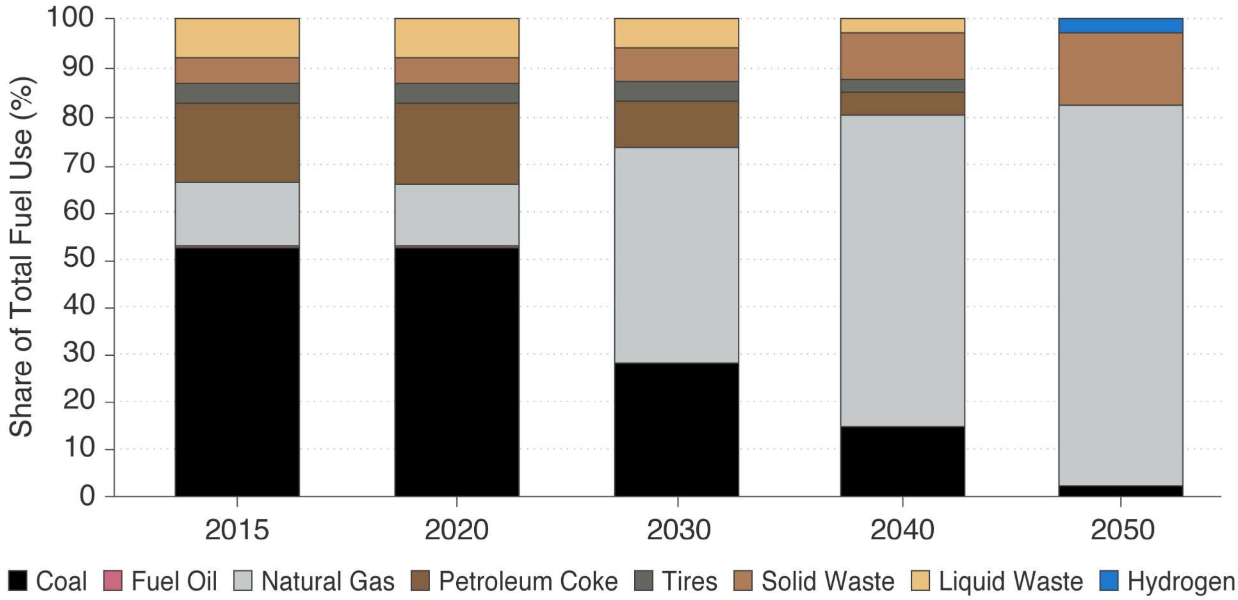

FIGURE A 11. FUEL MIX PROJECTIONS FOR THE U.S. CEMENT INDUSTRY UNDER NEAR ZERO GHG SCENARIO, 2015-2050

SOURCE: FUEL MIX FOR 2015 FROM USGS 2020.[476] PROJECTIONS BASED ON EXPERT ASSUMPTIONS.

[475] Based on expert assumptions and Figure 4.23 of International Energy Agency, *Energy Technology Perspectives 2017,* June 2017, https://www.iea.org/reports/energy-technology-perspectives-2017.

[476] Hendrik G. van Oss, *2016 Minerals Yearbook: Cement [Advance Release]*, U.S. Geological Survey, January 2020, https://d9-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/atoms/files/myb1-2016-cement.pdf.

Figure A 12 shows DOE's assumptions and projections of CO_2 emissions factor (kg CO_2/MWh) for the U.S. electricity grid used in this analysis. For the base year of 2015, the U.S. electricity generation and associated CO_2 emissions were obtained from EIA's United States Electricity Profile 2015.[477] The projections up to 2050 under each scenario were made based on historical trends of the U.S. grid's CO_2 emissions factor in the past 20 years, future projections for the share of renewable in the U.S. grid, as well as DOE's assumptions based on the definition of each scenario. The same projections were used for the analysis of all five industrial subsectors.

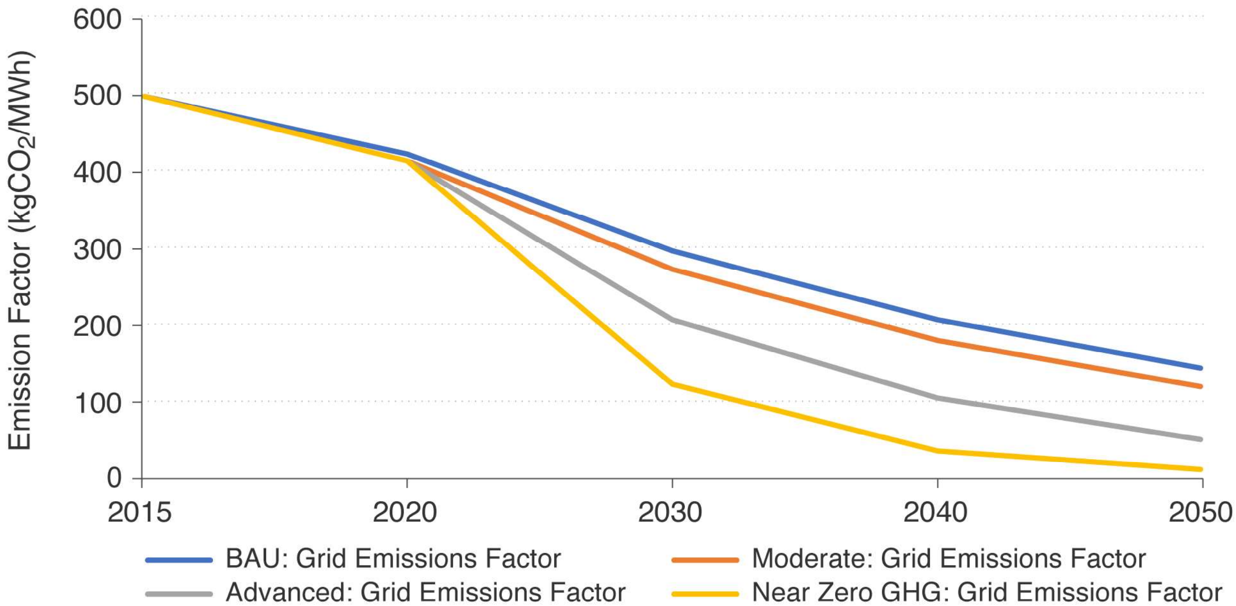

FIGURE A 12. PROJECTIONS OF CO_2 EMISSIONS FACTOR FOR U.S. ELECTRICITY GRID USED IN THIS ANALYSIS.

SOURCE: THIS WORK.

[477] "State Electricity Profiles: United States Electricity Profile 2015," U.S. Energy Information Administration, last modified January 17, 2017, https://www.eia.gov/electricity/state/archive/2015/unitedstates/.

8 Glossary

Some terms mentioned in the industrial subsectors may not be familiar to readers. In addition to the Acronyms and Key Terms noted at the beginning of the document this glossary is meant to provide additional information on terms in the subsectors. These terms are noted in the technology readiness (e.g., Figure 16) and landscape plots (e.g., Figure 18) and others come from the body of the report.

- **Carbon capture**: A process that captures carbon dioxide emissions from sources like coal-fired power plants.
- **Carbon content**: The physical quantity of carbon in a product.
- **Carbon footprint**: See **embodied carbon**
- **Carbon intensity**: The amount of carbon, carbon dioxide or carbon dioxide equivalents by weight emitted per unit of energy or mass consumed.
- **Carbon intensive**: Very high carbon intensity.
- **Carbon neutral**: Achieving net-zero carbon dioxide emissions. This can be done by balancing emissions of carbon dioxide with its removal (often through carbon offsetting) or by eliminating emissions from society (the transition to the "post-carbon economy").
- **Carbon sink**: Any reservoir, natural or otherwise, that accumulates and stores some carbon-containing chemical compound for an indefinite period and thereby lowers the concentration of CO_2 from the atmosphere. Globally, the two most important carbon sinks are vegetation and the ocean.
- **Carbon storage** (or sequestration): A process that takes captured CO_2 and stores it so it will not re-enter the atmosphere. CO_2 storage in geologic formations includes oil and gas reservoirs, unmineable coal seams and deep saline reservoirs.
- **Carbon utilization**: A process that can take the carbon that has been captured and utilizes it as a feedstock material.
- **Clean energy:** Energy produced from low- or no-carbon sources.
- **Embodied carbon**: Embodied carbon is the **carbon footprint** of a material. It considers how many greenhouse gases (GHGs) are released throughout the supply chain and is often measured from cradle-to-(factory) gate, or cradle-to-site (of use). Embodied carbon may also be measured with the boundaries of cradle-to-grave, which is the most complete boundary condition. This boundary includes the extraction of materials from the ground, transport, refining, processing, assembly, in-use (of the product), and finally its end of life profile.
- **Low-carbon:** A technology, fuel, or process, with low net GHG emissions to the atmosphere, as opposed to the carbon content of the fuel or energy source being utilized.
- **Low-net-carbon**: A product or process that emits slightly more carbon than it removes, not quite achieving carbon neutrality.
- **Lower-carbon**: Lower carbon intensity than for conventional products or processes
- **Near zero carbon**: Very low, almost zero carbon intensity

- **Negative emissions technologies:** Technologies and activities such as (1) afforestation and reforestation, (2) land management to increase and fix carbon in soils, (3) bioenergy production with carbon capture and storage (BECCS), (4) enhanced weathering, (5) direct capture of CO_2 from ambient air with carbon storage (DACCS), or (6) ocean fertilization to increase CO_2 removal.
- **Net-zero carbon**: See **carbon neutral.**
- **No-carbon**: Zero carbon intensity
- **Soft costs**: Any costs that are not considered direct construction costs or "hard costs." These costs typically are associated with non-tangible items, such as design, fees, taxes, and insurance. Soft costs can be a significant part of a project's budget.
- **Technology maturity:** Instead of identifying specific technology readiness levels by number, this report more generally categorize technology readiness as low, medium, or high technology maturity.

Iron and Steel Manufacturing

- **Clean hydrogen**: Hydrogen produced from low- or no-carbon sources of energy and feedstocks.
- **CO_2 trunk lines**: Major CO_2 pipeline network that conveys CO_2 between sources and storage areas.
- **Electrowinning**: The low-temperature electrolysis of iron ore.
- **Flash ironmaking**: A new process that uses natural gas and or hydrogen to both heat the iron ore concentrates in the furnace and to remove oxygen, converting the ore to iron metal.
- **HIsarna**: A direct reduced iron process for iron making in which iron ore is processed almost directly into liquid iron (pig iron).
- **Top gas recirculation**: Top-gas Recycling in Blast Furnaces with CCS.

Chemical Manufacturing

- **Acoustic methods**: Thermoacoustics, plasma.
- **Clusters**: Industrial clusters, or geographic areas where there is a high concentration of industry.
- **Electrical transfer**: Electrolyzers and electrochemistry.
- **Electrochem**: Electrochemistry.
- **Electrolysis-hydrogen:** Hydrogen produced through electrolysis.
- **Embodied carbon methodology**: Processes, methods, protocols to evaluate the carbon footprint of products. See **embodied carbon** definition.
- **New chem. w/ clean H_2**: New chemical processes and products made using nuclear, renewable, or low-carbon hydrogen.
- **Process heat portfolio**: A assembly of projects, technology development, demonstrations that drives the process in the use of low-carbon methods for supplying and utilizing process heat.

- **Systems optimization**: The activity of enhancing system capabilities and integration of subsystem elements to the extent that all components operate at or above user expectations.

Food and Beverage Manufacturing

- **Beer production**: Includes industry engaged in brewing beer, ale, malt liquors, and nonalcoholic beer. NAICS Code 312120.
- **Beet sugar manufacturing**: Obtained from refining sugar beets. Products include syrup made from sugar beets, molasses made from sugar beets, others. NAICS code 311313.
- **Cane sugar manufacturing**: Includes processing sugarcane and refining cane sugar from raw cane sugar. NAICS code 311314.
- **Fluid milk manufacturing**: Includes industries engaged in manufacturing processed milk products (incl. Pasteurized milk and cream, sour cream) and manufacturing fluid milk dairy substitutes. NAICS code 311511.
- **Hybrid boilers**: The combination of boilers with renewable systems to maximize efficiency.
- **Modularization**: Separating and recombining components of technologies or processes to advance efficiency.
- **Red meat product processing**: Includes industry engaged in processing or preserving meat and meat by-products (except poultry and small game). NAICS code 311612
- **Shelf life**: The length of time for which a food item remains usable.
- **Soybean oil manufacturing**: A vegetable oil that is extracted from the seeds of the soybean plant. Examples of products include protein isolates and concentrates. NAICS code 311224.
- **Waste heat recovery (WHR)**: Capturing and transferring waste heat from an industrial process back to another process as an extra energy source.
- **Wet corn milling**: A process of breaking down corn kernels into their parts, which include corn oil, corn starch, and others (except to make ethyl alcohol). Examples of products include corn sweeteners and starches. NAICS Code 311221.

Petroleum Refining

- **Fuel substitution**: Fuel substitution involves converting all or a portion of existing energy use from one fuel type to another to reduce GHG emissions.
- **Revamp**: To change the technology or processes used in a refinery.
- **Still gas**: Any form or mixture of gases produced in refineries by distillation, cracking, reforming, and other processes. The principal constituents are methane and ethane. May contain hydrogen and small/trace amounts of other gases. Still gas is typically consumed as refinery fuel or used as petrochemical feedstock. Still gas burned for refinery fuel may differ in composition from marketed still gas sold to other users.

Cement Manufacturing

- **Calcium looping**: It is a carbon capture scheme using solid CaO-based sorbents to remove CO_2 from flue gases, e.g., from a cement plant of a power plant, producing a concentrated stream of CO_2 (~95%) suitable for storage. The scheme exploits the reversible gas–solid reaction between CO_2 and CaO(s) to form $CaCO_3$(s).
- **Direct separation**: The process of providing indirect heat in the precalciner which allows production of a concentrated stream of CO_2 suitable for CCS.
- **Natural SCMs**: Supplementary cementitious material (SCM) that can be found in nature such as natural pozzolans and clay.