

# Industrial Decarbonization Roadmap - Overview

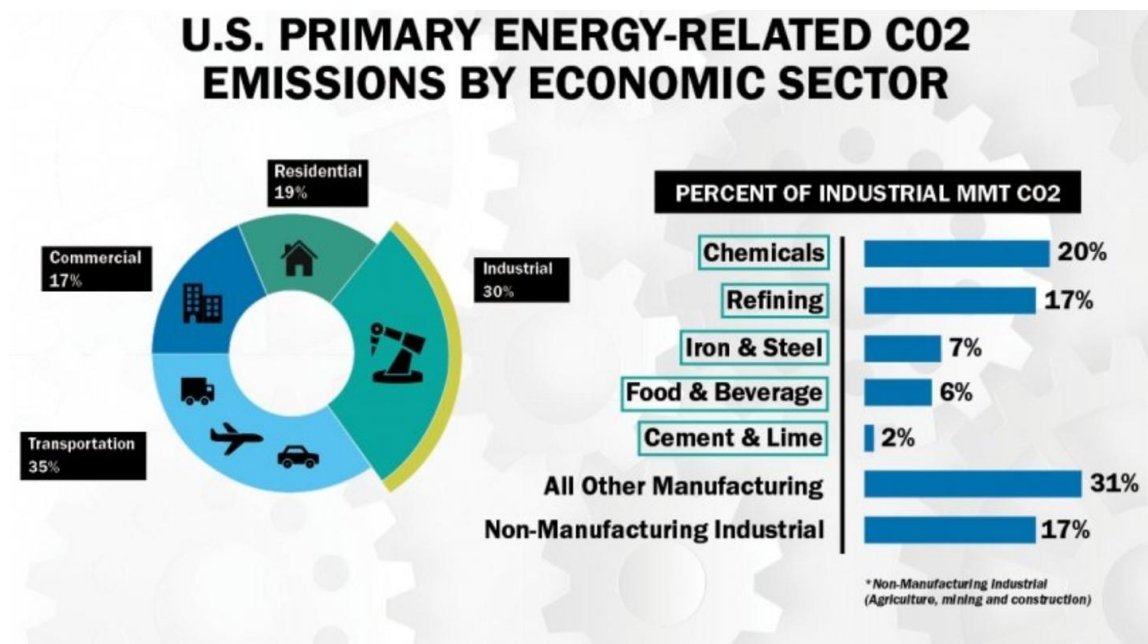
*By John Benson*

*October 2022*

## 1. Introduction

Occasionally I come across a document that is overwhelming in scope and information-content. This requires me to adjust how I post papers based on this document if it falls within the scope of subjects that I normally write about and contains information my readers would want to read. The title roadmap referenced at the end of this paragraph is one of those documents. It also covers subjects that I spent far more time researching and writing about several years ago, than I do currently.<sup>1</sup>

The DOE Site that led me to the title document had an excellent graphic that defined the scope of this document, and this is below. This page also provided a reasonable short summary of primary document.<sup>2</sup>



Data Source: "Annual Energy Outlook 2021 with Projections to 2050", U.S. Energy Information Administration, Feb. 3, 2021.  
Note: The roadmap analysis covered only part of the chemicals (ammonia, methanol, ethylene, and BTX) and food and beverage (wet corn milling, soybean oil, cane sugar, beet sugar, fluid milk, red meat product processing and beer production) subsectors.

From the above graphic you can see that the Industrial Economic Sector is one of the largest CO<sub>2</sub> emitters, and it also, by far, the most complex. The only sector larger than industry is transportation, and since I frequently write about the latter sector, I can safely

<sup>1</sup> Full List of authors, reviewers and supporting groups is contained on this document's front-matter pages xi -- xiv, U.S. Department of Energy, "Industrial Decarbonization Roadmap," September 2022, <https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf>

<sup>2</sup> U.S. Department of Energy (DOE), Office of Energy Efficiency & Renewable Energy (EERE), "DOE Industrial Decarbonization Roadmap," <https://www.energy.gov/eere/doe-industrial-decarbonization-roadmap?et rid=17039174&et cid=4397948>

say that it really only has ten to twenty major processes that covers manufacturing and support of three basic vehicle types (land, air and sea).

The definition of “industry” (noun root of industrial) is: *economic activity concerned with the processing of raw materials and manufacture of goods in factories* (Oxford-Languages). The manufacturing all non-transportation goods in our economy has hundreds to thousands of major processes. It’s easy to say one of the most powerful tools in decarbonizing most of the processes emitting greenhouse gases (GHG) is electric power. However, the devil is in the details, and there are a huge number of details here, plus other resources, and other tools that will be required to fully decarbonize and/or offset current GHG emissions from the industrial sector.

As I was skimming through the primary document, I decided pretty quickly that this would require multiple papers to cover, and thus a series. How are we going to do this? I will start with this paper, and post papers in this series as I complete them. These will be interleaved with other posts covering different subjects, but all parts of this series will start with “Industrial Decarbonization Roadmap.”

I believe that anyone that is interested in curing climate change should be interested in this series, as this will be an important part of this cure, and also one of the most difficult parts. After all, for any really complex task, the first 90 percent of the work accounts for the first 90 percent of the development time, and the remaining 10 percent of the task accounts for the other 90 percent of the development time.<sup>3</sup>

## 2. Executive Summary

The text below is from the Reference 1 Executive Summary, but has been reduced and edited by your author.

*The science is clear that significant greenhouse gas (GHG) emissions reductions are needed to moderate the severe impacts of ongoing climate change. 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. The U.S. Long-Term Strategy<sup>4</sup> 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 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.*

*The U.S. industrial sector is considered a “difficult-to-decarbonize” sector of the energy economy, in part because of the diversity of energy inputs that feed into a varied array of*

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<sup>3</sup> Tom Cargill, Bell Labs.

<sup>4</sup> 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>

*industrial processes and operations. Industrial sector emissions are attributed to a combination of sources, including:*

- *Fuel-Related Emissions: emissions associated with the combustion and use of fuels (from fossil or non-fossil sources) at industrial facilities for needs other than electricity (e.g., for process heat)*
- *Electricity Generation Emissions: emissions attributed to the generation of electricity used at industrial facilities, whether that electricity is generated onsite or offsite*
- *Industrial Process Emissions: non-energy-related process emissions from industrial activities (e.g., direct CO<sub>2</sub> 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; 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 (of reference 1).*

**Author's comment:** I will probably cover the subjects cited in the above paragraph in a final post. Section 4 is “Further Strategic Analysis Needs,” and a final paper (postscript) might be a good place to cover this.

*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<sub>2</sub> emissions in the U.S. industrial sector. Both*

geographically concentrated subsectors (chemicals, refining, iron and steel, and cement) and dispersed subsectors (food and beverage) are represented.

## 2.1. Four Pillars

Scenario modeling undertaken in this roadmap shows that application of these pillars can enable the industrial sector to reach near-zero CO<sub>2</sub> 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-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...

**Industrial electrification:** Over 50% of all manufacturing energy is used for thermal processing, and less than 5% of these operations are electrified.<sup>5</sup> 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 electro-technologies or hybrid systems, b) innovating new electric or hybrid systems, and c) overcoming economic and technical barriers to implementing electro-technologies in existing fossil-based processing systems...

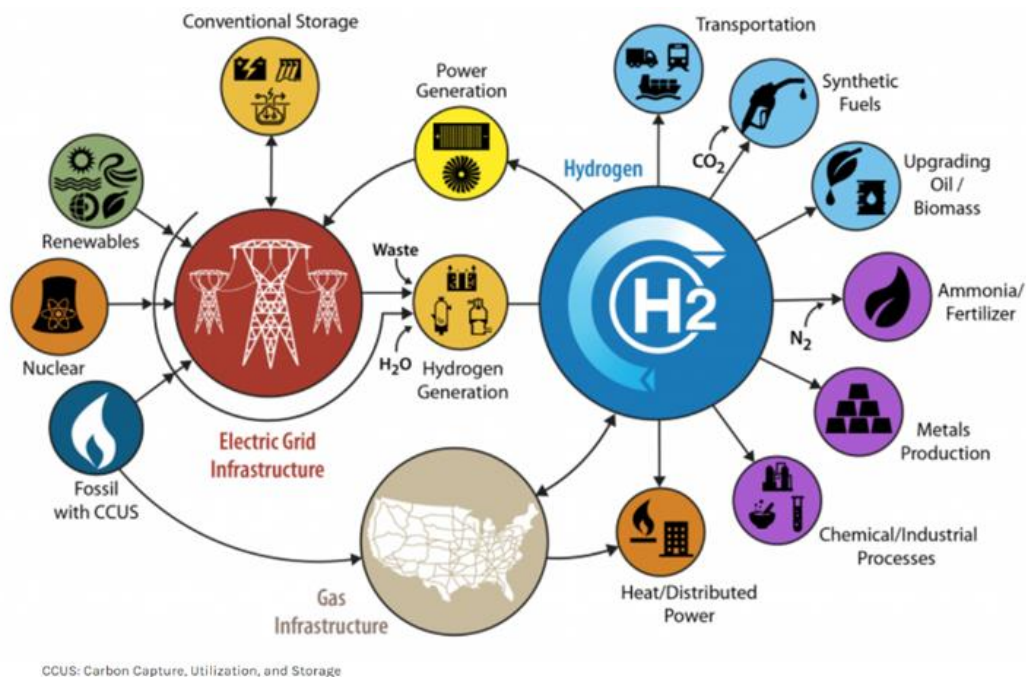
**Low-carbon fuels, feedstocks, and energy sources (LCFFES):** Adoption of clean energy technologies that do not release GHGs to the atmosphere from the production or use of energy sources will be critical for decarbonization; these approaches would include renewably sourced electricity, nuclear energy, concentrating solar power and geothermal energy for electricity and process heat. 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 research, development, and demonstration (RD&D).

**Authors comment:** The primary document uses many graphic images. I will only use those that effectively convey a concept, like the one referenced below and seen on the next page.

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<sup>5</sup> “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](https://www.energy.gov/sites/default/files/2022-01/2018_mecs_all_manufacturing_energy_carbon_footprint.pdf)





LCFFES technology includes fuel-flexible processes, clean hydrogen fuels and feedstocks, biofuels and bio-feedstocks, 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 above figure illustrates hydrogen applications and opportunities from the DOE H2@Scale initiative.<sup>6</sup> An example application involves decarbonizing primary steelmaking by using clean hydrogen to reduce iron ore, replacing carbon-based reductants that create CO<sub>2</sub> 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<sub>2</sub> reduction can enable captured CO<sub>2</sub> utilization as a feedstock, along with clean hydrogen, to produce synthetic hydrocarbon fuels with energy densities comparable to diesel, gasoline, and jet fuel.

**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<sub>2</sub> emissions are non-energy-related; they result from the chemical reduction of limestone to lime...<sup>7</sup>

<sup>6</sup> H2@Scale,” U.S. Department of Energy, accessed May 2022, <https://www.energy.gov/eere/fuelcells/h2scale>

<sup>7</sup> 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>

## 2.2. Alternate Approaches, Negative Emissions Technologies

Additional options are needed to address hard-to-abate emissions and reduce atmospheric presence of CO<sub>2</sub> (and in some cases, non-CO<sub>2</sub> GHGs) to achieve an industrial sector with net-zero emissions. Alternate approaches may include land use ecosystems management activities such as afforestation/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<sub>2</sub> from major emissions sources or from air (direct air capture, DAC). 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<sub>2</sub>. Technological breakthroughs in the other pillars could reduce the need for these approaches.

## 2.3. Emissions Categories

The coverage of emissions categories included in scenario modeling for each of the five subsectors is summarized in Table ES 1 (below, footnote next page). Fuel-related CO<sub>2</sub> emissions and electricity generation CO<sub>2</sub> emissions were included for all focus subsectors, while process-related CO<sub>2</sub> emissions were included for the steel and cement subsectors only. Contributions of non-CO<sub>2</sub> GHG emissions, such as methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O), 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). 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 research and analysis, scenario modeling will need to include additional subsectors and products, non-CO<sub>2</sub> GHGs, and further exploration of industrial process emissions.

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

Industry Subsector	Electricity Generation CO <sub>2</sub> Emissions	Fuel-Related CO <sub>2</sub> Emissions	Process-Related CO <sub>2</sub> Emissions	CH <sub>4</sub> , N <sub>2</sub> O, and Other Non-CO <sub>2</sub> 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<sub>2</sub> 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.<sup>8</sup>

## 2.4. Schedule

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<sub>2</sub> per year, by 2050 for the five subsectors studied.<sup>17</sup> With application of alternate approaches such as negative emissions technologies, a total of 457 million metric tons of annual CO<sub>2</sub> emissions can be avoided.

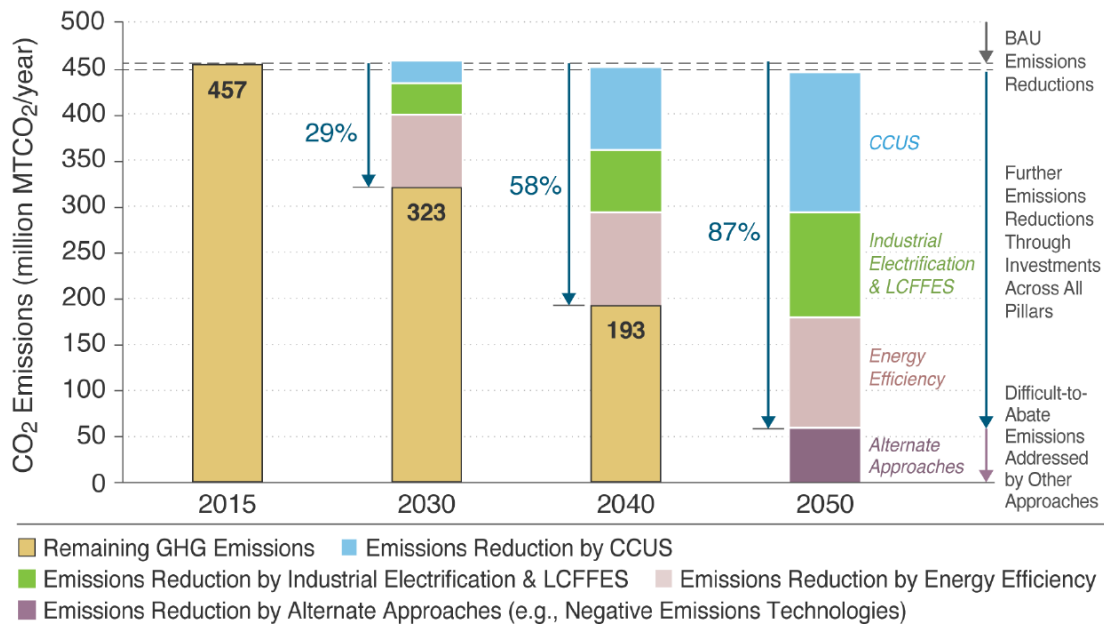


FIGURE ES 1. THE PATH TO NET-ZERO INDUSTRIAL CO<sub>2</sub> EMISSIONS IN THE UNITED STATES FOR FIVE CARBON-INTENSIVE INDUSTRIAL SUBSECTORS, WITH CONTRIBUTIONS FROM EACH DECARBONIZATION PILLAR: ENERGY EFFICIENCY; INDUSTRIAL ELECTRIFICATION; LOW-CARBON FUELS, FEEDSTOCKS, AND ENERGY SOURCES (LCFFES); AND CARBON CAPTURE, UTILIZATION, AND STORAGE (CCUS)). EMISSIONS ARE IN MILLIONS OF METRIC TONS (MT) PER YEAR.

SINCE INDUSTRIAL ELECTRIFICATION AND LCFES 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),

<sup>8</sup> 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>

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.

*Additional decarbonization strategies in these five subsectors, beyond the representative set of products selected for analysis, need to be assessed further. 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<sub>2</sub> per year by 2050—about 50% of the industrial sector’s 1,360 million metric tons of total energy-related CO<sub>2</sub> emissions in 2020.<sup>9</sup> Future work will 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.*

*The roadmap report scenario projections include only CO<sub>2</sub> 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<sub>2</sub> emissions associated with the manufactured products of the industries considered. Modeling did not include upstream and downstream CO<sub>2</sub> emissions, process CO<sub>2</sub> emissions (except for those involved in cement production), CO<sub>2</sub> emissions embodied into input materials (including imported materials), or non-CO<sub>2</sub> 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<sub>2</sub> 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...*

The Executive Summary has additional content, including:

- Sector Transformations Needed
- Key Recommendations
- Pathways to Net-Zero Emissions
- Reaching Net-Zero Carbon Emissions for the Entire Industrial Sector
- Reaching Economy-Wide Net-Zero Carbon Emissions

Some of these subjects will be covered in later papers in this series, and others are just too soon. Although I’m sure the team that created the primary source for this series

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<sup>9</sup> “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.



(Reference 1) did as good a job as possible of writing this content, the title project is a huge undertaking, even over the three decades allotted. Our country needs to continue working on quantifying the effort required for this undertaking while getting to work on the earliest stages this project (which we are doing). There will be many new challenges thrown at us by climate change, along with many new discoveries and inventions that will help our journey. Trying to predict how later stages will look at this point is akin to stacking imaginary bricks on top of other imaginary bricks.