Request for Information: Transforming Industry: Strategies for Decarbonization

DATE:	May 14, 2024
SUBJECT:	Request for Information (RFI)

Description

This is a Request for Information (RFI) issued by the U.S. Department of Energy's (DOE) Industrial Efficiency and Decarbonization Office (IEDO). The intent of this RFI is to obtain information to inform a new DOE vision study, *Pathways for U.S. Industrial Transformations: Unlocking American Innovation,* which is identifying cost-effective and industry-specific strategic pathways to achieve a thriving U.S. industrial sector with net-zero greenhouse gas (GHG) emissions by 2050.

This RFI seeks input on four categories: Category 1: Industrial Decarbonization Challenges, Barriers, and Cross-Cutting Strategies; Category 2: Framework for Industrial Decarbonization Pathways; Category 3: Impacts and Evaluation Criteria for Industrial Decarbonization Pathways; and Category 4: Net-zero Decarbonization Pathways for Specific Industrial Subsectors.

This RFI is focused on input on industrial technological, financial, social, environmental, and health aspects as they pertain to the challenges, barriers, opportunities, and pathways to achieve net-zero emissions from the industrial sector by 2050. IEDO seeks input from a diverse group of stakeholders (both within and outside of industry) who will be integral to the transformation of U.S. industry, including associated communities, utilities, low-carbon fuels suppliers, technology developers, engineering consultants, firms designing new facilities, local and regional governments, and more.

Context for this request is provided in the Background section directly below; the categories and questions start on page 10.

Background

This Request for Information (RFI) is issued by the U.S. Department of Energy's (DOE) Industrial Efficiency and Decarbonization Office (IEDO). IEDO provides funding, management, and the strategic direction necessary for a balanced national program of research, development, and demonstration (RD&D), as well as technical assistance and workforce development, to drive energy, materials, and production efficiency improvements and to accelerate industrial

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decarbonization.[1] IEDO and its programs are critical to putting the nation on a pathway to net-zero GHG emissions by 2050.

The Challenge

As highlighted by the United Nations Environment Programme (UNEP), we are no longer facing a question on whether a global sustainable resource consumption and production transformation[2] is necessary, but rather how do we make it happen now. Decarbonization is imperative for that transformation, and the 2021 *U.S. Long-Term Strategy* provides a national-level approach to net-zero GHG emissions economy wide by no later than 2050.[3] The U.S. industrial sector can play a lead role in this global transformation while thriving, innovating, and competing globally. Technological transitions must address GHG emissions and enable progress towards economic, national security, environmental, public health, and societal goals. As demand for clean materials and products increases, the United States has an opportunity to lead in the clean energy economy.

Due to the diversity and complexity of energy inputs, processes, and operations, the industrial sector is considered one of the most difficult to decarbonize. Approximately 38% of total U.S. economy emissions are attributable to the U.S. industrial sector (both energy-related and non-energy-related Scope 1 and Scope 2) as shown in Figure 1. Moreover, under business-as-usual operations, industrial sector energy consumption is projected to grow 30% by 2050, resulting in a 17% increase in energy-related carbon dioxide emissions.[4] Achieving net-zero GHG emissions across the U.S. economy by 2050 will require an accelerated, multidimensional approach to eliminate net industrial emissions. DOE estimates that more than 60% of heavy industry emissions reductions needed to achieve net-zero by 2050 will come from technologies that are still in the innovation pipeline and are not currently market ready.[5] We recognize this will be a challenge –which is why IEDO is leading a new DOE-wide vision study, *Pathways for U.S. Industrial Transformations: Unlocking American Innovation*, informed by stakeholder input from within and adjacent to the industrial sector.

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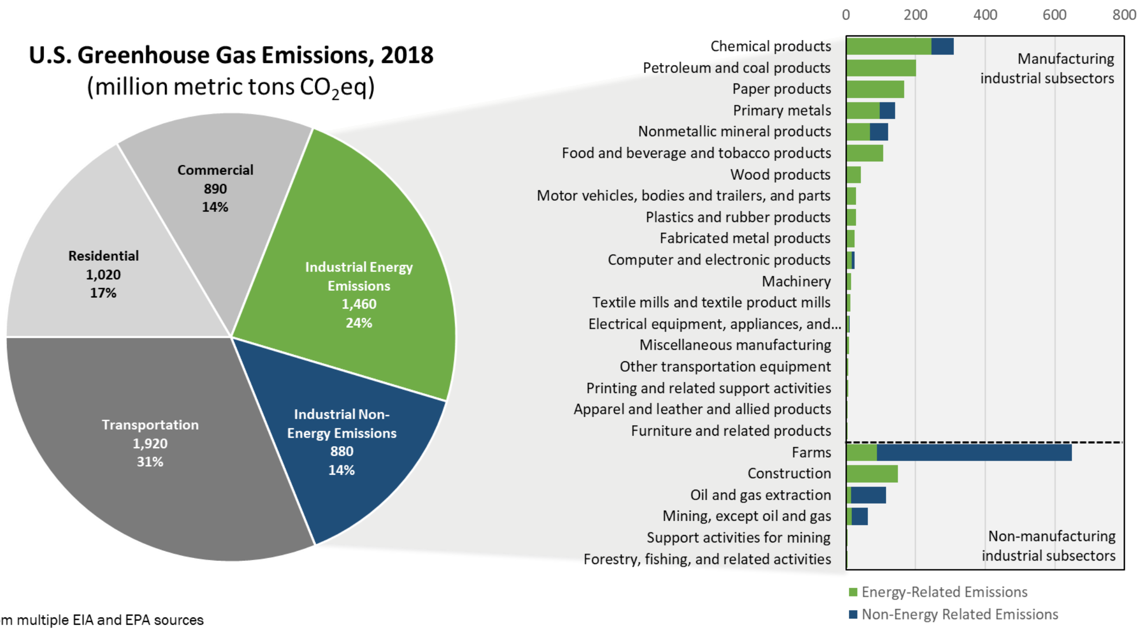
[1] The industrial sector is defined as the manufacturing subsector, the nonmanufacturing subsectors (agriculture and forestry; mining, oil, and gas; and construction), data centers, and water and wastewater treatment.

[2] In the Global Resources Outlook 2024, UNEP defines transformation as an "overall change or outcome of large-scale shifts in technological, economic and social systems." The transformation from a resource-intensive production paradigm to a sustainable one will require a decoupling of wellbeing and economic activity from resource use and environmental impacts

[3] United States Department of State and the United States Executive Office of the President. 2021. *The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050*.

[4] Annual Energy Outlook 2021 | U.S. Energy Information Administration

[5] The Pathway to: Industrial Decarbonization Commercial Liftoff Report | Department of Energy



Data compiled from multiple EIA and EPA sources

Figure 1. U.S. GHG emissions in 2018 by economic sector (left pie chart) and a breakout by industrial subsector (right bar chart). The carbon dioxide (CO_2)-equivalent emissions in million metric tons (MMT CO_2e) are shown, as well as the percent contribution of that sector to the whole economy. Both Scope 1 (from onsite combustion and process-generated non-energy) and Scope 2 (from consumption of offsite-generated electricity) emissions are included. Data compiled from multiple EIA and EPA sources: EIA Monthly Energy Review,[6] EIA Manufacturing Energy Consumption Survey,[7] EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks,[8] DOE IEDO EEIO-IDA Tool.[9] Note the large amount of non-energy emissions in the Farms subsector is due to multiple factors, including from the application of fertilizers, livestock, manure, and other factors.[10]

Industrial facilities are located across the country, affecting over 2,500 communities. These operations can produce significant amounts of energy- and non-energy-related GHG emissions, as well as air pollutants with harmful impacts on respiratory and cardiovascular health, including nitrogen oxides (NOx), carbon monoxide (CO), and particulate matter (PM). In the United States, disadvantaged communities are disproportionately exposed to these types of emissions, resulting in social, economic, and health burdens beyond those of the general population. Many of our country's industrial facilities are located in communities designated as Disadvantaged Communities, who both bear the brunt of the pollution burden that these

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[6] Monthly Energy Review | U.S. Energy Information Administration, Tables 11.1 through 11.5.

[7] Manufacturing Energy Consumption Survey | U.S. Energy Information Administration

[8] Inventory of U.S. Greenhouse Gas Emissions and Sinks | U.S. Environmental Protection Agency

[9] Environmentally Extended Input-Output for Industrial Decarbonization Analysis (EEIO-IDA) Tool | U.S. Department of Energy

[10] U.S. Environmental Protection Agency - Sources of Greenhouse Gas Emissions

facilities often generate today and stand to benefit most from the economic revitalization and reduced pollution that a just transition to clean manufacturing can provide.[11]

Building Off Previous Work

This vision study builds off significant prior research and stakeholder engagement. The 2022 *Industrial Decarbonization Roadmap*[12] continues to provide the framework for DOE's industrial decarbonization strategy and outlines technology opportunities and potential challenges for five major manufacturing subsectors (cement, chemicals, food and beverage, iron and steel, and petroleum refining). The *Roadmap* characterizes technology opportunities in the context of four industrial decarbonization pillars shown in Figure 2, which highlight the need for both cross-cutting technologies and systems solutions. This follow-on industrial decarbonization study extends and expands upon the *Roadmap* sectoral analysis, and also expands the cross-sectoral and cross-cutting systems-wide assessments.

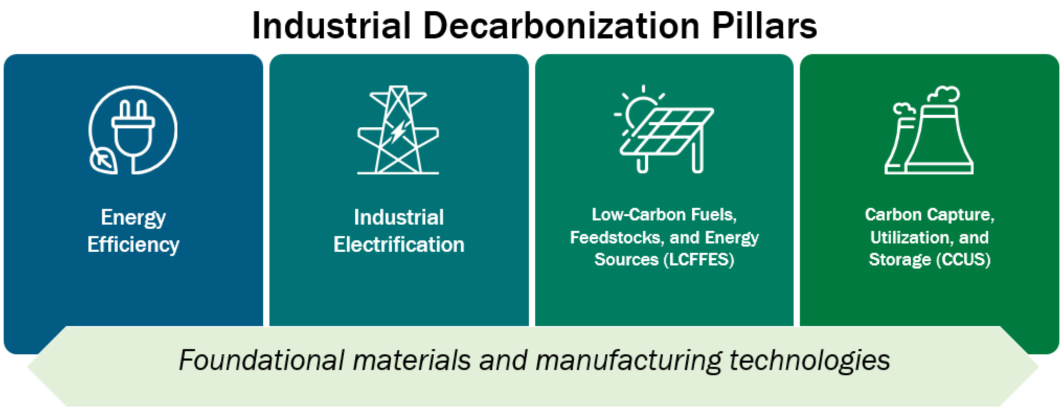

Figure 2. Pillars of industrial decarbonization from the Industrial Decarbonization Roadmap[13]

Continuing its lead role from the *Roadmap,* IEDO is leading subsector deep-dives to assess technology-specific impact and sensitivity modeling and analysis. This vision study looks beyond the original five *Roadmap* manufacturing subsectors by also including both energy-related and non-energy-related (e.g., process) emissions, material efficiency considerations, the pulp and paper subsector, and the decarbonization impacts on the rest of industry (other manufacturing subsectors; the non-manufacturing subsectors of agriculture and forestry, mining, oil, and gas, and construction; data centers; and water and wastewater treatment).

In addition to the *Roadmap*, DOE's *Pathways to Commercial Liftoff* reports[14] provide public and private sector capital allocators with a perspective as to how and when various technologies

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[11] Justice40 Initiative | U.S. Department of Energy

[12] Industrial Decarbonization Roadmap | Department of Energy

[13] Ibid.

[14] Pathways to Commercial Liftoff | Department of Energy

could reach full-scale commercial adoption, including specific reports focused on industrial decarbonization, hydrogen, and carbon management, among others.

Other industrial decarbonization-related strategies and roadmaps from DOE include the *U.S. National Clean Hydrogen Strategy and Roadmap,*[15] *Decarbonizing the U.S. Economy by 2050: A National Blueprint for the Buildings Sector,*[16] and the *U.S. National Blueprint for Transportation Decarbonization*.[17] This new vision study also leverages the insights from recent Funding Opportunities, other Requests for Information (including FECM's RFI on Industrial Deployment and Demonstration Opportunities for Carbon Capture Technologies[18]), industry and stakeholder convenings, and IEDO's robust suite of technical assistance programs, including the Better Climate Challenge, Better Plants, and Onsite Energy Technical Assistance Partnerships.[19] These roadmaps and blueprints collectively inform DOE's cross-office strategy in context with technology maturity and stage of investment.

This prior work indicates that incremental improvements in existing industrial processes will not put U.S. industry on a path to net-zero GHG emissions by 2050. The transformative, systemic challenge of industrial decarbonization will require a holistic broader industrial ecosystem viewpoint. The interconnection of materials, energy, and resources through value chains is complex, and sophisticated analytical frameworks and data-driven approaches to assess the net impacts of technological changes will be necessary.[20] Building these strategies within this complex ecosystem requires identification of the specific, most likely potential pathways towards decarbonization.

Pathways

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[15] U.S. National Clean Hydrogen Strategy and Roadmap | Department of Energy

[16] Decarbonizing the U.S. Economy by 2050: A National Blueprint for the Buildings Sector | Department of Energy

[17] The U.S. National Blueprint for Transportation Decarbonization: A Joint Strategy to Transform Transportation | Department of Energy

[18] Request for Information: Industrial Deployment and Demonstration Opportunities for Carbon Capture Technologies | Department of Energy

[19] DOE IEDO's Technical Assistance and Workforce Development Programs

[20] There are a range of materials flow analysis (MFA), life cycle analysis (LCA) and technoeconomic analysis (TEA) techniques that can be used; DOE has training, tools and methodologies available that can be applied based on need; see, for example: https://www.energy.gov/eere/iedo/life-cycle-assessment-and-techno-economic-analysis-training; https://www.netl.doe.gov/LCA; https://www.energy.gov/eere/greet; https://mfitool.nrel.gov/about

Net-Zero Emissions Pathway

As defined in the *Industrial Decarbonization Roadmap*, a ***pathway*** is a set of specific actions needed to achieve progress in and across the decarbonization pillars, while remaining informed and supplemented by RD&D to advance viable solutions (i.e., technologies, practices, approaches, behaviors) that will need to be adopted at scale in the marketplace.

The use of the term "pathways" is at the heart of this new vision study. There is no single pathway to net-zero emissions that will work for any single industrial subsector. Indeed, competition across different possible pathways will be essential to our success. This vision study seeks to refine and improve our understanding of potential pathways, including considering the following:

- Major production routes for each industrial subsector
- Major decision-points that might shape each pathway, relative timing between now and 2050 for these decision-points, and what information will be needed for those decision-points
- Primary factors that might determine how much of a subsector would choose an individual production route or technology
- Major similarities and differences in technologies and solutions across the major pathways and production routes
- What investments could be made in parallel and are no-regrets strategies, and where are the potential risks for creating stranded assets
- Portion of each pathway that can be achieved through enhancements to existing facilities vs. construction of new facilities
- Major barriers to successful development and accelerated deployment of key technologies and solutions within each pathway
- Major uncertainties across each pathway
- Economic, environmental, and social impacts of each pathway.

An All-Hands-on-Deck Approach

DOE is committed to pushing the frontiers of science and engineering, catalyzing clean energy jobs through research, development, demonstration, and deployment (RDD&D), and ensuring environmental justice and inclusion of underserved communities. To accelerate the development of emerging industrial decarbonization technologies, DOE created the Technologies for Industrial Emissions Reduction Development (TIEReD) Program.[21] This program leverages resources across DOE applied research offices to invest in fundamental science, research, development, initial pilot-scale demonstrations projects, and technical assistance and workforce development. Rooted in the principles identified in the 2022

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[21] Decarbonizing America's Industrial Sector | U.S. Department of Energy

Industrial Decarbonization Roadmap,[22] DOE is building an innovation pipeline to accelerate the development and adoption of industrial decarbonization technologies.

The TIEReD Program leverages resources, expertise, and investments from across DOE's Science and Innovation Portfolio. In 2022, we created the Industrial Efficiency and Decarbonization Office (IEDO) as DOE's first office to be solely focused on industrial efficiency and decarbonization. The structure of IEDO's RDD&D and Technical Assistance portfolio is directly modelled after the framework established with the 2022 *Industrial Decarbonization Roadmap*,[23] with a primary focus on major energy and emissions intensive subsectors and cross-cutting decarbonization technologies. Within IEDO, we have consolidated Science and Innovation investments in industrial energy efficiency and electrification.

IEDO and the Office of Fossil Energy and Carbon Management (FECM) partner on carbon capture and utilization investments. For the supply and utilization of low-carbon fuels, feedstocks, and energy sources, we combine investments from several offices: IEDO, Bioenergy Technologies Office (BETO), Hydrogen and Fuel Cell Technologies Office (HFTO), Solar Energy Technologies Office (SETO), and the Office of Nuclear Energy (NE). In addition, both our Advanced Materials and Manufacturing Technologies Office (AMMTO) and Office of Science (SC) invest in the foundational materials and manufacturing technologies required for the other industrial decarbonization pillars to be successful. ARPA-E supports all pillars by investing in high-potential, high-impact technologies that are too early for private-sector investment. The annual investments across these Science and Innovation offices total roughly $1 billion funded through annual appropriations from Congress.

The TIEReD program complements the demonstration and large-scale deployment efforts led by the DOE Office of Clean Energy Demonstrations (OCED), the Office of Manufacturing and Energy Supply Chains (MESC), and the Loan Programs Office (LPO). OCED led the selection and is leading the oversight of $6 billion for 33 projects across more than 20 states to decarbonize energy-intensive industries.[24] These projects were funded by $489 million from the Bipartisan Infrastructure Law and $5.47 billion from the Inflation Reduction Act. In addition, OCED currently invests $20 million in annual appropriations to support large industrial decarbonization demonstrations. MESC leads the Industrial Assessment Centers ($550 million from the Bipartisan Infrastructure Law and $16 million in ongoing annual appropriations)[25] and the Advanced Energy Manufacturing and Recycling Grant Program for facilities in communities

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[22] Industrial Decarbonization Roadmap | U.S. Department of Energy

[23] Ibid.

[24] Industrial Demonstrations Program Selections | Department of Energy

[25] Industrial Assessment Centers | Department of Energy

where coal mines or coal power plants have closed ($750 million from the Bipartisan Infrastructure Law).[26]

The relationship and connections between these Offices to holistically address the full risk profiles of advancing technologies, from initial discovery to widespread deployment, are shown in Figure 3 below.

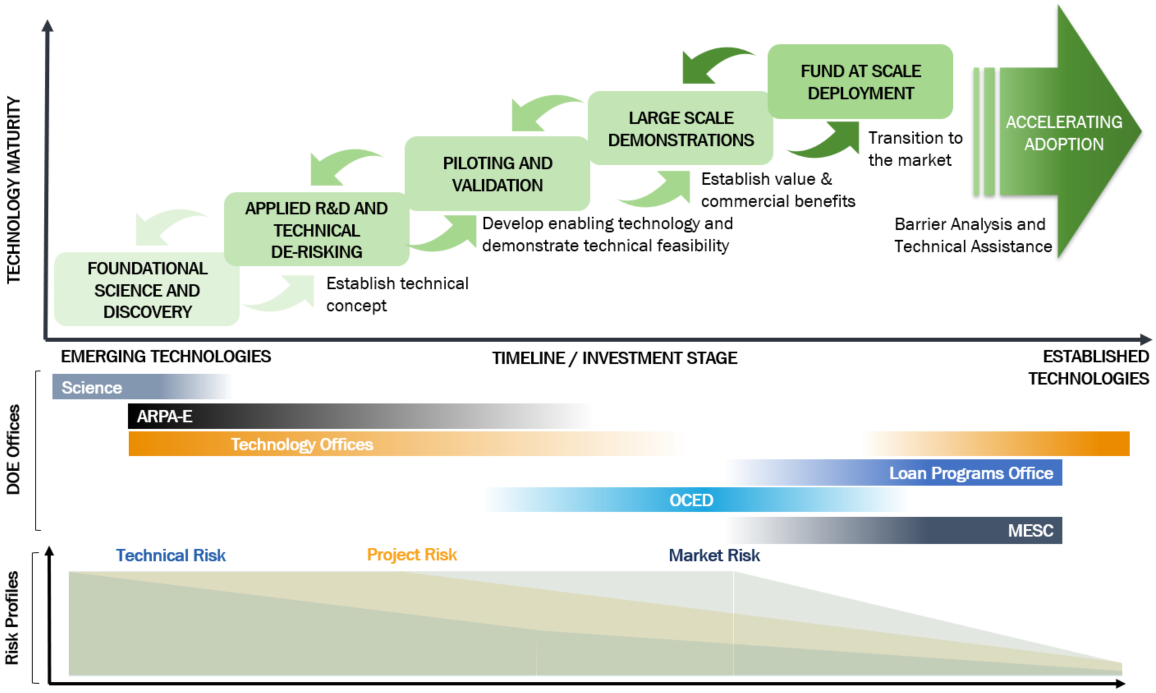

Figure 3. DOE's offices strategically coordinate investments across risk profiles for technology development

This vision study involves collaboration across the Federal government, including with the Environmental Protection Agency, the U.S. Department of Commerce, the National Institute of Standards and Technologies, the General Services Administration, the U.S. Department of Transportation, the U.S. Department of Homeland Security, the National Aeronautics and Space Administration, the U.S. Department of Agriculture, the U.S. Department of Defense, the U.S. Department of the Interior, and several White House Offices including the Climate Policy Office, Office of Science and Technology Policy, the National Economic Council, and Council on Environmental Quality. DOE will also seek input on this vision study from states, territories**,** local authorities, and Tribes.

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[26] Advanced Energy Manufacturing and Recycling Grant Program | Department of Energy

The shift towards net-zero GHG emissions by 2050 will require substantial investment from industry, alongside crucial government support. Decarbonizing industrial processes requires significant upfront costs for adopting advanced technologies and sustainable practices. At the same time, because the U.S. industrial ecosystem crosses borders and the industrial emissions can be shifted between countries, its global emissions contributions can appear artificially lower due to the import of high embodied carbon products or limited circular feedstocks. To discourage offshoring industrial emissions and supply chains, any decarbonization strategy must strengthen U.S. industry, ensuring it is globally and domestically competitive. Also, a strategy should position the United States for global leadership on industrial decarbonization technology and products. DOE can support industrial transformations through financial incentives, public-private partnerships, grants, and regulatory frameworks to mitigate financial burdens on industries, ensuring a smoother transition towards a sustainable future.

Industrial decarbonization also provides an opportunity to advance U.S. manufacturing competitiveness. Manufacturing innovations will position the United States as a leader in the production of clean energy technologies. As envisioned in the White House Office of Science and Technology Policy 2022 *National Strategy for Advanced Manufacturing*, U.S. manufacturing can positively transform using sustainable manufacturing practices and principles to minimize negative environmental impacts and address climate change through industrial decarbonization all while growing the economy, strengthening supply chains, and creating high-quality jobs, among other benefits.[27] To do so, the United States needs to develop and implement advanced manufacturing technologies, grow the advanced manufacturing workforce, and build resilient supply chains.[28] To achieve industry- and economy-wide net-zero emissions, our approach will need to ensure U.S. industry remains domestically and globally competitive, while feeding the innovation economy to create those advanced and environmentally-just[29] technologies, strengthening our manufacturing base with a skilled workforce, and encouraging continued onshoring to build resilient supply chains. Manufacturing drives both U.S. knowledge production and innovation,[30] areas that will be key to keep industry competitive in the development and deployment of decarbonization technologies both at home and abroad. DOE's vision is of a vibrant and productive decarbonized U.S. industry, supplying products, technologies, and strategies to enable global decarbonization. DOE's integrated and coordinated approach to investing in industrial technologies across the Department through Joint Strategy and Planning[31] is aligned with this vision.

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[27] National Strategy for Advanced Manufacturing | Office of Science and Technology Policy

[28] Ibid.

[29] Environmental Justice | Environmental Protection Agency

[30] Report to the President on Accelerating U.S. Advanced Manufacturing | President's Council of Advisors on Science and Technology

[31] See information about DOE's joint strategy planning: Industrial Technology Programs across the U.S. Department of Energy

Purpose

The purpose of this RFI is to solicit feedback from industry, academia, research laboratories, government agencies, and other stakeholders on issues related to industrial decarbonization strategies. EERE is specifically interested in information on research, development, demonstration, and deployment of strategies to address the technical, social, financial, and environmental challenges related to U.S. industrial decarbonization. Input from this RFI and other stakeholder engagement will inform a new DOE vision study, *Pathways for U.S. Industrial Transformations: Unlocking American Innovation*. This is solely a request for information and not a Funding Opportunity Announcement (FOA). EERE is not accepting applications.

Request for Information Categories and Questions

This RFI seeks input on four categories:

1. Industrial Decarbonization Challenges, Barriers, and Cross-Cutting Strategies
2. Framework for Industrial Decarbonization Pathways
3. Impacts and Evaluation Criteria for Industrial Decarbonization Pathways
4. Net-zero Decarbonization Pathways for Specific Industrial Subsectors
    a. Cement
    b. Chemicals
    c. Food and beverage
    d. Iron and steel
    e. Pulp and paper
    f. Petroleum refining
    g. Rest of industry (other manufacturing, agriculture and forestry, mining, oil, and gas; construction; data centers; and water and wastewater treatment).

Questions are included at the end of each category. Helpful responses will provide context around your response on details such as the timing (e.g., near-, mid-, or long-term as outlined in the *Roadmap*); needed enabling conditions (e.g., hydrogen cost parity, access to electricity infrastructure, market demand); geography/location; and other specifics.

Category 1: Industrial Decarbonization Challenges, Barriers, and Cross-Cutting Strategies

1A: Primary Challenges and Barriers to Decarbonization

Pathways to decarbonize extensive industrial ecosystems face a variety of technology, market, and infrastructure barriers. Barriers can exist within an industrial entity itself and more broadly within the industrial ecosystem. The flow of materials, energy, and resources through the value

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chain are essential to industry and are thus integral to the strategies used to decarbonize industry.

In the context of these strategies, the industrial ecosystem for an individual process is considered as the cumulative web of environmental, health, economic, social, and technological impacts surrounding and attributable to each of the process's value chain segments. The value chain is composed of five stages, interconnected by transport: initialization (formation/generation/extraction), transformation (in industry), distribution, consumption, and end-of-life. This scope goes beyond industry fence lines and requires financial and technological costs consideration in conjunction with environmental and social criteria. As part of this vision study, DOE is developing an updated framework for identifying and addressing major challenges and barriers to decarbonization. These are the primary challenges and barriers DOE has identified:

Thermal Systems Emissions. Thermal systems (e.g., process heat, combined heat and power) emissions represent about half of all energy-related industrial emissions with over 90% due to fossil fuel combustion.[32] Thermal systems operate over a broad temperature range and some ranges lack cost-effective zero-emissions technologies.

Process Emissions. Process emissions from material transformations are intrinsic to current domestic production of vital commodities (e.g., cement manufacturing process emissions) and can be difficult to reduce or decarbonize.

Constraints Within Industrial Entities. Current industrial entities' operation and structure can limit zero-emissions technologies adoption and material and energy efficiency improvements in existing processes. Beyond capital and operating budget limitations, barriers include:

- High cost and long lifetime of capital equipment.
- Risks associated with early adoption of unproven technologies.
- Equipping the workforce for the industrial transformation.
- Meeting zero-emissions technologies standards, permitting, and other regulations.
- Lack of incentives for material and resource efficiency improvements.
- Fully incorporating equity and justice for legacy, existing, and planned facilities' communities and stakeholders.

Decarbonization Infrastructure. All decarbonization pathways will require the expansion of decarbonization infrastructure (e.g., building out the clean electric grid, clean hydrogen and

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[32] See the All Manufacturing Energy and Carbon Footprint | Department of Energy

bioenergy pipelines and transport networks, and carbon transport, utilization, and sequestration) faces technological, geographical, and temporal limitations. The same decarbonization infrastructure is also facing growing demand from the transportation and buildings sectors. Moreover, access to decarbonization infrastructure will vary regionally.

Inefficient Information Flows. Data privacy concerns and lack of information sharing mechanisms and incentives can impact the scale and speed of industrial decarbonization efforts. Improved information exchange within industry and between stakeholders would allow for more optimal resource allocation. Examples include sharing information to: develop case studies that could encourage early technology adoption; allow companies to benchmark against their peers; inform analyses; assess targets; enlighten decision-makers, operators, and partners across industry; and enable an equitable transition with all stakeholders' input.

Underrepresented Social Criteria. Protecting the human element, including the workforce and associated communities that interact with industry, is a priority during the clean energy transition. However, lack of data and social metrics to measure community impacts can impede both the energy transition and social and environmental justice objectives. Inclusion of metrics in technology decision making can allow consistent and comparable social impact analysis to enable equitable outcomes. Examples of social and environmental justice metrics include contribution to economic development, incidence of detrimental labor practices, or hazardous substance management.[33] Further development of metrics and methodologies to evaluate social and environmental impacts can guide industry towards a sustainable and just energy transition.

Category 1A: Questions on Primary Challenges and Barriers to Decarbonization

This category is focused on challenges and barriers applicable across industry. Responses regarding subsector-specific decarbonization opportunities, barriers, and pathways should be submitted in Category 4.

1A.1 What feedback do you have on the primary industrial decarbonization challenges and barriers summarized above? Please list any additional barriers that you think are important.

1A.2 Which barriers do you feel are most important to address first?

1A.3 How would you recommend government engage to address these (or other) industrial decarbonization barriers?

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[33] United Nations Environment Programme. 2013. "The Methodological Sheets for Sub-categories in Social Life Cycle Assessment (S-LCA)." https://www.lifecycleinitiative.org/wp-content/uploads/2013/11/S-LCA_methodological_sheets_11.11.13.pdf.

1A.4 Aside from cost, what vulnerabilities/challenges do facilities face when adopting new technologies?

1A.5 What are the blind spots or unknowns when transferring technology from the bench-scale to commercial scale?

1A.6 What are the current and future gaps/barriers in workforce needs and availability?

1A.7 What are the differences in workforces across industries/across the country related to the availability of skillsets, staff, training, etc.?

1A.8 What resources is your organization using to identify and address workforce needs and are those resources effective?

1A.9 What other resources are needed to identify and address workforce needs?

1A.10 How can government broaden the reach of energy management education and training programs to engage a diverse audience, including outside the traditional sphere?

1B: Cross-Cutting Decarbonization Strategies

Subsequent research and stakeholder engagement has reinforced the four cross-cutting pillars of decarbonization identified in the DOE's 2022 *Industrial Decarbonization Roadmap*[34] and depicted in Figure 2: energy efficiency; industrial electrification; low-carbon fuels, feedstocks, and energy sources (LCFFES); and carbon capture, utilization, and storage (CCUS). We have also identified a fifth cross-cutting priority for the foundational materials and manufacturing technologies necessary for each pillar to be successful. The industrial decarbonization technological opportunity space is comprised of measures across all pillars. This section provides a high-level summary and more detail on the pillars can be found in the *Roadmap.*

Energy and Material Efficiency

Energy efficiency measures and system design are fundamentally important at all industrial decarbonization stages since they apply to incumbent and future technologies. Some examples include process integration, strategic energy management, and operational improvements to equipment such as motors. Energy efficiency barriers include inadequate awareness of efficiency measures and incentives; unfavorable return on investment due to low fossil energy cost and/or high additional equipment cost (particularly applicable to smart manufacturing); operations disruptions during retrofits; waste heat integration engineering constraints; lack of strategic energy management to ensure improvements persist; and rebound effects.

Materials and resources (including water[35]) entering, used or produced within, and leaving industrial facilities have embodied environmental impacts that are not fully characterized or

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[34] Referred to as the "*Roadmap*" within this RFI. Industrial Decarbonization Roadmap | Department of Energy

[35] U.S. Manufacturing Water Use Data and Estimates: Current State, Limitations, and Future Needs for Supporting Manufacturing Research and Development — National Renewable Energy Laboratory

understood and can significantly affect the environment and worker and community health and safety. More efficient use of materials and resources, waste reductions, and proper siting of industrial facilities can mitigate negative impacts and provide environmental and social benefits to impacted communities. Examples of material efficiency include redesign, reuse, repurposing, and recycling.[36] Material circularity and material efficiency barriers include absent or inadequate reverse supply chain infrastructure, scale-up risks and performance or quality trade-offs with alternative substitutes, higher costs relative to linear supply chains, concerns around labor costs, possible job losses, regulatory standards, and rebound effects.

Industrial Electrification

Electrification of fossil fuel-driven mechanical, thermal, and chemical processes can significantly reduce energy consumption and associated GHG emissions. This includes switching to heat pumps, electric boilers, electric furnaces, advanced electro-heating technologies (that rely on microwaves, infrared waves, electromagnetic induction, or plasma for instance), electro-chemical and electrically assisted biological processes, membrane separation, and electrification of rotary equipment.[37] As the grid decarbonizes, purchased electricity-related emissions will also reduce. Barriers to industrial electrification include clean electricity availability, reliability, and cost; inefficiencies and inadequacies in transmission and distribution infrastructure; scale-up risks and performance or quality trade-offs with electrified processes; high capital cost of electricity-driven equipment; disruption and/or drastic reconfiguration of existing processes during retrofits; material limitations under harsh environments; and constraints on type, grade, and availability of feedstocks that could be processed (e.g., steel scrap in electric arc furnaces).

Low-Carbon Fuels, Feedstocks, and Energy Sources

Manufacturing industry's almost ubiquitous demand for thermal energy for process heat, as well as demand for certain feedstocks, has the potential to at least partially be met with low- and zero-carbon alternatives.[38] These alternatives are collectively termed low-carbon fuels, feedstocks, and energy sources (LCFFES) in the vision study. Examples of LCFFES include replacing fossil fuels and fossil fuel-derived non-fuel feedstocks with low-carbon energy carriers and non-fuel feedstocks (such as hydrogen; ammonia; synthetic fuels including e-fuels; sustainably sourced biomass,[39] biogas,[40] and bioproducts; and chemical precursors from CO_2) and utilizing clean thermal energy sources (such as solar, geothermal, or small modular nuclear

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[36] More examples on circular economy strategies can be found in: Sustainable Manufacturing and the Circular Economy | Department of Energy

[37] See Thermal Process Intensification: Transforming the Way Industry Uses Thermal Process Energy | Department of Energy

[38] Thiel and Stark. 2021. *To decarbonize industry, we must decarbonize heat | Joule*.

[39] See 2023 Billion-Ton Report: An Assessment of U.S. Renewable Carbon Resources | Department of Energy

[40] Also referred to as renewable natural gas and landfill gas. See: Biogas-Renewable natural gas | Energy Information Administration

reactors). Beyond meeting industry's current demands, some strategies incorporating LCFFEES can provide the opportunity for a more robust system than is currently employed, with the integration of energy storage (such as thermal energy storage[41]). Each LCFFES will have a unique set of approaches, barriers, and opportunities. Example barriers include availability, inconsistent carbon accounting practices, or high cost compared to existing sources.

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[41] Energy StorM – DOE Office of Electricity Energy Storage Program (sandia.gov)

Carbon Capture, Utilization, and Storage
CCUS technology opportunities include capture and reuse (utilization for e-fuels, chemical precursors, etc.) or sequestration (long-term storage in geological formations, saline aquifers, minerals, etc.) of high-purity process CO_2 streams and low-purity combustion CO_2 streams.[42] Carbon capture shows promise in significantly reducing emissions, particularly for industrial processes generating low-CO_2 concentration streams. Yet it remains prohibitively expensive for most applications due to high capital costs and the parasitic energy loads they add. Other CCUS barriers include the uncertainty of merchant and captive CO_2 markets in a low-carbon future; concerns around feasibility, safety, and monitoring of a nationwide CO_2 pipeline transport and long-term CO_2 storage infrastructure; facilities' lack of proximity to a viable CO_2 storage location; and inadequate guidelines on captured, reused, and stored carbon accounting.

Category 1B: Questions on Cross-Cutting Decarbonization Strategies

This category is focused on cross-cutting technologies and strategies that apply across industry. Responses regarding subsector-specific decarbonization technologies and strategies should be submitted in Category 4.

1B.1 What are the most impactful cross-cutting and systems-wide strategies needed to decarbonize industry and why?

1B.2 What approaches are useful to allocate and structure investments for cross-cutting technologies vs. industry-specific technologies?

1B.3 Given the breadth of available and emerging technologies, which cross-cutting technologies are most in need of RD&D funding?

1B.4 Some example barriers to cross-cutting strategies are provided in this section. Are there additional barriers you believe hinder cross-cutting strategy/technology adoption?

1B.5 Which barrier(s) do you think is most important to address?

1B.6 Which barrier(s) do you believe to be most difficult to overcome and how might you do so?

1B.7 What approaches are needed to reduce or overcome the risk of deploying new cross-cutting technologies, catalyze uptake, and accelerate technology adoption?

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[42] For more information on carbon management and removal, see: Carbon Management - Pathways to Commercial Liftoff | Department of Energy and Roads to Removal (R2R): Options for Carbon Dioxide Removal in the United States

Category 2: Framework for Industrial Decarbonization Pathways

As stated previously, the plural use of the term “pathways” is at the heart of this new vision study. Decarbonizing industry will require a wide range of technology solutions across all the pillars of decarbonization. There is no single pathway that will work for any single industrial subsector. Indeed, competition across different possible pathways will be essential to our success. In Category 4, this study has outlined major net-zero emissions pathways for six manufacturing subsectors and begins to consider pathways for the rest of industry.

Factors for Different Pathways

There are many factors that influence which pathway any given industrial facility may take to achieve emissions reductions. These factors can include the following:

- Business-related
    - Product mix (steady or dynamic)
    - Domestic and international competition
    - Company-specific commitments
    - Potential return on investment and profit
    - Cost (e.g., financing, capital and operating expenses)
    - Secure and sustainable supply chains and customers
    - Risk tolerance and mitigation
    - Product impact
    - Practical feasibility within a given facility
    - Public perception and/or demand
- Workforce
    - Needed amount of workers
    - Workers with the right skill sets
    - Workers within a specific facility location
- Access to necessary infrastructure
    - Energy supply infrastructure: electricity, hydrogen, and bioenergy
    - Carbon storage infrastructure
    - Logistics infrastructure for supply chain and transport needs
- Policy-related
    - Federal, state, and local regulations (environmental, workforce, etc.)
    - International trade
    - Taxes and incentives
    - Corporate policies.

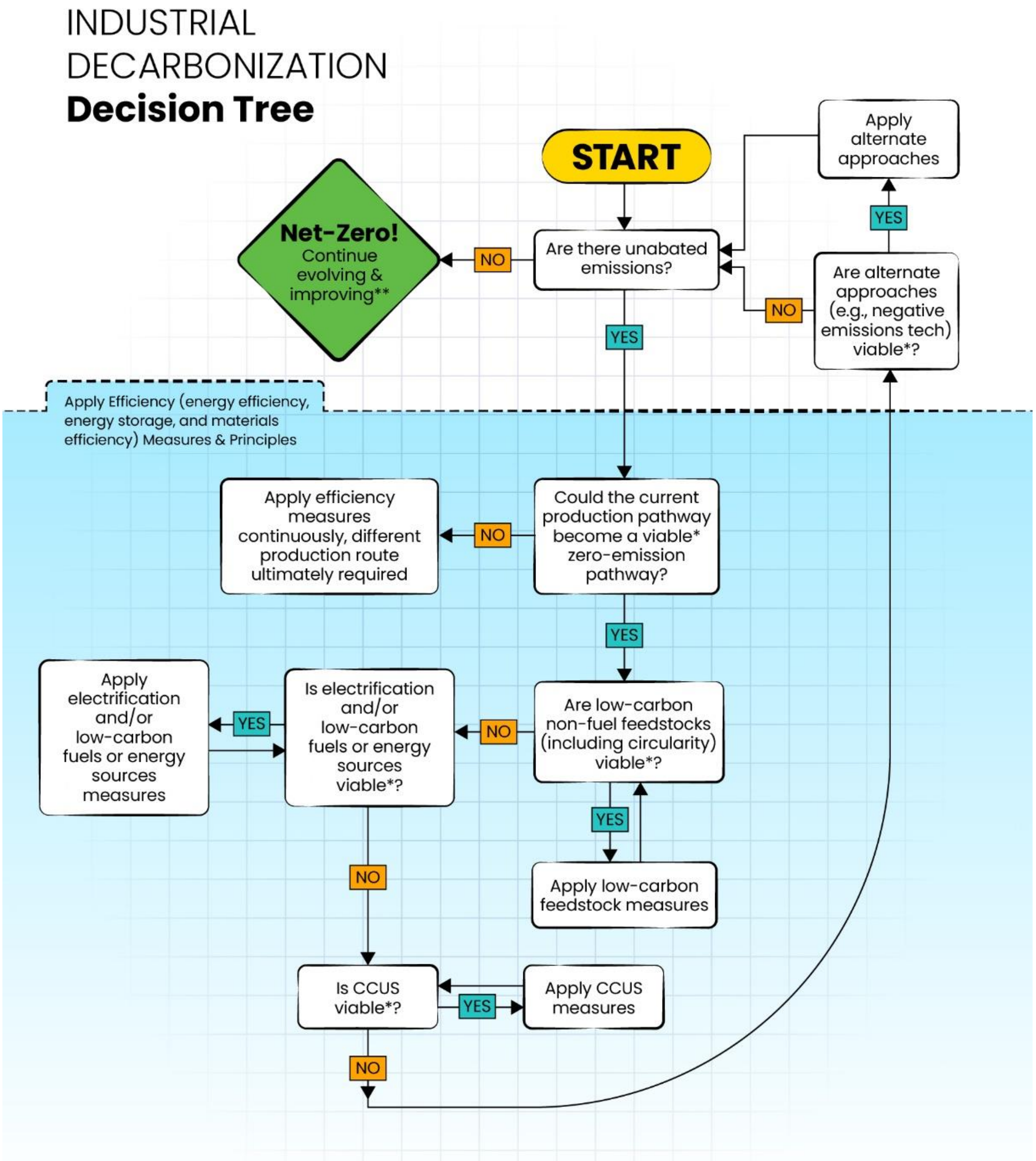
Collectively, pathways taken by individual facilities, corporations, and industrial subsectors cumulatively will be the sum of many decisions. Our goal with this RFI is to gain input and insights into the decisions made by facilities, companies, etc. that can inform DOE analysis, modeling, and ultimately DOE investments over time that will put the U.S. industrial sector to a path to net-zero emissions by 2050.

Decision Points Within Pathways

Pathways are not a single decision, but rather a series of decisions over time. Decarbonization pathways require decision making and investment under uncertainty. All pathways require parallel investments to achieve net-zero emissions by 2050. Due to the long lifetimes of industrial facilities and related infrastructure, timing is challenging for any pathway. As part of this study, we will be developing frameworks and data-informed decision tools to help map out and inform such decisions.

A notional approach describing the decisions within the industrial decarbonization opportunity space is shown in Figure 4. The specific approach to making technology choices for a particular industry or facility may deviate from the general decision tree shown in Figure 4. Many decarbonization technologies in the opportunity space covered by this decision tree are currently commercially viable, while others are expected to become commercial in the coming decades. Further, several decarbonization measures will likely rely on decarbonization of energy supply systems and development/expansion of massive energy and industrial infrastructure. Such interdependencies require a careful consideration of technology choices phasing, whether at a facility-level or an industry-wide scale, to avoid emission “lock-ins” or creating potential stranded assets or “dead-ends” in the future.

Decision trees such as the one shown in Figure 4 are intended to help us understand the promising high-level pathways that industry can pursue. This decision tree represents a continuous process that can be applied at different points of time.



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

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

Figure 4. An example of an industrial decarbonization decision tree. Note, sequencing and specific decarbonization strategies may vary. This figure is provided for discussion purposes and as a way to identify the barriers and opportunities in pathways to decarbonization and better understand decision making. It may be helpful for responses to questions posed later in this RFI to be framed in this decision tree context.

This vision study seeks to refine and improve our understanding of potential pathways and production routes within pathways, including considerations of the following:

- Major production routes for each industrial subsector
- Primary solutions/technologies leveraged from each decarbonization pillar for production routes
- Emissions reductions achieved by any production route, including percent of reductions achieved by each pillar in that route
- Main factors for what facilities will use one production route over others (e.g., access to carbon storage infrastructure or size of facility or certain products in that industry)
- Estimates on production route share for subsectors (e.g., percent of production in 2050; number of facilities in 2050)
- Major decision-points that might shape each pathway, relative timing between now and 2050 for these decision-points, and information needed for those decision-points
- Primary factors that might determine how much of a subsector would choose an individual production route or technology
- Major similarities and differences in technologies and solutions across the major pathways and production routes
- What investments could be made in parallel and are no-regrets strategies, and where are the potential risks for creating stranded assets
- Portion of each pathway that can be achieved through enhancements to existing facilities vs. require newly constructed facilities
- Major barriers to successful development and accelerated deployment of key technologies and solutions within each pathway
- Major uncertainties across each pathway
- Economic, environmental, and social impacts of each pathway

Category 2: Questions on Framework for Industrial Decarbonization Pathways

2.1 How does your organization approach planning for different pathways to decarbonization?

2.2 Given the uncertainty around considerations like cost and regulations, how does your organization make decisions under such uncertainty?

2.3 What strategic frameworks do you find helpful for your organization's decision making?

2.4 We have included an example decision tree in Figure 4 to summarize pathways. Questions 2.4.1 through 2.4.5 are focused on this example decision tree.

2.4.1 Do you find these types of structures useful for your industry or organization?

2.4.2 What would you change in the decision tree?

2.4.3 Is anything missing in the decision tree?

2.4.4 Are these the right decision points and/or order in the decision tree?

2.4.5 Do you know of other similar frameworks we should explore?

2.5 How can we differentiate "bridge" investments that produce emissions savings in the near/medium-term but are at least neutral for the path to net-zero emissions (e.g., installing new electrified equipment) versus the "dead-end" investments that produce emissions savings in the near/medium-term but delay or deviate from the path to net-zero emissions (e.g., efficiency improvements to fossil-fuel based systems), often causing stranded assets?

2.6 How can we build timelines into the pathways (e.g., how can we project when those major decarbonization investments will be possible/needed)?

2.7 What factors are important to include in projecting long-term investment needs or technology transition needs?

2.8 How does your organization (or other organizations) set climate-related goals and how do you identify the pathways for achieving those goals?

2.9 How does your organization (or other organizations) consider workforce capabilities needs within a pathway?

2.10 Are there current policies or interventions that are hindering implementing different decarbonization pathways?

2.11 What additional data and information is needed to support data-based decision making within a pathway framework?

2.12 What tools and models would assist decision making?

Category 3: Impacts and Evaluation Criteria for Industrial Decarbonization Pathways

Data-informed decision making along decarbonization pathways requires not only information about opportunities and barriers but also information about evaluation criteria and impacts for both the individual facility as well as across society. Although this study is focused on decarbonization, there are many concurrent factors for transformations in American industry as noted in Category 2. This study will identify impact and evaluation criteria for DOE to leverage in projecting the likelihood of different industrial facilities adopting different pathways as well as for quantifying the societal impacts of different portfolios of pathways. For all metrics it is important to not only evaluate aggregate impacts, but also distributional impacts (e.g., across different regions, communities, and sub-sectors) as well as impacts over time.

Economic

One of the primary criteria for cost-effective industrial decarbonization strategies is financial. However, several different financial metrics are relevant and will influence technology deployment. For example, it is unclear whether the best economic criteria is the cost of abating carbon, cost to produce a carbon-abated product, a levelized cost of heat (or clean energy), or a broader levelized cost of material transformation. Deployment costs include the initial design and analysis, permitting, regulatory compliance, training, downtime, capital, and operating costs. Additional economic factors include demand incentives (e.g., customer or shareholder preferences), risk of potential future regulatory or market drivers, competitiveness (both domestic and international), and resilience (e.g., from supply chain disruptions, natural disasters, energy supply disruptions, volatile energy prices, and other reliability and security risks).

Technological

A primary technological criterion is process or finished good energy intensity since decarbonization infrastructure will require efficient use of available energy. Beyond energy intensity, other technological criteria are needed to assess a decarbonization strategy's merits. The technological criteria spectrum is diverse and includes specific performance parameters, operational, scalability, availability (technology or resource), critical material usage, and required expertise.

Environmental and Health

Decarbonization pathways will be evaluated based on their reductions in both direct and indirect greenhouse gas emissions (GHG). Industry has many other environmental impacts that will also vary across pathways and need to be quantified, including criteria air pollutants, toxics, other air and water pollutants, waste, thermal pollution, and land use, and associated health impacts, such as on respiratory and cardiovascular health. In the United States, disadvantaged communities are disproportionately exposed to these pollutants and health burdens.

Societal

Equity and Environmental Justice: Many of our country's industrial facilities are located in communities designated as Disadvantaged Communities, who both bear the brunt of the pollution burden that these facilities often generate today, and who stand to benefit the most from the economic revitalization and reduced pollution that a just transition to clean manufacturing can provide. The Justice40 Initiative[43] and the DOE's Climate and Economic Justice Screening Tool (CEJST)[44] provide evaluation tools.

***Energy Costs and Infrastructure**:* Industrial decarbonization pathways can impact the scale of necessary energy infrastructure and operating costs across the full U.S. economy, which will in turn impact energy affordability for American families and businesses. The coincident decarbonization of buildings and industry put additional pressure on the same clean electricity and other clean energy sources.

Workforce: Building, equipping, and maintaining a strong domestic workforce with high quality jobs will be integral to all industrial transformation pathways. Impacts to workforces over time will vary across different pathways and include the creation and loss of jobs as well as the change in nature of the work, the expertise/training required (including the applicability of those skills to other industries), the health and safety for the position, and compensation.

National Security, Critical Materials, and Resilient Supply Chains: Portfolios of pathways will have different impacts on nation-wide societal impacts, such as national security, critical materials, and resilient supply chains.

Category 3: Questions on Impacts and Evaluation Criteria for Industrial Decarbonization Pathways

3.1 What criteria do your industry or organization primarily leverage in decision making?
3.2 How do you define, quantify, and compare these criteria, and what targets are assigned to them (if any)?
3.3 Which criteria would you use, and when would they be most useful, to assess the merits of a decarbonization strategy?
3.4 What feedback do you have on the impact and evaluation criteria summarized above? Please list any additional criteria that you think are important.

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[43] Justice40 Initiative | Environmental Justice | The White House
[44] Climate and Economic Justice Screening Tool | Department of Energy

3.5 Which criteria do you recommend government prioritize in quantifying the societal impacts of different net-zero emissions pathways?
3.6 What best practices would you identify for quantifying each criterion?
3.7 Some criteria are harder to quantify. What criteria should DOE prioritize for future research to develop new quantification tools?
3.8 How could DOE confirm that it is on the right path in measuring/assessing decarbonization success?
3.9 How does your organization work with communities to develop evaluation and impact criteria?
3.10 How should DOE work with communities to develop evaluation and impact criteria and evaluate individual decarbonization pathways?
3.11 How do you (or would you) account for impacts beyond the boundaries of an industrial facility (e.g., considering supply chain and Scope 3 GHG emissions)?
3.12 What resources are needed to account for impacts beyond the boundaries of an industrial facility (e.g., considering supply chain and Scope 3 GHG emissions)?
3.13 What threshold (for example monetary, energy intensity, throughput, emissions, etc.) does new technology need to meet to be worth the investment over existing technology (both from a company's perspective and at the national level)?
3.14 How can industry measure progress towards environmental justice and energy equity?
3.15 What are the most useful criteria/metrics for environmental justice and energy equity?

Category 4: Net-Zero Emissions Decarbonization Pathways for Specific Industrial Subsectors

Sections 4A-4F below provide a summary of the potential impacts and role of the four *Roadmap* pillars and material efficiency measures in net-zero emissions pathways for six manufacturing subsectors: cement, chemicals, food and beverage, iron and steel, pulp and paper, and petroleum refining. These six subsectors accounted for 79% of total U.S. manufacturing emissions in 2018.[45] A detailed overview of draft modeling results from net-zero emissions pathways analysis for these six manufacturing subsectors is available on the IEDO website.[46]

Net-Zero Emissions Pathway

As defined in the *Industrial Decarbonization Roadmap*, a ***pathway*** is a set of specific actions needed to achieve progress in and across the decarbonization pillars, while remaining informed and supplemented by RD&D to advance viable solutions (i.e., technologies, practices, approaches, behaviors) that will need to be adopted at scale in the marketplace.

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[45] See the Manufacturing Energy and Carbon Footprints | Department of Energy
[46] https://www.energy.gov/eere/iedo/industrial-decarbonization-pathways-modeling

Section 4G also discusses decarbonization opportunities for the rest of industry, defined as other manufacturing (the rest of the manufacturing subsector excluding cement, chemicals, food and beverage, iron and steel, pulp and paper, and petroleum refining), the nonmanufacturing subsector (agriculture and forestry; mining, oil, and gas; and construction), data centers, and water and wastewater treatment, though these subsectors have not been modeled in detail.

Example of key factors in the success of each industrial subsector's net-zero emissions pathway include access to clean electricity (through a decarbonized electric grid by 2050), ensuring each pathway addresses environmental justice and energy equity along the way, and continued efforts to overcome the structural and technical challenges that are apparent and will emerge. Some example challenges common to most subsectors include hesitancy towards emerging technologies demonstration and implementation, their cost, and lack of onsite infrastructure to support them; the availability of LCFFES and clean electricity; and regulatory barriers. In responses to the questions in sections 4A through 4G please identify the key factors to success from your perspective qualitatively, and quantitatively where possible.

4A: Cement

This section provides a high-level overview of the impact of the four decarbonization pillars and material efficiency in a net-zero emissions pathway by 2050 for U.S. cement manufacturing. A more detailed draft summary on IEDO's net-zero emissions pathways analysis can be found on the IEDO website.[47]

The U.S. cement industry is integral to the nation's infrastructure development. Cement production is expected to grow through 2050, driven by population growth and urbanization. In 2022, 95 million metric tons of cement were produced across 96 plants in the United States and two in Puerto Rico,[48] primarily using modernized dry kilns.[49] Cement manufacturing consumed 367 trillion British thermal units (TBtu) primary energy and 296 TBtu onsite energy and accounted for 66 MMT CO_2e total emissions in 2018.[50] Coal was the largest source of onsite energy (43%), followed by natural gas (22%) and petcoke (19%), with other fuels making up the balance.[51] The production of clinker, the intermediate product for cement, consumes the majority of energy in the overall cement production process–almost all fuels and around 60% of cement plant electricity – and accounts for around 95% of total cement CO_2 emissions. The cement industry also incurs a significant amount of process emissions (from the chemical

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[47] https://www.energy.gov/eere/iedo/industrial-decarbonization-pathways-modeling

[48] U.S. Geological Survey. 2023. "Cement." https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-cement.pdf.

[49] Low Carbon Cement - Pathways to Commercial Liftoff | Department of Energy

[50] See the All Manufacturing and Cement Energy and Carbon Footprints | Department of Energy

[51] Ibid.

conversion process used in the production of clinker, a component of cement), accounting for 59% of cement subsector total emissions.[52]

Due to the large share of process emissions, cement subsector decarbonization cannot be achieved by energy efficiency, fuel switching, or electrification alone. Other technologies, such as those that reduce clinker content with lower carbon-intensive options such as supplementary cementitious materials (SCMs) and alternative binders (considered as an option under the LCFFES pillar), and CCUS are necessary and expected to play a major role in decarbonizing cement production. Alternate approaches, powered by clean energy sources, outside the four *Roadmap* pillars will also be needed to bridge the remaining gap and reach net-zero emissions. Material efficiency measures can also assist subsector decarbonization, though impacts tend to be difficult to quantify.

Energy Efficiency: Because the subsector has a high amount of process emissions, energy efficiency may play a relatively minor role in cement decarbonization but will still make an impact. There are commercially available energy efficiency technologies for the cement subsector but most have not been adopted primarily due to economics. The use of high efficiency multistage pre-heat/precalciner kilns has already been widely adopted across the United States. Other technologies, such as waste heat recovery power generation, high efficiency clinker cooling, more efficient grinding, could have an impact in the near term if adopted. Emerging technologies are being explored, including those for grinding and raw material processing (e.g., high activation grinding, ultrasonic and plasma comminution).

Electrification: Electrification is expected to have a modest impact in a net-zero emissions pathway for the cement subsector. Around 85%-90% of the energy in cement manufacturing is consumed in thermal processing, predominantly fueled by carbon-intensive sources such as coal and petcoke. While challenges exist, electrification of the precalciner and kiln have gained significant interest in the industry. Electrification of heating and calcining will result in overall CO_2 emissions reductions, especially as the U.S. electric grid decarbonizes.

LCFFES: While SCMs and alternative binders have been explored for some time, challenges exist. Performance characteristics of SCMs and alternative binders are under intense scrutiny, with particular concern about their durability in diverse environmental conditions and their long-term safety. In addition, prescriptive building codes and standards, which require specific compositions or materials, do not allow the broad use of new SCMs and alternative binders, preventing adoption and implementation.

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[52] Ibid.

CCUS: CCUS can have a significant contribution to CO_2e emissions reduction for cement manufacturing through post-combustion capture and mineralization/utilization. Relative to other subsectors, carbon utilization and mineralization in cement products are a unique opportunity for cement producers. However, further work is needed to scale-up and reduce cost. Additionally, the energy and physical footprint needed to support carbon capture systems are not currently feasible for most cement plants.

Material Efficiency: Material efficiency measures such as concrete recycling and optimized concrete mixing can act as a significant decarbonization lever for this subsector. Material efficiency can be improved through optimized concrete recipes and the recycling of cement and concrete. By creating better designs that reduce cement and concrete demand, and through innovations in cement recipes, substantial reductions in material use and associated emissions could be achieved. Such optimizations aim to reduce the demand for raw materials and energy in the cement manufacturing process, thereby contributing to overall subsector decarbonization efforts.

Category 4A: Cement Questions

The following questions are focused on cement manufacturing decarbonization. Responses on cross-cutting technologies (applicable to multiple manufacturing subsectors) should be submitted in Category 1.

4A.1 How do you expect the U.S. demand and production of cement to change by 2050 and why?

4A.2 What do you think of the net-zero subsector emissions by 2050 pathway described above and detailed in the pathways analysis summary document (if reviewed)?

4A.3 What do you think are the primary production routes needed to decarbonize the cement subsector between now and 2050?

For each route for which you have knowledge or expertise, please share the following information. Please also provide any supporting references (if available).

4A.3.1 What are the primary solutions/technologies necessary for that production route?

4A.3.2 What is the likely utilization of that route in the near-term (now-2030), mid-term (2030-2040), and long-term (2040-2050) (such as the percent of cement production)?

4A.3.3 What are the main factors that influence choice of this production route at the facility level?

4A.3.4 What are the primary barriers/challenges faced by this route and how can they be overcome?

4A.3.5 What potential factors would hinder or maximize success of this production route?

4A.3.6 Are there any unique barriers/challenges for this production route?

Please answer questions 4A.3.1 through 4A.3.6 above for each production route you are replying for.

4A.4 What technical and/or technology solutions does the subsector need that are not currently available?

4A.5 What other solutions should be considered in characterizing/modeling a net-zero emissions cement subsector by 2050?

4A.6 What other sensitivities should be considered in characterizing/modeling a net-zero emissions cement subsector by 2050?

4A.7 Are there any other subsector-specific barriers, criteria, metrics, or targets that DOE should be aware of as a decarbonization strategy for this subsector is developed?

4B: Chemicals

This section provides a high-level overview of the impact of the four decarbonization pillars and material efficiency in a net-zero emissions pathway by 2050 for U.S. chemicals manufacturing. A more detailed draft summary on IEDO's net-zero emissions pathways analysis can be found on the IEDO website.[53]

U.S. chemicals manufacturing, with more than 11,000 facilities,[54] is the second largest chemicals producer globally, and consumed 25% of U.S. manufacturing energy and emitted 28% of the manufacturing subsector's emissions in 2018.[55] Chemicals manufacturing is comprised of multiple subsectors[56] covering numerous chemicals and categorized into four segments: agricultural chemicals, basic chemicals, specialty chemicals, and consumer products. Three subsectors (other basic organic chemicals, petrochemicals, and plastics materials and resins) account for 50% of the chemicals subsector's total emissions. Within the subsector, numerous processes yield multiple co-products, resulting in some chemical production being contingent on specific chemical processes. This subsector's intricate interdependencies and heterogeneity pose challenges for energy and emissions analysis and the development of decarbonization

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[53] https://www.energy.gov/eere/iedo/industrial-decarbonization-pathways-modeling

[54] Chemical Sector Profile | Cybersecurity & Infrastructure Security Agency

[55] See the All Manufacturing and Chemicals Energy and Carbon Footprints | Department of Energy

[56] Divided into 29 six-digit coded North American Industry Classification System subsectors.

strategies. This complexity sets it apart from more homogenous subsectors, making the task of devising effective decarbonization approaches more difficult.

A net-zero emissions chemical subsector requires adoption of a variety of decarbonization technologies and production pathways from the four decarbonization pillars across all its subsectors. Electrification and CCUS could have the largest emissions reduction impact for the subsector, followed by energy efficiency and a smaller amount of reduction from LCFFES. This goal of net-zero hinges on the adoption of transformative technologies and the incorporation of low-carbon manufacturing pathways. Such comprehensive strategies are essential for meeting the ambitious net-zero emissions target by 2050.

Energy Efficiency: The chemicals subsector is engaged in energy efficiency improvement and material efficiency strategies to minimize emissions. Improving energy efficiency involves implementing technical and operational measures, transitioning to more efficient manufacturing pathways, and adopting the best available technologies. Heat integration and optimizing heat utilization are key drivers for energy efficiency improvements. The subsector could implement both current operational improvements (enhanced process monitoring, improved solvents, regular maintenance, fixing steam leaks, better heat exchanger designs, and efficient motors) and large efficiency improvements (replacing equipment with cutting-edge technologies such as low-pressure catalysts for ammonia synthesis, membrane separation in steam cracking, and alternative configurations for chlor-alkali production).

Electrification: Electrification in the chemical industry holds significant potential for reducing emissions. Electrified technologies, such as high-temperature heat pumps and electric resistance heating, are lower energy intensity and offer substantial emissions reductions, especially when integrated with clean electricity. Transitioning to hydrogen produced via electrolysis would require ample access to clean electricity and cost reductions. Technological advancements are key for realizing electrification opportunities, but challenges persist, including current disparities in electricity prices compared to natural gas. The electrification pillar also includes electrochemical conversion processes (e.g., electrochemical CO_2 reduction, electrochemical process for oxidative coupling of methane).

LCFFES: LCFFES pillar approaches to reduce subsector emissions includes consumption of low-carbon fuels instead of natural gas or other carbon-intensive fuels, transitioning use of existing high-carbon non-fuel feedstocks to bio-feedstocks, and clean (sometimes called green or bio-) methanol production (utilizing biomass as a non-fuel feedstock and powered by clean energy). Bioethanol shows promise as a substitute for non-fuel petrochemical feedstocks, but challenges remain regarding its life cycle impacts. Additionally, clean hydrogen and renewable natural gas (also called biogas or biomethane) as low-carbon fuels are also viable options, though challenges such as competition with low-cost fossil fuels and policy uncertainties exist. Other clean sources like geothermal and solar are promising but dependent on specific processes and locations.

CCUS: While electrification, energy efficiency, and low-carbon fuels are primary decarbonization methods, CCUS can also play a role in reducing chemicals subsector emissions. CCUS may offer economic capture opportunities for hard-to-abate process emissions, such as the capture of high-purity biogenic process CO_2 from ethanol production.[57] However, challenges remain around the integration of CCUS into various processes due to lack of infrastructure support and financial incentives. Comprehensive carbon accounting and lifecycle analyses are needed to assess the long-term effectiveness of the utilization pathways and their emission impacts.

Material Efficiency: The chemicals subsector is engaged in material efficiency strategies to minimize emissions. Plastics, which are predominantly derived from petrochemicals, are currently recycled at a very low rate. Initiatives targeting plastic littering, single-use plastic restrictions, polymer recycling enhancement, agricultural practice improvement to reduce fertilizer demand, and increased recycling are key drivers to increase material efficiency. Achieving recycling goals will require changes in waste management practices, expansion of waste collection, and investment in advanced methods like chemical recycling.

Category 4B: Chemicals Questions

The following questions are focused on chemicals manufacturing decarbonization. Responses on cross-cutting technologies (applicable to multiple manufacturing subsectors) should be submitted in Category 1.

4B.1 How do you expect the U.S. demand and production of specific chemicals or classes of chemicals to change by 2050 and why?

4B.2 What do you think of the net-zero subsector emissions by 2050 pathway described above and detailed in the pathways analysis summary document (if reviewed)?

4B.3 What do you think are the primary production routes needed to decarbonize the chemicals subsector between now and 2050 (specific chemicals or classes of chemicals)?

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[57] For this example, it is important to note that bio-feedstock production for ethanol, land use, and fertilizer use significantly contribute to Scope 3 emissions.

For each route for which you have knowledge or expertise, please share the following information. Please also provide any supporting references (if available).

4B.3.1 What are the primary solutions/technologies necessary for that production route?

4B.3.2 What is the likely utilization of that route in the near-term (now-2030), mid-term (2030-2040), and long-term (2040-2050) (such as the percent of total chemical production)?

4B.3.3 What are the main factors that influence choice of this production route at the facility level?

4B.3.4 What are the primary barriers/challenges faced by this route and how can they be overcome?

4B.3.5 What potential factors would hinder or maximize success of this production route?

4B.3.6 Are there any unique barriers/challenges that may limit implementation of this production route?

Please answer questions 4B.3.1 through 4B.3.6 above for each production route you are replying for.

4B.4 What technical and/or technology solutions does the subsector need that are not currently available?

4B.5 What other solutions should be considered in characterizing/modeling a net-zero emissions chemicals subsector by 2050?

4B.6 What sensitivities should be considered in characterizing/modeling a net-zero emissions chemicals subsector by 2050?

4B.7 Are there any other subsector-specific barriers, criteria, metrics, or targets that DOE should be aware of as a decarbonization strategy for this subsector is developed?

4C: Food and Beverage

This section provides a high-level overview of the impact of the four decarbonization pillars and material efficiency in a net-zero emissions pathway by 2050 for U.S. food and beverage manufacturing. A more detailed draft summary on IEDO's net-zero emissions pathways analysis can be found on the IEDO website.[58]

The U.S. food supply chain is composed of multiple stages – agriculture, manufacturing (where products are packaged and prepared for eventual consumption), wholesale and retail, and

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[58] https://www.energy.gov/eere/iedo/industrial-decarbonization-pathways-modeling

consumption (both at homes and food services).[59] Additional areas of the supply chain with non-negligible energy consumption and emissions include post-harvest processing between manufacturing and agriculture and warehousing between manufacturing, wholesale, and retail. The United States manufactured a total of 209 million metric tons (MMT) of food in 2018 and is expected to increase production by about 20% through 2050 due to population growth and demand. Food and beverage manufacturing is heterogenous (composed of over 41,000 plants[60] across the United States of all sizes, producing vastly different products from milk to salad dressing to chocolate bars and everything in between), making it challenging to estimate the energy consumption or emissions of individual products. The subsector relies largely on natural gas and electricity for its main energy consumption demands (process heating, steam generation, machine drives like pumps and compressed air, etc.) with smaller amounts of other fuel types (e.g., coal, diesel fuel) accounting for the remainder.[61]

A net-zero emissions by 2050 pathway for food and beverage manufacturing would include widespread adoption of electrification (including heat pumps), significant adoption of energy efficiency measures (technologies and approaches such as energy management), and smaller impacts from adoption of low-carbon fuels (namely biomass and biogas with limited use of hydrogen as a fuel). Carbon capture and storage (CCS) will likely have minor impact subsector-wide. It is expected to only be economic for larger point-source emissions facilities, while the subsector is comprised of mostly small and medium-size facilities. Finally, alternate approaches falling outside of the four main decarbonization pillars (such as negative emissions technologies or alternative proteins) could be used to help the subsector reach net-zero. Because the food supply chain is so interconnected, it can be difficult to account for decarbonization impacts within only one specific stage. To achieve net-zero emissions by 2050, decarbonization efforts will need to be considered beyond manufacturing to other parts of the food supply chain.

Electrification: Electrification is expected to be the most impactful decarbonization pillar, as most processes that rely on steam, hot water, and hot air fall in the low- to medium-temperature range (below 400° Fahrenheit). It is relatively simpler to electrify low temperature heating equipment compared to high-temperature processes. Some electric equipment, such as hot water or steam-generating heat pumps, can be significantly more efficient than their fossil fuel counterparts and offer better temperature and process control capabilities. Other electrification technologies relevant to the subsector that could replace existing fossil fuel-using equipment include electric boilers and water heaters, advanced electro-heating technologies

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[59] Both agriculture and manufacturing are considered to fall under the industrial sector. IEDO's predecessor (AMO) only focused on the manufacturing stage, while the office is working to also consider impacts beyond manufacturing. Agriculture is additionally discussed in the "rest of industry" section below.

[60] References: County Business Patterns | U.S. Census Bureau; Food and Beverage Manufacturing | U.S. Department of Agriculture.

[61] For more detail, see: Food and Beverage Manufacturing Energy and Carbon Footprint | Department of Energy

(such as microwave, inductive, infrared, and ohmic heating), and electric pre-concentrators (membranes).

Energy Efficiency: The most significant energy efficiency opportunities exist in the highest energy consuming food and beverage manufacturing processes: boilers, ovens, and dryers; machine drive applications (pumps, fans and blowers, air compressors, refrigeration compressors); and process integration. Energy efficiency measures can also be adopted for other non-process end uses such as heating, ventilation, and air conditioning or facility lighting.

LCFFES: The subsector already consumes a small amount of low-carbon fuels, namely sugar manufacturing which use bagasse as a fuel and other subsectors which use some wood chips and bark as fuel. Increased low-carbon fuel consumption could come from biomass for steam generation, biogas produced via anaerobic digestion in place of natural gas, and hydrogen as a fuel (which is not expected to see significant use in this subsector). Carbon capture and storage is expected to play a limited role in food and beverage manufacturing decarbonization since it is comprised of mostly small-scale, dispersed facilities and lower concentration of point-source CO_2 emissions where carbon capture and storage (CCS) would prove uneconomic. If the electrification and energy efficiency emissions reduction potential is reached, it will be less necessary to rely on sourcing energy from LCFFES (e.g., for processes that cannot be electrified).

CCUS: CCUS has limited potential in food and beverage manufacturing because the subsector is comprised of mostly small-scale, dispersed facilities and lower concentration of point-source CO_2e emissions where CCUS would not be economical. Based on analysis of EPA data,[62] CCS (using amine absorption) may be applicable for larger capturable emitters in the grains and oilseed milling and beverage manufacturing subsectors, but is expected to account for a small fraction of overall subsector emission reduction.

Material Efficiency: Material efficiency for U.S. food and beverage manufacturing is complicated as most waste occurs in the consumer stage; over 30% of food purchased for consumption ends up wasted, usually in a landfill, incinerator, or sewer.[63] Although some food waste occurs in agriculture and manufacturing, most of it is already repurposed in some way (e.g., animal feed, industrial uses, land application, anaerobic digestion). Technologies and strategies that could be employed by food growers or manufacturers to reduce consumer food waste and reduce emissions could include increased product shelf life (edible coatings, active atmosphere, and processing changes), improved packaging materials and designs, and use of

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[62] U.S. Facility Level Information on GreenHouse gases Tool (FLIGHT) | Environmental Protection Agency

[63] For more information, see Section 5 of Sustainable Manufacturing and the Circular Economy | Department of Energy

distributed or controlled environment agriculture. However, it can be difficult to quantify material efficiency measures especially if the impacts occur outside the manufacturing stage.

Category 4C: Food and Beverage Questions

The following questions are focused on food and beverage manufacturing decarbonization. Responses on cross-cutting technologies (applicable to multiple manufacturing subsectors) should be submitted in Category 1.

4C.1 How do you expect the U.S. demand and production of the subsectors studied or other food and beverage products to change by 2050 and why?

4C.2 What do you think of the net-zero subsector emissions by 2050 pathway described above and detailed in the pathways analysis summary document (if reviewed)?

4C.3 Given the heterogeneity and diversity of food and beverage products, there can be many net-zero emissions pathways (see text box on page 24). There are 10 food and beverage manufacturing 4-digit North American Industry Classification System (NAICS) subsectors.[64] What do you think are the primary pathways needed to decarbonize a specific food and beverage manufacturing subsector between now and 2050?

For each subsector for which you have knowledge or expertise, please share the following information. Please also provide any supporting references (if available).

4C.3.1 For which specific subsector (by name/4-digit NAICS code) and/or product does this response apply?

4C.3.2 What are the primary solutions/technologies necessary for that pathway? What is the likely utilization of each solutions/technology by this subsector in the near-term (now-2030), mid-term (2030-2040), and long-term (2040-2050) (such as the percent of subsector production)?

4C.3.3 What are the main factors that influence choice of this pathway at the facility level?

4C.3.4 What are the primary barriers/challenges faced by this pathway and how can they be overcome?

4C.3.5 What potential factors would hinder or maximize success of this pathway?

4C.3.6 Are there any unique barriers/challenges for this pathway?

Please answer questions 4C.3.1 through 4C.3.6 above for each subsector you are replying for.

4C.4 How do Scope 3 GHG emissions affect the food and beverage manufacturing subsector?

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[64] As defined by NAICS, food and beverage manufacturing is divided into ten subsectors and associated 4-digit codes: grain and oilseed milling (3112); sugar and confectionery products (3113); fruit and vegetable preserving and specialty food (3114); dairy product (3115); animal slaughtering and processing (3116); seafood products (3117); bakeries & tortillas (3118); other food (3119); beverages (3121); and tobacco manufacturing (3122).

4C.5 What further actions do you expect to be most impactful towards reaching net-zero emissions after the "low-hanging fruits" have been exhausted?

4C.6 What technical and/or technology solutions does the subsector need that are not currently available?

4C.7 What level of impact do you expect sustainable food packaging to have in helping the subsector reach net-zero emissions and why?

4C.8 What other solutions should be considered in characterizing/modeling a net-zero emissions food and beverage manufacturing subsector by 2050?

4C.9 What sensitivities need to be considered in characterizing/modeling a net-zero emissions food and beverage manufacturing subsector by 2050?

4C.10 Are there any other subsector-specific barriers, criteria, metrics, or targets that DOE should be aware of as a decarbonization strategy for this subsector is developed?

4D: Iron and Steel

This section provides a high-level overview of the impact of the four decarbonization pillars and material efficiency in a net-zero emissions pathway by 2050 for U.S. iron and steel manufacturing. A more detailed draft summary on IEDO's net-zero emissions pathways analysis can be found on the IEDO website.[65]

Iron and steel manufacturing is one of the most energy- and emissions-intensive industries worldwide, accounting for around a quarter of global and 9% of U.S. manufacturing GHG emissions.[66,67] The U.S. steel subsector produced 82 MMT of crude steel in 2022, about 4% of global production and the fourth-largest producer of steel in the world behind China, India, and Japan.[68]

This subsector, known for its substantial carbon footprint due to reliance on traditional emissions-intensive methods such as the blast furnace-basic oxygen furnace (BF-BOF) production route, faces increasing pressure to transition towards more low-carbon and sustainable alternatives. Around 29% of steel in the United States is produced by primary steelmaking plants using the BF-BOF production route and 71% was produced by the electric arc furnace (EAF) route (typically called secondary steelmaking), which has about a third of BF-BOF produced steel emissions intensity.[69,70] Natural gas represented the largest share of energy consumption for U.S. iron and steel manufacturing, followed by coke and breeze, electricity,

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[65] https://www.energy.gov/eere/iedo/industrial-decarbonization-pathways-modeling

[66] Iron and Steel Technology Roadmap | International Energy Agency

[67] See: Iron and Steel and All Manufacturing Energy and Carbon Footprints | Department of Energy

[68] Iron and Steel | U.S. Geological Survey

[69] Ibid.

[70] How Clean is the U.S. Steel Industry? | Global Efficiency Intelligence

blast furnace and coke oven gases, coal, and a small amount of petroleum coke, distillate fuel oil, and waste gas.[71]

A net-zero emissions iron and steel subsector will require comprehensive adoption of decarbonization technologies across all pillars. Electrification is anticipated to make a large contribution to CO_2e emissions reduction, followed by the energy efficiency and LCFFES pillars. CCUS could have a smaller impact and could be used to help decarbonize remaining BF-BOF steel plants. While significant emissions reductions could occur through the four *Roadmap* pillars, the subsector would also need adoption of alternate approaches powered by clean energy sources (e.g., negative emissions technologies) to bridge the gap and reach net-zero emissions.

Electrification: Use of EAF steel production over other routes is a form of electrification, and most U.S. steel is produced via the EAF route. Using scrap-based EAF steel production to meet any new scale-up in domestic production is likely to be more economical and environmentally beneficial than adopting other steelmaking technologies, at least in the near- to medium-term but could be limited by scrap availability and quality requirements. Emerging technologies include two primary direct electrification processes for steel production–electrolysis and electrowinning–which offer distinct approaches to transforming iron ore into liquid steel. These electrolytic processes boast potential energy efficiency and reduced capital expenditure by bypassing upstream stages required in traditional steel production routes. The technical viability of electrochemical iron production has been demonstrated in laboratory and small pilot settings and could be a transformative technology in the long term. Other subsector electrification technologies include electrifying reheating furnaces; scaling up electric induction furnaces; switching ladle and tundish heating to resistance, infrared, or plasma heating; and steel galvanizing and heat treatment processes. Because all these processes are electricity-intensive, the U.S. electric grid CO_2 emissions factor significantly influences the electrification pillar emissions projection results.

Energy Efficiency: Energy efficiency opportunities within the steel industry include specific applications in coke-making, BF ironmaking, BOF and EAF improvements, and more efficient casting and rolling processes. This could include adoption of already commercially available technologies such as coke dry quenching or top-pressure recovery turbine plants, measures such as energy management or process control, and efficiency improvements in steam, motor, pump, fan, and compressed air systems. Measures for the BF-BOF route include waste heat recovery, improved insulation, and process optimization, while EAF steelmaking could adopt

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[71] See Table 3.2 and Table 5.2 of Manufacturing Energy Consumption Survey (MECS): 2018 MECS Survey Data | Energy Information Administration; Iron and Steel Manufacturing Energy and Carbon Footprint | Department of Energy

advanced furnace technologies, improved scrap preheating processes, and optimized operational practices. Each facility will need to balance efficiency investments on existing equipment with the long-term technology needs to reach net-zero emissions to avoid creating significant capital investments in potentially stranded assets.

LCFFES: A key LCFFES pillar technology to decarbonize steel is the use of hydrogen-based direct reduced iron (DRI)-EAF steelmaking, which uses hydrogen as an alternative reductant to produce iron that is then often processed into steel in an EAF. Hydrogen-DRI has one of the highest technology readiness levels and lowest development costs when compared with other emerging decarbonization technologies for the steel industry. DRI-EAF results in lower emissions compared to the BF-BOF steel production route, and further reduction of emissions can be achieved by utilizing hydrogen as an energy source (produced from clean energy sources) and as a reducing agent for DRI production (releasing water instead of CO_2).

CCUS: Post-combustion carbon capture could be used to decarbonize existing U.S. BF-BOF steel plants especially for those with a common flue stack for multiple processes. Natural gas-based DRI production can be retrofitted with post-combustion carbon capture. There are also CCUS applications for smelting reduction as well as reheating.

Material Efficiency: For iron and steel production, material efficiency can be a significant decarbonization lever. Multiple strategies exist in each product life-cycle stage, ranging from:

- Steel product design (e.g., improving design to have lighter products, optimizing to minimize material use, design for longer life, reusability, and ease of high-quality recycling)
- Steel product manufacturing (e.g., improving material efficiency in the production and fabrication processes, increasing material waste recycling)
- Steel product use (e.g., extending the building and product lifetime, intensifying product use, and switching to other low-carbon alternative materials, such as mass timber for certain kinds of buildings)
- Steel product end-of-life (e.g., increasing building component direct reuse, increasing the recycling rate of steel products, and remanufacturing of steel products)

Recycling scrap to make steel saves virgin raw materials as well as the energy required for converting them and reduces the CO_2 intensity of steel production. Steel is already considered a highly-recycled metal (69% in 2019),[72] but there are opportunities for that to increase while limited by scrap availability and quality. Scrap-based EAF steel production, which is already

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[72] American Iron and Steel Institute and Steel Manufacturers Association. 2021. "Technical Report: Determination of Steel Recycling Rates in the United States." https://www.steel.org/wp-content/uploads/2021/08/AISI-and-SMA-Steel-Recycling-Rates-Report-Final-07-27-2021.pdf.

widespread in the United States, would be classified as a material efficiency technology and can use a wide range of scrap types. However, the increase in scrap-based EAF could be limited by the availability of higher-quality scrap.

Category 4D: Iron and Steel Questions

The following questions are focused on iron and steel manufacturing decarbonization. Responses on cross-cutting technologies (applicable to multiple manufacturing subsectors) should be submitted in Category 1.

4D.1 How do you expect the U.S. demand and production of steel (and specific steel grades) to change by 2050 and why?

4D.2 What do you think of the net-zero subsector emissions by 2050 pathway described above and detailed in the pathways analysis summary document (if reviewed)?

4D.3 What do you think are the primary production routes needed to decarbonize the iron and steel subsector between now and 2050?

For each route for which you have knowledge or expertise, please share the following information. Please also provide any supporting references (if available).

4D.3.1 What are the primary solutions/technologies necessary for that production route?

4D.3.2 What is the likely utilization of that route in the near-term (now-2030), mid-term (2030-2040), and long-term (2040-2050) (such as the percent of steel production)?

4D.3.3 What are the main factors that influence choice of this production route at the facility level?

4D.3.4 What are the primary barriers/challenges faced by this route and how can they be overcome?

4D.3.5 What potential factors would hinder or maximize success of this production route?

4D.3.6 Are there any unique barriers/challenges that may limit implementation of this production route?

Please answer questions 4D.3.1 through 4D.3.6 above for each production route you are replying for.

4D.4 What specific barriers or risks do you expect from the increased consumption of scrap for U.S. steelmaking?

4D.5 What technical and/or technology solutions does the subsector need that are not currently available?

4D.6 What other solutions should be considered in characterizing/modeling a net-zero emissions iron and steel subsector by 2050?

4D.7 What sensitivities should be considered in characterizing/modeling a net-zero emissions iron and steel subsector by 2050?

4D.8 Are there any other subsector-specific barriers, criteria, metrics, or targets that DOE should be aware of as a decarbonization strategy for this subsector is developed?

4E: Pulp and Paper

This section provides a high-level overview of the impact of the four decarbonization pillars and material efficiency in a net-zero emissions pathway by 2050 for U.S. pulp and paper manufacturing. A more detailed draft summary on IEDO's net-zero emissions pathways analysis can be found on the IEDO website.[73]

The pulp and paper industry creates a wide variety of products, including graphic papers, newsprint, containerboard, linerboard, tissue, and specialty paper. In 2022, the United States produced approximately 65.3 million metric tons of paper and paperboard which constituted about 23.6% of global paper and paperboard production.[74] Over time, relative proportions of different pulp and paper products have changed. Recent years have seen a growth in digital and electronic media, leading to a decrease in newsprint and graphic papers. On the other hand, there has been a growth in hygiene- and packaging-related products due to COVID and the explosion of e-commerce.

The pulp and paper subsector accounts for 7% of total manufacturing emissions. The subsector consumes a substantial amount of biomass-based fuels, such as pulping liquor and waste wood, that emit biogenic emissions.[75] The pulp and paper industry has consistently reduced its energy and emissions intensity over time with the use of energy efficiency principles, fuel switching, combined heat and power, and increased recycling. Biobased fuels (pulping/black liquor and biomass) are the largest source of energy (65%), followed by natural gas (30%), and other fuels (5%). This results in substantial biogenic emissions, with some estimating up to 50%,[76] which are broadly considered net-zero due to CO_2 uptake during biomass growth.

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[73] https://www.energy.gov/eere/iedo/industrial-decarbonization-pathways-modeling

[74] Statista Research. 2024. "U.S. pulp and paper industry - statistics & facts." https://www.statista.com/topics/5268/us-pulp-and-paper-industry/.

[75] Tomberlin, Kristen E., Richard Venditti, and Yuan Yao. 2020. "Life Cycle Carbon Footprint Analysis of Pulp and Paper Grades in the United States Using Production-Line-Based Data and Integration." *BioResources* 15 (2): 3899–3914. https://doi.org/10.15376/biores.15.2.3899-3914.

[76] Ibid.

A net-zero pulp and paper subsector will require a comprehensive adoption of decarbonization technologies across all pillars. The relative impact of each pillar can vary depending upon assumptions made on the level of biomass availability to replace natural gas consumption (which would fall under the LCFFES pillar) – in a scenario where there is less available biomass for non-integrated mills, increased electrification through technologies like electric boilers would be needed to help reach net-zero emissions. The energy efficiency and CCUS pillars could play a more minor but still important emissions reductions role within the subsector.

LCFFES: At the mill-level, major emissions sources include process heat, steam generation, and cogeneration. Increasing the share of biobased fuels for these purposes could be expected to have significant emissions reduction impact by replacing a large portion of natural gas consumption. However, availability is a growing concern, especially as biomass is being targeted for several different applications, including sustainable aviation fuel. Reduced boiler efficiency when utilizing biomass is also a challenge, due to moisture content and biomass quality.

CCUS: Carbon capture is a unique opportunity for the pulp and paper subsector. Because most combusted fuel is biobased and considered zero-emission, capturing more than 25% CO_2 in this subsector represents an indirect removal of atmospheric CO_2. Despite this foreseeable benefit, there are currently no CCUS projects in the pulp and paper industry due to cost and infrastructure challenges.

Energy Efficiency: Energy efficiency could provide modest levels of emissions reductions subsector-wide and remains a key component in a net-zero pathway. This would include adoption of technologies such as waste heat recovery, advanced monitoring controls and digitalization, combined heat and power, and membrane concentration of black liquor.

Electrification: Electrification technology opportunities for the pulp and paper subsector are electrification of the auxiliary boilers in the pulping mills and downstream paper production processes, especially for non-integrated paper mills. Steam-generating heat pumps can also be utilized instead of electric boilers and supplement the steam from recovery boilers.
Finally, efficiency improvements and electrification are expected to provide modest decarbonization potential. The typical opportunities to reduce emissions apply, including increasing process and material efficiency, electrifying steam generation, recovering waste heat, implementing advanced controls and digitalization, and looking at alternative processes.

Material Efficiency: Some material efficiency technologies can influence demand in the subsector. Increased circularity is reflected in significant market share and overall production

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increases for modeled recycled mills, with traditional integrated mills (bleached and non-bleached) showing declines such that overall demand shows a modest increase.

Category 4E: Pulp and Paper Questions

The following questions are focused on pulp and paper manufacturing decarbonization. Responses on cross-cutting technologies (applicable to multiple manufacturing subsectors) should be submitted in Category 1.

4E.1 How do you expect the U.S. demand and production of paper and paperboard (and shifts in integrated or non-integrated mills) to change by 2050 and why?

4E.2 What do you think of the net-zero subsector emissions by 2050 pathway described above and detailed in the pathways analysis summary document (if reviewed)?

4E.3 Given the heterogeneity and diversity of pulp and paper mill and product types,[77] there are various net-zero emissions pathways (see text box on page 24). What do you think are the primary pathways needed to decarbonize a specific mill or product type between now and 2050?

For each mill and/or product type for which you have knowledge or expertise, please share the following information. Please also provide any supporting references (if available).

4E.3.1 For which mill and/or product type does this pathway apply?

4E.3.2 What are the primary solutions/technologies necessary for that pathway? What is the likely utilization of each solutions/technology by this subsector in the near-term (now-2030), mid-term (2030-2040), and long-term (2040-2050) (such as the percent of subsector production)?

4E.3.3 What are the main factors that influence choice of this pathway at the facility level?

4E.3.4 What are the primary barriers/challenges faced by this pathway and how can they be overcome?

4E.3.5 What potential factors would hinder or maximize success of this pathway?

4E.3.6 Are there any unique barriers/challenges for this pathway?

Please answer the questions 4E.3.1 through 4E.3.6 above for each mill and/or product type you are replying for.

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[77] The different type of mills modeled for this subsector include market pulp mill; tissue mill; specialty mill; recycled mill; bleached integrated mill; and unbleached integrated mill.

4E.4 What technical and/or technology solutions does the subsector need that are not currently available?

4E.5 What other solutions should be considered in characterizing/modeling a net-zero emissions pulp and paper manufacturing subsector by 2050?

4E.6 What sensitivities should be considered in characterizing/modeling a net-zero emissions pulp and paper manufacturing subsector by 2050?

4E.7 Are there any other subsector-specific barriers, criteria, metrics, or targets that DOE should be aware of as a decarbonization strategy for this subsector is developed?

4F: Petroleum Refining

This section provides a high-level overview of the impact of the four decarbonization pillars and material efficiency in a net-zero emissions pathway by 2050 for U.S. petroleum refining. A more detailed draft summary on IEDO's net-zero emissions pathways analysis can be found on the IEDO website.[78]

Petroleum refining plays a key role in the energy supply chain by delivering transportation and industrial fuels, petrochemical feedstocks, and other value-added products. U.S. petroleum refineries process over 16 million barrels of crude resources per day to produce liquid transportation fuels and other refined products.[79] In 2018, refining accounted for about 21% of total U.S. manufacturing GHG emissions.[80] The industry is highly integrated, efficient, and complex, which presents a challenge to decarbonize due to fundamental technical and economic factors. Additionally, combustion emissions from refinery products at their end use (e.g., gasoline consumed by a vehicle) are far greater than the Scope 1 and 2 emissions from the creation of those products at refineries. Importantly, the refining process produces abundant but low value self-generated byproduct fuels making many decarbonization measures economically challenging.

A net-zero emissions by 2050 pathway for petroleum refining would likely include widespread adoption of carbon-neutral feedstocks, including alternatives to fossil-based crudes and hydrogen. Energy efficiency gains might incremental and carbon capture opportunities would be most relevant for only large and high-return process units (e.g., steam methane reformers, cogeneration, fluid catalytic cracking). Electrification may have smaller impacts in the subsector, unless low-cost, carbon-free electricity improves the competitiveness of electrified processes. Alternate approaches, powered by clean energy sources, outside the four *Roadmap* pillars will also be needed to bridge the remaining gap and reach net-zero emissions.

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[78] https://www.energy.gov/eere/iedo/industrial-decarbonization-pathways-modeling

[79] Refinery & Blender Net Input | Energy Information Administration

[80] See All Manufacturing and Petroleum Refining Energy and Carbon Footprints | Department of Energy.

Additionally, the application of refinery decarbonization pathways will impact GHG emissions both upstream in crude production as well as in eventual combustion of refinery products.

Energy Efficiency: Increasing energy efficiency is a critical component to refinery decarbonization since it is typically cost-effective and reduces reliance on other decarbonization pillar impacts. Over the past decade, the refinery energy efficiency has improved but significant potential remains. A few typical energy efficiency applications for refineries include: combined heat and power, advanced heat exchanger and furnace designs, waste heat recovery, digitalization and advanced controls, strategic energy management, and process integration.

Electrification: Electrification may play a limited role due to the high thermal loads for refineries, high relative cost of electricity compared to other fuels, and lack of significant efficiency or productivity benefits. However, low-cost, carbon-free electricity may increase the electrification potential for some unit operations, such as process heating, separations, and chemical conversions. Other specific opportunities would be electrification of rotating equipment energy and specialty applications or replacing conventional thermal-catalytic process technologies with more electrochemical based conversion technology. Consumption of hydrogen produced from electrolysis with clean electricity would fall under the electrification pillar.

LCFFES: Because the refining subsector is a major consumer of hydrogen as feedstock for hydrotreating, decarbonizing hydrogen production will be a critical component to decarbonizing the subsector. However, emissions savings would actually be accounted for under electrification and CCUS (see above and below). There could be small emissions savings from the production of renewable diesel and sustainable aviation fuel as biorefinery waste gases combusted for fuel containing biogenic CO_2 emissions, which can be considered net-zero. Other LCFFES opportunities include combustion of biomethane/biogas in place of natural gas or use of cogeneration using clean energy sources (e.g., small modular nuclear reactors, solar, geothermal).

CCUS: Carbon capture opportunities in refining may focus on a few individually large processes (hydrogen production and cogeneration) and fluid-catalytic-cracking units. Broad-based carbon capture is limited by physical space onsite and low economies of scale. Technologies such as carbon capture will reduce emissions from refining and could also be applied to fossil and sustainable oil production; however, the use of sustainable oil substitutes in even small percentages can have large impacts on the emissions reduction associated with the fuel use due to upstream CO_2 uptake. Consumption of hydrogen produced from natural gas with carbon capture would fall under this pillar.

Category 4F: Petroleum Refining Questions

The following questions are focused on petroleum refining decarbonization. Responses on cross-cutting technologies (applicable to multiple manufacturing subsectors) should be submitted in Category 1.

4F.1 How do you expect the U.S. demand and production of petroleum refining products to change by 2050 and why?

4F.2 What do you think of the net-zero subsector emissions by 2050 pathway described above and detailed in the pathways analysis summary document (if reviewed)?

4F.3 Given petroleum refining is highly integrated and produces a wide range of products (including predominantly transportation fuels) from fossil-based inputs, what do you think are the primary pathways (definition on page 24) needed to decarbonize the subsector between now and 2050? If there are specific unit operations that have the potential to significantly reduce their operational emissions, please identify and describe those below.

For each pathway (and relevant unit operations), please share the following information. Please also provide any supporting references (if available).

4F.3.1 What are the primary solutions/technologies necessary for that pathway? What is the likely utilization of each solutions/technology by this subsector in the near-term (now-2030), mid-term (2030-2040), and long-term (2040-2050) (such as the percent of subsector production)?

4F.3.2 What are the main factors that influence choice of this pathway at the refinery level?

4F.3.3 What are the primary barriers/challenges faced by this pathway and how can they be overcome?

4F.3.4 What potential factors would hinder or maximize success of this pathway?

4F.3.5 Are there any unique barriers/challenges for this pathway?

Please answer the questions 4F.3.1 through 4F.3.5 above for each pathway you are replying for.

4F.4 What technical and/or technology solutions does the subsector need that are not currently available?

4F.5 What other solutions should be considered in characterizing/modeling a net-zero emissions refining subsector by 2050?

4F.6 What sensitivities should be considered in characterizing/modeling a net-zero emissions refining subsector by 2050?

4F.7 Are there any other subsector-specific barriers, criteria, metrics, or targets that DOE should be aware of as a decarbonization strategy for this subsector is developed?

4G: Rest of Industry (Other Manufacturing; Agriculture and Forestry; Mining, Oil, and Gas; Construction; Data Centers; and Water and Wastewater Treatment)

This section provides a high-level overview on the rest of industry and relevant decarbonization pathways and opportunities. Though these subsectors have not yet been modeled in detail, more information can be found in the detailed draft summary on IEDO's net-zero emissions pathways analysis can be found on the IEDO website.[81]

Beyond the six manufacturing subsectors covered above, the "rest of industry" is large and diverse, representing a footprint of over just under half of the industrial sector's energy-related emissions in 2018 as shown in Figure 1. "Rest of industry" is defined as other manufacturing (the rest of the manufacturing subsector excluding cement, chemicals, food and beverage, iron and steel, pulp and paper, and petroleum refining), the nonmanufacturing subsector (agriculture and forestry; mining, oil, and gas; and construction), data centers, and water and wastewater treatment. Each subsector is briefly described below, followed by a summary of decarbonization pathways and opportunities. Specific net-zero emissions pathways and models have not yet been identified and modeled in detail for the rest of industry, so the pathways and opportunities are described in general.

Other Manufacturing

"Other manufacturing" includes the manufacturing subsectors other than the six covered in detail above. The GHG emissions in other manufacturing accounted for 21% of total manufacturing emissions in 2018, and includes transportation equipment (including car and truck manufacturing) (2.8% of total manufacturing emissions), plastics (2.3%), electronics (2.1%), fabricated metals (2.1%), aluminum (primary and secondary) (1.8%), glass (1.3%), machinery (1.2%), textiles (0.8%), and foundries (0.6%) manufacturing subsectors.[82]

Process heating systems and thermal loads are vital in these subsectors for different operations (e.g., melting, heat treatment, molding, soldering, and drying). These processes require significant energy inputs, typically achieved through the combustion of fossil fuels or use of steam, and lead to substantial GHG emissions. The high temperatures needed for melting

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[81] https://www.energy.gov/eere/iedo/industrial-decarbonization-pathways-modeling

[82] Manufacturing Energy and Carbon Footprints | Department of Energy

metals like recycled aluminum, shaping plastics, or curing paints in automotive production not only contribute to direct emissions from furnaces and heaters but also to indirect emissions associated with steam consumption. The challenge for these subsectors is to balance the essential need for precise temperature control and thermal processing with the urgent need to reduce their carbon footprint while also maintaining production quality and efficiency.

Agriculture and Forestry

Agriculture and forestry involve the raising and harvesting of crops, animals, and timber. As noted in the food and beverage manufacturing section above, the U.S. food supply chain is composed of multiple stages beginning with agriculture and followed by manufacturing (where products are packaged and prepared for eventual consumption), wholesale and retail, and consumption (both at homes and food services). Additional areas of the supply chain with non-negligible energy consumption and emissions (and for which data generally is not available) include post-harvest processing (between manufacturing and agriculture) and warehousing (between manufacturing, wholesale, and retail). Because the food supply chain is so interconnected, it can be difficult to account for decarbonization impacts within only one specific stage. Additionally, there are significant data gaps within food and beverage manufacturing and across the entire supply chain.

Agriculture and forestry non-energy related emissions were significantly larger than energy-related emission in this subsector by almost a factor of seven in 2018. Beef cattle was responsible for the largest share of both energy-related and non-energy related emissions at over a third of the subsector total. Large contributors were methane emissions associated with enteric fermentation from feed digestion and nitrous oxide emissions from soil in pasturelands. Poultry and eggs were the next largest at 15% of subsector emissions and corn at 10%. Those three in combination were about half of all agricultural emissions. Indirect emissions from generation of purchased electricity were the largest energy-related source followed closely by diesel fuel combustion.

Outdoor operations, such as those for grains, livestock, and forestry, typically favor diesel fuel for energy consumption, mostly used for mobile equipment. Indoor operations, like nurseries and greenhouses, predominantly consume natural gas for space heating. Others, such as dairy, poultry, and eggs rely significantly on electricity for space cooling, lighting, and refrigeration. Subsector-wide, irrigation constitutes about one-seventh of agriculture and forestry energy consumption, over half of which is electricity and nearly a third is natural gas. Notably, agriculture and forestry products contribute about 5% of domestic energy production including ethanol, biodiesel and renewable diesel, biogas, and fuel wood. The industrial sector consumes almost half of this energy, primarily through combustion of wood and wood waste in wood products and paper industries, and the transportation sector consumed the next most at about one-third, primarily through biofuels.[83] Expansion of the bioenergy economy is an important decarbonization opportunity for this subsector. Additionally, some decarbonization technology opportunity areas that may overlap with the manufacturing subsector might include distributed or controlled environment agriculture, agrivoltaics, and others.

Mining, Oil, and Gas

Mining, oil, and gas involve the extraction of energy, metallic and non-metallic minerals, and other resources from the Earth's surface and underground. Emissions come from a combination of onsite fuel combustion, offsite grid electricity, and fugitive releases and non-energy combustion such as flaring. Natural gas extraction was by far the largest source of GHG emissions at over half of the subsector total. Oil extraction was one-quarter of emissions, coal mining about one-sixth, and the rest of mining at one-twelfth. Within oil and gas, non-energy related emissions were larger than energy related emission by almost two-to-one. Most of those emissions were due to the leakage of methane. Energy use comes mostly from the combustion of self-produced lease and plant fuels.[84]

For coal mining, non-energy related emissions, also mostly related to methane leakage, was higher than energy related emissions by over eight-to-one. Within oil and gas, most energy use was for motor drives to run drilling equipment, pumps, and compressors. Across the subsector, fuel use for off-grid generators was also a significant consumer of energy. Within mining, energy use varies significantly from site to site; though on average about half of energy use is for drilling, blasting, digging, and extracting ore including various equipment for materials handling and ancillary demands (e.g., ventilation and dewatering), and the other half of energy use is for concentration. This latter stage separates barren waste rock from valuable minerals through crushing and grinding followed by physical (e.g., gravity, floatation, magnetic) and chemical (e.g., froth floatation, leaching) separation.

Construction

Construction includes establishments engaged in the construction and engineering of residential and non-residential buildings, as well as infrastructure such as highways and utility system. Most emissions come from fuel combustion in mobile equipment for excavation, grading, materials handling, transportation, and so forth. In 2018, an estimated three-quarters were from gasoline and diesel fuel, which also include other smaller uses such as onsite electricity generation. The next largest source was indirect emissions associated with purchased

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[83] Biomass explained | U.S. Energy Information Administration

[84] As defined by EIA, lease and plant fuels are "natural gas used in well, field, and lease operations (such as gas used in drilling operations, heaters, dehydrators, and field compressors) and as fuel in natural gas processing plants." https://www.eia.gov/tools/glossary/index.php?id=Lease.

electricity at about 15%, which is typically used for tools and other equipment as well as worksite lighting. The remaining were from natural gas, lubricants, and other fuels. Natural gas and other manufactured gases are often used to provide temporary space heating for worksites and the proper curing of concrete during the colder times of the year.

In addition to energy, the construction subsector consumes significant amounts of materials such as sand, stone, and gravel used in site work and concrete mix, precast concrete and cement, steel for structural members, rebar, and framing, and many others. These materials have large energy and environmental footprints, and the construction industry could play an important role in motivating low GHG emissions intensive manufacturing. Finally, construction and demolition waste are substantial, more than twice that of municipal solid waste by weight,[85] and resource circularity could be an important way to decarbonization economy wide.

Data Centers

Data centers revolve around information technology infrastructure including servers, storage, networking equipment, and supporting auxiliary equipment. These buildings consume 10 to 50 times more energy per floor space compared to a typical commercial building and account for about 2% of total U.S. electricity consumption.[86] Emissions estimates focus on electricity consumption for operation of electronic equipment (e.g., servers, data storage, and networking) and infrastructure such as for equipment cooling, space conditioning, and power conversion. About half of energy use is for servers, a third for infrastructure, and most of the remaining sixth is for data storage.

Shipments of data center equipment have grown rapidly over the past years, though energy consumption has not grown proportionally. Equipment has become more efficient, for example through smaller transistor sizes in microchips and solid-state storage mediums, and more advanced power conversion devices. Data centers have also grown larger with higher utilization levels, leading to economies of scale and more efficient cooling.[87] While data centers constitute a significant driver of electricity demand growth, their impact is complex and related to the broader role information technology plays across the energy economy. Furthermore, as individual data centers grow, their local impacts on power system infrastructure may inhibit subsector growth or incentivize demand-side management to reduce peak loads and provide load flexibility.

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[85] Construction and Demolition Debris: Material-Specific Data | Environmental Protection Agency

[86] Data Centers and Servers | Department of Energy

[87] Shehabi, Arman et al. 2016. *United States Data Center Energy Usage Report.* https://www.osti.gov/biblio/1372902.

Water and Wastewater Treatment

The water and wastewater treatment subsector is associated with the delivery of water to building and facilities and the management of wastewater to remove contaminants and hazardous material before disposal or return to the water supply. Commercial and industrial wastewater treatment accounted for a total of 100 MMT CO_2e emissions in 2018 (less than 1% of total U.S. emissions).[88] The energy-related emissions are mainly from the electricity consumed for pumping water. Pumps also employ other fuels, particularly for industrial applications. In the western United States, water is also transported long distances to connect supply and demand.[89] Within treatment plants, removal of unwanted materials to meet water quality standards involves a series of stages from settling tanks and screening to remove large solids and aeration to accelerate microbial activity and the breakdown of organic matter. Subsequent stages could include filtration and ultraviolet disinfection. The remaining sludge is either burned, buried, sold as product (e.g., fertilizer), or sent to an anaerobic digestor for biogas production.[90]

The treatment of wastewater commonly leads to methane emissions as biogenic material breaks down under anaerobic conditions. Industrial wastewater treatment may have specialized methods to remove materials related to the source industry. From a facility perspective, these methane emissions can be far larger than the indirect emissions from electricity use.[91] Beyond subsector energy consumption and emissions, there are broader issues around water security, calls for greater circularity in water use, and needs for water by other sources, such as desalination of brackish water.

Decarbonization Pathways and Opportunities

Each subsector has a unique energy profile regarding major energy consuming processes and equipment, types of non-energy related emissions, and decarbonization opportunities, some of which overlap with those already discussed in the manufacturing subsectors above.

In the short term, decarbonization pathways might include deployment of energy efficiency measures across multiple subsectors (such as waste heat recovery, smart manufacturing, strategic energy management, and improving efficiency of energy support systems); addressing fugitive methane emissions in the mining, oil, and gas subsector; utilizing onsite renewable

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[88] 2018 electricity consumption estimated at 120 TWh/year from Water & Sustainability (Volume 4): U.S. Electricity Consumption for Water Supply not including irrigation and livestock which is included in Agriculture and Forestry. Fugitive emissions of 42.5 MMT CO_2 Eq. in 2018 from domestic and industrial wastewater treatment from Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2021 – Main Report (epa.gov)

[89] Geographic Footprint of Electricity Use for Water Services in the Western U.S. (Journal Article) | OSTI.GOV

[90] Opportunities for Recovering Resources from Municipal Wastewater (Technical Report) | OSTI.GOV

[91] Song, Cuihong et al. 2023. "Methane Emissions from Municipal Wastewater Collection and Treatment Systems." https://pubs.acs.org/doi/10.1021/acs.est.2c04388 https://doi.org/10.1021/acs.est.2c04388.

generation (e.g., solar, wind); electrifying drilling equipment, pumps, and compressors; and switching to available sustainable low-carbon fuel and feedstock sources.

Medium term decarbonization actions might include:

- Process emissions reductions (e.g., from the use of inert anodes)
- Material circularity increases (e.g., increased recycling)
- Supply chain decarbonization (e.g., adopting sustainable agriculture processes)
- Mobile equipment hybridization and electrification (especially in construction, mining, and agriculture)
- Improved agriculture practices adoption (e.g., soil management, optimized fertilizer application)
- Broader mining supply chain electrification (e.g., electrowinning for mineral processing, producing more direct reduced iron for the steel subsector)
- Use of feed additives for livestock to reduce methane emissions
- Increased bioenergy and bioproducts production.

Carbon capture and sequestration would have limited impact in the oil and gas subsector (e.g., at natural gas processing plants and switching from terrestrial to anthropogenic CO_2 sources for enhanced oil recovery and developing ways to ensure long term sequestration).

Longer term decarbonization pathways will depend on what is adopted in the short and medium terms. Additional information and input are needed to better understand and estimate the net-zero pathways for the rest of industry to help the industrial sector as a whole reach net-zero emissions by 2050 and what unique challenges and barriers those pathways may face.

Category 4G: Rest of Industry Questions

The following questions are focused on "rest of industry"[92] decarbonization. Responses on cross-cutting technologies (applicable to multiple manufacturing subsectors) should be submitted in Category 1.

4G.1 Which part(s) of the "rest of industry" do you expect to grow or shrink in production and/or demand by 2050 and why?

4G.2 What do you think are the primary pathways (definition on page 24) needed to decarbonize any specific "rest of industry" subsector between now and 2050? Please

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[92] Includes other manufacturing (the rest of the manufacturing subsector excluding cement, chemicals, food and beverage, iron and steel, pulp and paper, and petroleum refining); agriculture and forestry; mining, oil, and gas; construction; data centers; and water and wastewater treatment.

provide the subsector(s) to which your answer applies, details on technologies or approaches needed, and any references (if available).

4G.3 What technical and/or technology solutions does any specific “rest of industry” subsector need that are not currently available?

4G.4 What solutions should be considered in characterizing/modeling the net-zero emissions “rest of industry” subsectors by 2050?

4G.5 What sensitivities should be considered in characterizing/modeling the net-zero emissions “rest of industry” subsectors by 2050?

4G.6 Are there any other subsector-specific barriers, criteria, metrics, or targets that DOE should be aware of as a decarbonization strategy for any specific “rest of industry” subsector is developed?

Disclaimer and Important Notes

This RFI is not a Funding Opportunity Announcement (FOA); therefore, EERE is not accepting applications at this time. EERE may issue a FOA in the future based on or related to the content and responses to this RFI; however, EERE may also elect not to issue a FOA. There is no guarantee that a FOA will be issued as a result of this RFI. Responding to this RFI does not provide any advantage or disadvantage to potential applicants if EERE chooses to issue a FOA regarding the subject matter. Final details, including the anticipated award size, quantity, and timing of EERE funded awards, will be subject to Congressional appropriations and direction.

Any information obtained as a result of this RFI is intended to be used by the Government on a non-attribution basis for planning and strategy development; this RFI does not constitute a formal solicitation for proposals or abstracts. Your response to this notice will be treated as information only. EERE will review and consider all responses in its formulation of program strategies for the identified materials of interest that are the subject of this request. EERE will not provide reimbursement for costs incurred in responding to this RFI. Respondents are advised that EERE is under no obligation to acknowledge receipt of the information received or provide feedback to respondents with respect to any information submitted under this RFI. Responses to this RFI do not bind EERE to any further actions related to this topic.

Confidential Business Information

Pursuant to 10 CFR 1004.11, any person submitting information that he or she believes to be confidential and exempt by law from public disclosure should submit via email two well-marked copies: one copy of the document marked “confidential” including all the information believed to be confidential, and one copy of the document marked “non-confidential” with the information believed to be confidential deleted. DOE will make its own determination about the confidential status of the information and treat it according to its determination.

Evaluation and Administration by Federal and Non-Federal Personnel

Federal employees are subject to the non-disclosure requirements of a criminal statute, the Trade Secrets Act, 18 USC 1905. The Government may seek the advice of qualified non-Federal personnel. The Government may also use non-Federal personnel to conduct routine, nondiscretionary administrative activities. The respondents, by submitting their response, consent to EERE providing their response to non-Federal parties. Non-Federal parties given access to responses must be subject to an appropriate obligation of confidentiality prior to being given the access. Submissions may be reviewed by support contractors and private consultants.

Request for Information Response Guidelines

Responses to this RFI must be submitted electronically to Transforming-Industry@ee.doe.gov no later than 5 p.m. ET on June 24, 2024. Responses must be provided as attachments to an email. It is recommended that attachments with file sizes exceeding 25MB be compressed (i.e., zipped) to ensure message delivery. Responses must be provided as a Microsoft Word (.docx) attachment to the email, and no more than 50 pages in length, 12-point font, 1-inch margins. Only electronic responses will be accepted.

Please identify your answers by responding to a specific question or topic if applicable. Respondents may answer as many or as few questions as they wish.

EERE will not respond to individual submissions or publish publicly a compendium of responses. A response to this RFI will not be viewed as a binding commitment to develop or pursue the project or ideas discussed.

Respondents are requested to provide the following information at the start of their response to this RFI:

- Company / institution name
- Company / institution contact
- Contact's address, phone number, and e-mail address
- Type of company/institution you represent (institution of higher education [IHE]; Indian Tribe; for-profit entity; agency of Federal, State, or local government; federally funded research & development center [FFRDC]; other Federal Laboratory; nonprofit organization; or other [please specify if other])

- Briefly describe your company/institution and its role in industrial decarbonization
- Briefly describe your role in the company/institution.

This is a Request for Information (RFI) only. EERE will not pay for information provided under this RFI and no project will be supported as a result of this RFI. This RFI is not accepting applications for financial assistance or financial incentives. EERE may or may not issue a Funding Opportunity Announcement (FOA) based on consideration of the input received from this RFI.