Transforming Industry: Strategies for Decarbonization

Workshop Pre-read

May 14-15, 2024
Arlington, VA

Table of Contents

List of Figures

Purpose

The information herein is provided in advance of the May 14th-15th, 2024 *Transforming Industry: Strategies for Decarbonization* Workshop.[1] The goal is to give participants an opportunity to prepare before arrival and ensure a productive workshop.

Additional information will soon be available in a *Pathways Analysis Summary* on six industrial subsectors (cement, chemicals, food and beverage, iron and steel, petroleum refining, and pulp and paper) and a high-level review of the rest of industry (which includes other manufacturing, nonmanufacturing (agriculture and forestry; mining, oil, and gas; and construction), data centers, and water and wastewater treatment.

Introduction

The Challenge of Industrial Decarbonization

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

[1] U.S. Department of Energy Workshop on Transforming Industry: Strategies for Decarbonization | Department of Energy

[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

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.

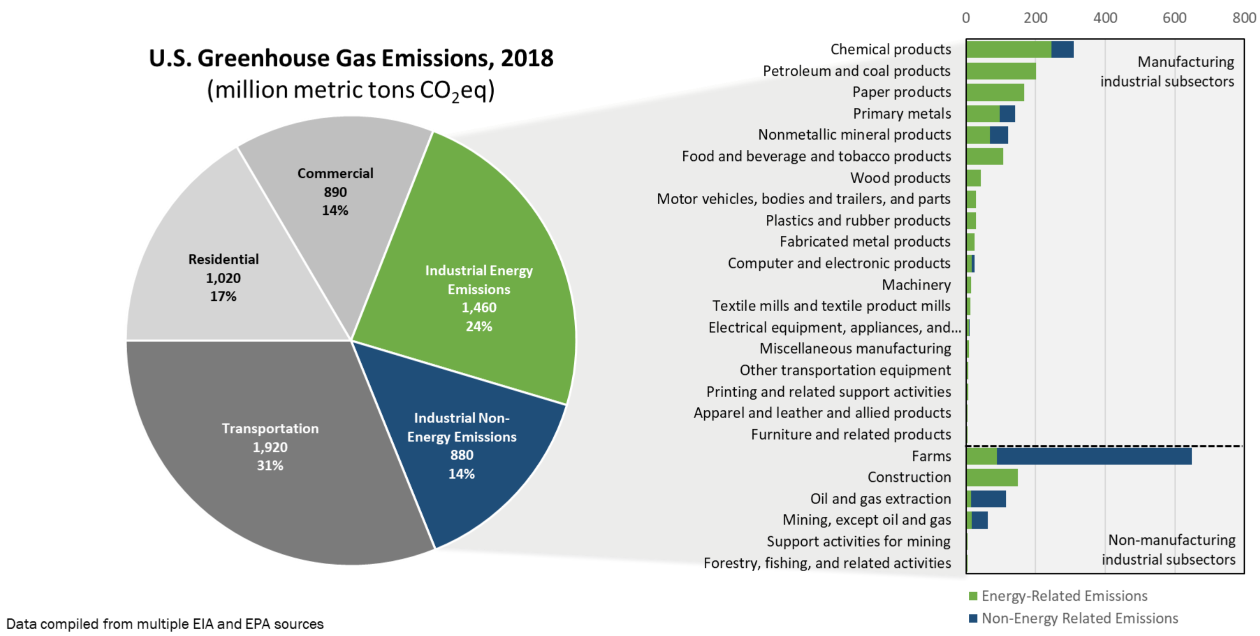

Figure 1. U.S. GHG emissions in 2018 by economic sector (left pie chart) and a breakout by industrial subsector (right bar chart) in million metric tons carbon dioxide (CO_2)-equivalent (MMT CO_2e)

Also provides percent contribution of that sector to the whole economy's emissions. 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

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

designated as Disadvantaged Communities, who both bear the brunt of the pollution burden that these 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.

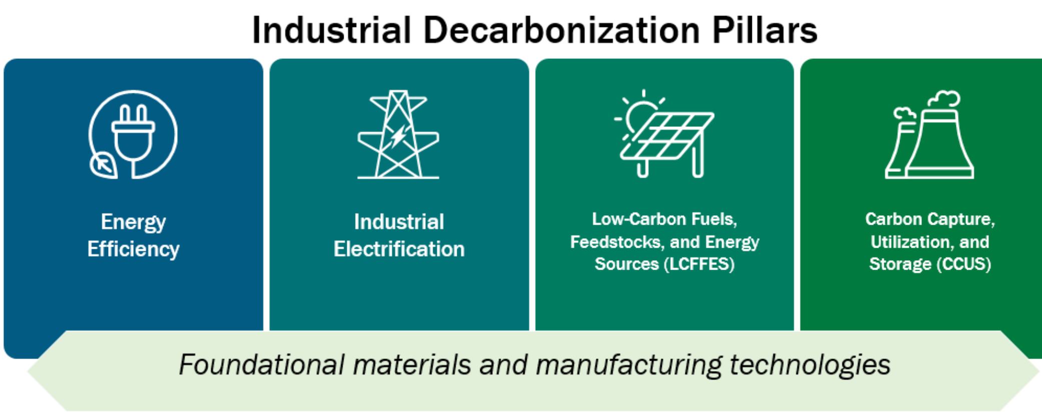

Figure 2. Pillars of industrial decarbonization from the Industrial Decarbonization Roadmap[13]

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).

---

[11] Justice40 Initiative | U.S. Department of Energy
[12] Industrial Decarbonization Roadmap | Department of Energy
[13] Ibid.

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

Other industrial decarbonization-related 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, 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.

[14] Pathways to Commercial Liftoff | Department of Energy

[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

Pathways

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:

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,

- 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 leading this vision study and 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. This vision study also involves collaboration across the Federal government, including with the Environmental Protection Agency, the Department of Commerce, the National Institute of Standards and Technologies, the General Services Administration, the Department of Transportation, the Department of Homeland Security, the National Aeronautics and Space Administration, the Department of Agriculture, the Department of Defense, the 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.

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.[21] To do so, the United States needs to develop and implement advanced manufacturing technologies, grow the advanced manufacturing workforce, and build resilient supply chains.[22] 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[23] 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,[24] 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

[21] National Strategy for Advanced Manufacturing | Office of Science and Technology Policy
[22] Ibid.
[23] Environmental Justice | Environmental Protection Agency
[24] Report to the President on Accelerating U.S. Advanced Manufacturing | President's Council of Advisors on Science and Technology

industrial technologies across the Department through Joint Strategy and Planning[25] is aligned with this vision.

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 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.[26] 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

[25] See information about DOE's joint strategy planning: Industrial Technology Programs across the U.S. Department of Energy
[26] See the All Manufacturing Energy and Carbon Footprint | Department of Energy

- 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 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.[27] Further development of metrics and methodologies to evaluate social and environmental impacts can guide industry towards a sustainable and just energy transition.

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. Example net-zero emissions pathways for six manufacturing subsectors have been

[27] 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.

outlined and detail will be provided in a *Pathways Analysis Summary* to be shared soon. This document also introduces pathways considerations 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. We are looking for 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 3. The specific approach to making technology choices for a particular industry or facility may deviate from the general decision tree shown in Figure 3. 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 3 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.

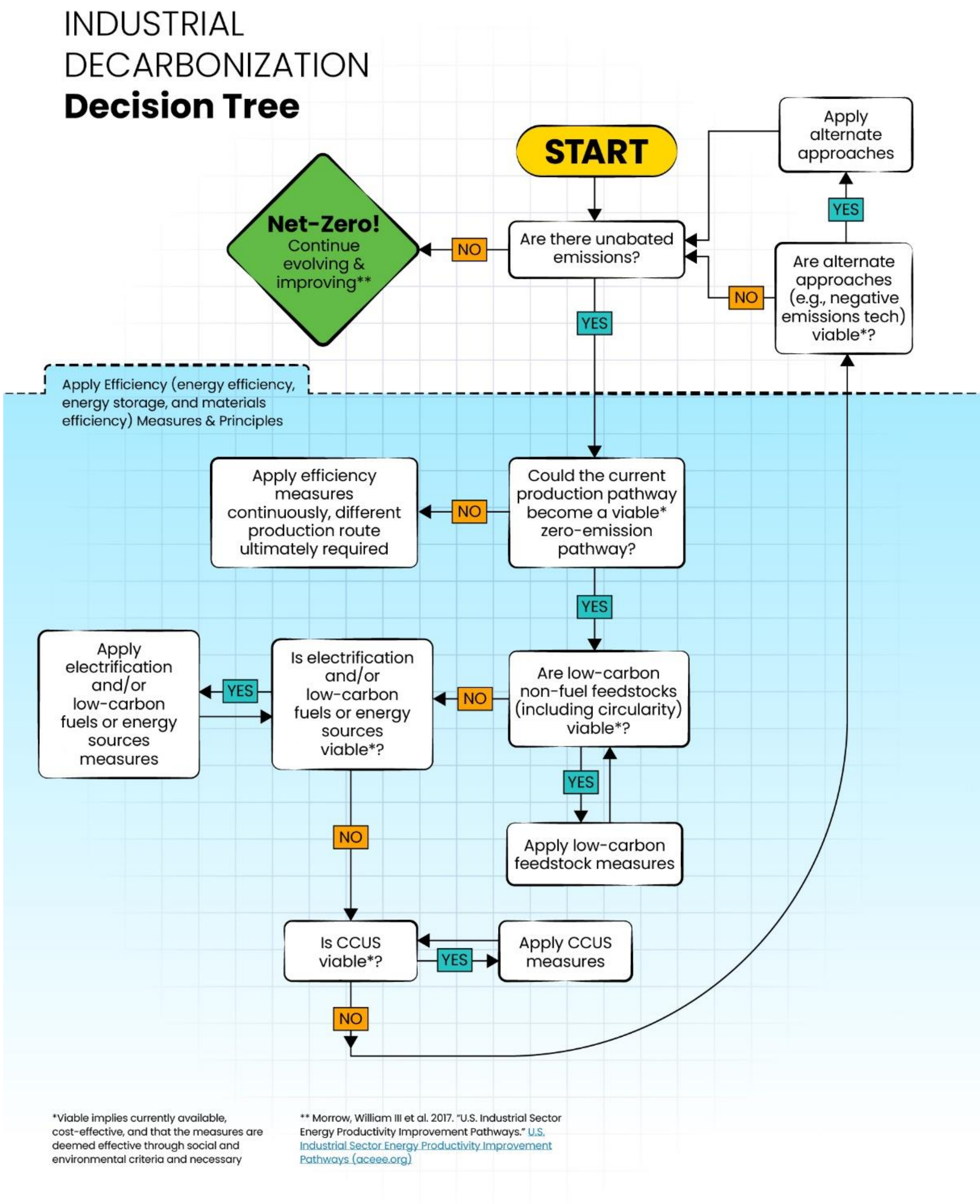

Figure 3. An example of an industrial decarbonization decision tree

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.

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, 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. 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

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. 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's unclear whether the best economic criterion 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[28] and the DOE's Climate and Economic Justice Screening Tool (CEJST)[29] 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.

---

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