Transforming Industry:

Paths to Industrial Decarbonization in the United States

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Executive Summary

KEY TAKEAWAYS

- Industrial decarbonization is essential to fighting climate change; doing it right is essential to the U.S. economy.
  - The industrial sector accounts for more than one-quarter of energy-related U.S. emissions; industrial emissions are projected to grow more than those of any other end-use sector through 2050.
  - The manufacturing subsector accounts for the largest share of industrial energy use and emissions and has the largest impact on the U.S. economy.
- Energy efficiency should be the foundation of industrial decarbonization because it can immediately and simultaneously reduce emissions, cut costs, and provide additional benefits like lower risk and increased competitiveness.
  - The manufacturing sector can leverage several other technical approaches: beneficial electrification; distributed energy resources; clean fuels; carbon capture, utilization, and storage; and the use of innovative processes.
- Manufacturing companies need to drive this transformation. To rapidly decarbonize, companies should:
  - Provide data and research that inform decision making. Transparent disclosure of energy use and emissions, as well as technology roadmaps, are critical to creating a glidepath to emission reductions.
  - Coordinate with other parts of the economy. Building relationships with utilities, labor, and government will increase industry's ability to implement a low carbon transformation.
- To accelerate the pace of industrial decarbonization, policymakers should do the following:
  - Prioritize reduction of industrial emissions at relevant agencies such as the U.S. Department of Energy (DOE), the National Institute of Standards and Technology (NIST), and the U.S. Environmental Protection Agency.
  - Initiate a technological innovation system focused on reducing industrial emissions. Greater coordination and cost sharing among government agencies, national labs, universities, and private industry could accelerate technology commercialization.
  - Develop a strong workforce and enough regulatory flexibility to overcome hurdles such as antitrust, intellectual property, permitting, and litigation rules. This workforce will increase industry's ability to implement a low-carbon transformation.
  - Support a market that encourages the production and consumption of low-carbon technologies and goods through the use of standardized tools, voluntary programs, incentives, and other market signals.

INTRODUCTION

To fight climate change, we must dramatically reduce energy use and greenhouse gas (GHG) emissions from the industrial sector. The twin goals of industrial decarbonization should be to reduce industry's energy consumption and emissions and to increase its productivity and competitiveness. In 2018 the industrial sector consumed 32% of U.S. primary energy and accounted for 28% of energy-related emissions; the manufacturing subsector consumed 24% of U.S. primary energy and produced roughly 20% of energy-related emissions.[1] Natural gas and petroleum are responsible for nearly all energy-related industrial emissions, which are expected to increase under a business-as-usual scenario. Although the manufacturing sector has dramatically reduced its energy intensity over the past three decades, it can still do much more to reduce its carbon intensity.

DECARBONIZING MANUFACTURING FACILITIES

Energy efficiency should be the foundational strategy for decarbonizing manufacturing facilities. Efficiency measures can potentially cut 15% of industrial emissions through relatively simple and inexpensive modifications to industrial buildings and equipment.[2] Focusing on energy management and smart manufacturing and incorporating efficient building systems and machine drives (which include pumps, fans, and compressors) would cut energy use and emissions immediately. Energy efficiency also has many nonenergy benefits including lower costs, mitigated risk, and increased competitiveness. Energy efficiency typically cuts costs across multiple years and may offer greater flexibility to enable other emission-reducing mechanisms.

Other methods of reducing emissions from the industrial sector include electrification, distributed energy resources (DERs), and low-carbon fuels. Numerous industrial technologies and processes rely on compressed air, steam, and heat; these can be electrified immediately. However, using electrification as an emission-reduction strategy hinges largely on decarbonizing the power sector. Onsite energy generation, produced by DERs like renewable energy and combined heat and power (CHP) technologies, along with onsite energy storage, not only reduces reliance on grid generation but also provides a measure of economic resilience. To achieve the high temperatures needed for many industrial processes, manufacturers currently rely on energy-dense fuels like petroleum products and natural gas. However, high temperatures can also be achieved through the use of low-carbon energy sources, creating a pathway to decarbonization.

Some types of carbon emissions are particularly difficult to abate, such as those resulting from industrial processes like iron smelting and lime calcination; these may require the use of carbon capture, utilization, and storage (CCUS) or new, innovative processes and technologies. CCUS can be applied across various manufacturing sectors to capture combustion and process emissions, and CO_2 utilization provides a potential revenue stream

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[1] EIA (Energy Information Administration). 2019. *Annual Energy Outlook 2019 with projections to 2050.* www.eia.gov/outlooks/aeo/pdf/aeo2019.pdf.

[2] Nadel, S., and L. Ungar. 2019. "Halfway There: Energy Efficiency Can Cut Energy Use and Greenhouse Gas Emissions in Half by 2050." Washington, DC: American Council for an Energy-Efficient Economy. aceee.org/research-report/u1907.

that can incentivize manufacturers to capture their emissions.[3] To reach global climate goals, we need a wider variety of cost-effective decarbonization technologies, which will require breakthroughs in materials science and novel process technologies. The strategies mentioned above—efficiency, electrification, low-carbon fuels, CCUS, and innovative processes—should be used to reduce emissions from process heat, which is the largest single source of manufacturing emissions.

DECARBONIZING SUPPLY CHAINS

Opportunities to reduce emissions go beyond individual facilities and companies; they also extend to supply chains. GHGs are emitted at each link of the supply chain as goods are produced, distributed, used, reused, and disposed of. On one end, manufacturers are major purchasers of raw materials, energy, and energy-intensive equipment; on the other, they produce the goods we consume, some of which—like cars, electronics, and other machinery—are responsible for emissions. Companies can leverage corporate policies and their own purchasing power to drive demand for low-carbon materials and goods and promote efficient practices.

Manufacturers can apply resource efficiency to optimize resource use while minimizing environmental impacts across the supply chain. They can either optimize raw material usage or alter product composition by choosing recycled or other low-carbon options, i.e., those that do not require significant emissions to grow, extract, or process. Manufacturers can also help reduce products' embodied carbon and emissions during subsequent stages of their life cycle. The manufacturing sector can increase its positive impact by making more efficient products that help to reduce emissions in other sectors, or by designing products that can be easily repaired, disassembled, reused, and recycled. Fully applying circular economy principles to cement, steel, plastic, and aluminum could reduce global CO_2 emissions by nearly 25%.[4]

MEETING CHALLENGES

While there are numerous opportunities to address emission reductions in the industrial sector, a number of technical and economic obstacles must be overcome to reach net-zero emissions by mid century. As technologies move from benchtops to pilots to commercial scale, technical challenges and bottlenecks arise; public and private capital must overcome these challenges to demonstrate commercial applicability. Market adoption of new technologies and materials can take decades due to underinvestment, limited opportunities for stock turnover, and risk aversion. Manufacturers may be hesitant to invest in large capital projects that fundamentally change their processes due to high upfront costs, long life spans of capital equipment, and concerns over competitive risk.

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[3] GCI (The Global CO_2 Initiative). 2016. "A Roadmap for the Global Implementation of Carbon Utilization Technologies."

[4] Material Economics. 2019. "Industrial Transformation 2050—Pathways to Net-Zero Emissions from EU Heavy Industry." materialeconomics.com/material-economics-industrial-transformation-2050.pdf?cms_fileid=303ee49891120acc9ea3d13bbd498d13.

POLICY AND FUNDING

Absent public policy, the path to a competitive and low-emissions industrial sector is difficult at best. Industry and government must envision this future together and lay out a pathway to success. Policies should couple the needs and expertise of industry with the priorities and resources of the public sector. The DOE Advanced Manufacturing Office (AMO), for example, is positioned to quickly and effectively respond to an industrial decarbonization agenda. Sustained federal research, development, and demonstration (RD&D) funding is needed to propel technologies to the commercial market; federal grants will be essential to support pilot projects and demonstrations of new technologies at commercial scale. Policies can also help establish standards, reduce risk, and induce market transformation. Removing market barriers will help to accelerate this transformation.

RECOMMENDATIONS

Industry must produce accurate data and additional research to inform decision making. Studies of carbon intensity, life cycle accounting, competitiveness, resilience, and impacts on energy-intensive trade-exposed U.S. industries are needed to guide decisions, track results, and establish benchmarks and standards. Establishing industry-specific technology roadmaps will provide a glidepath for transformation.

Manufacturers should coordinate with other parts of the economy, especially utilities and labor. Decarbonization will require electricity markets to deploy larger amounts of renewable energy, optimize rates, and develop programs that encourage emission reductions. Manufacturers will need to work closely with electric utilities in order to maintain grid reliability. Recruiting, training, and maintaining a skilled workforce will be critical to the industrial sector's transformation.

Policymakers should explicitly authorize relevant government agencies to address industrial emissions. Building on the current portfolio of program offerings, AMO could quickly increase the impact of its technical assistance programs and accelerate adoption of best practices that reduce emissions, such as strategic energy management and smart manufacturing. Authorizations could also accelerate deployment of currently available emission-reduction solutions through other programs such as DOE's Technology Commercialization Fund, NIST's Manufacturing Extension Partnership, and various other loan and technology-transfer programs.

Greater coordination among government agencies, national labs, universities, and private industry could accelerate technology commercialization. Public–private partnerships could leverage funds from both sectors to develop research projects that prioritize targeted solutions, bringing technologies to market faster than government or private RD&D alone. Sustained RD&D funding is needed to propel technologies to the commercial market. By developing harmonious research objectives, technology test beds, demonstration projects, and verification and validation programs, industry could improve the effectiveness of pre-competitive investment and spur greater deployment. Risk-sharing programs could help protect investments.

The regulatory environment must address market barriers that constrain innovation and investment. To encourage deployment of capital into emission-reduction solutions at the speed and scale required to meet climate goals, there must be enough flexibility to overcome hurdles such as antitrust, intellectual property, permitting, and litigation rules. Educational and professional training programs that develop and maintain the workforce of the future should be a priority of higher-learning institutions. Additionally, the market should encourage the production and consumption of low-carbon goods through the use of standardized tools, voluntary programs, and incentives; a federal procurement program could send a strong market signal.

The process of industrial decarbonization must be accelerated now, unleashing American innovation and ingenuity to propel the nation's industries into a prosperous, resilient future.

Introduction

Industrial decarbonization is essential to fighting climate change; doing it right is essential to our economy. Investor groups, nonprofits, private companies, and other organizations are calling on industry to reduce greenhouse gas (GHG) emissions to net zero by mid century. Decarbonization will require a suite of technologies, policies, and programs that combine emission reductions with carbon capture technologies. Targeted actions are needed immediately if net-zero emissions are to be achieved by mid century.

The Paris Agreement, ratified in 2015, calls on the global community to reduce GHG emissions in an effort to limit average global temperature increase to well below 2 °C relative to preindustrial levels (UNFCCC 2015). The Intergovernmental Panel on Climate Change released a report calling for a 45% decrease in emissions below 2010 levels by 2030 and net-zero emissions by 2050 in order to avoid a global temperature increase above 1.5 °C (2018). To achieve these goals, the United States must develop a pathway to a low-carbon economy, a transformation that requires immediate and sustained efforts at scale. These targets cannot be achieved without dramatically reducing emissions from the industrial sector, which accounts for 40% of U.S. GHG emissions (figure 1).

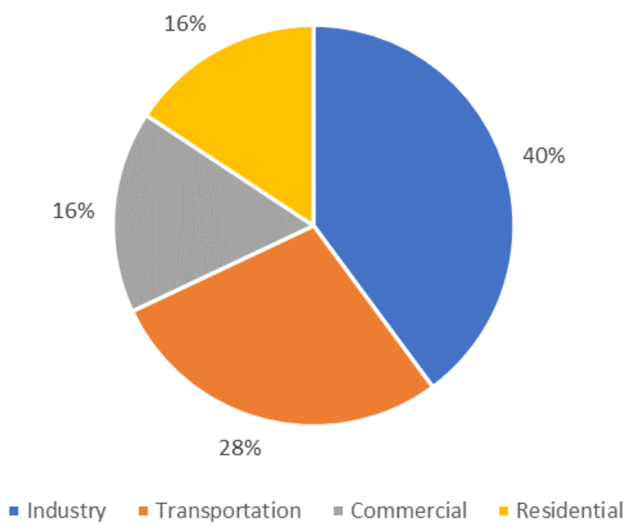

Figure 1. 2018 U.S. total GHG emissions by sector, with electricity-related emissions distributed. *Source:* EPA 2020, table 2-12.

This report is an overview of U.S. industrial decarbonization. Focusing on manufacturing, it describes areas of opportunity where emission reductions can be most easily accelerated and explores public policies that can help solve technical, market, and economic challenges. Just as the range of industries, energy sources, and supply chains in the U.S. industrial sector is diverse and complex, the industrial response will depend on a broad suite of technologies, policies, and programs. Decarbonization will require a market transformation, a sea change in processes and products. To bring about this transformation, we must identify the best opportunities to reduce emissions in the industrial sector and determine how to enable these changes at the necessary speed and scale.

INDUSTRY AND THE ECONOMY

The U.S. industrial sector is divided into groups by the North American Industrial Classification Codes (NAICS), and each of these groups can be further divided into more specific industries. The U.S. industrial sector includes four major subgroups (table 1).

Table 1. Industrial subsectors

NAICS code(s)	Subcategory
11	Agriculture, Forestry, Fishing, and Hunting
21	Mining, Quarrying, and Oil and Gas Extraction
23	Construction
31–33	Manufacturing

Source: BLS 2019c

The manufacturing sector encompasses a wide range of industries, including petroleum refining, food processing, and the production of chemicals, paper, cement, metals, and many other products. In 2018 the industrial sector produced 25% of the U.S. gross output.[5] As shown in figure 2, manufacturing accounted for 70% of industry's share, more than agriculture, mining, and construction combined (BEA 2019).

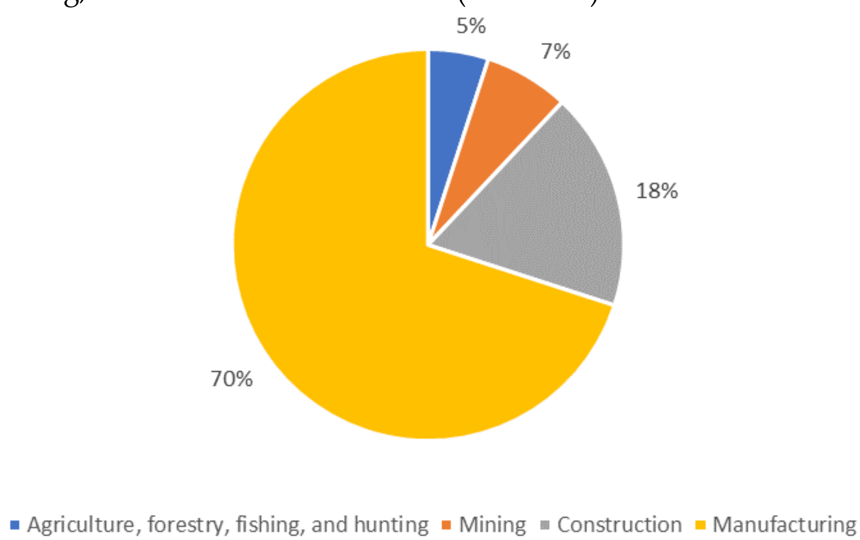

Figure 2. Gross output of U.S. industries in 2018. ***Source*****: BEA 2019.**

The industrial sector plays a critical role in the U.S. economy. Manufacturing industries have strong links to other economic sectors; they affect not only upstream materials producers and capital goods suppliers but also downstream businesses that rely on the goods being manufactured or the money that industrial workers spend. Backward links occur when growth of an industry stimulates growth in the upstream industries that provide inputs, such as materials and equipment suppliers. Forward links occur when the growth of an industry induces the development of products that rely on the outputs; for

[5] Gross output is the measure of total economic activity in the production of new goods and services in an accounting period.

example, the growth of EV battery manufacturing can encourage the development of the electric vehicle industry.

The industrial sector is capital intensive, accounting for more than 26% of all U.S. nonfarm business investments in 2017. These investments were made in fixed assets such as land, new and used structures, and equipment. The manufacturing sector accounted for 60% of the industrial sector's capital expenditures, driven mainly by investment in equipment like motors, mixers, chillers, and boilers. The manufacturing sector itself accounted for nearly 20% of all U.S. expenditures on equipment in 2017, investing more than $190 billion (Census 2019b). The useful life for many of these assets can range widely depending on the type of equipment. For example, industrial boilers can last more than 40 years, and it is estimated that it would take 15–20 years to replace roughly 80% of the industrial motors now in use (Xenergy 1998; Energy and Environmental Analysis, Inc. 2005).

While U.S. businesses lead global research and development (R&D) investment, their share fell from 40% in 2006 to 33% in 2016 (Wu 2018). Businesses invested $318 billion in R&D in the United States in 2016, making up 85% of all U.S. R&D investment that year. Manufacturing companies accounted for more than $210 billion of the total (Wolfe 2018). Business investments in basic and applied research have stagnated, while development activities focused on commercializing products and processes have been prioritized. Development received nearly 77% of R&D investment in 2016, with basic and applied research investments splitting the remainder (Wolfe 2018). Investment in R&D is critical in order to innovate industrial processes, technologies, and products to drive emission reductions. It also leads to greater productivity, employment, and competitiveness.

More than 20 million direct (and often well-paying) jobs in the United States are in the industrial sector, representing almost 15% of the workforce; the manufacturing sector accounted for nearly 13 million of these jobs (BLS 2019a, 2019b, 2019d). Manufacturing has some of the highest employment multipliers in the economy, meaning manufacturing induces job creation both directly and indirectly (Bivens 2019). For example, much of the global steel industry relies on iron ore miners, pellet producers, and technicians and engineers to operate blast oxygen furnaces and other equipment. The final product, steel, is then used by construction workers, autoworkers, and other manufacturers.

Most manufacturing firms in the United States are small. In fact, of the 254,941 firms identified by the Statistics of U.S. Businesses in 2016, only 6% had 100 or more employees (Census 2019a). There are major differences between small or medium-sized manufacturers and large multinational corporations. In addition to energy use and emissions, major differences exist in access to capital, existing infrastructure, workforce capacity, and many other characteristics. These small businesses are an essential part of supply chains; resources will need to be available and accessible to both the large and small businesses, and programs should be tailored to their different needs.

INDUSTRIAL ENERGY USE AND EMISSIONS

Primary energy consumption is the total energy value of primary energy sources like coal, natural gas, petroleum, and biomass products and the net electricity generation from nuclear and renewable sources consumed by end-use sectors. It includes losses from transformation (i.e., natural gas combustion for electricity generation) and distribution, as well as non-combustion uses of fossil fuels such as feedstocks, lubricants, and other uses. As shown in figure 3, the industrial sector consumed 32% of U.S. primary energy in 2018. Under the Energy Information Administration's reference scenario of domestic energy markets, industrial energy use is projected to increase more than that of any other end-use sector (EIA 2020).

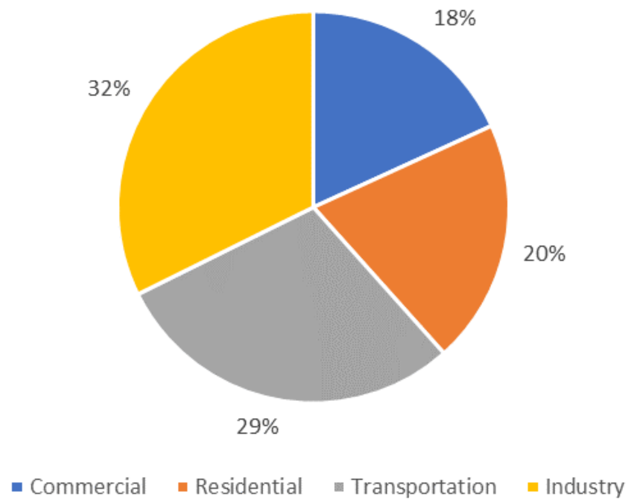

Figure 3. U.S. primary energy consumption by sector, 2019. *Source:* EIA 2020.

Figure 4 breaks down industry's primary energy use by major subsector, showing each subsector's percentage of total U.S. primary energy consumption. Manufacturing made up 24% of all U.S. primary energy use.

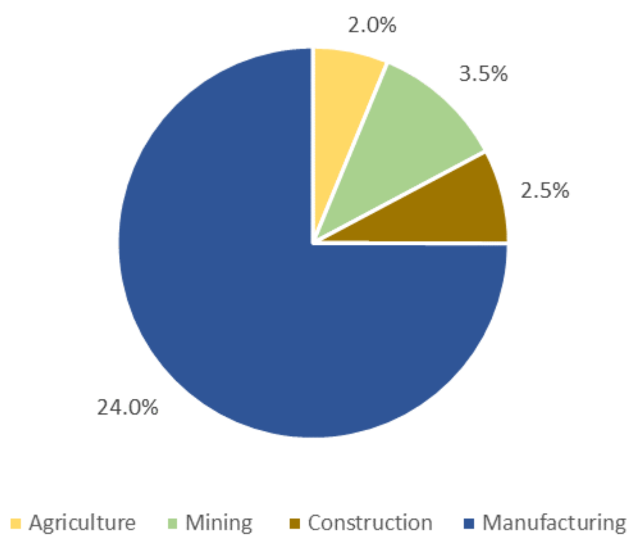

Figure 4. Primary energy use by industrial subsector, as percentage of total U.S. use in 2019. *Source:* EIA 2020.

The manufacturing sector's 24% share of primary energy consumption can be broken down further: 17% of total U.S. consumption was used to generate power and heat for processes such as material transformations, chemical reactions, fabrication, and separations, and 7% went toward non-combustion uses.[6]

As shown in figure 5, fossil fuels are the dominant energy source for the industrial sector.

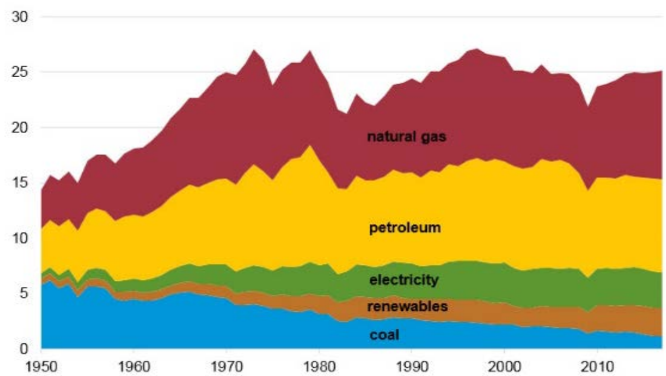

Figure 5. U.S. industrial energy sources, 1950–2018. *Source:* EIA 2019b.

The manufacturing industries that consume the most primary energy are bulk chemicals; oil and gas refining; paper; and iron, steel, and aluminum (EIA 2019a).

Industrial sector emissions come from the combustion of fossil fuels for energy use, process emissions, and other emissions including those from agriculture, mining, and pipelines.[7] Energy-related CO_2 emissions from combustion and processes constitute the largest portion of industrial emissions in equivalence, as seen in figure 6. Other GHGs (such as methane, sulfur hexafluoride, hydrofluorocarbons, and perfluorocarbons) have high global warming potential and will need to be reduced as well. Natural gas and petroleum are responsible for nearly all energy-related industrial emissions.

[6] Non-combustion uses of fossil fuels include use as feedstocks, building materials, lubricants, and solvents. For example, petroleum and natural gas are used to create a variety of products including gasoline, jet fuel, plastics, fertilizers, and other chemicals.

[7] Process emissions are created when materials are chemically or physically transformed in industrial processes, such as in the production of lime and cement.

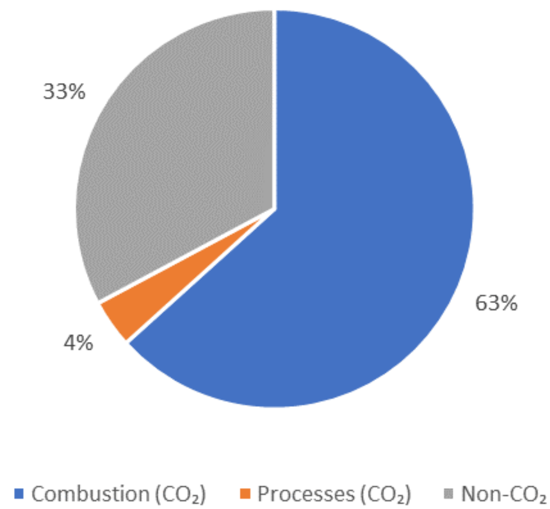

Figure 4. Total CO2e industrial emissions. *Source:* EIA 2011.

The industrial sector is responsible for 28% of energy-related CO_2 emissions in the United States, second only to the transportation sector, as seen in figure 7 (EPA 2017).

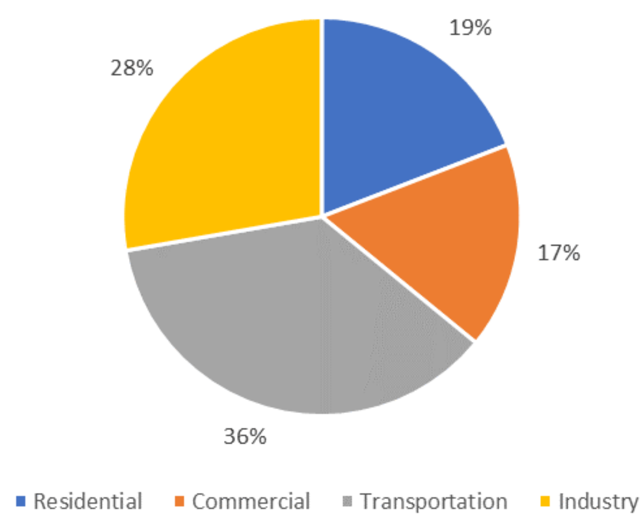

Figure 7. Energy-related CO_2 emissions by end-use sector. *Source:* EIA 2019a.

These CO_2 emissions can be categorized as direct or indirect. Direct emissions from onsite combustion of fossil fuels and from industrial processes account for more than 19% of total U.S. GHG emissions, while indirect emissions from industry's use of electricity generated offsite account for another 9% (EIA 2020). A less emission-intense electricity grid is needed, but this alone will not sufficiently reduce industrial emissions.

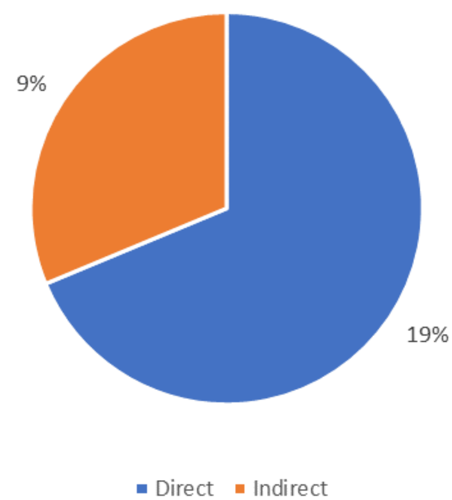

Figure 5. Source of energy-related CO_2 emissions in the industrial sector as a percentage of total U.S. emissions. *Source:* EIA 2019a.

Within industry, manufacturing produces about 80% of the sector's energy-related CO_2 emissions, an amount equal to about 20% of all U.S. energy-related CO_2 emissions (EIA 2019a). Refining, bulk chemicals, and iron and steel production account for most of those manufacturing emissions.

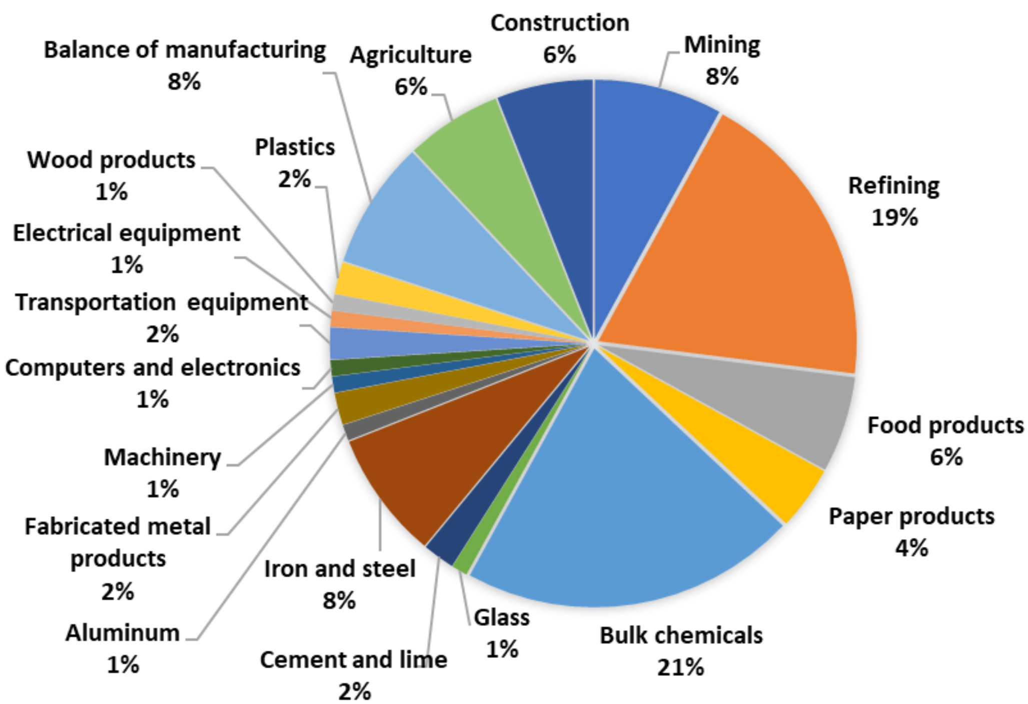

Figure 9. Percentage of GHG emissions by industrial and manufacturing subsectors in 2019. *Source:* EIA 2019a.

MANUFACTURING

The manufacturing sector presents the largest industrial opportunity to reduce emissions, and progress in this sector will have the greatest economy-wide impacts. As shown in figure 10, manufacturing has a history of continual improvement, having reduced its energy intensity dramatically for nearly four decades. These improvements are due to multiple factors, including the production of higher-value manufactured goods, improved energy efficiency, process and product innovations, and a shift to less energy-intensive manufacturing (Elliott 2017).

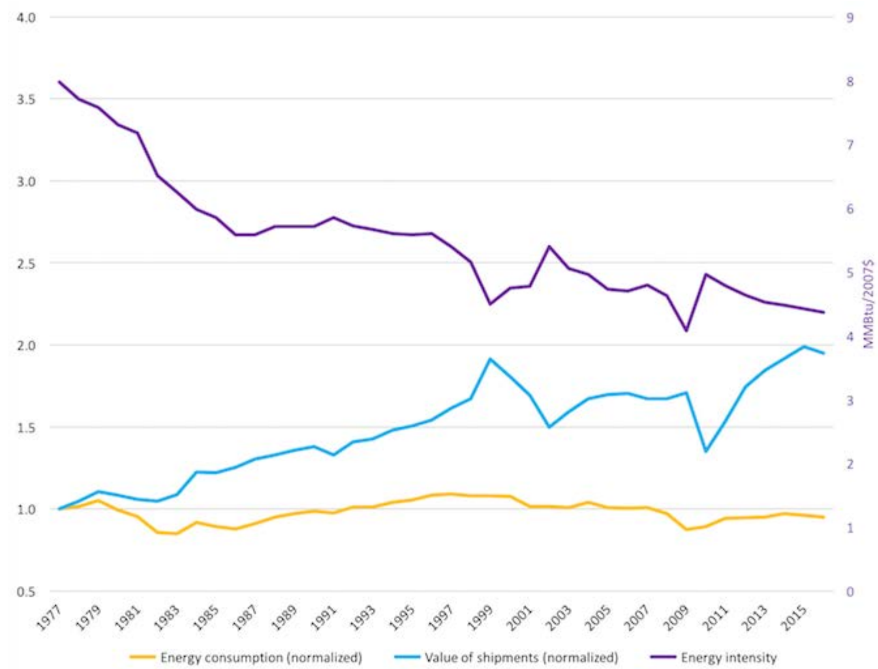

Figure 10. Energy intensity of the manufacturing sector, 1977–2017. *Source:* Elliott 2017.

A potentially more useful way to track the progress of industrial decarbonization is by measuring not energy intensity but carbon intensity, for example, tons of CO_2 per unit of manufacturing value added. The shift in electricity generation from coal to natural gas and the increasing availability of renewables have resulted in the emissions intensity of the grid decreasing since 2005 (EIA 2019a). Expansion of low- and no-carbon energy sources will further reduce the emissions intensity of power and heat generation; thus, emission reductions could be occurring even if reductions in energy use are not.

While absolute emission reductions are necessary to meet climate goals, the industrial sector is output-driven, and businesses will respond to product demand from end users. Focusing on the absolute emissions from manufacturing may create leakage—the transfer of production to areas with laxer emission constraints. Additionally, setting emission caps or similar limits on U.S. manufacturing would likely limit competitiveness.

Looking ahead, it seems clear that the industrial sector can thrive with a much lower emissions footprint. The twin goals of decarbonization should be to simultaneously reduce industry's energy use and emissions and increase its productivity and competitiveness. We can strengthen the economy even as we put the United States on a path to net-zero emissions by mid century.

Decarbonizing Manufacturing Facilities

Many manufacturing facilities can reduce energy consumption by 10% to 20% by starting with the tools available today and making simple changes. At least one-third of those savings can be achieved without any capital expense by modifying procedures and changing behaviors (Russell and Hudson 2014). Additional savings can be obtained by implementing energy-efficient technologies; building systems may be the easiest area to address since doing so does not require any changes to manufacturing processes and can bring immediate reductions in emissions while reducing energy bills.

Industrial decarbonization will also require capital investments. In addition to efficiency, there are a number of approaches and strategies that can help reduce emissions in manufacturing facilities. Efficient electrification can cut emissions from industrial processes like heating, separations, fabrication, and materials handling. Facilities can reduce indirect emissions by taking advantage of distributed energy resources (DERs) like onsite solar and storage, and they can reduce direct emissions by using low-carbon fuels and carbon capture technologies. They can also adopt transformational technologies with new processes that avoid emissions. As discussed at the end of this section, facilities can apply a number of these approaches to reduce their process heat emissions.[8]

ENERGY EFFICIENCY

Energy efficiency, including energy management and optimization, should be the foundational strategy for industrial decarbonization. Efficiency measures can potentially cut 15% of industrial emissions through relatively simple and inexpensive modifications to industrial buildings and equipment (Nadel and Ungar 2019). Efficiency also has many nonenergy benefits including lower costs, mitigated risk, and increased competitiveness (IEA 2014). A focus on energy management and optimization would cut energy use and emissions immediately. Energy efficiency typically cuts costs across multiple years and may offer greater flexibility to enable the other emission-reducing mechanisms discussed below. Lower energy use makes electric end-use technologies (EETs), DERs, and other emission-reduction practices technically feasible and/or more cost effective.

Building Systems

Non-process loads—HVAC, lighting, and other systems—consumed 12% of total industrial energy in 2014, with HVAC accounting for nearly two-thirds of this (EIA 2017). These loads are the low-hanging fruit. Manufacturers can improve the efficiency of heating and cooling units or otherwise save energy through system upgrades, by using properly sized equipment, by performing regular maintenance including air filter replacement and ductwork inspection, and by operating the equipment only as needed (DOE 2015). Lighting accounts for 12% of non-process energy use (EIA 2017). Switching to light-emitting diodes (LEDs) reduces energy bills as well as maintenance costs over their longer lifetimes. LEDs

[8] Process heat is the thermal energy used directly in the preparation or treatment of materials used to produce manufactured goods.

may also create a safer and more productive environment for workers. Other opportunities for saving energy and lowering emissions include ensuring that the building envelope is tight and that insulation is properly installed throughout the facility.

Machine Drives

Machine drives, including pumps, fans, and compressors, are required for materials handling and processing. These technologies consumed more than 2,000 trillion Btus (TBtus) in 2014, about 17% of manufacturing energy use, largely electricity (EIA 2017). Improving the efficiency of machine drives not only saves energy but can result in lower energy bills. Just as with building systems and most other types of technology and infrastructure, properly sized equipment, maintenance, and operation of equipment only as needed will reduce energy waste. Matching the load to the need optimizes energy use. For example, in compression systems, pressure levels can be adjusted to reduce energy consumption. It is also important to monitor line leaks; these lead to higher pressure requirements, causing wear and tear on the compressor and greater energy consumption. Another strategy is to use variable frequency drives, which allow greater control over motors, resulting in a more precise process. Of course, equipment choice also impacts energy use. Many types of machine drives have certification labels that distinguish them as high-efficiency products.

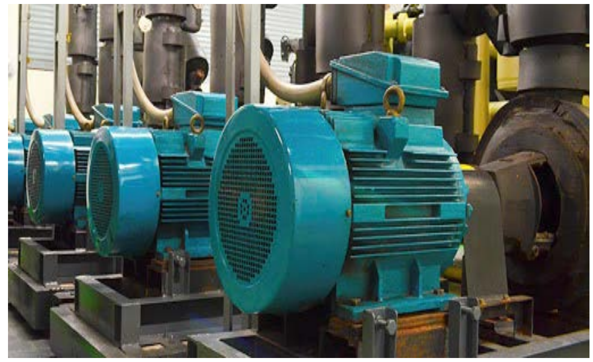

Figure 11. Motor bank in an industrial facility. *Source*: Recon Electrical 2020.

Strategic Energy Management

A good first step for enabling facility-wide emission reductions is strategic energy management (SEM), an approach that integrates continual energy improvement into the culture of a company and helps to ensure the effectiveness of more advanced control technologies. Starting with support from management, facilities and their workforce engage in energy efficiency projects and practices. Program administrators work with manufacturers to identify sources of significant energy use, implement energy efficiency measures, and track performance. SEM programs focus mainly on reducing electricity and natural gas use—thus reducing emissions—and can also result in less water usage and material waste. SEM programs deployed widely across the United States and Canada could save more than 1.9 million MWh and 27.3 million decatherms by 2030 (Rogers, Whitlock, and Rohrer 2019).

SEM programs not only prompt companies to think strategically about their energy management practices but also encourage them to participate in other utility or state efficiency programs. The relationships that SEM programs help build between program administrators and industrial customers may also lead to companies' greater investment in capital projects and energy management information systems.

Smart Manufacturing

Smart manufacturing, which includes information communication technologies and automated data processing systems like artificial intelligence, helps manufacturers save energy, maximize productivity, and reduce emissions. Process machinery uses sensors to monitor operational parameters like pressure, temperature, moisture content, and fuel mix, as well as for quality control. An energy management system can make automatic adjustments to parameters to optimize facility energy use. Machine learning and artificial intelligence are emerging areas that will continue to improve competitiveness while saving energy and reducing emissions. Smart manufacturing can reduce energy intensity in the manufacturing sector by 20% with current technologies, resulting in energy cost savings of $7 billion to $25 billion (Rogers 2014).

BENEFICIAL ELECTRIFICATION

Electrification offers the potential to cut industrial emissions in half (Steinberg et al. 2017). Numerous industrial technologies and processes relying on compressed air, steam, and heat can be electrified today, but given the low cost of alternatives like natural gas, electrification is unlikely to be driven by economics alone. However, electrification brings a number of additional benefits. For example, many EETs offer greater precision of heating or control of other parameters, resulting in better quality, strength, or other desirable characteristics of manufactured goods. EETs can also result in greater productivity and worker safety. Infrared heating, for instance, can reduce the time needed to heat materials and also does not require the same air-handling equipment needed for forced convection (EPRI 2016). EETs application to process heat is currently most effective for low-temperature processes, such as drying and curing (Gellings 2007). Electrolysis, a process that uses an electric current to separate compounds into its constituent parts, can be used for a variety of purposes discussed in more detail later in this report. Electrification may also be appropriate to replace machine drives in some building systems. For instance, electric actuators could be used in place of compressors for materials handling, or heat pumps could be used for HVAC.

Electrification's role in reducing emissions hinges on the ability of utilities and other power providers to generate adequate amounts of affordable, clean energy to industrial facilities. This is not something manufacturers can typically control, and it will vary by location (Rightor 2020). While electrification of industrial buildings and equipment can bring emission reductions to some facilities today, deeper reductions will require an increase in the proportion of low-carbon electricity on the grid.

DISTRIBUTED ENERGY RESOURCES AND COMBINED HEAT AND POWER

Renewable energy technologies can provide emission-free energy onsite, and energy storage allows users to deploy it as needed. Manufacturers generated roughly 4,200 TBtus of energy onsite in 2014 (EIA 2017). Combined heat and power (CHP), also known as cogeneration, involves efficient onsite systems that combine the production of electricity and useful heat. CHP is especially important for chemicals, pulp and paper, and petroleum and coal product manufacturers (DOE 2016). For example, the pulp and paper industry can use by-products like bark, wood chips, and other pulping residue as fuel rather than paying to dispose of them.

Producing renewable electricity and heat onsite also provides a measure of economic resilience for the manufacturing sector. Replacing some purchased power with self-generation can shield manufacturers from demand charges and price shocks. Onsite capacity also enables participation in utility markets that allow manufacturers to sell excess generation or participate in other revenue-generating programs.

LOW-CARBON FUELS

Low-carbon substitutes can replace the incumbent energy-dense fuels—like petroleum products and natural gas—that manufacturers rely on to achieve the high temperatures needed for many industrial processes. These substitutes include renewable natural gas (such as biogas from landfills and agricultural operations); hydrogen, which can be used as either a fuel or a fuel additive; and ammonia, an energy-dense product typically used as fertilizer. Currently hydrogen is most often produced through steam methane reforming, which relies on fossil fuels; however, hydrogen can also be produced through electrolysis. The electrolytic production of hydrogen with low-carbon energy would significantly reduce the carbon footprint of hydrogen production. Because hydrogen is also a feedstock for ammonia, increasing the production of low-carbon hydrogen would further enable low-carbon ammonia.

CARBON CAPTURE, UTILIZATION, AND STORAGE

Carbon capture, utilization, and storage (CCUS) is essential to achieving global climate goals (Page, Turan, and Zapantis 2018). This strategy can be applied across various manufacturing sectors, and while it may not currently be the most cost-effective solution, it is needed to reduce difficult-to-abate process emissions. Post-combustion carbon capture systems can be used to remove lower-quality CO_2 from energy-related emissions like those coming from refineries or from production of ethylene, cement, and iron and steel. CCUS can be used most effectively to capture emissions from processes with fairly pure CO_2 streams, such as steam methane reforming or the production of ethylene oxide.

Figure 12. Cement manufacturing facility. *Source:* ABB 2020.

After capture, CO_2 can be used for various purposes or sequestered in geologic formations. For example, Air Products and Chemicals, Denbury Onshore LLC, and the University of Texas captured more than three million metric tons of CO_2 from two steam methane reformers in Port Arthur, Texas, utilizing the sequestered CO_2 as an injection gas for enhanced oil recovery operations (MIT 2016).[9] The majority of captured CO_2 is currently being used for this purpose, but it can also be utilized in construction materials, polymers, chemicals, and fuels. CO_2 capture and utilization provides a potential revenue stream that can incentivize manufacturers to capture their emissions (GCI 2016).

NEW PROCESSES AND TECHNOLOGIES

Industrial decarbonization requires both the deployment of underutilized industrial processes and materials and the development of transformational technologies that change how goods are produced. Breakthroughs in materials science and novel energy-efficient process technologies are needed to develop and expand the suite of cost-effective decarbonization measures necessary to reach climate goals. Energy-intensive industries in particular need innovative materials and techniques that lower emissions and maintain or increase productivity and product performance.

The U.S. Department of Energy's *Quadrennial Technology Review* identified three manufacturing approaches that can lead to drastically lower energy consumption and emissions: process intensification, roll-to-roll processing, and additive manufacturing (DOE 2015). Process intensification (PI) involves the application of novel processes and technologies that combine separate unit operations such as reaction and separation into a single piece of equipment that optimizes chemical process efficiency. PI has had success in the past; for example, the dividing wall column reduces the number of steps required for chemical separations by enabling multiple separations to occur in a single distillation tower (Bielenberg and Bryner 2018).

Similar to an ink-jet printer, roll-to-roll (R2R) manufacturing is a continuous substrate-based process that was pioneered by the film products industry. Advances in R2R are leading to new applications of this familiar process including optical films, flexible electronics and energy technologies, separation membranes, and biomedical devices (O'Conner, Beaulieu, and Rothrock 2016). R2R manufacturing can enable production at scale.

Additive manufacturing (AM), commonly referred to as 3D printing, uses computer-aided design to precisely build materials into complex structures layer by layer to create various products. This approach can use less energy and create less waste than traditional methods like casting or machining (DOE 2019a).

Many applications of these innovative processes are in early stages and not yet ready for large-scale commercial application. Key research must be conducted in materials, equipment optimization, process modeling and control, and other supporting practices like modular design, integration, and interoperability. Additionally, validation and demonstration will be needed to demonstrate to industry that these processes and technologies are commercially viable (DOE 2015).

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[9] Gas injection used for enhanced oil recovery uses gases that expand in a reservoir to push additional oil to a production wellbore, or otherwise increases viscosity and improves the flow rate (NETL 2010).

PROCESS HEAT

Process heat constitutes the largest single source of energy use in the manufacturing sector. Common process heating technologies include furnaces, kilns, ovens, and boilers using fossil fuels. In 2014, the most recent year for which data are available, manufacturing processes consumed 10,273 TBtus of primary energy, of which process heat accounted for about 70% (figure 13).

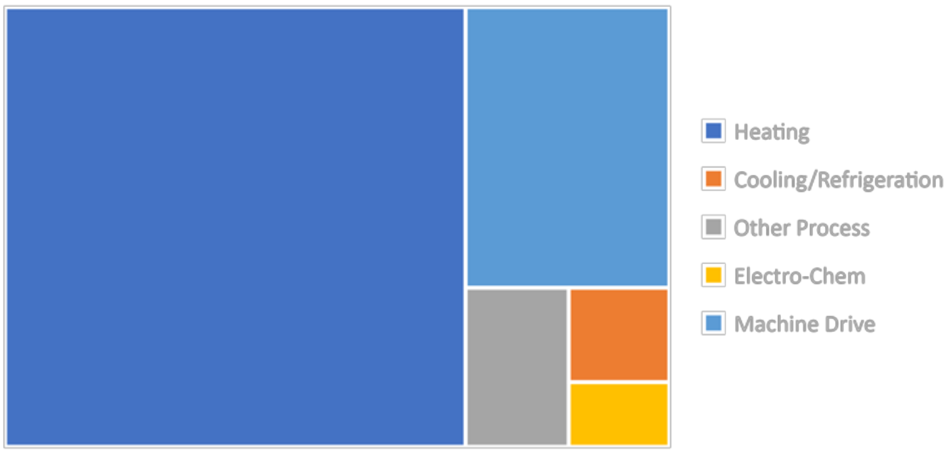

Figure 13. Energy consumption by process type. *Source:* EIA 2017.

Electrification

Emissions from process heat can be reduced through electrification. Only 5% of the energy needs for process heat were met through electricity in 2014 (EIA 2017), leaving a great deal of opportunity for decarbonization in this area. Electric process heating often has less thermal waste (due to better precision and process control), can improve product quality (e.g., strength or purity), and can reduce material waste.

Figure 14. An electric arc furnace used for smelting metal. *Source:* CRU Group 2020.

A number of EETs can replace fossil fuel–powered process heating technologies. Electric boilers can reduce some of the costs associated with maintaining a boiler system, including insurance, maintenance, and air permitting. Some textile manufacturers use infrared heat in place of steam to dry delicate fabrics. Not only does this save energy and reduce emissions, but it improves yield as a result of less damage to the threads. Other electrification opportunities for process heat include microwave and ultraviolet radiation.

Electrolysis

Electrolysis has the potential to reduce the emissions of a number of manufacturing industries, including those that produce metals like aluminum and steel and chemicals such as chlorine and sodium hydroxide. For example, molten oxide electrolysis can reduce iron ore into iron and oxygen, replacing traditional methods such as blast-oxygen furnaces that use a carbon source to reduce iron ore into iron and carbon dioxide. Emissions reductions may also be on the horizon for aluminum smelting. A joint venture between Alcoa and Rio Tinto has patented a new electrolytic smelting process called ELYSIS. It replaces the carbon anode commonly used for aluminum smelting with an inert anode that releases oxygen instead of CO_2.

Low-Carbon Fuels

While a major advantage of the electrification of process heating is reduced waste heat, some industries that require high temperatures, like chemicals and refining, integrate waste heat into other processes. Emissions from process heat can still be reduced in these cases by replacing natural gas and other fossil fuels with low-carbon or renewable fuels such as biofuel, syngas, and hydrogen. In Freeport, Texas, for example, Yara has partnered with BASF to operate an ammonia production facility that uses a hydrogen by-product from nearby chemical plants (TFI 2018).

DERs

Onsite renewable energy systems can also generate process heat, using strategies that are receiving increased attention from national labs, universities, and industry. As shown in figure 15, many renewable energy technologies can produce heat for processes like cooking, sterilization, and drying.

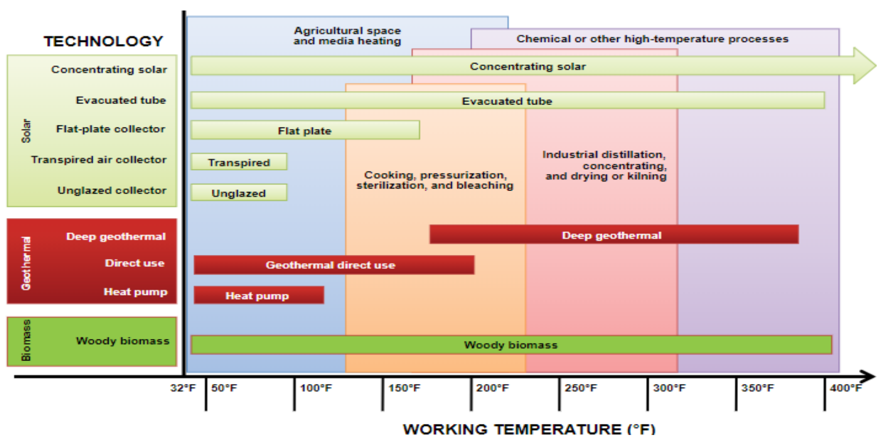

Figure 15. Renewable energy technologies by working temperature. *Source:* EPA 2017.

Heavy industrial facilities using renewable energy include Nucor Steel, which is developing a "micro" mill in Sedalia, Missouri, that will be the company's first U.S. steel production plant to run on wind energy (Tomich 2019). Heliogen, a clean energy company backed by Bill Gates, has demonstrated that its concentrated solar power technology can reach 1,000 °C, and it is working toward 1,500 °C. This will meet the high-temperature needs of cement production and could even generate liquid fuels (Spector 2019). Additionally, work continues on small modular reactors, which could provide clean, high-temperature heat at manufacturing facilities.

Decarbonizing Supply Chains

Opportunities to reduce emissions go beyond individual facilities and companies and extend to supply chains. A supply chain is the sequence of processes by which goods are produced, distributed, used, and reused or disposed of. The industrial sector is in a unique position to affect both upstream and downstream emissions. On one end, it is a major purchaser of raw materials, energy, and energy-intensive equipment; on the other, it produces the goods we consume, some of which—like cars, electronics, and other machinery—are responsible for emissions.

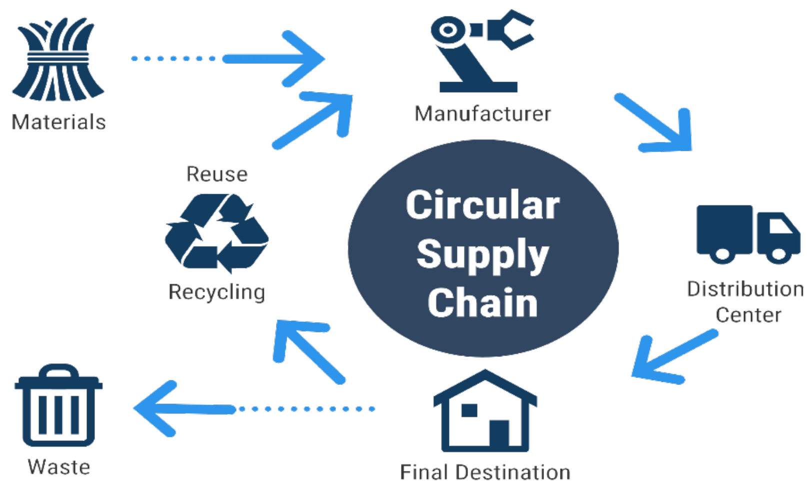

Figure 16. Simple representation of a circular economy. *Source*: Datex 2020.

GHGs are emitted along each step of the supply chain and add up to what is known as a product's life cycle emissions. The Greenhouse Gas Protocol (2011) defines these emissions as "all the emissions associated with the production and use of a specific product, from cradle to grave, including emissions from raw material, manufacture, transport, storage, sale, use and disposal."

A product's embodied carbon is the sum of all the CO_2 emitted at the various stages of its life cycle. For example, the agricultural products purchased by food processors embody all the CO_2 emitted from upstream processes including raising and transporting livestock, using fertilizers, and operating agricultural equipment. CDP, an international organization that helps track emissions from businesses and governments, estimates that 40% of embodied emissions are from manufacturers' upstream suppliers and often exceed emissions from a manufacturer's onsite activities (Smith-Gillespie et al. 2017). However, the embodied emissions from suppliers, onsite emissions, and product use and disposal vary dramatically by industry.

Companies can leverage corporate policies and their purchasing power to drive demand for low-carbon materials and goods and efficient practices. Manufacturers can encourage their suppliers to reduce their emissions in a number of ways. Some encourage their suppliers to sign sustainability pledges, set goals, or report energy use and emissions. Dell Technologies requires 95% of its direct materials suppliers to set specific emission-reduction targets and publish sustainability reports according to the Global Reporting Initiative or another global framework standard (Ungar and Whitlock 2019). Others engage with utilities that serve their suppliers in order to ensure that their suppliers have access to effective energy efficiency programs or renewable energy. Some offer direct support; for example, VF Corporation, an apparel company, helped 13 of its strategic suppliers save 35 million kWh, more than 19,000 metric tons of CO_2 equivalent, and $2.2 million in costs by providing funding for capital equipment improvements (Ungar and Whitlock 2019).

Manufacturers can also play a role in reducing supply chain emissions by substituting production materials and implementing design changes that reduce their demand for carbon-intensive resources, cut emissions from the use and disposal of their products, and enabling materials recycling and reuse. Resource efficiency optimizes resources while minimizing environmental impacts across the supply chain.

Manufacturers can replace raw materials with recycled materials or other low-carbon options, ones that do not require significant emissions to grow, extract, or process. The steel industry is a leader in recycling, as roughly 86% of steel in the United States is recycled. Not only does this reduce the energy use and emissions associated with extraction and production of raw steel, but the energy needed to re-form secondary steel is much lower. Similarly, nearly 70% of paper products are recycled, and some estimates suggest that using recycled paper consumes 40% less energy than is needed to produce paper from virgin material (SOE 2016).

Other production material changes, like altering the composition of manufactured products or switching materials altogether, can also reduce emissions. For example, the production of clinker, a material used in cement, releases large amounts of CO_2. Limestone ($CaCO_3$) is heated at high temperatures and is converted into lime (CaO) and CO_2 in a process known as calcination; this process is responsible for roughly half of the carbon emissions associated with cement production. Using a substitution for clinker, or lowering clinker content in Portland cement by adding other materials, could cut emissions, and replacing Portland cement with novel cements could reduce emissions by up to 90% (Lehne and Preston 2018). To give another example, carbon fiber can decrease a vehicle's weight, and a 10% reduction in vehicle weight can improve fuel efficiency by 6% to 8% (DOE 2013). Other production material changes may increase resource efficiency by reducing waste or increasing yields.

Manufacturers can also help reduce products' embodied carbon and emissions during the subsequent stages of their life cycle. Some manufactured products have positive environmental impacts, benefits that are referred to as a handprint (Panjula et al. 2018). The manufacturing sector can increase its handprint by making more efficient products that help to reduce emissions in other sectors. Some products (e.g., lighting, appliances, and vehicles) are subject to minimum energy performance standards that require the manufacturer to regularly improve efficiency. Other manufactured goods, such as insulation and lubricants, can increase the efficiency of the buildings or devices in which they are used. Similarly, wind turbine manufacturers and fabricators of photovoltaic panels enable emission reductions from energy production. Manufacturers can also create new value chains that feature low-carbon goods. For example, cross-laminated timber, an engineered wood product, can substitute for some of the carbon-intensive steel and cement in the construction of tall buildings.[10] Additionally, designing products to have a longer useful life reduces emissions through less frequent turnover.

Figure 17. Norway's Mjøstårnet, the world's tallest timber building as of March 2019, stands over 280 ft. *Source:* De Zeen 2019.

Manufacturers can also reduce emissions by designing products for recycling and reuse. In doing so, they can contribute to what is called a circular economy, a system that eliminates waste and recycles resources. Products that can be easily repaired, disassembled, reused, and recycled require less raw material extraction and extract greater value from the same materials, changes that can result in fewer overall emissions. Fully applying circular economy principles to cement, steel, plastic, and aluminum could reduce global CO_2 emissions by nearly 25% (Material Economics 2019).

Meeting Challenges

While there are many opportunities to effect emission reductions in the industrial sector, a number of economic, technical, and informational needs must be met in order to reach net-zero emissions by mid century. Moving at the pace required to meet emission-reduction goals will require not only transformational changes to industrial processes but also targeted capital investments, innovative electricity rate design, a capable workforce, and accurate data on manufacturing processes.

SLOW PACE OF CHANGE

An analysis of a series of Department of Energy (DOE) "bandwidth studies" estimated that currently available, state-of-the-art technologies could save nearly 20% of energy use in the

[10] Buildings are a large source of embodied carbon. Nearly 6% of annual emissions in the United States are embodied in buildings from the manufacture of energy-intensive construction materials such as steel and concrete (Abergel et al. 2018).

examined industries (Ungar and Whitlock 2019).[11] However market adoption of new technologies and materials can take decades as a result of underinvestment, limited opportunities for stock turnover, and risk aversion.

As figure 18 shows, market share grows as groups of adopters implement new technologies.

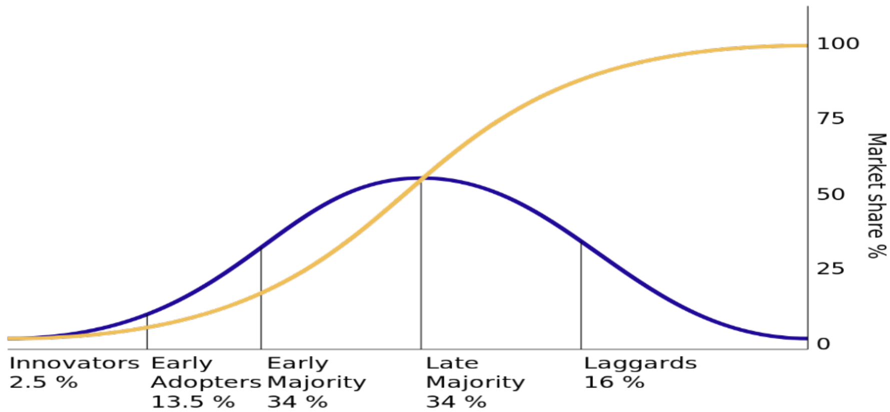

Figure 18. Diffusion of innovations. *Source:* Rogers 2003.

Some manufacturers are proactive in addressing the size of their environmental footprints, setting goals, taking actions to reduce their energy use and emissions, investing in RD&D, and implementing new technologies. Others continue using less efficient technologies and emitting higher levels of GHGs. These discrepancies result from differences in the availability of capital, willingness to accept risk, company culture, pressure from external stakeholders, or a number of other factors that may relate to a company's size. Multinational companies will have needs that differ from those of small and medium-sized manufacturers. Promoting the adoption of new technologies and materials will require different incentives for different companies and different industries.

Sustained emission reductions are possible, and with the right market signals and policies, they can be accelerated. However, to meet the challenge of decarbonization, industry needs to dramatically ratchet up its efforts beyond the incremental improvements that have been implemented to date. A step change is necessary in order to decrease GHG intensity at a scale meaningful for reaching U.S. climate goals by mid century.

TECHNICAL AND MARKET BARRIERS

Many of the transformational technologies with significant potential to reduce industrial emissions face technical and market barriers. While early-stage RD&D may receive government funding, a gap often appears when a project nearing commercialization needs technology validation and demonstration. This "second valley of death" presents a challenge that public and private capital must overcome in order to demonstrate commercial applicability (Hart 2017). As technologies move from benchtops to pilots to commercial scale, new research questions and technical challenges arise, and issues around

[11] The Manufacturing Energy Bandwidth Studies can be found at www.energy.gov/eere/amo/energy-analysis-data-and-reports.

throughput, quality, and reliability must be addressed. Bottlenecks may develop due to permitting issues, limiting the effectiveness of incentives, programs, and policies designed to support innovation and the implementation of new technologies. Suppliers will eventually need the capacity to produce new systems at scale.

Given these challenges, there is a critical need for focused research, development, and demonstration (RD&D) programs for transformative technologies and low-carbon products. The need goes beyond basic science research and benchtop testing, spanning all technology readiness levels (figure 19).

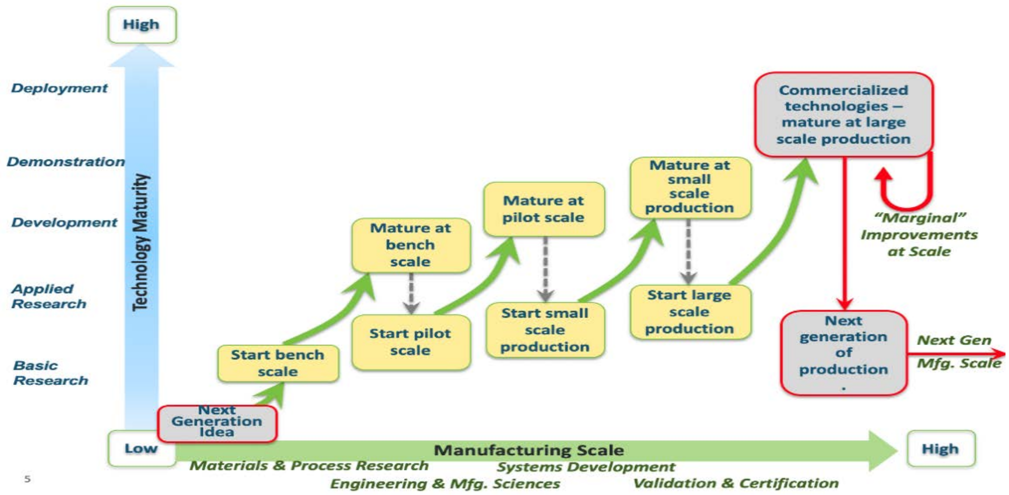

Figure 19. Technology maturity at manufacturing scale. *Source:* Cresko 2018.

CAPITALIZATION AND STRANDED ASSETS

While manufacturers can substantially reduce emissions without investing in new technologies, in many cases they would have to replace current best-available systems with newer ones in order to reach net-zero emissions by mid century. However, they may be hesitant to invest in large capital projects that fundamentally change their processes due to high upfront costs; potential unknowns regarding throughput, product quality, and competitive risk; and the long life spans of capital equipment.

Industrial equipment is extremely long-lasting, which can be a barrier to change. Capital investments in process technologies are locked in for the useful life of the equipment, which can range from 10 years to more than 40. If the original technologies are replaced before they have fully depreciated, these stranded assets could impair a company's bottom line. New technologies must therefore present clear economic benefits to accelerate the turnover of assets.

Initial capitalization is also an issue. Most manufacturers operate on thin margins and tight schedules. Emission-reduction projects face competition for capital. Even when there are favorable economics, these projects may not be adopted due to competing priorities, the perceived risk of investment, and shorter paybacks on other projects. It is clear that manufacturers will need assistance with financing and a backstop to risk if they are to accept an accelerated capital cycle.

NEW DEMAND AND LOAD PROFILES

Manufacturers are high-value customers for utilities and often pay lower rates due to their consumption levels. Higher levels of electrification and DERs at manufacturing facilities will change their demand and load profiles, which are already dependent on a wide range of variables specific to individual facilities. Manufacturers will need to work closely with electric utilities in order to maintain grid reliability. Electricity markets will need to accommodate such shifts, and utilities will have to optimize rates and programs.

Utility demand-side management programs attempt to influence manufacturing energy use patterns. Industrial program offerings like SEM can help build relationships between utilities and manufacturers, bringing energy savings and opening the door for participation in other utility programs, including demand response and prescriptive rebates. Manufacturers will need to have equipment and energy management systems that are compatible with demand response programs and offer a value proposition (DOE 2015). Impacts of electric rate design such as time-of-use rates, demand charges, and standby rates on manufacturers are important considerations.

LACK OF SKILLED WORKFORCE

Recruiting, training, and maintaining a skilled workforce will be at the forefront of the industrial sector's transformation. Motivated and capable technicians will help drive energy savings and emission reductions. The manufacturing sector has identified a skill gap that may leave half of new manufacturing jobs unfilled in part due to shifting skill sets and retirements (Giffi et al. 2018). As transformation proceeds, workers in many areas will need to be retrained. Engineers and technicians will have to learn how to operate new technologies and smart manufacturing systems as well as implement best practices to ensure that facilities and equipment are operating efficiently. They must also be trained to recognize sources of energy waste, take action to mitigate them, and monitor ongoing progress. Jobs related to the recycling and circular economies require specific capabilities that are currently underdeveloped in the United States.

DATA GAPS

Another challenge to decarbonization is the inadequate collection and sharing of data about manufacturing and manufactured products. Industry lacks aggregated data on fuel use, energy consumption, and energy management to help identify trends and to show how new practices, technologies, and policies would impact the sector. In addition, whereas the most useful data are often generated at the plant level, manufacturers typically regard these numbers as sensitive and proprietary, and companies must also be careful not to violate antitrust laws when sharing information.

It is clear that accurate data are needed to inform decisions around potential emission-reduction strategies such as establishing benchmarks and standards and tracking results. Industry needs a transparent system for measuring, testing, and reporting in order to develop metrics and conduct studies on carbon intensity, life cycle accounting, competitiveness, resilience, and impacts on energy-intensive trade-exposed U.S. industries.

Policy and Funding

Absent public policy, the path to a competitive and low-emissions industrial sector is difficult at best. Industry and government need to envision this future together and lay out a plan for success. Policies should couple the needs and expertise of industry with the priorities and resources of the public sector. They should accelerate the implementation of best practices, the deployment of current technologies, and the development of new ones.

More specifically, government can provide manufacturers with tools and resources to identify and act on energy-saving opportunities and pursue transformational innovations. Federal policies and programs should support energy efficiency, encourage investments that foster a strong and resilient economy in a low-carbon world, and foster a highly skilled workforce to install and operate new technologies and systems.

Three policy areas are essential to this transformation:

- Incentives and technical assistance
- Standards, loans, and market signals
- Research, development, and demonstration

Incentives and Technical Assistance

Public policy should enable industry to rapidly deploy the energy-efficient technologies that exist today. The entire range of companies, from the innovators and early adopters to those slower to act, need incentives to reduce emissions. Incentives can spur competition and technology adoption. For example, the appliance tax credit for manufacturers incentivized the production of units that met specified efficiency standards and increased their market share (Doris et al. 2009; Gold and Nadel 2011). Investment tax credits can stimulate investment in new machinery, equipment, and software that help reduce emissions (Hart and Noll 2019). The business energy investment tax credit can reduce the cost of renewable energy systems by up to 30% and CHP by up to 10% (DSIRE 2020a). The modified accelerated cost recovery system allows businesses to recover investments in CHP and renewable systems through depreciation (DSIRE 2020b).

While financial incentives can encourage industries to act, some companies need additional help. Technical assistance provides manufacturers with resources to identify opportunities for emission reductions, implement best practices, and develop skills in their workforce. Government programs and tools directed to these ends should be strengthened and expanded. The DOE Advanced Manufacturing Office (AMO), for example, is positioned to quickly and effectively respond to an industrial decarbonization agenda. This office currently administers a number of successful programs increasing the efficiency, productivity, and competitiveness of U.S. manufacturing through collaborative partnerships.

One such AMO program, Better Plants, helps manufacturers become more energy efficient. This program has served more than 220 companies at 3,200 different facilities, helping them save 1.3 quadrillion Btus of energy and $6 billion in energy costs (DOE 2019b). Small and medium-sized manufacturers have access to 31 active or planned industrial assessment centers, university programs that conduct student-led energy audits of plants at no cost. The program has completed more than 19,000 assessments; facilities could achieve an average yearly savings of $137,126 by adopting all recommendations (IAC 2019).

DOE also provides tools for manufacturers. The Manufacturing Energy Assessment Software for Utility Reduction (MEASUR) combines and expands a number of legacy energy assessment tools that enable manufacturers to improve the efficiency of their facilities by analyzing the performance of systems such as pumps, fans, air compressors, process heating technologies, and steam systems (DOE 2020b). The 50001 Ready tool, also created by DOE, helps manufacturers implement SEM. Based on International Organization for Standardization (ISO) 50001, the tool serves as a step-by-step guide to SEM without the expense of certification required by ISO 50001 (DOE 2020a).

STANDARDS, LOANS, AND MARKET SIGNALS

Policies can also help establish standards, reduce risk, and induce market transformation. Coupled with verification and validation programs, government standards for manufacturing equipment will ensure that efficient technologies enter the market. Standards should be performance based rather than technology based in order to compare equipment currently in use with new technologies. Labeling initiatives like DOE's ENERGY STAR®, the Hydraulic Institute's energy rating for pumps, and the National Electrical Manufacturers Association's designation of premium-efficiency motors help consumers identify the most efficient equipment. New labels that identify low-carbon products can be used in the same way.

Government programs that reduce risk can also help industry make investments to lower emissions. For example, the DOE Loan Guarantee Program aims to reduce the cost of financing high-risk projects that "avoid, reduce, or sequester" GHGs (DSIRE 2016).

Other risk reduction mechanisms include green banks, revolving loan funds, and cost-sharing programs, and policymakers should focus on industrial equipment that lowers carbon intensity. Other possible policy initiatives include science-based emission-reduction targets for individual industries and a market-based trading system that allows industries to buy and sell credits.

The federal government should also send a market signal by purchasing low-carbon goods for its own operations. A "buy-clean" procurement policy would create a competitive and performance-based market signal for these types of products. State and municipal governments would be likely to follow suit.

RESEARCH, DEVELOPMENT, AND DEMONSTRATION

Currently available but underutilized technologies can achieve nearly half the emissions reductions needed to reach net zero by 2050, but policy is required to accelerate their deployment in industry (Nadel and Ungar 2019). Establishing a research-to-marketplace pipeline that enables transformational change is critical to meeting climate goals and maintaining the competitiveness of the industrial base. RD&D programs that develop transformational industrial technologies should be a priority.

Sustained federal RD&D funding is needed to propel technologies to the commercial market. Key agencies include AMO, the National Institute of Standards and Technology (NIST), and the Office of Technology Transitions (OTT) at DOE. Federal grants will be essential to support pilot projects and demonstrations of new technologies at commercial scale. The Small Business Innovation Research and Small Business Technology Transfer programs are funded by a small percentage of the RD&D budgets of several federal agencies. Their competitive grants provide capital to small domestic businesses with innovative and potentially cost-effective concepts and enable collaboration with research institutions to reach commercialization. They are currently funding work on catalysts, membranes, advanced materials, waste heat recovery, thermal process intensification, and other innovative technologies that show promise for industrial decarbonization (DOE 2020c).

Public–private partnerships will also continue to be an effective way to conduct RD&D, combining the resources of government and the expertise of industry. The ability of industry to collaborate is hindered by antitrust, intellectual property, and licensing strictures. Reforming these rules for projects that specially target emissions would enable more collaboration. One successful RD&D program, Industries of the Future, formed a partnership between the government and energy-intensive manufacturers to create technology road maps. Industry groups incorporated many of these road maps after the program ended.

While traditionally focusing on late-stage RD&D, corporate investment can also help spur innovation. Breakthrough Energy Ventures, a private investment group, identifies emission reduction in the manufacturing sector as one of its grand challenges. It invests in efforts to develop low-carbon versions of products like chemicals, steel, cement, and paper (Breakthrough Energy 2020). Technology competitions, such as those hosted by the XPRIZE Foundation, can also generate new solutions. A current XPRIZE competition offering a $20 million prize challenges teams to transform CO_2 into valuable products (XPRIZE 2020).

Recommendations

Immediate action must be taken to reduce the carbon intensity of the industrial sector. This sector plays a critical role in the U.S. economy and in national decarbonization efforts due to both its own emissions and the role it plays in enabling GHG reductions in other economic sectors. With comprehensive efforts that unleash innovation and encourage investment, the industrial sector can be transformed as part of a thriving, low-carbon economy. Emission reductions can be realized in short order through adoption of best practices and energy efficiency improvements. Additionally, the federal government should implement policies and programs that set the stage for an industrial transformation. To drive this transformation, it is essential to leverage both public and private funds. These actions must enable a step-change in industry, replacing the incremental improvements that have been implemented to date.

Industry must produce accurate data and additional research to inform decision making. Studies of carbon intensity, life cycle accounting, competitiveness, resilience, and impacts on energy-intensive trade-exposed U.S. industries are needed to guide decisions, track results, and establish benchmarks and standards. Establishing industry-specific technology roadmaps will provide a glidepath for transformation.

Manufacturers should coordinate with other parts of the economy, especially utilities and labor. Decarbonization will require electricity markets to deploy larger amounts of renewable energy, optimize rates, and develop programs that encourage emission reductions. Manufacturers will need to work closely with electric utilities in order to maintain grid reliability. Recruiting, training, and maintaining a skilled workforce will be critical to the industrial sector's transformation.

Policymakers must prioritize the reduction of industrial emissions at relevant agencies. Explicit authorization to address industrial emissions could enable greater focus and expansion of programs at government agencies. The track record of successful collaboration between AMO and industry indicates that this office is positioned to most quickly and effectively respond to an industrial decarbonization agenda. Building on the current portfolio of program offerings, AMO could quickly increase the impact of its technical assistance programs and accelerate adoption of emission-reducing best practices such as strategic energy management and smart manufacturing. This prioritization could also enable quicker deployment of currently available emission-reduction solutions through other programs such as DOE's Technology Commercialization Fund, NIST's Manufacturing Extension Partnership, and various other loan and technology-transfer programs**.**

Government, academia, and the private sector should initiate a technological innovation system focused on industrial emissions. Greater coordination among government agencies, national labs, universities, and private industry could accelerate technology commercialization. These partnerships, which can leverage public and private funds to develop research projects aimed at targeted solutions, can bring technologies to market faster than government or private RD&D alone. A long-term focus on transformational technologies and sustained RD&D funding to bridge the innovation gap will be needed to propel technologies to the commercial market and meet emission-reduction targets. Developing harmonious research objectives, technology test beds, demonstration projects, and verification and validation programs could improve the effectiveness of pre-competitive investment and spur greater deployment. Developing risk-sharing programs could serve as a backstop to industry investments.

Regulators must increase the capacity to enable transformation. Addressing market barriers that constrain innovation and investment will require a regulatory environment that encourages deployment of capital into emission-reduction solutions at the speed and scale required to meet climate goals. The need to rapidly scale up and deploy technology should be met with enough flexibility to overcome hurdles, such as antitrust regulations and intellectual property rights, that prevent collaboration and shared use of innovative technologies. Revision of permitting and litigation rules can help mobilize investment and minimize project delivery times.

Policymakers should support a low-carbon market. Markets that support manufacturers that efficiently use resources, produce emission-reducing technologies, and advance circular economy concepts should be encouraged. Transforming the market to encourage the production and consumption of low-carbon goods would accelerate the transition to a low-carbon economy. Standardizing tools like environmental product disclosures and life-cycle assessments are essential for benchmarking. Incentives that increase the supply and demand for low-carbon products can help develop a strong market and encourage competition.

The U.S. industrial sector can thrive with a much smaller emissions footprint. Government and industry will need to work together to reach net-zero emissions and map out the path to a low-carbon economy supported by the workforce of the future. The process of industrial decarbonization must be accelerated now, unleashing American innovation and ingenuity to propel the nation's industries into a prosperous, resilient future.

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