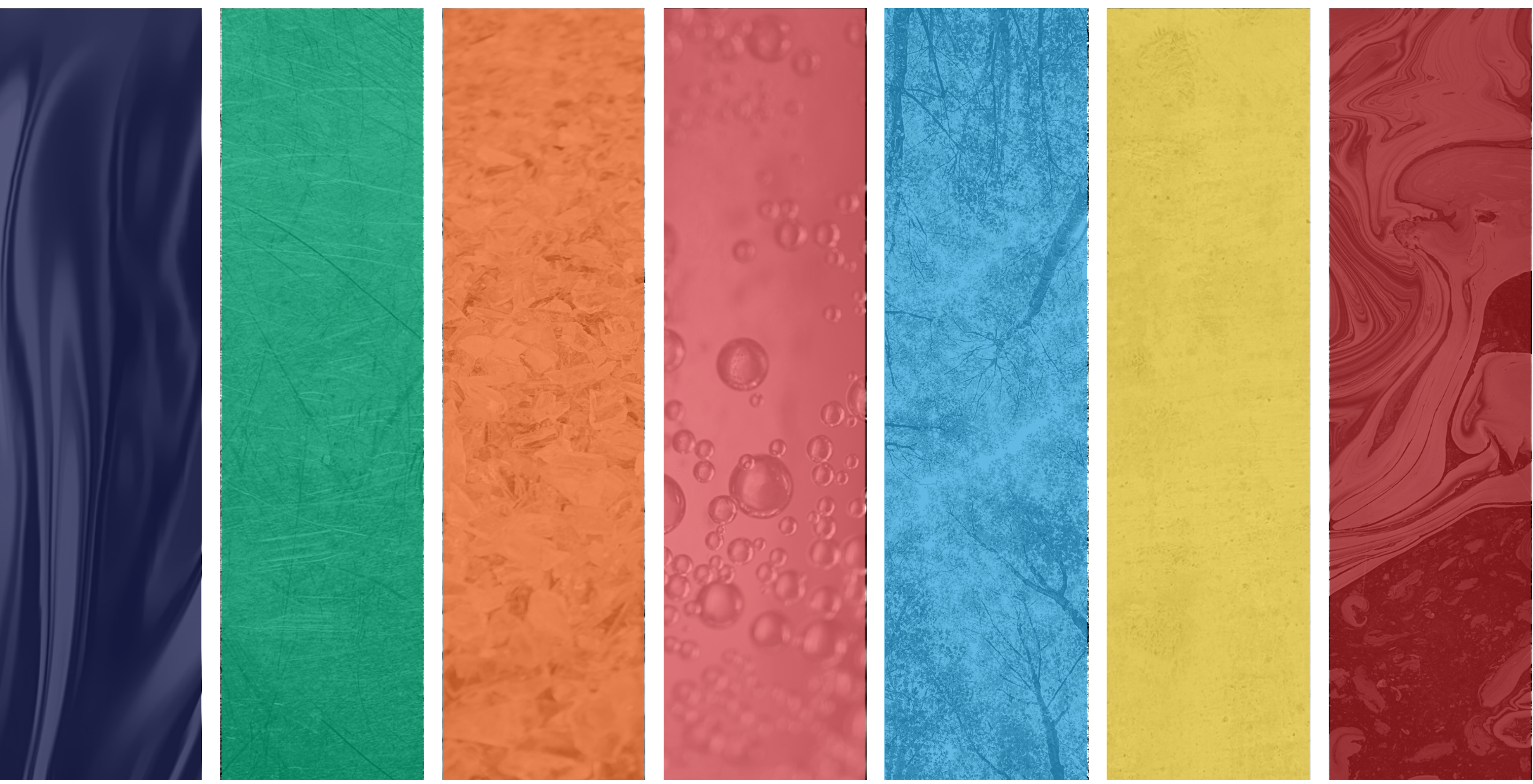
ENABLING INDUSTRIAL DECARBONIZATION

A policy guidebook for U.S. states



UNITED STATES
CLIMATE ALLIANCE

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ABOUT THIS DOCUMENT

The United States Climate Alliance ("the Alliance") commissioned ACEEE to produce the following Policy Guidebook. It was prepared with guidance and significant contributions from the Alliance's Industrial Decarbonization Working Group, which includes staff from various state government agencies and offices. Not all states in the Alliance participated in this process.

This Guidebook is not meant to represent a policy plan for the Alliance or any Alliance states, but is rather a resource designed to highlight the highest-impact opportunities for states to focus on to decarbonize their industrial sectors. The Guidebook covers policy developments through September 2022. All figures created with Datawrapper.

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UNITED STATES CLIMATE ALLIANCE

The United States Climate Alliance is a bipartisan coalition of governors committed to reducing greenhouse gas emissions consistent with the goals of the Paris Agreement. Each member state commits to:

- Reducing collective net GHG emissions at least 26-28 percent by 2025 and 50-52 percent by 2030, both below 2005 levels, and collectively achieving overall net-zero GHG emissions as soon as practicable, and no later than 2050.
- Accelerating new and existing policies to reduce GHG pollution, building resilience to the impacts of climate change, and promoting clean energy deployment at the state and federal level.
- Centering equity, environmental justice, and a just economic transition in their efforts to achieve their climate goals and create high-quality jobs.
- Tracking and reporting progress to the global community in appropriate settings, including when the world convenes to take stock of the Paris Agreement

ACEEE

Smart Energy. Clean Planet. Better Lives.

The American Council for an Energy-Efficient Economy (ACEEE), a nonprofit research organization, develops policies to reduce energy waste and combat climate change. Its independent analysis advances investments, programs, and behaviors that use energy more effectively and help build an equitable clean energy future.

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EXECUTIVE SUMMARY

Over the past decade, climate and clean energy policies have helped slow the growth rate of global greenhouse gas (GHG) emissions. Yet, GHG emissions are at their highest levels in human history, and much more needs to be done to avoid the worst impacts of climate change. Worldwide, policy attention and investment have been uneven across major emitting sectors, with most attention over the past several decades focused on transportation, buildings, and utilities. However, industrial energy and electricity consumption account for 34 percent of global net GHG emissions, the largest emissions source by far. [1] In the United States, this trend also holds true. In 2020, the industrial sector was responsible for 24 percent of direct GHG emissions (30 percent including indirect emissions from electricity use). [2] Although industrial GHG emissions remained flat over the past decade, the sector is projected to become the largest source of national GHG emissions by 2030 absent additional policy intervention. [3]

The U.S. Climate Alliance ("the Alliance"), a coalition of 24 governors committed to achieving the goals of the Paris Agreement, commissioned the development of this guidebook to help states attain those goals by exploring pathways and policy options to decarbonize their industrial sectors. The guidebook focuses on describing current industrial decarbonization policy efforts in the United States at the state level, where substantial work toward decarbonization is underway and accelerating. This guidebook also provides references to federal and international policy efforts that support industrial sector transitions.

The industrial sector is complex and inextricable from other sectors. Policymakers therefore need up-to-date information on the different approaches states are pursuing for decarbonization, in the context of a broader global perspective. While 'industry' is a broad term, this guidebook focuses on the opportunities and challenges of decarbonizing some of the largest energy consumers and GHG emitters in the manufacturing sector. The information in this guidebook can serve as a launching point and reference for states interested in developing a policy approach to industrial decarbonization that meets their climate goals.

The overall strategy

Within the industrial sector, energy consumption typically parallels GHG emissions. Manufacturing consumes the largest portion of energy (81 percent), with agriculture, construction, and mining consuming the rest. [4] Seven subsectors account for the majority of manufacturing's energy consumption [5] and GHG emissions, offering a lens to narrow states' focus (***Figure ES-1***). [6] These include:

Heavy industries, defined as being energy-intensive and/or involving high use of process heat:

- Chemical production
- Petroleum refining
- Iron and steel production
- Cement production
- Glass production

Light industries, defined as having modest energy consumption and/or process heat demands:

- Forest product production
- Food and beverage processing

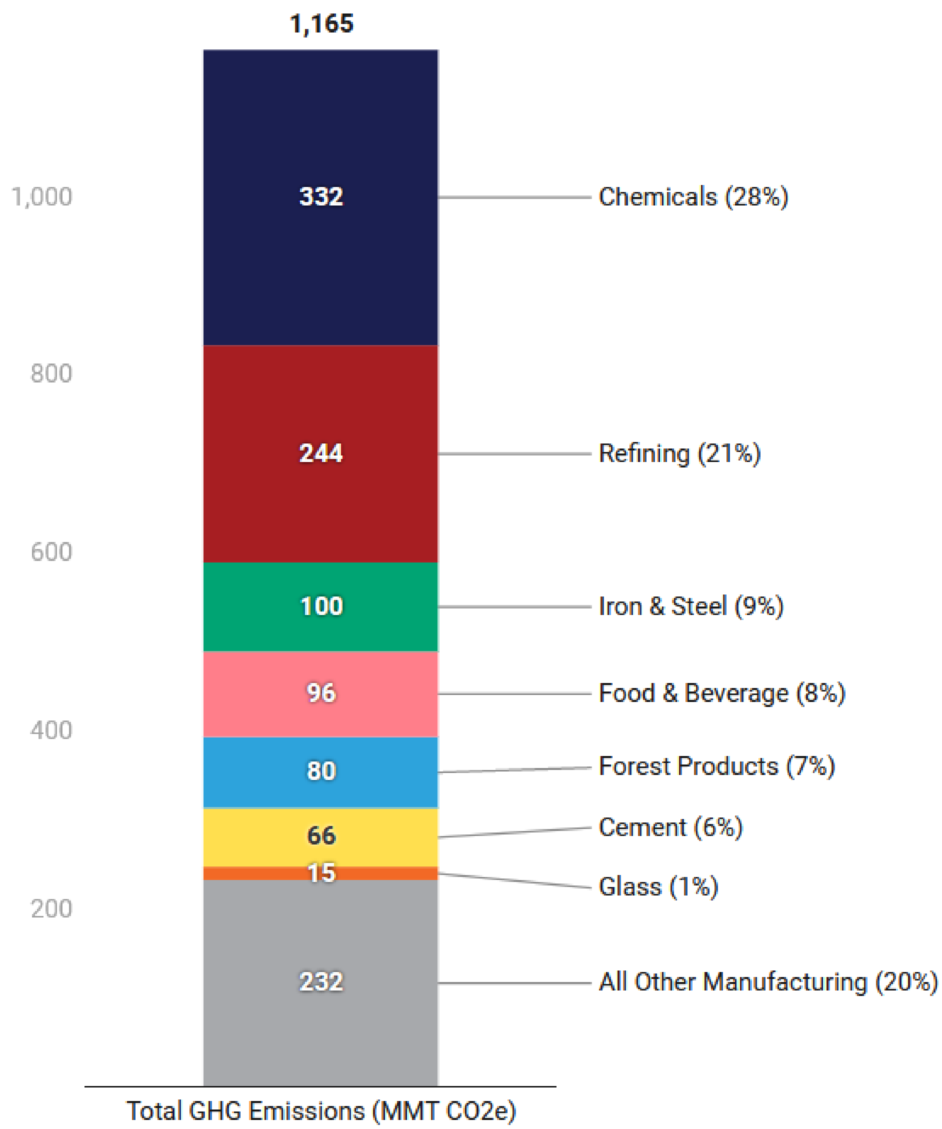

Figure ES 1: GHG emissions from U.S. manufacturing sector in 2018, by subsector (left) and percentage of total (right). Includes direct (onsite) and indirect (offsite) emissions. Source: U.S. Department of Energy, Manufacturing Energy and Carbon Footprints.

Each of these subsectors faces different challenges and opportunities to reduce GHG emissions over different timescales (***Figure ES-2***). However, state policymakers can consider five cross-cutting pillars for industrial decarbonization that point the way to net-zero GHG emissions for most industrial activities:

1. Efficiency (of energy, materials, and waste heat recovery) is the most cost-effective, near-term opportunity for reducing energy use and GHG emissions across industries. There may be a significant opportunity in light industry, where efficiency has not received as much attention.

2. Electrification (of equipment and processes where viable and served by low-carbon sources) is a near- to mid-term opportunity, with greater potential in lighter industries like food and paper, which have lower temperature heating requirements.

3. Low-carbon fuels & feedstocks (such as biomass and hydrogen with low lifecycle GHG emissions, to displace fossil fuels) offer mid- to long-term opportunities for heavy industries with high-temperature heating needs that cannot be electrified or abated otherwise, or industries like plastics and fertilizer producers that currently transform natural gas into precursor chemicals, like methanol, ethylene, and ammonia. Solar thermal, geothermal, and nuclear offer solutions for zero-carbon process heat at low- to medium-temperatures across industries.

4. Carbon capture, utilization, and storage technologies offer mid- to long-term solutions for mitigating emissions that cannot be reduced through other pillars.

5. Procurement (by public and private entities) offers near- to mid-term opportunities to drive demand and create new markets for low-carbon industrial products, thereby rewarding industry's investment in implementing the other pillars.

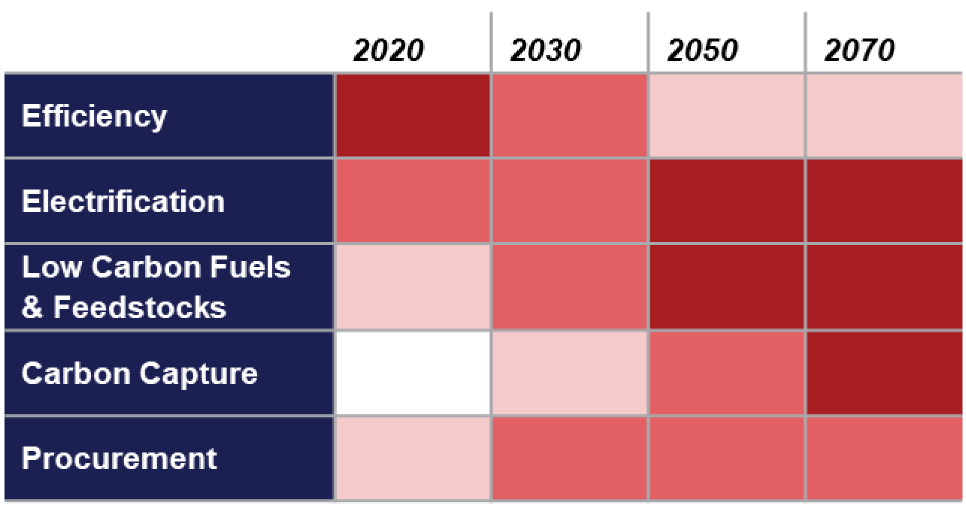

Figure ES-2: Relative timeframe for each decarbonization pillar to realize maximum GHG emissions reductions in the industrial sector, from 2020 to 2070. Darker shades signify greater GHG emissions impact due to technology scaling, commercial availability, and build-out of supporting markets and infrastructure.

Some of these pillars face larger barriers than others to deploy at scale (such as costs, infrastructure requirements, level of technical maturity, application at commercial scale, and stakeholder support), so policy will be critical to support and pursue these GHG emissions reduction opportunities.

Policy options & considerations

In the United States, programs that directly address industrial GHG emissions, particularly those from manufacturing, constitute an emerging policy space. While each state's approach will need to be tailored to its own unique challenges and opportunities, states can leverage numerous new technologies and approaches as well as existing legal authorities that cut across the five decarbonization pillars (***Figure ES-3***) to overcome the challenges that industry faces in achieving net-zero GHG emissions. In fact, many of the solutions borrow approaches and lessons learned from decarbonization efforts from other energy-related sectors like electricity, buildings, and transportation. Multiple states have already initiated these types of policies – this work identified over 100 relevant policies in place across U.S. states. State experience and learnings may provide valuable perspective for the national discussion on the framework of industrial decarbonization policies.

<table>
<tr><th></th><th>Efficiency</th><th>Electrification</th><th>Low Carbon Fuels & Feedstocks</th><th>Carbon Capture</th><th>Procurement</th></tr>
<tr><td rowspan="3">Planning & Governance</td><td colspan="5">State emissions and efficiency targets</td></tr>
<tr><td colspan="5">State analysis and roadmaps</td></tr>
<tr><td colspan="5">State governance structures</td></tr>
<tr><td rowspan="2">Research, Development, Demonstration, & Deployment</td><td colspan="4">Direct investment</td><td>Pilot projects</td></tr>
<tr><td colspan="4">Tax credits</td><td>Product life cycle assessments</td></tr>
<tr><td rowspan="3">Carbon Pricing</td><td colspan="5">Regulated carbon markets</td></tr>
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<tr><td rowspan="2">Incentives</td><td colspan="5">Financial incentives (incl. grants, rebates, cash)</td></tr>
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<tr><td rowspan="3">Standards</td><td colspan="5">Emissions standards</td></tr>
<tr><td>Efficiency standards</td><td colspan="2">Clean heat standards</td><td rowspan="2">Carbon management standards</td><td>Clean product standards</td></tr>
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<tr><td colspan="5">Diverse workforce development</td></tr>
<tr><td colspan="5">Industry clustering</td></tr>
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Figure ES-3: Interaction of policy landscape with decarbonization pillars. Source: This work.

Other high-level challenges that policymakers should consider while developing industrial decarbonization policies include administrative complexity, clean energy timing and sequencing, transition costs, environmental impacts, GHG emissions reduction target complexities, and considerations for small and medium manufacturers.

Industry subsector specifics

Seven major industrial subsectors accounted for 80 percent of the manufacturing sector's direct and indirect GHG emissions in 2018: 1) chemicals, 2) refining, 3) iron & steel, 4) cement, 5) glass, 6) forest products, and 7) food & beverage. These subsectors warrant focus due to their energy and emissions footprint, their production of key inputs for downstream manufacturers, and their geographic distribution across the United States.

The role that each of the major pillars of industrial decarbonization will play in reducing GHG emissions across various industrial subsectors will vary, as some pillars will align with technology, business, economic, and geographic opportunities earlier than others. ***Figure ES-4*** summarizes the opportunities for GHG emissions reduction impact, timing, and pillar alignment for each subsector.

	Efficiency		Electrification		Low Carbon Fuels & Feedstocks		Carbon Capture		Procurement	
Timeline	*2020 - 2030*	*2030 - 2050*	*2020 - 2030*	*2030 - 2050*	*2020 - 2030*	*2030 - 2050*	*2020 - 2030*	*2030 - 2050*	*2020 - 2030*	*2030 - 2050*
Chemicals	EE↓↓, ME↓↓↓		H&M↓↓↓, PF↓↓↓		H2↓↓↓, BM↓↓↓, RE↓		CCU↓↓↓, CCS↓↓↓		LCPM↓	
Refining	EE↓↓↓*, ME↓↓		H&M↓↓		H2↓↓↓, BM↓↓↓		CCU↓↓↓, CCS↓↓↓		()	
Iron & Steel	EE↓↓↓, ME↓↓↓		H&M↓↓↓*, PF↓↓		H2↓↓↓, BM↓, RE↓		CCU↓, CCS↓↓		LCPM↓↓↓	
Cement	EE↓↓↓, ME↓↓↓*		H&M↓↓		H2↓, BM↓↓↓*		CCU↓↓↓, CCS↓↓↓		LCPM↓↓↓	
Glass	EE↓↓↓, ME↓↓		H&M↓↓↓		H2↓, BM↓↓↓, RE↓		()		LCPM↓↓↓	
Forest Products	EE↓↓↓*, ME↓↓		H&M↓↓↓		BM↓↓↓*, RE↓		()		LCPM↓↓	
Food & Beverage	EE↓↓↓, ME↓		H&M↓↓↓		RE↓↓		()		LCPM↓↓	

Figure ES-4: Alignment of pillars with near and long-term technical opportunities for GHG reduction by industry subsector. Color gradient indicates timing to achieve greatest impact (darker color = more impact).

EE = energy efficiency; ME = material efficiency; H&M = Heating and mechanical energy; PF = process energy fuel-switching; RE = renewable fuel/feedstock (solar thermal, geothermal); H2 = hydrogen fuel/feedstock; BM = biomass fuel/feedstock; CCU = carbon capture and utilization; CCS = carbon capture and storage; LCPM = low carbon products and materials.

*Number of ↓ indicates emissions impact potential: ↓↓↓ = high; ↓↓ = medium; ↓ = low. * = technology is already widely applied in a subsector. () = unlikely use case*

Sources: Adapted from Worrell and Boyd (Table 1) and Energy Systems Integration Group (Table 1).

Transforming these industries to achieve net-zero GHG emissions will be exceptionally challenging given the sector's complexity, high degree of capital investment, and long lifetime of equipment. However, progress is being made to understand the opportunities and develop pathways towards decarbonization. For each of these major sectors, national and international coalitions have developed sector-specific roadmaps, and many manufacturing companies have set their own GHG emissions reduction targets and are developing specific plans to achieve them. At the same time, there are numerous policy opportunities available for states to address persistent barriers and help the industrial sector accelerate its decarbonization efforts.

Conclusion

The path to industrial decarbonization will be a multi-decade transformation that requires a multi-layered, multi-stakeholder approach.[7] Regional partnerships across states, targeted work with industrial clusters, and learning and collaboration with federal, state, and international peers can help achieve the most efficient transformation. At the same time, decarbonizing the industrial sector presents an opportunity to cut the wider environmental footprint of manufacturing, improve competitiveness, address environmental justice concerns, and broaden workforce diversity. States have multiple policy levers that can be used to help achieve these benefits, like investing in low-carbon infrastructure, leveraging financing, adopting regulations and standards, supporting technical assistance, preferentially purchasing low-carbon products, and supporting worker training programs. While the current industrial decarbonization policy landscape is in its early stages, states are in a prime position to take swift and innovative action to help accelerate the sector's efforts to reach net-zero GHG emissions.

Using This Guidebook

The U.S. Climate Alliance's Industrial Decarbonization Working Group requested guidance to help states navigate state and national climate goals, emissions targets, and pathways to achieve transformational industrial decarbonization goals at the state level. Therefore, this guidebook is geared towards state policymakers focused on climate and clean energy goals that sit within the executive branch, including state agencies, governors' offices, and quasi-governmental institutions. Additional audiences include stakeholders participating in the industrial energy transition, such as officials at the local or federal levels of government, industry, industry associations, and NGOs that advise on policy.

This guidebook describes current industrial decarbonization policy efforts in the United States at the state level, where decarbonization work is in its early stages but accelerating rapidly. This work identified over 100 policies relevant to industrial decarbonization in varying stages of implementation across U.S. states. The guidebook also provides references to federal and international policy efforts that support industrial sector transitions. Because industrial decarbonization is a policy area that is evolving rapidly at the state and federal levels, this guidebook is intended as an introduction, rather than an exhaustive review, of the industrial decarbonization policy space. It aims to fill a significant knowledge gap on the best ways to enable industrial decarbonization through policy, the potential timing and sequencing of such policies, and the different considerations states must weigh in policy development.

As state (and federal) industrial decarbonization policy grows and matures, this guidebook may be updated to capture more well-defined policy strategies, approaches, and applications. The information in this guidebook can serve as a launching point and reference for states interested in developing a policy framework and approach to industrial decarbonization that ensures their climate goals are met.

This resource is organized into the following sections:

- Chapter 1. The Overall Strategy: Provides an overview of the industrial sector's GHG emissions and energy use (within a global and U.S. context), projected trends, and primary decarbonization opportunities (referred to as pillars).

- Chapter 2. Policy Options & Considerations: Describes the major policy options critical to enabling and advancing the decarbonization pillars, with a focus on U.S. state policy development based on a landscape analysis of over 100 policies. The chapter covers six categories of policies: 1) planning & governance, 2) research, development, demonstration, and deployment, 3) carbon pricing, 4) incentives, 5) standards, and 6) supporting policies & actions. The chapter also describes high-level challenges that policymakers should consider while developing industrial decarbonization policies. It includes references to relevant federal and international policy approaches.

- Chapter 3. Industry Subsector Specifics: Describes the emissions, technical barriers, and policy opportunities specific to the following seven industries, which correspond to the largest energy consumers and GHG emitters: 1) chemicals, 2) refining, 3) iron & steel, 4) cement, 5) glass, 6) forest products, and 7) food & beverage.

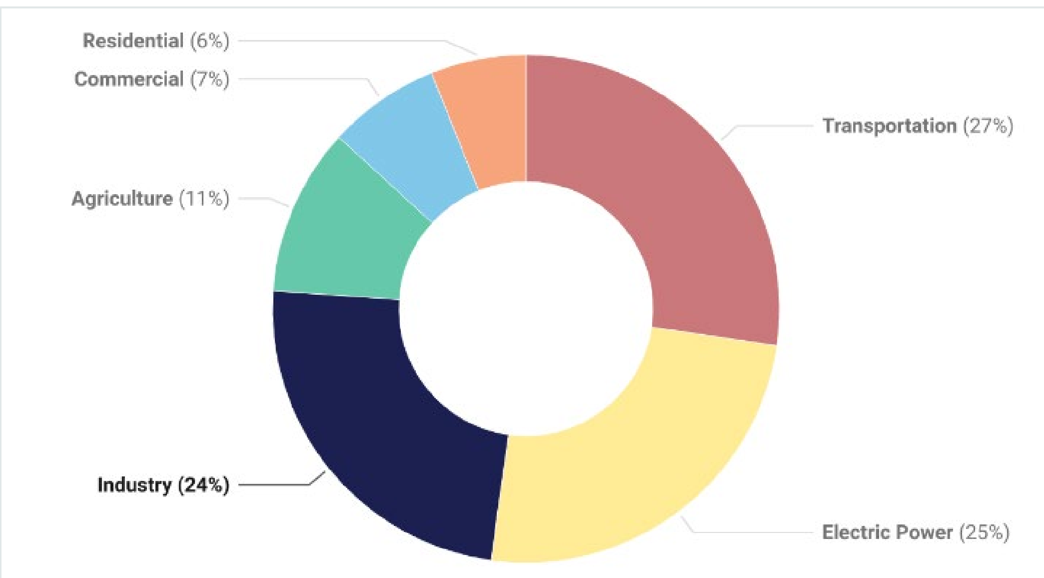
- Appendices: Expanded detail on new federal actions supporting industrial decarbonization; subsector emissions data; lists of additional resources such as tools, strategies, roadmaps, and guides; and glossary of terms and acronyms.

CHAPTER 1. THE OVERALL STRATEGY

1.1 The Opportunity

Climate and clean energy policies and advances in low-carbon technologies have helped slow the growth rate of global greenhouse gas (GHG) emissions over the past decade. Despite this progress, the latest Intergovernmental Panel on Climate Change (IPCC) report notes that global GHG emissions are at their highest levels in human history, and much more needs to be done to avoid the worst impacts of climate change.[8] Policymaker attention and investment has been uneven across sectors, especially in industry, despite this sector's energy and electricity consumption accounting for 34 percent of net GHG emissions—the largest emissions source by far. Without policy attention, industrial emissions will likely increase as the demand for materials like cement, plastics, and steel increases globally.[9]

These trends also hold true in the United States, where the industrial sector currently contributes 24 percent of economy-wide GHG emissions (and 30 percent, when considering indirect emissions[a]) (***Figure 1***).[10] While total U.S. gross GHG emissions fell by 19.5 percent between 2005 and 2020 (driven largely by reductions in the electric and transportation sectors), industrial GHG emissions remained



[a] 'Indirect' emissions are associated with offsite electricity use (i.e., Scope 2 emissions), which can be significant for certain industries like steel production via electric arc furnace and aluminum production, or for food processors.

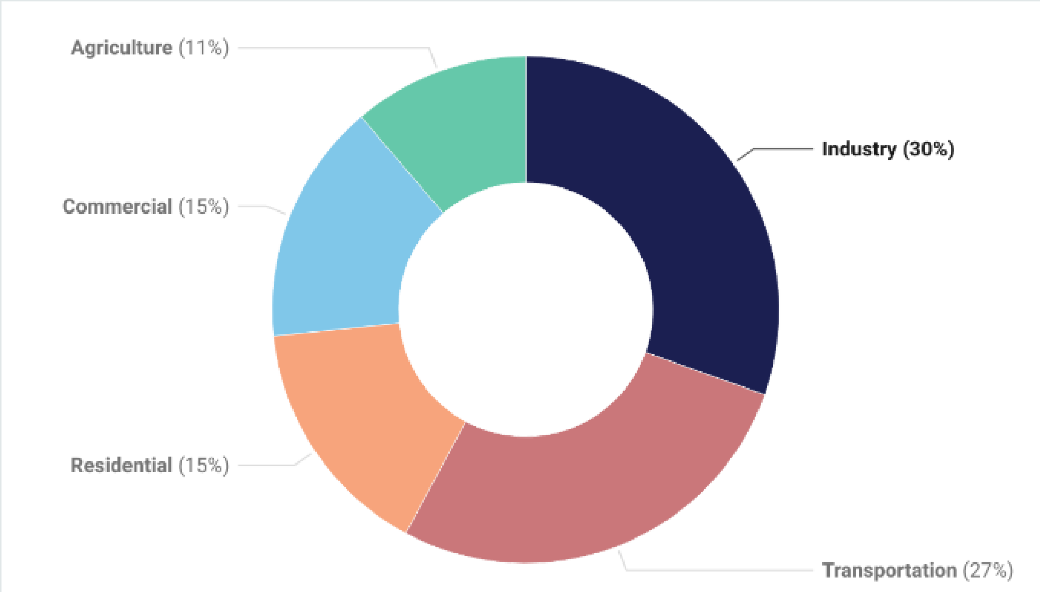


Figure 1: Sources of U.S. GHG emissions by economic sector (top). Sources of U.S. GHG emissions, with electricity emissions allocated by end use sector (bottom). Industry slice in dark blue. Source: U.S. EPA.

relatively flat[b] over the same time period.[11] Onsite fossil fuel combustion, mostly used for process heat generation, accounts for over half of industrial direct emissions.[12] The majority of the sector's remaining direct emissions is a result of utilizing fuels in production (e.g., feedstock fuels like natural gas used to make plastics); chemical reactions that release carbon dioxide as a byproduct during the production of chemicals, iron and steel, and cement; and natural gas system leaks.[13]

Within the industrial sector, manufacturing consumes the largest amounts of energy (81 percent).[14] Seven subsectors[c] account for almost 90 percent of the manufacturing sector's energy consumption[15] and 80 percent of its GHG emissions (***Figure 2***).[16] These include:

Heavy industries, defined as being energy-intensive and/or including high use of process heat:

- Chemical production
- Petroleum refining
- Iron and steel production
- Cement production
- Glass production

Light industries, defined as having modest energy consumption and/or process heat demands:

- Forest products production
- Food and beverage processing

[b] According to U.S. Environmental Protection Agency (EPA) data, the 'industry' sector's emissions were 1,536 million metric tons (MMT) carbon dioxide equivalent (CO_2e) in 2005 and 1,426 MMT CO_2e in 2020–a 7 percent decrease.

[c] The source (the U.S. Energy Information Administration [EIA]) describes six, not seven, subsectors, but EIA lumps cement and glass production under the "nonmetallic mineral products" category.

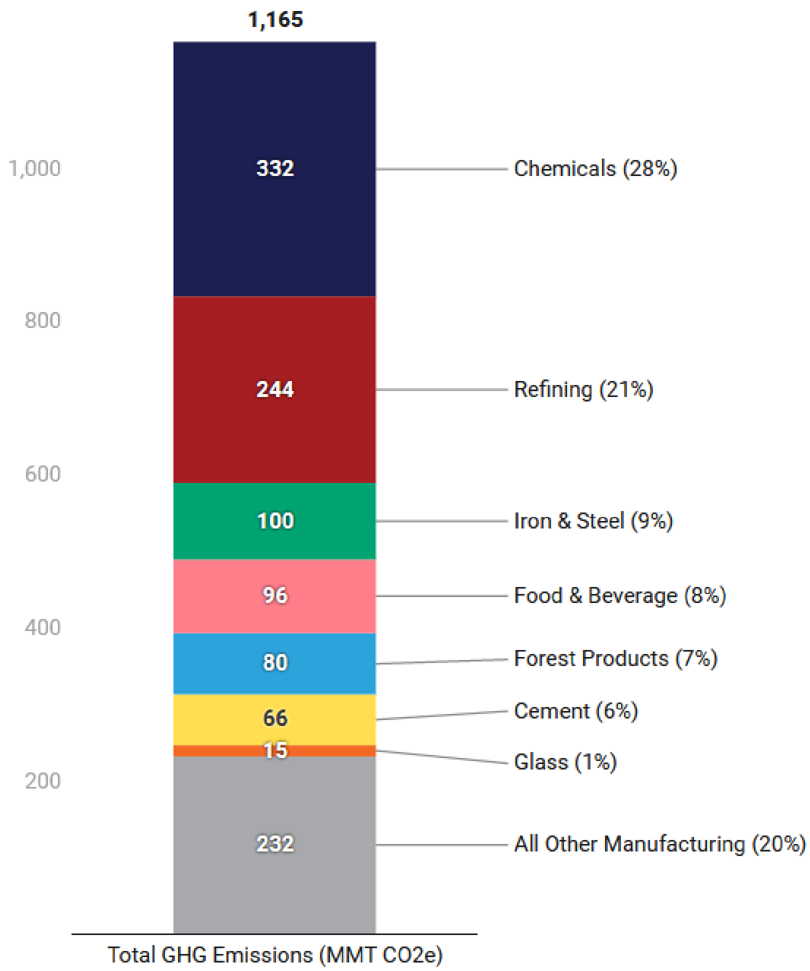


Figure 2: GHG emissions from U.S. manufacturing sector in 2018, by subsector (left) and percentage of total (right). Includes direct (onsite) and indirect (offsite) emissions. Source: U.S. Department of Energy, Manufacturing Energy and Carbon Footprints.

Absent additional policy and investment, industry is projected to become the largest source of national GHG emissions by 2030. [17] Over the longer term, the U.S. Department of Energy (DOE) anticipates a 30 percent growth in product demand by 2050 (with a 15 percent associated increase in GHG emissions). [18] These projected trends suggest that GHG reductions far beyond incremental improvements will be needed to reach a near-zero GHG footprint by 2050. Considering the magnitude of the transformation required, it is imperative to promptly accelerate the pace of action and to invest across near- and long-term objectives, learn and adapt to the changing needs of industry, and engage a broad range of stakeholders to leverage and encourage involvement of the entire distribution of actors in the industrial sector. In the United States, states have a unique opportunity to spur action given their involvement in energy and regional planning, economic development, infrastructure financing and permitting, and their leadership on climate policy, as demonstrated by coalitions like the U.S. Climate Alliance. [19]

1.2 Five Pillars of Industrial Decarbonization

Even though there are a broad variety of activities across the wide range of industrial sectors—each with different challenges and opportunities to reduce GHG emissions—there are several common pillars, or strategies, that policymakers can deploy to decarbonize industry. In September 2022, DOE released its *Industrial Decarbonization Roadmap*,[20] which identifies four cross-cutting pillars critical to reducing emissions in the manufacturing sector, including:

- **Energy efficiency,**
- **Industrial electrification,**
- **Low-carbon fuels, feedstocks, and energy sources,** and
- **Carbon capture utilization and storage.**

These pillars will likely be key to DOE and the Biden Administration's pursuit of industrial decarbonization, with many policy opportunities for state policymakers as well. This guidebook considers these and one additional pillar, **procurement of low embodied carbon products**, given recent momentum at both the state and federal levels.[21] For additional detail on these pillars, reference other roadmaps[22, 23] and studies.[24, 25, 26, 27]

Efficiency

Energy efficiency (EE) is the most cost-effective option for reducing energy and GHG emissions in the near term, while also providing multiple energy and non-energy benefits. EE can also lower the energy and resource demand prior to implementation of more costly transformative technologies. For example, minimizing industry's overall energy demand may end up requiring less construction of new zero-carbon infrastructure such as renewable energy and storage to meet future industrial energy demand. Thus, it is vital to continue pursuing EE along the entire course of the decarbonization transformation.

Studies indicate U.S. industry could reduce its energy use by 14–22 percent in the near term.[28] According to several decarbonization projections, the global rate of industrial EE improvements needs to more than triple from its current rate (0.5 to 1 percent per year).[29] This goal appears achievable in the United States, supported by evidence and experience across the 250 manufacturing partners in the DOE's Better Plants program, where participants report energy intensity improvement rates of 2.5 percent per year.[30]

Example: waste heat recovery (WHR). Waste heat is energy that is released during energy production or consumption but is not put to effective use, such as exhaust gases from boilers, furnaces, and other process heating equipment. For industry, some 20–50 percent of energy input is lost as waste heat,[31] providing a large opportunity to capture and reuse it where possible. One study estimates there are up to 14.6 gigawatts in WHR potential for U.S. manufacturing.[32] This is equivalent to the power that could be generated from over 45 million photovoltaic solar panels or nearly 5,000 utility scale wind turbines.[33] Recovering and reusing waste heat can generate cost savings, improve workflow and productivity, and decrease environmental impact. Although it is not always feasible or economic to recover waste heat, there are numerous technologies commercially available for WHR.[34]

Example: material efficiency (ME), circular economy, and related resource conservation approaches (e.g., waste management and per-unit materials optimization). These approaches can decrease industrial energy demand and GHG emissions by reducing the need for new raw materials. For example, ME approaches can provide up to 30 percent of the emissions reduction targets in cement, steel, and aluminum.[35]

Electrification

The U.S. industrial sector only meets around 13 percent of its overall energy needs with electricity.[36] However, this usage share varies considerably, from 14 percent in cement, glass, and ceramics to 65 percent in primary aluminum production.[37] Assuming the grid continues to decarbonize by transitioning from fossil to clean energy generation, multiple studies have identified near to mid-term opportunities to increase beneficial electrification in industry to reduce carbon emissions.[38, 39, 40, 41]

Example: process heat. One of the top electrification opportunities is for process heat,[42] which accounts for 61 percent of the onsite energy used in manufacturing. For industry overall, some 44 percent of the process heat is below 200°C (392°F), and more than 50 percent of it is below 300°C (572°F).[43] For some industries, the proportion of low-temperature heat in overall process heat is even higher, such as for food and textiles.[44] There are several commercial electric technologies that can provide heat below those levels, making industrial electrification a significant near- to mid-term opportunity. Although there are multiple options for generating low-carbon electricity (e.g., wind, solar, solar thermal, biomass), these choices must be balanced with the need to deliver this electricity efficiently, reliably, and consistently, as many industries consume energy 24 hours per day, seven days per week.

Example: leveling the cost playing field. Currently, electricity provides less than five percent of heavy industry's process heating.[45] A primary barrier to accelerating beneficial electrification is the electricity/natural gas price disparity. In many regions of the country, electricity costs multiple times more than natural gas for equivalent energy, which is a hurdle for accelerated adoption of low-carbon process heat options such as industrial heat pumps.[46] There is an opportunity to minimize this hurdle through policy approaches. Some of the international approaches being considered are contract for differences (CfD) which provides economic renumeration for the difference in cost based on the value of carbon reductions to the environment,[47] reallocating the cost of carbon to current fossil fuel use (including taxes, levies, reduced subsidies), changes in the network charges for delivered power, and changes in the delivered costs for power purchase agreements of renewable power.[48]

Low-carbon fuels & feedstocks (LCFF)

Industry consumes a variety of fuels for producing process heat. The refining and chemicals sectors use additional feedstocks to generate a complex array of products and materials. Fossil-based sources currently dominate these fuels and feedstocks.[49] Low-carbon alternatives to these fuels and feedstocks include biomass with low lifecycle GHG emissions, low-carbon hydrogen, other hydrogen derivatives like ammonia and methanol, and synthetic hydrocarbon fuels (derived from captured carbon dioxide). For a zero-carbon heat source that requires no combustion, solar thermal, geothermal, and nuclear power offer low and medium-temperature heating solutions.[50] Fuel applications of these low-carbon sources could include combustion in furnaces, boilers, or direct-fired applications to generate process heat. This is particularly of interest for high-temperature process heat (above 500 ° C) where the technical and economic opportunity is more favorable than other pathways like electrification. Potential applications of low-carbon fuels include the kilns in metal, cement, and chemical production facilities and refineries.

Example: hydrogen. Low-carbon hydrogen is a promising feedstock candidate that can be used to synthesize other high-energy carriers or precursor chemicals, such as methanol and ammonia.[51] For example, hydrogen can be combined with carbon monoxide to make synthesis gas (syngas), which can then produce other commodity chemicals.[52] Using low-carbon hydrogen to make ammonia will ultimately help reduce the chemical fertilizer industry's GHG footprint, which currently accounts for around one percent of global emissions.[53]

Hydrogen can be produced via various methods with different inputs, each with a corresponding variation in GHG intensity. A color spectrum is often used to describe these types of hydrogen, the most common examples below:

- Green: made through electrolysis of water molecules, using renewable energy
- Pink: made through electrolysis of water molecules, using nuclear power
- Blue: produced from methane, *with* carbon capture
- Grey: produced from methane, but *without* carbon capture[54]

In the marketplace, all types of hydrogen will compete with incumbent hydrogen production from highly optimized steam methane reformers (SMRs), also known as 'grey' hydrogen, which dominates the available capacity.[55] Because hydrogen is also produced as a byproduct in some industrial processes (e.g., ethane crackers in chemical plants, metal production), there is an opportunity to increase its use within the industries where it is a byproduct. It is important then to grow the market and application diversity for low-carbon hydrogen in parallel with enhancing the production and infrastructure capabilities.[d]

Carbon capture and storage (CCUS)

Carbon capture, utilization, and storage (CCUS) technologies could play a significant role in mitigating industrial emissions that cannot otherwise be reduced through other pillars.[56] CCUS refers to the capture of carbon dioxide from large point sources such as industrial facilities, and is a recognized and developed technology following decades of research and demonstration projects.[57] If the captured carbon dioxide is not utilized onsite, then it needs to be transported (e.g., via pipeline networks) to a site for reuse applications or injected into deep geological formations for permanent storage. Additionally, mineral carbonation, which is a process that converts carbon dioxide into construction materials like concrete, is being explored.[e]

Procurement

Both states and the federal government procure large amounts of carbon-intensive products, such as construction materials like cement, concrete, steel, glass, and aluminum. From 2008 to 2018, public infrastructure projects accounted for 32 percent of the total embodied carbon emissions from construction in the United States—over 150 million metric tons (MMT) CO_2e per year.[58] Public procurement programs can provide a price signal for manufacturers to preferentially produce lower-carbon materials, and thus invest in process or equipment upgrades (covered by the other four pillars) that reduce

[d] For an updated list of large-scale, lower-carbon hydrogen projects in development in the United States, visit this resource and this resource.
[e] For updated lists of large-scale CCUS projects in the United States, visit this resource and this resource.

their energy/material use and GHG emissions. Procurement policies may also demonstrate that industry will be compensated for what may be a higher-priced product (at least initially) and seed a viable market for future participation from private actors as well. [59]

Example: "Buy Clean." Procurement policies and programs can be an effective lever for driving demand and creating new markets for low-carbon industrial products. "Buy Clean" policies, for example, aim to ensure that publicly purchased products and materials are manufactured with a lower GHG emissions intensity through a combination of emissions standards, reporting requirements, and industry incentives. They can also ensure publicly funded infrastructure projects support clean domestic manufacturing and jobs and reduce industrial sector emissions. [60] See ***Section 2.6: Supporting Policies & Actions, Low-carbon material procurement***, for more detail on state action on buy clean.

1.3 Pillar Sequencing

Some of the industrial decarbonization pillars face significant barriers and therefore may take longer to deploy and fully realize their GHG emissions benefits (***Figure 3***). These barriers include costs, infrastructure requirements, level of technical maturity, application at commercial scale, and stakeholder support. For example, electrification, low-carbon fuels and feedstocks, and CCUS involve higher capital investments, have greater infrastructure needs (e.g., pipelines), and may require multi-stakeholder approval (e.g., public utility commissions, rights of way, community approvals). Other pillars, such as energy and materials efficiency, can often be deployed quickly because they are relatively low cost and well established in the marketplace.

Additional timing and sequencing considerations include:

- **Energy and materials efficiency** will be vital to pursue aggressively in the 2020s to realize readily available GHG emissions reduction opportunities as well as lower the cost burdens for more-expensive pillars. Efficiency will remain an important criterion throughout industry's transition to a net-zero future to continually optimize processes, save costs, and yield additional emissions reductions.

- **Electrification** is a near- to mid-term opportunity as there is significant political momentum to lower the carbon intensity of the electrical grid. Numerous states and the federal government have committed large amounts of funding in recent legislation to expand renewable generation capacity, transmission, and distribution (see ***Appendix A: New Federal Investments and Programs***). However, industry often needs reliable, continuous (i.e., 24/7) power to support their processes. Thus, electrification must find a way to bridge from intermittent sources like wind and solar to the steady power needs of industrial users. Energy storage (through electrical, chemical, thermal, mechanical, or other means), sensing/controls, local substations, and transformers will be needed to support this transition. Crucially, greater electricity demand from industry will require vast quantities of renewable electricity, so the build out and availability of that zero-carbon electricity will continue to be a key bottleneck. [61]

- **Low-carbon fuels & feedstocks** are mid- to long-term opportunities for most industries, as the supply chains, economics, and technologies for solutions like low-carbon biofuels and green hydrogen will take time to commercialize and scale. For example, the current cost of low-carbon hydrogen is substantially higher than grey hydrogen, so its near-term deployment makes little economic sense outside of certain industries like steel and ammonia production that lack direct electrification potential.[62]

- **Carbon capture, utilization, and storage** is a proven technology that has seen little at-scale commercial adoption in the industrial sector to date. CCUS's ability to abate difficult-to-decarbonize industrial processes will grow with the pace of pipeline and storage infrastructure development, policies to reduce capture and storage costs, and further R&D into carbon dioxide utilization options within industry fence lines (e.g., reuses other than enhanced oil recovery). Due to its cost and need for pure carbon dioxide streams, CCUS is likely a last merit order decarbonization solution for most industrial facilities.

- **Procurement** (by public and private entities) offers near- to mid-term opportunities to drive demand and create new markets for low-carbon industrial products, thereby rewarding industry's investment in implementing the other pillars.

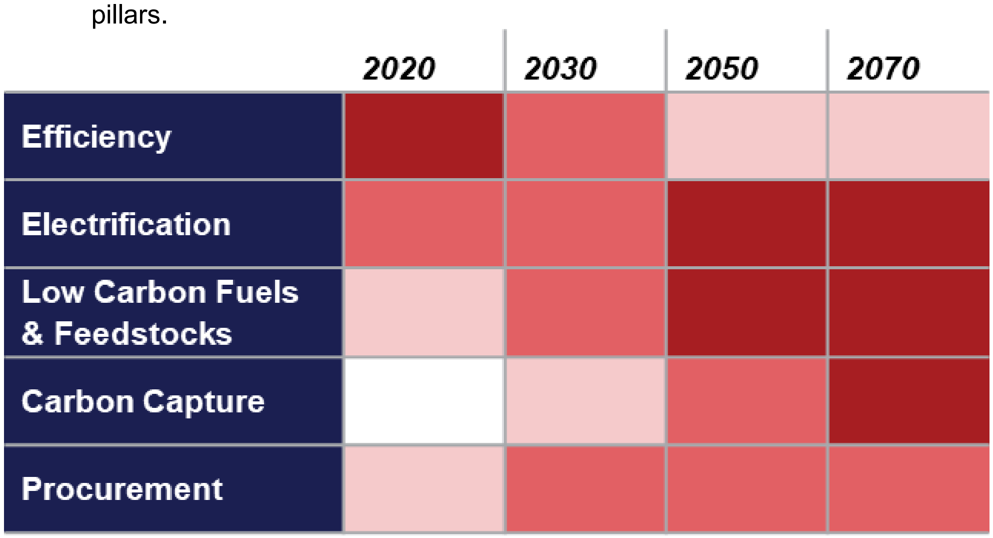


Figure 3: Relative timeframe for each decarbonization pillar to realize maximum GHG emissions reductions in the industrial sector, from 2020 to 2070. Darker shades signify greater GHG emissions impact due to technology scaling, commercial availability, and build-out of supporting markets and infrastructure. Source: This work.

For additional information on the relative costs and timing of the industrial decarbonization pillars, please see the IPCC *Sixth Assessment Report*[63] and the Grantham Institute for Climate Change technology review.[64]

CHAPTER 2. POLICY OPTIONS & CONSIDERATIONS

In the United States, developing programs to directly reduce industrial greenhouse gas (GHG) emissions, particularly those in manufacturing, is an emerging policy space. Multiple challenges in the industrial sector have, until recently, stymied policy adoption at the state and federal level, as summarized in the recently released U.S. DOE *Industrial Decarbonization Roadmap* (***Table 1***).[65] Few states have existing programs or policies that explicitly require or incentivize industrial emissions reductions; and at the federal level, most existing industry-related programs provide targeted support towards energy efficiency and early-stage research and development. Although electric sector policies like renewable portfolio standards and energy efficiency programs have certainly helped to reduce emissions from industry, they alone will not align manufacturing activity with long-term, net-zero emissions pathways.

Table 1: Cross-cutting challenges to industrial decarbonization. Adapted from U.S. Department of Energy, Industrial Decarbonization Roadmap.

Challenges	Details
Industrial Heterogeneity	A few industries provide the bulk of emissions, but the distribution of emitters is very broad; certain industry subsectors may be very heterogenous (e.g., Chemicals)
	Slower adoption given tailored implementation and integration needs
	Optimal decarbonization strategies are influenced by many variables (e.g., sector; location; process needs; variations between small, medium, and large manufacturers)
	Material inputs/use varies widely
	Supply chains are complex and emissions sources distributed throughout the supply chain are difficult to address
	Manufacturer needs vary with size, resources, and workforce capabilities both within and between industrial sectors.
Incumbent Technologies and Practices	Equipment has long service life; replacement requires years of planning
	Low penetration of technologies (such as electrification) that will transition naturally to low-carbon footprint as the electric grid decarbonizes in crosscutting applications such as process heat
	High integration, so downstream impacts must be considered
	Hesitancy to change due to unvalidated performance of new equipment
	Low current availability of low-cost, broadly recognized, reliable, and certified low-carbon-intensive materials
High Costs	Capital costs are typically up front, increasing investment risk
	Lifecycle costs are not transparent
	Energy costs for low-carbon solutions start at high multiples of incumbent fossil fuel sources

Challenges	Details
Lack of Commercial Scale	Technology maturation and reaching commercial scale, with competitive economics, is a challenge
	Lack of vendor support and continuity for scaling, integration, and adaptation
	Interconnections for low-carbon solutions are new and need development
	Potential gaps exist in clean energy supply chains, infrastructure, and reliable delivery at plant gate of industrial facilities

With industry accounting for 11 percent of gross domestic product nationally and employing more than 12.6 million workers,[66] states have an opportunity to highlight and pursue paths to reduce GHG emissions while improving competitiveness, employment opportunities, and workforce diversity and capabilities. Industry involves many complex technologies, practices, and interrelated supply chains, creating challenges for state policymakers to understand where and how to meet their unique state GHG reduction targets. However, states can leverage new and existing legal authorities to help overcome these challenges and reduce industrial emissions through several avenues, many of these borrowing approaches and lessons-learned from driving down emissions in other energy-related sectors like electricity, buildings, and transportation. Multiple states have already initiated these types of policies (this work identifies over 100 of them) and can be early leaders that help shape a national agenda.

Figure 4 illustrates where major policy opportunities to accelerate industrial decarbonization interact with the five pillars outlined in ***Section 1.2***. These policies include incentives and standards to spur adoption of beneficial electrification, low-GHG-emissions process heat, and infrastructure investment to support the delivery of low-carbon electricity, low-carbon fuels and feedstocks, (e.g., clean hydrogen, biomass/fuels) and carbon dioxide transport/use/storage. Preferred procurement of low-carbon materials is a nascent area, and there are multiple areas where capabilities need to be developed (e.g., transparent data storage, harmonization of procedures and methods, following carbon throughout supply chains) to accelerate the impact of the pillars.

<table>
<tr><th></th><th>Efficiency</th><th>Electrification</th><th>Low Carbon Fuels & Feedstocks</th><th>Carbon Capture</th><th>Procurement</th></tr>
<tr><td rowspan="3">Planning & Governance</td><td colspan="5">State emissions and efficiency targets</td></tr>
<tr><td colspan="5">State analysis and roadmaps</td></tr>
<tr><td colspan="5">State governance structures</td></tr>
<tr><td rowspan="2">Research, Development, Demonstration, & Deployment</td><td colspan="4">Direct investment</td><td>Pilot projects</td></tr>
<tr><td colspan="4">Tax credits</td><td>Product life cycle assessments</td></tr>
<tr><td rowspan="3">Carbon Pricing</td><td colspan="5">Regulated carbon markets</td></tr>
<tr><td colspan="5">Carbon taxes</td></tr>
<tr><td colspan="5">Border carbon adjustments</td></tr>
<tr><td rowspan="2">Incentives</td><td colspan="5">Financial incentives (incl. grants, rebates, cash)</td></tr>
<tr><td colspan="5">Financing (incl. loans, bonds, green banks)</td></tr>
<tr><td rowspan="3">Standards</td><td colspan="5">Emissions standards</td></tr>
<tr><td>Efficiency standards</td><td colspan="2">Clean heat standards</td><td rowspan="2">Carbon management standards</td><td>Clean product standards</td></tr>
<tr><td>Circularity and recycling standards</td><td colspan="2">Clean fuel standards</td><td>Embodied emissions standards</td></tr>
<tr><td rowspan="7">Supporting Policies</td><td>Strategic energy management</td><td colspan="4">Low-carbon infrastructure investment</td></tr>
<tr><td colspan="2">Technical assistance</td><td colspan="3">Low-carbon material procurement</td></tr>
<tr><td colspan="5">Labeling and certification</td></tr>
<tr><td colspan="5">Emissions disclosure and monitoring</td></tr>
<tr><td colspan="5">Equity and environmental justice</td></tr>
<tr><td colspan="5">Diverse workforce development</td></tr>
<tr><td colspan="5">Industry clustering</td></tr>
</table>

Figure 4: Interaction of policy landscape with decarbonization pillars. Source: This work.

2.1 Planning & Governance

Overview

State climate planning and governance are essential for creating a policy environment that coordinates and directs the industrial sector’s emissions towards zero. Just as in other energy-related sectors, state target-setting, roadmap development, and stakeholder engagement can establish market signals for greener products and emissions-reducing technologies. These actions can also coordinate parallel policy components such as workforce development to accommodate industrial transitions and ensure disadvantaged communities receive equitable benefits from the transition. Although many states have established sector-specific climate targets, decarbonization roadmaps, and governance structures for power, buildings, and transportation (***Table 2***), largely they have yet to tackle the industrial sector.[f]

State actions

Three states have established sector-specific GHG emissions targets for industry: **Colorado** targets a 20 percent emissions reduction below 2015 levels by 2030;[67] **Massachusetts** aims to reduce emissions from industrial energy use and non-GHG emissions 34 percent below 1990 levels by 2025 and 48 percent by 2030;[68] and **Maine** intends to hold its industrial emissions "flat through 2030" and "reduce them" through 2050.[69] **California** is the only state to adopt a GHG goal specific to an industrial sub-sector, aiming to reduce the GHG intensity of cement used in the state 40 percent below 2019 levels by 2035 and achieve net-zero emissions associated with cement use by 2045.[70] However, 15 states have adopted economy-wide net-zero GHG targets, which they are unlikely to achieve without developing policies to reduce industrial GHG emissions.

Table 2: Examples of state governance, targets, and plans for other non-industrial energy sectors.

	Power	Buildings	Transportation
Governance	• Connecticut: Distributed Generation Policy Working Group • Delaware: Renewable Energy Taskforce • Illinois: Offshore Wind Energy Economic Development Policy Task Force	• Maryland: Building Energy Transition Implementation Task Force • Massachusetts: Commission on Clean Heat • Oregon: Task Force on Resilient Efficient Buildings	• Colorado: Transportation Electrification Working Group • Michigan: Council on Future Mobility and Electrification • Rhode Island: Mobility Innovation Working Group
Targets	• New York: 100% zero emissions by 2040 • North Carolina: 70% CO_2 reduction below 2005 levels by 2030, 100% carbon neutral by 2050 • Oregon: 80% GHG reduction by 2030, 90% by 2035, 100% by 2040	• Massachusetts: 33% GHG reduction below 1990 levels by 2025, 50% by 2030 (residential heating and cooling) • New York: 2 million climate-friendly, electrified, or electrification-ready homes by 2030 • New York: 185 TBtu energy use reduction from 2025 forecast	• California: 100% zero-emissions vehicles (new sales of light-duty vehicles) by 2035, 100% zero-emissions vehicles (new sales of medium- and heavy-duty vehicles) by 2045 • New Jersey: 330,000 zero emissions vehicles deployed by 2025 • North Carolina: 50% zero emissions

[f] At least ten states have advanced policies to reduce methane from their oil and gas, landfill, and agriculture industries, and 11 states developed regulations to phase out hydrofluorocarbons—both topics outside the scope of this resource. However, states followed similar approaches to get there: they set targets, created working groups and task forces, and developed plans and programs to meet those targets.

	Power	Buildings	Transportation
			vehicles (new sales) by 2030
Plans	• Colorado: *Roadmap to 100% Renewable Energy By 2040* • Rhode Island: *The Road to 100% Renewable Electricity by 2030* • Wisconsin: *Clean Energy Plan*	• California: *Building Decarbonization Assessment* • Maryland: *Building Energy Transition Plan* • Massachusetts: *Clean Energy and Climate Plan for 2030 Stretch Code*	• Connecticut: *Electric Vehicle Roadmap for Connecticut* • Maine: *Clean Transportation Roadmap* • Pennsylvania: *Electric Vehicle Roadmap*

In the past two years, **Louisiana**,[71] **Michigan**,[72] **Washington**,[73] and **Wisconsin**[74] all released climate and energy action plans that made policy recommendations to decarbonize their industrial sectors. Louisiana in particular outlined four strategies and 13 policy actions the state could pursue to enhance industrial efficiency, switch to lower-carbon fuels, and create markets for clean industrial products. Draft climate action plans from **California**,[75] **Minnesota**,[76] and **New York**[77] also indicate a larger focus on industrial solutions than previous iterations, but these are not yet final.

To date, few states have established interagency governance structures dedicated to exploring policy opportunities for industrial decarbonization. Some states have convened stakeholders through topic-specific subcommittees under their climate councils, such as **Michigan**'s Energy Intensive Industries Workgroup,[78] but these tend to be short-lived and cease to function following the release of climate plans. On the other hand, **Maine** established an Industrial Innovation Task Force within its governor's office, which serves as a forum for industrial representatives, government officials, and academics to make recommendations that increase industrial efficiency and reduce GHG emissions.[79]

Other states have developed plans, conducted analyses, and stood up new governance structures that focus on specific industrial decarbonization pillars. For example:

- *Low-carbon fuels & feedstocks*
  - Several states are analyzing opportunities in their state to deploy low-carbon hydrogen, including by establishing new governance structures (e.g., **Washington** Office of Renewable Fuels,[80] **Illinois** Hydrogen Economy Task Force[81]) and commissioning reports and analyses (e.g., **Colorado**,[82] **New Mexico**,[83] **Oregon**[84]).
- *Carbon capture, utilization, and storage (CCUS)*
  - **Colorado**'s Carbon Capture, Utilization and Sequestration Task Force recently released its evaluation of the role CCUS could play in meeting state climate goals.[85]
- *Procurement*
  - Multiple states are investigating opportunities and barriers to reduce the climate impacts of construction materials. For example, **Washington** is

developing and testing a prototype database for reporting environmental and labor information for state construction projects.[86] **Minnesota** is conducting an environmental impact study of construction materials.[87]

Gaps and opportunities
While some states have explored the potential for certain low-carbon technologies, most states have not conducted assessments of their industrial sectors' broad efficiency, electrification, and low-carbon fuel opportunities, leaving a gap in baseline knowledge needed for transition planning. Significant physical infrastructure will be needed to transition industry off fossil fuel energy sources and towards electrification, LCFF, CCUS, and other decarbonization strategies. This includes:

- Expanding new renewable generation, transmission, energy storage, and site capabilities (e.g., substations, dynamic sensing/control, demand flexibility, onsite WHR and renewable energy) to deliver low-carbon electricity to meet new industrial demand;

- Building out pipelines, transportation, and storage technology to integrate new LCFF into industrial processes;

- Conducting in-depth supply chain and industrial cluster analysis to identify new opportunities for increasing material efficiency and utilizing process heat (e.g., district heating and cooling); and

- Developing, demonstrating, and installing sensing control systems so industry subsectors with flexible demand that could undertake load shifting can optimize production rates when low-carbon electricity is available and cost effective.

2.2 Research, Development, Demonstration, & Deployment (RDD&D)

Overview
RDD&D covers the suite of activities needed to develop and commercially scale industrial decarbonization solutions in the near term while advancing innovative solutions for the long term. Policies that support industrial decarbonization RDD&D will help drive down the cost of emissions-reducing technologies and serve as a complement to and accelerant of other policy solutions.[88]

While universities and corporations largely conduct early-stage research and development (R&D), government RDD&D policies broadly enhance the investment muscle and speed of technology maturation, in addition to reducing market and financial barriers the private sector will not overcome on its own. The United States has a far-reaching ecosystem of RDD&D, including its national laboratories, public-private partnerships, research institutes, and incentives for corporate R&D. This ecosystem has helped reduce the cost and increase the scale of critical clean energy technologies in the power and transportation sectors.[89]

State actions
States have complemented federal programs and fostered innovation primarily through two policy mechanisms: direct investment in state-level RDD&D programs and supporting innovative companies with tax credits. The following examples highlight state actions supporting industry:

- **California's** Electric Program Investment Charge (EPIC) program invests over $130 million per year in R&D projects that advance the sustainability and reliability of the electric system. This includes $133 million invested over 10 years toward industrial and agricultural innovation projects. [90]

- The **Maine** Clean Energy Innovation Challenge, a joint initiative of the Governor's Energy Office and the Maine Technology Institute, is a $500,000 grant program that helps clean energy startups or small businesses market and scale technologies that will help the state reach its climate goals. [91]

- The **Massachusetts** Clean Energy Center funds numerous programs to accelerate clean energy technologies, such as InnovateMass, which provides up to $250,000 in bridge funding and technical support to help early-stage companies achieve commercialization, [92] and IncubateMass, which funds climate and clean technology startups. [93]

- To help meet state climate goals, **Michigan** provided $1.55 million in seed funding to a cleantech accelerator hosted by Lawrence Technological University. The C3 Accelerator offers $50,000, zero-interest investments to support the commercialization of "renewable energy, energy efficiency, emission reduction, clean air and water, and recycling and upcycling technologies." [94]

- **Minnesota's** Conservation Applied Research and Development (CARD) program is a state-sponsored applied research and development program that funds projects that help utilities achieve energy efficiency goals. [95]

- **New York's** Innovation Program supports multiple types of clean energy incubators and accelerators, including Scale for ClimateTech, which helps startup companies overcome commercialization and scaling barriers. [96] New York is currently developing a $10 million Carbontech Development Initiative, which aims to "develop support for emerging technologies, and award grants to advance technologies that capture existing carbon or lower carbon emissions and transform this carbon into useful products." [97]

Gaps and opportunities

To reach 2050 net-zero milestones, government, academia, and industry will need to greatly increase their RDD&D in multiple areas to develop and deploy technologies associated with the pillars and to overcome barriers (***Figure 5***). [98] These barriers range from technology- or industry-specific (e.g., iron ore electrolysis for steel, green hydrogen-based ammonia for chemicals) to broad, cross-cutting breakthroughs (e.g., transitioning process heat to non-combustion technologies, such as high-temperature heat pumps).

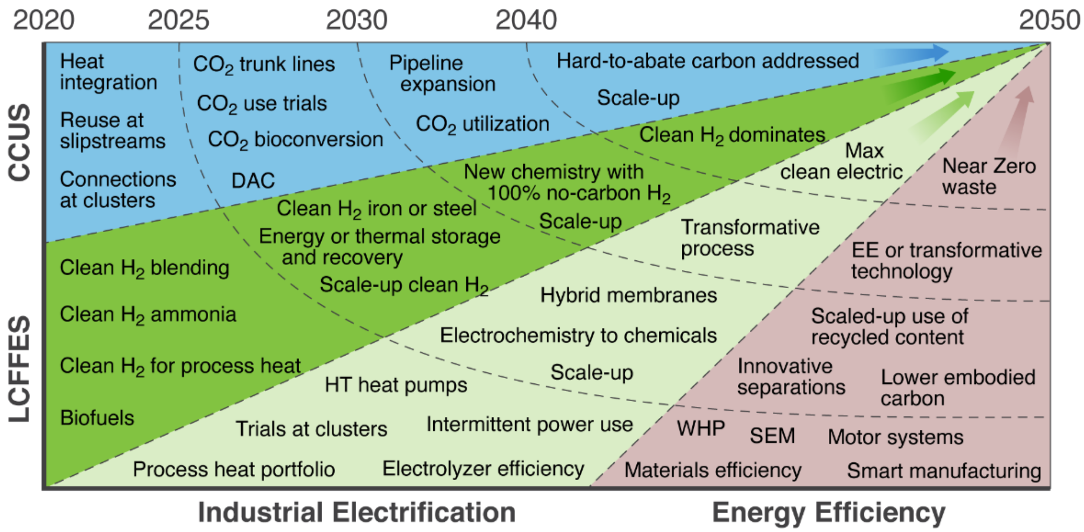


Figure 5: Landscape of major RD&D investment needs and opportunities for decarbonization, by decade and decarbonization pillar. LCFFES = Low carbon fuels, feedstocks, and energy sources. CCUS = carbon capture, utilization, and storage. Source: U.S. Department of Energy.

In recent climate and clean energy action plans, some states have recommended investment to develop and expand LCFF and CCUS specifically (i.e., **Louisiana, Michigan, Washington, Wisconsin**); while **New York** has proposed establishing a "research agenda" for industrial decarbonization solutions broadly. [99]

2.3 Carbon Pricing

Overview
Carbon pricing policies, such as cap-and-trade programs and carbon taxes, establish a direct or indirect price on units of GHG emissions (dollars per ton) in a defined market. By imparting a cost to carbon pollution, these policies incentivize investment in low-carbon fuels and energy-efficient practices and technologies. Unlike some regulatory standards, carbon pricing policies offer a technology-neutral approach for driving down emissions and a cost-effective option for the diverse industrial sector, which requires a wide range of technologies and process changes to reduce emissions. [100] Carbon pricing programs can also generate revenue that state governments can redeploy toward other critical policy arenas such as industrial decarbonization RDD&D, incentives, and technical assistance, and targeting investments towards disadvantaged communities. [101]

State actions
States operate the only existing carbon market programs in the United States: **California's** Cap-and-Trade Program, [102] **Washington's** Climate Commitment Act (an under-development cap-and-invest program), [103] and the Regional Greenhouse Gas Initiative (**RGGI**, a power sector cap-and-trade program on the East Coast). [104] However, only California and Washington's programs cover industrial facilities (with annual emissions greater than 25,000 Mt CO_2e), as RGGI only targets emissions from the electric power sector. While **Oregon's** Climate Protection Program (CPP) does not directly establish a price on carbon, it does set a declining emissions cap on fossil fuels used throughout the economy, including the industrial sector. CPP also regulates GHG emissions, including process emissions, from highly emitting new and existing industrial facilities, by requiring these entities to conduct "best available emissions reduction

assessments." [105] For additional information on Oregon's program please reference ***Section 2.5: Standards***. No U.S. states or regions have adopted a carbon tax, although as of 2022 at least 28 countries are implementing carbon tax initiatives. [106] **Hawaii** studied how it could implement a carbon tax in a 2021 report. [107]

In the United States, RGGI proceeds are being used for industrial decarbonization through energy efficiency and GHG abatement programs. In 2019, **Maine** used RGGI revenues to provide electric rate relief for large manufacturers and invested in commercial and industrial prescriptive and custom energy efficiency programs. [108] In the past, **New York** has used RGGI revenues for the Industrial Innovations Program, which funds the development and demonstration of high-potential GHG emissions reduction technologies for the state's manufacturing industries. Grantees could supplement existing federal funds with RGGI dollars to carry out projects. [109] The program's administrator, the New York State Energy Research and Development Authority (NYSERDA), no longer issues solicitations or offers support under the Industrial Innovations Program but is working to support industrial innovation in the future.

California's *Cap-and-Trade Auction Proceeds Fourth Investment Plan* recommends prioritizing investment in low-carbon industry, among other sectors. In particular, the Plan prioritizes innovative projects that reduce industrial emissions through energy efficiency, renewable energy, electrification, and low-carbon hydrogen/natural gas. [110] In **New Jersey**, over $54 million of RGGI revenues have been earmarked by the New Jersey Economic Development Authority to use over the next year to establish a statewide green bank, which will leverage private funds for renewable and clean energy projects, energy efficiency, and energy storage projects in the commercial, industrial, and institutional sectors. [111] At the time of this report's writing, New Jersey's funds had not yet been expended so they are not listed in ***Table 3***. More information on programs and funding can be found below.

Table 3: Reinvestment of revenues from state carbon pricing policies for industrial decarbonization.

State	Incentive Title	Program Administrator	Funding Source	Year	Budget ($Millions)	Description
California	Food Production Investment Program	California Energy Commission	California Climate Investments	2018-2020	124	The program provides grants for food processors to implement projects that reduce GHG emissions such as clean technologies and efficient equipment.
Maine	Efficiency Maine Commercial and Industrial (C&I) Prescriptive Initiative	Efficiency Maine Trust	RGGI	2019	0.83	The C&I Prescriptive Initiative provides incentives for large energy customers in Maine, including manufacturing organizations and other industrial facilities. The program incentivizes energy-efficient solutions for heating, cooling, lighting and controls, compressed air, agriculture, water heating, and refrigeration.
Maine	Efficiency Maine Commercial and Industrial	Efficiency Maine Trust	RGGI	2019	1.4	The C&I Custom Program allows customers to implement cost-effective and site-specific energy efficiency and distributed generation projects that are not covered by incentives from the C&I

State	Incentive Title	Program Administrator	Funding Source	Year	Budget ($Millions)	Description
	(C&I) Custom Program					Prescriptive Initiative. Eligible customers include businesses, institutions, nonprofits, and governments. The Custom Program funds projects ranging from $10,000 to $1 million per customer and offers free scoping audits and technical assistance incentives.
New Hampshire	All-Fuels Program	New Hampshire electric and natural gas utilities	RGGI	2016 - 2018	1.2	The All-Fuels program targets EE measures for retail businesses and large commercial and industrial energy users.
New York	Industrial Innovations Program	NYSERDA	RGGI	2020	11.8	The Industrial Innovations Program supports development and demonstration of technologies with substantial GHG reduction potential. It focuses on thermal-efficiency innovations that reduce fossil fuels and high replication potential for manufacturing base. *Note that there have been no new solicitations or market offerings since 2014.*

Gaps and opportunities

Carbon pricing policies can indirectly contribute to "carbon leakage," which refers to the phenomenon of emissions shifting from one region to another due to an imbalance in climate policies between regions. For example, carbon-intensive industry subjected to more-stringent policies in one state could be economically disadvantaged compared to competitors in a less-regulated jurisdiction, and thus incentivized to move production across borders. [112] Existing carbon pricing schemes typically address leakage by freely allocating emissions allowances to a select set of industries, so as to ease their cost of compliance under the policy. For example, in developing their cap-and-invest program, **Washington** regulators created a separate emissions reduction pathway for about 40 facilities identified as "emissions-intensive, trade-exposed" (EITE) industries. This allowance carveout for EITEs is designed to protect these industries from dramatic market changes that would force them to limit or close operations or transfer production to a region that does not regulate carbon emissions. [113] However, policymakers have recognized that free allocation [g] is likely an inadequate solution for long-term industrial decarbonization. [114]

Border carbon adjustments (BCA), also known as border tax adjustments (BTA) and carbon border adjustment mechanisms (CBAM), are a novel set of policy tools that would complement carbon pricing policies and potentially address carbon leakage. A BCA would add a tariff to imports based on their GHG emissions profile and could add a rebate on exports. The goal of a BCA is to "level the playing field" between domestic and foreign firms that manufacture similar materials but adhere to dissimilar climate

[g] When linked to output, free allocation can effectively create a performance standard.

regulations.[115] Although only a theoretical policy at the national level at this time—and despite compatibility concerns with international trade law—policymakers around the world have expressed growing interest in implementing a BCA. For example, the European Union's Fit for 55 plan proposes a CBAM to cover multiple EITE sectors that may be launched at a global scale in 2023. Over the past two years, U.S. Congress introduced at least seven bills that included some form of BCA.[116]

If the United States fails to implement a national BCA, states are likely unable to implement their own due to the Constitution's dormant commerce clause, which prohibits state tax policies from discriminating interstate commerce. However, some scholars argue a state BCA could theoretically be designed to withstand legal challenge, based on precedent and creative interpretations of tax law.[117, 118]

Regardless of BCA policy advancement, more states with carbon prices and other industrial decarbonization policies will help reduce the threat of carbon leakage, as jurisdictions adopting similar policy environments will reduce the chance of significantly disadvantaging their local industry to those operating elsewhere.

2.4 Incentives

Overview
Economic incentives are among the most common policy tools governments deploy to promote decarbonization.[119] Incentives can be fiscal (e.g., tax credits, tax exemptions, subsidies) or offer competitive financing (e.g., low-interest loans, loan guarantees, low-cost insurance) to help industry defray the upfront cost of an efficiency or technology investment. Incentives in the form of competitive grants are also quite common.

State actions
States can design incentives to cover all pillars of industrial decarbonization or target specific adoption of low-carbon technology and fuels, low-carbon manufacturing and retooling, low-carbon appliances and equipment, or energy or material efficiency improvements. Most state incentives to date have focused on improving industrial energy efficiency through a combination of financial and technical assistance.[h] Many states fund their programs through federal sources, carbon market revenues, or utility ratepayer funds, although large-scale industrial decarbonization projects may require more creative financing solutions (***Box 1***).

- *Efficiency*
    - Financial Incentives: States commonly offer a suite of incentives for industrial facilities to invest in energy efficiency improvements (e.g., **Massachusetts's** Mass Save Program,[120] **New Jersey**'s Large Energy Users Program,[121] **Wisconsin's** Focus on Energy Large Energy Users program[122]). Other forms of incentives include cost-sharing for hiring energy management personnel (e.g., **New York's** On-site Energy Manager Program[123]).
    - Grants: **California's** Food Production Investment Program,[124] **Colorado's** Clean Air Program Grants,[125] **Delaware's** Energy Efficiency Industrial Program,[126] **Maryland's** Commercial, Industrial & Agricultural Grant Program,[127] **Maine's** Commercial and Industrial Custom

[h] Technical assistance is described in further detail in ***2.6 Supporting Policies & Actions***

Program,[128] **Mississippi's** Industrial Energy Efficiency Program,[129] **New York's** Commercial & Industrial Carbon Challenge[130]

- Rebates: **Minnesota's** Conservation Improvement Program,[131] **Oregon's** Energy Trust industry programs[132]

- Loans: **Delaware's** Energy Efficiency Investment Fund,[133] **Minnesota's** Green Business Loan Program and Trillion Btu Program,[134] **Tennessee's** Energy Efficiency and Renewable Energy Loan Program[135]

- *Electrification*
  - Financial Incentives: Some states offer incentives for industrial facilities to install on-site renewable energy, either as standalone programs (e.g., **New York's** NY-Sun Program,[136] **New Hampshire's** Commercial & Industrial Solar Incentive Program[137]) or paired with their energy efficiency programs (e.g., **Maine**,[138] **Massachusetts**,[139] **Minnesota**[140]).
  - Grants: **Colorado's** Clean Air Program[141] provides grants to facilities that install renewable energy or undergo "strategic electrification," which would involve converting fossil fuel-powered equipment or process to electric fuel. **New York's** Commercial & Industrial Carbon Challenge[142] provides grants for projects that reduce manufacturing emissions and energy use through beneficial electrification or installing on-site renewable energy systems.

- *Low-carbon fuels & feedstocks*
  - Financial Incentives: **Washington** created a tax exemption for producing renewable and electrolytic hydrogen.[143]
  - Grants: **Colorado's** Clean Air Program[144] provides grants for projects that produce or utilize "clean hydrogen," with an explicit priority for green hydrogen. **New York's** Commercial & Industrial Carbon Challenge provides grants for projects that reduce manufacturing emissions and energy use with low-carbon fuel technologies.[145]

- *Carbon capture, utilization, and storage (CCUS)*
  - Grants: **Colorado's** Clean Air Program[146] provides grants for carbon capture projects on industrial facilities and direct air capture. **New York's** Commercial & Industrial Carbon Challenge provides grants for projects that reduce manufacturing emissions and energy use with carbon capture technologies.[147]

- *Procurement*
  - Financial Incentives: **New Jersey** created tax incentives for residential and commercial properties that utilize lower-carbon concrete,[148] while **Colorado** established a sales and use tax exemption for "decarbonizing building materials."[149]

- Grants: **Oregon's** Department of Transportation is required to create grant program to assist manufacturers in preparing or submitting EPDs. [150]

Box 1: Financing and funding mechanisms for large projects

Industrial decarbonization solutions tend to require substantial capital investments in large-scale projects. States can consider a variety of financing and funding approaches that leverage joint financing with public and private partners, as summarized in a recent white paper[151] and adapted here for illustrative purposes:

- **Pursuing blended finance options**. Transformative industrial technologies can cost upwards of $1–1.5 billion per project, so coordination among multiple federal and state agencies is important to maximize impact on major projects. At the federal level, the U.S. DOE Loan Programs Office (LPO), Small Business Innovation Research (SBIR), and Small Business Administration (SBA) may offer helpful financing options.
- **Packaging projects to better attract financing.** Grouping projects into portfolios that appeal to financial institutions may help secure their participation and financing. Focusing on this element may also align with state interests in leveraging private financing to a greater degree in industrial decarbonization and deployment projects. This approach could also help de-risk a group of technology projects that have common barriers.
- **Leveraging commercial financing, philanthropy, and community development financing institutions**. Green bonds have been successfully used to scale clean energy projects. For example, the Delaware Sustainable Energy Utility (DESEU) developed the first scalable green bond in 2007, creating a platform to standardize, aggregate, and scale efficiency and renewable energy investments.[152] Green banks use market development strategies along with private investors to accelerate the commercialization of key clean energy technologies. There are 21 green banks across the country. Green banks can be established through various legislative directives, structures, and funding sources (including grants, carbon market revenues, and electricity rate charges). In their decade-long history, green banks have proven a very effective means for deploying public and private capital. Since 2011, state green banks have produced $7 billion in clean energy investment, with almost $1.7 billion invested in 2020 alone. This funding has also catalyzed overall investment by about 3.7 times the amount of green bank investment in 2020.[153]

Gaps and opportunities

Most state incentive programs for industry have focused on energy efficiency and neglected support for the major emissions opportunities of other decarbonization pillars. However, the passage of the *Inflation Reduction Act of 2022* added a host of new tax, grant, and financing incentives to support industrial electrification, low- and zero-carbon process heating, CCUS, and production of low-embodied-carbon materials (see ***Appendix A: New Federal Investments and Programs***). State policy gaps include:

- *Electrification, Low-carbon fuels & feedstocks*
    - States largely lack programs that focus on incentivizing reductions in industrial GHG emissions through electrification and low-carbon fuel technologies, as existing programs tend to reward performance based on energy usage, regardless of the source of energy. **Louisiana,** [154] **Michigan,** [155] and **Washington** [156] have all proposed developing programs that support and incentivize these efforts in recent climate or clean energy action plans.
- *Carbon capture, utilization, and storage (CCUS)*
    - With current technology and policies, CCUS is typically not financially viable for industrial plants (unless they produce pure streams of CO_2). [157] States can play an important role in developing incentives that improve the economics of carbon capture for industrial facilities. Policies can include grants and loans for related infrastructure, off-take agreements, and tax incentives for CCUS. [158] The *Inflation Reduction Act's* adjustments to the 45Q CCUS tax credit may provide a significant boost to the economics of these projects. [159]
- *Procurement*
    - Material embodied emissions information and data are essential to developing effective procurement policies. Driven largely by voluntary efforts in the green buildings industry and some state and local policies, environmental product declarations (EPDs) have emerged as the foundational tool for disclosure and transparency of environmental footprints, especially as it relates to the embodied carbon of commodity materials. EPDs play an important role in quantifying Scope 3 supply chain emissions, a growing focus for meeting sustainability goals. [160] However, EPDs are not based on consistent facility-specific data, are not intended to compare products, are not intended serve as the basis for a regulatory program, are not yet widely available across regions or for all relevant materials, and developing EPDs has high upfront costs. [161] **California** is understanding these EPD limitations through its initial implementation of the *Buy Clean California Act* and is seeking other data sources and improvements to EPDs to support program implementation. States can support manufacturers with financial and technical assistance programs to help expand the availability and quality of EPDs, a proposal mentioned in **Washington's** clean energy action plan. [162]

2.5 Standards

Overview

Standards "specify levels of performance [that] businesses or equipment must achieve." [163] Standards, such as those targeting appliances, commercial and industrial equipment, and vehicles, have a global track record of successfully reducing energy and emissions. [164] In the United States, the EPA's National Ambient Air Quality Standards (NAAQS) have successfully reduced criteria air pollutants by 73 percent since 1980. [165] Standards can also accelerate the development and deployment of new technologies: for example, from 2000 to 2015, state-level renewable portfolio standards (RPS) drove 60 percent of new renewable energy capacity additions in the United States.[166]

Standards can be technology- or performance-based in design. Technology standards require the use of a specific technology or process to achieve energy and emissions goals, while performance standards require achievement of a specific benchmark without prescribing the technological choice, providing room for innovative approaches. A tradeable performance standard would include a crediting system, introducing more flexibility for compliance and an incentive for outperforming the benchmark.[167]

Industrial standards can be tailored to meet unique aspects and challenges of decarbonizing specific subsectors. They could be developed to target a specific type of facility or product (e.g., cement), manufacturing process (e.g., boilers), or fuel.[168] Due to the variety of processes and products that underlie the manufacturing sector, and limited foresight into all possible technology solutions for reducing emissions, it may be prudent for states to adopt performance standards that maximize flexibility and minimize cost. A tradeable performance standard could serve as an alternative to carbon pricing policies, forgoing a direct price on pollution but retaining the benefits of cost and flexibility.[169]

State actions
In theory, states can develop standards to address all pillars of industrial decarbonization, either through explicit design considerations (e.g., a technology standard for industrial electrification) or a flexible performance-based standard that accommodates all pillars (e.g., a broad emissions standard). However, outside of the economy-wide emissions requirements dictated by California's and Washington's cap-and-trade programs, few examples that directly target industrial sources currently exist.

- *Efficiency*

    - Efficiency (and Emissions) Standards: **Colorado's** Greenhouse Gas Emissions and Energy Management for Manufacturers (GEMM) regulation provides an approach where large, Energy-Intensive Trade-Exposed (EITE) manufacturers conduct a "GHG Best Available Emissions Control Technology (GHG BAECT)" and "Energy Best Management Practices" audit every five years and use the results to demonstrate they are controlling their GHG emissions. If they can demonstrate they are utilizing GHG BAECT, the facility is required to reduce emissions by an additional five percent. If they are not using GHG BAECT, the facility must implement strategies to meet the GHG BAECT emissions rate or be subject to further GHG regulation.[170] **Oregon's** Climate Protection Program regulates GHG emissions, including process emissions, from highly emitting new and existing industrial facilities. The program requires these entities to conduct "best available emissions reduction assessments."[171] **Louisiana** proposed developing both industry efficiency standards and a net-zero industry standard in its climate action plan.[172]

    - Circularity and Recycling Standards: Many states regulate their waste management to penalize the disposal of valuable materials and preserve limited landfill space. **Massachusetts**, for example, requires recycling for ten categories of materials, including containers, construction waste, and mattresses.[173] In 2021, **Maine** became the first state to enact an extended producer responsibility (EPR) law for paper and plastic packaging.[174] EPR is a concept that shifts the burden of managing a product's end-of-life from the consumer to the producer. EPR can incentivize manufacturers to design products that are easier to reuse and recycle.[175] **Oregon**[176] and **California**[177] each passed related EPR legislation while four other states advanced similar bills.[178]

- *Low-carbon fuels & feedstocks*
    - Clean Fuel Standards: **California**,[179] **Oregon**,[180] and **Washington**[181] have adopted clean fuel standards (CFS) to increase the use of low-carbon fuels in the transportation sector. However, these standards can also support the growth of renewable fuels industries and lower the carbon intensity of fossil fuels consumed by industrial facilities. CFS can also incentivize the use of CCUS, as is the case with California's Low Carbon Fuel Standard (LCFS), which credits projects by transportation fuel producers that deploy CCUS.[182]
- *Carbon capture, utilization, and storage (CCUS)*
    - Carbon Management Standards: States play an important role in creating a policy environment that ensures the long-term sequestration and climate benefits of CCUS. These policies include setting standards that clarify the siting, monitoring, and liability of captured carbon transportation and storage projects.[183] Examples include passing laws to define ownership of carbon dioxide and its pore space (**Montana**, **North Dakota**, and **Wyoming**) and establishing trust funds to ensure states can finance the long-term monitoring and management of sequestered carbon (**Kansas**, **Louisiana**, **Montana**, **Texas**, and **Wyoming**).[184] **West Virginia** recently enacted a bill that defines liability and creates sequestration regulations for permitting, injection well drilling, and project completion.[185] In 2018, **California** adopted a CCS Protocol as part of amendments to its LCFS to describe requirements transportation fuel producers must meet for a CCS project to be recognized in that program.[186]
- *Procurement*
    - Embodied Emissions Standards: The *Buy Clean **California** Act* requires the state to establish and publish "maximum acceptable global warming potential (GWP) limits" for select construction materials, which were finalized in January 2022. Starting in July 2022, all covered materials used in public construction projects must prove they meet the applicable GWP limit.[187] A **Colorado** bill enacted in 2021 calls for the development of similar GWP standards to support a 'buy clean'-type program for the state's buildings and transportation projects.[188] See ***Section 2.6: Supporting Policies and Actions*** for more information on procurement policies.

Gaps and opportunities
Some states are in the early stage of developing standards that address material efficiency, CCUS, and embodied emissions, but little work has advanced to comprehensively target electrification and other fuel-switching opportunities. Standards that accommodate the needs of small- and medium-sized manufacturers and lighter industry are also missing. Various research groups have proposed novel policy concepts

for standards that have no real-world counterpart, but states could serve as valuable proving grounds for them. For example:

- *Efficiency*
    - Circularity and Recycling Standards: These policies would increase material efficiency through "circular economy" principles, which references a portfolio of solutions to maximize the useful life of manufactured goods and reduce waste and the need for virgin materials. These would expand existing recycled content standards and recycling incentives to cover major industrial materials and incorporate concepts like EPR and material recirculation.[189, 190] **Massachusetts** released a *2030 Solid Waste Master Plan*, recommending regulations and strategies to reduce disposal to landfill by 90 percent by 2050.[191]
- *Electrification, Low-carbon fuels & feedstocks*
    - Clean Heat Standards: Also known as "thermal renewable portfolio standards"[192] or "low-emissions heat portfolio standards,"[193] clean heat standards would establish an emissions performance standard for industrial heat that could be met by a variety of sources, including (but not limited to) renewable electricity, low-carbon hydrogen, biofuels, solar thermal, geothermal, and other innovative solutions. Groups have suggested these standards be modeled after renewable portfolio standards to help scale the supply of low-carbon industrial heat sources, just as RPS approaches accelerated the supply of wind and solar electricity. States like **New Hampshire** and **Massachusetts** have added renewable thermal as a qualifying resource under their existing RPS[194] or as a complementary standard,[195] while **Wisconsin** proposed adopting a renewable thermal standard in its recent clean energy plan.[196]
- *Carbon capture, utilization, and storage (CCUS)*
    - Carbon Management Standards: States have an opportunity to accelerate CCUS project permitting while also creating risk-based and environmentally protective safety standards for carbon storage. One avenue is obtaining primacy over Class VI wells, which EPA currently administers in all but two states (**North Dakota** and **Wyoming**).[197] EPA's Class VI well requirements protect drinking water sources by regulating the siting, monitoring, and operation of geologically sequestered carbon.[198] However, EPA's Class VI permitting can take years and its requirements are floors that can be exceeded by state standards.[199] Four states (**Arizona**, **Louisiana**, **Texas**, and **West Virginia**) are in the process of applying for primacy, although this approval process may also take many years.[200] Pore space ownership is another area that requires state attention, given the variability and complexity of property rights in the United States.[201]
- *Procurement*
    - Clean Product Standards: Clean product standards (CPS) would establish a market-wide emissions standard for industrial products, essentially applying the global warming potential (GWP) or embodied emission standard of a Buy Clean policy to cover *all* products sold within

a certain jurisdiction, not just the products purchased by state governments.[202] A CPS could be viewed as a natural expansion of a Buy Clean policy: after government creates the initial market for lower-carbon products and develops the supporting infrastructure (e.g., data, monitoring and evaluation), it can create a CPS to bring the rest of the market onboard to incentivize deeper and broader emissions cuts from manufacturers. It could also be designed to deal with carbon leakage by applying to both imports and exports.[203] World Resources Institute (WRI) has explored what a tradeable CPS would look like for the cement and steel industries.[204, 205]

- Embodied Emissions Standards: There may be opportunities to layer policies at the state and local level to address the embodied carbon of different materials. For example, local or state building codes could incorporate embodied emissions standards for construction materials, although only one jurisdiction (Marin County, California) has implemented this concept to date.[206] In theory, however, material regulations could be integrated into structural building codes.[207, 208] In addition, at least 20 cities and municipalities have adopted embodied carbon policies across the United States.[209]

2.6 Supporting Policies & Actions

Supporting policies can lower the costs and boost the effectiveness of many policy types described above through improved information and economic assistance.[210] These policies can build an enabling knowledge infrastructure (e.g., disclosure and labeling programs, technical assistance, workforce training), create new markets (e.g., procurement policies, certification programs), and invest in physical infrastructure. Supporting policies may be designed to complement existing policies, reinforce positive outcomes, and avoid unintended negative consequences.

Low-carbon material procurement
States can help develop markets for industrial materials with lower embodied emissions through low-carbon procurement policies like “Buy Clean,” a concept pioneered in **California** and now taking hold in several other states and the federal government. Buy Clean policies leverage the purchasing power of public authorities and combine disclosure, incentives, and emissions standards to create a market for lower-carbon products and materials.[211] "Buy Fair" is an expansion of the concept that also incorporates working conditions, such as disclosure and standards around compensation, working hours, and collective bargaining. **Washington** is currently conducting pilot studies on both Buy Clean and Buy Fair.[212]

Five states (**California**,[213] **Colorado**,[214] **New Jersey**,[215] **New York**,[216] and **Oregon**[217]) have enacted embodied carbon legislation to date, although only California’s program is in effect as of July 2022. **Colorado** is developing its program to cover materials used in building and transportation projects, while **Oregon** is tasked with developing a program to reduce emissions from constructing and maintaining transportation infrastructure. **New Jersey** and **New York’s** bills focus only on concrete while the others cover multiple materials. Both **Minnesota**[218] and **Washington**[219] are conducting clean construction studies, pilot projects, and test databases, while **Maryland**[220] is evaluating policies to increase low-carbon concrete in state projects. Three states (**Louisiana,**[221] **Michigan,**[222] **Wisconsin**[223]) recommended adopting a Buy Clean policy in their 2022 climate or clean energy action plans, and at least three other states (**Connecticut**, **Hawaii**,

Massachusetts) have introduced—but not passed—embodied carbon legislation in recent years.[224]

State policies vary in their coverage of materials and expertise on embodied carbon data. The most commonly covered materials are steel, concrete, glass, asphalt, and wood products. Some state programs (**California, Colorado, Oregon, Washington**) target multiple material types while others (**Maryland, New Jersey, New York**) target only one. Buy Clean policies depend on a foundation of high-quality embodied carbon data, most commonly through environmental product declarations (EPDs) from industry. However, EPDs are not yet widely available across regions, or for all relevant materials, or at a level of consistency to compare materials effectively.[225] States—in coordination with each other, industry, and the federal government—can help harmonize data sources, material coverage, and standards to create a stronger and more-consistent market for lower-carbon materials.

Strategic energy management (SEM)

SEM provides a framework of practices and processes to identify and implement energy efficiency projects through systematic improvement. It emphasizes a focus on people and organizational change to enable persistent energy savings and related emissions reductions.[226] A recent study for Canada showed SEM could potentially achieve up to 20 percent of the country's emissions reduction goal for heavy industry.[227]

To accelerate SEM's growth and impact, policy support is needed for training, financial assistance, and developing improved reporting and monitoring for both energy and emissions. States can implement SEM programs on their own or in partnership with federal programs.[i] For example, the Energy Trust of **Oregon** supports industry through numerous programs, including SEM, which includes free training for industrial facilities and cash incentives for achieving energy saving milestones. Participating facilities typically see energy efficiency gains of 5–10 percent per year.[228] **Colorado's** Industrial Strategic Energy Management program offers similar services.[229] **New York's** SEM program is available to both commercial and industrial facilities, comprising a coaching and training program and "virtual treasure hunts" to identify energy-saving projects.[230]

However, many states do not fund SEM programs that target industrial facilities and current SEM programs tend to limit their focus on small manufacturers, thereby neglecting medium and large customers, especially those that have opted out of their utilities' energy efficiency programs. This trend may be changing, as at least three states (**Louisiana,**[231] **Washington,**[232] **Wisconsin**[233]) have recommended establishing SEM programs for industry as part of recent climate or clean energy action plans.

Technical assistance (TA)

Decarbonization is a daunting challenge for private-sector actors in the industrial sector to address alone. Government-funded TA can help companies overcome cost barriers for devising plans and projects to reduce GHG emissions. TA is particularly valuable for small- and medium-sized companies that are limited in personnel and experience. See ***Section: 2.7 Remaining Challenges***, where small and medium manufacturers and light industry are covered further, but it is important to note here as well as TA is a broad opportunity for state policy that connects with workforce development and current program offerings.

[i] DOE's Industrial Assessment Centers (IACs) are based in dozens of universities across the United States. IACs expand the energy-saving workforce and reduce emissions by training students and performing energy use assessments for small industrials at no cost to the customer.

States can leverage existing federal programs (e.g., DOE's Better Plants Program, DOE's Industrial Assessment Centers, EPA's ENERGY STAR Program) or deploy their own, such as **New York's** FlexTech Program [234] and **Washington's** Efficiency Services for Manufacturing and Industrial Facilities. [235] Other states like **Maine**, [236] **Oregon**, [237] and **Wisconsin** [238] offer TA through their industrial incentive programs.

Labeling and certification
As a complement or alternative to procurement policies, labeling and certification schemes can help expand the market for low-carbon industrial goods. These programs not only help educate consumers of industrial goods, but they also give public recognition to companies for taking steps to reduce their environmental impact. EPA has already developed robust set of *Recommendations of Specifications, Standards, and Ecolabels for Federal Purchasing*, covering a variety of commonly procured goods, [239] and the EPA ENERGY STAR certification recognizes buildings and industrial plants for superior energy performance. [240]

For industrial decarbonization, this is a nascent policy area. Green building certifications and standards have driven EPD development and use to date, helping to increase understanding of construction materials' embodied GHG emissions. [241] **Oregon** partnered with its local concrete industry to expand the labeling and use of EPDs, for example. [242] In recent climate and clean energy plans, **Louisiana** [243] and **Wisconsin** [244] proposed developing voluntary industrial certification programs to incentivize and recognize facilities for implementing GHG or energy reduction measures.

Emissions disclosure and monitoring
Designing effective decarbonization policy depends on a foundation of robust energy and GHG emissions data. In the United States, the Greenhouse Gas Reporting Program (GHGRP) requires facilities emitting over 25,000 metric tons CO_2e per year to report their emissions to the EPA. This threshold applies to about 7,600 electric and industrial facilities and 1,000 fuel/gas suppliers, accounting for nearly 90 percent of total national GHG emissions. [245] Industrial data is also tracked or consolidated by EIA, [246] the National Renewable Energy Laboratory (NREL), [247] and other sources. While these national datasets are useful for state policymakers to understand major industrial sources of emissions within their own borders, federal data have several limitations on their level of granularity, timing of disclosure, and scope of facility coverage.

Some states have developed their own compulsory disclosure schemes to meet specific policy needs. For example, **California's** Regulation for the Mandatory Reporting of Greenhouse Gas Emissions [248] complements and expands on EPA's GHGRP by requiring more-detailed emissions monitoring and disclosure, which inform the state's cap-and-trade program and GHG emissions inventory. All facilities are subject to a lower reporting threshold (10,000 metric tons CO_2e per year) and certain activities like cement and nitric acid production, lime manufacturing, and petroleum refining must report regardless of emissions level. [249] **Colorado** has also adopted a GHG Reporting Requirement (Regulation 22, Part A) that complements EPA's GHGRP, for use in inventory and regulation development as well as compliance for existing regulations. [250] **Louisiana,** [251] **New York**, [252] and **Washington** [253] have all proposed developing GHG reporting programs to build datasets that help decarbonize industry in recent climate or clean energy action plans.

Low-carbon infrastructure investment
Infrastructure investments are going to be vital to allow for low-carbon electricity and hydrogen delivery and the transportation and storage aspects of CCUS. Given state authorities and responsibilities on resource planning and infrastructure—such as

permitting, rights of way, and other regulations—states can take action to ensure that the infrastructure needs across all five decarbonization pillars are met. Revenues from existing state programs like carbon markets (where/when available) or gasoline taxes can be used to help accelerate infrastructure deployment.

Equity and environmental justice

Industrial facilities emit air, water, and soil pollutants that disproportionately contaminate low-income and BIPOC (Black, Indigenous, People of Color) communities,[254] and major sources of industrial GHG emissions can sometimes be the biggest sources of air pollutants.[255] **California** has found that communities of color received the majority of the health benefits of its GHG reduction policies targeting industrial and heavy-duty vehicle emissions.[256] Advancing industrial decarbonization thus offers a strong opportunity to address environmental damages, injustice, and public health.

Going forward, states should aim to direct the benefits of industrial decarbonization, while minimizing any further impacts (See ***2.7 Remaining Challenges***), to disproportionately impacted communities. To help achieve this outcome, states should ensure that their equity and environmental justice (EJ) policies include:

- Acknowledgment of the disproportionate impacts across historically underserved and vulnerable populations;
- Identification of solutions for pollution reduction from industrial sources;
- Creation of mapping tools that communities can access and data visualization options to support communication;
- Establishment of easy-to-access communication portals and processes for engaging with communities early and often on pertinent issues like infrastructure siting and just transition;
- Articulation of EJ priorities in budgets and spending plans;
- Designation of a lead agency, council, or commission and personnel to support EJ activities within the state government; and
- Establishment of advisory panels to advise on and guide EJ efforts at the accountable agency or council.[j]

Diverse workforce development

As industry decarbonizes, a talented, diverse, and committed workforce will be essential to overcome the numerous technical, economic, business, and culture change hurdles that are currently in place. States should ensure a just transition for workers whose industries are being replaced in the new low-carbon economy while creating jobs for and offering skilled training to a diverse range of workers from disadvantaged communities. Approaches for facilitating such a transition include:

- Developing just transition roadmaps;
- Setting aside economic resilience funds for workers and their communities;
- Creating and using stakeholder communication platforms to share information with affected workers and collect their input on the just transition process; and
- Proposing timelines and sequencing pathways for the transition process.

States can also initiate training programs and engage with IACs and other programs where new or retrained workers can participate in overcoming decarbonization

[j] For additional information on this topic, see *A 50-State Survey of State Policies and Decision Makers to Help Ensure Federal Investments Go to "Disadvantaged Communities" Under Biden's J40 Initiative* here.

challenges. These programs allow states to leverage technical assistance to help establish a path to well-paying jobs and improve the competitiveness of industry.[k]

Targeting industry clusters
Industry tends to "cluster" in concentrations of companies providing specialized goods or services. Clusters form around access to specific natural resources (e.g., energy sources, water, raw materials), transportation options, a similar customer base, and skilled pools of labor. Examples include biotech companies clustered around three nearby universities in North Carolina's Research Triangle Park, wind energy R&D and manufacturing in the Great Lakes region, and petrochemical companies clustered around the Houston Ship Channel and the Mississippi River in Louisiana. Ports are another common example of industrial clusters (***Box 2***).[257]

Clusters of companies have great potential to collaborate on the step changes needed to reduce GHG emissions. "Net-zero clusters" are a high investment priority in the UK, the Netherlands, and other countries in the European Union,[258] and have been studied in the United States.[259] For example, an industry cluster could work together and with supply chain partners to:

- Quickly implement programs focused on accelerating energy efficiency improvements, reducing both energy use and GHG emissions.
- Develop methods and track data to help quantify and reduce the embodied carbon of products.
- Support low-carbon electricity generation (e.g., wind, solar, micro-nuclear) at brownfield sites near the cluster, which would facilitate beneficial electrification.
- Cost-effectively build out infrastructure for LCFF (e.g., hydrogen and carbon dioxide for CCUS), in partnership with pipeline companies and government agencies. For example, an estimated $28 billion in infrastructure costs is needed to reduce 25 million tons of carbon dioxide per year in the Houston port area, highlighting a role for public policy support to attract private investment.[260, 261]

Clusters can also be crucial for job creation and workforce training. Industry can partner with nearby institutions of higher learning to actively train the future workforce while improving diversity, equity, and inclusion. At the same time, environmental justice groups need to be engaged to understand how clusters can best help reduce the environmental impact of industry.

[k] For additional information on this topic, see *The Just and Equitable Transition State Policy Framework* and its accompanying *Resource Guide* here and here.

Box 2: Ports as Industrial Hubs

Ports, including both marine and airport facilities managed by the same "port authority," provide hubs of infrastructure, skilled labor pools, and often large concentrations of industrial facilities. These areas present opportunities for focused innovation, investment, and policy aimed towards decarbonization. GHG emissions reductions can be achieved by connecting infrastructure and decarbonization approaches at ports and other industrial hubs by applying technologies and practices such as emissions controls, electrification, energy management, low-carbon fuels (e.g., green hydrogen), and CCUS. Ports are also essential for connecting local, regional, national, and international markets to low-carbon energy and goods. A combination of state policy, federal policy, corporate engagement, and regional cooperation are needed to further develop low-carbon or net-zero industrial hubs at ports. Engagement with port authorities, local governments, and environmental justice communities will be critical.

The EU and UK have already accelerated decarbonization of industrial clusters as primary components of their industrial decarbonization strategies. The Port of Rotterdam, for example, is working with the local port authority and community to create a port where business and trade continue to grow sustainably through shared infrastructure, waste heat reuse, electrification, green hydrogen, and other strategies.[262]

In the United States, several prominent ports are exploring decarbonization approaches that leverage shared infrastructure and other cluster characteristics. For example:

- The Port of Seattle is evaluating the potential role of green hydrogen for maritime industrial uses.[263]
- The Port of Houston is evaluating the costs associated with an ammonia export terminal that would include carbon dioxide capture infrastructure, green hydrogen infrastructure, and renewable power supply.[264]
- At the Port of Baton Rouge, Grön Fuels is developing a $9.2 billion carbon-negative renewable fuel complex that will produce renewable diesel, sustainable aviation fuels, green hydrogen, and bio-plastic feedstocks.[265]
- The Port of Los Angeles opened two hydrogen fueling stations in mid-2021 and debuted five new hydrogen fuel cell Class 8 trucks.[266]

The *Inflation Reduction Act* includes $3 billion to reduce air pollution in ports, complementing another $1 billion for low-emissions, heavy-duty vehicles and $17 billion for port upgrades in the *Infrastructure and Investment Jobs Act.*[267]

Collaboration with state and federal partners
Both the U.S. Climate Alliance[268] and the Biden Administration[269] have highlighted the need to decarbonize industry, making this sector ripe for multi-state collaboration and state-federal policy alignment. States and the federal government can play complementary roles in implementing best practices, developing new markets for cleaner products, and providing financial and technical support to decarbonize existing facilities. As in other sectors, such as transportation and refrigerant management, industry is most amenable when regulations are consistent across markets and cognizant of their needs. States working together and with the federal government to develop substantially similar policies can ensure efficient knowledge-sharing, stakeholder engagement, rule development, and enforcement.

There are multiple ways in which policymakers can join forces to increase leverage (of financial impact, workforce development, infrastructure deployment, etc.). For example, several states established regional partnerships to develop clean hydrogen hubs in this past year, including in the Intermountain West,[270] the Northeast,[271] and the Gulf South.[272]

New federal programs and investments enabled by recent legislation offer significant opportunities for states to share information, collaborate on best practices, and implement and scale technologies to decarbonize their industries. A DOE analysis found that the combination of programs and incentives in the *Inflation Reduction Act* (IRA) and *Infrastructure Investment and Jobs Act* (IIJA) will reduce national GHG emissions by almost 1,150 MMT CO_2e by 2030, with industrial emissions reductions representing the second-largest driver of the reductions.[273]

Each law contains significant provisions for industrial emissions abatement, with the IRA projected to drive impacts in the next decade and the IIJA making a down-payment on technologies that will drive deeper emissions cuts after 2030. ***Table 4*** and ***Table 5*** below map these industrial-focused programs against the five decarbonization pillars.

Table 4: Industrial decarbonization provisions in the Inflation Reduction Act of 2022.

Decarbonization Pillar	Specific Programs
Efficiency	• Advanced Industrial Facilities Deployment Program ($5.812B – efficiency projects eligible) • 48C Advanced Energy Project Tax Credit (extension and expansion – energy and material efficiency projects that reduce GHGs eligible)
Electrification	• PTC, ITC for renewable energy (extension and expansion) • Advanced Industrial Facilities Deployment Program ($5.812B – electrification and low/zero-carbon heating projects eligible) • 48C Advanced Energy Project Tax Credit (extension and expansion – low/zero-carbon heating projects that reduce GHGs eligible)
Low Carbon Fuels & Feedstocks	• Clean Hydrogen Production Tax Credit (new)

Decarbonization Pillar	Specific Programs
	• Advanced Industrial Facilities Deployment Program ($5.812B – low/zero-carbon fuels and low/zero-carbon heating projects eligible) • 48C Advanced Energy Project Tax Credit (extension and expansion – low/zero-carbon heating projects that reduce GHGs eligible)
Carbon Capture	• 45Q Carbon Capture and Storage Tax Credit (extension and expansion) • Advanced Industrial Facilities Deployment Program ($5.812B – CCUS projects eligible) • 48C Advanced Energy Project Tax Credit (extension and expansion – CCUS projects that reduce GHGs eligible)
Procurement	• Environmental product declaration assistance ($250M) • Low-embodied carbon labeling for construction materials for transportation projects ($100M) • GSA Use of Low-Carbon Materials ($2.15B) • DOT Low-Carbon Transportation Materials Grants ($2B) • FEMA Building Materials Program
Other Industrial Provisions	• Advanced Manufacturing Production Credit (for solar and wind components, batteries, and critical minerals) • Advanced technology vehicle manufacturing ($3B) • Domestic Manufacturing Conversion Grants ($2B) • Alternative Fuel and Low-Emission Aviation Technology Program ($297M) • Methane Emissions Reduction Program ($1.55B, incl. waste methane fee, starting at $900/ton up to $1500/ton in 2026) • HFCs reduction via implementation of the American Innovation and Manufacturing Act ($38.5M)

Table 5: Industrial decarbonization provisions in the Infrastructure Investment and Jobs Act of 2021.

Decarbonization Pillar	Specific Programs
Efficiency	• Advanced Energy Manufacturing and Recycling Grant Program ($750M – energy and material efficiency projects eligible) • Industrial Emission Demonstration Projects ($500M – energy and material efficiency projects eligible)
Electrification	• Advanced Energy Manufacturing and Recycling Grant Program ($750M –low/zero-carbon process heat, renewables, fuel cells, grid modernization, electrolyzer projects eligible) • Industrial Emission Demonstration Projects ($500M – low-GHG medium/high-temperature process heat projects eligible)

Decarbonization Pillar	Specific Programs
Low Carbon Fuels & Feedstocks	• Advanced Energy Manufacturing and Recycling Grant Program ($750M –low/zero-carbon process heat and electrolyzer projects eligible) • Industrial Emission Demonstration Projects ($500M – low-GHG medium/high-temperature process heat and chemical production projects eligible) • Regional Clean Hydrogen Hubs ($8B) • Clean Hydrogen Electrolysis Program ($1B) • Clean Hydrogen Manufacturing and Recycling Program ($500M)
Carbon Capture	• Advanced Energy Manufacturing and Recycling Grant Program ($750M – CCUS projects eligible) • Industrial Emission Demonstration Projects ($500M – CCUS projects eligible) • Carbon Storage Validation and Testing ($2.5B) • Carbon Capture Demonstration Projects Program ($2.54B) • Carbon Capture Large-Scale Pilot Projects ($937M) • CO_2 Transportation Infrastructure Finance and Innovation ($2.1B) • Carbon Utilization Program ($310M) • Carbon Capture Technology Program ($100M) • Underground Injection Control Grants ($50M)
Procurement	• All manufactured products and construction materials used in infrastructure projects financed by the bill must be domestically produced
Other Industrial Provisions	• Industrial Research and Assessment Centers ($150M) • Smart Manufacturing Leadership Grants ($50M) • Battery Materials Processing Grants ($3B) • Battery Manufacturing and Recycling Grants ($3B) • Critical Material Innovation, Efficiency, and Alternatives R&D ($600M) • Battery and Critical Mineral Recycling R&D ($125M)

See ***Appendix A: New Federal Investments and Programs*** for more detail.

Learning from international approaches

As industry's direct GHG emissions are responsible for 24 percent of emissions globally, industrial decarbonization is one of the leading priorities of countries all over the world to reach climate goals.[274] Although the barriers to industrial decarbonization vary by the economic status, intensity of industry, energy mix, available trained workforce, and political climate of different countries and regions, states can learn from international approaches taken to address industrial emissions.

Several countries are leveraging innovative, cross-cutting policy approaches both within their own borders and in collaboration with other countries and the private sector. Leading countries in addressing emissions reductions across all sectors—including Canada, the UK, the EU, and Japan—are also in the process of developing industrial decarbonization guides. The guides identify the decarbonization challenges that need to be addressed, as well as timelines, coordination goals, sector targets, and establish funding and budget programs for R&D. Some common approaches include innovation funds, grant funding, tax incentives, regulatory reform (including standardization), legislative support, data infrastructure, and transparency.[275, 276, 277] Specific examples include Manitoba's Sustainable Development and the Expert Advisory Commission, which considers best steps towards developing decarbonization plans for individual sectors, and action 4.6 in the UK's *Industrial Decarbonization Strategy,* which outlines how to engage the cement industry to decarbonize sites at dispersed locations. These international approaches are summarized in ***Table 6***.

In terms of plans for specific industrial sectors, examples include the EU's *New Industrial Strategy* and its plans to decarbonize steel, chemicals, and textiles, while Canada is developing a roadmap to net-zero carbon concrete, and Manitoba and Ontario have developed province-based initiatives towards reducing food waste.

Table 6: International policy approaches to enable industrial decarbonization. Click examples in the table to view more information.

Policy Approach	International Policy Examples
Planning & Governance	• UK's Industrial Decarbonization Strategy • EU's New Industrial Strategy • Japan's National-level Carbon Neutral Society Framework • EU's Circular Economy Action Plan
RDD&D	• UK's Industrial Decarbonization Challenges • UK's Industrial Decarbonization Research and Innovation Centre
Finance and Incentives	• Japan's Guidelines for Climate Transition Finance • Alberta's Sector-Specific Industrial Energy Efficiency Grant Program
Standards	• Alberta's Technology Innovation and Emissions Reduction Regulation • Ontario's Emissions Performance Standards • Manitoba's Carbon Pricing for Large Emitters
Supporting Policies	• UK's Industrial Clusters Mission • EU's Industrial Cluster • EU's Observatory for Clusters and Industrial Change • EU's Strategy for Smart Sector Integration • Canada's Buy Clean • EU Structural and Investment Funds • EU's Territorial Just Transition Plans • EU's Skills Agenda for Europe

There have been many international strategies toward decarbonization with crosscutting approaches. The clusters approach is one that is being employed by both the EU and the UK. For example, the UK's plan includes up to £170 million, matched by £261 million from industry, to invest in developing technologies such as carbon capture and storage and hydrogen fuel switching and to deploy and scale up these technologies within the UK's largest industrial clusters.[278] The EU's European Industrial Cluster aims to generate joint actions for collaboration on industrial modernization and Industry 4.0 to foster sustainability and emissions reductions.[279] The EU has also established several financing programs such as public-private partnerships for energy (EU PPP-e 2020),[280] the European Clusters Alliance,[281] the European Observatory for Clusters and Industrial Change (EU Clusters 2020),[282] and the EU Innovation Fund.[283]

Other crosscutting strategies of industrial decarbonization include demand-side approaches (e.g., Canada's Buy Clean), performance standards (e.g., Ontario's Emission Performance Standards), support for R&D (e.g., the UK's Industrial Decarbonization Research and Innovation Center), and workforce development (e.g., the EU's Skills Agenda for Europe).

Sufficient capital to accommodate low-carbon transitions is one of the most significant barriers for industrials in pursuing decarbonization at every level. To overcome this barrier, some international strategies include loan guarantees (e.g., Alberta's Climate Change Innovation and Technology Framework, which provides $400 million worth of backstopped financing for qualified companies that are investing in industrial efficiency).[284] Other strategies include emissions reduction funds (e.g., the Ontario Carbon Trust) and carbon pricing (e.g., the Manitoba output-based carbon pricing system for large emitters). Countries have also implemented strategies including rebates and tax credits to incentivize improved energy efficiency and emissions savings. One example of this is in Germany, where since 2012 large energy users are eligible to apply for a 90 percent reduction in energy taxes if they prove that they have implemented a high standard of energy management system.[285]

2.7 Remaining Challenges

All states will face unique or special circumstances that may impact industrial decarbonization policy planning. These include their existing energy infrastructure and energy mix, whether code councils and public utility commissions are staffed through appointments or by elections, and how the state defines and includes (or excludes) the industrial sector in state programs and regulations. For example, in **Colorado** the definition of 'industry' includes manufacturing facilities that may not have equally cost-effective opportunities they can pursue. Some manufacturers might end up with greater upfront capital costs to meet the same reduction thresholds as others. However, **Colorado** also developed an EITE industry-specific approach that uses best-available control technologies and third-party audits. Through this process, the audit identifies and evaluates an essential list of equipment and technology opportunities (e.g., CCUS, energy efficiency, fuel switching). Based on the audit results, facilities may choose a variety of compliance pathways to meet reduction goals. Other challenges include:

Administrative complexity
Industrial decarbonization policies can be administratively complex, given the gaps in data and information, the heterogeneity of industry, and potential number of facilities to address. To minimize this burden and get the 'biggest bang for their buck,' states could focus their initial policy attention on the most upstream producers of primary industrial materials and goods. These industry types largely align with the subsectors covered in ***Chapter 3*** and tend to be the most energy- and/or emissions-intensive, the fewest in number, and report into longstanding national datasets, such as the U.S. EPA's Greenhouse Gas Reporting Program (GHGRP).[286]

Clean energy definitions and associated pathways
The GHG benefits of fuel switching, renewable energy consumption, and electrification can depend on how a state defines "clean" versus "renewable" energy and whether the

state continues to use and/or incentivize fossil energy. Because of this, states should establish clear definitions of "clean energy" and "renewable energy" at the beginning of the policymaking process, looking to other states or countries that have successfully done so. For example, **Washington** State's *Clean Energy Transformation Act* (CETA) requires the state's electric utilities to eliminate carbon emissions from their energy resources by 2045. It follows a transition pathway that requires all electric utilities serving Washington state customers to eliminate coal-fired generation by 2025, achieve GHG neutrality by 2030 (allowing for offsets with renewable energy, energy efficiency, carbon reduction project investments, or payments funding low-income assistance), and ultimately generate 100 percent of their power from zero-carbon sources by 2045.[287]

Decarbonization transition costs
Industrial facilities assessing their decarbonization options frequently express concerns that the fuel costs for natural gas are almost always lower than electricity costs. The price ratio of electricity/natural gas varies by state.[288] For example, states in the northwest or northeast tend to have a lower price ratio due to the high availability of hydropower, which provides relatively low electricity rates. In these states, the cost barrier to electrification will be somewhat lower. However, even in these states, and especially in states where the ratio is higher, incentives that offset this disadvantage for electrification could be considered to spur decarbonization, along with utility rate design reform. For example, a production or investment tax credit could be developed for industrial electric usage, or industrial equipment that uses low-carbon electricity instead of fossil fuels. States and industry should leverage support from the federal government for R&D, infrastructure development, and demonstration project funding through loans, grants, and cooperative partnerships to further address these and other transition cost challenges.

Environmental impacts
As industrial processes are redesigned to incorporate low-carbon technologies and produce low-carbon materials, they will likely also lead to reductions in overall environmental damage, as emissions-intensive processes are often large sources of air pollution.[289] However, understanding and avoiding unintended consequences associated with these changes will be critical to minimize all environmental impacts, especially with emergent technologies like green hydrogen and CCUS.

- For hydrogen, storage, pipeline, and transfer facilities will need to be rigorously maintained and monitored because hydrogen gas is flammable, explosive, and prone to leaking and degrading materials not specially suited for its transport and storage due to its small molecular size. Hydrogen's use as a combustible fuel is relatively untested, with early research suggesting elevated release of nitrous oxide emissions compared to natural gas.[290] Research also suggests hydrogen's role as an "indirect GHG" could offset its climate benefits without proper protocols and care to prevent leakage.[291]

- For CCUS, geologic sequestration projects must meet specific EPA regulations (Class VI regulations). Class VI regulations include specific permitting, construction, operating, monitoring, and closure requirements for the well and injection site. These regulations are intended to ensure the containment of carbon dioxide in stable geologic formations, protect underground drinking water sources, and ensure the safety of project operations. The DOE also leads research efforts to decrease the risk and uncertainty associated with carbon sequestration, including projects characterizing geologic storage sites and development of new techniques to monitor underground carbon dioxide plumes. However, only two Class VI projects have operated to date. Long-term safety of sequestration projects will depend upon continued research to improve risk mitigation and commitment from project operators and regulatory bodies.

Other unintended environmental impacts associated with constructing supporting infrastructure to transport and store hydrogen and carbon (e.g., pipelines) may revolve around land use and how neighboring communities are impacted. Additionally, disposal of equipment that is retired and replaced should consider reuse possibilities (instead of landfill disposal), and processes should be designed for eventual disassembly and reuse.

GHG emissions reduction target complexities
Different types of GHG emissions reduction goals and standards can be used to help decarbonize industry. These include:

- **Voluntary corporate goals**. Many companies—including several manufacturers—are starting to set science-based targets (SBTs) that align with the level of decarbonization required to meet the global temperature goals of the Paris Agreement.[292] While larger companies have set sustainability goals, reducing scope 3 emissions (i.e., all indirect emissions outside of electricity consumption that occur in the value chain of the reporting company, including both upstream and downstream emissions) is challenging due to the complexity of supply chains, limited data, and confusion on emissions attribution.

- **Sector-wide GHG emissions reduction goals**. State climate action plans may identify the contribution that the industrial sector must play in order to meet the state's economy-wide GHG emissions reduction target. However, industrial activity data and GHG emissions abatement potential have historically been a limiting factor in setting robust, sector-specific targets. Additionally, policymakers must weigh the pros and cons of absolute GHG emissions reduction goals versus GHG intensity-based goals for the industrial sector. For example, states should consider whether absolute emissions limits would inadvertently disincentivize production in certain industries, especially manufacturers of high-volume commodity products. If intensity-based goals are preferred—as they are by most industries—then they will have to be carefully defined (e.g., units of carbon [CO_2] or GHGs [CO_2e] emitted per ton of material produced) and avoid gamification (e.g., using physical units, like tons, rather than dollar value of output, as economic metrics may obfuscate the carbon information relevant to climate goals). Intensity targets can help normalize states' assessment of emissions across diverse industries.[293]

- **Product-specific standards.** Regulations like embodied emissions standards and clean product standards set performance-based GHG limits for specific products produced and/or consumed by in-state entities (see ***Section 2.5: Standards*** for more information).

Given the numerous complexities in quantifying and setting GHG emissions reduction targets, states should work closely with industry on setting any sort of sector-specific goal and help develop the data infrastructure that companies need to better quantify their own GHG emissions and track progress.

Balancing goals with industrial concerns
Establishing strong targets (and effective incentives and standards) requires a robust foundation of data. One area where concerns arise is in the choice between intensity

reduction goals and mass-based goals.[l] Multiple environmental groups have stated a preference for mass-based goals. However, industry often prefers intensity-based goals due to sensitivities around divulging production data to competitors. It is important to protect businesses and not drive them out of state, yet regulations and goals must be made strong enough to incentivize industries to decarbonize. Also, some industries are projected to grow, and there is a broader political push to increase domestic manufacturing. Policymakers must be sensitive to this tension of maintaining a business-friendly climate in the state while ensuring industry contributes to state GHG reduction goals.

- Intensity in pounds produced is a competitive parameter. While EPA and California have required GHG reporting, there is no mechanism to require production numbers for use in the same system. In **California**, however, an industrial facility may report production data pursuant to the Mandatory Reporting of Greenhouse Gas Emissions Regulation, enabling allowance allocation to that facility under the Cap-and-Trade Program. Confidentiality and proprietary concerns present potential issues associated with reporting production numbers.

- When tracking embodied carbon across the whole lifecycle of a product like cement, the fuel used to heat the kilns and the emissions per unit of mass (e.g., grams CO_2/kg cement) will need to be evaluated across multiple steps in production, storage, and transportation. Multiple business-sensitive parameters may be part of those calculations. The development of standardized and transparent protocols and verification by third-parties parties with nondisclosure agreements for information (that has an acceptable degree of sensitivity) should provide a suitable route to obtain reliable information on embodied carbon while balancing business sensitivities.

Small and medium manufacturers (SMM) and light industries

Over 90 percent of the 300,000 manufacturing companies in the United States are defined as 'small and medium manufacturers' with fewer than 500 employees (most have fewer than 20 employees).[294] Many SMMs are also considered 'light industry,' which are not as energy intensive as 'heavy industry.' These manufacturers include industries like food and beverage, fabricated metals, and transportation equipment, as well as downstream companies that transform, combine, and customize heavy industry's products into intermediate or finished products.

Given the wide diversity of SMMs, these manufacturers typically face different challenges and solutions to decarbonization compared to major heavy industry manufacturers. They are also largely absent from national datasets containing industrial emissions and energy use information. In contrast to heavy industry, lighter-industry SMM industries spend less money on energy, use a greater portion of electricity to meet their energy needs, require less high-temperature process heat, and rely on simpler manufacturing processes. These differences also represent great opportunities for state policymakers to achieve near-term GHG reductions. For example:

- Light industry can use up to four times more electricity than fossil fuels, which suggests a lower barrier to adopting beneficial electrification than in heavy

[l] Intensity of emissions is the volume of emissions per unit of GDP. Setting reduction targets based on carbon emissions intensity refers to reductions per unit of economic output. However, as GDP grows so do total carbon emissions. Mass-based reductions in total emissions refer to actual carbon reductions measured in tons.

industry. One analysis estimated 25 percent of light industry heat demand could be met by renewables.[295]

- Energy efficiency could also play an outsized role in reducing GHGs from lighter industry, delivering more than 40 percent of potential GHG reductions in one analysis.[296]

Table 7 describes the crosscutting challenges for SMM industrial decarbonization, state actions that can help overcome those challenges, and policy mechanisms that can enable such actions and drive emissions mitigation.

Table 7: Common barriers and policy opportunities for SMMs across industry.

Challenge / Barrier	State Opportunities	Policy Connections
Energy a smaller driver for companies	● Stimulate energy & material productivity (yield, value return, customer satisfaction, margin retention, GHG reduction)	● Expand communication, outreach, networking, visibility of star performers ● Leverage guides on energy & material efficiency (e.g., U.S. EPA ENERGY STAR)
Limited personnel/ resources	● Expand support, decrease hurdles/ transaction friction	● Support energy managers at company or cohort, energy assessments ● Incentivize project implementation
Combined waste high, but for individual company it can be low	● Develop programs to reduce waste ● Accumulate and transform, reuse where possible	● Incentivize waste reduction ● Incentivize collection, reuse, transformation of waste ● Give breaks to companies that collect/ transform waste
Limited capacity to consider / pursue decarbonization	● Provide information on pathways ● Simplify solution options ● Consider working with third-party aggregators to reach, collaborate with, and serve SMMs	● Provide decarbonization roadmaps tailored to SMM / communicate ● Involve SMM in pilots / demos of transformative technology ● Incentivize equipment low-carbon technology choices commercial today ● Provide support for implementation of low-carbon tech to SMMs ● Expand leverage with current utility providers to reach SMMs
Limited access to emerging low-carbon infrastructure	● Ensure SMM access needs considered in planning	● Consider SMM needs in infrastructure planning (build experience at clusters) ● Provide grants to build connections where efficient
Lack of standardization	● Work with associations and others to develop / deploy standards	● Work across jurisdictional levels to develop / convey standards

CHAPTER 3. INDUSTRY SUBSECTOR SPECIFICS

As described in ***Chapter 1.*** The Overall Strategy, seven subsectors account for most of the manufacturing sector's energy consumption and GHG emissions. These subsectors' GHG emissions result from a similar set of on and offsite sources and processes, although the relative contribution of each source varies considerably between industries. For example, process emissions dominate the emissions footprint of Iron & Steel and Cement, while offsite emissions from electricity and steam generation account for most of the Food & Beverage subsector's emissions (***Figure 6***).[297]

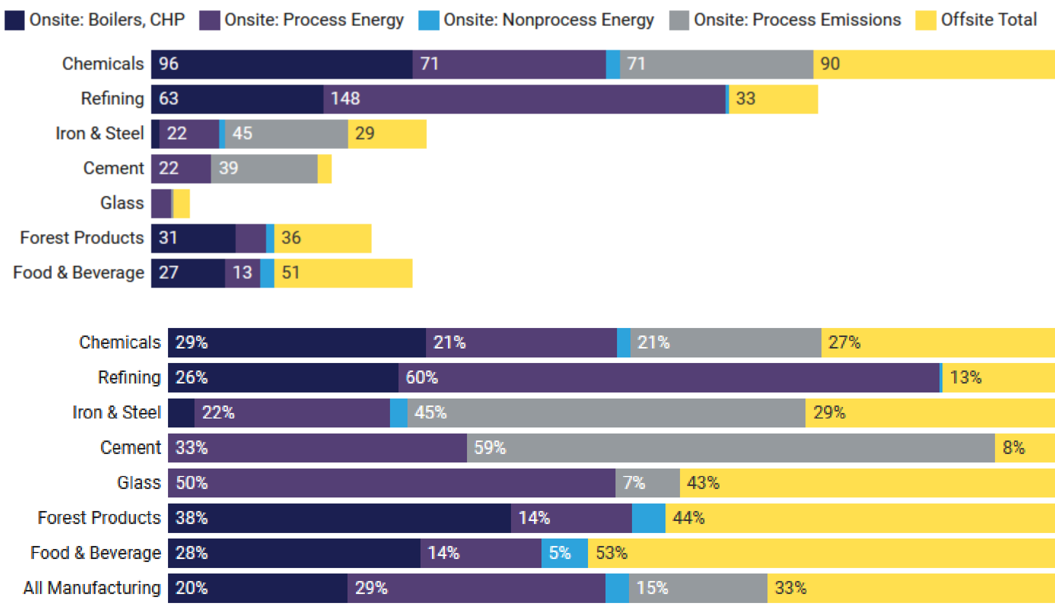


Figure 6: Total GHGs emitted by each of the seven industrial subsectors in 2018, by million metric tons carbon dioxide equivalent (MMT CO_2e) per major source (top) and by percentage contribution per major source (bottom). Includes direct (onsite) and indirect (offsite) emissions. CHP = combined heat and power generation. 'Process energy' includes emissions from process heating and cooling, power motor systems, and other industry-specific operations. 'Nonprocess energy' includes emissions from non-manufacturing operations, including lighting, HVAC, and other categories. Source: U.S. Department of Energy, Manufacturing Energy and Carbon Footprints.

Each of the major emissions sources (e.g., Onsite: Process Energy) in the above figure can be further disaggregated into major end uses (e.g., Process Heating, Machine Drive, Process Cooling).[m] Although these end uses consume a variety of fuels, with electricity fueling a substantial portion of several end uses (Machine Drive, Facility Lighting, Process Cooling); natural gas dominates as a fuel on both an absolute and percentage basis across manufacturing industries. Gas's influence is particularly notable in the

[m] See ***Appendix B: Industry Subsector Carbon Footprints*** for more information about these sources and end uses.

Process Heating, CHP and/or Cogeneration, and Conventional Boiler end use segments (***Figure 7***).[298]

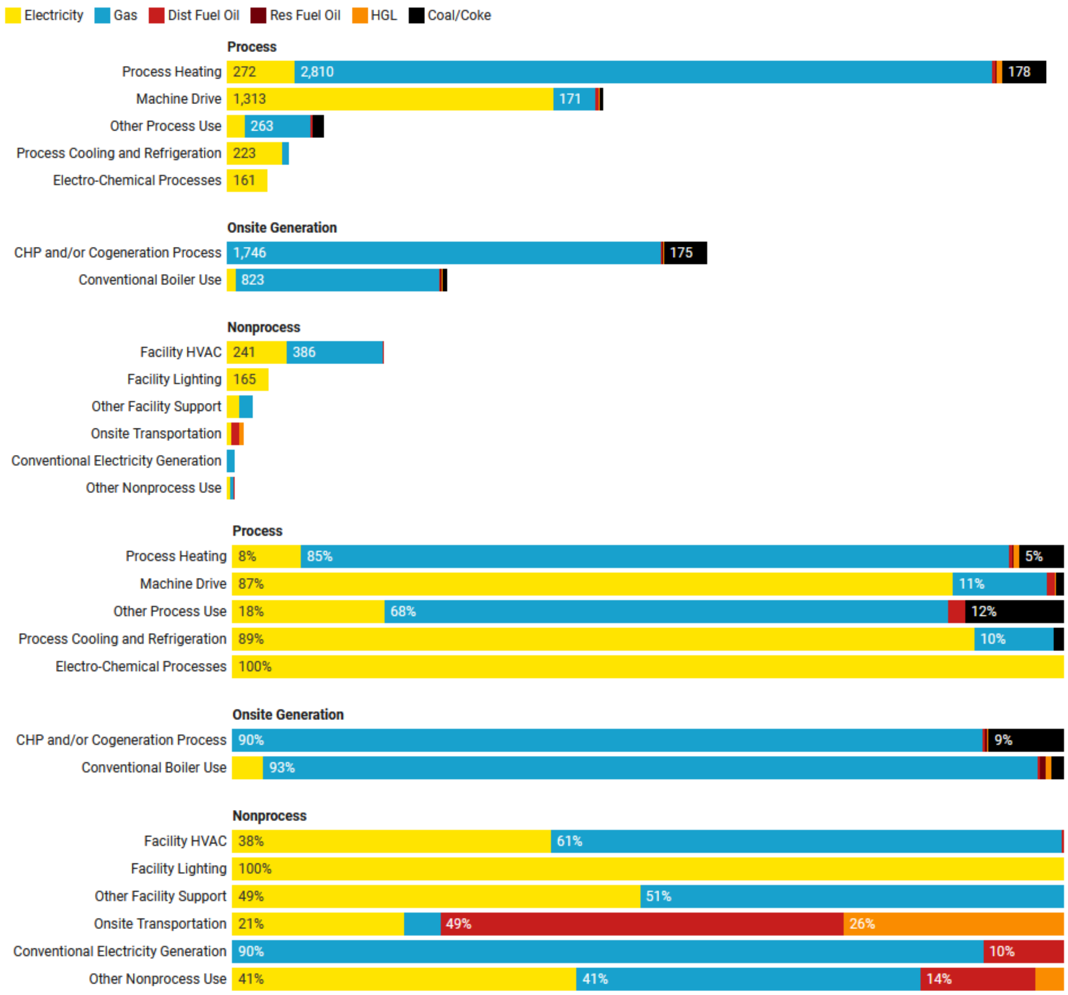


Figure 7: Industrial use of fuels per end use in 2018, by trillion Btu per end use (top) and by percentage contribution per end use (bottom). Figure excludes unreported end uses, which comprise an additional 5,389 trillion Btu. Source: U.S. EIA, Manufacturing Energy and Consumption Survey 2018, Table 5.2.

The role that each of the major pillars of industrial decarbonization will play in reducing GHG emissions across various industrial subsectors will vary, as some pillars will align with technology, business, economic, and geographic opportunities earlier than others. ***Figure 8*** shows a high-level summary of the ways that various pillars could help reduce GHG emissions in these seven major subsectors.[299, 300] Here, the darker shades within a color scheme signify greater opportunity for GHG reductions and major opportunities are listed in the boxes as examples. Additional perspective on the barriers that need to be overcome, opportunities for GHG reduction impact, timing, and pillar alignment for seven major industrial subsectors can be viewed in the following section.

	Efficiency	Electrification	Low Carbon Fuels & Feedstocks	Carbon Capture	Procurement
Timeline	2020 - 2030 / 2030 - 2050	2020 - 2030 / 2030 - 2050	2020 - 2030 / 2030 - 2050	2020 - 2030 / 2030 - 2050	2020 - 2030 / 2030 - 2050
Chemicals	EE↓↓, ME↓↓↓	H&M↓↓↓, PF↓↓↓	H2↓↓↓, BM↓↓↓, RE↓	CCU↓↓↓, CCS↓↓↓	LCPM↓
Refining	EE↓↓↓*, ME↓↓	H&M↓↓	H2↓↓↓, BM↓↓↓	CCU↓↓↓, CCS↓↓↓	()
Iron & Steel	EE↓↓↓, ME↓↓↓	H&M↓↓↓*, PF↓↓	H2↓↓↓, BM↓, RE↓	CCU↓, CCS↓↓	LCPM↓↓↓
Cement	EE↓↓↓, ME↓↓↓*	H&M↓↓	H2↓, BM↓↓↓*	CCU↓↓↓, CCS↓↓↓	LCPM↓↓↓
Glass	EE↓↓↓, ME↓↓	H&M↓↓↓	H2↓, BM↓↓↓, RE↓	()	LCPM↓↓↓
Forest Products	EE↓↓↓*, ME↓↓	H&M↓↓↓	BM↓↓↓*, RE↓	()	LCPM↓↓
Food & Beverage	EE↓↓↓, ME↓	H&M↓↓↓	RE↓↓	()	LCPM↓↓

Figure 8: Alignment of pillars with near and long-term technical opportunities for GHG reduction, by industry subsector. Color gradient indicates timing to achieve greatest impact (darker color = more impact).

EE = energy efficiency; ME = material efficiency; H&M = Heating and mechanical energy; PF = process energy fuel-switching; RE = renewable fuel/feedstock (solar thermal, geothermal); H2 = hydrogen fuel/feedstock; BM = biomass fuel/feedstock; CCU = carbon capture and utilization; CCS = carbon capture and storage; LCPM = low carbon products and materials.

*Number of ↓ indicates emissions impact potential: ↓↓↓ = high; ↓↓ = medium; ↓ = low. * = technology is already widely applied in a subsector. () = unlikely use case*

Sources: Adapted from Worrell and Boyd (Table 1) and Energy Systems Integration Group (Table 1).

3.1 Chemicals

The chemicals industry is a $768 billion enterprise that generates around 25 percent of U.S. gross domestic product (GDP), producing more than 70,000 products that reach over 750,000 end users.[301] The 11,000 manufacturers, employment of over 529,000 skilled workers, and supply chain networks touch more than 96 percent of manufactured goods.[302] Because the chemical sector's products help enable energy and GHG emissions reductions in other sectors, decarbonizing the chemical industry and expanding production of low-embodied-carbon products can have impacts across multiple sectors.

The chemicals industry is the largest energy consumer in the U.S. industrial sector when both fuel use and feedstocks are included.[303] The majority of energy consumed comes from natural gas and related products (hydrocarbon gas liquids [HGLs]). Fuel oil and heavy liquids, coal, and coke account for about 10 percent of the total combined energy consumption (Figure 9).[304]

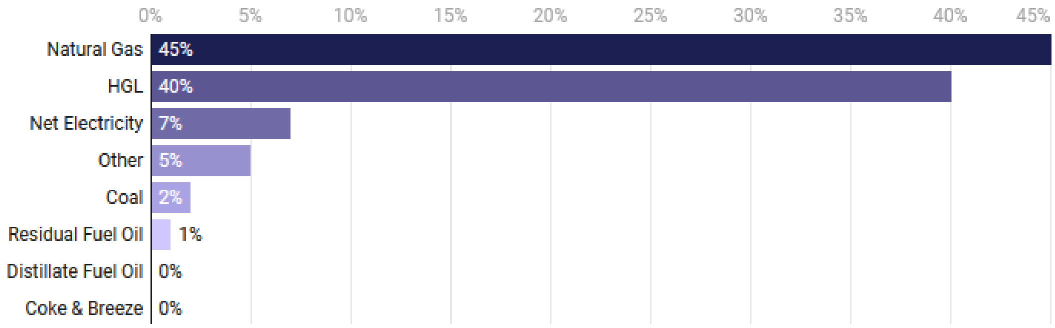


Figure 9: Chemicals sector fuel and non-fuel uses of energy in 2018 (as a percentage of total trillion Btu). Source: U.S. EIA, MECS 2018, Table 1.2.

The chemical sector emits around 332 MMT CO_2e/year (including emissions from offsite generation), with process emissions, process heating, and combined heat and power (CHP) accounting for the most direct emissions (***Figure 10***). [305]

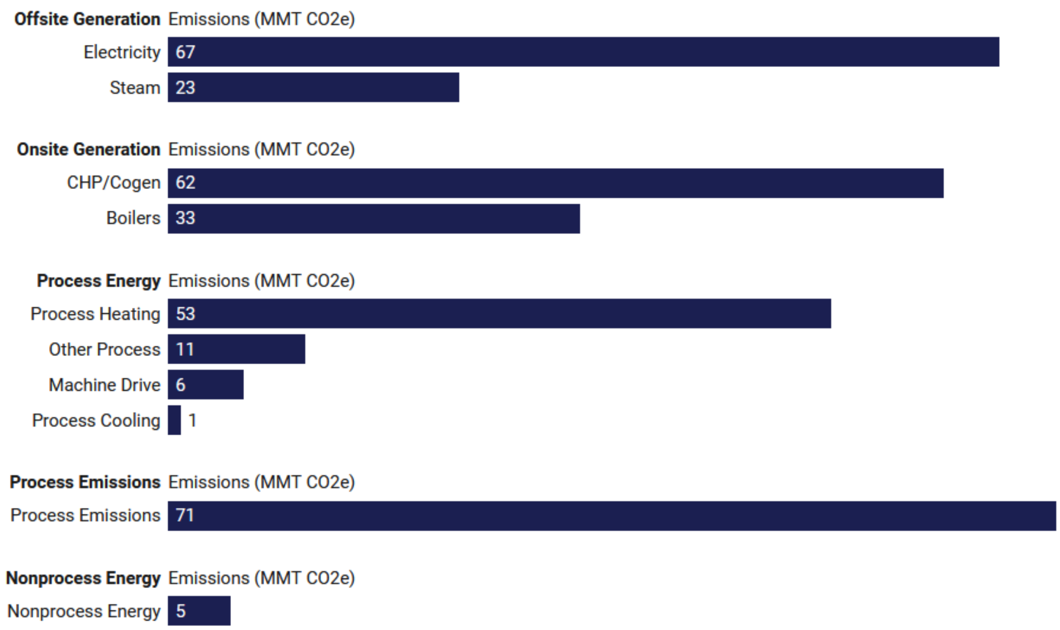


Figure 10: Chemical sector sources of GHG emissions in 2018, by major end use. Source: U.S. DOE, Manufacturing Energy and Carbon Footprint: Chemical Sector.

The chemicals sector comprises a diverse subset of manufactured goods. Petrochemical production—a class of chemicals derived from petroleum or natural gas—accounts for most (32 percent) of the overall chemical sector's direct GHG emissions. Ethylene (a plastics precursor), methanol (a precursor to formaldehyde and other chemicals), and carbon black (a rubber additive) production account for most petrochemical emissions. Another large portion (22 percent) of GHG emissions is associated with hydrogen production—a foundational building block for ammonia and methanol—two large-volume commodity chemicals. Ammonia and nitric acid are both primarily used in fertilizer production. Nitric acid is also a feedstock for producing adipic acid, a major constituent of nylon (***Figure 11***).[306]

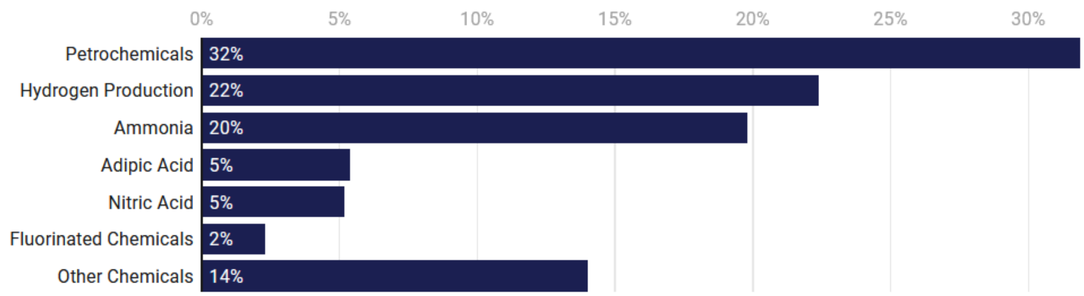
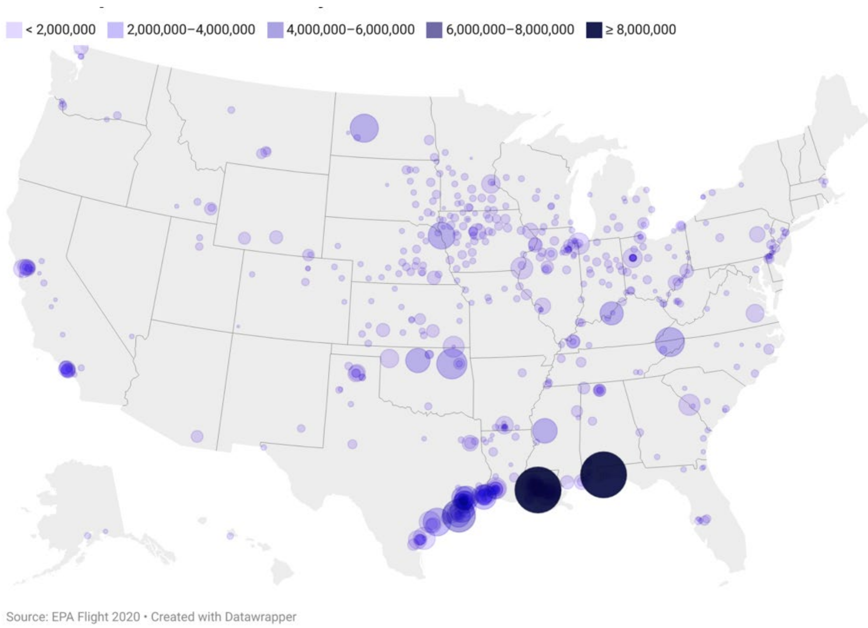


Figure 11: Relative contribution of direct GHG emissions in the chemical sector (as a percentage of MMT CO_2e). Source: U.S. EPA, Greenhouse Gas Reporting Program.

These GHG emissions data suggest early ways to engage the decarbonization pillars mentioned earlier, including:

- Replacing fuel oil / heavy liquids and coal / coke with low-carbon feedstocks such as biofuels or renewable natural gas where feasible;
- Transitioning natural gas usage to biofuels and low-carbon electricity;
- Transitioning hydrogen production from steam methane reformers to electrolysis (e.g., using electricity generated from wind, solar);
- Electrifying process heat where multiple electric technologies are commercial, given that the generation and use of process heat accounts for 55 percent of the energy spend,[307] with 60 percent of that heat being at or under 150^{o} C;[308]
- Utilizing low-carbon hydrogen for higher temperature process heat applications;
- Scaling up use of biomass and renewable natural gas (RNG) to use for process heat applications and other fuels and feedstocks uses;[309]
- Increasing energy and materials efficiency; and
- Utilizing carbon capture from major point (typically dilute) and relatively pure sources.



State	Total GHG Emissions	Facilities
TX	57,824,880	117
LA	41,280,991	81
IA	10,963,159	44
FL	9,974,360	13
CA	9,781,735	32
OK	8,349,657	9
IL	6,185,997	38
MS	4,540,634	10
TN	4,428,031	12
OH	4,413,403	30

Figure 12: Location and total reported emissions (metric tons CO_2e) of chemical manufacturing plants in the United States (left). Top 10 states by total GHG emissions from chemical facilities (right table). Size and darkness of bubbles scale with level of emissions. Source: U.S. EPA, FLIGHT.

As exemplified in ***Figure 12***,[310] the chemical industry is typically clustered for historical, feedstock and energy availability, market proximity, and transportation reasons.[n] This geographic concentration has implications for decarbonization pathways. For example, the concentration of chemical production in several areas may align well with proposed hydrogen or carbon dioxide pipelines, particularly where there is relatively high-purity carbon dioxide that can be captured (e.g., from the production of bioethanol in the upper Midwest). This is important when considering the decarbonization pathways in roadmaps that address general industry decarbonization routes[311, 312, 313] or are more specific to the chemical industry (many chemical industry roadmaps are largely from outside the United States).[314, 315, 316]

[n] Many chemical facilities are collocated with refineries, especially along the Gulf and Pacific Coasts, but this figure disaggregates chemical from refining facilities. See ***Section 3.2: Refining*** for more information on refineries.

Several chemical companies have established GHG reduction goals, with some (mostly smaller) setting science-based targets.[317] The goals range from ambitious to modest, with a few targeting carbon neutrality.[318] Companies are pursuing decarbonization pillars in near- and longer-term initiatives aligned with their goals. For example, BASF (the largest global chemical producer) is exploring industrial heat pumps (near-term) and electric cracker technology (longer-term).[319] In another example, Dow Chemical is pursuing a zero-emissions ethylene complex,[320] as well as partnering on an electric cracker.[321]

Transforming the chemical industry to achieve net-zero GHG emissions will be exceptionally challenging given the manufacturing complexity, high degree of capital investment, and long lifetime of equipment. Additional considerations for the chemicals industry include the $208 billion that has been invested across 351 projects in the last decade: due to the shale gas boom, chemical producers invested heavily in state-of-the-art ethylene crackers and downstream facilities, so this long-term investment into natural gas will be difficult to override.[322] Near-term options for these major point sources include fuel-switching to renewable natural gas, capture and reuse of hydrogen from the cracking process, and carbon dioxide capture. There are opportunities for states to lower the barriers and help companies accelerate the adoption of multiple decarbonization pillars, described in ***Table 8***.

Table 8: Decarbonization barriers and policy opportunities for the chemical industry.

Challenge / Barrier	State Opportunities	Policy Connections
Low price of fossil energy / feedstocks means substantial cost increase for low-carbon alternatives	• RD&D, energy and materials efficiency for emerging / transformative technologies can help • Early on, incentives, carbon pricing, or performance standards be needed to counteract cost disadvantage	• Support energy managers for small/medium manufacturers and encourage efficiency networks, waste reduction/reuse • Design incentives, provisions to defray cost increases for low-carbon technologies
High capital costs, large portion of new capital (shale gas)	• Start with low-capital replacement strategies (energy, material efficiency)	• Design incentives for low-carbon technologies so when capital replacement opportunities arise (e.g., boilers) the low-carbon choices are favored
Electrification has a low penetration rate that is increasing slowly	• Spark electric technology adoption in parallel with greening of the grid • Encourage direct use of low-carbon electricity at clusters to advance integrated solutions	• Incentivize electric technology adoption • Support infrastructure to bring low-carbon electricity to industry, integrate storage and control systems • Devise incentives to address electric / natural gas price disparity
Ability to quantify embodied carbon and follow in supply chains nascent	• Advance understanding of embodied carbon in materials for state sponsored projects	• Engage on initiatives to improve knowledge infrastructure, in parallel with efforts to increase market pull for low-carbon products

Challenge / Barrier	State Opportunities	Policy Connections
Capture of GHGs very expensive Few carbon dioxide reuse cases within facility fence lines Multitude of smaller sources	• Understand major carbon dioxide sources, encourage plans to address them • Pilot / demo capture and reuse at chemical facilities • Support mini-CCS capture pilots	• Support infrastructure and interconnections for mitigation • Stipulate a reduction plan for facilities in future air permits • Engage in pilots
Workforce largely untrained in decarbonization solutions	• Develop training • Support curricula development	• Initiate training programs, on-site internships, re-skilling, etc. for decarbonization in partnership with industry
Value return for material recycling highly uncertain	• Support programs that find additional value return options	• Mandate base levels for recycled content • Mandate only recyclable materials • Increase costs for disposal

Roadmaps for the Chemicals Industry

- France Chemical Industry Decarbonization Roadmap (2021) [English summary]
- Germany, Working towards a GHG Neutral Chemical Industry in Germany, VCI, (2019)
- Japan Decarbonization and Transition Finance Roadmap for the Chemicals Sector (2021)
- Netherlands, Chemistry for Climate: Roadmap for the Dutch Chemical Industry Towards 2050, VNCI, (2018)
- UK Roadmap for Chemicals (2015)
- UK Roadmap for Chemicals (Appendices) (2015)
- Planet Positive Chemicals: Pathways for the chemical industry to enable a sustainable global economy, SystemIQ (2022)

3.2 Refining

The petroleum refining sector in the United States produced over 18 million barrels of oil per day in 2021.[323] Refineries take raw materials, typically crude oils and semi-processed hydrocarbon mixtures, and refine them into various petroleum products including chemical feedstocks, transport fuels, industrial fuels, and others. These products are integrated into many large and diverse sectors of the economy, especially transportation and chemical manufacturing. The United States consumed over 20.5 million barrels per day of refined oil in 2019.[324] The transportation sector consumed approximately 70 percent, while manufacturing processes consumed an additional 24 percent as feedstock and fuels.[325] In 2019, the U.S. petroleum refining sector generated $551 billion in product[326] and employed over 69,000 workers.[327]

Given refined petroleum's key role across the U.S. economy, decarbonizing the refining sector is essential. However, it will also be difficult given that most refining processes in the United States are highly optimized and integrated by connected process flows. Integrated solutions that would reduce emissions are beyond the control of the refining sector alone. Petroleum refining is also very carbon intensive given its process unit complexity and heavy reliance on fossil fuel feedstocks and fuel carbon content (***Figure 13***).[328]

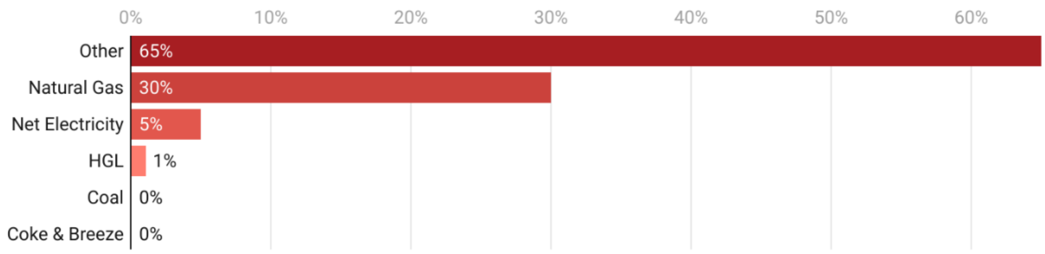


Figure 13: Refining sector fuel and non-fuel uses of energy in 2018 (as a percentage of total trillion Btu). Source: U.S. EIA, MECS 2018, Table 1.2.

The refining sector emits around 244 MMT CO_2e/year (including emissions from offsite generation), with process heating, combined heat and power (CHP), and boilers accounting for the most direct emissions (***Figure 14***).[329]

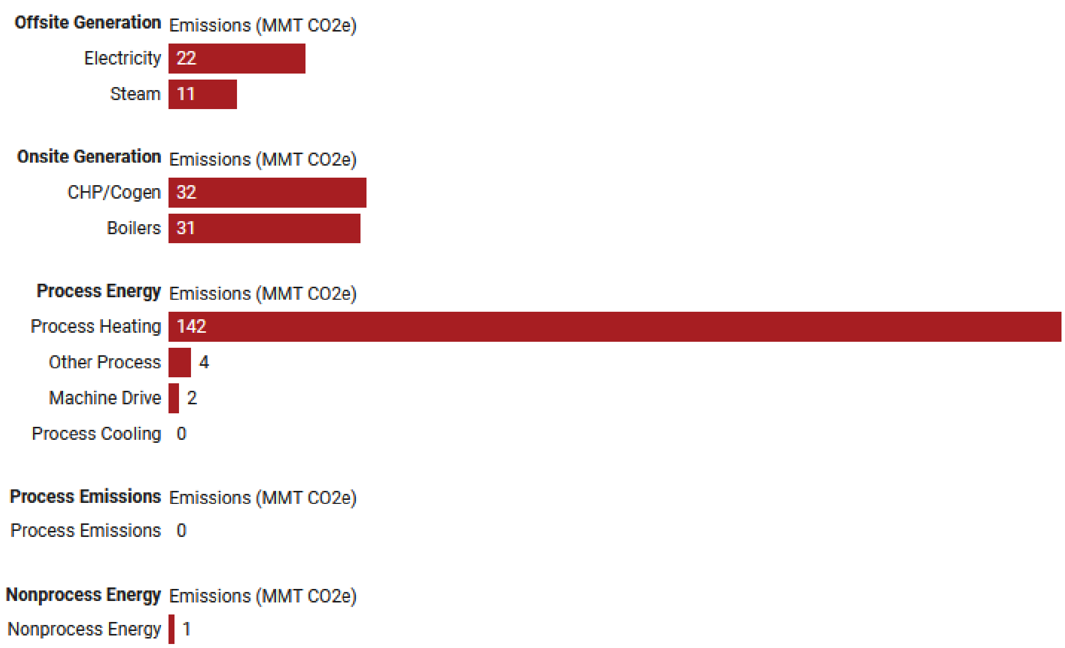
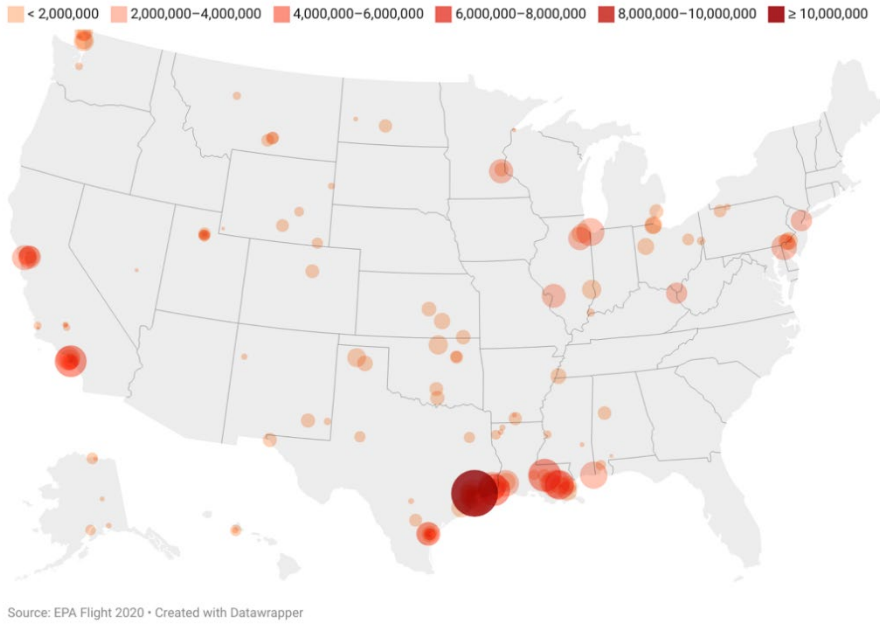


Figure 14: Refining sector sources of GHG emissions in 2018, by major end use. Source: U.S. DOE, Manufacturing Energy and Carbon Footprint: Petroleum Refining Sector.

Figure 15 depicts regional petroleum refining facilities' locations and GHG emissions, which concentrate mostly in coastal states near ports and industrial clusters.[330]



State	Total GHG Emissions	Facilities
TX	52,242,917	32
LA	26,654,659	18
CA	21,636,619	20
IL	8,459,555	4
WA	5,407,375	5
OK	4,323,052	6
OH	4,136,493	4
IN	3,907,928	2
MS	3,767,979	3
MN	3,478,918	2

Figure 15: Location and total reported emissions (metric tons CO_2e) of petroleum refining plants in the United States (left). Top 10 states by total GHG emissions from refining facilities (right table). Size and darkness of bubbles scale with level of emissions. Source: U.S. EPA, FLIGHT.

Options to reduce direct emissions at the refinery level include energy efficiency, material efficiency, alternative feedstocks (e.g., biomass), and carbon dioxide capture and reuse. For reuse, carbon dioxide can be combined with hydrogen to form synthesis gas, which can be used to make many chemicals.

Several corporate commitments have a reliance on offsets, so there is an opportunity to steer GHG reduction strategies to direct reductions of onsite emissions.

Large companies—including Motiva, Marathon, and ExxonMobil—have focused their corporate GHG reductions primarily on waste reduction, ISO 14001 and ISO 9001 certifications, logistics improvements, and emissions monitoring. Opportunities for further emissions reductions exist in efficiency improvements in both processes and onsite power and steam generation, reducing the carbon intensity of refiners' feedstocks and energy sources by introducing renewables and lower-carbon fossil fuel-based energy, and the capture of carbon dioxide emitted by refiners for storage or utilization. [331, 332]

Marathon Oil is one of the largest petroleum companies in the United States, with 16 refineries in 13 states and producing over three million barrels per day. Marathon has a goal of reducing GHG emissions intensity by a minimum of 50 percent by 2025 vs. a 2019 baseline. Currently, emissions intensity in Marathon Oil refining is approximately 20.4 metric tons of CO_2e/MBOE (million-barrel oil equivalent). The company plans to meet its targets through soil carbon sequestration and by purchasing of renewable energy credits to fully offset scope 2 emissions. However, it is important to note that these strategies include a mixture of onsite and offsite (e.g., offset) approaches, which do not all address direct emissions from the source. [333]

Valero Energy is another of the largest petroleum refining companies in the United States with 13 refineries in five states and over two million barrels refined per day. Valero plans to reduce and offset 100 percent of its global refining scope 1 and 2 GHG emissions by 2035. The company is approaching these targets through several strategies, including embracing low-carbon renewable fuels and increasing efficiency through energy and material management, which has recycling, risk assessment, and energy auditing components. [334] Reaching these goals will require both additional private action and supportive public policy.

Decarbonization of the refining sector will require enabling policies, programs, capital investments, and R&D to overcome barriers that include significant amounts of high-grade waste heat, capital constraints, the interconnectedness of refinery processes, and regulatory issues such as permitting. It will also require the proactive pursuit of low-carbon fuels and feedstocks routes that are available to industry today (e.g., biomass and RNG, see sections below) as well as actively engaging in the planning and development of longer-range solutions (e.g., hydrogen, CCUS). Refining emissions will also likely decrease as demand for its products decline. For example, the transportation sector is rapidly moving towards low-carbon alternatives (e.g., electric and hydrogen light-, medium-, and heavy-duty vehicles, sustainable aviation fuels). However, there will still be near-term need to decarbonize the refining sector given that this transition will likely last several decades and there will still be some demand for petroleum feedstocks and fuels consumed by other manufacturing processes. Additional policies will complement the modest progress made by private companies in their primarily offsite commitments to emissions mitigation. The barriers and policy connections are summarized in ***Table 9***.

Table 9: Decarbonization barriers and policy opportunities for the refining sector.

Challenge / Barrier	State Opportunities	Policy Connections
Supportive R&D needs to increase penetration of innovative decarbonization technology options	• Low-carbon electrolysis of hydrogen, low-carbon feedstocks, increased use of biomass for fuel, biogenic feedstocks, and CCUS are key routes to reduce emissions	• State funds leveraged with federal funds in R&D can help bridge the gap between innovative options and commercial viability
Emerging efficiency improving technologies need to be implemented	• New heat exchangers and motors, electrified boilers, and technical reconfiguration of refineries' processing can save energy and emissions now • Energy management systems and strategic planning to reduce emissions can enable more efficiency measures	• Incentives and rebates for replacing old technology with new controls, process optimizing technology • Mandates for energy management, statewide energy management programs, energy audits, can enable more industrial efficiency
Refining produces significant amounts of waste heat	• Enhanced recovery of low-grade heat for reuse and interunit heat integration; large refineries typically have enhanced capability to capture useful waste heat	• Incentives for industrial clusters and other shared industrial infrastructure can aid waste heat reuse

Roadmaps for Refining Industry

- Japan Decarbonization Roadmap and Transition Finance for Oil and Gas Refining (2022)
- UK Roadmap for Refining Sector (2015)
- UK Roadmap for Refining Sector (Appendices) (2015)
- WRI: Technological Pathways for Decarbonizing Petroleum Refining (2021)

3.3 Iron & Steel

Crude steel is commonly manufactured in two ways: via a blast oxygen furnace (BOF) or the use of an electric arc furnace (EAF). Both processes involve reducing iron ore into iron and converting iron into steel in a furnace. They differ, however, in that the BOF pathway uses coal, blast furnaces, and pig iron, while the EAF pathway uses syngas, shaft furnaces, direct reduced iron (DRI), and recycled iron scrap. The EAF process is less carbon intensive than the BOF process. Most iron and steel sector decarbonization efforts are centered around policies that support:

- The transition of BOFs to EAFs (dependent on the availability of high-quality scrap and low-carbon electricity to be an effective GHG reducing measure) in producing crude steel

- The use of more DRI, especially coupled with the production of low-carbon, electrolytic hydrogen to convert iron ore and scrap going into EAFs [335]

The U.S. steel industry produced an estimated 87 million tons of crude steel in 2021. [336] Thirty-three percent was produced by steelmaking facilities using BOF at eleven steel mills owned by three companies. The remaining 67 percent was produced by EAF at 101 mills owned by 50 companies. The United States also imported 25 million tons of steel. In 2018, steel plants employed approximately 81,000 people, while iron and steel foundries employed another 64,000. [337] Construction accounts for the most steel consumption in the United States, followed by transportation, machinery and equipment, appliances and energy, and other applications. Indiana accounted for the highest percentages of total crude steel production with 27 percent, followed by Ohio, Pennsylvania, Illinois, Texas, and Michigan. [338]

Iron and steel manufacturing is both energy and carbon intensive. The use of coal as a primary feedstock leads to high carbon dioxide emissions–approximately five percent of total industrial GHG emissions. The need for decarbonization is exacerbated by the fact that global demand for steel is projected to increase by approximately 30 percent by 2070. [339] Natural gas, coal, and coke and breeze products comprise the majority of the sector’s fuel and non-fuel use of energy ***(Figure 16***). [340]

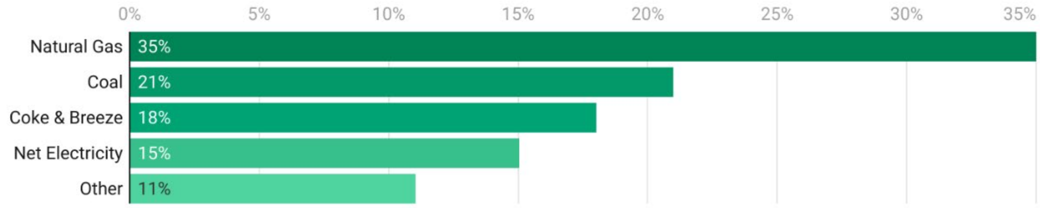


Figure 16: Iron and steel sector fuel and non-fuel uses of energy in 2018 (as a percentage of total trillion Btu). Source: U.S. EIA, MECS 2018, Table 1.2.

The iron and steel sector emits around 100 MMT CO_2e/year (including emissions from offsite generation), with process emissions and process heating accounting for the most direct emissions (***Figure 17***).[341]

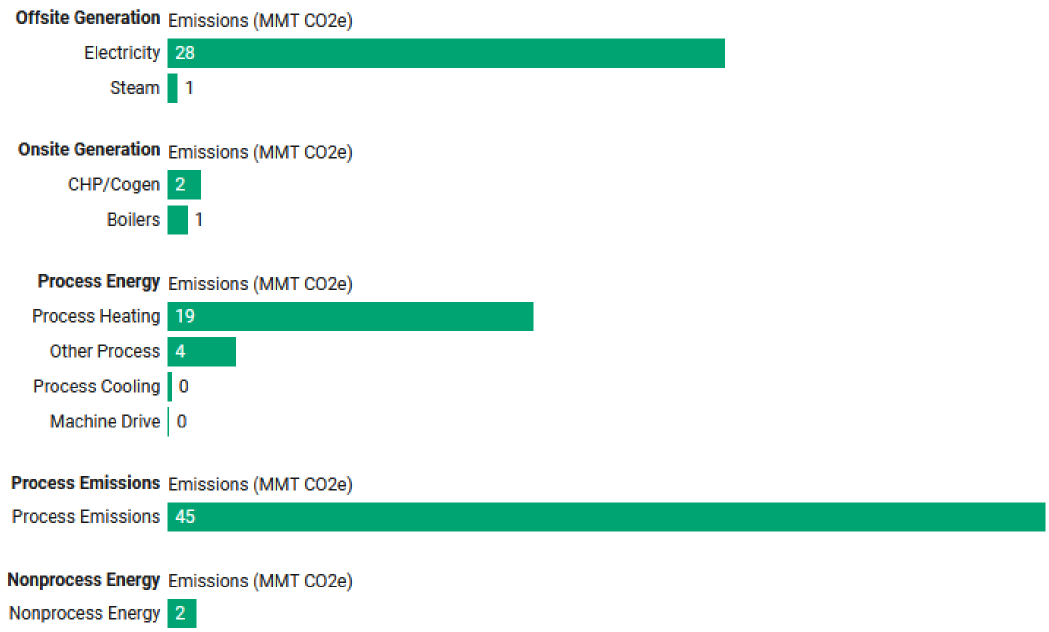
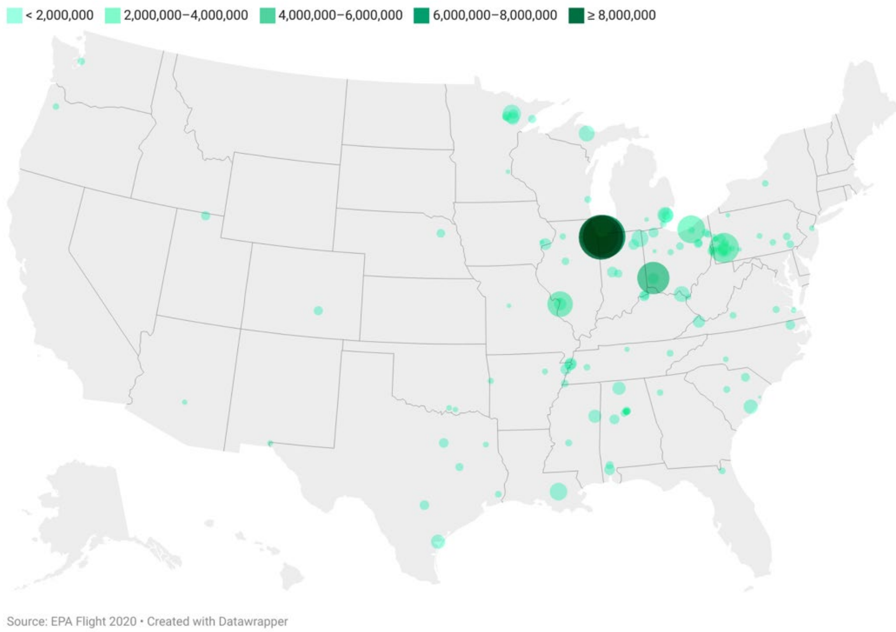


Figure 17: Iron and steel sector sources of GHG emissions in 2018, by major end use. Source: U.S. DOE, Manufacturing Energy and Carbon Footprint: Iron and Steel Sector.

Iron and steel plants are located largely in Ohio, Illinois, Pennsylvania, and Michigan, consistent with the states responsible for the most emissions from iron and steel manufacturing (***Figure 18***).[342]



State	Total GHG Emissions	Facilities
IN	26,757,113	11
OH	9,532,641	15
PA	5,660,326	20
IL	3,473,264	9
MI	2,714,139	8
MN	2,467,679	8
AL	1,918,839	9
TX	1,523,394	7
AR	1,312,598	5
LA	1,068,285	2

Figure 18: Location and total reported emissions (metric tons CO_2e) of iron and steel manufacturing plants in the United States (left). Top 10 states by total GHG emissions from iron and steel facilities (right table). Size and darkness of bubbles scale with level of emissions. Source: U.S. EPA, FLIGHT.

Several large iron and steel manufacturers have established sustainability targets or made significant efforts in improving energy efficiency aimed towards reducing emissions in their manufacturing processes. ArcelorMittal, one of the largest steel manufacturers in the world, has a target of 25 percent global carbon emissions reduction by 2030.[343] U.S. Steel, the eighth-largest steel producer in the world, has a roadmap to help achieve net-zero GHG emissions by 2050.[344]

Steel companies plan to pursue these targets by taking actions like:

- Transitioning from coal to natural gas in the blast furnace
- Process optimization and clean energy procurement
- Energy transformation fostered by green and blue hydrogen, CCUS, and electrification
- Increased use of scrap
- Sourcing lower-carbon electricity
- Offsetting residual emissions not addressed by other strategies

Decarbonization of iron and steel manufacturing will require policies and programs at the state and federal level, and alignment between such policies. The summary in ***Table 10*** highlights the connections between challenges and state policy opportunities.

Table 10: Decarbonization barriers and policy opportunities for the iron and steel industry.

Challenge / Barrier	State Opportunities	Policy Connections
Lack of new energy efficiency options in highly integrated iron and steel manufacturing makes high-temperature processes difficult to decarbonize	• Information and systems efficiency approaches may yield additional gains • States can support the proliferation and use of these approaches / technologies	• Support studies on applications of process control, machine learning, and automation • Incentivize the further development and application of these technologies • Incentivize the uptake and integration of such technologies
Lack of resource management, waste heat management means untapped savings potential	• Strategic energy management (SEM) can help save energy, emissions • Significant opportunity for waste heat recovery	• Statewide support for SEM managers and programs can yield substantial energy and GHG reductions, in particular for small- and medium-sized companies • Increased support for energy audits and capital to pursue projects is needed
R&D is needed to improve the economics and integration aspects of multiple low-carbon technology options	• Electrification of reheating furnaces, CCUS in post combustion, electrolysis of iron ore, hydrogen in smelting to improve viability at scale	• State funds coupled with federal funds in R&D can help bridge the gap between innovative options and commercial viability in industrial facilities
Circularity and recyclability of steel scrap needs continual improvement	• Using steel scrap in the steel production process reduces carbon dioxide emissions by 58 percent and air pollution by 86 percent[345]	• Procurement of recycled steel for state infrastructure projects • Incentives for steel mills that do onsite recycling or use recycled steel pellets

Roadmaps for the Iron and Steel Industry

- European Steel Industry Decarbonization Roadmap (2019)
- International Energy Agency, Iron and Steel Decarbonization Roadmap (2020)
- Japan Roadmap for Iron and Steel (2021)
- UK Roadmap for Iron and Steel (2015)
- UK Roadmap for Iron and Steel (Appendices) (2015)

3.4 Cement

In 2020, the United States produced about 89 million metric tons of cement at 96 plants in 34 states and two plants in Puerto Rico. Texas, Missouri, California, and Florida (in descending order) account for nearly 45 percent of all U.S. cement production. The total value of cement produced in the United States is $12.7 billion and the industry employs 12,500 workers across 34 cement producing states. The majority (70–75 percent) of cement that is produced is used by ready-mix concrete producers, 10 percent by concrete product manufacturers, and the remainder is used by contractors and other customers. The United States is the fourth-largest producer of cement worldwide after China, India, and Vietnam.[346, 347]

Cement manufacturing is energy intensive and a major source of GHG emissions. In 2018, cement manufacturing comprised roughly 8 percent of the manufacturing sector's direct (onsite) emissions.[348] The cement sector emits around 66 MMT CO_2e/year (including emissions from offsite generation), with process emissions and process heating accounting for the most direct emissions (***Figure 19***).[349] Lifecycle assessment of the cement manufacturing process indicates that GHG emissions impacts are primarily driven by energy use (electricity and thermal fuels) during the pyro-processing of limestone to produce clinker (40 percent) and the calcination process itself which releases carbon dioxide (60 percent). The amount of clinker present in cement therefore defines the emissions profile of the final cement product. The greater the clinker content, the higher the emissions. After clinker, the second largest contributor to emissions is raw material extraction followed by raw material transportation.[350]

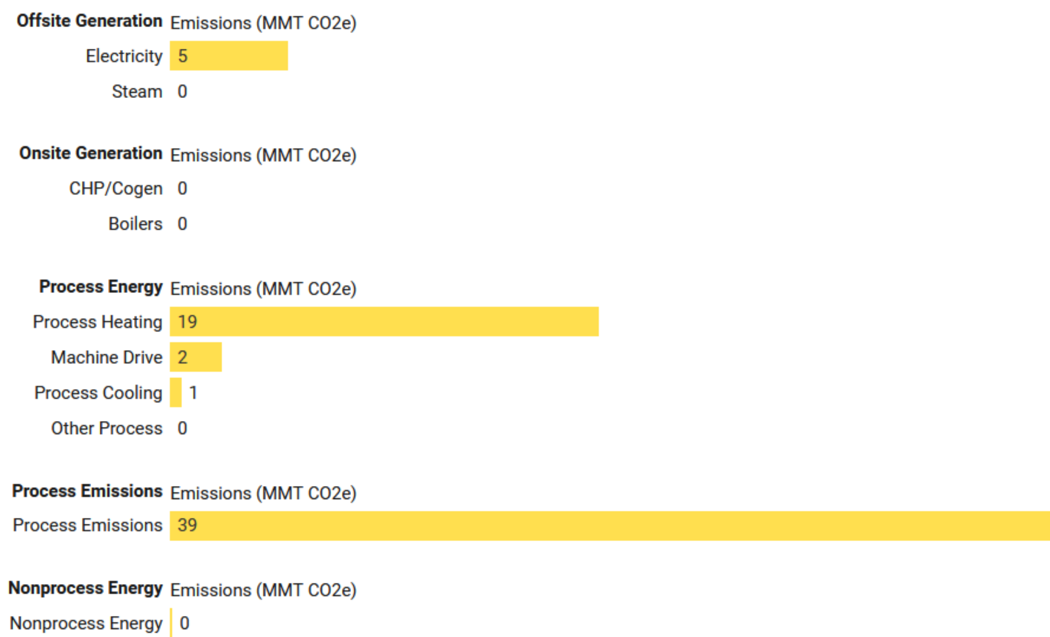
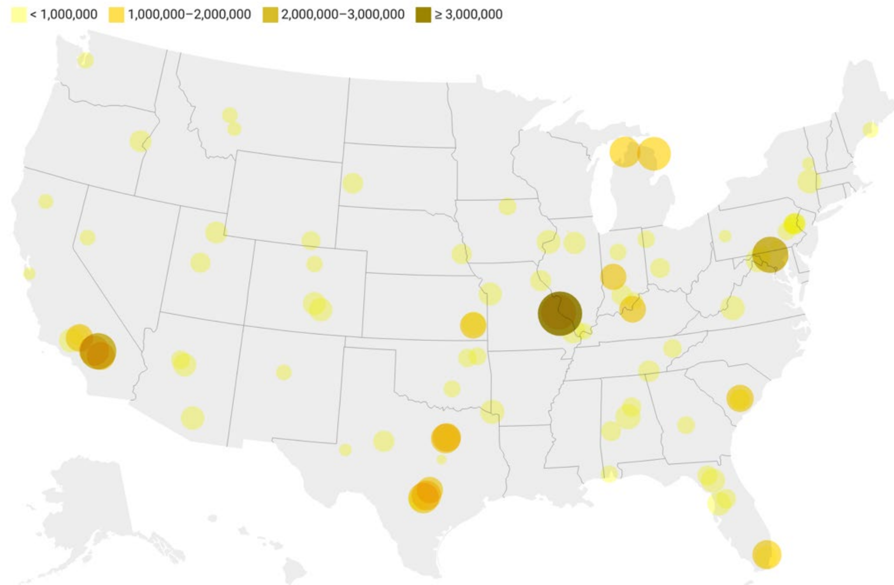


Figure 19: Cement sector sources of GHG emissions in 2018, by major end use. Source: U.S. DOE, Manufacturing Energy and Carbon Footprint: Cement Sector.

Figure 20 shows the distribution of cement facilities across the United States.[351]



State	Total GHG Emissions	Facilities
TX	9,198,706	11
CA	7,542,301	9
MO	7,247,143	5
FL	4,684,844	7
MI	3,185,504	2
PA	2,898,599	8
MD	2,506,244	2
AL	2,397,871	4
IN	2,388,556	4
SC	2,200,545	3

Source: EPA Flight 2020 • Created with Datawrapper

Figure 20: Location and total reported emissions (metric tons CO_2e) of cement manufacturing plants in the United States (left). Top 10 states by total GHG emissions from cement facilities (right table). Size and darkness of bubbles scale with level of emissions. Source: U.S. EPA, FLIGHT.

The majority (about 90 percent) of cement produced in the United States is Portland cement, with the remaining 10 percent distributed between masonry cement, blended-hydraulic cement, and Portland-limestone cement in decreasing order of quantities. As of 2019, most clinker (80–90 percent) in the United States is produced using a dry process with preheater and precalciner technology, which represents the most efficient technology currently available and in use. Because Portland cement represents the bulk of cement production in the United States, the remainder of this section provides energy and emissions data for this type only.

Maintaining the high combustion temperature in a cement kiln (1,100–1,500°C) to form clinker requires a primary fuel source with a high-energy output, like coal or petroleum coke coal (9,000–12,000 Btu/lb). This comes at a cost. A large volume of coal is required to maintain the high temperatures in the kiln, which comes with high transportation costs (typically train, truck, or barge, all of which rely on diesel and release their own carbon emissions). As a result, the industry has been supplementing coal with waste heat and burning of hazardous waste (e.g., waste oils, spent organic solvents, sludges from the paint and coatings industry, waste paints and coatings from auto and truck assembly plants, and sludges from the petroleum refining industry) with a similar energy output profile to offset the amount of coal/coke burned in the kiln.[352, 353] The cement manufacturing process also uses electricity to run crushing and grinding operations. ***Figure 21*** shows a breakdown of the cement sector's uses of energy sources.[354]

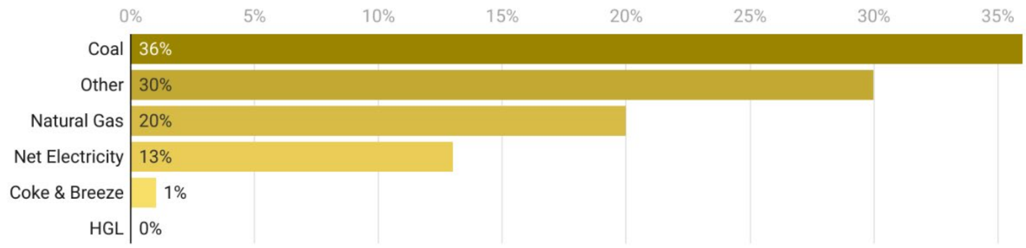


Figure 21: Cement sector fuel and non-fuel uses of energy in 2018 (as a percentage of total trillion Btu). Source: U.S. EIA, MECS 2018, Table 1.2.

In 2019, the U.S. EPA estimated the carbon intensity of U.S. cement plants ranged from 0.787 to 0.934 metric ton of carbon dioxide per metric ton of clinker produced, with 25 percent of plants at the high end of the range and 25 percent of the plants at the low end of the range. The median carbon intensity was 0.838 metric tons of carbon dioxide per ton of clinker produced. When considering the carbon intensity per metric ton of cement produced from clinker, the range was 0.886 to 0.722 metric ton of carbon dioxide.[355] The slight reduction in carbon intensity factor may be attributed to energy and material efficiency strategies applied in the production of cement from clinker.[356] However, according to the International Energy Agency (IEA), the direct carbon dioxide intensity of cement production increased 1.8 percent each year during the period 2015–2020 globally. The IEA recommends that to meet net-zero emissions goals by 2050, a 3 percent annual decline in carbon intensity is necessary, which may be achieved through a particular focus on reducing the clinker-to-cement ratio (by promoting greater uptake of blended cements) and deploying carbon capture technologies (CCUS). Thus, funding research, development, and demonstration efforts and adopting carbon dioxide emissions reduction policies offer two key policy approaches to achieve these goals.[357]

Several large cement companies have established sustainability targets or made significant efforts in improving their operations. Cement companies have announced new product lines, renewable energy use plans, decarbonization research initiatives, and other innovations aligned with the industry's overall commitment to sustainability. Many cement plants have also installed emissions reduction equipment to comply with the 2010 *National Emissions Standards for Hazardous Air Pollutants* (NESHAP). This has led to the shutting down, idling, or reducing use of some cement kilns (for compliance reasons) and associated reductions in cement production.[358]

Lafarge Holcim, the largest cement manufacturer in both the United States and the world, has established net-zero goals validated by the Science-Based Targets initiative (SBTi), such as:

- Until 2030, accelerating carbon dioxide intensity reductions to exceed 20 percent (compared to 2018 baseline)
- After 2030 establishing the first climate targets with SBTi for a 1.5°C future in the cement sector
- By 2050, committed to long-term targets for full scope of emissions
- Reduce scope 3 emissions by 90 percent compared to 2020 or 90 percent of total absolute emissions (as per SBTi net-zero requirements).[359]

Other large producers such as CEMEX[360] and Heidelberg Cement[361] have also issued sustainability targets.

Table 11: Decarbonization barriers and policy opportunities in the cement industry.

Challenge / Barrier	State Opportunities	Policy Connections
Energy efficiency	• Establish efficiency goals to decrease energy use while improving flexibility and resilience	• Support fuel efficiency standards • Support energy managers at small/medium cement/concrete plants • Encourage efficiency networks to leverage common efforts within/across industries (e.g., waste reduction/reuse) • Recognition/credit for industry reduction
Transition to low-carbon feedstocks and energy sources	• Promote coal and coke switch with other high-energy, lower-carbon sources like biomass and waste-derived fuels • Promote circular economy with other industries that can provide low-carbon fuel feedstock • Promote alternative fuels and other technologies	• Support air regulations to allow transition from heavy hydrocarbons to biomass and waste-derived fuels • Promote infrastructure and regulation to divert non-recyclable, solid, and hazardous waste streams from landfills to kilns for incineration where they reduce net energy and GHGs • Promote funding/investing in industrial hub zones and clusters to spur low-carbon technology adoption
Electrification: near-, mid-, longer-term time horizons	• Promote adoption of electric technologies in conjunction with greening of the grid.	• Support infrastructure to bring low-carbon electricity to industry • Incentivize renewables (i.e., solar, wind) in onsite generation, microgrid development, and main grid generation/storage • Promote reduction/elimination of grid interconnection fees for low-carbon energy and expand net energy metering rules • Use Tax exemptions for electricity use in industrial processes to spur adoption
Material efficiency	• Develop and expand markets and infrastructure for end-of-life reuse and recycling of concrete construction and demolition debris	• Support use of blended cements and cement mixes with alternative materials/additives/supplementary cementitious materials (SCM) • Reduce or eliminate minimum-clinker requirements in government procurement requests • Promote circular economy policies
Define current level of embodied carbon and developing new processes for products	• Promote low-embodied-carbon cement materials for state sponsored projects • Promote low-carbon alternative cements and concrete • When new or major plant upgrades proposed, tie incentives	• Engage on initiatives to preferentially purchase low-embodied-carbon products • Promote and adopt local green building codes and performance-based standards for building materials • Incentives for deployment of low-carbon process technologies

Challenge / Barrier	State Opportunities	Policy Connections
	to lower-embodied-carbon cement production	• Streamline regulation, siting, and permitting to modernize facilities • Support leakage protections for domestic manufacturers against less-regulated imports (border states)
Capture major direct emissions from plants and reduction in carbon dioxide	• Coordinate/integrate CCUS deployment with cement industry plants (co-location, industrial hubs) • Facilitate carbon sinks in public infrastructure	• Fund/invest in CCUS infrastructure and interconnections between industries for mitigation, transport, storage (including multi-state/regional initiatives) • Stipulate a reduction plan for facilities in future air permits • Consider market-based carbon price (e.g., cap-and-trade mechanisms) • Promote use of concrete in infrastructure (e.g., roadways) to enlarge carbon sink capacity • Support/incentivize development of cost-competitive, commercial-scale solutions to trap carbon
Workforce development	• Develop / expand capabilities of a diverse future workforce	• Initiate training programs, onsite internships, re-skilling (e.g., energy managers) for decarbonization in partnership with industry

Roadmaps for the Cement and Concrete Industry

- Portland Cement Association: Roadmap to Carbon Neutrality by 2050 (2021)
- CEMBREAU Cement Roadmap to 2050 (Webpage, Full Report)
- International Energy Agency (IEA) Cement Roadmap (2009 Report, 2021 Report)
- Japan Technology Decarbonization Roadmap and Transition Finance for Cement Industry (2022)
- Global Cement and Concrete Association 2050 Roadmap for Net Zero Concrete (2021 Report, Webpage)
- World Business Council for Sustainable Development - Cement Roadmap (2018)

3.5 Glass

Glass manufacturing is a $27.6 billion sector of the U.S. economy, employing more than 93,000 workers. U.S. glass manufacturing creates over 16.5 million tons per year of glass products.[362] The majority of glass produced is container glass, followed by flat glass and glass wool.

Glass manufacturing emits around 15 MMT CO_2e/year (including emissions from offsite generation), with process heating accounting for the most direct emissions (***Figure 22***).[363] Like cement, glass production requires high temperature heat, primarily for the initial batch processing stage in large furnaces. These furnaces are mostly fueled by natural gas (***Figure 23***).[364]

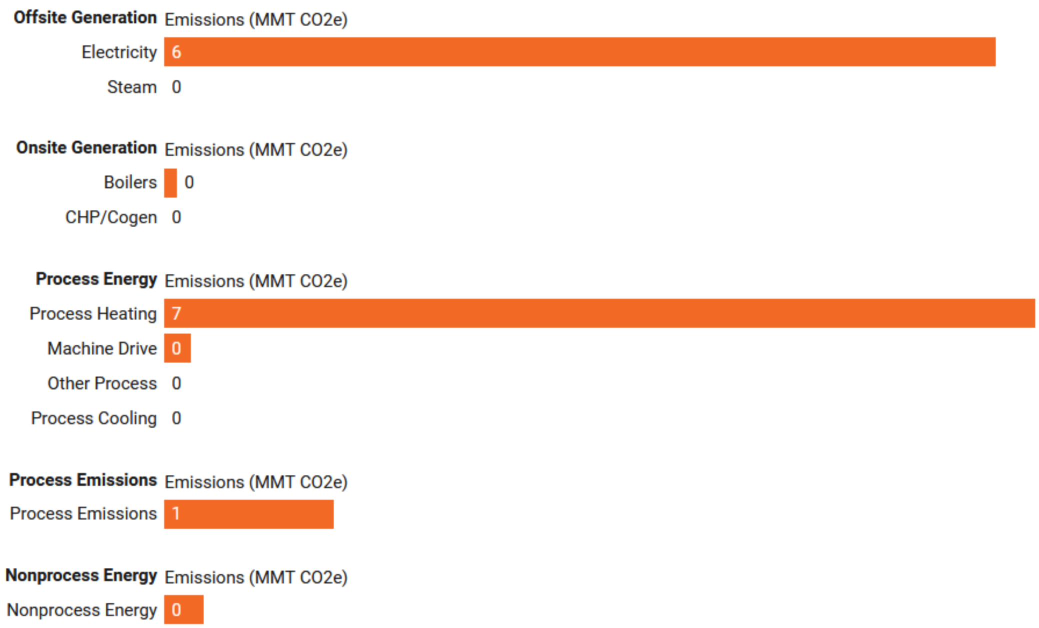


Figure 22: Glass sector sources of GHG emissions in 2018, by major end use. Source: U.S. DOE, Manufacturing Energy and Carbon Footprint: Glass Sector.

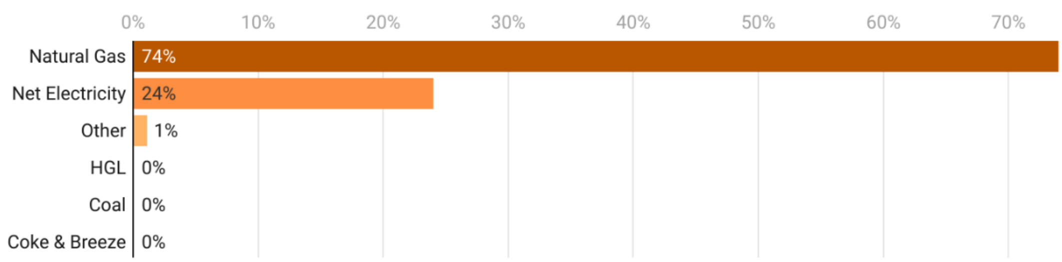
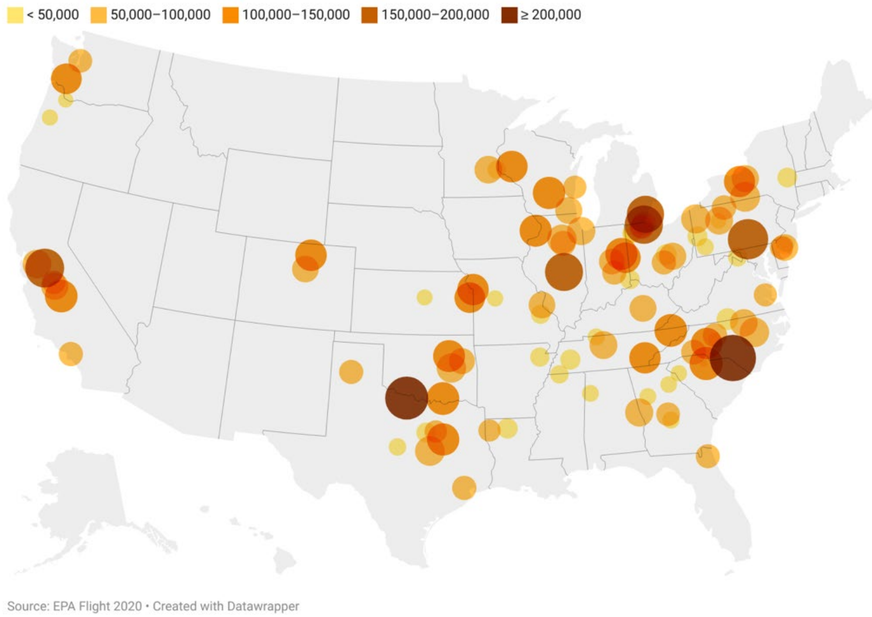


Figure 23: Glass manufacturing sector fuel and non-fuel uses of energy in 2018 (as a percentage of total trillion Btu). Source: U.S. EIA, MECS 2018, Table 1.2.

Like cement, glass manufacturing is highly dispersed (***Figure 24***).[365]



State	Total GHG Emissions	Facilities
NC	671,255	7
TX	663,636	8
OH	593,069	10
CA	574,788	9
PA	512,974	10
IL	409,927	5
OK	395,346	5
IN	383,488	5
TN	377,870	6
WI	358,728	4

Figure 24: Location and total reported emissions (metric tons CO_2e) of glass manufacturing plants in the United States (left). Top 10 states by total GHG emissions from glass facilities (right table). Size and darkness of bubbles scale with level of emissions. Source: U.S. EPA, FLIGHT.

Several large glass producers have established sustainability targets or made significant efforts in improving energy efficiency aimed towards reducing emissions in their manufacturing processes. Gentex Corp, which employs about 5,000 people in Michigan, has established goals to reduce its GHG emissions 15 percent below 2020 levels by 2026, 40 percent by 2031, 70 percent by 2041, and achieve carbon neutrality by 2049. Some of the strategies being employed by Gentex include environmental management systems based on ISO 14001 standards, waste reduction policies, and multiple process-based energy efficiency improvements in manufacturing.[366] Pella Corp, which employs over 2,200 people in Iowa, is a volunteer partner in the ENERGY STAR program and is a member of the U.S. Green Building Council.[367]

State procurement policies can incentivize the decarbonization of glass manufacturing by creating a market for glass with less embodied emissions. For example, **California's** Buy Clean policy has established a maximum acceptable carbon intensity of 1.43 metric tons of CO_2e per metric ton for flat glass used in public works projects.[368] Policies that encourage the electrification of furnaces, general energy efficiency, and that establish emissions targets for industrial sectors as a whole also have the potential to help reduce emissions from glass. Examples include **Colorado's** target for the industrial sector to reduce emissions by 20 percent by 2030 from a 2015 baseline, **Delaware's** Energy Efficiency Industrial (E2I) program, and energy management programs in **Oregon**, **New York, Louisiana,** and elsewhere.[369, 370]

Table 12 describes additional state actions that can help overcome persistent barriers and challenges in the glass industry.

Table 12: Decarbonization barriers and policy opportunities in the glass industry.

Challenge / Barrier	State Opportunities	Policy Connections
Long equipment lifetimes / few opportunities to change capital	• Infrastructure investments, incentives will be needed to replace incumbent technology	• Mandates, incentives, rebates, efficiency standards, energy managers, and energy audits all can reduce the capital barriers associated with long technology lifetimes
R&D is needed to spur innovation and adoption of decarbonization technology options	• Electrification of large, high-temperature furnaces, CCUS, and carbon-neutral feedstocks will be essential to decarbonizing glass	• State funds leveraged with federal funds in R&D can help bridge the gap between innovative options and commercial viability in industrial facilities
Emerging efficiency improving technologies need to be implemented	• Variable speed drive motors, new grinding technologies, process and compressor controls	• Incentives and rebates for replacing old technology with new controls, process optimizing technology
Circularity and recyclability of glass is an untapped decarbonization pathway	• Some 75 percent of container glass has potential to be recycled	• Procurement of recycled glass for state infrastructure projects • Incentives for glass manufacturers that do onsite recycling or private companies that buy recycled glass

Roadmaps for the Glass Industry

- UK Roadmap for Glass (2015)
- UK Roadmap for Glass (Appendices) (2015)

3.6 Forest Products

The U.S. DOE includes the lumber sector (NAICS 321) and the pulp and paper sector (NAICS 322) in its energy and carbon footprint analysis for the forest products industry.[371] The pulp and paper sector warrants specific attention because:

- the pulp and paper sector generates most of the total value of shipments from the forest products industry, estimated to be around 50 percent in 2013;[372] and

- of the lumber and pulp and paper sectors, pulp and paper facilities account for over 97 percent of their combined direct reported emissions. On average, a large pulp and paper facility emits 175,0000 metric tons CO_2e per year while a large lumber facility (e.g., sawmill) emits 40,000 tons CO_2e per year.[373]

However, DOE has not developed a *Manufacturing Energy and Carbon Footprint* for the pulp and paper sector alone. Therefore, this section will begin by describing the forest products industry as a whole before narrowing its focus on the pulp and paper sector.

Forest Products Industry

The forest products industry accounts for approximately four percent of U.S. manufacturing GDP (on par with the plastics and automotive industries). It produces nearly $300 billion in products per year that are essential to construction, housing, communications, hygiene and sanitation, packaging, biofuels, and biochemical feedstocks and pays approximately $4.4 billion a year in state and local taxes. This sector is among the top 10 manufacturing sector employers in the majority of states (45), employing approximately 950,000 workers, corresponding to a payroll of approximately $60 billion.[374] In 2016, there were over 22,000 U.S. manufacturing facilities, including around 17,000 for wood products (including lumber and furniture) and 5,000 for pulp and paper.[375]

The forest products industry is the third-largest industrial consumer of energy[376] and emits around 80 MMT CO2e/year (including emissions from offsite generation), with CHP/cogeneration and process heating accounting for the most direct emissions. Nearly half (45 percent) of its emissions come from offsite electricity and steam generation (***Figure 25***).[377]

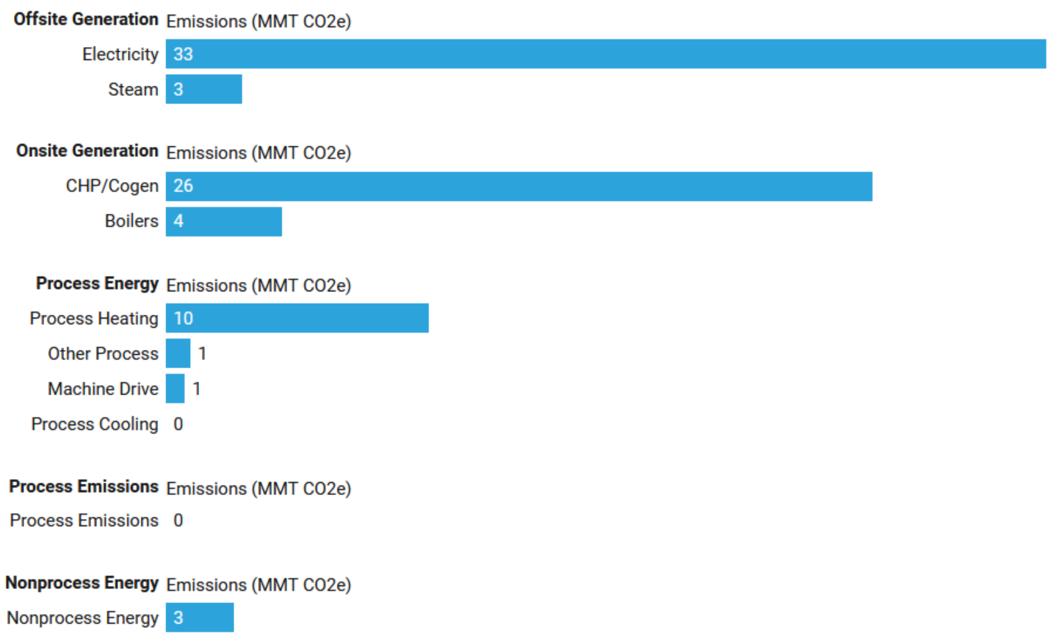


Figure 25: Forest products sector sources of GHG emissions in 2018, by major end use. Source: U.S. DOE, Manufacturing Energy and Carbon Footprint: Forest Products Sector.

Since 2005, the forest products industry has reduced its GHG emissions by 24 percent by improving energy efficiency, fuel switching to low-carbon sources, and increased use of renewable bioenergy.[378] The industry has used energy efficiency, technology upgrades at mills, and switching to lower-carbon-intensive fuels to achieve a 48 percent reduction in nitrogen oxide and 82 percent reduction in sulfur dioxide emissions between 2000 and 2018.[379]

Pulp & Paper Sector

As described above, the pulp and paper sector is quite energy intensive. For example, producing one metric ton of paper requires about 24.5 million BTUs.[380] However, the pulp and paper industry produces more bioenergy than any other industrial sector to power mills through the efficient use of leftover materials. For example, almost 60 percent of its own energy comes from woody waste products and other renewable fuel sources such as bark, wood, and pulping liquor.[381] At the same time, natural gas still plays a prominent role in the sector's fuel needs (***Figure 26***).[382]

99 percent of the electricity produced by the paper and wood products industry is generated by CHP technologies, which in turn supplies CHP-generated power to local utilities at avoided cost. Furthermore, over two-thirds of paper consumed in the United States in 2021 was recovered through recycling.[383]

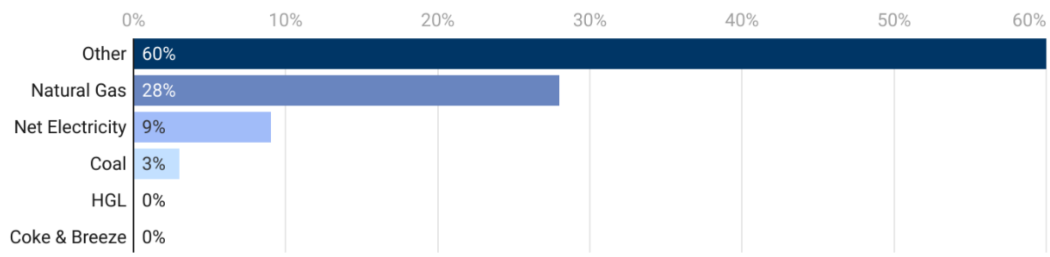
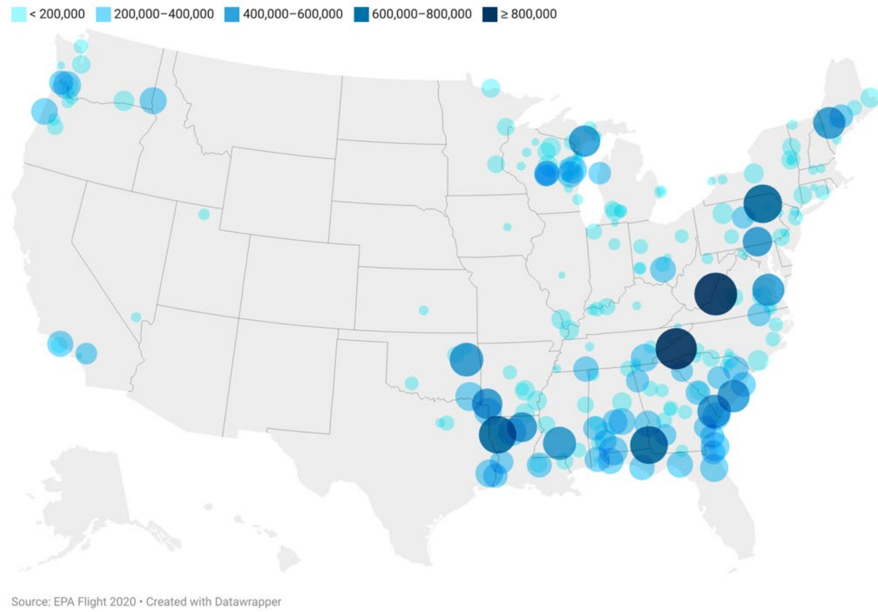


Figure 26: Pulp and paper sector fuel and non-fuel uses of energy in 2018 (as a percentage of total trillion Btu). Source: U.S. EIA, MECS 2018, Table 1.2.

Energy bandwidth studies of U.S. manufacturing sectors can serve as foundational references in framing the range of potential energy savings opportunities. For the pulp and paper industry, a 2015 bandwidth study relies on multiple sources to estimate the energy used in six individual process areas, representing 52 percent of sector-wide energy consumption. Energy savings opportunities for individual processes are based on technologies currently in use or under development; the potential savings are then extrapolated to estimate sector-wide energy savings opportunity.[384]

Figure 27 shows the distribution of pulp and paper plants across U.S. states, with most facilities concentrated in the eastern, southern, and northwestern United States.[385]



State	Total GHG Emissions	Facilities
GA	3,493,114	17
WI	2,840,332	29
AL	2,822,444	14
LA	2,502,209	9
VA	2,034,057	10
SC	2,015,126	10
FL	2,003,985	7
PA	1,878,778	12
NC	1,535,815	7
MI	1,431,788	14

Figure 27: Location and total reported emissions (metric tons CO_2e) of pulp and paper manufacturing plants in the United States (left). Top 10 states by total GHG emissions from pulp and paper facilities (right table). Size and darkness of bubbles scale with level of emissions. Source: U.S. EPA, FLIGHT.

The largest pulp and paper manufacturers in the United States include companies like International Paper, which is aligned with the UN Sustainable Development Goals, has set Vision 2030 goals, and offers a tracker to monitor how it met its 2020 goals.[386] Another leading manufacturer is Kimberly Clark, which aims to halve its carbon footprint by 2030, among other goals.[387] Weyerhaeuser has released its '3 by 30' goals to be achieved by 2030.[388] In addition, the American Forest & Paper Association has established five quantifiable sustainability goals that the industry aims to meet by 2030.[389] These include:

- Reducing total scope 1 and 2 GHG emissions intensity 50 percent by 2030 from a 2005 baseline and establishing a goal for relevant scope 3 emissions by 2025;
- Advancing a circular value chain, including by increasing the utilization of recycled fiber and wood residuals in manufacturing across the industry to 50 percent and increasing the percentage of products that are recyclable or compostable; and
- Driving water stewardship while advancing more resilient forest.

On the way to meeting these sustainability goals, some common barriers pulp and paper industry plants face are described in ***Table 13*** along with their policy connections. Several studies and reports elaborate further on these barriers.[390, 391]

Table 13: Decarbonization barriers in the pulp and paper industry.

Challenge / Barrier	State Opportunities	Policy Connections
Feedstock availability (biomass)	• Forest stewardship	• Promote low-carbon paper and related technologies
Pulp and paper waste generation	• Establish clusters/circular economy hubs	• Promote infrastructure development
Energy efficiency	• Establish efficiency goals to decrease energy use while improving flexibility and resilience	• Support fuel efficiency standards • Support CHP and waste heat transfer • Recognition/credit for industry reduction
Electrification: near-, mid-, longer-term	• Promote adoption of electric technologies in conjunction with greening of the grid	• Support infrastructure to bring low-carbon electricity to industry • Incentivize renewables (e.g., solar, wind) in onsite generation, microgrid development, and main grid generation/storage • Promote reduction/elimination of grid interconnection fees for low-carbon energy and expand net energy metering rules • Use Tax exemptions for electricity use in industrial processes to spur adoption
Capture major direct emissions from plants and reduction in carbon dioxide emissions	• Coordinate/Integrate CCUS deployment with cement industry plants (e.g., co-location, industrial hubs) • Facilitate carbon sinks in public infrastructure	• Fund/invest in CCUS infrastructure and interconnections between industries for mitigation, transport, storage (including multi-state/regional initiatives) • Stipulate a reduction plan for facilities in future air permits • Consider market-based carbon price (e.g., cap-and-trade mechanisms)
Workforce development / lack of skilled labor	• Develop / expand capabilities of a diverse future workforce	• Initiate training programs, onsite internships, re-skilling (e.g., energy managers) for decarbonization in partnership with industry

Roadmaps for the Pulp and Paper Industry

- Japan Technology Decarbonization Roadmap and Transition Finance for Pulp and Paper Industry (2022)
- UK Roadmap for Pulp and Paper (2015)
- UK Roadmap for Pulp and Paper (Appendices) (2015)
- American Forest & Paper Association (Better Practices, Better Planet 2030)

3.7 Food & Beverage

The food and beverage manufacturing industry is a critical, $359 billion sector of the U.S. economy. The sector employs more than 1.7 million workers (14.6 percent of all U.S.

manufacturing employees) at over 36,000 food and beverage processing plants, owned by over 31,400 companies. With complex supply chains stretching all over the United States and throughout nearly every part of the economy, food and beverage manufacturing is diverse, dispersed, and challenging to regulate. [392]

Food and beverage manufacturing is also one of the largest GHG-emitting and energy-consuming industries in the United States. The sector emits around 96 MMT CO_2e/year (including emissions from offsite generation), with CHP, boilers, and process heating accounting for the most direct emissions. Over half (53 percent) of its emissions come from offsite electricity and steam generation (***Figure 28***). [393] Most energy consumed in food and beverage manufacturing (over 55 percent) is natural gas, with much of the rest coming from grid electricity (***Figure 29***). [394]

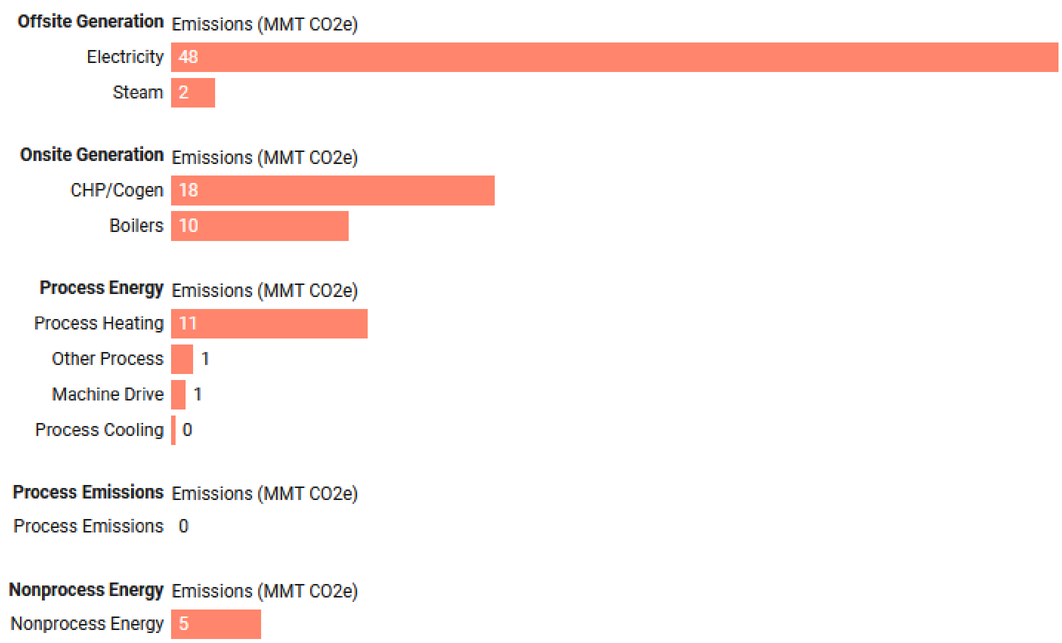


Figure 28: Food and beverage sector sources of GHG emissions in 2018, by major end use. Source: U.S. DOE, Manufacturing Energy and Carbon Footprint: Food and Beverage Sector.

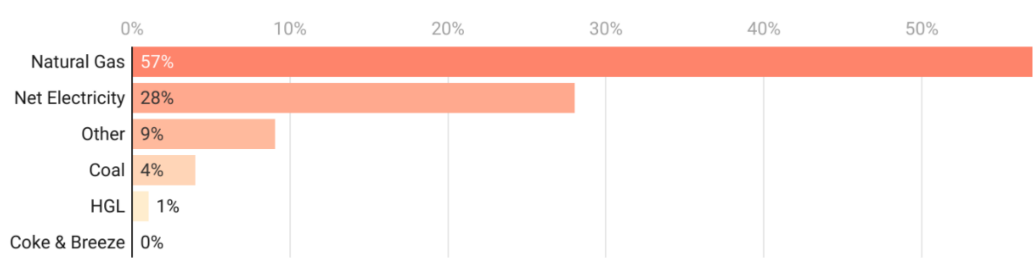
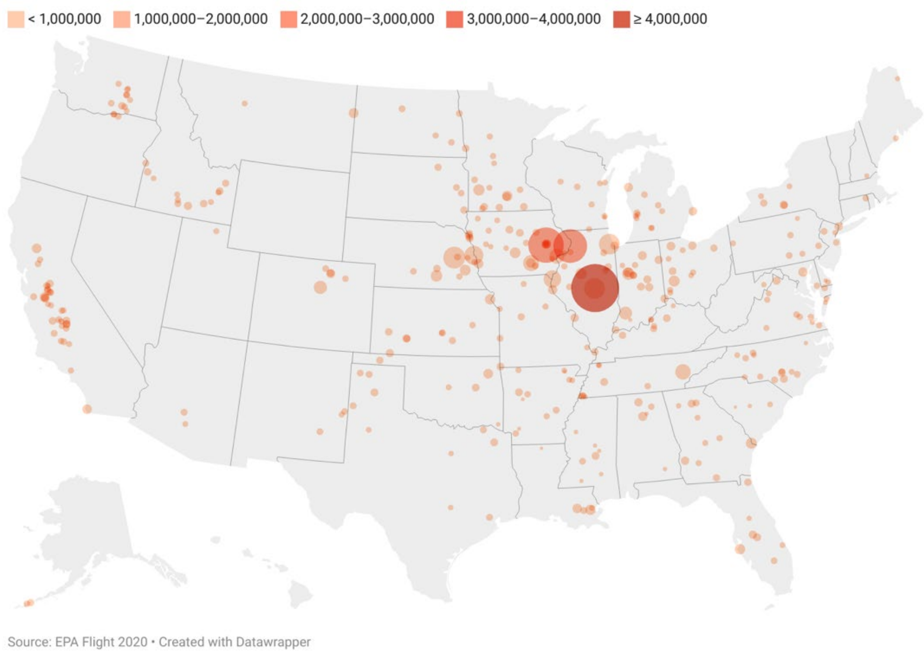


Figure 29: Food and beverage sector fuel and non-fuel uses of energy in 2018 (as a percentage of total trillion Btu). Source: U.S. EIA, MECS 2018, Table 1.2.

Food and beverage manufacturing is highly dispersed (***Figure 30***). [395] Most processing facilities are in the general proximity of major population centers, and/or close to material sources in their supply chains.[396] Because of this, the GHG emissions associated with the transportation of these goods leads to higher embodied emissions. The states with the most food and beverage manufacturing plants in 2017 were California (5,731), followed by New York (2,573) and Texas (2,273), but the states with the facilities contributing the most GHG emissions differ (Iowa, Illinois, and Nebraska).



State	Total GHG Emissions	Facilities
IA	7,001,172	31
IL	6,461,579	16
NE	2,036,680	11
CA	1,668,320	42
IN	1,366,774	20
MN	798,979	15
TN	632,072	12
OH	606,993	11
KS	548,501	9
GA	543,162	12
ID	487,478	13

Figure 30: Location and total reported emissions (metric tons CO_2e) of food and beverage manufacturing plants in the United States (left). Top 10 states by total GHG emissions from food and beverage facilities (right table). Size and darkness of bubbles scale with level of emissions. Source: U.S. EPA, FLIGHT.

The top five food manufacturing companies in the United States by 2019 food and beverage sales have all established science-based sustainability and emissions reduction targets. For example:

- Nestle, which was responsible for 92 million tons of GHG emissions in 2018, is a signatory of the UN Business Ambition for 1.5°C pledge and plans to halve its emissions by 2030 and achieve net zero by 2050.[397]
- PepsiCo is committed to reducing scope 1 and 2 emissions by 75 percent and scope 3 emissions by 40 percent by 2030.[398]
- JBS has committed to achieving net-zero GHG emissions by 2040 and has also signed on to the UN Business Ambition pledge.[399]
- Tyson Foods is targeting net-zero GHG emissions by 2050.[400]
- Archer Daniels Midland intends to lower its GHG emissions by 25 percent and reduce energy intensity by 15 percent by 2035.[401]

Common approaches to reach these decarbonization goals include supporting regenerative agriculture practices, supply chain management, investing in carbon offsets, redesigning packaging to reduce waste, and conducting internal carbon prices pilots. However, these goals overlook many readily available opportunities for enhanced energy efficiency and process electrification.

On the agricultural side, better land use and fertilizer management, crop rotation, no-till practices, agroforestry, and precision agriculture can help reduce net GHG emissions and reduce waste. Another high-potential opportunity for with short-term savings includes food waste reduction, which translates directly to mitigated carbon dioxide emissions in the supply chain. Though difficult to achieve because of the diversity of supply chains, policies and programs aimed towards material efficiency, packaging redesigns, and recycling have the potential to make a meaningful difference. Information communication technologies can support automation and process optimization. Other opportunities include waste heat recovery, industrial heat pumps, and regulatory changes that provide greater flexibility for process innovation.

There are many examples of existing state-level policies or programs aimed at reducing emissions from food and beverage manufacturing. **New York** recently detailed the possibility for carbon capture utilization technologies to create savings in beverage carbonation, food freezing, chilling, and packaging, and in horticulture.[402] **Delaware** and **Maryland** both have statewide agricultural audit and implementation (incentives and training) programs that are aimed at promoting the uptake more-efficient agricultural practices and technologies to reduce energy use and waste.[403, 404] **Washington** state's *2021 Energy Strategy* indicates the potential for GHG reduction measures such as fuel-switching boilers, industrial heat pumps, alternative drying strategies, and ultraviolet or microwave pasteurization/sterilization to help decarbonize food and beverage manufacturing.[405]

Internationally, Canadian provinces Manitoba and Ontario have developed province-based initiatives towards reducing food waste while the EU has created a *Circular Economy Action Plan* that includes sections on packaging and recycling.[406, 407, 408] The EU has also investigated the potential of demand-side strategies such as public procurement of food to support the market for less-carbon-intensive food products as well as manufacturing processes that are responsible for less emissions.[409]

Decarbonization of the food and beverage sector will require enabling policies, programs, capital investments, and R&D to overcome barriers that include inadequate funding, health and safety scrutiny, few uses for waste heat, sector diversity, and geographic constraints. The barriers and policy connections are summarized in ***Table 14***.

Table 14: Decarbonization barriers in the food & beverage industry.

Challenge / Barrier	State Opportunities	Policy Connections
Health, safety, quality scrutiny of food and beverage products create additional costs and stipulations on process change	• These hurdles, while necessary, can be minimized by articulating benefits to supply chain partners, customers, regulators… of energy efficiency, low-carbon technologies, and getting buy-in for changes	• Workforce training and technical assistance for efficiency improvements • Address negative perceptions about process changes to food quality and show benefits to society, consumers, government, companies
Underutilized waste heat recovery opportunities	• Industrial heat pumps can provide significant GHG and energy savings in process heat and uses for waste heat	• Capital costs may have to be augmented to make heat pumps viable at scale • Industrial clusters can be encouraged to more effectively reuse waste heat, adopt low-

Challenge / Barrier	State Opportunities	Policy Connections
	• Industrial clusters can increase waste heat use • Energy management can help reduce energy/heat demand	carbon technologies, and update infrastructure • Support for SEM managers (especially SMM) while developing workforce
Capital costs associated with electrification	• Food and beverage is well suited for electrification because of high modularization of heating potential, low process heat	• Electricity: natural gas price disparity is an opportunity for incentives to spur electric technology adoption
Diversity of the sector, geographic distribution	• Industrial clusters can be a route to counter geographic disparity • Supply chain inefficiency is a major source of emissions	• States can revitalize industrial clusters as a locus for supply chain resiliency • RFIDs, supply chain transparency and optimization, EPDs, can aid transformation
Food waste is a huge source of ineffective embodied carbon	• Packaging redesign, recycling, material efficiency can significantly reduce waste and embodied emissions • Information and communication technologies (ICTs) can reduce food waste through sensors, optimization	• State mandates on plastic use recyclability of packaging, use of imperfect produce, and extended shelf lives can reduce food waste • R&D and incentives are needed to accelerate the proliferation of ICTs in food and beverage manufacturing
R&D needed to increase the feasibility of decarbonization technology options	• Smart manufacturing, beneficial electrification, low-carbon fuels, CCUS have the potential to reduce emissions significantly	• State funds leveraged with federal funds in R&D can help bridge the gap between innovative options and commercial viability

Roadmaps for the Food & Beverage Industry

- Decarbonization Roadmap for the EU Food Industry (2021)
- UK Roadmap for Food (2015)
- UK Roadmap for Food (Appendices) (2015)

CONCLUSION

The path to industrial decarbonization will be a multi-decade transformation that requires a multi-layered, multi-stakeholder approach.[410] That approach will need to be tailored to the unique challenges and opportunities that exist in each state. A range of structural, technical, and economic challenges demand a wide range of solutions that will have a ripple effect across industries and complex supply chains.

However, state policymakers can start mapping out how to help support their industrial sectors to achieve near-zero GHG emissions by considering the five pillars of industrial decarbonization described throughout this report. While these pillars vary in their timing of impact, cost, and complexity, regional partnerships across states, targeted work with industrial clusters, and learning and collaboration with state, federal, and international peers can help achieve the most-efficient transformation.

Decarbonizing the industrial sector also presents an opportunity to cut the wider environmental footprint of manufacturing, improve competitiveness, address environmental justice concerns, and broaden workforce diversity. States have multiple policy levers that can be used to help achieve these benefits, like investing in low-carbon infrastructure, leveraging financing, adopting regulations and standards, supporting technical assistance, preferentially purchasing low-carbon products, and supporting worker training programs.

While the current industrial decarbonization policy landscape is in its early stages, the magnitude of the transformation needed requires swift and innovative action. States are in a prime position to help accelerate industrial decarbonization effort, and there is no time to waste.

APPENDICES

Appendix A: New Federal Investments and Programs

The Inflation Reduction Act of 2022 (H.R. 5376)

Enacted in August 2022, the Inflation Reduction Act contains a record $369 billion in clean energy and climate investments, including at least $17 billion (excluding tax credits) that explicitly supports industrial decarbonization.

Summary of Industry Specifics:

- Tax credits:
    - **45Q Carbon Capture and Storage Tax Credit**: Applies to any projects that commence construction before 2033, expands credit value from $50/ton to $85/ton sequestered ($180/ton for direct air capture), and awards $60/ton for utilization ($130/ton for direct air capture). (Sec. 13104)
    - **Clean Hydrogen Production Tax Credit**: "Clean hydrogen" defined as not greater than 4 kg/CO_2e per kg/H_2 (~50% lower GHGs than typical H_2); awards a 10-year $0.60/kg clean H_2 credit (inflation adjusted); reward increases with lower lifecycle GHG emissions, up to a 100% multiplier for H_2 produced with <0.45kg/CO_2e footprint (well to gate). (Sec. 13204)
    - **48C Advanced Energy Project Credit**: Adding eligibility to projects that retrofit facilities with technologies (including low-carbon process heat, CCUS, energy and material efficiency) that reduce GHG emissions by at least 20% and produce or install energy storage systems, low carbon fuels, energy efficient equipment, EV and fuel cell vehicles and their related components and charging infrastructure, and process, refine, or recycle critical materials. (Sec. 13501)
    - **Advanced Manufacturing Production Credit**: Tax incentives for production and sale of solar and wind components, batteries, and critical minerals to these technologies. (Sec. 13502)
- Grants and financing for retooling existing manufacturing facilities to reduce GHG emissions:
    - **$5.812B for Advanced Industrial Facilities Deployment Program**: Financial assistance for energy-intensive manufacturing facilities (including iron, steel, aluminum, cement, concrete, glass, pulp, paper, ceramics, chemicals) to purchase and install technologies directly involved with making products (including energy efficiency, electrification, low/zero-carbon fuels, low/zero-carbon process heating, CCUS) that reduce GHG emissions. Prioritized based on GHG reductions, benefits to local communities, partnerships with purchasers of the output. (Sec. 50161)
- Grants and financing for retooling existing manufacturing facilities to produce clean energy technologies or to build new facilities that produce (or recycle) clean energy technologies:

    - **$3B for Advanced Technology Vehicle Manufacturing**: Retrofitting or expanding existing facilities (or building new facilities) to manufacture low- or zero-emission vehicles. (Sec. 50142)
    - **$2B for Domestic Manufacturing Conversion Grants**: Producing various low- or zero-emission vehicles. (Sec. 50143)
    - **$297M for Alternative Fuel and Low-Emission Aviation Technology Program**: Grants to produce sustainable aviation fuels and more fuel-efficient or lower GHG-emitting aircraft/engines. (Sec. 40007)
    - **$15M for EPA's new Renewable Fuel Program**, with $5M for fuel test and protocol development and $10M in grants to industry for investments in advanced biofuels. (Sec. 60108)
- Funding to support the use of low-embodied carbon materials:
    - **$250M to support industry in developing and standardizing environmental product declarations (EPDs),** including states, tribes, and nonprofits that support industry in doing so. (Sec. 60112)
    - **$100M for EPA to work with FHWA and GSA to identify and label low-embodied carbon construction materials and products**. Explicitly suggests consulting with state agencies to develop this program. (Sec. 60116)
    - **$2B for DOT to reimburse or provide incentives to offset the cost differences of low-embodied carbon materials** for highway construction projects. (Sec. 60506)
    - **$2.15B for GSA to purchase low-carbon materials for their buildings**. (Sec. 60503)
    - **Authorizes FEMA to provide financial assistance and incentives to purchase low-carbon materials** and energy projects for their buildings. (Sec. 70006)
- Programs to address short-lived climate pollutants:
    - **$38.5M for supporting AIM Act implementation to phase out HFCs**. (Sec. 60109)
    - **$1.55B for a Methane Emissions Reduction Program**, of which $850M is appropriated for methane mitigation and monitoring, with an additional $700M for incentives for methane mitigation from conventional wells. Places a Waste Emissions Charge on excess methane emissions — $900 per metric ton in 2024, $1200 per metric ton in 2025, and $1,500 per metric ton by 2026 (and each year thereafter). (Sec. 60113)

The Infrastructure Investment and Jobs Act of 2021 (H.R. 3684)
Enacted in November 2021, the $1 trillion Infrastructure Investment and Jobs Act (IIJA) contains multiple billions in provisions related to climate and clean energy. For the industrial sector, IIJA primarily advances an innovation agenda to build new supply chains and infrastructure for emerging technologies, focusing on hydrogen, CCUS, and critical minerals.

The IIJA also includes opportunities for partnerships to accelerate learning around industrial decarbonization. For example, the IIJA includes funding for the Energy Act of 2020,[411] which created an Industrial Technology Innovation Advisory Committee composed of members of state government, federal agencies, academia, industry, and other relevant entities. The Committee will oversee the Industrial Emissions Reduction Technology Development Program.

Summary of Industry Specifics:
★Stars indicate state government recipient eligibility. Additional program specifics available at https://www.whitehouse.gov/build/.

- Grants and financing for retooling existing manufacturing facilities to reduce GHG emissions:
  - **$750M for Advanced Energy Manufacturing and Recycling Grant Program**: Grants for small and medium manufacturers (SMMs) in coal communities to implement GHG emission reduction projects (low/zero-carbon process heat, CCUS, energy and material efficiency) or produce/recycle clean energy projects (renewables, fuel cells, grid modernization, CCUS, electrolyzers, efficiency, ZEVs). (Sec. 40209)
  - **★ $500M for Industrial Emission Demonstration Projects**: Grants and partnerships to test/validate technologies that reduce emissions from high-emitting processes (iron, steel, steel mill products, aluminum, cement, concrete, glass, pulp, paper, and industrial ceramics); medium/high-temperature process heat; and chemical production. Energy and material efficiency projects also eligible. (Sec. 41008)
- Grants to advance manufacturing technical assistance:
  - **$150M for Industrial Research and Assessment Centers**: Grants to expand IACs. (Sec. 40521)
  - **★ $50M for Manufacturing Leadership**: Grants for states to help small and medium manufacturers to invest in smart manufacturing technologies or access high-performance computing resources for manufacturing analysis. (Sec. 40534)
- Programs to develop and scale clean hydrogen:
  - **★ $8B for Regional Clean Hydrogen Hubs**: Funds to support development of at least 4 hubs, envisioned as a network of clean hydrogen producers, potential clean hydrogen consumers, and connective infrastructure located in close proximity. The hubs are expected to use diverse feedstocks, have diverse end uses (including industrial), and geographically diverse. (Sec. 40314)
  - **★ $1B for Clean Hydrogen Electrolysis Program**: R&D program to commercialize low-cost electroylzer hydrogen. (Sec. 40314)
  - **★ $500M for Clean Hydrogen Manufacturing and Recycling Program**: Funds for new hydrogen production and recycling techniques. (Sec 40314)
- Programs to develop and scale CCUS and direct air capture (DAC):
  - **★ $2.5B for Carbon Storage Validation and Testing:** Funding for large-scale carbon sequestration projects and associated transportation infrastructure. (Sec. 40305)
  - **★ $2.54B for Carbon Capture Demonstration Projects Program**: For developing 6 facilities that will demonstrate new technologies that will improve the efficiency, effectiveness, costs, emissions reductions, and environmental performance of coal and natural gas use, including in manufacturing and industrial facilities. (Sec. 41004)
  - **★ $937M for Carbon Capture Large-Scale Pilot Projects**: Funds for developing new technologies that will improve the efficiency,

    effectiveness, costs, emissions reductions, and environmental performance of coal and natural gas use, including in manufacturing and industrial facilities. (Sec. 41004)
  - ★ **\$2.1B for CO_2 Transportation Infrastructure Finance and Innovation**: Financing for companies building CO2 transport infrastructure projects that cost more than \$100M. (Sec. 40304)
  - ★ **\$310M for Carbon Utilization Program**: Grant program for states and governmental entities to procure and use products that are derived from carbon and reduce greenhouse gas emissions. (Sec. 40302)
  - ★ **100M for Carbon Capture Technology Program**: Front-end engineering and design program for carbon dioxide transport infrastructure necessary to enable deployment of carbon capture, utilization, and storage technologies. (Sec. 40303)
  - ★ **\$50M for Underground Injection Control Grants**: Grants to states seeking Class VI primacy for CO2 storage. (Sec. A)
  - ★ **\$3.5B for Regional Direct Air Capture Hubs**: Funding for hubs that facilitate the deployment of direct air capture projects; have the capacity to capture, sequester, or utilize at least one million metric tons of CO_2 annually; demonstrate the capture, processing, delivery, and sequestration of captured carbon; and have potential for developing a regional or inter-regional network to facilitate CCUS. (Sec. 40308)
  - **\$115M for DAC Technologies Prize**: \$15 million for DOE to award a competitive technology prize for the pre-commercial capture of CO_2 from dilute media and \$100 million for commercial applications of direct air capture technologies. (Sec. 41005)
- Funding to develop new supply chains for critical minerals and energy storage:
  - ★ **\$3B for Battery Materials Processing Grants** (Sec. 40207)
  - ★ **\$3B for Battery Manufacturing and Recycling Grants** (Sec. 40207)
  - **\$600M for Critical Material Innovation, Efficiency, and Alternatives R&D** (Sec. 41003)
  - ★ **\$125M for Battery and Critical Mineral Recycling R&D** (Sec. 40207)
- Buy America provisions:
  - IIJA requires that all manufactured products and construction materials used in infrastructure projects financed by the bill are domestically produced.

IIJA defines clean hydrogen and hydrogen in a technology neutral manner and requires DOE and EPA to develop an initial carbon standard for projects to qualify as clean hydrogen production, eligible for the variety of incentives throughout the bill. Clean hydrogen means "hydrogen produced with a carbon intensity equal to or less than 2 kilograms of carbon dioxide (CO_2)-equivalent produced at the site of production per kilogram of hydrogen produced." The standard must consider technological and economic feasibility and allow production from fossil fuels with CCUS, hydrogen carrier fuels, renewables, nuclear and other methods that DOE determines are appropriate.

The CHIPS and Science Act of 2022 (H.R. 4346)
Enacted in July 2022, the CHIPS and Science Act includes $54.2 billion in subsidies for domestic semiconductor manufacturing (which will support domestic solar and EV industries) as well as subsidies and authorizations for more than $170 billion in new and expanded research programs. However, $67 billion over the next five years will also go towards growing zero-carbon industries and climate research, with new authorizations for DOE, NIST, NSF, and NASA. Relevant provisions include advanced research and databases, metrics/standards development, national labs funding, expansion of Manufacturing USA ($829M) and the Manufacturing Extension Partnership ($2.3B), and STEM education and workforce development. See summary for more information.

Other industry-related highlights include:

- **Sustainable Chemistry Research**, **Materials Research Database**, **Carbon Materials Science** Initiative, and the **Carbon Sequestration Research** and Geologic Computational Science Initiative (Sec. 10102)
- **Biological and Environmental Research**: Support research for advanced biofuels, bioenergy, biobased materials; new centers, industry partnerships. (Sec. 10103)
- **Low-Emissions Steel Manufacturing Research Program**: Includes an R&D program, 5-year strategic plan, and demonstration projects. Focus areas: medium/high-temp heat tech (hydrogen & biomass fuels, solar & geothermal, electrification & electrolysis); carbon capture; smart manufacturing; material efficiency; and innovative materials. (Sec. 10751)
- **Advanced Nuclear Technologies Federal Research, Development, and Demonstration Program**: Prioritizes demonstration projects that supply heat for industrial processes and chemical production. (Sec. 10781)

Other ongoing federal actions that may accelerate state level decarbonization efforts include:

- U.S. DOE's new partnerships to help decarbonize industry.[412]
- The Clean Competition Act, which advances border adjustment mechanisms.[413]
- The General Services Administration and the Department of Transportation promoting the use of low carbon materials in construction projects.[414]
- The First Movers Coalition, which is securing corporate purchasing agreements for low-carbon products through the State Department.[415, 416]
- The White House Buy Clean Task Force.[417]

Appendix B: Industry Subsector Carbon Footprints

The subsector energy and emissions data presented in ***Chapters 1 and 3*** is largely derived from the U.S. Department of Energy's 2018 Manufacturing Energy and Carbon Footprints. Published in 2021, these footprints "map the flow of energy supply, demand, and losses as well as greenhouse gas (GHG) emissions in diverse U.S. manufacturing industries, based on Energy Information Administration Manufacturing Energy Consumption Survey data and U.S. Environmental Protection Agency emissions data." [418]

Each datapoint in the table below was extracted or derived from subsector-specific Footprints. Each Footprint is linked in the table.

Methods:

- **Total**: Extracted from page 3 (top), "Total GHG Emissions"
- **% Total Mfg.** (*manufacturing*): Derived by dividing row total by total number in "All Manufacturing" row.
- **Offsite Total**: Derived by subtracting Onsite Total from Total
- **Onsite Total**: Extracted from page 2 (top), "Onsite Emissions."
- **Onsite Generation**: Derived by summing combustion emissions (light purple) from Conventional Boilers, CHP/Cogeneration, and Other Electricity Generation on page 3.
- **Process Energy**: Derived by summing combustion emissions (light purple) from Process Heating, Process Cooling and Refrigeration, Other Process Uses, Electro-Chemical, and Machine Drive on page 3.
- **Process Emissions**: Extracted from process emissions value (dark purple) on page 3.
- **Nonprocess Energy**: Derived by summing combustion emissions (light purple) from Facility HVAC, Facility Lighting, Other Facility Support, Onsite Transportation, and Other Nonprocess on page 3.

Detailed definitions for each of the emission sources above can be found in this accompanying glossary. [419]

	Total GHG Emissions (MMT CO_2e)				**Onsite GHG Emissions (MMT CO_2e)**			
	Total	*% Total Mfg.*	**Offsite Total**	**Onsite Total**	**Onsite Generation**	**Process Energy**	**Process Emissions**	**Nonprocess Energy**
Chemicals	**332**	*28%*	90	242	96	71	71	5
Refining	**244**	*21%*	33	211	63	148	0	1
Iron & Steel	**100**	*9%*	29	71	3	22	45	2
Cement	**66**	*6%*	5	61	0	22	39	0
Glass	**15**	*1%*	6	9	0	7	1	0
Forest Products	**80**	*7%*	36	44	31	11	0	3
Food & Beverage	**96**	*8%*	51	45	27	13	0	5
All Manufacturing	**1,165**	-	**385**	**780**	**234**	**336**	**180**	**30**

Appendix C: Additional Industrial Decarbonization Resources

TOOLS

Datasets and Databases

- Building Transparency, EC3 Tool (2022)
- National Renewable Energy Laboratory (NREL), 2018 Industrial Energy Data Book
- National Renewable Energy Laboratory (NREL), US Department of Energy, Economic Feasibility for CO_2 Utilization Data Visualization Tool (2022)
- National Renewable Energy Laboratory (NREL) US Department of Energy, Global CCUS Database (2022)
- U.S. Environmental Protection Agency (EPA) GHGRP:
  - Inventory of U.S. Greenhouse Gas Emissions and Sinks
  - Sector Data Highlights
  - Facility Level Information on Greenhouse Gas Tool Database (FLIGHT)
- U.S. Environmental Protection Agency (EPA), EnergyStar, Certified Plant Locator Tool (2022)
- U.S. Energy Information Administration (EIA) Manufacturing Energy Consumption Survey
- U.S. Environmental Protection Agency (EPA) National Emissions Inventory (NEI)
- U.S. Department of Energy, Industrial Assessment Centers (IAC) Database
- U.S. Department of Energy (USDOE) Advanced Manufacturing Office Software Tools

Toolkits and Policy Aids

- American Council for an Energy Efficient Economy (ACEEE): Governors Energy Efficiency Toolkit (2019)
- American Council for an Energy Efficient Economy (ACEEE): Self-Direct Programs for Large Energy Users (2019)
- EPA State Inventory (and Projection) Tool
- Carbon Leadership Forum, Embodied Carbon Policy Toolkit (2021)
- Great Plains Institute. 2022. An Atlas of Carbon and Hydrogen Hubs for United States Decarbonization
- Industrial Innovation Institute (I^3). 2021. Decarbonizing Industry by 2050: A Federal and State Policy Blueprint
- National Association of State Energy Officials (NASEO). 2021. Hydrogen: Critical Decarbonization Element for the Grid, Manufacturing, and Transportation: State Energy Policy, Program, and Planning Considerations.
- National Association of State Energy Officials (NASEO). 2021. Carbon Capture, Utilization, and Storage: Overview and Considerations for State Planning.
- National Governors Association, State Energy Efficiency Policy in a New Era Toolkit for Governors (2021)
- U.S. Department of Energy (USDOE), Better Plants Program (2022)
- U.S. Department of Energy (USDOE) Industrial Plants, Industrial Energy Management Information Center (2022)

Technical Assistance Peer Networks

- Colorado Industrial Energy Challenge
- Southwest Energy Efficiency Project (SWEEP), Industrial Energy Efficiency Peer Networks

- Utah Industrial Energy Challenge

Federal (DOE Advanced Manufacturing Office) Resources for Industry Subsectors

- Aluminum
- Chemicals
- Forest Products
- Glass
- Metalcasting
- Mining
- Other Industries
- Petroleum Refining
- Steel

International Resources

- Germany National Energy Efficiency Action Plan (NAPE) and Energy Efficiency Network
- Global CCS Institute (2022)
- International Energy Agency, Industrial Policy Database from National Governments (2022)
- International Energy Agency, Hydrogen Project Database (2022)

STRATEGIES, SCOPING PLANS, ACTION PLANS

U.S. State Climate or Clean Energy Plans [o]

- Louisiana Climate Action Plan (2022)
- Michigan MI Healthy Climate Plan (2022)
- New York Climate Action Council Draft Scoping Plan (2021)
- Washington State Energy Strategy: Chapter E. Industrial Transformation and Workforce Development (2021)
- Wisconsin Clean Energy Plan (2022)

Other Organizations

- National Governors Association, State Energy Goals and Strategies

International Resources

- UK's Industrial Decarbonization Strategy
- UK Zero Carbon Hubs
    - Industrial Clusters
    - National Strategy
    - Regional Strategy
- EU New Industrial Energy Strategy

ROADMAPS

Industry

- Portland Cement Association -- Roadmap to Carbon Neutrality by 2050 (October 2021)

[o] Highlighted for their focus on industrial decarbonization solutions

International Resources

- Canadian Cement and Concrete Industry 2050 Roadmap to Net-Zero Concrete (expected release mid-2022)
- Canada Buy Clean Roadmap
- CEMBREAU Cement Roadmap to 2050
- Global Cement and Concrete Association (October 2021): 2050 Roadmap for Net Zero Concrete
- EU ENTSO-E Research, Development & Innovation Roadmap 2020–2030
- European Steel Industry Decarbonization Roadmap (2019)
- Decarbonization Roadmap for the EU Food Industry (2021)
- France Chemical Industry Decarbonization Roadmap (2021)
- International Energy Agency (IEA) Cement Roadmap (2009)
- International Energy Agency, Iron and Steel Decarbonization Roadmap (2020)
- Japan Technology Decarbonization Roadmap and Transition Finance for Chemicals Industry (2021)
- Japan Technology Decarbonization Roadmap and Transition Finance for Oil and Gas Refining Industry (2022)
- Japan Technology Decarbonization Roadmap and Transition Finance for Iron and Steel Industry (2021)
- Japan Technology Decarbonization Roadmap and Transition Finance for Pulp and Paper Industry (2022)
- Japan Technology Decarbonization Roadmap and Transition Finance for Cement Industry (2022)
- United Kingdom (UK) Industrial Decarbonization and Energy Efficiency Roadmaps to 2050 (2021)
- World Business Council for Sustainable Development - Cement Roadmap (2018)

HOW-TO-GUIDES

Other Organizations

- Science Based Targets Initiative (SBTI) Quick Guide to the Sectoral Decarbonization Approach (2015)
- U.S. Environmental Protection Agency (USEPA), EnergyStar, Energy Guides for Industrial Plants (2022)
- U.S. Environmental Protection Agency (USEPA), EnergyStar, Buy Clean Procurement and EnergyStar Guide (2022)
- U.S. General Services Administration (GSA). GSA Green Building Advisory Committee Advice Letter: Policy Recommendations for Procurement of Low Embodied Energy and Carbon Materials by Federal Agencies (2021)
- World Resources Institute (2021). Toward a Tradable, Low Carbon Product Standard for Steel, Policy Design Considerations for the United States (2021)
- World Resources Institute (2021). Toward a Tradable, Low Carbon Product Standard for Cement, Policy Design Considerations for the United States (2021)

International Resources

- UN Industrial Development Organization (UNIDO) and Leadership Group for Industrial Transition, Fostering Industry Transition Through Green Public Procurement: A How to Guide in the Cement and Steel Sectors (2021)
- UN Industrial Development Organization (UNIDO) and Leadership Group for Industrial Transition, Target Setting for Green Public Procurement Programs (2021)

Appendix D: Acronyms

Acronym	Definition
AFPA	American Forest & Paper Association
BACT	Best available control technology
BASF	Baden Aniline and Soda Factory
BF-BOF	Blast furnace – Blast oxygen furnace
Btu	British thermal unit
CCUS	Carbon capture, utilization, and storage
CCR	Coal combustion residuals
CEMBRAU	European Union Cement Trade Association
CHP	Combined heat and power
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
COP	Coefficient of performance
DAC	Direct air capture
DEEP	Department of Energy and Environmental Protection
DOE	Department of Energy
DOT	Department of Transportation
EAF	Electric arc furnace
EE	Energy efficiency
EIA	Energy Information Administration
EITEs	Energy-intensive, trade-exposed
EPA	Environmental Protection Agency
EPD	Environmental product declaration
EU	European Union
FLIGHT	Facility Level Information on GHGs Tool
GCCA	Global Cement and Concrete Association
GDP	Gross domestic product
GHG	Greenhouse gases
GHGRP	Greenhouse Gas Reporting Program
GJ	Gigajoules
GW	Gigawatts

Acronym	Definition
GWP	Global warming potential
IPCC	Intergovernmental Panel on Climate Change
H_2	Hydrogen
HHV	Higher heating value
IAC	Industrial Assessment Center
ICT	Information, communication technology
IEA	International Energy Agency
IHP	Industrial heat pump
IIJA	Infrastructure, Investment, and Jobs Act
ISO	International Organization for Standardization
JTF	Just Transition Fund
JTM	Just Transition Mechanism
kW	Kilowatt
KWh	Kilowatt hour
LC	Low carbon
LCA	Life cycle assessment
LCF	Low-carbon fuels
LCFF	Low-carbon fuels & feedstocks
LPG	Liquified petroleum gas
MBOE	Million-barrel of oil equivalent
ME	Materials efficiency
MECS	Manufacturing Energy Consumption Survey
MMBtu	Millions of British thermal units
MMT	Millions of metric tons
MT	Metric tons
MTPA	Million tons per year
MW	Megawatts
MWh	Megawatt hours
NAICS	North American Industry Classification System
NEMS	National Energy Modeling System
NERC	North American Electric Reliability Corporation
NESHAP	National Emissions Standards for Hazardous Air Pollutants

Acronym	Definition
NGLs	Natural gas liquids
NGO	Non-government organizations
NREL	National Renewable Energy Laboratory
NYSERDA	New York State Energy Research & Development Authority
OPM	Office of Policy and Management
PPA	Power purchase agreements
PUC	Public utility commission
R&D	Research and development
RD&D	Research, development, and deployment
RFID	Radio Frequency Identification
RGGI	Regional Greenhouse Gas Initiative
RNG	Renewable natural gas
RPS	Renewable portfolio standards
SAF	Sustainable aviation fuel
SBT	Science based targets
SCM	Supplementary Cementitious Materials
SEM	Strategic energy management
SIC	Standard Industrial Classification
SLCP	Short-lived climate pollutants
SMM	Small, medium manufacturers
SMR	Steam methane reformers
UK	United Kingdom
UN	United Nations
WHR	Waste heat recovery

Appendix E: Glossary/Key Terms

Term	Definition
BF-BOF	Steel production process. Blast furnaces produce steel from iron ore. Blast oxygen furnaces turn iron and scrap into steel
Buy clean	A procurement policy approach that aims to incentivize the production of low-carbon materials through purchasing requirements for government infrastructure projects
CCUS	CCUS encompasses technologies and methods of removing CO_2 from industrial processes and the atmosphere, and the recycling of that CO_2 for utilization or storage
CHP	An energy efficient technology that generates electricity and captures waste heat for reuse in industrial processes
Cap and trade	A system for reducing emissions that sets an upper limit on individual emission sources, but allows for further emissions capacity to be bought from companies that have not reached the limit
Carbon intensity	The amount of CO_2 emitted per unit energy consumed or product created
Carbon neutrality	A state of net-zero carbon dioxide emissions
Carbon pricing	Carbon pricing captures the external costs of emissions and connects them to their sources through a price on CO_2
Clusters	Groups of interrelated industries in the same location that can share infrastructure
Crude steel	Steel in its first solid state after the melting process
Decarbonization	The reduction of carbon – the conversion to an economy that sustainably reduces CO_2 emissions.
Demand-side	Intended to stimulate demand
EAF	Steel production process. Uses electricity as its main source of energy to melt scrap into steel
EPDs	Quantifies environmental and carbon intensity data on the life cycle of a product. Independently verified.
Electric cracker	Performs the first step in converting ethane to ethylene and plastics
Electrification	The conversion of industrial systems to the use of electricity

Feedstock	The raw fuel used to supply an industrial process with energy
Green bank	Financial institutions that use market development strategies in partnership with private enterprises to accelerate the commercialization of clean energy technologies
Greenhouse gas	A gas that contributes to the greenhouse effect, accelerating climate change
Heavy industry	Industrial subsectors that consume a significant amount of process heat
Kiln	An oven or furnace used in cement production
Light industry	Industrial subsectors that do not consume a significant amount of process heat
Low carbon fuel	Fuel alternatives that have lower emissions factors than traditional fuels
Manufacturing	The process of turning raw materials into finished goods. Includes all the industrial sectors highlighted in this guidebook.
Net-zero	A target of entirely negating any GHG emissions
Non-energy benefits	All benefits in addition to reducing emissions and energy use, including pollutant reduction, job creation, etc.
Carbon offsets	Reduction of emissions in order to compensate for emissions elsewhere. Often purchased.
PUC	Governing bodies that regulate services and rates of public utilities
Payback	The amount of time it takes for the initial capital cost of something to be compensated by the savings it provides
Pilot	Initial small-scale implementation of a technology to assess feasibility
Policymakers	Those that are involved in crafting policy and making policy decisions. Includes all levels (local, state, and federal)
Process integration	Designing an industrial process to minimize energy consumption and consolidate all components of the manufacturing process
Renewable natural gas	Biogas that is at a quality similar to fossil fuel natural gas

Science-based targets	Targets that are in line with what the most current science defines as necessary in order to reach the goals of the Paris Agreement
Scrap	Recyclable steel materials remaining after consumption and manufacturing. Can be reused in steel manufacturing.
Supply chain	The entire sequence of processes involved with the supply, manufacturing, sale, and consumption of a product
Supplementary Cementitious Materials	Materials that are used in conjunction with Portland cement, Portland limestone cement or blended cements, to contribute to the properties of hardened concrete through hydraulic and/or pozzolanic activity. When added to concrete they make concrete mixtures more economical, reduce permeability, increase strength, or influence other concrete properties. Examples of SCMs include blast furnace slag and fly ash (by-products of the iron and coal industries).
Tax credits	Tax incentives that allow eligible entities to subtract credit from the total owed to the state
Technical assistance	The act of providing specific, targeted support in the use of new technologies or processes

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