NET-ZERO INDUSTRY IN MICHIGAN

GROUNDWORK FOR MITIGATING HARD-TO-ABATE EMISSIONS

5lakes energy

March 2026

Authors

Maxim Kostylev, PhD (contact: mkostylev@5lakesenergy.com)
Elizabeth Boatman, PhD, PE
Haoyu Ma, MS

About 5 Lakes Energy

5 Lakes Energy is a Michigan-based consultancy supporting nonprofits, businesses, and government agencies in their pursuit of clean energy goals, design and implementation of climate solutions, and delivery of economic, public health, and other benefits to the people they serve.

Acknowledgements

The findings presented in this white paper incorporate the perspectives of an array of stakeholders, including those affiliated with the industrial sector and utilities in Michigan, clean technology manufacturers, and others. We extend our appreciation for their time and willingness to participate.

Portions of this paper appear in contemporary publications on industrial decarbonization in Minnesota and Wisconsin produced by 5 Lakes Energy.

Executive Summary

Michigan is a major manufacturing state with a diverse set of industries that have a wide range of energy needs and emission profiles. The industrial sector, mostly constituted of manufacturing, is responsible for 17.5% of the state's total greenhouse gas (GHG) emissions. Therefore, an understanding of the technologies and approaches available for decarbonizing the industrial sector, and especially its manufacturers, is essential to develop a comprehensive strategy needed to reach Michigan's 2050 net-zero target. This white paper lays out cross-cutting and sector-specific approaches to decarbonizing the state's top-emitting industries, major barriers to decarbonization, options for managing emissions that are unlikely to be eliminated directly in the coming decades, and the role of policy in supporting the decarbonization process. The presented information incorporates industrial stakeholder perspectives based on interviews conducted during research for this project.

This white paper focuses on industrial 'hard-to-abate' GHG emissions, which include emissions from the combustion of fossil fuels for high-temperature (>500°C) process heat as well as carbon dioxide (CO_2) generated as a chemical byproduct in certain industrial processes (including lime, cement, and iron manufacturing). In 2023, Michigan's hard-to-abate industrial emissions constituted more than 8 million metric tons of CO_2-equivalent.[1]

TECHNICAL APPROACHES TO DECARBONIZING HARD-TO-ABATE EMISSIONS

Michigan's manufacturers can pursue several approaches to reduce or mitigate hard-to-abate emissions:

- **Improvements in energy and material efficiency** can be the most cost-effective way to minimize process-related emissions. The main approaches include the adoption of energy-efficient technologies, systems optimization, and waste heat recovery. Major barriers include internal competition for capital and short-term requirements for return-on-investment, insufficient incentives from the government or utilities, and a lack of familiarity and technical expertise in available solutions at many facilities.
- **Electrification** of process and space heat is the most direct way to eliminate emissions from fuel combustion at manufacturing facilities. However, current constraints, including low technology readiness and economic considerations, make the electrification of high-temperature process heat particularly challenging in most industries. The high cost of electricity per unit of energy compared to natural gas is a major barrier to the electrification of industrial heat, especially for high-temperature applications.
  - Industrial heat pumps and electric boilers are commercially ready cross-cutting technologies capable of supplying process heat up to 200°C and 350°C, respectively. Although limited to lower temperature outputs, heat pumps can play a significant role in waste heat recovery, even at facilities that rely primarily on high-temperature heat.
  - Thermal batteries are an important cross-cutting technology capable of storing and delivering electrified process heat across a wide temperature range, while enabling electricity demand flexibility. These batteries are more advanced for low- to medium-temperature industrial heat applications, but several companies are

---

[1] In addition to CO_2, other GHGs include methane, nitrous oxide, hydrofluorocarbon, perfluorocarbon, and sulfur hexafluoride. Each gas has a known different global warming potential value, which is used to convert absolute emissions to a CO_2-equivalent (CO_2e) value for easier tracking and data comparisons.

developing models that can generate heat up to 1,500-1,800°C, providing a potential electrification pathway for high-temperature industrial heat. To be cost-competitive with fossil fuel-based heat, thermal batteries would need new electricity rate structures that incorporate the benefits of large load demand flexibility in pricing.

- **Alternative low-carbon-intensity fuels** can provide practical decarbonization options for some industrial processes that cannot be readily electrified. Alternative fuels relevant for industrial process heat include biomass and biomass-containing waste, renewable natural gas, scrap tires, and hydrogen. Availability and consistency of supply, logistical readiness, and cost are important challenges in implementing alternative fuels. Based on current constraints, hydrogen is unlikely to be a viable option in the near future as an industrial fuel due to severe challenges with scalability and cost.
- **Carbon capture, utilization, and storage (CCUS)** is increasingly seen by businesses and governments as an essential component of the industrial decarbonization portfolio, reflecting the reality that not all industrial emissions will be directly eliminated in the coming decades. CCUS includes the capture of CO_2 at or near the emitting facility, compression and transport of the captured CO_2, and either sequestration in an underground storage site or use in other industrial applications. Major barriers for CCUS include the cost of capture and lack of existing infrastructure (pipelines for transportation and established injection sites).
- **Atmospheric carbon dioxide removal (CDR)** can be included in comprehensive industrial decarbonization strategies as an indirect approach to mitigating emissions that cannot be realistically eliminated from manufacturing. CDR includes both established, relatively inexpensive approaches, such as improved forest management, afforestation, and reforestation, and novel approaches under active development and facing many of the same barriers as the decarbonization approaches described above. Industry can support CDR efforts via financing of projects, knowledge and infrastructure sharing, project development, and integration of CDR in existing operations.

THE ROLE OF POLICY IN INDUSTRIAL DECARBONIZATION

Industrial decarbonization — especially in the hard-to-abate subsectors — faces major challenges and barriers, including long lifespans of legacy equipment, significant upfront capital expenses, potential increases to operating costs associated with electrification, unique facility needs and designs, a general resistance to change, and a lack of markets willing to pay higher prices for products with a lower carbon footprint. Policy-based avenues that can directly impact the pace of industrial decarbonization in Michigan include financial and technical support for solution implementation, gradual strengthening of standards and mandates, electricity rate reform, state or regional commitments to procure locally produced low-carbon products, and support for carbon management approaches to mitigate emissions that cannot be directly eliminated. Policies informed via the continuous engagement of stakeholders with different perspectives will help ensure that the decarbonization transition is economically viable, lasting, and fair.

Table of Contents

Introduction

Industry in Michigan is the third-largest greenhouse gas (GHG) emitting economic sector in the state, contributing about 17.5% of the state's total emissions.[2] As one of the top manufacturing states in the nation,[3] Michigan has a diverse set of industries with a wide range of energy needs and emission profiles. Recognizing the sector's complexity, diversity, and economic importance, the strategies and plans for how Michigan's industries will meet the state's 2050 net-zero target must be developed now.

> *Michigan's industrial sector is responsible for more than 17% of the state's total GHG emissions.*

The focus of this white paper is on the industrial emissions that will be the most difficult to eliminate due to the inherent nature of the processes used in certain manufacturing pathways, as well as technical limitations and costs. To help decision makers and stakeholders develop long-term plans for mitigating these so-called 'hard-to-abate' emissions within the context of broader industrial decarbonization strategies, we present relevant cross-cutting technical decarbonization approaches along with corresponding challenges and barriers. We then describe how these emissions mitigation approaches can be applied in Michigan's prominent hard-to-abate industries. Finally, we discuss policy opportunities that can effectively support industrial decarbonization efforts in the state. This white paper is intended to complement RMI's recently published Michigan Clean Manufacturing Roadmap, which focuses on industries that can be largely decarbonized with proven, commercially available technologies.[4]

Industrial Emissions Overview

Industrial scope 1 GHG emissions are produced on-site at manufacturing facilities and can be classified in two distinct categories: 'combustion' and 'process' (Figure 1), described in more detail below. Scope 2 emissions result primarily from off-site electricity generation to power industrial equipment and facilities. On average, electricity accounts for more than 20% of industrial on-site energy use.[5] Although scope 2 emissions are a significant component of emissions due to industrial activity, they are considered indirect and are typically included in the power sector rather than in the industrial sector totals (e.g., in Michigan's Comprehensive Climate Action Plan or CCAP). Emissions resulting from upstream and downstream activities along the value chain for a given product are referred to as scope 3 emissions, and these vary greatly for different products. In some cases, such as petroleum refining, these emissions can be far greater than scope 1 and 2 emissions.

---

[2] "Michigan's Comprehensive Climate Action Plan," Michigan Department of Environment, Great Lakes, and Energy, December 2025.

[3] National Association of Manufacturers: Federal and State Data, accessed February 2026.

[4] E. Albergo, B. Cangelose, J. Corvidae, et al., "Michigan Clean Manufacturing Roadmap," RMI, October 2025.

[5] J. Cresko, E. Rightor, A. Carpenter, et al., "Industrial Decarbonization Roadmap," U.S. Department of Energy, September 2022.

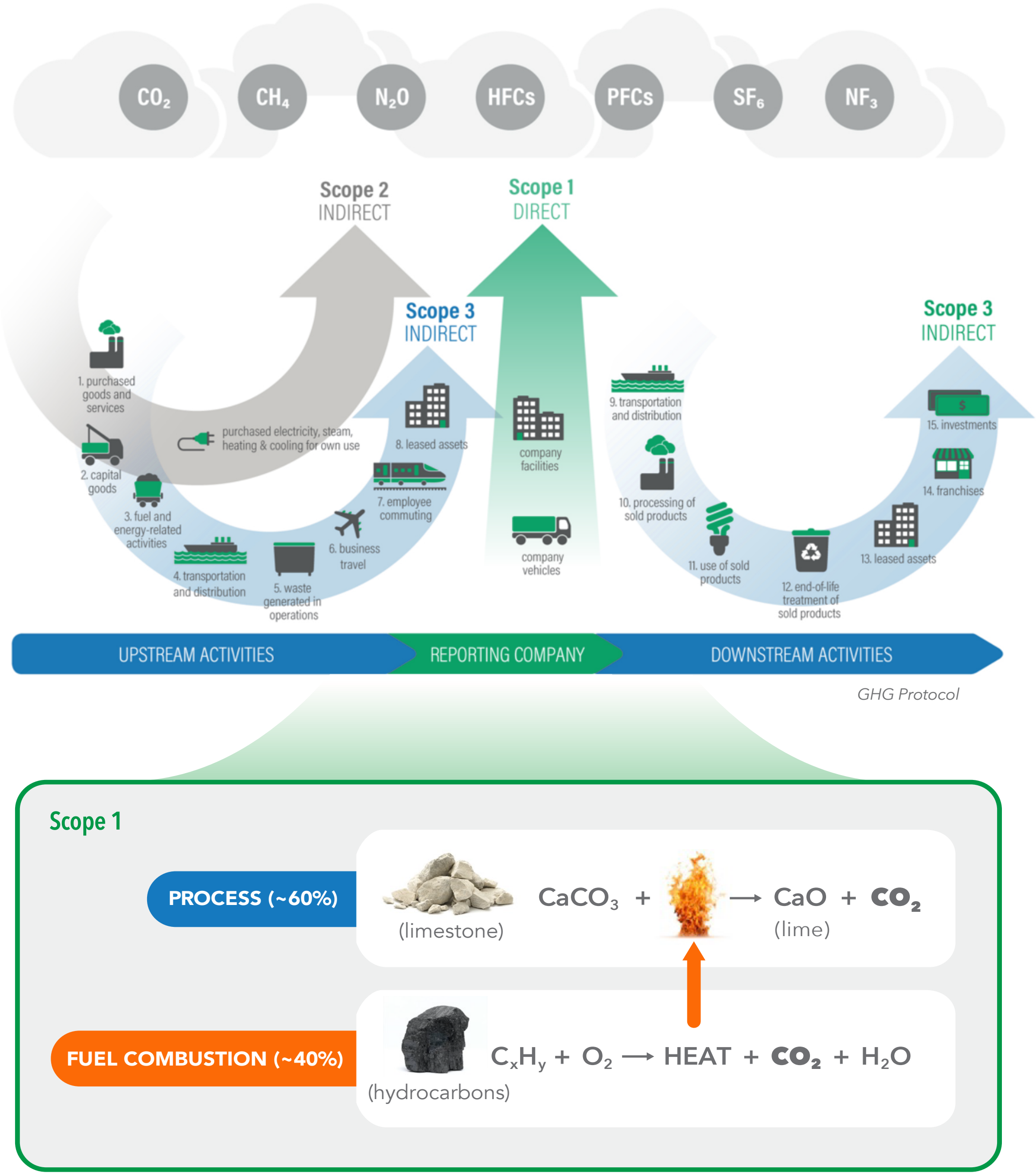


Figure 1 *Different categories of GHG emissions associated with manufacturing. Scope 1 emissions originate at the manufacturing facility and are the focus of this paper. Scope 1 emissions are composed primarily of fuel and process emissions. Fuel emissions are produced during combustion of fossil fuels, like coal or natural gas. Process emissions are generated as a chemical byproduct during the manufacturing process, regardless of the heating source. Lime production from limestone, which is a major source of process emissions in Michigan, is shown as an example. For some facilities, scope 1 emissions also include those derived from wastewater treatment or the landfilling of waste. Scope 2 emissions are produced primarily from off-site electricity generation to power industrial equipment and facilities. Scope 3 emissions are generated during upstream and downstream activities, associated with the products manufactured at the facility. Upper image in the figure was reprinted, with permission, from "Technical Guidance for Calculating Scope 3 Emissions," p. 6, GHG Protocol, 2013.*

The focus of this white paper is on scope 1 emissions. However, changes implemented to reduce scope 1 emissions would inevitably affect scope 2 emissions due to resulting shifts in electricity demand (e.g., lower demand due to efficiency gains and higher demand due to electrification of process heat generation).[6] Scope 3 emissions would also likely be impacted by scope 1 reduction measures, but the extent of the impact would largely depend on the specific approaches utilized to reduce carbon intensity and the targeted processes.

---

[6] When the power grid is fully decarbonized, all scope 2 emissions will be reduced to zero.

HARD-TO-ABATE EMISSIONS

In 2023, Michigan's hard-to-abate industrial emissions were more than 8 MMT CO_2e.

Industrial subsectors that are particularly hard to decarbonize — due to either economic limitations and/or available technologies — are commonly referred to as 'hard-to-abate.' These industries are energy intensive, requiring large quantities of high-temperature heat, and/or they generate large amounts of non-fuel process emissions, as described below. Michigan's top-emitting hard-to-abate subsectors include cement manufacturing, iron and steel production (a value chain that includes iron ore mining), lime manufacturing, petroleum refining, and hydrogen production (Figure 2). In 2023, Michigan's hard-to-abate industrial emissions constituted 8.1 million metric tons (MMT) of CO_2-equivalent (CO_2e), or about 57% of the state's total manufacturing emissions.[7],[8]

Combustion emissions

Combustion emissions result from the burning of fossil fuels like coal and natural gas primarily to produce the heat that drives most industrial processes (e.g., baking, sterilizing, distilling, hydrocarbon cracking, smelting, calcining). Process heat temperatures vary by application and are commonly categorized as low (<200°C), medium (200-500°C), or high (>500°C).[9] A fraction of the produced heat may also be used for space heating of the industrial facilities themselves. Some facilities utilize combined heat and power systems, which generate both heat and electricity from fuel combustion, with the generated electricity typically used to power the facility or, in some instances, sold to the grid. For this white paper, hard-to-abate industrial fuel-based emissions are primarily considered as those that result from fossil fuel combustion to generate high-temperature process heat. In 2023, the combustion of fossil fuels for high-temperature industrial heat at Michigan's manufacturing facilities produced about 4.6 MMT CO_2e.[10]

Process emissions

Process emissions refer to CO_2 formed as a byproduct of chemical reactions that occur in certain manufacturing pathways. These emissions are considered hard-to-abate because they are generated regardless of the nature of the heat source and would thus require wholesale changes to existing production methods to be eliminated. Among Michigan's industries, the most significant sources of process emissions are the conversion of limestone to lime (which includes both standalone lime production and cement clinker manufacturing),[11] the integrated manufacturing of steel from iron ore (until the recent idling of the Cleveland-Cliffs Dearborn Works facility), and hydrogen production from natural gas (Figure 2). In 2023, Michigan's industrial process emissions accounted for about 3.5 MMT CO_2e.[12]

---

[7] In addition to CO_2, other GHGs include methane, nitrous oxide, hydrofluorocarbon, perfluorocarbon, and sulfur hexafluoride. Each gas has a known different global warming potential value, which is used to convert absolute emissions to a CO_2-equivalent value for easier tracking and data comparisons.

[8] 5 Lakes Energy (5LE) analysis based on U.S. EPA GHGRP data in FLIGHT. Included in 5LE analysis are all subsectors under NAICS codes 31-33, as well as iron ore mining. Note that the total emissions assigned to the industrial sector in Michigan's Comprehensive Climate Action Plan, calculated using both EPA's State Inventory Tool and GHGRP, cover a wider scope of emissions than those referenced in this white paper.

[9] The exact temperature values prescribed to the three categories are not standardized and vary slightly among different publications.

[10] 5LE analysis based on U.S. EPA GHGRP data in FLIGHT. Included in 5LE analysis are all subsectors under NAICS codes 31-33, as well as iron ore mining.

[11] Lime is also produced at all four of Michigan's beet sugar facilities and at two pulp and paper mills. In beet sugar manufacturing, the process CO_2 that is generated during lime production is captured and then mineralized (i.e., sequestered) in downstream processes. In pulp and paper manufacturing, lime is commonly made from biologically derived carbonate, and the generated process CO_2 is therefore classified as biogenic.

[12] 5LE analysis based on U.S. EPA GHGRP data in FLIGHT. Included in 5LE analysis are all subsectors under NAICS codes 31-33, as well as iron ore mining.

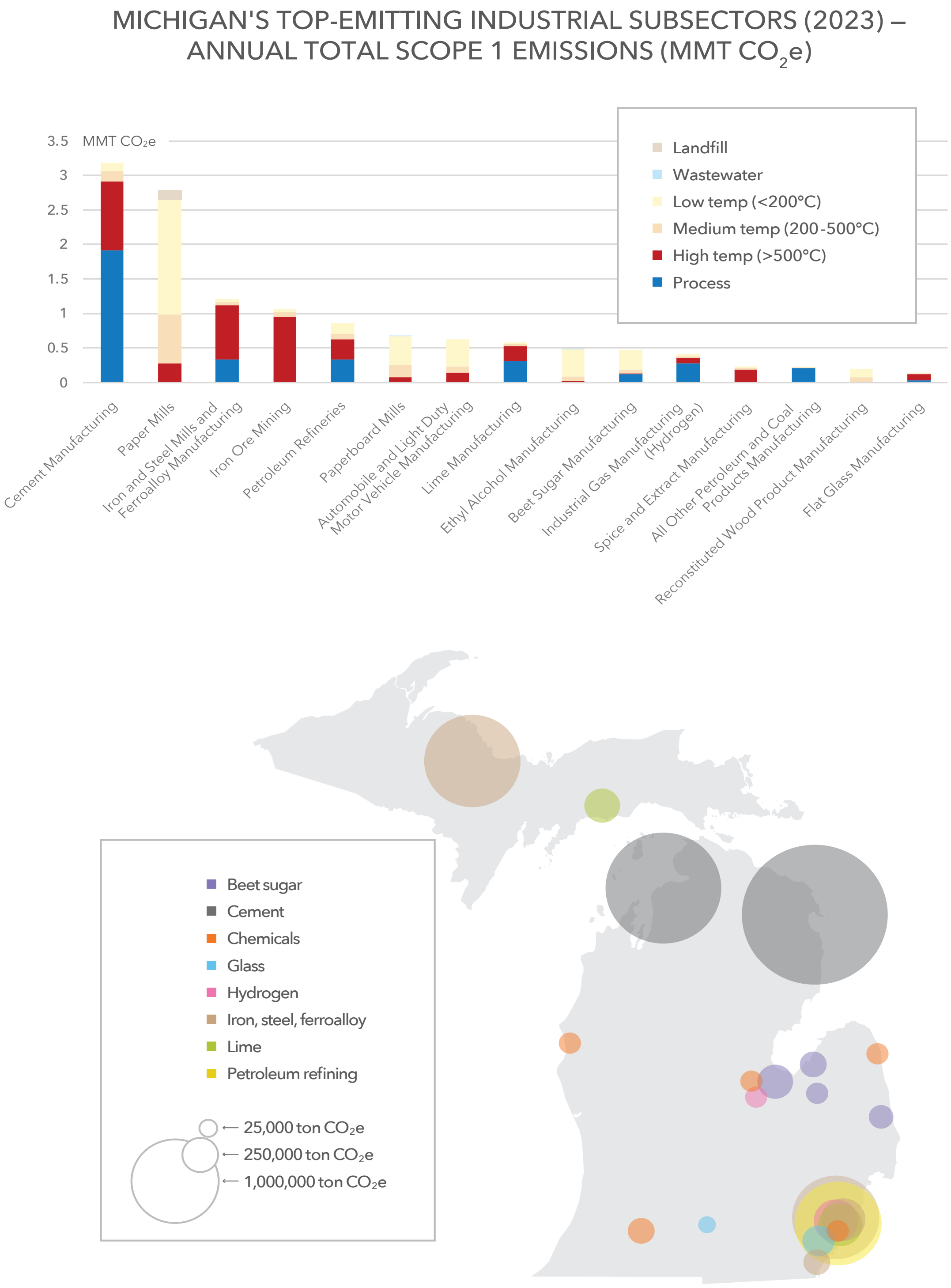


Figure 2 *Michigan's top-emitting manufacturing subsectors. Top panel: Annual total emissions by subsector, in million metric tons (MMT) of CO_2-equivalent (CO_2e). Process and high-temperature heat-derived emissions are considered hard-to-abate and are the focus of this white paper. For petroleum refining, process emissions include gas flaring emissions. Emission values for the following subsectors include biogenic emissions, with the percentage of the total value shown in parentheses: paper mills (59%), paperboard mills (29%), and reconstituted wood product manufacturing (34%). All values are based on 5 Lakes Energy analysis of the facility level data reported to U.S. EPA's GHGRP and accessed in FLIGHT. Subsectors correspond to 6-digit NAICS classifications. Bottom panel: Map of Michigan's facilities in the hard-to-abate industries.*

Technical Approaches to Decarbonizing Hard-to-Abate Emissions

In most industries, the primary tactics for reducing scope 1 emissions are minimizing on-site fuel combustion by increasing energy and material efficiency (i.e., reducing input requirements and waste generation) and electrifying the generation of heat where possible. For some heavy industries, such as cement and iron production, major efficiency gains or electrification may not be accessible at present due to the prior optimization of legacy fossil fuel-powered equipment and/or a lack of sufficiently developed, cost-effective electric equipment. For processes that are especially difficult to electrify, the use of alternative fuels with a low carbon intensity may offer another option. Finally, for residual carbon emissions that cannot be abated with existing approaches, carbon capture or atmospheric carbon removal will likely be needed to achieve net-zero. The tools for and challenges associated with implementing these strategies are discussed below.

IMPROVED EFFICIENCY

Measures to increase efficiency and reduce waste are typically the most cost-effective options for facilities to lower their carbon intensity.[13] In support of this idea, the efficiency measures implemented by the growing number of industrial partners in the U.S. Department of Energy's Better Plants Program — currently including more than 3,700 industrial plants — have delivered a 1.8% average annual energy intensity improvement rate, leading to two impressive savings totals since 2009: 2.8 quadrillion BTU of industrial heat and $14.1 billion in facility costs.[14] The most impactful areas for efficiency enhancements at energy-intensive industrial facilities include the adoption of energy-efficient technologies, systems optimization (via the use of sensors, analytics, smart manufacturing tools, and strategic energy management), and waste heat recovery.[15] Specific solutions vary by subsector, facility, and process, and a high level of customization is required to implement some of the most impactful measures, especially those related to systems optimization and waste heat utilization.

> *Industrial heat pumps can play a key role in waste heat recovery measures, leading to system efficiency gains.*

Industrial heat pumps can play a key role in waste heat recovery and reuse, while providing space or low-temperature process heat. Heat pumps, typically powered by electricity, transfer heat from one location to another — an approach that is significantly more energy efficient than technologies like resistance heating units, which convert electricity to heat directly. The efficiency of heat pumps is related to the required temperature 'lift,' or the difference between the temperature of the source heat and the higher temperature needed for the manufacturing process. Therefore, the recovery of waste heat using a heat pump has a double advantage, in that it reduces energy losses from the system while simultaneously enabling greater efficiency (or higher output temperature) per unit of electrical energy supplied to power the pump.

---

[13] J. Cresko, E. Rightor, A. Carpenter, et al., "Industrial Decarbonization Roadmap," U.S. Department of Energy, September 2022.

[14] U.S. DOE's Better Plants infographic 2025, accessed February 2026.

[15] J. Cresko, E. Rightor, A. Carpenter, et al., "Industrial Decarbonization Roadmap," U.S. Department of Energy, September 2022.

The use of waste heat recovery to generate electricity, in a process known as 'waste heat to power' or WHP,[16] is another key approach for system-level efficiency in manufacturing. In WHP systems, thermal energy from waste heat is used to drive a turbine, which generates electrical power. Optimizing the use of WHP technology depends on the specific system and waste heat characteristics, such as temperature[17] and consistency. The generated electricity can be used on-site or sold to the grid.

Although, as stated above, enhanced efficiency measures are often highly cost-effective, a variety of barriers can either prevent or slow down their implementation.[18] Major barriers include internal competition for capital and requirements for short-term return-on-investment, insufficient incentives from the government or utilities, and a lack of familiarity and technical expertise in available solutions at many facilities.

ELECTRIFICATION

In 2023, fuel combustion for industrial process heating across all temperatures accounted for about 10.5 MMT CO_2e in Michigan.[19] Electrification of process heating, *paired with continued grid decarbonization*, presents a major opportunity to lower carbon intensity of the manufacturing sector. Importantly, the replacement of fossil fuel-powered equipment with electric heat generation at industrial facilities would eliminate major sources of hazardous air pollutants at hundreds of locations across Michigan,[20] thus providing significant co-benefits in the form of a higher quality of life and healthcare cost savings.[21] Furthermore, compared to combustion, electrified heat generation is typically more efficient because it does not produce hot exhaust gases or water vapor as byproducts that constitute significant energy losses in combustion-based systems.

In 2023, fuel combustion for industrial process heating accounted for about 10.5 MMT CO_2e in Michigan.

A variety of electricity-powered industrial heat-generating equipment is available at various stages of technological readiness, with some technologies available for mass deployment and others at earlier stages of development (Figure 3). In general, electrification options for heat generation are more advanced for lower temperature applications, with some technology types ready to be deployed at scale. While some subsector-specific high-temperature electrified technologies are already employed in industry, cross-sector technologies, such as electrified replacement options for furnaces and kilns, are at earlier stages of development, increasing the barriers to mass deployment in the near-term.

Industrial heat pumps and electric boilers are commercially ready cross-sector bulk heating technologies, but they are limited to the generation of heat up to 200°C and 350°C, respectively. Both technologies have been discussed extensively in several recent reports, including RMI's Michigan Clean Manufacturing Roadmap, as important for the decarbonization

---

[16] "Waste Heat to Power," U.S. DOE's Combined Heat and Power Technology Fact Sheet Series, accessed February 2026.

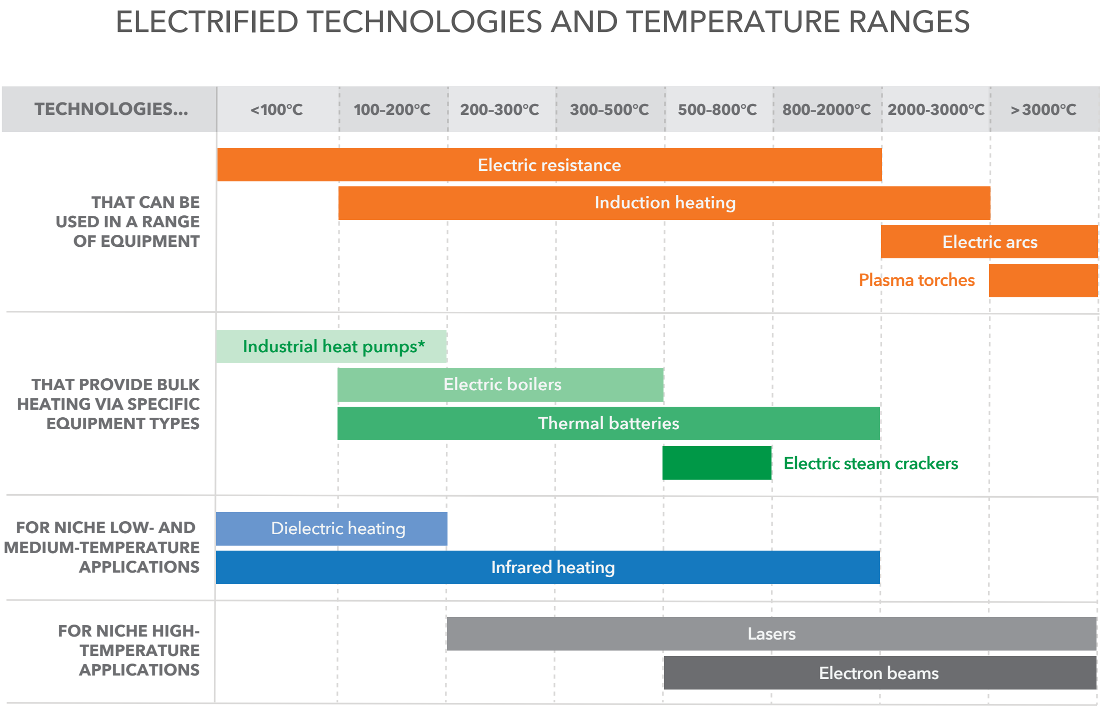
[17] Traditionally, only waste heat temperatures greater than ~235°C have been considered practical, but newer technologies are lowering that threshold (see: "Waste Heat to Power").

[18] "Barriers to Industrial Energy Efficiency: Report to Congress," U.S. Department of Energy, June 2015.

[19] 5LE analysis based on U.S. EPA GHGRP data in FLIGHT. Included in 5LE analysis are all subsectors under NAICS codes 31-33, as well as iron ore mining.

[20] National map of industrial boilers, Evergreen Action, accessed February 2026.

[21] "Michigan's Comprehensive Climate Action Plan," Michigan Department of Environment, Great Lakes, and Energy, December 2025.



** up to 160°C, some up to 200°C*

NOT INCLUDED: *UV light and electrolysis, which are both non-thermal forms of energy that can replace heating in specific applications*

Figure 3 *Industrial electrified heating technologies and their temperature ranges. Image reprinted from S. Baldwin, S. Desphande, N. Sawe, et al., "Overcoming All Barriers to Industrial Electrification," Energy Innovation, June 2025.*

of low- to medium-temperature industrial heat.[22] Importantly, while heat pumps are unable to meet directly the high-temperature heat requirements of the hard-to-abate subsectors, which are the focus of this report, they can be used to reduce the overall energy requirements at some facilities by enabling the recovery of waste heat (as discussed in the previous section) to pre-heat input materials or gasses.

A major barrier to industrial electrification across applications and technologies is the higher cost of electricity compared to natural gas. In Michigan, the ratio of electricity to gas price per unit of energy – commonly referred to as the 'spark gap,' – is greater than three (Figure 4), and would lead to higher operating costs of electrified heat generation compared to natural gas combustion.[23] Alternative electricity rate designs that incentivize demand flexibility may be needed to help reduce the spark gap, as discussed in Electricity rate structures and flexible demand, below.

Thermal batteries

Thermal batteries are a key promising technology for meeting a wide range of industrial heating needs, capable of providing heat up to 1,800°C. Two primary characteristics of thermal batteries are: 1) their ability to convert electricity to heat, and 2) their capacity to store heat for long periods of time – hours to days – with minimal loss (Figure 5). The coupling of both

---

[22] E. Rightor, P. Scheihing, A. Hoffmeister, and R. Paper, "Industrial Heat Pumps: Electrifying Industry's Process Heat Supply," ACEEE, March 2022; S. Smillie, D. Alberga, R. Locken, et al., "Decarbonizing Industrial Heat: Measuring Economic Potential and Policy Mechanisms," Energy and Environmental Economics, Inc., October 2024; The Renewable Thermal Vision, Renewable Thermal Collaborative, accessed February 2026; E. Albergo, B. Cangelose, J. Corvidae, et al., "Michigan Clean Manufacturing Roadmap," RMI, October 2025.

[23] E. Albergo, B. Cangelose, J. Corvidae, et al., "Michigan Clean Manufacturing Roadmap," RMI, October 2025.

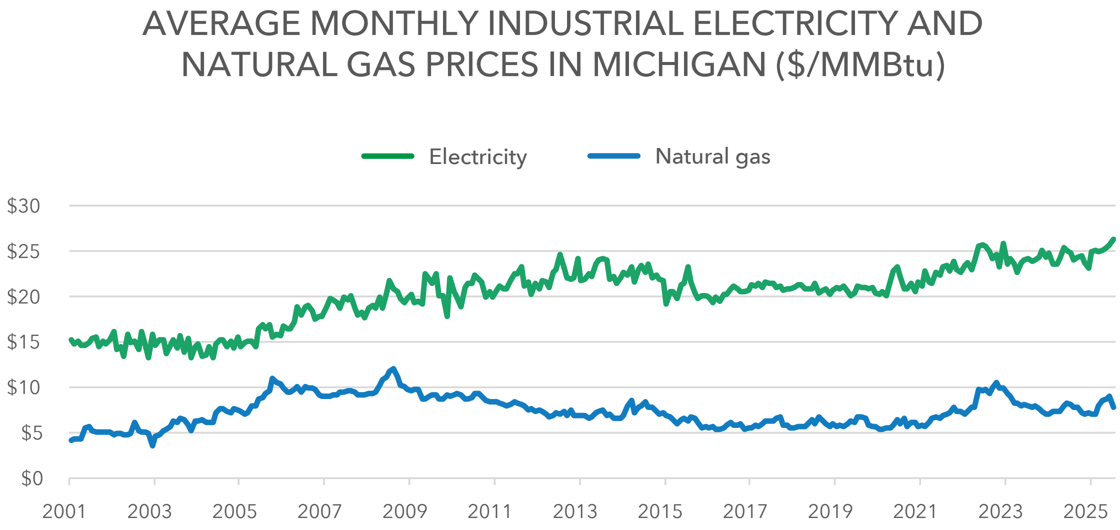


Figure 4 *Average monthly industrial electricity and natural gas prices in Michigan, normalized to dollars per million British thermal unit (MMBtu). Source: U.S. Energy Information Administration MI Natural Gas Industrial Price and Historical State Data.*

capabilities is the central feature of thermal batteries that can help meaningfully address the electricity cost barrier for manufacturing electrification and enable greater reliance on intermittent solar and wind power, at both the facility and grid level.

Thermal batteries typically use inexpensive materials (e.g., graphite, clay bricks, salts, crushed rocks, slag byproduct) capable of storing large quantities of high-temperature heat, which is generated by running an electric current through either a resistor or the storage material itself. A flow of air or liquid through the hot storage material is then used to deliver the battery's stored heat to the industrial process. Thermal batteries can achieve efficiencies (thermal

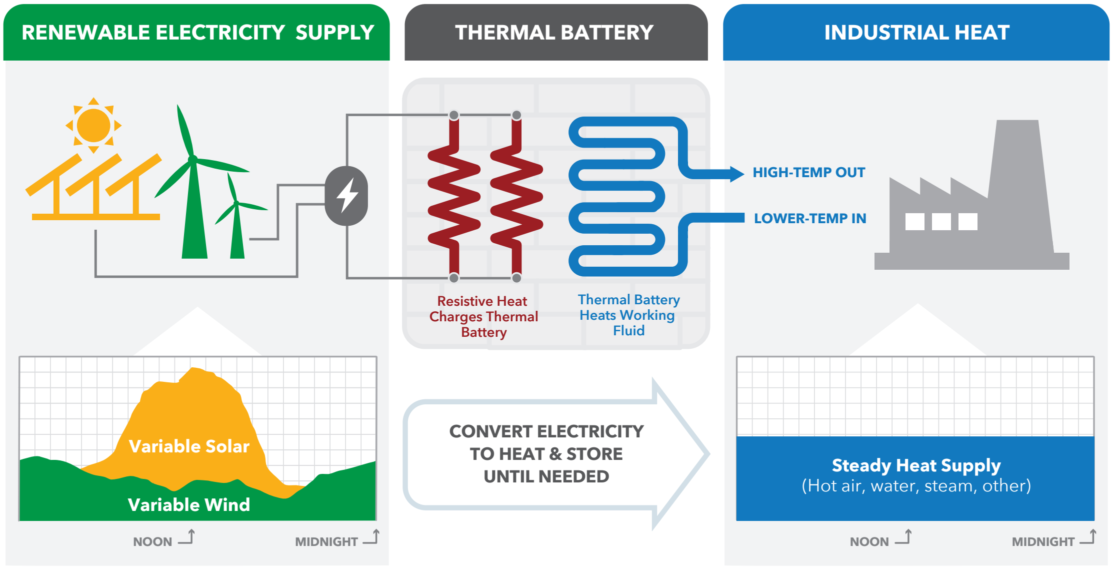


Figure 5 *Typical thermal battery configuration. Image adapted from K. Spees, J. M. Hagerty, and J. Grove, "Thermal Batteries: Opportunities to Accelerate Decarbonization of Industrial Heat," The Brattle Group, Center for Climate and Energy Solutions, and Renewable Thermal Collaborative, with permission from the authors.*

energy output versus electrical energy input) of 90-98% and can operate without degradation over many cycles and years.[24] As with other electrified heat technologies, thermal battery development is more advanced for low- to medium-temperature ranges.[25] Several companies are actively developing batteries capable of providing heat at temperatures of 1,500-1,800°C, aiming to electrify industries that include cement, primary steel, and refining.[26] Although the core technologies of thermal batteries are becoming well-established, the high energy intensity requirements paired with unique needs and specifications of the hard-to-abate industrial subsectors inherently present additional challenges for the adoption and integration of thermal batteries in existing configurations and facilities.

Beyond heat delivery, thermal batteries can function as an energy storage mechanism similar to electrochemical batteries (e.g., lithium ion). This means thermal batteries are an alternative technology with the potential to help manage load variability on electrical grids as they become increasingly constituted by renewable generators. In this context, the thermal battery can be charged during times of excess electricity supply, when generation capacity exceeds load from other customers. On the output side, thermal batteries can supply constant, uninterrupted heat to meet the specific requirements of the industrial users (see Figure 5). They can be powered by the grid, as well as by dedicated renewable electricity generation, either in front of or behind the meter.

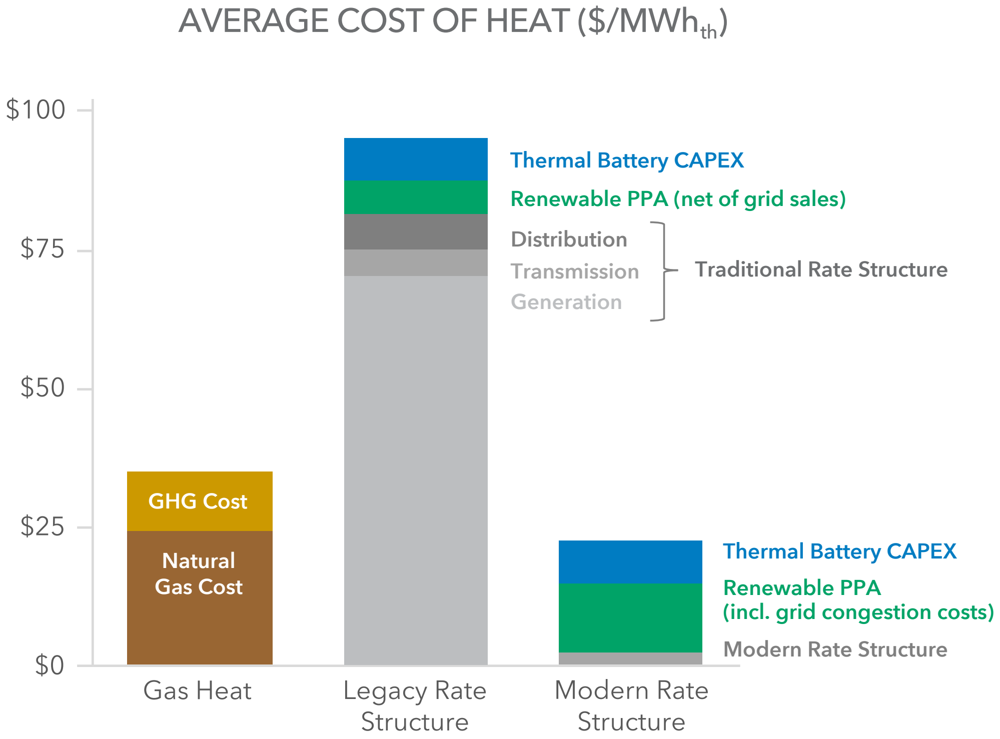


Figure 6 Thermal battery-generated heat is highly sensitive to electricity rate structures. Under legacy rate structures, thermal batteries are not cost-competitive with natural gas on a levelized cost of heat (LCOH) basis. However, a modern rate structure with a time-of-use pricing scheme that offers access to market-based electricity prices could reduce thermal battery LCOH below that of a natural gas-powered boiler. Adapted from K. Spees, J. M. Hagerty, and J. Grove, "Thermal Batteries: Opportunities to Accelerate Decarbonization of Industrial Heat," The Brattle Group, Center for Climate and Energy Solutions, and Renewable Thermal Collaborative, with permission. Data for the figure was kindly provided by The Brattle Group.

---

[24] K. Spees, J.M. Hagerty, and J. Grove, "Thermal Batteries. Opportunities to Accelerate Decarbonization of Industrial Heat," The Brattle Group, October 2023.

[25] According to conversations with thermal battery manufacturers, although some thermal batteries are already capable of storing and discharging heat at temperatures up to 1,500-1,800°C, their integration in high-temperature industrial operations requires additional extensive engineering and optimization to ensure compatibility with existing processes and equipment. For this reason, most companies have focused early applications at the lower to medium temperature ranges such as boiler replacement and steam generation.

[26] For example: Antora Energy, Electrified Thermal Solutions, Rondo Energy. All accessed February 2026.

While thermal batteries have a clear potential to support electricity demand flexibility, thereby enabling greater penetration of intermittent renewable power generation into Michigan's grid and ensuring more efficient use of existing resources, outdated electricity pricing schemes threaten their adoption.[27] As shown in Figure 6, the levelized cost of heat from thermal batteries is highly sensitive to electricity rate structures. According to analysis presented in a recent report,[28] access to wholesale electricity pricing could make thermal battery heat competitive with natural gas-powered heat in Michigan with economics expected to become more favorable as the intermittent renewable power generation increases. Therefore, key to supporting wide-scale thermal battery adoption in the state will be the implementation of supportive policies, continued grid decarbonization, and alternative electricity rate structures (see further discussion in Electricity rate structures and flexible demand, below).

ALTERNATIVE FUELS

The existing barriers to electrification — namely, cost and technological readiness — will likely necessitate alternative approaches for reducing the carbon intensity of some industrial heat processes, especially in the near term. Low-carbon-intensity fuels may offer a practical solution by serving as drop-in options that existing combustion systems rely on, enabling faster progress toward decarbonization in some sectors. The primary options (discussed below and summarized in Table 1) are biomass and biomass-containing waste (such as residues from agriculture, food processing, and construction), renewable natural gas (RNG), scrap tires, and hydrogen. However, the overall potential of these fuels is constrained by their availability and the likelihood of cost increases as demand grows.

ALTERNATIVE FUEL	BENEFITS	DISADVANTAGES
Biomass and biomass-containing waste (e.g., agricultural, construction, demolition)	• High biogenic (renewable) carbon content in many materials • Avoids methane emissions from landfilling • High temperature combustion can eliminate toxins from waste materials	• Inconsistent supply • May require modifications to the operating parameters of combustion equipment • Combustion generates particulate matter and other air pollutants
Scrap tires	• High energy density • Minimized upstream emissions associated with fuel sourcing • Reduces potential for uncontrolled tire fires • Low cost	• Sequestered CO_2 is released during combustion • Higher value applications for scrap tires are rapidly developing and can continue to sequester the tire carbon instead of releasing it during combustion
Renewable natural gas (RNG)	• Drop-in replacement for fossil natural gas • Utilization and diversion of waste • Avoided methane emissions from waste resources	• Limited supply • High cost compared to fossil natural gas • Highly distributed resources with limited capacities • Some fugitive methane emissions are likely
Hydrogen	• Can be produced with zero or very low carbon emissions and does not produce CO_2 when burned • Can be used to generate very high-temperature process heat that may not be easy to electrify • Can be used in existing equipment and configurations with some modifications	• Electrolysis-based hydrogen is energy-intensive, requiring large amounts of clean electricity to produce • High cost • Current lack of dedicated infrastructure (e.g., pipelines) • Higher-value competing uses for clean hydrogen and clean electricity

Table 1 Benefits and disadvantages of alternative fuels for industrial process heat.

---

[27] In conversations with representatives from thermal battery manufacturers, electricity pricing was constantly mentioned as the main barrier to thermal battery adoption.

[28] K. Spees, J.M. Hagerty, and J. Grove, "Thermal Batteries. Opportunities to Accelerate Decarbonization of Industrial Heat," The Brattle Group, October 2023.

Biomass and biomass-containing waste

Biomass and biomass-containing waste can include unused fractions from existing industrial feedstocks and processes — such as bark, sawdust, dried pulp, fruit pits — and construction and demolition debris. When burned, these materials can supply high-temperature heat for various industrial applications with a lower carbon footprint compared to fossil fuels. Practical considerations for using biomass as fuel include handling requirements, compatibility with existing heating equipment, material composition, supply consistency, and proximity to source. In some industries, such as pulp and paper and beet sugar, significant quantities of biomass waste are generated on-site, making utilization more feasible and economically viable.

As a GHG emissions reduction approach, the use of biomass for industrial heat is most advantageous when it replaces landfilling. Decomposition of biomass in landfills typically occurs under low-oxygen conditions, which results in the generation of methane, a GHG far more potent than CO_2. However, in certain cases, repurposing or recycling biomass waste into new products may offer greater climate benefits by keeping carbon locked in materials rather than releasing it through combustion. Therefore, decisions about biomass use should be guided by comprehensive life-cycle assessments to ensure genuine reductions in the carbon intensity of industrial heat. In addition, it is important to consider that the burning of biomass is documented to have negative impacts on air quality due to the release of particulate matter and other criteria pollutants.[29]

> *Michigan's landfill tipping fee of only $0.36 per ton - far below the regional average - disincentivizes the utilization of waste as an alternative to landfilling.*

A major barrier to using waste as a low-carbon fuel is Michigan's landfill tipping fee[30] of $0.36/ton, which is far below the regional average and does not encourage alternative uses for the waste. The low tipping fee was explicitly mentioned by some stakeholders as having a negative impact on the availability of alternative fuels. An increase of the tipping fee to $5/ton has been proposed by Governor Whitmer's 2026 fiscal budget to bring Michigan in line with neighboring states. However, the same proposal did not pass in the 2025 budget.

Renewable natural gas (RNG)

RNG is pipeline-grade methane gas derived from renewable sources — organic waste — rather than extracted from fossil reserves. It can be used interchangeably with conventional natural gas, making it a practical drop-in substitute for existing systems. RNG potential in Michigan was analyzed in a 2022 study ordered by the Michigan Public Service Commission (and prepared by ICF Resources LLC).[31] Here, key relevant points from that publication are summarized, but additional details can be found in the ICF report. Current RNG production relies mainly on anaerobic digestion of feedstocks such as landfill waste, wastewater treatment byproducts, and animal manure. Future supply could expand to include agricultural residues, dedicated energy crops, forestry waste, and municipal solid waste. One challenge currently facing the broader adoption of these pathways is the need for thermal gasification — a process in early commercialization, which is currently more expensive than anaerobic digestion. In all, the ICF report estimates that Michigan-sourced RNG could meet between 8.5% and 22% of the state's

---

[29] A. Tomlin, "Air Quality and Climate Impacts of Biomass Use as an Energy Source: A Review," Energy and Fuels, 35: 14213-1240, 2021.

[30] A landfill tipping fee is a charge for a given quantity of waste disposed at a landfill.

[31] "Michigan Renewable Natural Gas Study," ICF Resources, LLC, prepared for the Michigan Public Service Commission, September 2022.

current average annual natural gas demand, depending on factors that include feedstock availability, market conditions, and relevant policies. While most of the currently produced RNG in Michigan is used for transportation, the growth of market demand from other sectors, such as manufacturing, would likely stimulate the continued investment and expansion of RNG production in the state.

Michigan-sourced RNG could meet between 8.5% and 22% of the state's current demand for natural gas.

RNG production pathways have a wide range of associated costs, which are driven largely by the production equipment, feedstock collection and handling, scale of operations, and the need for conditioning and purification of the final product. Furthermore, interconnection and infrastructure buildout to the production points, which are commonly located far from major demand centers, can add substantial upfront capital costs to projects. According to the ICF report, the lowest cost of RNG in Michigan – sourced from landfill gas – is about $10/MMBtu, while other sources are more expensive and can exceed $30/MMBtu on the upper end. For comparison, over the past two decades, industrial natural gas prices in Michigan have typically hovered in the range of $5-$9/MMBtu, rarely exceeding $10/MMBtu (Figure 4), making RNG's higher cost a significant hurdle.

When evaluating RNG as a decarbonization strategy, the cost of avoided emissions is another important consideration. In the case of emissions from process heat that cannot be directly electrified due to low technology readiness or unfavorable economics, RNG may provide a cost-effective alternative option. RNG carbon intensity is highly feedstock dependent.[32] Therefore, careful life-cycle assessments paired with techno-economic analyses are essential to determine when RNG could be a cost-effective decarbonization option for specific facilities.

Scrap tires

Each year in the United States, more than 260 million scrap tires are collected and processed for secondary use.[33] In Michigan, approximately 10 million tires are generated and processed annually.[34] Beginning in the early 1990s, many states, including Michigan, enacted policy and regulatory changes to manage the growing issue of scrap tire accumulations that created significant fire and public health hazards across communities.[35] As a result of these changes, a common application for scrap tires became their use as fuel (termed 'tire-derived fuel' or TDF), primarily in cement lime kilns and pulp and paper mills, as well as some industrial boilers.[36] The primary benefit of TDF is the displacement of coal at facilities, enabled by TDF's higher energy density (~25%) and lower NO_X emissions compared to coal.

Despite some clear benefits of using scrap tires as TDF, the burning of tires releases CO_2, most of which is derived from petroleum and that could otherwise be sequestered via other uses. In 2023, changes in Michigan law explicitly excluded tires and TDF from being considered as renewable energy resources,[37] which had previously been allowed. This change makes tire

---

[32] According to analysis in the American Gas Foundation's 2025 assessment, RNG derived from food waste, dairy manure, and swine manure has especially high potential for mitigating GHG emissions from those sources.

[33] "2023 End-of-Life Tire Management Report," U.S. Tire Manufacturers Association, 2024.

[34] E. Seltzer, B. Hall, and C. Theriot, "Scrap Tire Market Development Study," RRS recycle.com, prepared for Michigan Department of Environment, Great Lakes, and Energy, January 2020.

[35] For example, see: "Used Tires," U.S. EPA, May 2025.

[36] "2023 End-of-Life Tire Management Report," U.S. Tire Manufacturers Association, 2024.

[37] Legislative Analysis, Clean and Renewable Energy Standards, Senate Bill 271 (S-3) as passed by the Senate.

burning no longer eligible for renewable energy credits. At the same time, the technologies and markets for the second life (repurposing) of scrap tires in higher-value applications are advancing.[38] These include rubber-modified asphalt, playgrounds and athletic fields, conversion to transportation fuels and carbon black via pyrolysis, and others.

In summary, TDF is a relatively straightforward, low-technology solution to the problem of scrap tire accumulation and has some clear benefits over coal. However, because alternative higher value applications of scrap tires, which continue to sequester tire carbon, are becoming available, the use of TDF for industrial process heat should not be seen as an optimal decarbonization pathway for the longer term.

Hydrogen

Hydrogen (H_2) is a highly flammable gas that does not emit CO_2 when burned in the presence of oxygen.[39] Hydrogen burns hotter than natural gas and has been considered as a potential low- or zero-carbon fuel for generating high-temperature industrial heat. While hydrogen combustion for heat is technically a possible option, several longstanding challenges, which are summarized below, make hydrogen an unlikely candidate as a viable decarbonization option for industrial heat under current circumstances.

Although the burning of hydrogen does not generate CO_2, hydrogen can still be a carbon-intensive fuel, from the perspective of the life cycle of its production pathway. Currently, most hydrogen in the United States is produced via steam methane reforming (SMR) of natural gas, which results in 10-11 kg CO_2e/kg H_2. Cleaner production pathways for hydrogen include the SMR method with carbon capture or the use of low-/zero-carbon electricity to split water into hydrogen and oxygen (i.e., electrolysis), an energy-intensive process. The main challenges for low-carbon hydrogen pathways are technology readiness, scalability, and costs. According to the U.S. National Clean Hydrogen Strategy and Roadmap, hydrogen would need to cost ~$1/kg to be considered an economically realistic option for industrial heat. However, recent analyses of hydrogen production pathways continue to estimate production costs for low- and zero-carbon hydrogen well above that target.[40]

The storage, transportation, and burning of hydrogen require dedicated or modified equipment due to hydrogen's high reactivity, which would further raise costs for potential users. Additional challenges arise from competing uses for clean electricity (e.g., data centers and broad electrification targets) and existing higher-value applications for clean hydrogen (e.g., as a feedstock for ammonia, methanol, and semiconductors). Finally, the early ending of the federal clean hydrogen production tax credit, known as 45V and designed to incentivize clean hydrogen production, is likely to reduce interest from potential developers and investors in new projects.[41]

Based on the magnitude and combination of the above challenges and the shifting of priority decarbonization strategies at the federal level, the use of hydrogen as a fuel for industrial heat seems unlikely in the near term. Notably, none of the stakeholders interviewed for this white paper mentioned hydrogen-fueled process heat as a major decarbonization pathway in their

---

[38] E. Seltzer, B. Hall, and C. Theriot, "Scrap Tire Market Development Study," RRS recycle.com, prepared for Michigan Department of Environment, Great Lakes, and Energy, January 2020.

[39] The burning of hydrogen still results in the formation of nitrous oxides because the high combustion temperature drives the reaction between nitrogen and oxygen in the air. See "Does the use of hydrogen produce air pollutants such as nitrogen oxides?," U.S. Department of Energy, accessed February 2026.

[40] "Pathways to Commercial Liftoff: Clean Hydrogen," U.S. DOE's Update 2024, December 2024.

[41] 45V is a clean hydrogen production tax credit up to $3.00/kg H2 available for 10 years after the production facility is placed in service. The federal budget passed in summer 2025 severely constrained the potential impact of the tax credit by shifting the deadline to initiate construction of production facilities from December 31, 2032, to December 31, 2027, for eligibility.

current plans and strategies. However, the case for hydrogen as a potential low-carbon fuel for industrial heat should be re-examined periodically in the coming years to account for possible technological advances in existing low-carbon hydrogen production pathways, the emergence of new clean hydrogen resources (e.g., geological hydrogen, which may be particularly relevant in Michigan),[42] or changes in federal decarbonization priorities.

CARBON CAPTURE, UTILIZATION, AND STORAGE (CCUS)

The industrial decarbonization strategies discussed above are constrained by a multitude of factors that include but are not limited to economic competitiveness, technological availability, and the high diversity of facility needs and designs. According to the 2022 U.S. Department of Energy Industrial Decarbonization Roadmap, energy efficiency, electrification, and alternative fuels will reduce industrial emissions by about 40% by 2050, with most of the remaining emissions mitigated via carbon capture.[43] Capture of CO_2 at the point sources of emissions and sequestration via storage in geological formations is increasingly seen as a major strategy for addressing residual carbon emissions, and CCUS is included in many businesses' long-term decarbonization plans. Multiple industrial stakeholders interviewed for this white paper confirmed their companies' interest in CCUS as a potential strategy to address residual carbon emissions. At the same time, CCUS remains a controversial decarbonization approach due to questions around its scalability, economic viability, and the moral hazard of continued reliance on fossil fuels that CCUS arguably enables.[44]

CCUS involves three main steps: 1) CO_2 capture at or near the emitting facility, 2) compression and transport of the captured CO_2 to the utilization or storage site, and 3) either sequestration of the captured CO_2 via permanent storage in depleted oil and gas fields[45] or suitable geologic formations,[46] or use in various applications.[47] Globally, 77 projects capturing a total of 64 million tons of CO_2 per year are currently in operation, spanning a wide range of industries. Another 47 projects are in construction, with an expected capacity of 44 million tons of CO_2 capture per year. In addition, more than 600 projects are in various stages of development.[48] Michigan has favorable geology for storing vast amounts of captured CO_2,[49] with the overall capacity well above the state's current and future emissions. However, as with many of the decarbonization approaches described above, cost and scalability are major current barriers to CCUS.

The established CO_2 capture process is highly energy intensive and makes up the largest fraction of the total cost of CCUS.[50] According to a 2024 Carbon Solutions report, which compiled data from several sources, the cost per ton of captured CO_2 in 2021 dollars ranges

---

[42] See Governor Whitmer's Executive Directive No. 2026-1, January 2026.

[43] J. Cresko, E. Rightor, A. Carpenter, et al., "Industrial Decarbonization Roadmap," U.S. Department of Energy, September 2022.

[44] K. Lebling, A. Gangotra, K. Hausker, and Z. Byrum, "7 Things to Know About Carbon Capture Utilization and Sequestration," World Resources Institute, accessed February 2026.

[45] Another common application for captured CO_2 has been its use for extracting oil reserves (termed enhanced oil recovery or EOR). This approach is considered 'utilization' but is controversial because it supports the continued use of fossil resources, which should be phased out as part of a comprehensive decarbonization strategy.

[46] Once the carbon has been stored, the site must be continuously monitored over the ensuing decades for potential leaks.

[47] Common applications include in the food and beverage sector and fertilizer production, which result in short-lived carbon sequestration. Other applications, such as building materials, fuels, and chemicals, are in early development.

[48] "Global Status of CCS 2025: Staying the Course," Global CCS Institute, October 2025.

[49] Carbon Capture, Utilization and Storage – Michigan Geological Survey, accessed February 2026.

[50] Most mature carbon capture technologies utilize amine-based solvents that bind and release CO_2 under different conditions. The release of CO_2 from the solvents requires a lot of heat, making the overall process energy intensive.

from about $20 to more than $70 depending on the industrial subsector.[51] Transport via pipelines and storage costs can add about $12-$22 per ton of CO_2 depending on travel distance and storage site characteristics. It is important to note that CO_2 capture cost estimates vary widely among publications, reflecting the high level of uncertainty associated with their modeling due to factors such as unique facility engineering requirements, energy costs, purity and concentration of CO_2 in the emission stream, and scale of operations. As a result, the economic viability of CCUS remains in question, requiring continued technological developments and support for demonstration projects that will generate real-world data in a wide range of scenarios. The 45Q federal carbon capture tax credit, which provides up to $85 per ton of CO_2 captured for 12 years of operation, is considered an essential incentive for any industrial carbon capture project in the United States. However, based on the above estimates and conversations with stakeholders, this credit is unlikely to sufficiently offset the costs of many CCUS projects.

Besides storage, an alternative option for captured CO_2 is use as a feedstock for new products, such as fuels and chemicals, which could reduce reliance on fossil feedstocks. However, to achieve net-zero targets, any strategy for utilizing captured CO_2 should focus on long-term sequestration of the carbon in the final products,[52] ensuring that it will not be emitted within a short time frame. The potential impact of captured CO_2 utilization as a feedstock is difficult to predict due to the low level of technology readiness. One stakeholder suggested that creating CO_2 utilization industrial hubs could spur developments in this area, eventually helping advance the economic viability and environmental benefits of industrial carbon capture.

In summary, CCUS is widely considered to be an important and potentially essential strategy for addressing hard-to-abate industrial emissions, and Michigan's geology is favorable for carbon storage at capacities that would be required. However, the economic viability and scalability of CCUS remain uncertain due to the high costs associated with CO_2 capture from industrial streams. Additional barriers could also arise from the current lack of CO_2 pipeline infrastructure and established injection sites. Infrastructure buildout can face unexpected costs and delays during the permitting process and from potential community opposition.[53]

CARBON DIOXIDE REMOVAL (CDR)

Although the range of decarbonization strategies and pathways discussed above provides many potential opportunities for facilities to reduce their emissions, a subset of industrial emissions is unlikely to be eliminated due to a combination of technical and cost constraints. The 2022 U.S. Department of Energy Industrial Decarbonization Roadmap estimates that by 2050, 13% of 2015-level industrial emissions – or more than 50 million tons of CO_2 – will require mitigation via so-called 'alternate approaches' that remove carbon dioxide from the atmosphere.[54] A recent global assessment of CDR needs estimated that by 2050, 7-9 gigatons of CO_2 removal per year will be needed to achieve the Paris Agreement limit of global

---

[51] E. Middleton, M. Ford, M. Miranda, et al., "National Industrial Sector Decarbonization: Extent of Carbon Capture Opportunities and Network Optimization Across the United States," Carbon Solutions, May 2024.

[52] Examples of potential durable materials that could utilize captured CO_2 include concrete and other construction materials, carbon fiber, and plastics. For a detailed discussion, see: J. Bobeck, J. Peace, F.M. Ahmad, R. Monson, "Carbon Utilization – a Vital and Effective Pathway for Decarbonization," Center for Climate and Energy Solutions, August 2019.

[53] For example, see: Louisiana Residents Sue Over CO_2 pipeline Land Seizures, Carbon Herald, accessed February 2026.

[54] J. Cresko, E. Rightor, A. Carpenter, et al., "Industrial Decarbonization Roadmap," U.S. Department of Energy, September 2022.

temperature rise of no more than 2°C,[55] underscoring the overall scale of need for carbon removal. Industry can play an active role in the advancement of CDR efforts through a variety of pathways. These can include the incorporation of carbon removal in existing industrial operations, supplying large volumes of feedstocks and materials, including waste, for certain CDR approaches, and/or the financing of external CDR projects.[56]

A variety of CDR approaches exist at different levels of technological readiness, scalability, sequestration potential, and durability.[57] The approaches can be broadly categorized as either biological or geochemical.[58] Biological approaches rely on natural CO_2-fixing mechanisms, primarily photosynthesis, to remove CO_2 from the air in biomass. Established (or 'conventional') biological pathways include improved forest management and conservation, reforestation, afforestation, grassland and wetland restoration, agroforestry, soil carbon sequestration via regenerative agriculture practices, and durable wood products. Several emerging (or 'novel') biological CDR pathways[59] are in development, with many active pilot and demonstration projects in the United States and globally. Geochemical pathways rely on non-biological chemical processes that capture CO_2. Many such processes occur naturally but can be enhanced through human intervention, such as reactions between minerals and atmospheric CO_2 that result in the formation of solid carbonates or dissolved bicarbonates. In other processes, specifically formulated solvents or suitable industrial wastes can be manipulated to bind and release atmospheric CO_2, producing a concentrated stream for utilization or storage. All geochemical CDR approaches can be categorized as novel because they are in earlier stages of development and are not yet deployed at scale.

Some biological CDR approaches already operate at scale and cost less than $20 per ton of CO_2 removed.

The current average estimated amount of CO_2 removed from the atmosphere globally via CDR efforts is about 2,200 million tons per year,[60] with 99.9% captured via conventional approaches (afforestation, reforestation, forest management). A large uncertainty is associated with this estimate due to the complexity of estimating carbon removal via improved forest management.[61] Although the overall global rate of CDR has slowed slightly in recent years, the research, development, deployment, and net capacity of novel CDR pathways is rapidly increasing.

---

[55] S. M. Smith, O. Geden, M. J. Gidden, et al., "The State of Carbon Dioxide Removal: A global, independent scientific assessment of Carbon Dioxide Removal," University of Oxford's Smith School of Enterprise and the Environment, 2024 (2nd edition).

[56] C. Maesano, E. Mitchell-Larson, K. Clark-Sutton, and D. Pike, "Seizing the Industrial Carbon Removal Opportunity: To reach net zero, and go beyond, heavy industries need to adopt carbon removal practices," RMI, April 2025.

[57] In the context of CDR, durability refers to the typical time scale that the captured carbon remains sequestered from the atmosphere, which is in the range of years to millennia, depending on the pathway. Although there is no universally defined time scale that is acceptable for CDR classification, only approaches that result in at least several decades of carbon storage are included in broadly accepted accounting methods. For example, corn-based ethanol, when combusted as a motor fuel, does not count as a CDR pathway.

[58] O. Geden, S. M. Smith, and A. Cowie, "Chapter 1: Introduction," in The State of Carbon Dioxide Removal: A global, independent scientific assessment of Carbon Dioxide Removal, 2024.

[59] The most advanced emerging pathways include bioenergy with carbon capture and storage (BECCS) and biochar. Other approaches include bio-oil storage, biomass burial or sinking, ocean fertilization.

[60] J. Pongratz, S. Smith, C. Schwingshackl, et al., "Chapter 7: Current Levels of CDR" in The State of Carbon Dioxide Removal: A global, independent scientific assessment of Carbon Dioxide Removal, 2024. Note that the 2,200 million tons of CO_2 captured per year via CDR is orders of magnitude more than the 64 million tons of CO_2 currently captured per year via CCUS.

[61] Accounting for carbon removal via improved forest management is complicated due to the difficulty of determining how much carbon is removed from the atmosphere specifically due to human activity in *addition* to the inherent carbon uptake that occurs in natural systems. This aspect is referred to as 'additionality'. The other complication comes from accounting for the global impacts of reduced harvests in one area due to improved forest management, which can result in *increased* harvests elsewhere. This aspect is referred to as 'leakage'.

Industry can play a major role in increasing the impact of both conventional and novel CDR pathways through financing, development, and/or integration of CDR with industrial activities. Companies can finance CDR projects by purchasing carbon credits on the voluntary carbon market or by partnering directly with project developers. The cost of CDR carbon credits[62] varies widely by approach. In 2023, the average price paid per CDR credit generated via forest management and afforestation/reforestation methods was $12 and $16, respectively. Notably, these figures are significantly less than the current estimates to achieve the same amount of carbon abatement via CCUS, as described above. Other CDR credits were priced one or two orders of magnitude higher, ranging from $111 to $1,402 per credit, reflecting the need for continued research and development of alternative carbon removal pathways.[63]

> *Some CDR pathways can be integrated in existing industrial operations or value chains.*

Industrial entities can identify opportunities to help bring down CDR costs by utilizing appropriately scaled resources, such as waste materials that can be used in the CO_2 capture process. Industries can also provide valuable experience and the infrastructure needed to handle and process large quantities of materials (e.g., crushing rock), which can accelerate large-scale CDR project development. Industries should also work to identify novel approaches to directly and measurably incorporate CO_2 into durable manufactured products (e.g., construction materials), which can help companies meet their sustainability and net-zero goals, as well as potentially provide additional revenue streams via the carbon market.

Although some CDR pathways — namely, forest management, afforestation, and reforestation — are already well established, scalable, and relatively inexpensive, the inclusion of CDR as an explicit approach to industrial decarbonization also faces barriers. Like CCUS, CDR is susceptible to the criticism that its use creates a moral hazard because it can enable companies to continue relying on fossil fuels, while formally meeting carbon reduction goals. In addition, the CDR sector is undergoing active development in the technical, certification, and market development aspects, which means that there is a wide range of quality — and consequently confidence — in CDR projects and the carbon credits they generate. Active engagement and collaborations among CDR stakeholders including project developers, certifiers, government, academia, and businesses will be needed if CDR is to be employed as an effective tool at scale for addressing residual industrial emissions without disincentivizing the decarbonization efforts that minimize emissions in the first place.

---

[62] One carbon credit equals one ton of CO_2 removed from the atmosphere or avoided from being emitted. Although the distinction between carbon removal and avoidance in forest management projects has not always been clear historically, methods for better differentiating the two types of credits are improving.

[63] S. Fuss, I. Johnstone, R. Hoglund, and N. Walsh, "Chapter 4: The Voluntary Carbon Market," in The State of Carbon Dioxide Removal: A global, independent scientific assessment of Carbon Dioxide Removal, 2024.

Industrial Subsector-Specific Decarbonization Strategies

CEMENT MANUFACTURING

Michigan's cement manufacturers emit the largest fraction of GHG emissions of any industrial subsector in the state. Two plants operate in the state: St. Marys Cement in Charlevoix and Amrize (formerly Holcim) in Alpena. The St. Marys Charlevoix plant's annual production capacity is about 2 million tons of cement, distributing through terminals in Wisconsin, Chicago, and western Michigan.[64] The Amrize Alpena facility is one of the largest cement plants in North America, with a production capacity of about 2.4 million tons of cement per year. It serves customers across the Great Lakes region in the United States and Ontario, Canada.[65] In 2023, the St. Marys and Amrize plants reported to the U.S. EPA Greenhouse Gas Reporting Program (GHGRP) total CO_2e emissions of 1.4 and 1.8 MMT, respectively. For both plants, nearly all emissions derive from cement kilns used to make clinker, the main ingredient in cement.[66] These emissions are considered hard-to-abate because they result from fuel combustion to generate high-temperature heat (up to 1,500°C or 3,000°F) and from the conversion of limestone to lime (the primary reactive ingredient in cement clinker), which releases CO_2 as a byproduct (see Figure 1). Although the GHG emissions reported by both facilities are not separated into fuel and process emissions, as much as two-thirds of the total emissions resulting from clinker production can be process emissions.[67,68]

The main approaches for decarbonizing the cement industry are:

- The use of alternative low-carbon-intensity fuels to generate heat for the cement kilns
- Reducing the amount of clinker in cement by using supplementary cementitious materials
- CCUS for cement kiln emissions

Both of Michigan's cement manufacturers utilize alternative fuels – various waste materials – to displace a fraction of the fossil fuels (including coal, petroleum coke, and natural gas) used to fire their cement kilns.[69] Since 2023, Amrize Alpena Cement also uses 2.2 million waste tires per year to supply about 10% of its thermal needs.[70] Logistical challenges in using variable waste materials as fuels include supply inconsistency and a need to adapt the handling and combustion processes to accommodate the different physical and chemical properties of materials. At present, Michigan's low landfilling fee of $0.36/ton also acts as an important barrier to increasing the fraction of waste materials used as fuel, by not incentivizing these alternative uses.

A less explored but emerging potential option for decarbonizing the process heat used in cement production is electrified heat generated using thermal batteries. A few companies are developing batteries capable of producing 1,500-1,800°C heat.[71] As battery technologies

---

[64] "Cementing the Future," St. Marys Cement, November 2024, accessed February 2026.

[65] "About Cement," Amrize Alpena Cement Plant, accessed February 2026.

[66] Ordinary Portland cement is typically about 95% clinker.

[67] G. Habert, S. A. Miller, V. M. John, et al., "Environmental Impacts and Decarbonization Strategies in the Cement and Concrete Industries," Nature Reviews Earth and Environment, 1: 559-573, 2020.

[68] Cement kilns have a common exhaust stack and, therefore, report a single total emissions value that includes both fuel and process emissions.

[69] According to data reported to U.S. EPA GHGRP.

[70] "Holcim Alpena cement plant opens new tyre-derived fuel facility," World Cement, June 2023.

[71] For example: Antora Energy, Electrified Thermal Solutions, Rondo Energy. All accessed February 2026.

mature, additional research, development, and engineering will be needed to effectively incorporate them into the existing cement manufacturing process. In addition, thermal batteries need cheap renewable electricity to be economically viable, as discussed above in Thermal batteries. In the coming years, Michigan could promote the adoption of thermal batteries at its cement facilities by working with stakeholders to help fund pilot and demonstration projects in the state while continuing the state's push to decarbonize its power grid. Other relevant considerations would include lowering barriers to behind-the-meter renewable energy projects and developing electricity rate structures that incentivize demand flexibility made possible by thermal batteries (and other storage technologies; see Electricity rate structures and flexible demand, below).

> *Performance-based rather than composition-based standards can incentivize and accelerate the adoption of new reduced-carbon-intensity cement.*

In addition to lowering the carbon intensity of heat generated to power cement kilns, another approach actively being explored within the cement industry is reducing the amount of clinker (the main product from cement kilns) in cement formulations by blending with supplementary cementitious materials (SCMs). SCMs have much lower carbon intensity but can replace a fraction of clinker without compromising the performance of the cement product. They can include byproducts from other industries (e.g., coal fly ash from power generation, blast furnace slag from ironmaking), fine limestone, calcined clays, and a range of other natural or synthetic materials. SCMs can replace up to 50% of clinker in cement blends, reducing carbon intensity of the product by nearly 40%.[72] Utilization is influenced by both the regional availability of suitable materials and local regulations. Performance-based regulations can incentivize and accelerate the adoption of new reduced-carbon-intensity cement, whereas composition-based, prescriptive regulations for cement and concrete can act as barriers to deviations from historical formulations. This is particularly relevant for road and building materials standards, which directly impact cement and concrete formulation allowances.

Even with the full decarbonization of cement manufacturing process heat (e.g., via the use of high-temperature thermal batteries), limestone-based cement production will generate significant process emissions from the conversion of limestone to lime during clinker production (see Figure 1). Because these emissions are a byproduct of the process itself, they cannot be avoided without changing the way that cement is made.[73] In reflection of this reality, carbon capture is widely considered to be a key long-term strategy for addressing process emissions from clinker production. However, the current additional costs of CCUS present a major economic challenge to the industry even with the 45Q federal tax credit (which provides up to $85 per ton of captured carbon). Therefore, technological advances, additional state or federal incentives, and/or a market willingness to pay a higher price for low-carbon-intensity cement and concrete may be needed to stimulate the incorporation of CCUS in the cement industry. Alternatively, high-quality CDR projects may need to be developed — either directly integrated within the cement and concrete manufacturing process (or the value chain) or indirectly via dedicated funding of off-site projects (e.g., afforestation, wetland restoration) — to verifiably remove all CO_2 generated by cement manufacturing in the state from the atmosphere each year.

---

[72] "Pathways to Commercial Liftoff: Low-Carbon Cement," U.S. Department of Energy, September 2023.

[73] Alternative cements are being explored but are not currently a viable option.

PETROLEUM REFINING

Michigan has one petroleum refinery, located in Detroit and owned and operated by Marathon Petroleum Corporation. The refinery is a large consumer of hydrogen, which is supplied by a dedicated neighboring facility owned and operated by Air Products and Chemicals. The refinery processes sweet and heavy sour crudes and has a refining capacity of 140,000 barrels per day. Its products include gasoline, asphalt, fuel-grade petroleum coke, chemical-grade propylene, and propane.[74] In 2023, the Detroit Refinery and the Air Products and Chemicals hydrogen plant reported to the U.S. EPA's GHGRP total CO_2e emissions of 0.92 and 0.39 MMT, respectively. More than two-thirds of the refinery's emissions (0.66 MMT) derive from stationary fuel combustion, with the rest coming from the refining processes and gas flaring.[75] Air Products and Chemicals plant's emissions are all from hydrogen production via the steam reforming of methane in natural gas.[76] In comparison, the calculated scope 3 emissions associated with the eventual combustion of the refinery's products in 2023 were nearly 22 MMT CO_2.[77]

The main approaches to decarbonizing the petroleum refining industry are:

- Improved energy efficiency
- CCUS
- Clean hydrogen production
- An eventual switch from crude oil to renewable feedstocks for processing

Refineries have a wide range of process heat needs that span temperatures from less than 100°C to greater than 700°C. The exact heat needs depend on specific facilities, the properties of the crude oil, and the range of products made. Regardless, most combustion emissions at refineries can be classified as hard-to-abate due to the heavy reliance on refinery fuel gas (RFG), a residual waste byproduct of refining with properties similar to natural gas, for process heating. At the Detroit refinery, the combustion of RFG accounted for nearly 90% of the total reported fuel emissions in 2023.[78] RFG has high levels of impurities and is of little value other than use as on-site fuel.[79] Consequently, energy efficiency improvements and carbon capture are the main options available to reduce the carbon intensity of petroleum refining. According to Marathon's 2024 Sustainability Report, the company has actively pursued energy efficiency as its primary emissions reduction strategy, which has helped reduce company-wide scope 1 and 2 GHG emissions by 28% from the 2014 baseline.[80] The report also lists CCUS as a potential strategy for mitigating emissions but acknowledges its limited implementation to date.[81]

Carbon capture could, in principle, also be used to mitigate emissions associated with natural gas-derived hydrogen production at the nearby Air Products and Chemicals facility. Alternatively, zero-carbon hydrogen could be produced via electrolysis powered by renewable electricity. Both approaches would have significant capital costs and increase the cost of

---

[74] Detroit Refinery fact sheet, Marathon Petroleum Corporation, November 2024, accessed February 2026.

[75] Gas flaring is the combustion of excess flammable gas released by safety valves to relieve unexpected pressure spikes. Values are from the emissions reported to U.S. EPA GHGRP.

[76] "Air Products to Build Michigan Hydrogen Plant to Supply Marathon's Detroit Heavy Oil Upgrade Project," Air Products News Release, April 2009, accessed February 2026.

[77] According to data reported to U.S. EPA GHGRP.

[78] According to data reported to U.S. EPA GHGRP.

[79] Z. Byrum, H. Pilorge, and J. Wilcox, "Technological Pathways for Decarbonizing Petroleum Refining," World Resources Institute, September 2021.

[80] According to Marathon's 2024 Sustainability Report, the companywide target is to reduce scope 1 and 2 GHG emissions by 38% from 2014 levels by 2035.

[81] "2024 Sustainability Report," Marathon Petroleum Corporation.

hydrogen. For carbon capture, the continued availability of the 45Q federal tax credit (which provides up to $85 per ton of CO_2 captured) could partially offset the additional costs. However, the upcoming deadline for the 45V federal clean hydrogen production tax credit[82] makes the current economic case for electrolysis-powered hydrogen production much more challenging without other forms of support.

The most impactful approach to lowering the carbon footprint of petroleum refining is to reduce the demand for petroleum-derived products (e.g., by maximizing electrification of the transportation sector) paired with a switch to renewable feedstocks such as biomass. As the technologies needed for the conversion of biomass to chemicals and fuels continue to be developed, bio-based feedstocks and intermediates may be incorporated into existing petroleum refineries for co-processing, with the eventual goal of minimizing the petroleum-based fraction. However, such co-processing is not allowed under current U.S. EPA regulations and would require policy changes at the federal level.[83] At the state or regional level, the transition to bio-based fuels and chemicals can be accelerated via a combination of incentives and mandates for low-carbon products (such as 'clean' fuels), engagement with existing refineries, and the financial support for pilot and demonstration projects.

IRON AND STEEL MANUFACTURING

Michigan is home to a range of facilities that play a role in the iron and steel production value chain, including 10 that are large enough to mandate emissions reporting to U.S. EPA's GHGRP.[84] These include one iron ore mine in the Upper Peninsula, two 'integrated' primary steel mills on the south side of Detroit, a coke plant (EES Coke) that has historically served those mills and other consumers of coal coke in Michigan (and the region), and six specialty iron and steel casting or finishing plants. Both primary steel mills were largely idled at the time of the writing of this paper. All production systems except some steel finishing lines at Great Lakes Works[85] in Ecorse have been idled since 2020. U.S. Steel, the owner of Great Lakes Works, is exploring options for the site's long-term outlook, including its possible redevelopment as a brownfield, but the facility's fate as part of the steel industry remains unclear. Dearborn Works, owned by Cleveland-Cliffs, has been idled since mid-2025,[86] and the long-term outlook for this facility is also unclear. In all, the total emissions from this production ecosystem reported to U.S. EPA in 2023 were 2.6 MMT CO_2e but are likely lower today by about 0.6 MMT annually due to the 'indefinite' idling of Dearborn Works.

The EES Coke plant, Great Lakes Works, and Dearborn Works facilities have collectively been subject to a series of recent fines for Clean Air Act violations,[87] as well as lawsuits.[88] Because the facilities are located in proximity[89] to each other, their air pollution creates cumulative impacts

---

[82] To be eligible for the 45V credit, the hydrogen facility construction must begin before January 1, 2028.

[83] See: Approved Pathways for Renewable Fuel, U.S. EPA, accessed February 2026.

[84] GHG emission threshold for reporting to the EPA is 25,000 tons of CO_2e per year.

[85] "U.S. Steel to Indefinitely Idle Operations at Great Lakes Works," Metal Center News, December 2019, accessed February 2026.

[86] "An idled Dearborn steel factory tells a larger story about tariffs and the economy," Michigan Public, July 2025, accessed February 2026.

[87] See detailed reports on U.S. EPA Enforcement Compliance History Online for Great Lakes Works, Dearborn Works, and EES Coke, all accessed February 2026.

[88] "Dearborn steel company to pay $100 million in violations settlement with EPA," Bridge Detroit, October 2023; "DTE's Zug Island operation switched fuel sources after damage to facility: Court testimony," Planet Detroit, September 2025, both accessed February 2026.

[89] See Air Monitoring (EGLE) and Industrial Equity Mapper (Industrious Labs), both accessed February 2026.

for fenceline communities. Tilden Mine, which is also owned by Cleveland-Cliffs, has been the focal point of a recent controversy[90] tied to the state's 2023 Clean Energy Legislation.[91]

The main approaches to decarbonizing iron and steel production include:

- Improved energy efficiency
- Replacing blast furnaces used for crude iron production at primary mills with hydrogen-ready direct reduced iron (DRI) production and pairing them with electric arc furnaces for crude steel production
- Electrification, including replacing fossil fuel-powered iron scrap and steel slab reheating furnaces with electrified induction heaters
- Electrifying non-stationary equipment

Most of the activities within the iron and steel manufacturing space are classified as high-temperature. For example, iron ore production at Tilden Mine involves taconite pellet induration, a continuous-feed firing process carried out above 1,000°C and powered by natural gas. While U.S. EPA classifies these emissions as 'process,' they are almost entirely associated with natural gas combustion and thus are more accurately categorized as fuel combustion emissions. The pellets are then converted into crude iron in blast furnaces within the Cleveland-Cliffs primary steel mill fleet, including Dearborn Works (before its idling). Blast furnaces operate with multiple internal zones, the highest of which exceeds 2,000°C. The heat supplied to blast furnaces arises both from chemical reduction of iron ore to metal iron (as an exothermic reaction) and combustion of a combination of coal products, including coking coal and other coal additions. Basic oxygen furnaces (BOFs), installed at both of Michigan's idled primary steel mills, are used to convert crude iron to crude steel. BOFs operate at temperatures above 1,600°C and are entirely self-powered by exothermic reactions. Ferrous metal reheating (without melting) is commonly carried out using specialty natural gas-fired furnaces. Iron and steel casting foundries and finishers employ a range of high-temperature furnaces for reheating (commonly >1,000°C) and melting operations (1,300-1,500°C), largely fired by coal coke (cupolas) or natural gas (other unit types) in Michigan. Lastly, coke batteries like EES Coke are constructed of a series of large, interconnected ovens that bake coal at temperatures greater than 1,000°C, producing large quantities of highly volatile, highly toxic, hot coke oven gas. Great Lakes Works had served as an off-taker for EES Coke's byproduct coke oven gas. However, due to Great Lakes Works' closure, EES Coke now handles its own byproduct gas, which has led to an increase in facility flaring (a major source of toxic air emissions, sometimes uncontrolled) in recent years.[92]

As identified in EGLE's CCAP, there are better, cleaner, more efficient technologies available for all these processes today. Solutions that reduce the firing temperature needed for producing iron ore pellets are emerging and could cut associated fuel needs, and thus emissions, by up to 80%.[93] The modern direct reduced ironmaking (DRI) furnace can be powered by either reformed natural gas, pure hydrogen, or a tailored mixture of CO and H_2 reducing gases produced through an electrochemical reformer.[94] Using natural gas can cut GHG emissions

---

[90] "Fact Check: Clean and renewable energy laws are not a threat to UP gas plants," Sierra Club Michigan Chapter, November 2025, accessed February 2026.

[91] 2023 Energy Legislation, Michigan Public Services Commission, accessed February 2026.

[92] According to data reported to U.S. EPA GHGRP.

[93] For example, see Binding Solutions, accessed February 2026.

[94] For example, see Helix Carbon, accessed February 2026.

from ironmaking by half, whereas using pure zero-carbon hydrogen nearly eliminates them.[95] While natural gas-based DRI production may be more viable currently due to the economic and technical constraints associated with zero-carbon hydrogen production, new DRI plants should be made hydrogen-ready, to reduce barriers to future hydrogen use. Because DRI technology processes the iron ore in the solid state, without melting, it also drastically reduces the criteria air pollutants developed during the process.[96] Within the primary steel mill industry, a range of tactics for lowering the carbon intensity of blast furnaces are being considered, including natural gas injection, hydrogen injection, and coke oven gas injection. Outside of the industry, these are commonly regarded as 'false solutions,' because they have limited potential to reduce GHG emissions from the overall ironmaking process and have shown no evidence of cutting air pollution. Instead, DRI production can be paired with either an electric arc furnace or an electric smelting furnace that feeds into an existing primary steel mill's BOF, for production of the crude steel product. Both cases require access to significant quantities of clean electricity to achieve a crude steel product with the lowest embodied carbon.

> *Comprehensive decarbonization of iron and steel making will require access to significant quantities of clean electricity.*

In many cases, iron and steel natural gas-powered reheating furnaces can be replaced with electric induction furnaces. The case for replacing coke-powered cupola furnaces with electrified alternatives like induction furnaces for melting applications is more complex, largely because these furnaces are housed inside foundry buildings, which may or may not possess appropriate space for constructing the electrified melting system to replace the cupola. Because many foundries rely on one cupola furnace for central operations, forcing a facility shutdown to convert the facility could cost 6 months or more in terms of lost production time, which is cost-prohibitive. Stakeholders report that for iron foundries, full facility decarbonization would require shifting of space heating loads from natural gas to electricity via, for example, heat pumps, in a strategy that would further require power grid decarbonization. In this context, foundries with coal coke-powered cupolas typically consume about two-thirds of their natural gas demand in space heating applications, with the remaining one-third going to metal processing. This point underscores the importance of considering space heat, building envelopes, and power grid decarbonization even for high-temperature industries where most industrial activities are carried out indoors.

In contrast to the above technological opportunities, there are no clear options for decarbonizing coke plants due to their complete reliance on coal. While utilization of coke oven gas as fuel can reduce a coke facility's emissions, the reality is that a long-term shift away from the coal coke consumed in crude iron production, iron and steel foundries, and lime production will significantly impact the coke market. In Michigan's case, this factor is compounded by the extra operating penalties enforced by EGLE and U.S. EPA associated with hazardous emissions. In a recent court case, EES Coke leadership testified that mandating enhanced pollution control systems at a cost of ~$150 million would essentially bankrupt the facility.[97] As part of a comprehensive decarbonization strategy for the iron and steel sector, Michigan should create meaningful opportunities to counterbalance potential negative

---

[95] M. Masterson, K. Ramirez, T. Ha, and C. Gamage, "Reline or Revitalize: The Narrowing Window to Modernize the U.S. Steel Industry," RMI, January 2025, accessed February 2026.

[96] M. Masterson, K. Ramirez, T. Ha, and C. Gamage, "Reline or Revitalize: The Narrowing Window to Modernize the U.S. Steel Industry," RMI, January 2025, accessed February 2026.

[97] "EES Coke Battery exec: Pollution controls cost more than Zug Island facility is worth," Planet Detroit, September 2025, accessed February 2026.

economic impacts of reduced activity or even shuttering of the EES Coke plant. The state can work with labor groups to identify realistic transition pathways such as training and workforce development programs for displaced workers to enable their participation in other industries.

CHEMICAL MANUFACTURING

Michigan has eight chemical manufacturing facilities that report emissions to U.S. EPA's GHGRP.[98] These facilities make a diverse range of products (pharmaceuticals, herbicides, insecticides, plastics, polyurethanes, salts, specialty chemicals, etc.), which are produced via correspondingly diverse production pathways. Two of the seven facilities classified as chemical manufacturers produce hydrogen to supply the Detroit Refinery (see Petroleum refining, above) and Hemlock Semiconductor. The total emissions from chemical manufacturing reported to the EPA in 2023, excluding the two dedicated hydrogen production facilities, were 0.28 MMT CO_2e. All reported manufacturing emissions originated from stationary combustion, powered almost entirely by natural gas.[99] The two hydrogen producing facilities, both of which use steam reforming of methane in natural gas, reported 0.41 MMT CO_2e, with most (0.39 MMT) emitted by the Air Products and Chemicals facility discussed in Petroleum refining, above.

The main approaches to decarbonizing the chemicals industry are:

- Improved energy efficiency
- Electrification
- Substitution of fossil-derived feedstocks and energy-intensive processes with bio-based alternatives

The temperature needs in chemical manufacturing can vary greatly for different pathways and processes. On average, more than two-thirds of the heat energy used in this subsector is below 300°C. Energy efficiency improvements and process optimization can help facilities reduce carbon emissions in a cost-effective manner. Electrification of process heat generation could drastically reduce emissions at the facilities but would likely result in higher operating costs due to higher electricity costs compared to natural gas. However, the use of heat pumps to recover waste heat and thermal batteries with favorable electricity rate structures could make electrification more economically viable. Michigan's individual chemical facilities (not including the Detroit Air Products and Chemicals hydrogen plant) reported emissions between 21,000 and 90,000 tons of CO_2e in 2023. These relatively small emission volumes would challenge the economic viability of CCUS using current approaches, which benefit from economies of scale. However, future technologies could make small-scale capture more practical.[100]

> *The use of bio-based feedstocks and production pathways instead of fossil-derived precursors and energy-intensive processes can substantially lower carbon intensity of some chemicals.*

---

[98] The GHG emission threshold for reporting to the EPA is 25,000 tons CO_2e per year.

[99] U.S. EPA FLIGHT

[100] "Techno-Economic Assessment of Small-Scale Carbon Capture for Industrial Power Systems," IEAGHG, March 2024.

An alternative approach to reducing the carbon intensity of some chemicals is the use of bio-based feedstocks and production pathways instead of fossil-derived precursors and energy-intensive processes. A growing portfolio of bio-based molecules and products is becoming available as identical drop-in replacements or better-performing alternatives to existing chemicals and materials.[101] Bio-based production commonly requires fewer process steps, often takes place under milder conditions, including lower temperatures, and has few if any toxic inputs. Molecules can be synthesized in vivo (within) microorganisms or plants or in vitro (outside living cells) using enzymes and other biologically produced components. Typical inputs for bio-based production pathways include sugars and/or other nutrients. There is already a long history of bio-based industrial manufacturing for a wide range of products, especially in the food and pharmaceutical industries. Although many potential bio-based alternatives to fossil-derived chemicals are currently not cost-competitive or ready to scale, continued research and development in this area is likely to expand economically viable low-carbon alternatives in the coming years.

GLASS MANUFACTURING

Glass manufacturing is an energy-intensive process due to the high temperatures required for melting input materials during production. Michigan has two glass manufacturing facilities that report emissions to U.S. EPA's GHGRP: Guardian Industries in Carleton and Knauf Insulation in Albion, which produce flat glass and glass fibers, respectively.[102] In 2023, the Guardian Industries facility reported a total of 145,000 tons of CO_2e emissions, which included 110,000 tons CO_2e from two natural gas-powered furnaces and 31,000 tons process CO_2. In the same year, the Knauf Insulation facility reported 26,000 tons CO_2e with nearly 25,000 and 1,500 tons coming from stationary combustion and process emissions, respectively. Notably, the Knauf Insulation facility has four electric melters, and its stationary combustion emissions are from general process burners used for purposes other than melting, such as space heating.[103]

The main approaches to decarbonizing the glass manufacturing industry are:[104]

- Improved energy efficiency and material circularity (recycling)
- Electrification
- Adoption of alternative fuels

Maximizing waste heat recovery is a key tactic for reducing carbon intensity of glass manufacturing.

The high operating temperatures of glass melting and glass forming result in significant generation of high-temperature waste heat. As a result, maximizing the recovery of waste heat is one of the key strategies for increasing facility-level energy efficiency and reducing the carbon intensity of glass manufacturing. Some waste heat recovery is already common practice in the industry, primarily for the preheating of combustion air. However, additional options not sufficiently utilized include preheating of input materials, facility space heating, and

---

[101] R. Cywar, N. Rorrer, C. Hoyt, et al., "Bio-based polymers with performance-advantaged properties," Nature Reviews Materials, 7: 83-103, 2022.

[102] For Guardian Industries, see: Line 2 Glass Processing Emissions Test Report, Air/Compliance Consultants, Inc., September 2015; For Knauf Insulation, see Renewable Operating Permit Staff Report, MI Department of Environment, Great Lakes, and Energy, April 2022.

[103] See Renewable Operating Permit Staff Report for Knauf Insulation and data reported to U.S. EPA GHGRP.

[104] M. Zier, P. Stenzel, L. Kotzur, and D. Stolten, "A review of decarbonization options for the glass industry," Energy Conversion and Management: X, 10: 100083, 2021.

power generation via WHP.[105] Additional energy and emissions savings in glass manufacturing can be gained via the use of waste glass (called cullet) to displace raw materials. Glass can be remelted infinitely without the loss of desired properties, but the composition of waste glass may impact the properties of the final product. As a result, in cases where the manufactured glass composition and properties must meet stringent requirements, only the recycling of internally generated cullet (i.e., products manufactured at the same facility that did not meet quality standards) is likely to be suitable for recycling in large quantities. In 2021, as part of production expansion at its Albion facility, Knauf Insulation stated that it will utilize 64 million pounds of recycled glass per year, recovered in part through Michigan's Bottle Deposit Law, in addition to 30 million waste glass bottles used at its facilities per month nationwide.[106] The Guardian Industries Carleton facility experimented with making glass containing 73-100% cullet in 2023 as part of its effort to increase energy efficiency and reduce resource consumption.[107]

The technologies needed to electrify the glass manufacturing process are already commercially available, as evidenced by the utilization of electric melters at the Knauf Insulation facility. Besides reducing point source emissions, electric melters have substantially higher thermal efficiencies compared to combustion-based furnaces (at smaller capacities, electric furnaces can be twice as efficient).[108] Electric melters also have lower investment costs and can generate indirect operational savings due to fewer hazardous pollutants such as particulate matter and NO_X. A key limitation of currently available electric melters is their lower capacity compared to combustion-powered counterparts. In addition, high electricity costs can more than offset efficiency and capital-related savings.

Alternative fuels may provide another option for reducing the carbon intensity associated with the high-temperature heat needed for glass manufacturing. As a direct replacement for fossil natural gas, RNG would be easiest to incorporate into existing infrastructure, although the economic case and carbon intensity reduction will depend on the regional resource availability. Conceptually, biomass could also be used as fuel, but it may contain contaminants that impact the glass properties, making its use case more challenging. Hydrogen is another potentially suitable fuel, but currently unlikely to be economically viable, as discussed in Hydrogen, above.

PULP AND PAPER PRODUCTION

Although most of the GHG emissions from pulp and paper (P&P) manufacturing are not technically 'hard-to-abate,' Michigan's 10 facilities nonetheless emit a collective 3.5 MMT CO_2e (including biogenic emissions), putting this subsector on par with cement manufacturing, which is the state's other highest-emitting industrial subsector (Figure 2). Therefore, emphasis on decarbonization opportunities in the P&P industry is important for Michigan's overall industrial decarbonization efforts. In considering potential decarbonization opportunities for the P&P subsector, it is important to recognize that the existing industry is already under pressure from the global market and shifting consumer preferences (e.g., reduced use of office paper and increasing use of recycled packaging materials in recent decades), which can result in additional barriers (or opportunities) to change.

---

[105] M. Zier, P. Stenzel, L. Kotzur, and D. Stolten, "A review of decarbonization options for the glass industry," Energy Conversion and Management: X, 10: 100083, 2021.

[106] "Knauf Insulation Increases Loose-Fill Production with Expansion in Albion, Michigan," Knauf Insulation, December 2021, accessed February 2026.

[107] "Use of Cullet to Help Reduce Raw Materials and Energy Consumption," Guardian Glass, accessed February 2026.

[108] M. Zier, P. Stenzel, L. Kotzur, and D. Stolten, "A review of decarbonization options for the glass industry," Energy Conversion and Management: X, 10: 100083, 2021.

The main strategies for decarbonizing the P&P subsector include:[109]

- Improving energy efficiency
- Increasing the utilization of solid waste/byproduct biomass combustion
- Electrification of process heat through the adoption of industrial heat pumps[110]
- Targeted electrification of some drying processes

The U.S. Department of Energy estimates that nationwide, the above-listed approaches could steer the country's pulp and paper subsector toward GHG reductions nearing 95%.[111] The economic viability of lower temperature heat pumps replacing fossil-powered boilers can be enhanced via waste heat recovery, favorable electricity rates, and/or financial incentives. Similarly, the impact of various electric rate structures and financial incentive schemes should be evaluated based on the economics of integrating thermal batteries to meet the different temperature needs and scales at P&P facilities.

The P&P industry is well-positioned to utilize carbon capture and storage both to decarbonize process heat and to generate additional revenue from so-called negative carbon emissions. The majority of GHG emissions generated at Michigan's existing facilities is due to the combustion of biomass, which is composed of carbon removed from the atmosphere during tree growth. Therefore, the capture and sequestration of these emissions — an approach referred to as 'bioenergy with carbon capture and storage', or 'BECCS' — can be monetized on the carbon market as CDR credits (as long as the input biomass is sustainably grown and harvested, thus enabling the continuous removal of carbon from the atmosphere). In addition, the 45Q federal tax credit would provide up to $85 per ton of CO_2 captured for 12 years of operation.[112]

The Role of Policy in Industrial Decarbonization

Industrial decarbonization — especially in the hard-to-abate subsectors — faces major challenges and barriers, which include long life spans of legacy equipment, significant upfront capital expenses, potential increases to operating costs associated with electrification, unique facility needs and designs, a general resistance to change, and a lack of markets willing to pay higher prices for products with a lower carbon footprint. The state can play an enabling role to help address these challenges and thus accelerate the decarbonization transition among Michigan's industries, as outlined in RMI's recently published Michigan Clean Manufacturing Roadmap focused on decarbonizing manufacturing subsectors primarily with low- and medium-temperature process heat needs. Although most of the strategies discussed in the RMI report apply across the industrial manufacturing sector, the hard-to-abate subsectors will likely need additional support and considerations from the state to overcome unique barriers. The discussion below reflects feedback from industrial stakeholders who were interviewed for this white paper.

---

[109] "Transformative Pathways for U.S. Industry: Unlocking American Innovation," U.S. Department of Energy, 2025.

[110] E. Rightor, P. Scheihing, A. Hoffmeister, and R. Papar, "Industrial Heat Pumps: Electrifying Industry's Process Heat Supply," ACEEE, March 2022.

[111] "Transformative Pathways for U.S. Industry: Unlocking American Innovation," U.S. Department of Energy, 2025.

[112] The credit is expected to increase with inflation beginning in 2027.

A STABLE, COORDINATED, AND FAIR POLICY LANDSCAPE

In conversations with stakeholders, there was a broad and consistent agreement that the stability of any policy, whether an incentive or a mandate, is critical for business planning. This is especially important for decarbonization efforts that need to be planned years in advance and may cost tens or hundreds of millions of dollars. Michigan currently has an executive directive to reach economywide carbon neutrality by 2050. In line with this directive, in 2022 the state published the MI Healthy Climate Plan (MHCP), a framework for achieving its climate targets. The MHCP is organized around six pillars, one of which is an aim to "drive clean innovation in industry." Michigan also recently published its Comprehensive Climate Action Plan (CCAP), which analyzes specific measures needed for economywide decarbonization, including in the state's industrial sector. The state should continue to develop comprehensive strategies together with clear, consistent policies and regulatory mechanisms that will support its manufacturers in their decarbonization efforts. To ensure that the decarbonization transition will be fair, lasting, and economically viable, regular engagement of stakeholders – including the businesses and the communities in which they are located – should inform decision making and policy designs.

> *The stability of any policy, whether an incentive or a mandate, is critical for business planning.*

Principles of effective industrial decarbonization policy

Industrial decarbonization policies are more likely to be effective if they are designed as competitiveness and risk-management tools in conjunction with emissions-reduction mandates.[113,114] For manufacturers operating on tight margins and selling into regional or global markets, the cost uncertainty, capital constraints, and execution risks related to emerging decarbonization technologies can be an especially high barrier.[115,116] Therefore, policies that reduce upfront capital burden, shorten payback periods, and provide reliable signals about future market conditions can help facilities act earlier while minimizing the risk of relocation or closure due to eventual mandates.[117]

> *Grid decarbonization and utility planning are critical elements of industrial decarbonization.*

Coordination across systems that manufacturers do not control, such as infrastructure development, is another important aspect of enabling policy.[118] In particular, a reliable supply of clean electricity will be needed for extensive industrial electrification, which depends not only on facility-level decisions but also on utilities' ability to forecast and deliver affordable power under conditions of uncertainty (such as limited relevant historical data and emerging load growth pressures from data centers).[119] To aid and support decarbonization efforts by

---

[113] J. Flegal, "Industrial Policy Synergies: Industrial Policy + Climate Policy," Roosevelt Institute, April 2023.

[114] J. Meckling, "Making Industrial Policy Work for Decarbonization," Global Environmental Politics, November 2021.

[115] A. Gangotra, K. Kennedy, and W. Carlsen, "Next Generation of US Policies for Industrial Innovation," World Resources Institute, December 2024.

[116] "The State Industrial Policy Playbook – A Policy Guide for Low-Emission Heavy Industry," Clean Air Task Force, October 2025.

[117] M. Freed and T. Dolan, "Powering Progress: Industrial Decarbonization Planning at the State Level," RMI, March 2025.

[118] M. Freed and T. Dolan, "Powering Progress: Industrial Decarbonization Planning at the State Level," RMI, March 2025.

[119] A. Gangotra, K. Kennedy, and W. Carlsen, "Next Generation of US Policies for Industrial Innovation," World Resources Institute, December 2024.

Michigan's industrial facilities, the state can build on the MHCP, CCAP, and its renewable energy standard (which commits Michigan to 100% clean energy by 2040) by requiring utility planning to ensure an adequate supply of clean energy to meet the expected demand.[120] Multiple stakeholders expressed support, and a clear need, for Michigan's push to decarbonize the electric grid as part of a comprehensive decarbonization strategy in the state.

Michigan's unwavering commitment to achieve net-zero by 2050 complemented with meaningful incentives and eventual mandates to decarbonize will provide clear signals that businesses rely on for long-term planning.

Michigan's policy portfolio should combine near-term 'no-regrets' actions (efficiency, assessments, operational improvements) with longer-lead market-building mechanisms (demonstration projects, standards, procurement, and credible embodied carbon measurements).[121] An unwavering commitment by the state to achieve carbon neutrality by 2050, complemented with meaningful incentives and eventual mandates to decarbonize, will provide clear signals that businesses rely on for long-term planning. If policies and regulations can be sustained through multiple political cycles – which is more likely to happen if feedback from stakeholders is meaningfully incorporated in policy design – then industrial decarbonization will benefit from state-supported programs for facilities working to meet increasingly stricter regulations, while creating opportunities to participate in regional and global markets for low-carbon products.[122,123]

STANDARDS, REGULATIONS, AND MANDATES

To achieve economywide carbon neutrality by 2050, Michigan will likely need to implement increasingly stricter standards and regulations (e.g., efficiency standards, clean heat mandates). A major challenge for regulations at the state level is the potential for a negative impact on the competitiveness of facilities operating under stricter rules than regional or global competitors. As a result, some businesses are concerned about state-imposed regulations around GHG emissions. In working toward a fair and effective set of policies aimed at decarbonizing Michigan's industries, the state should build on the industrial GHG reduction measures specified in the state's CCAP to identify science-based, economically viable targets for carbon intensity of manufactured materials and products. The state can then work with businesses to develop optimal roadmaps – including early state-based incentives and a gradual strengthening of regulations – toward economywide net-zero. In addition, as a member of the U.S. Climate Alliance and the Midwestern Governors Association, Michigan can work to coordinate the enhancement of standards across state borders in order to maintain a regulatory level playing field throughout the decarbonization transition of the state's facilities.

---

[120] For additional discussions, see: E. Albergo, B. Cangelose, J. Corvidae, et al., "Michigan Clean Manufacturing Roadmap," RMI, October 2025.

[121] "Enabling Industrial Decarbonization: A Policy Guidebook for U.S. States," United States Climate Alliance, December 2022.

[122] "The State Industrial Policy Playbook – A Policy Guide for Low-Emission Heavy Industry," Clean Air Task Force, October 2025.

[123] "Enabling Industrial Decarbonization: A Policy Guidebook for U.S. States," United States Climate Alliance, December 2022.

FINANCIAL SUPPORT

In the near term, most existing decarbonization approaches other than efficiency improvements are likely to lead to higher direct costs for businesses, which is a major barrier. It is, therefore, unsurprising that efficiency improvements account for the majority of decarbonization efforts by Michigan's manufacturers to date. Higher costs may be incurred by facilities as capital expenditures ('CAPEX') due to equipment additions, replacements, or upgrades and as operating expenses ('OPEX') due to higher costs of electricity or alternative fuel use. In addition, retraining or hiring personnel may be needed to operate new equipment, further raising costs. To increase the companies' willingness and ability to switch from fossil fuels for process heat generation, financial support (with eventual clean heat mandates) will likely be needed. Due to the unique needs and decarbonization-related challenges faced by the state's largest industrial emitters, many of which generate hard-to-abate emissions, custom approaches and mechanisms will be required for the different facilities, likely increasing costs.

Financial support for the manufacturing of low-carbon products can include grants and cost-shares for new equipment (reducing CAPEX), production tax credits for low-carbon-intensity heat or final products (mitigating higher OPEX), low-interest loans and loan loss reserves (lowering barriers to financing), and technical assistance (optimizing solutions). In determining an appropriate level of support for different facilities, a comprehensive evaluation of net benefits should be taken into account. For example, the replacement of an industrial natural gas boiler with an electric boiler can quantifiably reduce negative health impacts in the nearby community by lowering NO_X levels. Improved health among nearby residents can translate to fewer hospital visits, lower overall healthcare costs, and higher productivity in the community.[124] Other factors that should be considered when evaluating the level of appropriate financial support for industrial facilities and the impact of different decarbonization options include the net energy savings, expected life of the existing fossil- fueled equipment, and the cost of avoided carbon emissions. The latter metric is especially important for identifying the most cost-effective options to achieve Michigan's net-zero targets.

Many of the technologies and approaches required for deep decarbonization of the manufacturing sector are still in the emerging category. A crucial phase in technology development and widescale adoption is that of demonstration projects, which provide essential data under real-world conditions for design improvements and eventual commercialization. Because demonstration projects are inherently unique and, therefore, expensive and high-risk, they typically require external cost-share, such as grants. Although large-scale demonstrations have been commonly funded by the federal government, Michigan can enhance the success rate of such projects in the state by providing some cost-share to match federal grants (which are currently limited but may expand under future federal administrations). Additionally, the state could directly help fund smaller demonstration projects, such as the implementation of industrial heat pumps in some of the state's manufacturing facilities. Such projects would help inform technology designs and configurations, incorporating region-specific variables like climate and resource availability.

---

[124] "Michigan's Comprehensive Climate Action Plan," Michigan Department of Environment, Great Lakes, and Energy, December 2025.

ELECTRICITY RATE STRUCTURES AND FLEXIBLE DEMAND

In Michigan, the ratio of the cost of electricity to the cost of natural gas per unit of energy — the spark gap — is greater than three (Figure 4), and according to projections by the U.S. Energy Information Administration, without policy interventions this difference is expected to remain largely unchanged through 2050.[125] The spark gap is the main cause of higher OPEX for electrified heat generation compared to natural gas combustion. The price of electricity reflects the overall costs associated with the infrastructure needed to generate, transmit, and distribute electricity. Electricity demand varies greatly throughout the day and over the course of the year, with peak loads occurring for short periods of time — typically hours — during the hottest summer days.[126] The current capacities of regional grids are intended to provide reliable power during peak hours and are underutilized most of the time. As a result, the existing electric grids could accommodate additional loads without increasing capacity if the new loads have enough flexibility to curtail demand during peak hours. Importantly, greater utilization of the existing capacity could lead to lower electricity rates, as more power will be procured from the existing resources.

A recent study from Duke University's Nicholas Institute for Energy, Environment and Sustainability estimates that 76-126 GW of additional load could be added to the U.S. grid at current capacity if the new loads can be curtailed for 0.25-1.0% of their operating time (corresponding to 1.7-2.5 curtailment hours per event). For the Midcontinent Independent System Operator, which serves nearly all of Michigan together with other parts of the Midwest and the South, 11.6-18.5 GW of load could be added to the existing capacity with the same curtailment limits.[127] Consistent with the above conclusions, a recent analysis prepared by NV5 and Slipstream for the Michigan Public Service Commission found that a robust implementation of demand response programs across the state could reduce electricity peak demand by 15-23%.[128] One possible implication of these findings is that electrifying industrial process heat generation could be more cost-effective than current electricity rates would suggest, if two conditions are met: 1) new loads have built-in flexibility and 2) demand flexibility is rewarded by electricity rate structures. In addition, electricity rates could be made more affordable for customers across the region due to better utilization of the existing grid resources and/or the ability to incorporate a greater share of intermittent renewable electricity generation on the grid.

Industrial power demand flexibility will vary by facility. With appropriately designed electricity rate structures that incentivize flexibility, some facilities could plan for operation curtailment during peak hours, while for others, the installation of generators or electrochemical battery storage on-site could become cost-effective. Thermal batteries are an emerging electrified process heat technology that is uniquely suited for enabling flexible power demand and can, therefore, play a major role in electrifying industrial heat under current constraints. By design, thermal batteries convert variable electric power to a consistent output of thermal energy, which can also be stored for hours or days. If deployed at scale, thermal batteries could enable greater reliance on intermittent wind and solar power generation, thus helping decarbonize the grid.

---

[125] E. Albergo, B. Cangelose, J. Corvidae, et al., "Michigan Clean Manufacturing Roadmap," RMI, October 2025.

[126] The peak load is expected to change with widespread electrification.

[127] T. Norris, T. Profeta, D. Patino-Echeverri, and A. Cowie-Haskell, "Rethinking Load Growth: Assessing the Potential for Integration of Large Flexible Loads in US Power Systems," Nicholas Institute for Energy, Environment, and Sustainability, Duke University, February 2025.

[128] "2025 Energy Waste Reduction, Demand Response, and Efficient Electrification Statewide Potential Study; Volume III – Demand Response," NV5 and Slipstream, submitted to the Michigan Public Service Commission, October 2025.

As discussed in Thermal batteries above, the levelized cost of heat generated by thermal batteries is highly sensitive to electricity rate structures (Figure 6). Therefore, new electricity rate classes and designs should be explored to incentivize thermal battery (as well as electrochemical battery storage) installations across the manufacturing sector. In evaluating potential new rate classes for electrified industrial facilities, the full benefits of large-scale flexible demand should be accounted for to ensure fair pricing while making sure that other customers do not subsidize industrial rates. One goal of the new rate classes should be to maximize the utilization of cheap electrons during periods of high supply and low demand on the grid. Industrial customers could work with utilities to optimize charging periods and thus minimize the overall cost per unit of energy. Even if the introduction of new electricity rate structures alone is insufficient to immediately close the spark gap, the significant reduction in the cost of heat afforded by flexible demand could help make the economic case for the wide-scale deployment of thermal batteries (and other electrified technologies paired with electrical storage) across Michigan's manufacturers, especially with the increased penetration of cheap renewable electricity on the grid. For additional reading, a recently published white paper by the American Council for an Energy-Efficient Economy provides an informed perspective on the need for new electricity rate structures as a means to support industrial electrification in Michigan and Illinois.[129]

> *New electricity rate classes that incorporate fair pricing for large load demand flexibility could provide significant support for industrial electrification efforts.*

BUY CLEAN

Strong market signal for low-carbon-intensity products is another powerful incentive for manufacturers to decarbonize operations. A market for low-carbon products creates a business case for making those products, thus helping justify the needed investments. States already procure large volumes of materials from hard-to-abate sectors such as concrete, steel, and asphalt for use in construction projects. Therefore, a self-imposed requirement and commitment by the state to buy materials with low embodied carbon, paired with a preference for products manufactured within the state, could provide a needed boost to the rate of decarbonization of the state's industries. In designing 'buy clean' programs, Michigan can look to other states that already have 'buy clean' initiatives, such as Minnesota and California, for lessons learned. In addition, a 'buy clean' regional program involving multiple states could have a greater impact by increasing the market for low-carbon products and helping decarbonize more supply chains and products. Notably, the Midwest is a manufacturing powerhouse that produces a wide range of products suitable for 'buy clean' programs, thus enabling a focus on local industries and supply chains.

> *Robust 'buy clean' programs can create a market signal for low-carbon products, helping justify the investments needed to decarbonize manufacturing.*

An effective 'buy clean' program will require engaging businesses to determine realistic expectations for feasible carbon intensity reductions and cost premiums for the low-carbon versions of products. While stakeholders were generally positive about the concept of a state

---

[129] A. Johnson, A. Hoffmeister, R. Hart, and F. Omotesho, "Industrial Rate Impacts on Electrification Projects in Illinois and Michigan," ACEEE, February 2026.

or regional 'buy clean' program, some expressed caution regarding potential negative impacts, such as loss of purchasing contracts if certain carbon intensity requirements are not met. Although this could be an especially sensitive issue for smaller businesses or those operating on tight margins, the pairing of 'buy clean' with financial support programs, such as grants or incentives, could prove to be a successful combination for helping such businesses remain competitive during the decarbonization transition.

CARBON MANAGEMENT

Carbon capture, utilization, and storage (CCUS)

CCUS is increasingly seen by businesses and governments as an essential component of the industrial (and energy) decarbonization portfolio due to a lack of options for abating some high-temperature and direct process emissions. However, CCUS also faces major challenges including high cost, scalability, and a current lack of the infrastructure needed for transport and storage of captured CO_2 (pipelines and established injection sites). In addition, CCUS is controversial and faces opposition from some environmental groups and communities due to safety concerns (potential leakage during transport or from storage sites) and the moral hazard of enabling prolonged fossil fuel use. At the time of publication of this paper, Michigan's legislature was considering a set of bills aimed at establishing a CCUS regulatory framework in the state. The version of the bills that passed the State Senate in September 2025 was criticized by several groups for inadequate guardrails regarding safety, liability, and prolonged reliance on fossil fuels.[130] Given that continued opposition to CCUS regulations could lead to lengthy delays and increased project costs, meaningfully addressing concerns regarding the current bills could ultimately lead to faster development and deployment of CCUS in the state.

> *The state can have an outsized impact on CCUS potential by coordinating and planning infrastructure buildout, while minimizing the overall costs and community disruptions.*

A key area where the state could have an outsized impact on the potential success of CCUS as an industrial decarbonization tactic is the coordination of and support for long-term infrastructure planning to achieve faster buildout while minimizing costs and community disruptions. For potential CCUS projects, the lack of infrastructure is a major barrier that can be the limiting factor in moving forward. Therefore, the development of a clear plan with transparent costs and predictable timelines for the buildout of pipeline and storage site network throughout the state could encourage development of early CCUS projects, especially those not located close to suitable injection sites. A relevant example illustrating the critical impact of state-supported infrastructure development is the case of electric transmission capacity expansion in Texas, which relieved congestion issues faced by the rapidly growing wind power projects in that state, ultimately helping Texas become a national leader in installed wind power capacity.[131]

Given the emerging status of CCUS as a GHG emissions abatement strategy, its expected potential and the public attitude toward it will continue to evolve. Michigan's CCUS policy should reflect the best available data now and in the future. CCUS costs, safety concerns, and

---

[130] "Michigan Senate approves carbon capture legislation," Michigan Public, September 2025; "Michigan Senate approves risky carbon sequestration despite threats to forests, groundwater, and health," Michigan Environmental Council, September 2025; both accessed February 2026.

[131] D. Rode, J. Anderson, H. Zhai, and P. Fischbeck, "Six principles to guide large-scale carbon capture and storage development," Energy Research and Social Science, 103: 103214, 2023.

competition with direct decarbonization approaches will likely remain major points of debate among stakeholders, which the state will need to carefully balance. Continued engagement with industry and potentially impacted communities will need to be part of policy development and infrastructure planning. Importantly, policies that enable and support CCUS should be designed to encourage facilities to prioritize any viable direct decarbonization technologies available to them before investing in CCUS, with the ultimate aim of minimizing fossil fuel use in the future.

Carbon dioxide removal (CDR)

There is a broad consensus that not all anthropogenic GHG emissions can be eliminated in the coming decades, due to technological and economic limitations. Furthermore, the existing high levels of CO_2 in the atmosphere due to historic human activities are already driving the increasingly devastating impacts of climate change.[132] Therefore, CDR — or so-called 'net-negative' emissions approaches — will need to play a role in comprehensive climate action and net-zero plans. Whereas many novel CDR technologies are in early stages of development and face similar barriers to other decarbonization strategies described in this white paper (such as cost and scalability), the more established and widely deployed CDR approaches (e.g., afforestation, reforestation, improved forest management) face a distinct set of challenges.

> *There is a broad consensus that not all anthropogenic GHG emissions can be eliminated in the coming decades.*

Unlike CCUS, which captures carbon emissions at the source, CDR approaches remove CO_2 from the atmosphere. Because CDR would offer an indirect approach to mitigating industrial emissions, the stakeholders interviewed for this white paper expressed mixed sentiments regarding reliance on CDR (via carbon offsets or credits) for carbon accounting. Some companies already actively rely on carbon credits purchased on the voluntary carbon market, but others are hesitant to consider it as a mitigation strategy. One stakeholder provided an informative perspective, stating a clear preference for CCUS because it enables the treatment of captured CO_2 as an additional waste stream that can be integrated in existing operations and business plans. In addition, the reliance on CDR credits for carbon management can be perceived by the public as 'greenwashing' because it provides opportunities for companies to claim carbon reductions without decarbonizing their operations. Finally, the quality of CDR credits can vary substantially, further undermining confidence in CDR as a carbon management strategy. To that end, accounting and verification methods are still evolving to better guarantee that CDR credits or offsets accurately represent additional carbon removed from the atmosphere due to the funded activities ('additionality') with no increase in emissions elsewhere ('leakage').[133]

The carbon offset market could grow globally to $1 trillion by 2050.[134] In the U.S., states like Michigan can play an active role in developing and scaling CDR as a reliable, transparent, and trusted carbon management strategy used to mitigate hard-to-abate emissions from different sectors of the economy. In addition to mitigating GHG emissions, well-designed CDR projects can increase economic revenue, create jobs, and provide environmental co-benefits. Critically, policies should be designed to ensure that CDR is utilized specifically to address unavoidable

---

[132] "Climate Change 2021: The Physical Science Basis," IPCC Sixth Assessment Report, 2021.

[133] I. Schulte, J. Burke, S. Arcusa, et al., "Chapter 10: Monitoring, Reporting, and Verification," in The State of Carbon Dioxide Removal: A global, independent scientific assessment of Carbon Dioxide Removal, 2024.

[134] "Carbon Offset Market Could Reach $1 Trillion with Right Rules," Bloomberg NEF, January 2023, accessed February 2026.

emissions and does not disincentivize direct decarbonization efforts, such as those described in this white paper. A key principle in focusing CDR efforts on unavoidable emissions (or on reducing current CO_2 levels in the atmosphere) is to have separate targets for GHG emissions reductions (by sector) and for CDR, guided by carbon accounting and the state's overall climate targets.[135]

> *States should set separate targets for emissions reductions and CDR.*

In considering possible approaches to CDR policy development, Michigan can look to other states that have already made progress in this area (e.g., California, New York, Massachusetts).[136] However, state-level CDR policies have an advantage in that they can be tailored to each state's geographic, political, and economic realities. Therefore, Michigan should explore the specific opportunities and needs for its CDR policies via commissioned studies or workgroups, to inform decision making. In relevance specifically to industrial decarbonization, Michigan should examine how CDR activities could be integrated into various industrial activities (e.g., iron mining, pulp and paper manufacturing, construction) to help businesses tap into additional revenue sources while decarbonizing their operations. CDR policies should be designed to align with the MHCP's commitment to environmental justice and meet the plan's stated aims to drive clean innovation in industry and protect the state's land and water.

Conclusions and Key Takeaways

The primary objectives of this white paper were to lay out potential decarbonization pathways available to Michigan's industries, with a focus on emissions that are considered hard-to-abate. The state's industrial sector is highly diverse, which means that a wide range of customized decarbonization approaches will be required to achieve net-zero. The information presented in this paper can help guide strategy development to meet the state's climate targets. Key takeaways are summarized below:

CURRENT STATE

- Michigan's industrial sector is responsible for over 17% of the state's GHG emissions.
- Hard-to-abate industrial emissions in Michigan account for more than 8 MMT CO_2e, or 57% of the state's manufacturing emissions.
- Michigan's top-emitting, hard-to-abate subsectors include cement manufacturing, iron and steel production (including iron ore mining), lime manufacturing, petroleum refining, and hydrogen production.

---

[135] I. Wood, M. Kirley, K. Clark-Sutton, "US States and Carbon Dioxide Removal: Leadership Opportunities and Key Principles for Policymakers," RMI, October 2024, accessed February 2026; S. Li, W. Carlsen, H. Harasaki, C. Ribeiro, "How US States Can Lead on Carbon Removal Policy," World Resources Institute, October 2024, accessed February 2026; S. Nordahl, R. Hanes, K. Mayfield, et al., "Carbon accounting for carbon dioxide removal," One Earth, 7: 1494-1500, 2024.

[136] "How US States Can Lead on Carbon Removal Policy," World Resources Institute, October 2024, accessed February 2026.

POTENTIAL DECARBONIZATION PATHWAYS AND BARRIERS TO IMPLEMENTATION

- Improved energy and material efficiency can be the most cost-effective way to minimize process-related emissions. Internal competition for capital and short-term requirements for return-on-investment, insufficient incentives from the government or utilities, and a lack of relevant expertise are major barriers.
- Waste heat recovery may be a particularly impactful decarbonization measure at facilities that produce large quantities of high-temperature process heat. Waste heat can be used to generate electricity, optimizing system-level efficiency.
- Industrial heat pumps are much more efficient than combustion- or electric resistance-based heating equipment. Although not suitable for high-temperature industrial heat, heat pumps can transfer waste heat to input materials or gases for high-temperature processes, reducing overall energy consumption.
- Thermal batteries can play a key role in electrifying industrial heat, including for high-temperature applications. They can store heat for hours or days with minimal loss, enabling electrical demand flexibility and thus increasing reliance on intermittent renewable electricity and maximizing the utilization of grid resources. Legacy electricity rate structures that do not fairly price large load demand flexibility are a significant barrier to the adoption of thermal batteries.
- Alternative fuels such as biomass-based waste, renewable natural gas, and scrap tires can be used as drop-in replacements for fossil fuels to generate high-temperature industrial heat. Supply availability, logistics, and cost are primary barriers. Other important considerations include potential for air pollution and lifecycle assessment-based carbon intensity comparisons against other potential applications.
- Although hydrogen is a technically suitable fuel for clean high-temperature industrial heat, the high cost of low- or zero-carbon hydrogen production currently makes it an unlikely candidate as a fuel. A higher priority application for clean hydrogen would be its use as a feedstock in petroleum refining and chemical production.
- Carbon capture, utilization, and storage is likely necessary to abate some emissions that cannot be directly eliminated. Michigan has well-suited geology to store vast amounts of captured CO_2. High cost of carbon capture and a current lack of infrastructure are major barriers. CCUS faces opposition from communities and environmental groups due to concerns around safety and the moral hazard of continued fossil fuel use.
- Atmospheric carbon dioxide removal can be used to offset unavoidable industrial emissions. Some biological CDR approaches already operate at scale and cost less than $20 per ton of removed CO_2. Incorporation of CDR as an industrial decarbonization strategy can be seen as 'greenwashing' by the public, which is an important challenge. Industry can work to incorporate novel CDR approaches in existing processes and operations, share knowledge and infrastructure with CDR projects, and help fund project development.

POLICY CONSIDERATIONS

- Michigan's industrial decarbonization policies should balance incentives and financial support with gradually enhanced clean standards and mandates. The state's progress toward carbon neutrality should, on balance, create jobs and avoid pushing businesses out of state. Workforce development and retraining programs should be provided to counteract some inevitable job losses during the transition period.
- Continuous stakeholder engagement throughout the decarbonization transition will be

important for policy efficacy, fairness, and stability. Policy stability is critical for long-term business planning.

- New electricity rate structures can be a major driver for industrial electrification. New rate classes that fairly price and incentivize flexible demand for large industrial electricity loads can substantially reduce the existing price gap between electricity and natural gas. Care must be taken to not shift the cost burden of industrial electrification to other customers.
- State or regional 'buy clean' initiatives for low-carbon products and materials can provide a strong market signal for manufacturers weighing decarbonization options. State commitment to purchase locally produced low-carbon products at a premium can help justify decarbonization-related investments and offset higher operating expenses.
- CCUS policies should aim to meaningfully address concerns of stakeholders, helping manage opposition to project development. The state can have an outsized impact on CCUS potential via the coordination and planning of infrastructure buildout, working to minimize overall costs and community disruptions.
- Incorporation of CDR as a component of comprehensive industrial decarbonization policy should be examined. A key consideration will be to ensure that CDR is solely used to offset unavoidable emissions and does not disincentivize the implementation of any available decarbonization measures.