MANUFACTURING SECTOR DECARBONIZATION STRATEGIES AND IMPACTS IN THE STATE OF MARYLAND

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UNIVERSITY OF MARYLAND 1856
SCHOOL OF PUBLIC POLICY
CENTER FOR GLOBAL SUSTAINABILITY

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Summary for Policymakers | October 2022

KEY FINDINGS

- **Non-federal action is a critical pillar of climate mitigation in the United States**, especially from pioneering states such as Maryland. Maryland's Climate Solutions Now Act of 2022 calls for 60% emissions reductions by 2031, the most ambitious target in the country, as well as a 2045 net-zero goal. The state must take action in all sectors to achieve its climate targets, including in the manufacturing sector.
- **The manufacturing sector in Maryland represented nearly 10% of statewide emissions in 2020.** Though a smaller sector, as Maryland's economy continues to grow and diversify, it will be necessary for the state and industry to take steps to decarbonize manufacturing.
- We find the manufacturing sector can reduce emissions by 54.8% by 2031 and 83.8% by 2050 from 2006 levels. **These reductions would account for 9.3%—roughly one-tenth—of total emissions reductions** needed to reach net-zero state-wide without compromising economic and social growth.
- Emissions from the manufacturing sector in Maryland derive from fuel use, industrial processes, and product use. Cement production and super-polluting F-gases represent the largest sources of emissions, with both significant challenges and opportunities for reductions.

Cement production is currently the largest contributor to emissions in the Maryland manufacturing sector, dominated by process emissions with limited mitigation options. Cement facilities in Maryland have already taken actions or made plans to reduce emissions, but significant efforts are required to reach sectoral net-zero emissions.

Fuel use (non-cement) is another significant source of emissions, presenting a challenge as an integral component of manufacturing production. Abatement is possible through strategies like electrification and improving energy efficiency.

F-gases, such as HFCs, are substitutes for ozone-depleting substances (ODS). Most emissions are released during product use, not manufacturing processes, requiring different strategies targeting consumer behavior in addition to technical manufacturing actions.

- **Reducing emissions from the manufacturing sector not only offers economic opportunities but also solidifies Maryland's position as a climate leader.** By including the manufacturing sector in state climate targets and regulations, and taking advantage of federal support, policymakers can facilitate the sector's low-carbon transition through market- and non-market-based policy mechanisms.

The State of Maryland advanced its national leadership on climate change with the passage of the Climate Solutions Now Act (CSNA) of 2022 and the Greenhouse Gas Reduction Act (GGRA) of 2016. These laws require Maryland to reduce state-wide greenhouse gas (GHG) emissions by 60% from a 2006 baseline by 2031 while ensuring a positive impact on Maryland's economy, protecting manufacturing jobs, and creating new jobs in the State. In addition, Maryland has set a 2045 goal for net-zero emissions. These legislative outcomes will drive rapid emissions reductions in the State and, if done well, can energize the economy and increase the state's global competitiveness as the world also shifts toward a rapid, just, and affordable clean energy transition. The State is already on a path toward rapid reductions. Statewide emissions have decreased by approximately 30% between 2006 and 2020, with the largest reductions coming from the electricity sector, road transportation, and industrial fuel use.

Maryland's manufacturing sector, while relatively small as a part of the economy, will play a critical role in the State's ability to achieve these diverse climate and economic goals. Currently, the GGRA exempts the manufacturing sector from GHG regulations due to concern regarding possible financial burdens or negative employment impacts. Nevertheless, to achieve Maryland's ambitious climate targets, the state needs to take action in all sectors, including manufacturing. To better understand the economic and social impacts of decarbonizing this sector, this report evaluates the GGRA's manufacturing exemption as the State Assembly considers whether to maintain or remove the exemption. We find that additional abatement strategies targeting the manufacturing sector—a sector that accounted for 10% of statewide emissions in 2020—specifically for cement production, fuel use, and F-gases, can significantly reduce manufacturing emissions and help put the state on a successful decarbonization pathway.

The manufacturing sector is key for reaching Maryland's 2031 and 2045 emissions reduction goals, and our analysis demonstrates that the rapid pace and large scale of reductions needed in this sector are challenging but feasible for the State. Importantly, many industry leaders support action to decrease emissions and, in many cases, already have plans to reduce their emissions. At the same time, our cost estimates demonstrate that some mitigation strategies will require large capital investments. Regulatory frameworks that clarify expectations will be critical to underpin these significant capital allocation decisions within parts of the manufacturing sector. In this context, policymakers should focus on supporting rapid emissions reductions through appropriate regulations and incentives. **Accordingly, achieving the pace and scale of change needed may require a revisiting of the GGRA exemption for the manufacturing sector, as certain types of regulatory frameworks, pricing, or other actions may be needed to provide the appropriate long-term policy clarity for these major investments.**

MANUFACTURING SECTOR IMPACT IN MARYLAND

Emissions from the manufacturing sector in Maryland derive from industrial fuel use, industrial processes, and product use. Cement production and F-gases represent the most significant sources of emissions and are also two of the hardest to abate. Economy-wide, over 6,500 manufacturing facilities employ over 100,000 people within the state. In recent years, the manufacturing sector's real economic output has been trending upward slightly to over 20 billion in 2012 U.S. dollars. High-value activities include computer and electronic products and chemical manufacturing.

Cement production is the largest contributor to emissions in the Maryland manufacturing sector, with cement plants being the top two highest-emitting manufacturing facilities in Maryland. Lehigh Hanson's Union Bridge plant was the highest-emitting manufacturing facility in the state, with more than four times the emissions of the next highest-emitting facility in 2020. Combined, the two cement facilities alone represent 35% of industrial emissions. Demand for cement is expected to grow through 2050; emissions will increase along with the demand without immediate action.

Fuel use (non-cement) is another significant source of emissions in Maryland's manufacturing sector. Manufacturing accounts for most industrial fuel combustion emissions, including coal burning in cement production. Non-cement manufacturing fuel combustion emissions have declined by about 73% from 2006 to 2020. The main non-cement manufacturing sectors, in terms of GHG emissions, include chemicals, pulp, paper, wood, food processing, and other nonmetallic minerals.

Fluorinated gases (F-gases) are a category of man-made greenhouse gases that substitute for ODS (ozone-depleting substances) but can be hundreds to thousands of times more potent than carbon dioxide. F-gases were the largest source of Industrial Processes and Product Use emissions in Maryland's 2020 GHG Inventory. In Maryland, F-gas emissions are expected to grow through 2050, with refrigeration and air conditioning representing the largest contributors. Unlike cement production and fuel use, F-gases are often emitted during product use rather than during the manufacturing process itself.

MANUFACTURING SECTOR CHALLENGES

A significant challenge in decarbonizing Maryland's manufacturing sector is that the primary emissions contributors (cement production, fuel use, and F-gases) blend into other major sectors, including transportation, energy, and buildings. These overlapping emissions materialize as the transportation of raw materials, electricity usage in facility buildings, and energy use required to power manufacturing processes.

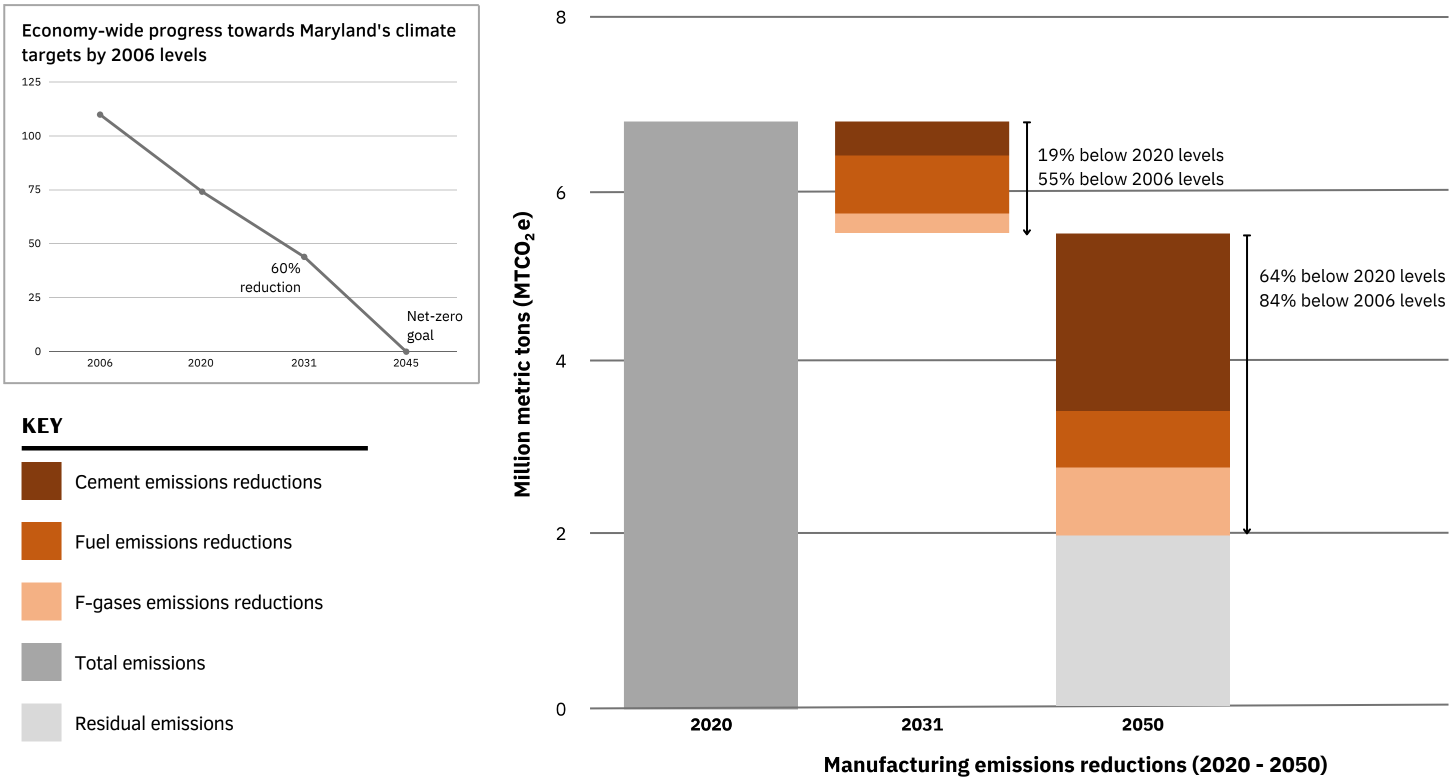
Additionally, sources of emissions in the manufacturing sector are particularly difficult to abate. In cement production, the majority of emissions occur due to process emissions in clinker production - the active ingredient required to create cement. Process emissions are a chemical byproduct of the materials used in clinker production and cannot be avoided based on the established recipe for cement. For F-gases, since emissions are mostly released during use rather than manufacturing, consumer-based abatement alternatives are needed in addition to manufacturing actions.

MANUFACTURING SECTOR ABATEMENT OPPORTUNITIES

Although the manufacturing sector poses challenges, there are also numerous opportunities to implement effective abatement strategies. For example, the Hagerstown cement facility invested nearly $100 million to improve its efficiency of cement production, leading to significant emissions reductions and increased production. Both facilities also have plans to reduce clinker reliance with new cement mixes and to phase-down coal use.

For fuel usage, there is high abatement potential through energy efficiency, demand and material efficiency, and electrification. Energy efficiency can be improved by improving manufacturing equipment and building efficiency, especially for aging and out-of-date infrastructure such as mills. An important F-gas abatement strategy focuses on consumer behaviors, leak repairs, and material substitutions. Implementing state-wide supportive policies can help facilitate the adoption of technical abatement solutions to decarbonize manufacturing. Market-based policies, circular economy principles, and supportive policies can help maintain Maryland cement manufacturers' competitiveness and support their decarbonization pathways.

FIGURE 1 | Maryland manufacturing emissions reductions potential from 2020 to 2050 with potential contribution to Maryland's climate targets



PATHWAY TO DECARBONIZATION

Beginning this year, the state can take action on demand and material efficiency, energy efficiency, electrification, and clean product procurement in the manufacturing sector. The analysis presented in this report shows that by 2031, these steps can potentially reduce sector emissions 55% below 2006 levels. Fuel use emissions in the manufacturing sector could reduce 50% relative to 2020, and 87% relative to the 2006 baseline. Cement sector emissions and F-gas emissions are likely to remain above the 2006 baseline through 2031, but could contribute to emissions reductions toward net-zero goals in the longer term.

By 2050, the cement sector could reduce emissions by 82% through fuel switching and carbon capture and storage. F-gas emissions could reduce 25% relative to 2006, and fuel use could reach near net-zero emissions. Altogether, these strategies can reduce sector emissions by 84% relative to 2006 by 2050. Significant reductions can be achieved in the near term with cost-saving measures, but longer-term deep decarbonization will require large capital investments.

When decarbonizing any sector—let alone one that is growing and employing many skilled workers—a major concern is the economic impact on industry, labor, and communities. All of the strategies mentioned above could potentially create direct jobs on-site and indirect jobs across the supply chain. For example, adding carbon capture and storage to cement facilities is predicted to create hundreds of construction jobs, plus 20 to 30 permanent operational jobs at each location.

CONCLUSION

Manufacturing emissions can be difficult to abate, but options do exist, especially in a state such as Maryland that is leading the nation on climate and has the political will and interest from the private sector to take ambitious action. The manufacturing sector comprises many diverse opportunities for abatement that present unique challenges. Yet we find that the state can take near-term action to help deliver significant reductions toward the 2031 goal. Through a robust, multifaceted approach with some residual emissions left to be offset by other sectors, Maryland is primed to be a national leader in manufacturing decarbonization through 2050.

CHAPTER 1. INTRODUCTION

Subnational climate actions are a critical pillar of U.S. climate mitigation strategy. The State of Maryland is one of the pioneer states in climate mitigation and set the most ambitious emissions reductions target in the country in its Climate Solutions Now Act of 2022.[1] To achieve a 60% reduction in greenhouse gas (GHG) emissions from 2006 levels by 2031 and to reach net-zero by 2045, the state of Maryland will need enhanced actions from all sectors of the economy. While the Greenhouse Gas Reduction Act (GGRA) exempted the manufacturing sector from GHG regulations due to the possible financial burden or negative employment impact in the manufacturing sector,[2] the General Assembly requested a better understanding of such economic and social impacts to re-evaluate this exemption.[3] This independent study was undertaken per §2–1207 to analyze the economic impacts through 2050 of requiring emissions reductions from the manufacturing sector in Maryland.

Since the adoption of the GGRA, emissions have decreased steadily in the state, as reported every three years by the Maryland GHG inventory (Figure 1).[4] Maryland emissions in 2020 are primarily attributed to transportation (road and non-road) and the electricity sector. The remaining emissions are attributed to commercial, industrial, and residential fuel use, industrial processes and product use (IPPU), waste management, and agriculture. Statewide emissions have decreased by approximately 30% between 2006 and 2020, with the largest reductions coming from the electricity sector, road transportation, and industrial fuel use.[4]

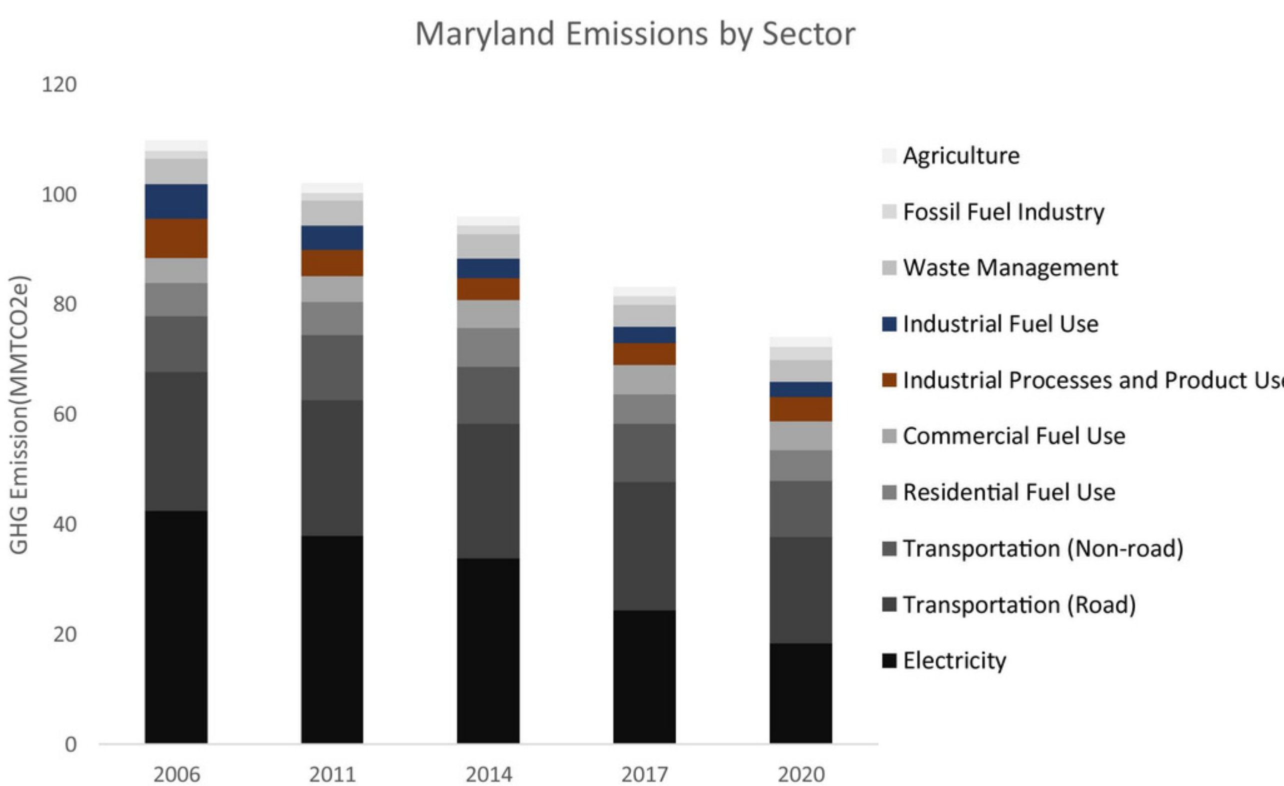
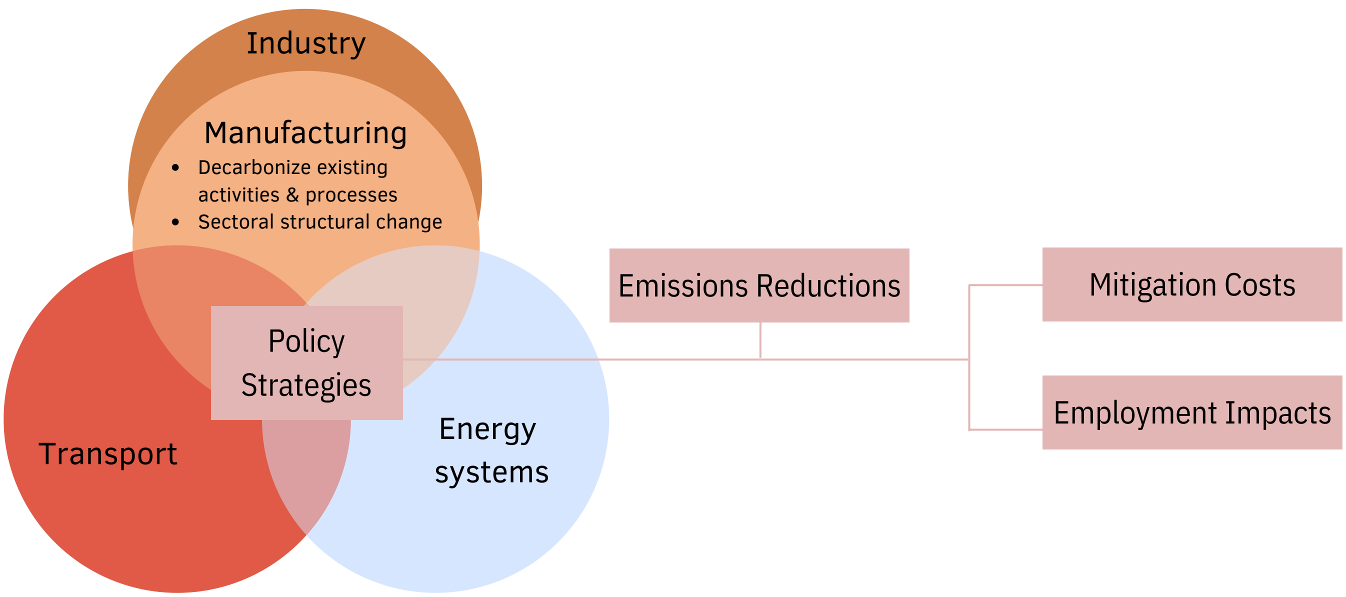


Figure 1. *Emissions by sector from Maryland Greenhouse Gas Emissions Inventories 2006-2020, using a 100 year global warming potential (GWP). *Some industrial process data for 2020 is from a 2019 SIT dataset.*

This report analyzes pathways to decarbonize the manufacturing sector, which covers the "Industrial Fuel Use" and "Industrial Processes and Product Use" emissions in the Greenhouse Gas Inventory shown in Figure 1. Together, these categories represented approximately 9.7% of total state emissions in 2020, slightly decreased from the 2006 baseline. The manufacturing sector represents a relatively minor source of emissions in Maryland compared to other sectors; however, it remains a key challenge for state decarbonization goals due to certain difficult-to-abate emissions categories. Manufacturing sector emissions are also interdependent with other sectors in the state economy. Emissions from the transportation of raw materials and manufactured products, electricity usage in manufacturing processes, and energy usage in manufacturing facilities all contribute to the total impact of manufacturing on the state's GHG budget. While these sectors are not included in the scope of the analysis presented here, this context is essential to crafting policies that will holistically address the impact of manufacturing activities.

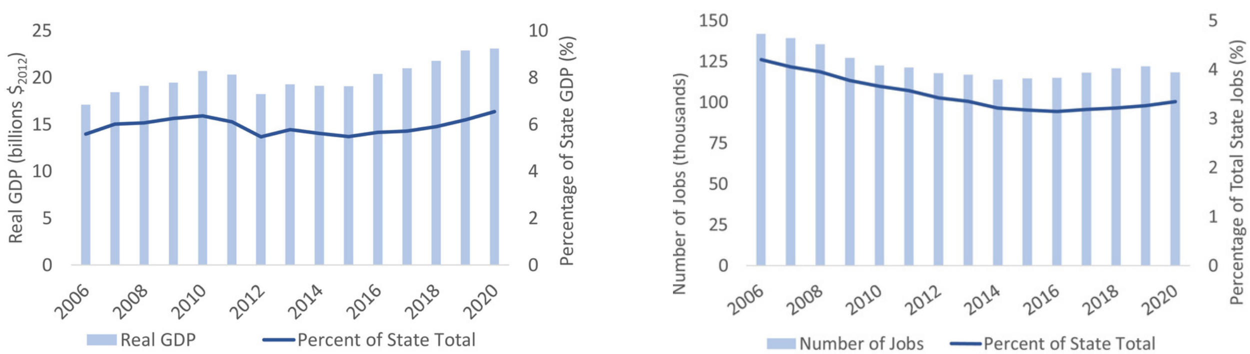


Scheme 1. *Schematic showing the interaction between sectors and design of report analysis. The manufacturing sector is a main part of industry and interacts with energy supply, transport, and buildings. This analysis focuses on the low-carbon transition of Maryland's manufacturing sector itself, including existing activities and processes and sectoral structural changes. We estimate the emissions reductions by different strategies through 2050 and the potential mitigation costs and employment impacts.*

CHAPTER 2. MARYLAND MANUFACTURING: HISTORY OF EMISSIONS AND CURRENT SOURCES

Maryland's manufacturing sector is a small but essential part of the state's economy and employment. It is characterized by activities with particularly difficult-to-abate emissions, making it a key challenge for the state's net-zero ambitions. Here, we provide an overview of the sector in the context of emissions reduction goals.

Over 6,500 manufacturing facilities within the state employ over 100,000 people (Figures 2 and 3).[5] These facilities are distributed widely across the state, with most zip codes hosting at least one manufacturing facility (Supplementary Figure 1). The number of jobs in the sector has declined slightly since 2006, and by 2020 manufacturing represented just over 3% of overall state employment. The sector's economic output, however, has increased over that period, rising from approximately $16 to $23 billion in 2012 USD, and from 5% to 6.5% of the total state Gross Domestic Product (GDP). This contrasts with the overall trend in the U.S., where manufacturing has declined as a portion of total GDP from 12.7% to 11.8% in the same period, despite increasing slightly in real dollars.



a. b.

Figure 2. *Manufacturing (a) GDP and (b) Employment with absolute quantities on the left axes and ratios to total Maryland values on the right axes. Data from Bureau of Economic Analysis (BEA).*[6]

Real GDP output is distributed unevenly across manufacturing facilities in the state, as seen in Figure 3. Particularly high-value activities include computer and electronic products and chemicals manufacturing, which also account for over half the jobs in the manufacturing sector. Notably, energy consumption by activity is non-proportional to the number of firms involved and the GDP associated with the activity (Figure 3). However, energy consumption in Figure 3 does not correspond directly to emissions, as the GHG intensity of energy depends on the energy source (e.g. carbon-intensive fuels such as coal vs. electricity from renewable sources).[7] A more detailed breakdown of emissions by sectoral activity is discussed in Chapter 4.

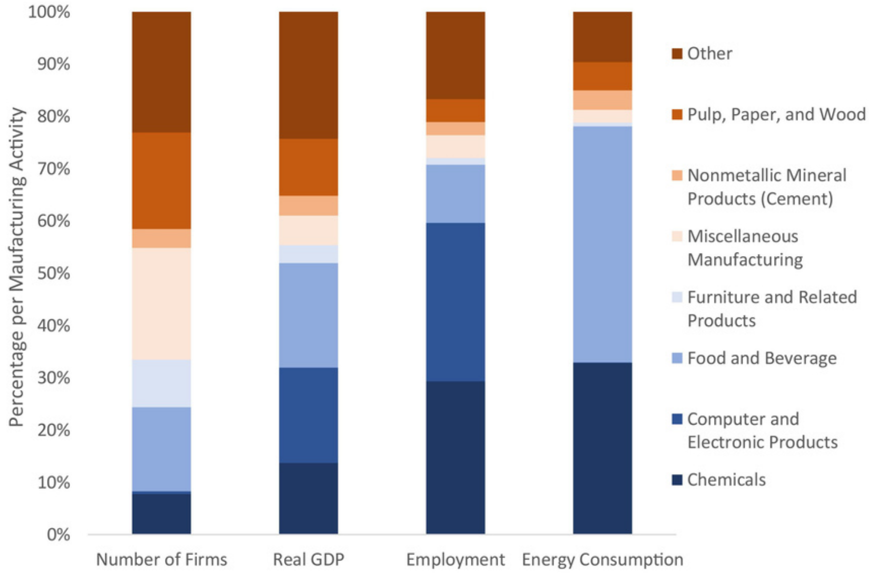


Figure 3. *Energy consumption, number of firms, real Gross Domestic Product (GDP), and employment with breakdown by manufacturing activity. See Technical Appendix for details.*

Industrial emissions in the state fall into two broad categories - fuel combustion and IPPU. IPPU emissions can include CO_2 production as a byproduct of a chemical reaction and as a release of synthetically produced fluorinated gases (f-gases). These emissions are often more complex to mitigate than fuel combustion emissions. Total industrial emissions in Maryland have decreased by 46% since the state's 2006 baseline GHG inventory (Figure 4). A critical driver of this decrease was the ramp-down of production and subsequent closure of the RG Steel plant in 2011, which contributed to a decrease in both process emissions and coal fuel usage (Figure 4 and Figure 5). Another driver for industrial emissions reductions in Maryland was a transition from coal to natural gas between 2014 and 2020, where emissions from coal dropped from 45% to 31% of total fuel emissions and natural gas rose from 21% to 36% of total fuel emissions.

In 2020, the largest contributors to industrial emissions were coal fuel usage, cement process emissions, and the use of ozone-depleting substance (ODS) substitutes. Cement and ODS substitute emissions have increased, growing 21% and 42%, respectively, from the 2006 baseline. In contrast, coal combustion emissions have declined steadily, decreasing to 70% of the 2006 baseline by 2020. Overall, industrial fuel emissions in 2020 declined by 46% relative to the 2006 baseline.

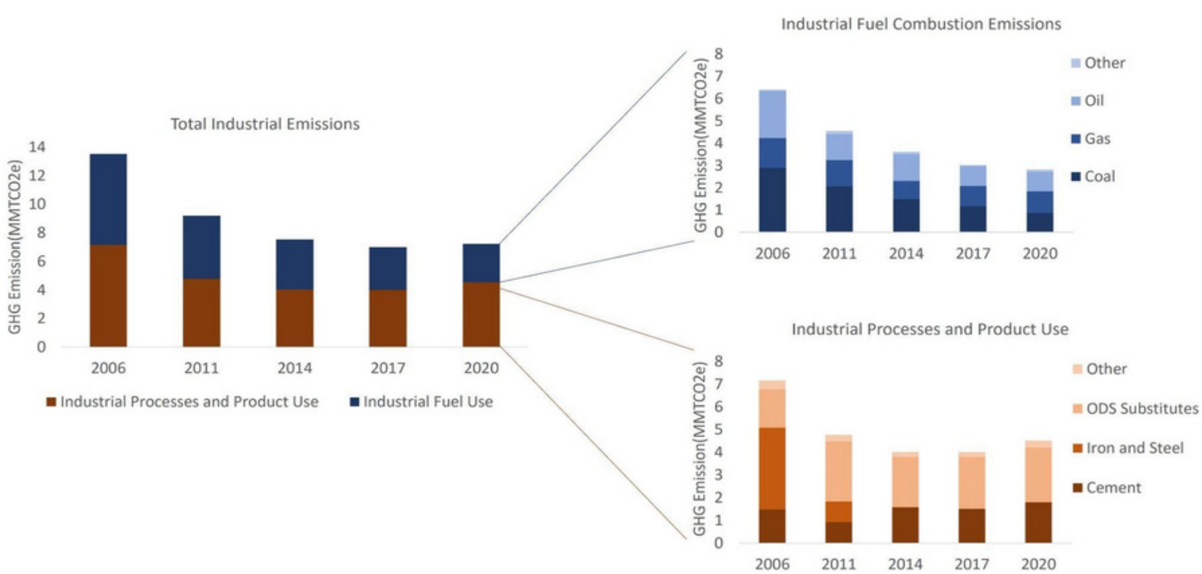


Figure 4. *Breakdown of Maryland industrial emissions into fuel combustion and industrial processes. Data from the Maryland Greenhouse Gas Emission Inventory.*[4]

To further understand the drivers of these trends, it is helpful to identify the manufacturing facilities within the state that contribute the largest share of overall emissions. Figure 5 shows the highest-emitting facilities within Maryland's manufacturing sector. Three of the listed facilities, RG Steel - Sparrows Point, Perryman, and National Gypsum, have gone out of business during the period shown, and the five remaining facilities, Lehigh - Union Bridge, Holcim - Hagerstown, American Sugar Refining, GRACE, and Gold Bond, are the highest-emitting manufacturing facilities as of 2020.

Notably, RG Steel's Sparrows Point facility was the largest emitter in the state before its closure in 2012.[8] Before its closure, Sparrows Point was one of the largest steel manufacturing facilities in the U.S. and was a major employer in the Baltimore area. After remaining vacant for over a decade, this facility is currently being retrofitted to serve the needs of the growing offshore wind industry in Maryland (see Chapter 4).

The top two highest-emitting manufacturing facilities in Maryland are both cement plants. Lehigh Hanson's Union Bridge plant was the highest-emitting manufacturing facility in the state in 2020 by a considerable margin, with more than four times the emissions of the next highest emitter. Combined, the five largest facilities represent 39% of total industrial emissions; the two cement facilities alone represent 35% of industrial emissions. Chapter 3 addresses the unique challenges of decarbonizing cement production in the context of these two facilities.

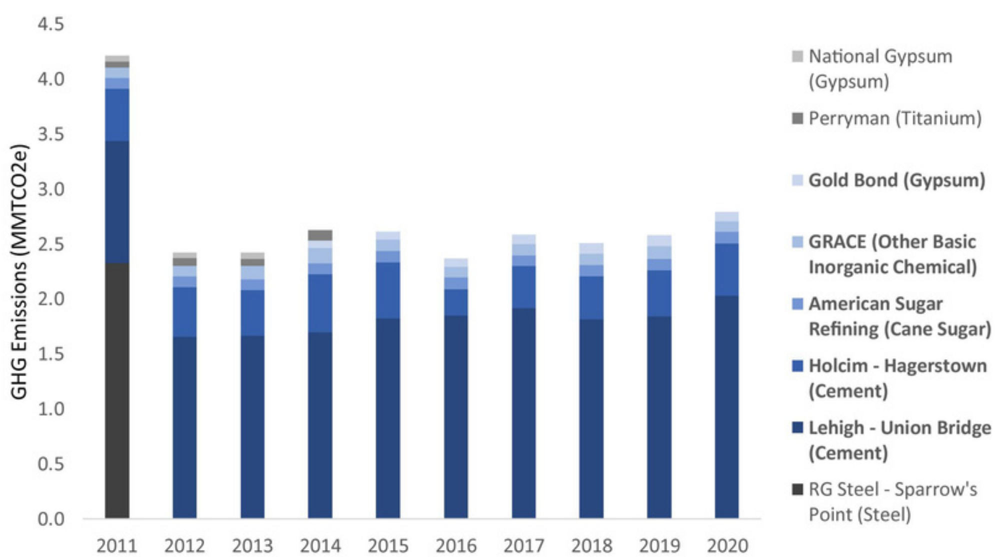


Figure 5. *Maryland Manufacturing Facility Emissions. Highest emitting single facilities based on EPA emissions data.*[9] *Lehigh - Union Bridge and Holcim - Hagerstown are cement production facilities, GRACE is other basic inorganic chemical manufacturing, Gold Bond is gypsum product manufacturing, Perryman is other miscellaneous manufacturing, and American Sugar Refining is cane sugar manufacturing. Facilities in operation as of 2020 are labeled in bold.*

CHAPTER 3. CEMENT: CHALLENGES AND OPPORTUNITIES

CHALLENGES

Concrete is a composite heavy building material that is composed of water, aggregate, and cement paste.[10] Concrete is the second most consumed material on Earth, behind water, and is responsible for approximately 8% of global CO_2 emissions.[10, 11]

Emissions associated with concrete primarily occur during cement manufacturing.[12] Emissions arise at all stages of cement manufacturing. However, the majority of emissions are attributed to process emissions from clinker production and emissions from fuel use. Clinker, the active ingredient in cement, are small, round nodules that produce unavoidable process emissions during their formation. Emissions also result from burning fuel to create the high-temperature process heat required to produce clinker. Although cement manufacturing is emissions-intensive, concrete reabsorbs some CO_2 emissions throughout the use and end-of-life stages through a process called carbonation.[13] After the use stage, concrete can either be landfilled or recycled and repurposed by grinding up concrete debris to be used as aggregate in new concrete mixes.

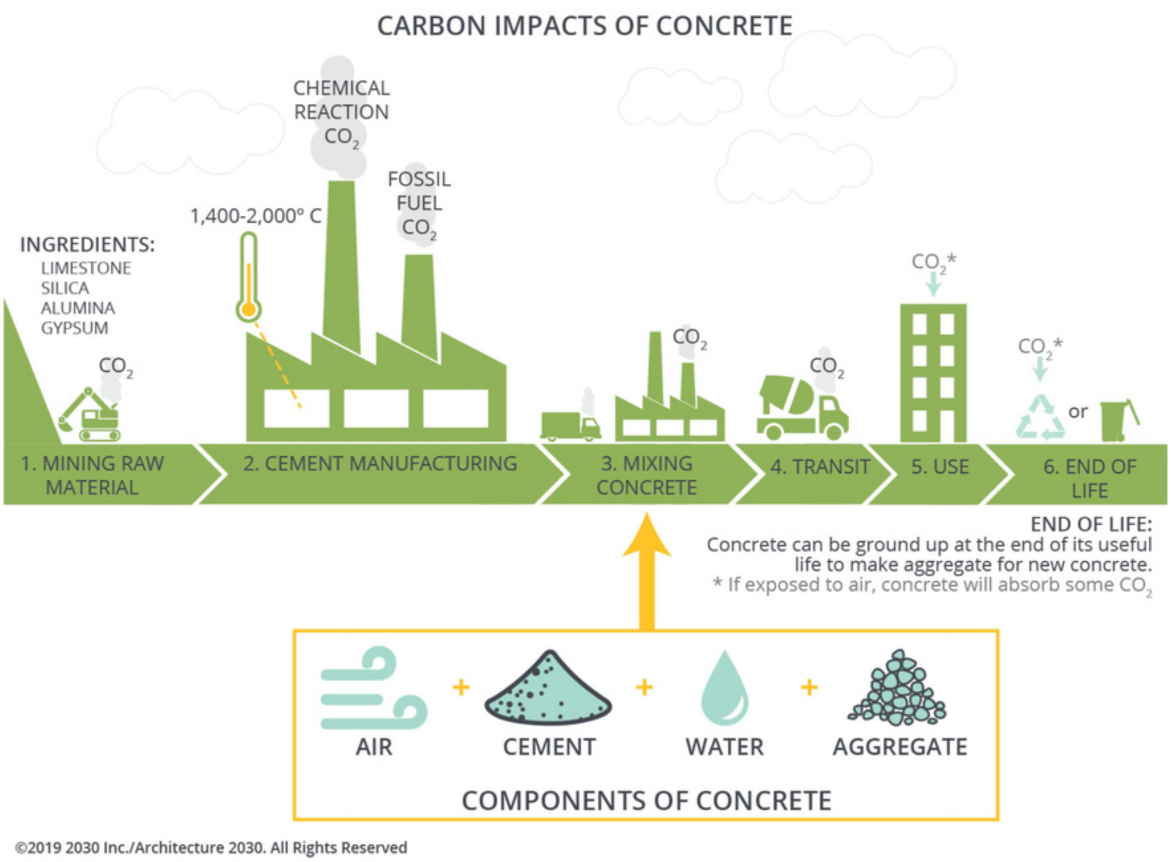


Figure 6. *Schematic of the lifecycle of concrete.[12] Reproduced with permission from Architecture 2030.*

In Maryland, the two highest emitting manufacturing facilities are cement production plants - Lehigh Hanson's Union Bridge facility and LafargeHolcim's Hagerstown facility. The Union Bridge and Hagerstown cement production plants accounted for a combined ~35% of total industrial emissions in Maryland in 2020.[4]

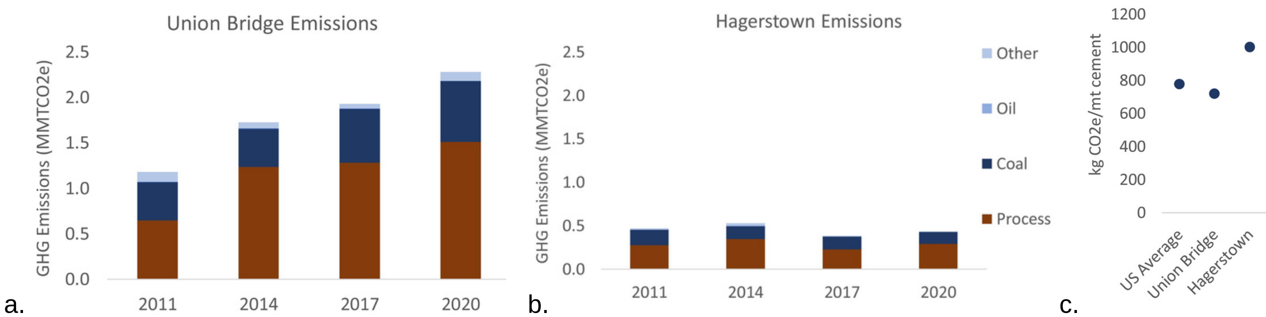


Figure 7. *Breakdown of cement production emissions in Maryland. (a) shows the fuel and process emissions for Lehigh Hanson's Union Bridge plant, and (b) shows the fuel and process emissions for the LaFargeHolcim's Hagerstown plant. Data from Maryland GHG Inventory and provided by facilities.*[4,15,16]

Figure 7 provides an overview of the cement production emissions from the Union Bridge and Hagerstown facilities between 2011 and 2020, the latest year that data is available. The emissions data at each facility is broken down into process emissions and fuel emissions from coal, oil, and others.

Process emissions dominate in both facilities, representing 66% of total emissions at the Union Bridge facility and 67% of total emissions at the Hagerstown facility. Fuel emissions constitute the remaining 34% and 33%, respectively, with the majority of fuel emissions attributed to coal combustion and the remainder to burning oil and other fuels.

There is a considerable disparity in the scale of total emissions between the two cement production facilities. Union Bridge emitted 2,277,259 tCO_2 in 2020, more than five times the 431,936 tCO_2 emitted by the Hagerstown facility in the same year.[4] Although the Union Bridge facility emits several times more CO_2 than the Hagerstown facility, Union Bridge is also more efficient and produces less CO_2 per metric ton of cement manufactured. The industry average emissions intensity for cement production in the U.S. is 776 kg CO_2/mt of cement.[14] Union Bridge's emissions intensity is slightly more efficient than average at 720 kg CO_2/mt of cement, while Hagerstown's emissions intensity is significantly less efficient than average at ~1000 kg CO_2/mt cement (Figure 7c).[15,16]

Demand for cement is expected to grow by 12% to 23% between 2018 and 2050, with a commensurate increase in emissions unless action is taken.[17] The combination of projected demand growth, the need for further development for abatement technologies, and the high cost to decarbonize suggests that the manufacturing sector is likely to decarbonize more slowly than the rest of Maryland with respect to the 60% reduction from 2006 levels by 2031 goal outlined in the Climate Solutions Now Act of 2022.

OPPORTUNITIES

The Union Bridge and Hagerstown facilities have invested in efficiency improvements to reduce CO_2 and non-CO_2 GHGs, including sulfur dioxide (SO_2) and nitrogen oxide (NOx). LafargeHolcim invested $96 million in 2016 to transition the Hagerstown facility from a traditional rotary cement kiln to a more efficient vertical kiln with a preheater tower, reducing emissions and increasing clinker capacity. The improved emissions efficiency of the new preheater tower system at the Hagerstown facility can be seen in Figure 7, where process emissions dropped significantly between 2014 and 2017, despite an expansion in production capacity. LafargeHolcim also installed an on-site solar array at the Hagerstown facility that has been in operation since 2020 and that provides approximately 25% of the power consumed by the Hagerstown facility.[16] Lehigh Hanson invested $12 million across 11 facilities, including Union Bridge, to reduce non-CO_2 emissions as part of a 2019 settlement.[18]

Lehigh Hanson and LafargeHolcim also have other ongoing plans to improve efficiency further and reduce emissions at their respective cement production facilities. Lehigh Hanson intends to increase production at Union Bridge overall and also intends to offset the increased emissions from production through various actions. Union Bridge will switch from manufacturing Ordinary Portland Cement (OPC) to manufacturing Portland Limestone Cement (PLC) by January 2023.[15] The cement recipe for OPC allows up to 5% of clinker to be replaced with limestone, resulting in an equivalent reduction in emissions. PLC allows 5% to 15% of clinker to be replaced by limestone, significantly reducing emissions from cement manufacturing without sacrificing product performance.[19-21] Union Bridge intends to address its fuel use emissions by transitioning from burning carbon-intensive coal to lower-emissions natural gas via a 28 mile natural gas pipeline extension connecting the Union Bridge facility to the Transco natural gas pipeline. The Union Bridge natural gas pipeline extension is anticipated to be completed in 2028.[15] HeidelbergCement, the parent company for Lehigh Hanson, is committed to reducing emissions per ton of cement by 22% relative to a 2016 base year by 2030 and to be net-zero by 2050 - this target has been verified by the Science Based Targets initiative.[22]

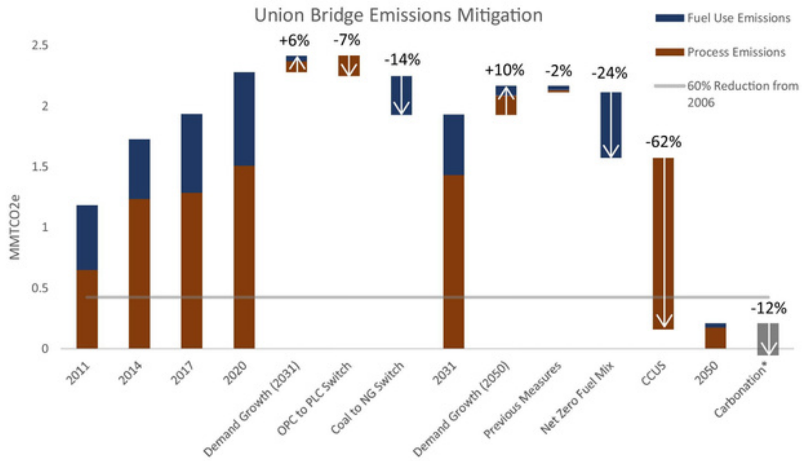
LafargeHolcim also has existing plans to reduce emissions further and improve efficiency at the Hagerstown facility. Hagerstown intends to transition from OPC to entirely PLC production in 2023.[16] Hagerstown also intends to transition up to 43% of its fuel mix over a 3 to 5 year period from coal to a refuse-derived fuel (RDF) mix, provided by LafargeHolcim's subsidiary Geocyle. Geocycle 'pre- and co-processes' waste products by shredding and mixing them together to form a fuel mix that can be burned for energy in applications like heating cement kilns. Geocycle's RDF mix is less carbon-intensive than coal, and the transition to RDF will further reduce emissions at the Hagerstown facility.[23] LafargeHolcim committed to reducing emissions per ton of cement by 21% relative to a 2018 base year by 2030 and achieving net-zero by 2050 - this target is verified by the SBTi.[22]

PATHWAY TO DECARBONIZING CEMENT PRODUCTION IN MARYLAND

By taking on the following actions, Hagerstown can reduce emissions by 87% and Union Bridge by 80% compared to 2006—contributing a total of 1.12 MMTCO_2e reductions to Maryland's climate goals. We detail the emissions reduction potential and costs associated below.

Product Switching: OPC to PLC

Portland Limestone Cement (PLC) is anticipated to dominate the Maryland cement market, replacing Ordinary Portland Cement (OPC) as the most commonly produced cementitious product as early as 2023. Both the Union Bridge and Hagerstown facilities intend to be 100% PLC producers in 2023.[15,16] PLC contains 5% to 15% more limestone and equally less clinker than OPC, resulting in an equivalent reduction in CO_2 emissions.[21] For Figure 8, a 7% clinker-replacement factor was assumed for the Union Bridge based on information provided by the facility, resulting in a 7% overall reduction in emissions relative to the calculated peak emissions in Figure 8).[15] The Hagerstown facility was unable to provide a specific estimate of the clinker-replacement factor, so a maximum of 10% was assumed based on standard industry values.[21] This may represent an overestimate of reduction potential, particularly in the near term. The transition from OPC to PLC is both an emissions and cost-saving measure, as PLC saves between $10 to $30 per t$CO_2$ relative to OPC.[24] The transition from OPC to PLC is not anticipated to significantly impact direct or indirect employment. ASTM International develops and publishes voluntary consensus technical standards for a wide range of materials, products, systems, and services, including concrete and cement.[25] ASTM standards for cement are recipe-based, limiting the inclusion of additional decarbonated materials as clinker replacements. Transitioning ASTM standards for cement products to performance-based standards would increase the abatement potential of cement products without sacrificing product performance. The Maryland legislature could appeal to ASTM to consider transitioning from recipe-based to performance-based standards. Type 1P pozzolanic cement is another low-carbon alternative to OPC that replaces between 15% and 40% of clinker with natural or artificial pozzolans; this report focused on PLC instead of pozzolanic cement due to the impending transition from OPC to PLC planned at both the Hagerstown and Union Bridge facilities in 2023.[20,26]



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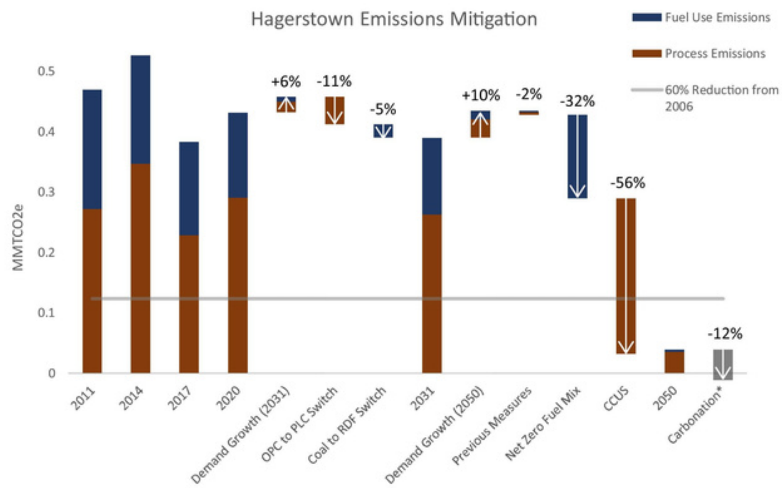


b.

Figure 8. *Mitigation pathways for cement based on MD GHG Inventory historical data, information provided by the facilities, and industry projections.*[4,17] *Percentage emissions increases are calculated relative to 2020 emissions levels. Percentage emissions decreases are calculated relative to the maximum projected emissions which occur after increased demand through 2031. (a) Lehigh's Union Bridge facility emissions projection. (b) Holcim's Hagerstown facility emissions projection.*

Fuel Switching: Coal to Natural Gas

Lehigh Hanson's Union Bridge cement plant currently plans to reduce their fuel emissions by transitioning from coal to pipeline-delivered natural gas as the primary fuel for their cement kilns. Union Bridge plans to construct a 28 mile natural gas pipeline extension to connect the Union Bridge facility to the Transco natural gas pipeline. Lehigh Hanson estimates that the pipeline extension infrastructure will cost approximately $50 million USD and anticipates the project will be completed in 2028.[15] Natural gas is approximately 45% less carbon-intensive than coal but is also more expensive.[27] In 2020, the average cost per MMBtu for all coal ranks was $1.92 and $2.40 per MMBtu for natural gas.[28] The transition from coal to natural gas at the Union Bridge facility will reduce overall emissions by about 13% from peak emissions. While the transition to natural gas is expected to have little impact on direct manufacturing jobs, pipeline construction is estimated to create 58 jobs for every mile of pipeline built.[29] The transition from coal to natural gas will significantly reduce emissions from the Union Bridge facility; however, the pipeline extension's high capital cost and infrastructure investment would likely lock in natural gas as the long-term primary fuel for Union Bridge. This cost could limit Union Bridge's capacity to eliminate fuel use emissions by transitioning to a net-zero fuel mix. Since the transition to natural gas does not completely eliminate fuel use emissions, any Carbon Capture Utilization and Storage (CCUS) infrastructure would have to operate at an increased capacity to capture those unmitigated fuel emissions from natural gas, increasing CCUS operating costs. Natural gas pipelines are also vulnerable to leakage; over 2,600 pipeline leakages occurred in the U.S. between 2010 and 2021, resulting in $4 billion USD in damages and emergency services, the deaths of 122 people, and the release of 26.6 billion cubic feet of fuel as methane or carbon dioxide.[30] Under the Waste Emissions Charge included in the Inflation Reduction Act (IRA), Lehigh Hanson would be subject to fines for every tonne of methane leaked, up to $1,500 a tonne by 2026.[31]

Fuel Switching: Coal to RDF

LafargeHolcim intends to transition up to 43% of their fuel mix at the Hagerstown facility from coal to an RDF mix over the next 3 to 5 years.[16] The RDF mix will be provided by LafargeHolcim's subsidiary, Geocycle, which sources and "pre- and co-processes" the waste products, including solids, sludge, and some liquids, into usable fuel.[23] EPA Commercial and Industrial Solid Waste Incineration Units (CISWI) rules set performance standards and emission guidelines for burning solid waste in commercial and industrial incinerators. CISWI rules limit the use of waste for fuel at commercial and industrial facilities, including cement plants, inhibiting emission reductions through RDF mixes. By 'pre- and co-processing' waste products before they enter the landfill and become officially designated as waste, Geocyle's RDF mix circumvents CISWI standards that otherwise inhibit the use of waste products in U.S. cement facility fuel mixes.[32] RDF mixes are less carbon-intensive than coal, with an emissions reduction of approximately 35% relative to coal; however, the exact percentage reduction in emissions varies by the contents of the mix.[33] A 43% transition to an RDF mix at the Hagerstown facility was calculated to reduce overall plant emissions by approximately 5% compared to peak levels. There is uncertainty as to the range of costs for RDF mixes; McKinsey & Company estimates that utilizing an RDF mix is likely to cost between 0$ to $100 per ton of CO_2 reduced.[24] LafargeHolcim could not provide the exact cost for their RDF mix due to the proprietary nature of the figure. Utilizing RDF mixes has several benefits: RDF mixes reduce emissions relative to coal, reduce the amount of waste entering the landfill, and do not require significant infrastructure adjustments to burn at cement facilities. While switching to a partial RDF mix will likely not have a significant impact on direct jobs at the Hagerstown facility, expansion in the RDF mixing industry is a potential source of indirect jobs.

Fuel Switching: Net-zero Fuel Mix

It is possible to eliminate fuel use emissions from cement manufacturing by utilizing a net-zero fuel mix. Hanson UK, a subsidiary of HeidelbergCement, trialed the cement industry's first net-zero fuel mix in 2021 at their Ribblesdale, UK cement plant.[34] The net-zero fuel mix at the Ribblesdale plant contained 39% hydrogen, 12% meat and bone meal (MBM), and 49% glycerine and successfully eliminated 100% of fossil fuel usage. The Ribblesdale study used 'gray' hydrogen produced from fossil fuels as a proof of concept; however, net-zero fuel mixes would ideally utilize 'green' hydrogen produced cleanly by electrolysis using renewable energy, which is currently much more expensive. While net-zero fuel mixes are technically feasible, they require additional research and piloting to refine the process and reduce costs. The hydrogen production tax credit (PTC) introduced in the IRA under section 45V of the Internal Revenue Code will offer a credit of $0.60 to $3.00 per kg of hydrogen produced. The value of the credit offered is dependent on how the hydrogen was produced and on compliance with the prevailing wages and apprenticeship requirements of the IRA PTC.[35] Green hydrogen qualifies for the $3.00 per kg credit, bringing the current cost of production for green hydrogen down from around $6.00 to $3.00 per kg.[36] Including the PTC credits, a transition to a net-zero fuel mix would cost between -$126 and $238 per tCO_2. Transitioning to a net-zero fuel mix eliminates fuel use emissions, reducing the operating costs to capture remaining cement production emissions using CCUS. Investing in significant fuel-switching infrastructure, such as natural gas pipeline extensions, may reduce the likelihood of adopting and/or push back the adoption date of a net-zero fuel mix. The transition to a net-zero fuel mix is unlikely to have a significant impact on direct employment in cement manufacturing. Still, it is likely to create jobs in the hydrogen and biomass production industries due to increased demand. Utilizing a net-zero fuel mix is estimated to reduce emissions at the Union Bridge facility by 22% and 30% at the Hagerstown facility (Figure 8).

Carbon Capture Utilization and Storage (CCUS)

Carbon Capture Utilization and Storage (CCUS) is essential to capture the unavoidable CO_2 process emissions from cement production. CCUS has the potential to capture an estimated 90% of remaining cement production emissions; however, CCUS is also very expensive to build and operate.[37] To minimize operating impact, emissions reduction strategies should be implemented first, reducing the volume of emissions needed to be captured and sequestered. Assuming that all other emission reduction strategies have been implemented before CCUS adoption, CCUS is projected to reduce overall emissions by 59% from peak levels at the Union Bridge facility and 56% from peak levels at the Hagerstown facility (Figure 8). McKinsey estimates that implementing CCUS will cost between $40 to $200 per tCO_2e, depending on the type of CCUS technology utilized and not including 45Q credits.[24] Geologic storage of captured CO_2 is estimated to cost an additional $50 per tCO_2.[38] Section 45Q of the Internal Revenue Code provides a tax credit for carbon sequestration and utilization. The 45Q tax credits were expanded under the IRA from $50 to $85 per ton of CO_2 for sequestration and $35 to $60 per ton of CO_2 for utilization.[35] 45Q credits are available for the first 12 years of operation for projects beginning construction by the end of 2032, with the tax credit eligible for direct pay. Including the updated 45Q tax credits, the cost per tCO_2 for carbon capture and sequestration drops to between $5 to $165 per tCO_2. The implementation of CCUS technology has the potential to create an estimated 20 to 30 long-term positions at a given cement production facility. It will result in the creation of hundreds of indirect jobs to build and several to maintain the CCUS infrastructure. HeidelbergCement has 8 CCUS projects at various stages of development or operation across Europe and North America, including two under construction at their Edmonton, Alberta plant and their Mitchell, Indiana plant.[39] Interviews with HeidelbergCement representatives indicate that these locations were chosen based on the availability of financial support for the large investment required. LafargeHolcim currently operates over 20 CCUS projects across Europe and North America, including one project in Colorado.[40]

Carbonation

Concrete carbonation is a significant CO_2 sink currently in the Maryland state GHG inventories. The surface area of concrete exposed to air will reabsorb CO_2 during the use and end-of-life stages through a chemical reaction called carbonation. Notably, this process can take decades or even up to a century before the exposed concrete becomes fully saturated with CO_2.[13] Studies report a wide range of estimates for how much CO_2 is absorbed through carbonation, and the parameters needed to calculate precise absorption quantities are the subject of active research. Without considering demolition, which exposes more concrete surface area to the air and increases carbonation, concrete is estimated to reabsorb 7.6% to 24% of associated CO_2 emissions throughout its lifetime. When demolition is considered, the carbonation range increases to as high as 57%.[13] Post-demolition cement debris in Maryland is either landfilled or ground up by private cement recyclers to be used as aggregate for future cement mixes. The carbonation potential of landfilled cement is difficult to estimate due to the substantial variation in the exposed surface area of debris.[41] The waterfall chart in Figure 8 uses a conservative 10% carbonation coefficient. Developing methods to include sequestration via carbonation in-state GHG inventories would more accurately reflect net CO_2 emissions from the cement industry. It would assist in offsetting residual emissions from cement manufacturing. More research is needed to better quantify and form a consensus on the amount and timeline of CO_2 that can be sequestered by concrete carbonation. An emerging technology known as mineralized concrete has the potential to immediately realize the emissions reductions from carbonation by injecting CO_2 that has been captured via CCUS directly into cement mixes as a supplementary cementitious material. Mineralized concrete can achieve full carbonation in as little as 28 days, reducing or eliminating the need for geologic storage for captured CO_2, while improving the structural properties of the cement product relative to OPC. No ASTM standard for mineralized concrete currently exists; however, ASTM is currently developing methods for mineralized concrete products.[42]

Abatement Technology	Cost ($/$tCO_2e$)	Total Annual Emissions Reductions (tCO_2e) Union Bridge	Hagerstown	Annualized Cost ($/year) Union Bridge	Hagerstown
Product switching to Portland Limestone Cement (PLC)	-$10 to -$30	150,962	29,073	$1,500,000 to $4,500,000 in savings	$300,000 to $900,000 in savings
Fuel switch from coal to natural gas	$20 to $26	298,982	N/A	$3,600,000 in fuel + 4,200,000 to 2,300,000 in annualized infrastructure cost	N/A
Fuel switch from coal to RDF mix	$0 to $100	N/A	20,590	N/A	$0 to $2,059,000
Fuel switch to net-zero fuel mix	$173 to $530 or-$52 to $228*	369,881	116,221	$130,000,000 to $200,000,000 or -$19,000,000 to $85,000,000*	$22,000,000 to $47,000,000 or -$4,000,000 to $21,000,000*
Carbon Capture Utilization and Storage	$90 to $250 or$5 to $165**	1,311,691	239,446	$118,000,000 to $328,000,000 or $7,000,000 to $216,000,000**	$22,000,000 to $60,000,000 or $1,200,000 to $40,000,000**

Table 1. *Cost per ton of CO_2 to abate, the total abatement potential, and annualized costs for cement sector emissions abatement technologies at the Union Bridge and Hagerstown facilities.*

A range of costs exists for cement emissions abatement technologies. Some technologies, such as the transition from OPC to PLC and possibly the transition to a net-zero fuel mix, can both reduce emissions and the costs of manufacturing cement. Other technologies, such as CCUS and the transition from coal to natural gas, have the potential to significantly reduce emissions, but also increase costs. Large uncertainties exist in the cost per tCO_2 for fuel switching from coal to an RDF mix, transitioning to a net-zero fuel mix, and for installing and operating CCUS technology. The uncertainty for the coal to RDF mix is due to the wide range of contents that can constitute an RDF mix and the inability of cement facilities to provide an exact cost estimate due to confidentiality concerns. Uncertainty for the net-zero fuel mix is mostly due to the range in projected costs for hydrogen as a component of the fuel mix. Uncertainty for CCUS costs is due to the wide spectrum of projected potential costs to install and operate various CCUS technologies. With supporting financial incentives at the state and federal levels to transition to and install emissions abatement technologies, the cement industry may be able to dramatically reduce their associated emissions without diminishing market competitiveness.

Abatement technology	**Direct jobs** *Union Bridge*	*Hagerstown*	**Indirect jobs** *Union Bridge*	*Hagerstown*
Product switching to Portland Limestone Cement (PLC)	No impact expected		No impact expected	
Fuel switch from coal to natural gas	No impact expected	N/A	Construction of ~30 mile pipeline with estimated 58 jobs per mile (1,740 jobs), pipeline maintenance	N/A
Fuel switch from coal to RDF mix	N/A	No impact expected	N/A	RDF manufacturing and transportation
Fuel switch to net-zero mix	No impact expected		RDF/hydrogen/biofuels manufacturing and transportation of fuel mix	
Carbon Capture Utilization and Storage	Approximately 20 to 30 long term positions at each facility		Hundreds of construction jobs	

Table 2. *Estimated impact on direct and indirect jobs due to cement sector emissions abatement technologies at the Union Bridge and Hagerstown cement plants.*

The GGRA includes language that state regulators cannot require the manufacturing sector to reduce GHG emissions, nor can regulations place a higher financial burden on Maryland manufacturers unless required at the federal level.[43] This exemption extends to jobs as well, with the GGRA requiring that policies "directly cause no loss of existing jobs in the manufacturing sector."[2] The emissions abatement technologies for the cement sector proposed in this report are not anticipated to result in any job losses. Instead, they may result in net job creation in the manufacturing sector. The most significant direct job creation in manufacturing is likely to result from operating CCUS, which is estimated to create 20 to 30 long-term positions for each installation. Indirect jobs are primarily generated from construction projects, particularly the construction of Union Bridge's planned 28 mile natural gas pipeline extension and the construction of CCUS infrastructure. Additional indirect jobs are likely to be generated by increased demand for low-carbon alternative fuels, such as in the production and transportation of an RDF mix or a hydrogen-based net-zero fuel mix. Assuming policies are implemented such that low-carbon products are properly valued in markets, and the Hagerstown and Union Bridge facilities, therefore, remain competitive, cement manufacturing jobs will not be negatively impacted by the abatement technologies discussed here and may even experience job growth.

CEMENT SUPPORTIVE POLICY RECOMMENDATIONS

In addition to technical abatement solutions, implementing supplemental supportive policies at the state and local levels can help to facilitate decarbonization in Maryland cement manufacturing. Market-based policies, including carbon pricing, carbon border adjustment mechanisms (CBAM), expansion of investment frameworks, and low-carbon fuel switching incentives, can help maintain Maryland cement manufacturers' competitiveness and support their decarbonization pathways.

Carbon Pricing

Carbon pricing or emissions trading systems (ETS) level the playing field for manufacturers by putting a price on emissions and incorporating the cost of emission externalities. Carbon pricing or an ETS holds high emitters accountable and pushes them to decarbonize while maintaining the competitiveness of manufacturers who take an active approach to decarbonization. Over 40 countries and more than 20 cities, states, and provinces have implemented some form of the carbon pricing mechanism.[44] The Regional Greenhouse Gas Initiative (RGGI) is a cap-and-trade program intended to limit emissions from the power sector that currently has 12 participating states, including Maryland. RGGI requires fossil fuel power plants with a capacity greater than 25 megawatts to obtain an emissions allowance for each ton of carbon dioxide they emit annually.[45] A similar program could be enacted for cement manufacturers to form a state coalition to reduce emissions from cement production. While carbon pricing is a valid policy option to reduce emissions from manufacturing, it is insufficient alone and must be supported by additional emissions reduction policies. Carbon pricing has been found to reduce emissions by 0% to 2% annually, which falls below the ~3% annual economy-wide emissions reduction needed from 2020 levels to achieve the goals outlined in the Climate Solutions Act of 2022.[46] When utilized with additional supportive policies, carbon pricing or an ETS can maintain the competitiveness of actively decarbonizing cement manufacturers while meaningfully reducing emissions in the manufacturing sector.

Carbon Border Adjustment Mechanism (CBAM)

The competitiveness of manufacturers who invest in decarbonization can be further protected by implementing CBAM. CBAM is an environmental trade policy that consists of charges on imports and sometimes rebates on exports for carbon-intensive goods to protect domestic manufacturers, reduce carbon leakage, and prevent a ‘race to the bottom’ for potentially cheaper yet more carbon-intensive, foreign goods.[47] The European Union passed legislation that goes into partial effect in 2023, and full effect in 2026, to implement CBAM policies on several goods, including cement, fertilizers, iron, steel, aluminum, and electricity.[48] California has operated a CBAM exclusively for the power sector since 2013 that holds the first deliverers of imported electricity liable for the emissions associated with electricity generated in sources outside California, provided that the state does not have an ETS linked to California’s one.[49] Maryland could institute a CBAM, similar to the EU and CA examples, that specifically targets cement products.

Financial Incentives for Abatement Technologies

Implementing financial incentives for emissions abatement technologies would further support decarbonization efforts for Maryland cement manufacturers by partially subsidizing the cost to transition. The federal Infrastructure Investment and Jobs Act (IIJA) contains more than $62 billion for the U.S. Department of Energy (DOE) to support a green energy transition in U.S. manufacturing, including $8 billion for four hydrogen research hubs, one of which will focus on industrial use. The IIJA also contains $3.47 billion for large-scale CCS pilot and demonstration projects and $500 million for industrial efficiency demonstration projects.[50] The IRA implemented a hydrogen production tax credit for up to $3/kg for hydrogen, depending on the production method, produced for the first 10 years of operation of projects beginning construction by 2032, with the tax credit eligible for direct pay. The IRA also contains $5.8 billion in financial assistance to install advanced industrial technology at manufacturing facilities.[35] The DOE released the Industrial Efficiency and Decarbonization funding opportunity announcement (FOA) in September 2022, which includes $104 million to advance decarbonization technologies in the industrial sector.[51] Maryland could follow the federal example and provide additional funding to subsidize abatement technologies. Streamlining the regulation, siting, and permitting practices for cement plants can also help by improving the rate of adoption for facility and infrastructure modernization.

Circular Economy Policies

Circular economy policies, such as demand reduction incentives and utilizing waste streams, can also support decarbonization in cement manufacturing. Demand reduction strategies, such as incentivizing the renovation of buildings rather than promoting new construction and avoiding overbuilding in new structures, can reduce cement manufacturing emissions by reducing demand for cement products. Utilizing waste streams and supporting reuse strategies wherever possible, such as reusing building debris as concrete aggregate or clinker replacements, can reduce the reliance on virgin raw materials and further reduce emissions. Replacing cement with less carbon-intensive materials where appropriate is another strategy to reduce demand and bring down emissions from cement manufacturing.[52] Even with these demand reduction strategies, global demand for cement is expected to increase significantly through 2050.[17]

Procurement Policies

State and local procurement policies, such as "Buy Clean" programs, can also significantly impact emissions reductions from cement manufacturing. At the state and local levels, procurement power can catalyze demand for low-carbon products as a first adopter market, building off of EPA programs with labeling and environmental product declarations (EPDs). The IRA contains $2.15 billion for the procurement of low-carbon materials in buildings owned by the General Services Administration (GSA), $2 billion for procuring low-carbon materials for uses in highway construction projects, $250 million for the EPA to develop Environmental Product Declarations (EPDs) for manufactured products, and $100 million to institute a labeling program for construction material EPDs, such as concrete.[35] On September 15, 2022, the White House announced that it is prioritizing the Federal Government's purchase of steel, concrete, asphalt, and flat glass products produced with lower levels of embodied GHG emissions. On the same date, the federal Department of Transportation released its first agency-wide Buy Clean policy and launched an Embodied Carbon Work Group to support the use of sustainable materials across its programs.[53] The Maryland legislature could similarly direct major state cement consumers, such as the Maryland Department of Transportation (MDOT), to prioritize procuring low-carbon cement products for major state projects, such as bridge construction. Several states, including California, Colorado, Minnesota, New Jersey, New York, Oregon, and Washington, have introduced and/or passed "Buy Clean" or similar legislation to establish the Global Warming Potential (GWP) of building materials, including cement, through EDPs and to provide corporation business tax (CBT) credits to producers of low GWP materials.[54-60] Maryland also has a proposed Buy Clean bill that has been rereferred to the Senate Budget and Taxation committee.

Coalition Building

Coalition building between stakeholders in the cement industry could spur additional demand and maximize purchasing power to procure low-carbon products, rally support for relevant policies, and facilitate knowledge-sharing and local engagement. The U.S. Council of Mayors demonstrated the potential of coalition building for spurring low-carbon cement procurement in 2019 when over 1400 mayors of U.S. cities, including several in Maryland, unanimously agreed to promote the procurement of mineralized concrete for projects within their jurisdictions.[62]

State Policy Actions	Mitigation Strategies Supported by Policy
Implement carbon pricing or an emissions trading system to place a price on externalities from emissions and to maintain the competitiveness of Maryland manufacturers who pursue decarbonization.	• All measures
Implement a carbon border adjustment mechanism (CBAM) to further protect the competitiveness of Maryland manufacturers who pursue decarbonization by placing a tariff on carbon-intensive imported goods.	• All measures
Provide additional and support existing financial incentives for abatement technologies to assist Maryland manufacturers in decarbonizing by partially subsidizing transition costs.	• Carbon capture utilization and storage • Fuel switching
Implement circular economy and demand reduction policies to support decarbonization in Maryland manufacturing by reducing waste, replacing or supplementing carbon-intensive materials, utilizing waste streams as fuel, and by preventing unnecessary- or overuse.	• Demand reduction • Fuel switching
Implement procurement policies, such as Buy Clean policies, to drive demand for low-carbon cement products, such as PLC or other products with low GWP.	• Product switching
Build coalitions amongst stakeholders to spur additional demand and maximize purchasing power to procure low-carbon products, rally support for relevant policies, and facilitate knowledge-sharing and local engagement.	• Product switching

Table 3. *State actions that can support emissions reductions within the cement manufacturing subsector.*

CHAPTER 4. FUEL USAGE AND OTHER PROCESS EMISSIONS: CHALLENGES AND OPPORTUNITIES

Fuel Usage Emissions

Manufacturing emissions are a subset of the total industrial emissions reported in the Maryland GHG inventory. In Figure 9a, we estimate the percentage of industrial fuel emissions attributed to manufacturing activities after excluding the cement industry emissions discussed in Chapter 3. The MD GHG inventory data separated cement emissions from other industrial emissions. A dataset from the Global Change Analysis Model (GCAM) detailing energy consumption by major industries by fuel type was used to estimate the percent allocation of fuel consumption between manufacturing and non-manufacturing industries. We find that manufacturing accounts for a majority of industrial fuel combustion emissions, and both total industrial emissions and manufacturing-specific emissions have decreased significantly since the 2006 baseline. Overall, non-cement manufacturing fuel combustion emissions have declined by about 73% from 2006 to 2020. Figure 9b shows the breakdown of emissions by fuel for the non-cement manufacturing sector. Coal emissions declined to nearly zero in 2020, while natural gas emissions have increased since 2014.

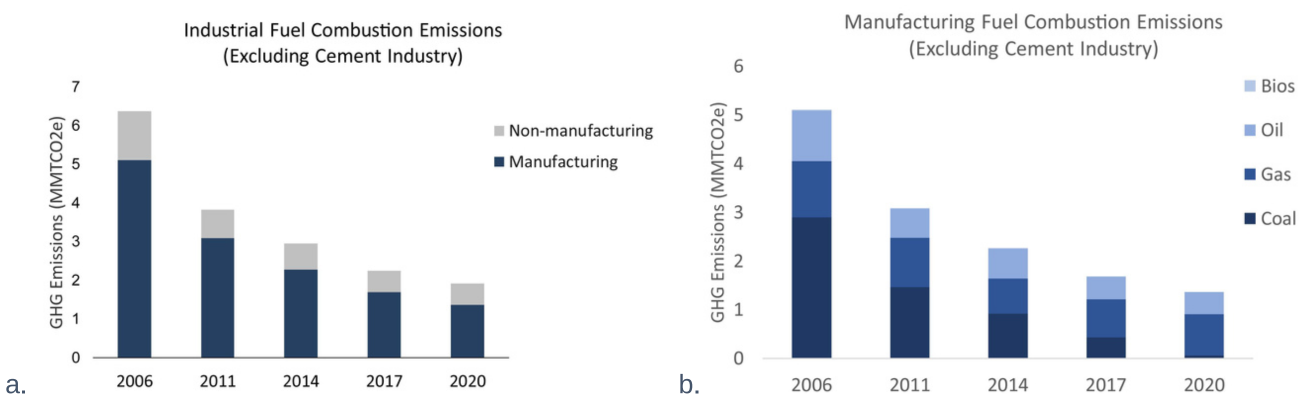


Figure 9. *Breakdown of industrial fuel usage emissions for the non-cement industries in Maryland. (a) shows the fuel emissions for manufacturing and non-manufacturing industries, and (b) shows the emissions by fuel type.*

The main non-cement manufacturing sectors in terms of GHG emissions include chemicals, pulp, paper, and wood, food processing, and other nonmetallic minerals. Although the proportions of non-cement manufacturing sector emissions are not detailed in the Maryland GHG inventory data, they are extrapolated here based on other data sources, including the Bureau of Economic Analysis and the Maryland Manufacturing Directory.

The abatement potential of carbon reduction strategies, including energy efficiency, demand or material efficiency, electrification, fuel switching, and CCUS across different manufacturing sectors, are summarized in Table 4. Sectoral emissions reduction potentials of listed strategies are categorized as having low, medium, or high abatement potential.[7,63]

Sector	Energy efficiency	Demand or material efficiency	Electrification	Fuel switching	CCUS
Pulp, paper, and wood	High (e.g. improving equipment and building efficiency)	High (Increased use of recycled material)	High (low-temp heat; e.g. electric dryers, electric boilers, and heat pumps)	n.a.	n.a.
Food processing	Medium (e.g. improved motor efficiency)	High (Reduce food waste)	High (low-temp heat; e.g. electric boilers and heat pumps)	n.a.	n.a.
Chemicals	Medium (e.g. better process integration)	Medium (Increased use of recycled material)	Low (high-temp heat)	Medium (to biomass or hydrogen)	Likely needed
Other nonmetallic minerals (gypsum, glass, etc.)	Medium (e.g. efficient furnace technologies)	Medium (Increased use of recycled material)	High (low-to-medium temp heat; e.g. electrification of furnaces)	n.a.	n.a.

Table 4. *Abatement potential of emissions reduction strategies across non-cement manufacturing sectors.*

Pulp, Paper, and Wood

There is high abatement potential in the pulp, paper, and wood industry regarding energy efficiency, demand and material efficiency, and electrification. Energy efficiency can be improved by likewise improving manufacturing equipment and building efficiency. Many mills in this industry use relatively older, low-capacity equipment, providing additional opportunities to improve energy efficiency.[7] Demand and material efficiency can be improved through greater use of recycled materials.[7] Given the low temperatures used in the manufacturing process, electrification also has a high abatement potential through the use of electric dryers, electric boilers, and heat pumps.[63] CCUS infrastructure is not currently feasible at U.S. pulp mills due to the small size and location of the pulp mills.[7] Fuel used in the pulp, paper, and wood industry already relies on a high share of self-generated biofuels in integrated chemical pulping plants, leaving little room for further emissions reduction through fuel switching.[7,64]

Food Processing

There is high abatement potential in the food processing industry via reducing food waste and the electrification of electric boilers and heat pumps.[7,63] Energy efficiency has medium abatement potential for this sector through improved motor efficiency.

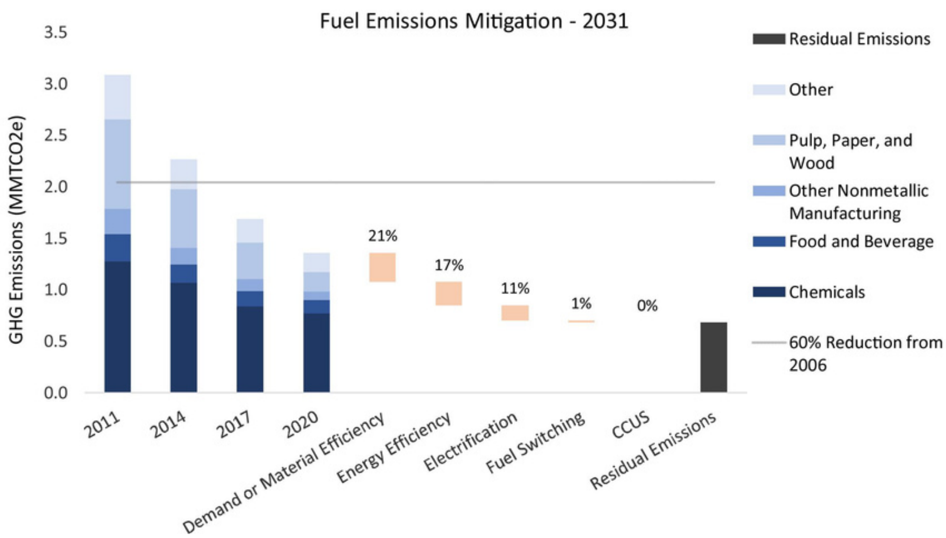
Other Nonmetallic Manufacturing

For other nonmetallic manufacturing, such as glass, energy efficiency can be improved by using efficient furnace technologies.[7] Waste product recycling rates can be improved to further reduce emissions.[7] The electrification of furnaces also has high abatement potential.[7]

Chemicals

Energy efficiency in the chemical industry can be improved through better process integration, such as improving the process design of reactors, distillation and separation processes, and/or heat recovery.[7] Demand-reduction strategies and the utilization of recycled materials can also contribute to emissions reductions in the chemical industry.[7] There is low abatement potential for electrification in the chemical industry due to the reliance on high process heat for key bulk chemicals. Renewable feedstocks such as biomass can be used in manufacturing some bulk chemical products, such as bioplastics.[7]

Fuel switching has a medium abatement potential in the chemical industry. Hydrogen and biogas can be utilized as replacements for fossil feedstocks or as fuel in high-temperature furnaces.[7] Other forms of renewable energy, such as deep geothermal energy, may be used to provide heat or power.[7] CCUS is necessary to deeply decarbonize the sector.[7] Ammonia, hydrogen, and ethylene oxide plants emit a pure CO_2 stream which can be captured via CCUS.[7] Other processes, particularly large furnaces, would need to be adapted for the use of CCUS.



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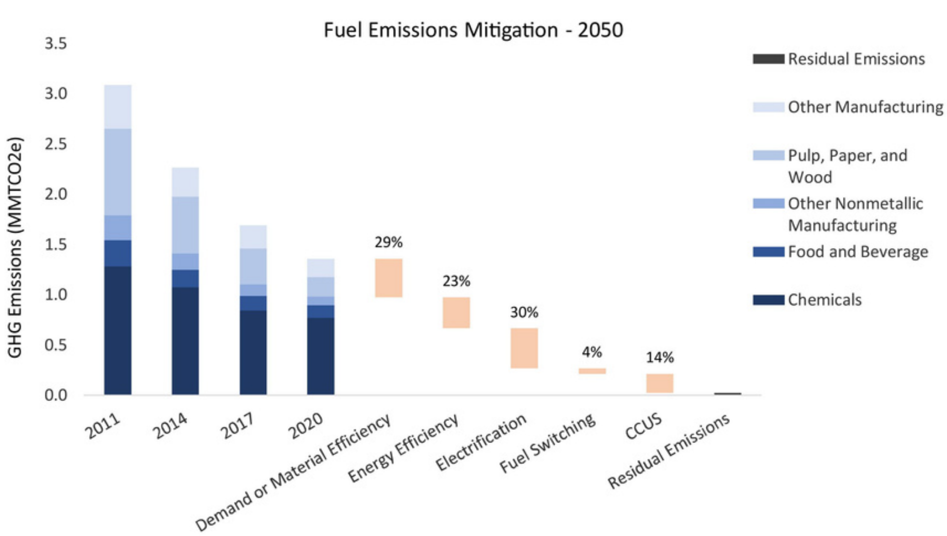

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Figure 10. *a) Mitigation pathways through 2031 for fuel use emissions of non-cement manufacturing sectors. b) Mitigation pathways through 2050 for fuel use emissions of non-cement manufacturing sectors. Historical data is taken from the MD GHG Inventory historical data, abatement potentials are calculated based on literature estimates.*[7,63] *Percentage emissions reductions are calculated relative to 2020 emissions levels.*

Figure 10 shows the fuel emissions reported from each non-cement manufacturing sub-sector from 2011 to 2020 and projects the abatement potential between 2020 to 2050 for each emissions reduction strategy. The total emissions data from 2011 to 2020 is sourced from the Maryland Greenhouse Gas Inventory, and the ratios within each year are calculated from a Global Change Analysis Model (GCAM) data set. Because the GCAM dataset is only available through 2015, the 2015 ratio between sectors was applied to 2017 and 2020. The chemical industry accounts for the majority of carbon emissions from the non-cement manufacturing sector, followed by the pulp, paper, and wood industries. The order of implementation for emissions reduction strategies in Figure 10 is structured to minimize costs and maximize emissions reductions, with lower-cost strategies implemented first.

Figure 10a shows the mitigation pathways through 2031 for fuel use emissions of non-cement manufacturing sectors. Based on the carbon costs in Table 5 and current technology development, the timelines for implementing reduction strategies are classified into three categories: (1) Demand efficiency and energy efficiency, which are assumed to be implemented from 2022-2035; (2) Electrification and Fuel switching are assumed to be implemented from 2022-2050; (3) CCUS is assumed to be implemented from 2036-2050. The reductions within an implementation period are estimated linearly to calculate the reduction potential by 2031. By 2031, demand and material efficiency will play a major role in contributing to 21% emissions reduction, followed by energy efficiency (17%) and electrification (11%). In total, we estimate that emissions from fuel use can be reduced by 50% compared to emissions in 2020 for the non-cement manufacturing sector by 2031. Using the 2006 emissions as the baseline, these strategies can reduce emissions by 87% by 2031, exceeding the state target of 60% emissions reduction by the same year.

Figure 10b shows the mitigation pathways through 2050 for fuel use emissions of non-cement manufacturing sectors. Electrification contributes to the largest emissions reductions by 2050, reducing emissions by 30% from 2020 levels. Sustainable demand growth through waste reduction and material efficiency can reduce emissions by 29% from 2020 levels, and energy efficiency measures can reduce emissions by 23% from 2020 levels. Fuel switching can reduce emissions by 4% from 2020 levels. To minimize operating costs, CCUS would be implemented last and could capture an estimated 14% of emissions from 2020 levels by 2050. Altogether, these strategies can reach near net-zero emissions from fuel use for the non-cement manufacturing sector by 2050.

In Table 5, the costs per ton of carbon emissions reductions are collected from various studies and reports. When single cost numbers are presented, they represent the average costs obtained from the literature. The total emission reduction of each strategy is the reduction quantity from Figure 10 panel b. Negative carbon reduction costs indicate that the specific carbon reduction strategy is cost-saving and directly generates positive economic benefits. The average cost per tCO_2e of emissions reductions for energy efficiency and demand or material efficiency is lower than that of electrification, fuel switching, and CCUS. There is also significant uncertainty in the costs of abatement, depending on the specific technologies and characteristics of the emissions sources.

Abatement Strategy	Cost ($/t$CO_2$e)	Total Emissions Reductions (tCO_2e)	Annual Cost ($)
Demand or Material Efficiency	-$10 [64]	390,000	-$3,900,000
Energy Efficiency	-$130 to $150 [65]	310,000	-$40,300,000 to $46,500,000
Electrification	$11 to $170 [66,67]	400,000	$4,400,000 to $68,000,000
Fuel Switching	$0.00 to $120 [65]	53,000	$0 to $6,400,000
Carbon Capture Utilization and Storage	$91 to $260 [65]	190,000	$17,000,000 to $50,000,000

Table 5. *Costs of emissions abatement strategies for the non-cement manufacturing sector.*

From 2006 to 2020, employment in the chemical industry stayed roughly constant, from 21,286 to 21,716 jobs, according to the Bureau of Economic Analysis. Jobs in the food processing industry increased slightly from 20,835 in 2006 to 22,581 in 2020. However, all other manufacturing categories experienced at least some job decrease over that period. Employment in other nonmetallic mineral products dropped from 5,291 to 4,251 jobs, pulp paper and wood decreased from 9,394 to 4,929 jobs, and other manufacturing industries dropped from 76,586 to 59,736 jobs. Exploring the potential to increase these industries' demand, material, and energy efficiency, strengthening their competitiveness, and reversing the employment trend could provide a double-dividend in climate policy. The offshoring of manufacturing jobs mainly drove job losses in these sectors, along with the growing U.S. trade deficit and the pandemic shutdown in 2020.[69,70] However, carbon mitigation measures can potentially bolster manufacturing jobs by creating direct on-site jobs that require new skills and knowledge, increasing indirect jobs across the supply chain of new technologies, and boost the project construction supporting jobs in the local communities. According to the report from the White House, the actions that the Biden administration has taken, including clean manufacturing of steel, aluminum, and concrete, added 367,000 manufacturing jobs during President Biden's first year in office.[71] According to the forecast by Economic Policy Institute, the total nationwide manufacturing jobs supported by investing in infrastructure, clean energy, and energy efficiency will reach 822,800 by 2024, including 31,700 in the pulp, paper, and wood industry, 1,200 in the food processing industry, 30,400 in the chemical industry, and 7,100 in other nonmetallic mineral industry.[72] According to the same study, there will be significant economy-wide job growth in Maryland by 2024 spurred by investments in clean energy and energy efficiency.[72]

The employment impacts of emissions abatement strategies are summarized in Table 6. These strategies could potentially create direct jobs on-site and indirect jobs across the supply chain. Energy efficiency can create energy and facility management jobs on-site and energy efficiency equipment manufacturing, supply, and contract jobs indirectly. Demand or material efficiency can indirectly create operations management jobs on-site and recycling jobs along the supply chain. Fuel switching can create renewable energy management and operation jobs directly and renewable energy equipment manufacturing, supply, and contract jobs indirectly. Electrification can create new facility management jobs directly and relevant manufacturing and contract jobs indirectly. CCUS can create on-site operation jobs and construction jobs. Fuel switching and electrification strategies might replace traditional energy operation jobs. However, proper re-training could equip these traditional workers with new skills and help retain these workers.

Abatement strategy	**Direct jobs created**	**Direct jobs replaced**	**Indirect jobs created**
Energy Efficiency	EE, energy, and facility management jobs	N\A	EE manufacturing, supply and contractor jobs
Demand or Material Efficiency	Operations management jobs	N\A	Recycling jobs
Fuel Switching	RE management and operation jobs	Traditional energy operations jobs	RE manufacturing, supply and contractor jobs
Electrification	Electrification management and operation jobs	Traditional energy operations jobs	Electrification equipment manufacturing and contractor jobs
Carbon Capture Utilization and Storage (CCUS)	On-site operation jobs	N\A	Hundreds of construction jobs per CCUS site

Table 6. *Employment impacts of emissions abatement strategies across the non-cement manufacturing sector.* [73,74]

Impacts of Off-shore Wind Industry Growth on Manufacturing Emissions and Employment

Maryland is ideally situated to be a major center for the offshore wind turbine industry in the U.S. due to its location near favorable geology along the Atlantic coast and the presence of existing infrastructure at the deep water Port of Baltimore.[75] The scale of the components required for offshore wind turbines necessitates production facilities with ready access to water transportation and specially designed ships that can install the components.[76] There are currently four planned offshore wind projects in Maryland that are expected to deliver a combined 2,022.5 MW, all of which will use the Port of Baltimore as their marshaling and assembly port. A significant part of the supply chains necessary for these projects is the steel fabrication of components, such as monopile foundations.[77-79] Two facilities have been announced as suppliers for the planned projects - the Sparrows Point facility for US Wind and Crystal Steel's Federalsburg facility for Ørsted.

The Sparrows Point facility is the same facility shown in Figure 5 as "RG Steel," which ended steel production in Maryland when it closed in 2012. It is now being retrofitted for steel fabrication rather than steel production and will produce monopile foundations for the US Wind offshore wind projects.[79] The facility is expected to open in 2025, and at full capacity, it will consume 110,000 tons of steel plate per year and create up to 550 full-time jobs.[79,80] Monopile construction consists of steel roll bending, welding, and coating.[79,80] None of these activities are as emissions-intensive as steel production, and facility emissions are not expected to return to pre-2011 levels.

The Crystal Steel Federalsburg facility is already operational and has contracted with Ørsted to fabricate components used in wind turbine foundations such as boat landings, ladders, internal and exterior platforms, railings, grating, and other items.[78] These components can range from 9 to 16 tons each, and the facility expects to use 20,000 tons of steel per year for offshore wind turbine manufacturing.[78] This work will generate approximately 50 additional full-time jobs at the facility, according to company estimates.[78] Activities at the facility will include less energy-intensive processes such as welding and coating, similar to the Sparrows Point facility.

Because the expected activities at these facilities are low-temperature and not emissions-intensive, the same strategies described above are applicable for these facilities. Efficiency measures and electrification are expected to be the primary methods of emissions reduction. Therefore, further facility-specific analysis is not provided here. Further discussion of policies relevant to these mitigation strategies is provided at the end of this chapter.

F-Gas Emissions

Fluorinated gases (F-gases) were the largest source of Industrial Processes and Product Use emissions in Maryland's 2020 GHG Inventory. F-gases are man-made greenhouse gases that can be hundreds to thousands of times more potent than carbon dioxide.[81] They include hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF6), and nitrogen trifluoride (NF3).[82] These gases are commonly used as replacements for ozone-depleting chlorofluorocarbons (CFCs), which were phased out under the Montreal Protocol.[83] F-gases used in this way are often referred to as ozone-depleting substance (ODS) substitutes, as in the Maryland Greenhouse Gas Inventory (Figure 4b). There are no historical measurements of ODS substitute use in Maryland, instead, estimates relying on downscaling national numbers based primarily on population. This analysis utilizes EPA state-level projections for F-gas emissions and abatement potentials through 2050 as the best available estimates for Maryland.

Figure 11 shows projected F-gas emissions for Maryland through 2050 broken down by source. Refrigeration and air conditioning (AC) are the largest emissions source, followed by aerosols and foam manufacturing. Most F-gas emissions are released during product use through leaks, servicing, and disposal rather than during manufacturing processes. This means F-gas abatement requires strategies targeting consumer behaviors and manufacturer actions.

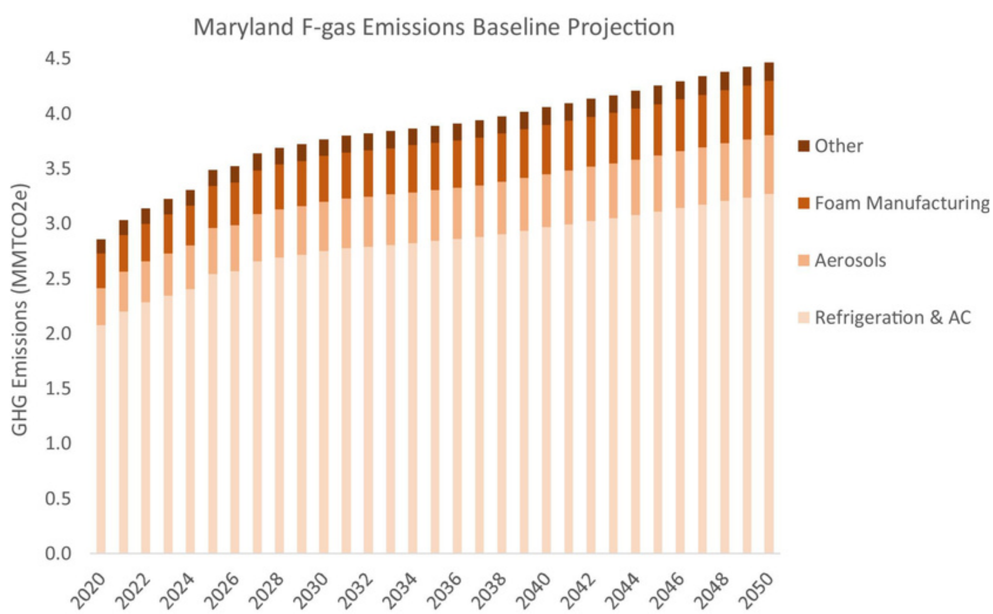


Figure 11. *Projected F-Gas emissions for the state of Maryland for 2020 - 2050 using EPA data from the U.S. State-level non-CO_2 GHG Mitigation Report.*[84] *Categories included in "other" are fire protection, solvents, semiconductor manufacturing, electric power systems, and photovoltaics manufacturing.*

Figure 12 summarizes the abatement potential and cost of F-gas mitigation strategies. Notably, significant reductions compared to the baseline can be achieved at zero cost or cost savings through measures such as leak repair and material substitutions.[84,85] If all zero-cost mitigation measures are taken, F-gas emissions would remain roughly constant at 2020 levels. To achieve reductions below the 2006 baseline, more aggressive actions will need to be taken at additional cost. However, even with the implementation of all technical mitigation measures, residual emissions are expected in 2050. The synthetic nature of F-gases means that it is theoretically possible to fully abate their emissions through demand reduction and technical solutions,[82] but until strategies to do so become technically and financially feasible, these residual emissions will need to be addressed through offsets in other sectors. These results are in line with other estimates in the literature, which suggest potential reductions of 50% in the manufacturing of F-gases, 10% to 40% reductions in refrigeration usage emissions, and higher reduction potentials in smaller categories of emissions.[82] Further reductions could potentially be realized from the recovery of refrigerant gases at the end of a product's life and the destruction of F-gases at manufacturing facilities or dedicated destruction facilities.[82]

Costs for F-gas abatement vary widely depending on the emissions source, ranging from -45.75 to 436.80 $/tCO_2e$. Figure 12b summarizes these costs to show the overall cost savings (blue line) or additional favorable costs (red line) associated with abatement strategies. By 2050, cost savings from abatement will be significant enough to offset additional costs, resulting in a net-negative cost for F-gas abatement across the state.

a.

b.

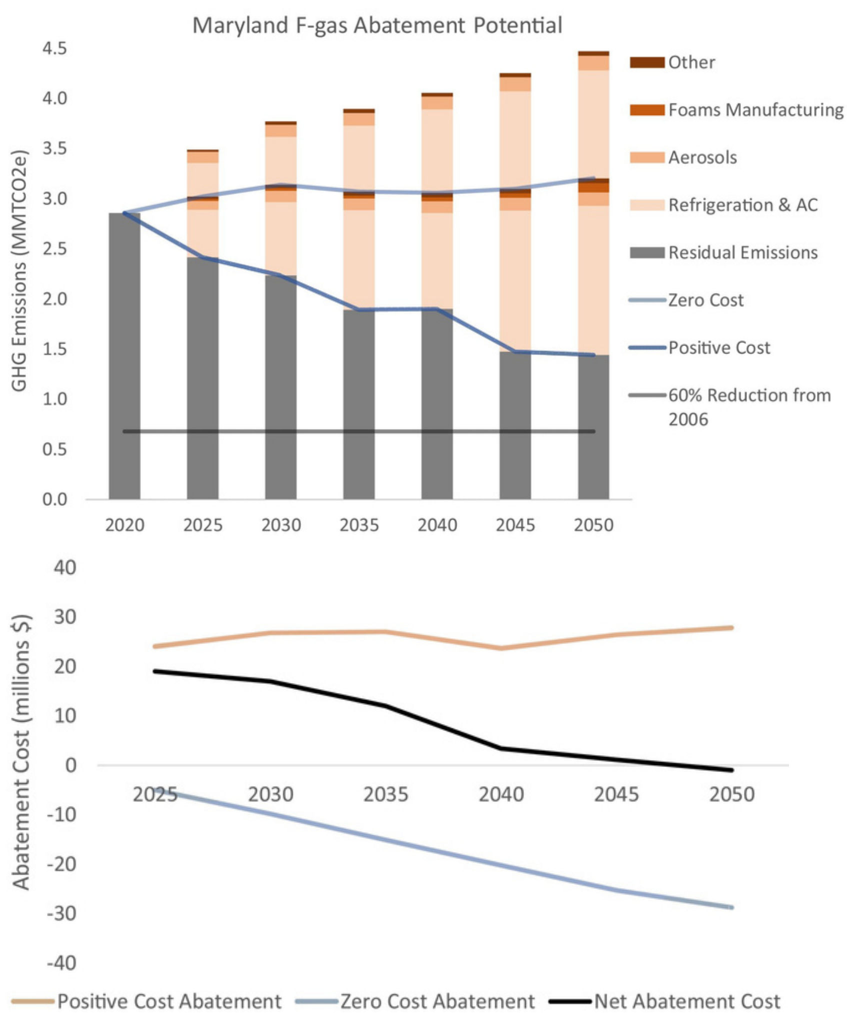


Figure 12. *a) Mitigation measures for F-gas emissions through 2050, broken down by source. b) Cost estimates for abatement measures with zero cost or cost savings, and that will require additional costs. Categories included in "other" are fire protection, solvents, semiconductor manufacturing, electric power systems, and photovoltaics manufacturing.*

Maryland has already taken regulatory action to prohibit the use of certain HFCs for specific end-uses, which was expected to reduce emissions by 12% by 2020 and 25% by 2030.[86] However, the lack of state-level data makes it difficult to track the impact of this regulation, and the Maryland GHG Inventory estimates emissions from ODS substitutes have continued to grow through 2020.[4] Recent federal action is expected to increase pressure to reduce HFCs while reconciling goals and efforts across states. The American Innovation and Manufacturing (AIM) Act set a goal to reduce HFC emissions by 85% by 2036, subsequently implemented as an allowance and trading program through the EPA that regulates both production and consumption of HFCs.[87] This brings the U.S. into compliance with the Kigali Amendment to the Montreal Protocol, which the U.S. Senate ratified on September 21, 2022.[88] Additional state action could complement these federal goals by expanding ambition on HFCs and other F-gases, supporting compliance efforts at in-state facilities, and developing better monitoring of in-state F-gas emissions to fill the current data gap.[82]

The impact of F-gas emission reductions on industry costs and jobs is expected to be minimal in the state of Maryland. Some of the impacted manufacturing sectors have little to no presence in the state and therefore pose no risk of job losses.[86] Primarily for the chemicals manufacturers who are subject to current federal and potential future state regulations, EPA analysis suggests that employment effects are likely to be insubstantial due to the low cost of compliance compared to total costs and due to the low labor intensity in the chemicals industry.[89] Indirect impacts from the regulation of F-gases could include cost-savings for importers and consumers from switching to lower-cost alternatives, with some unevenness across the sector meaning a minority will see price increases.[89] There is also potential for short-term job creation from the installation of conversion equipment and other upgrades.[89] Finally, innovative products from manufacturers of clean products may see an increase in international demand due to global commitments to phase down HFC emissions under the Kigali Amendment to the Montreal Protocol and other national efforts.[82,83,89] Industry groups and the U.S. Chamber of Commerce strongly support measures to reduce F-gas emissions, stating that ratification of and compliance with the Kigali Amendment would lead to an increase in the U.S. global market share for key products and substantial job creation.[91,92]

POLICY RECOMMENDATIONS FOR NON-CEMENT MANUFACTURING SECTORS

Recent federal actions have created a uniquely favorable environment to address difficult-to-abate emissions in the Maryland manufacturing sector in the coming years. The American Innovation and Manufacturing (AIM) Act raised ambition around reductions in synthetic greenhouse gas emissions, the IIJA provided funding for innovative industrial efficiency and emissions reduction technologies, and the IRA provided substantial financial incentives and funding for the implementation of these new technologies.[35,50,93] Relevant provisions for businesses include $5.8 billion in financial assistance to install advanced industrial technology at manufacturing facilities (IRA), $500 million for industrial efficiency demonstration projects (IIJA), and $4.15 billion for procurement of low-carbon materials (IRA).[35,50] Provisions that could support state action include $7 billion for state or city-level green banks (IRA) that could help expand the Maryland Clean Energy Center,[94] the creation of environmental product declaration and labeling programs at the EPA (IRA), and an allowance and trading program to phase down hydrofluorocarbons through 2036 (AIM).[35,50,93]

In this context, action at the state level can leverage federal programs and funding to enhance ambition and support manufacturing decarbonization. Table 7 summarizes ways the state can support the mitigation strategies discussed above.

State Policy Actions	Mitigation Strategies Supported by Policy
Develop state procurement guidelines that build off of the EPA labeling and EPD programs to “Buy Clean” and support demand for low carbon products	• Demand reduction • Material efficiency
Use convening power to build coalitions with manufacturers, academic institutions, and large consumers (e.g. construction industry) that can support knowledge sharing about strategies for emissions reductions, best practices for implementation, and sources of support at the local, state, and federal levels	• Demand reduction • Material efficiency • Energy efficiency • Electrification • Fuel Switching • F-gas mitigation
Pursue federal funds to expand the Maryland Clean Energy Center, making explicit provision for some funds to be used to support small business cost-saving efficiency measures that also reduce emissions	• Energy efficiency • Electrification • F-gas mitigation
Implement standards for F-gas monitoring, recycling, and disposal	• Material efficiency • F-gas mitigation
Support state facilities applying for federal industrial efficiency funding opportunities	• Energy efficiency
Support in-state research programs for immature technologies that can partner with local manufacturing facilities for demonstrations and implementation, utilizing federal funding opportunities	• Fuel switching • Carbon capture utilization and storage
Support state facilities seeking federal permits for carbon sequestration and 45Q tax credits	• Carbon capture utilization and storage
Work with EPA and other states for better bookkeeping of F-gases at the state-level rather than relying on downscaling, which could over- or under-estimate state progress	• F-gas mitigation
Provide investment tax credits for capital expenditures that can demonstrably reduce industrial emissions	• Energy efficiency • Electrification • Fuel switching • Carbon capture utilization and storage • F-gas mitigation
Provide production tax credits for manufactured goods made using electrified industrial heat or zero-emissions fuels	• Electrification • Fuel switching

Table 7. *State actions that can support emissions reductions within the manufacturing sector.*

The policies presented in Table 7 are primarily based on policies previously implemented at the state or federal level. Proposed “buy clean” legislation has already been introduced in Maryland, and passing such a bill could help energize a market for low-carbon versions of carbon-intensive products like steel and cement within the state.[66] Knowledge sharing for manufacturing decarbonization practices could build off of existing initiatives such as the state-funded ENERGY EDGE program at the Regional Manufacturing Institute.[95] The Department of Energy’s Industrial Assessment Centers also offer a model of how academic institutions and manufacturers can collaborate to improve manufacturing processes.[96] Expanding knowledge-sharing programs to support the development of circular economy principles, transitions to electrified processes and clean fuels, and trials of new technologies such as carbon capture and storage can offer manufacturers essential support in the transition to clean manufacturing. These collaborative efforts could also support facilities seeking to apply for federal funding opportunities to reduce emissions. Another potential venue for these kinds of improvements and collaborations is an expanded Maryland Clean Energy Center (MCEC), which could assist manufacturers in reaching decarbonization goals by increasing access to capital, advancing innovation, and facilitating educational outreach.[94]

Tax incentives are an established way to accelerate the adoption of clean technology deployment. The federal investment tax credit (ITC) and production tax credit (PTC) for renewable energy are well-known examples of this, and the IRA recently introduced a new federal PTC for hydrogen fuel.[35,97] Similar policies could be applied to the manufacturing industry through an investment tax credit for electrification, equipment upgrades to allow for the use of zero-emissions fuels, or carbon capture.[98] Similarly, a production tax credit could be offered for the production of low-carbon manufactured goods that use electrified industrial heat.[98]

F-gas mitigation could benefit from some of the above strategies but also requires different approaches due to the importance of product use rather than solely the manufacturing processes. One key improvement would be better data collection and monitoring at the state level, which would allow Maryland to accurately track progress from interventions rather than relying on downscaling of national data, which might not reflect state progress accurately. Another important policy intervention for F-gas mitigation is setting standards for recycling and disposal of gases.[82] For instance, requiring inspections of large industrial refrigeration systems for leaks and setting up procedures for re-use of refrigerants could provide substantial emissions reductions with a potential for cost savings to the facilities as a result.[82,84]

CHAPTER 5. CONCLUSIONS AND POLICY RECOMMENDATIONS

The Maryland manufacturing sector includes several difficult-to-abate emissions categories, such as cement process emissions and F-gases. These emissions will be significant in the near term, given the state's ambitious goal of 60% emissions reduction from a 2006 baseline by 2031. While some emissions, such as fuel combustion, are on track to meet or exceed this goal using currently available technologies, deep decarbonization in difficult-to-abate sectors relies on immature technologies with high current costs. A small number of residual emissions may need to be offset outside the manufacturing sector to fully decarbonize and reach net-zero.

Despite these difficulties, the decarbonization of the manufacturing sector represents an opportunity for net job creation. Minimal impacts are expected on on-site jobs, but substantial indirect job creation is possible along clean manufacturing supply chains. Key facilities in the state are already taking action and developing plans to achieve net-zero in line with longer-term decarbonization goals. State policymakers can enable these industry leaders by creating policies that support key mitigation strategies within the manufacturing sector in the near term and long term.

Strong federal legislation passed in recent years presents a unique opportunity for ambitious action in difficult-to-abate sectors. Maryland's history as a climate leader means it is ideally situated to take advantage of federal funding opportunities and pursue deep decarbonization of manufacturing in the state. With sufficient policy action, Maryland can act as a global leader in manufacturing decarbonization and ensure the competitiveness of its industries in a net-zero future.

Across all manufacturing activities, we find that the most impactful strategies the state could pursue in the near term to mitigate manufacturing emissions in Maryland are:

1. Demand reduction and material efficiency, supported by state coalition building and knowledge sharing around circular economy principles
2. Incentives and standards for industrial efficiency and electrification, such as state tax credits
3. State procurement programs to "buy green" and develop markets for clean manufacturing products
4. Support for in-state facility access to federal research and funding for longer-term technical solutions that are less mature

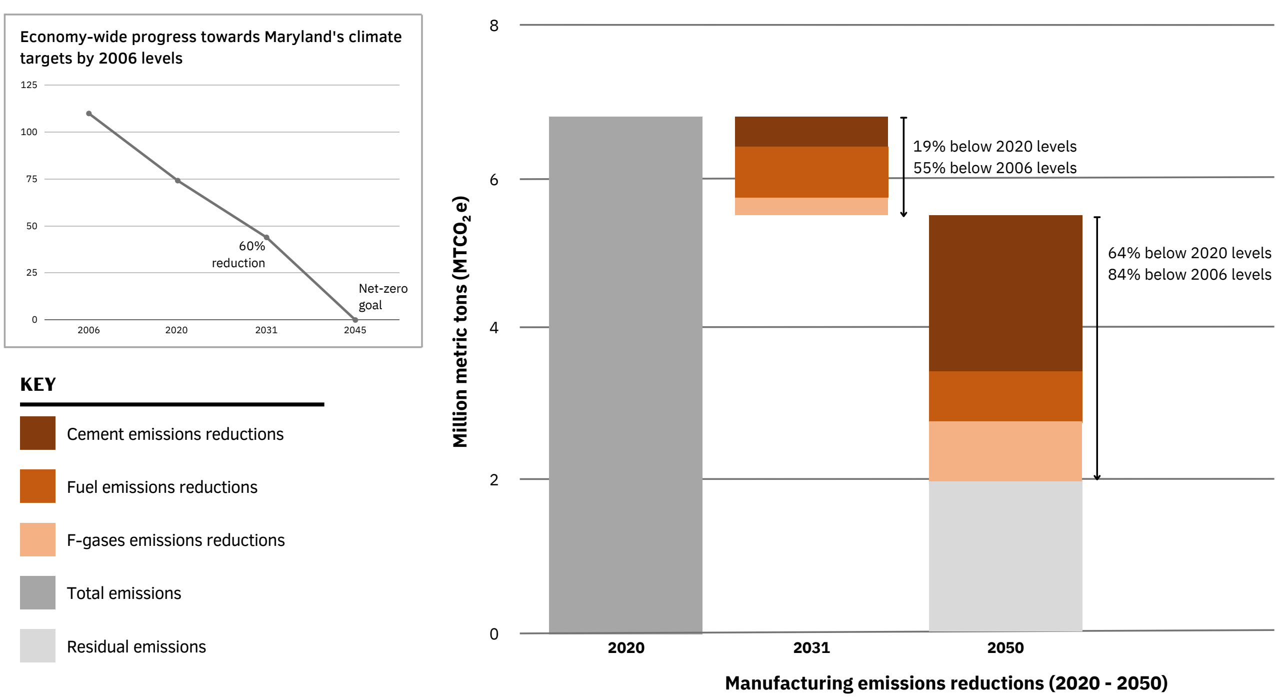


***Figure 13**. Combined emissions reductions for the manufacturing sector for 2031 and 2050.*

Demand reduction and material efficiency can slow the increase in emissions from cement facilities, provide cost savings while decreasing F-gas emissions, and substantially reduce emissions from key manufacturing sectors such as food processing, chemicals, other nonmetallic minerals, and pulp, paper, and wood. A key barrier to realizing these reductions is a lack of awareness of these strategies and knowledge of how to implement them. Building coalitions among manufacturers, consumers, and academic researchers to share best practices can help overcome this challenge. Regulatory action, such as building codes and standards, could also support broader adoption of these strategies.

Substantial knowledge exists about improving industrial efficiency across all sectors and electrifying many light industry processes, such as food processing. By providing tax incentives for these actions, the state can make the capital investment required for these transitions more attractive, thereby accelerating the adoption of these technologies. Stable regulatory frameworks that clarify expectations could also provide a critical framework for these significant capital allocation decisions within parts of the manufacturing sector.

State procurement programs that create stable demand for low-carbon manufactured products can boost confidence that manufacturers will remain competitive when they invest in emissions reductions. This is important both to create markets for low-carbon products that may require cost increases to decarbonize (e.g. green chemical production), and to accelerate acceptance of products that may reduce costs but are less well-known to consumers (e.g. Portland Limestone Cement).

Deep decarbonization of all manufacturing activities will require implementing technologies that are not yet mature enough for commercial implementation. By supporting in-state research at academic institutions and manufacturing facilities, Maryland can build partnerships around solutions and become a leader in manufacturing decarbonization. This can be achieved in part by encouraging eligible coalitions of state entities to pursue federal funding for innovative decarbonization technologies, such as the hydrogen hub mandated in the IRA that will focus on industrial use of hydrogen.[35] Achieving the pace and scale of change needed for full decarbonization may require revisiting the GGRA exemption for the manufacturing sector, as certain types of regulatory frameworks, such as carbon border adjustment mechanisms or access to RGGI-style carbon markets, and other actions may be needed to provide the appropriate long-term policy clarity and cost reductions for these major investments.

Overall, we find that these measures will likely result in cost savings for manufacturers rather than cost increases. Full decarbonization of the sector will require investment in currently immature and expensive technologies such as hydrogen fuel and carbon capture and storage. Still, significant reductions can be realized through these measures in the near term. Similarly, the effect on employment is expected to be a net benefit for the sector, with job creation in operations, facility management, recycling, and equipment retrofitting. Some traditional energy jobs may be lost due to electrification, and support for worker retraining may be important to reduce the impact on communities with high concentrations of traditional energy jobs. Because the above measures primarily provide cost savings while producing low-carbon products, they may also be able to support the competitiveness of Maryland manufacturers and strengthen the sector. This will be particularly true if demand for low-carbon products rises based on current emissions reduction commitments, making Maryland products more desirable to consumers.

Future analysis and tracking of decarbonization progress in the state would be significantly assisted by filling key data gaps faced in this study. Disaggregation of emissions by manufacturing activity, tracking of energy consumption by activity, state-level tracking of F-gas emissions, and analysis of cement carbonation as a carbon sink would all improve the accuracy of future analysis and Greenhouse Gas Inventory calculations. A more comprehensive picture of the impacts of manufacturing sector decarbonization would also be achieved through a study that examined the entire state economy and was, therefore, able to analyze the indirect impacts on manufacturing through interactions with other sectors such as buildings and transportation. These effects were outside the scope of the analysis presented here and should be assessed in future research.

TECHNICAL APPENDIX

Background of Maryland GHG Emissions Reduction Policies and Targets

The Greenhouse Gas Reduction Act (GGRA) of 2009 required Maryland to reduce state-wide greenhouse gas (GHG) emissions by 25 percent from a 2006 baseline by 2020 while ensuring a positive impact on Maryland's economy, protecting manufacturing jobs, and creating new jobs in the State. The GGRA was reauthorized in 2016 to incorporate additional reporting and mid-course reaffirmation goals and set a new benchmark of a 40% emissions reduction from 2006 levels by 2030. The Climate Solutions Now Act of 2022 increased the ambition of Maryland state emission reduction targets, calling for a 60% gross reduction of GHGs from 2006 levels by 2031 and net-zero emissions by 2045.[1] The emissions reduction target set by the Climate Solutions Now Act of 2022 is the most ambitious state target in the U.S.

The GGRA prohibits the state from requiring GHG emissions reductions from Maryland's manufacturing sector, causing a significant increase in costs to Maryland's manufacturing sector, or directly causing the loss of e*xisting jobs in the manufacturing sector unless required at the federal level or by existing state law.*[2] *The General Assembly created a process to re-evaluate this provision based on an independent study of the economic impact of requiring greenhouse gas emissions reductions from the State's manufacturing sector, to be overseen by the Maryland Commission on Climate Change.*[3]

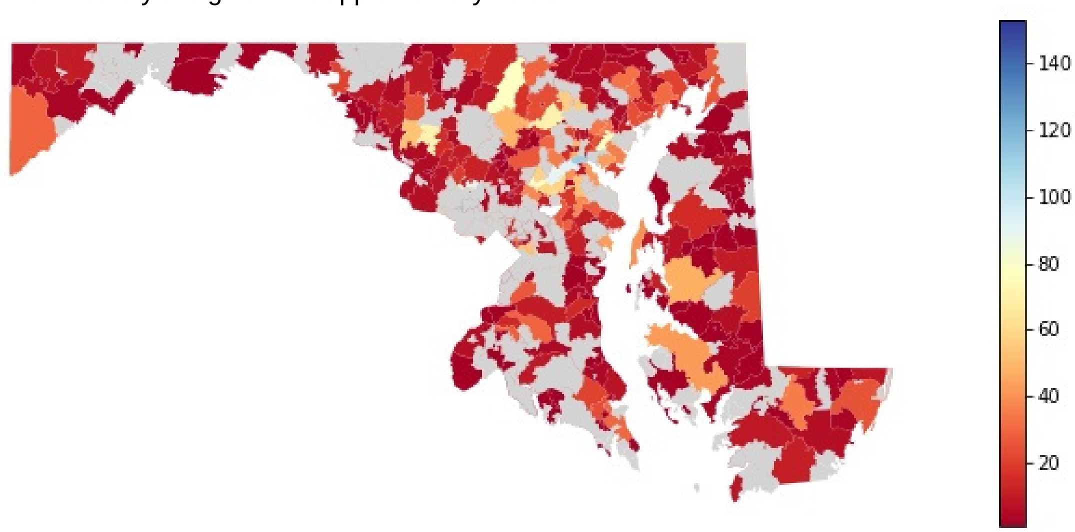
Definitions and Descriptions of Maryland Manufacturing

Definition of Manufacturing

Manufacturing is defined as activities falling within North American Industry Classification System (NAICS) codes 31-33 where possible in this analysis. When an activity is ambiguous or unknown, the categories "Industrial Fuel Use" and "Industrial Processes and Product Use" in the Maryland Greenhouse Gas Inventory are taken as the default boundaries because they form the legal basis for greenhouse gas reduction plans and the scope of this work.

Description of Manufacturing Activities in Maryland

There are 6,693 manufacturing facilities listed in the Maryland Manufacturing Directory. The geographical distribution of these facilities is shown in Supplementary Figure 1. The top 5 most common manufacturing activities in the Directory are given in Supplementary Table 1.



Supplementary Figure 1*. Map of density of manufacturing facilities by zip code in Maryland. Data from Maryland Manufacturing Directory.*

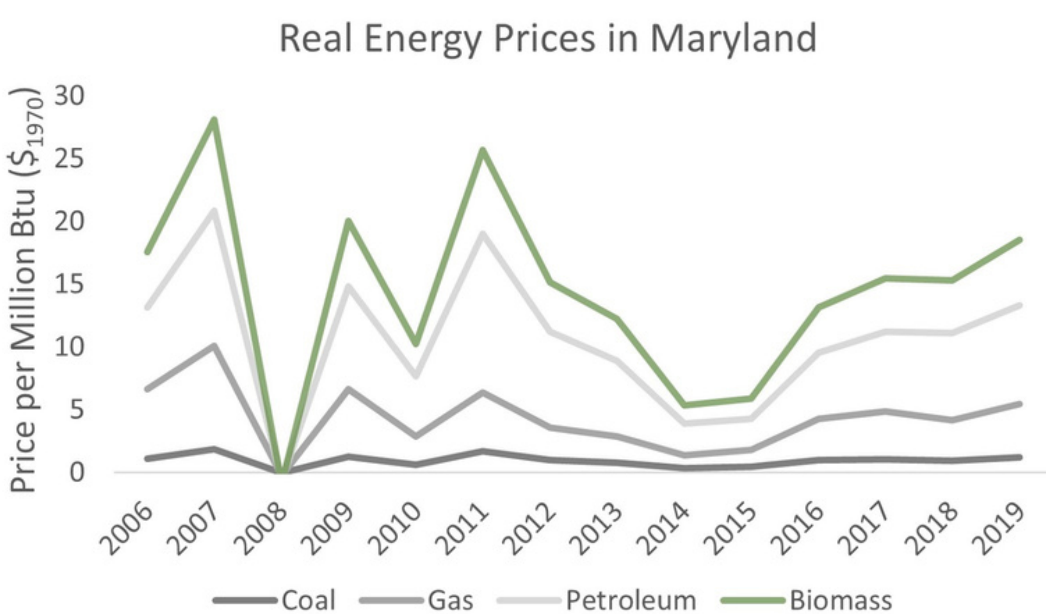
NAICS code	NAICS code description	Number of facilities
323111	Commercial Printing (except Screen and Books)	463
311811	Retail Bakeries	419
339999	All Other Miscellaneous Manufacturing	328
339950	Sign Manufacturing	277
337110	Wood Kitchen Cabinet and Countertop Manufacturing	262

Supplementary Table 1. *Most common manufacturing activities by NAICS code in the Maryland Manufacturing Directory.*

Maryland Greenhouse Gas Emission Inventory

The Maryland Greenhouse Gas Emission Inventory is publicly available for years 2006, 2011, 2014, and 2017. A draft version of the 2020 inventory was supplied by the Maryland Department of the Environment for this analysis. All emissions in the inventory are calculated based on a 100-year global warming potential (GWP).

Historical Fuel Prices in Maryland



Supplementary Figure 2. *Real energy prices in Maryland for 2006-2020. Data from EIA and BLS.*[99,100]

Fuel prices in the industrial sector have fluctuated over time, but those fluctuations in prices do not correlate with similar fluctuations in GDP or employment (Figure 2), indicating that the sector is resilient to fuel price changes of this magnitude.

Harmonization of Manufacturing Categories Across Figure 3 Datasets

Category	**Energy Consumption**	**Number of Firms**	**Real GDP**	**Employment**
Source	Manufacturing Energy Consumption Survey,100 MD Manufacturing Directory 101	MD Manufacturing Directory 101	Bureau of Economic Analysis 5	Bureau of Economic Analysis 5
Date	MECS Survey 2018Manufacturin g Directory accessed 8-10-2022	Accessed 8-10-2022	Proportions based on 2020 data	Proportions based on 2020 data
Chemicals	NAICS code 324-325	NAICS code 324-325	Chemicals manufacturing, Petroleum and coal products manufacturing	Chemicals manufacturing, Petroleum and coal products manufacturing
Computer and Electronic Products	NAICS code 334, No code but self-description with “computer”	NAICS code 334, No but code self-description with “computer”	Computer and electronic product manufacturing	Computer and electronic product manufacturing
Food Processing	NAICS code 311-312, No code but Self-description with “food”	NAICS code 311, No code but Self-description with “food”	Food and beverage and tobacco product manufacturing	Food manufacturing, Beverage and tobacco product manufacturing
Furniture and Related Products	NAICS code 337	NAICS code 337	Furniture and related product manufacturing	Furniture and related product manufacturing
Miscellaneous	NAICS code 339	NAICS code 339	Miscellaneous manufacturing	Miscellaneous manufacturing
Nonmetallic Mineral Products	NAICS code 327	NAICS code 327	Nonmetallic mineral product manufacturing	Nonmetallic mineral product manufacturing
Printing and Related Support	NAICS code 323	NAICS code 323	Printing and related support activities	Printing and related support activities

Pulp, Paper and Wood	NAICS code 321-322	NAICS code 321-322	Paper manufacturing, Wood product manufacturing	Paper manufacturing, Wood product manufacturing
Other	All other NAICS codes 31-33 not listed in this table.		Primary metal manufacturing, Fabricated metal product manufacturing, Machinery manufacturing, Electrical equipment, appliance, and component manufacturing, Textile mills, Textile product mills, Apparel manufacturing, Leather and allied product manufacturing, Plastics and rubber products manufacturing	
Transportation Equipment	NAICS code 336	NAICS code 336	Motor vehicles, bodies and trailers, and parts manufacturing Other Transportation Equipment	Motor vehicles, bodies and trailers, and parts manufacturing Other Transportation Equipment

Supplementary Table 2*. Explanation of categories and data sources for Figure 3.*

Calculation of Cement Emissions Reductions (Figure 8) and Costs (Table 1)

OPC to PLC Switch

Abatement potential from transitioning from OPC to PLC cement manufacturing at the Hagerstown facility was calculated using a 10% industry default emissions reduction coefficient.[21] The industry default emissions reduction coefficient was multiplied by Hagerstown's total process CO_2 emissions in 2020 to calculate the abatement potential. Union Bridge provided an abatement potential estimate of 7% from OPC to PLC switching at the Union Bridge facility that was used instead of the industry default.

$$0.10 * \text{ } Total\ Emissions = \ Abated\ tCO_2\ at\ Hagerstown$$
$$0.7 * \text{ } Total\ Emissions = \ Abated\ tCO_2\ at\ Union\ Bridge$$

Switching from OPC to PLC is estimated to reduce costs by between \$10 to \$30 per ton of CO_2.[24] The range of savings from switching from OPC to PLC were calculated by multiplying the total CO_2 emissions by either \$10 or \$30.

$$\$\ saved\ per\ tCO_2 \ * \ Abated\ tCO_2 \ = Annualized\ savings$$

Coal to Natural Gas

The EIA estimates a 44.7% emissions reduction coefficient for the transition from coal to natural gas.[27] Abatement potential for the coal to natural gas transition at the Union Bridge facility was calculated by multiplying the 44.7% emissions reduction coefficient by Union Bridge's total coal CO_2 emissions in 2020.

$$0.447 * Total\ Coal\ Emissions = Abated\ tCO_2$$

The cost to transition from coal to natural gas was calculated by adding annualized infrastructure costs and annualized fuel costs. Union Bridge estimates that installing natural gas infrastructure, including the 28 mile natural gas pipeline, will cost $50 million. A range of annualized infrastructure costs were calculated by dividing the $50 million in infrastructure costs by a 12 and 22 year lifespan representing a potential switch to net-zero fuels by 2040 and continual use of the pipeline through 2050 respectively. Fuel costs were calculated by subtracting the annual cost of coal consumed at Union Bridge from the annual cost of natural gas to replace coal. The annual cost of coal at Union Bridge was calculated by multiplying the cost per ton of coal in 2020 by the total tons of coal consumed in 2020.[102] The cost to replace coal with natural gas was calculated by dividing the cost of natural gas per MMBtu by the cost of coal per MMBtu and then multiplying that quotient by the annual cost of coal in 2020.[28]

$$\$\ per\ ton\ of\ coal * tons\ of\ coal = Annualized\ cost\ of\ coal$$

$$\frac{\$50{,}000{,}000}{Pipeline\ lifetime\ in\ years} = Annualized\ infrastructure\ costs$$

$$\left(\frac{Cost\ of\ natural\ gas\ per\ MMBtu}{Cost\ of\ coal\ per\ MMBtu}\right) * Annualized\ cost\ of\ coal = Annualized\ cost\ of\ NG$$

$$Annualized\ cost\ of\ NG - Annualized\ cost\ of\ coal = Annualized\ cost\ to\ switch\ fuels$$

$$Annualized\ infrastructure\ cost + Annualized\ cost\ to\ switch\ fuels = Annualized\ cost\ to\ switch\ to\ NG$$

Coal to RDF Mix

Literature estimates suggest a 35% emissions reduction coefficient for the transition from coal to a RDF mix.[33] The Hagerstown facility intends to transition up to 43% of their fuel mix from coal to a RDF mix over a 3 to 5 year period. Abatement potential for the coal to RDF mix transition at the Hagerstown facility was calculated by multiplying the 35% emissions reduction coefficient by the 43% transition coefficient and then by Hagerstown's total coal CO_2 emissions in 2020.

$$Emissions\ Reduction\ Coefficient * Percent\ of\ fuel\ to\ be\ switched * Total\ Coal\ Emissions = Abated\ tCO_2$$

Transitioning from coal to a RDF mix is estimated to cost between $0 to $100 per ton of CO_2.[24] The cost to transition from coal to a RDF mix at the Hagerstown facility was calculated by multiplying the tons of CO_2 abated by the transition by either $0 or $100.

$$\$\ per\ tCO2 * Abated\ tCO_2 = Annualized\ cost\ for\ coal\ to\ RDF\ switch$$

Natural Gas/RDF to Net-Zero Fuel Mix

The transition from either natural gas or a coal and RDF fuel mix to a net-zero fuel mix is assumed to totally eliminate the remaining fuel emissions at each facility. Abatement potential at the Union Bridge and Hagerstown facilities was calculated by subtracting the abatement potentials of the fuel-switching transitions at each facility from each facility's total coal CO_2 emissions in 2020.

$$Total\ Coal\ Emissions - Prior\ Fuel\ Switching\ Abatement\ Potential = Abated\ tCO_2$$

The cost for each facility to transition to a net-zero fuel mix was calculated based on the net-zero fuel mix demonstrated by HeidelbergCement at the Ribblesdale, UK cement facility. The Ribblesdale net-zero fuel mix consisted of 39% gray hydrogen (placeholder for green hydrogen), 12% meat and bone meal, and 49% glycerin.[34] The cost of green hydrogen was calculated both with and without the $3 per kg hydrogen PTC offered through the IRA under section 45V.[35] The range of costs for green hydrogen without the IRA PTC are $2.00 to $3.40 per kg.[103] We assume full compliance with the prevailing wages and apprenticeship requirements of the IRA PTC. With the $3 green hydrogen IRA PTC, the cost per kg drops to between -$1.00 and $0.40. The range of costs for green hydrogen were converted from the price per kg to the price per ton, totaling $707.60 to $1,202.93 per ton without the IRA PTC and totaling -$353.80 to $141.52 with the IRA PTC. Meat and bone meal cost $198.50 per ton in May 2020 and glycerin cost $726.29 per tonne in 2019.[104,105] The cost of glycerin was converted from cost per tonne to cost per ton, totaling $658.88 per ton. The cost per ton for each component was multiplied by their percentage make-up of the fuel mix to find the cost per ton of the complete fuel mix. The cost per ton of the net-zero fuel mix was calculated to form four separate values by using the high and low range of hydrogen under both the inclusion and exclusion of the IRA PTC hydrogen credits.

$$(\$/ton\ green\ hydrogen\ *.39) + (\$/ton\ MBM\ *.12) + (\$/ton\ glycerin\ *.49) = \$/ton\ net\ zero\ fuel\ mix$$

The annual cost to fully transition to a net-zero fuel mix at each facility was calculated by multiplying the cost of the net-zero fuel mix per ton by the number of tons needed to maintain the same Btu value at each facility and then subtracting the annual cost of the preceding fuel, either coal and RDF or natural gas, from the replacement cost. The volume of the net-zero fuel mix needed to replace coal at each facility was calculated by dividing the total Btu value of coal consumed in 2020 by the Btu per ton of the net-zero fuel mix. The Btu value of coal consumed in 2020 was calculated by multiplying the Btu value per ton of coal by the total volume of coal consumed at each facility in 2020.[102] The Btu value of the net-zero fuel mix was calculated by multiplying the Btu value per ton for each component and then again by the percentage of each component in the fuel-mix.[34, 106-108] Then the total Btu value of coal consumed in 2020 was divided by the Btu value of the net-zero fuel mix to find the number of tons of net-zero fuel mix needed to maintain the facility's Btu value. The annual cost to transition to a net-zero fuel mix at each facility was calculated by multiplying the cost per ton of the net-zero fuel mix by the number of tons needed to maintain the Btu and then by subtracting the annual cost of the preceding fuel.

$$Tons\ of\ coal\ consumed\ *\ Btu/ton\ of\ coal = total\ Btu\ consumption$$

$$0.39 * \frac{Btu}{ton\ of\ hydrogen} + 0.12 * \frac{Btu}{ton\ of\ MBM} + 0.49 * \frac{Btu}{ton\ of\ glycerin} = \frac{Btu}{ton\ net\ zero\ fuel\ mix}$$

$$\frac{Total\ Btu\ consumption}{Btu\ per\ ton\ of\ net\ zero\ fuel\ mix} = Tons\ of\ netzero\ fuel\ mix\ needed$$

$$Tons\ of\ netzero\ fuel\ mix\ needed * \frac{\$}{ton\ net\ zero\ fuel\ mix} - cost\ of\ preceding\ fuel = cost\ to\ switch\ to\ net\ zero\ fuel$$

CCUS

We assumed a 90% capture efficiency for the implementation of CCUS.[37] Abatement potential was calculated by subtracting the sum of all preceding abatement potentials, including the OPC to PLC switch, either the coal to natural gas or coal to RDF mix fuel switch, and the transition to a net-zero fuel mix, from each facility's total CO_2 emissions in 2020.

$$0.9 * (Total\ Emissions - OPC\ to\ PLC - Fuel\ Switching - Net\ Zero\ Fuel\ Mix) = Abated\ tCO_2$$

The cost of CCUS was calculated both with and without including the 45Q tax credits that were expanded in the IRA to $85 per ton of CO_2 for capture and sequestration.[35] We assume full compliance with the prevailing wage, hour, and apprenticeship requirements of the 45Q tax credits. The cost of CCUS implementation without 45Q credits ranges from $40 to $200 per ton of CO_2 captured with an additional $50 per ton of CO_2 to sequester geologically.[24,38] The cost of CCUS implementation, including both sequestration costs and the 45Q credits, ranges between $5 and $165 per ton of CO_2. The cost to implement CCUS at the Union Bridge and Hagerstown facilities was calculated by multiplying the range of costs both with and without the 45Q credits by the total CO_2 abated by CCUS implementation.

$$\$ \; per \; tCO_2 \; * \; CCUS \; Abatement \; = \; Cost \; to \; implement \; CCUS$$

Carbonation

Literature estimates suggest that pre-demolition concrete can recapture between 7.6% to 24% of the emissions released during cement production over its lifetime through carbonation. We assume 10% of emissions are recaptured as a conservative lower bound.[13]Abatement potential was calculated by multiplying the 10% recapture rate by the total CO_2 emissions at each facility in 2020.

$$0.1 \; * \; Total \; Emissions \; = \; Abated \; tCO_2$$

Cement Timeline and Demand Projections

The IEA estimates global demand for cement will grow between 12% and 23% between 2018 and 2050.[17] In Figure 8, a median 17.5% linear increase in demand from 2018 levels was assumed, split between the 2031 and 2050 emissions timelines. We assumed a proportionate increase in emissions due to demand growth from 2020 levels. We assumed a 6% increase in demand growth and emissions between 2020 and 2031 and a 10% increase in demand growth and emissions from 2020 levels between 2031 and 2050. Due to this split in expected demand increase, the OPC to PLC switch and the initial fuel switching planned at each plant were applied separately to the demand increase in 2031 to 2050, which was not included in the 2020-2031 calculations. This separate calculation is represented in Figures 8a and 8b as reductions from "Previous measures."

Interviews with Cement Facility Representatives

IO1: Lehigh Hanson	**Date:** 07/15/2022 **Attendees:** Adam Swercheck - North American Environmental Director at Lehigh Hanson, Kent Martin - Plant Manager at Union Bridge, Kurt Deery - Environmental Engineer at Union Bridge, David Perkins Vice President of Government Affairs and Communications at Lehigh Hanson, Mark Stewart - Climate Change Program Manager at MDE, Christopher Beck - Division Chief of Climate Change Program at MDE, John Artes - Engineer at MDE, Alexander Holt - Engineer at MDE, Matthew Helminiak - Commissioner of Labor and Industry at Maryland Department of Labor, James Rzepkowski - Acting Secretary of Labor at Maryland Department of Labor **Abstract:** Lehigh Hanson and Union Bridge facility staff invited representatives from CGS, MDE, and the Department of Labor to tour the Union Bridge facility and to present and discuss Lehigh Hanson and Union Bridge's goals and plans to decarbonize.

IO2: LafargeHolcim	**Date:** 07/26/2022 **Attendees:** Jill Benoit - Regional Manager of Government Affairs at LafargeHolcim, Paul DeSantis - Environmental Counsel at LafargeHolcim, Mike Knoll - Regional Environmental Manager at Hagerstown facility, Mark Stewart - Climate Change Program Manager at MDE, Christopher Beck - Division Chief of Climate Change Program at MDE **Abstract:** LafargeHolcim invited CGS and MDE representatives to attend an online meeting to discuss LafargeHolcim and the Hagerstown facility's goals and plans to decarbonize.

Non-cement Fuel Usage Calculations and Category Harmonization

Allocation of Emissions in Figure 9

Figure 9 was composed using both MD inventory data and GCAM data. The MD inventory contains the total carbon emissions from all major fuels, industry sources, and the carbon emissions from the cement industry, thus allowing for the separation of non-cement industry emissions from cement industry emissions. The GCAM data contains the energy consumption for major industries broken down by fuels. The GCAM data does not directly address emissions, but was used to estimate the percent allocation of fuel consumption between manufacturing and non-manufacturing industries.

Timeline Assumptions for Mitigation Strategies in Figure 10

The timeline for mitigation strategy is based on the availability of technologies and economic efficiency. Some sectors already show potential to increase profits, and reduce emissions by recycling or implementing more fuel-efficient contemporary technologies. Due to the economic efficiency and technology feasibility, energy efficiency and demand or material efficiency strategies are expected to be implemented in the first half of the 2020-2050 timeline.

On the other hand, the carbon capture and storage strategy are expected to be implemented in the second half of the 2020-2050 timeline. Although theoretically, the CCUS strategy has great potential for the Chemistry sector, the technologies for CCUS are not mature at the current stage. Because the availability time for CCUS is uncertain, assuming it will be implemented in the second half of the 2020-2050 timeline is more reliable.

The timeline of electrification and fuel switching strategies will be longer than demand and energy efficiency and implemented earlier than the CCUS strategy. Electrification and fuel switching strategies are already technologically feasible and continuously improving, so they can be implemented now, not in 2035 like the CCUS strategy. However, in many sectors, electrification and fuel switching strategies are not economically efficient, so these two strategies should be implemented at a slower pace, so the manufacturing sectors would have time to adjust themselves.

Non-cement fuel use abatement cost calculations and sources

The cost of non-cement fuel use abatement cost is based on the order of implementing reduction strategies. Studies indicate that the reduction strategies reduce emission by ratio,[7,38,64] so the emission reduction from specific strategy is based on emission amount when implemented. As there are totally 5 strategies, the final emission of strategy *i* is shown as follows:

$$Remaining\ emission\ =\ initial\ emission * \prod_{i=1}^{5}(1 - strategy\ i\ reduction)$$

The reduction of specific strategy *i* in order *j* is as follows:

$$Emission\ reduction_{i,j+1}\ =\ initial\ emission_{j} * (strategy\ i\ reduction)$$

To minimize the cost, we order the strategies based on their average costs, and thus the final costs of reduction is as follows:

$$Total\ emission\ reduction\ cost\ = \sum_{i=1}^{5} Emission\ reduction_{i,j+i} * average\ reduction\ cost_{i}$$

The annualized reduction, on the other hand, assumes a linear reduction from year to year based on the effective reduction strategies.

Harmonization of Manufacturing Categories for Figure 10 Datasets

Global Change Analysis Model	**Bureau of Economic Analysis**	**Manufacturing Energy Consumption Survey**
Chemicals	Chemical Petroleum and coal products	Ethyl Alcohol Industrial Gases Nitrogenous Fertilizers Other Basic Inorganic Chemicals Other Petroleum and Coal Products Petroleum Lubricating Oil and Grease Products Petroleum Refineries Pharmaceutical Preparation Photographic Film, Paper, Plate, and Chemicals Plastics Materials and Resins Pharmaceuticals and Medicines Chemicals
Food Processing	Food	Animal Slaughtering and Processing Beverages Dairy Product Fruit and Vegetable Preserving and Specialty Food Grain and Oilseed Milling Tobacco Food

Other Nonmetallic Minerals	Non metallic mineral product	Clay Building Material and Refractories Glass and glass product manufacturing Gypsum Lime Nonmetallic Mineral Products Mineral Wool Other Pressed and Blown Glass and Glassware Flat Glass Glass Containers Glass Products from Purchased Glass
Pulp, Paper, and Wood	Paper Printing and related support Wood product	Paper Mills, except Newsprint Pulp Mills Other Wood Products Veneer, Plywood, and Engineered Woods Paper Sawmills Wood Products
Other	Apparel Computer and electronic product Electrical Equipment, appliance, and component Fabricated Metal Product Furniture And Related Product Leather and Allied Products Machinery Miscellaneous Motor Vehicles,bodies and trailers,and parts Other Transportation Equipment Plastics and rubber products Primary Metal Textile Mills Textile Product Mills	Aircraft Artificial and Synthetic Fibers and Filaments Asphalt Paving Mixture and Block Asphalt Shingle and Coating Materials Automobiles Light Trucks and Utility Vehicles Aerospace Product and Parts Apparel Computer and Electronic Products Electrical Equip., Appliances, and Components Furniture and Related Products Leather and Allied Products Miscellaneous Plastics and rubber products Textile Mills Textile Product Mills Transportation Equipment

Supplementary Table 3. *Categories used in Figure 10 to allocate emissions by manufacturing sector.*

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