MANUFACTURING SECTOR DECARBONIZATION STRATEGIES AND IMPACTS IN THE STATE OF MARYLAND: TECHNICAL APPENDIX

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SCHOOL OF PUBLIC POLICY
CENTER FOR GLOBAL SUSTAINABILITY

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 *existing 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]

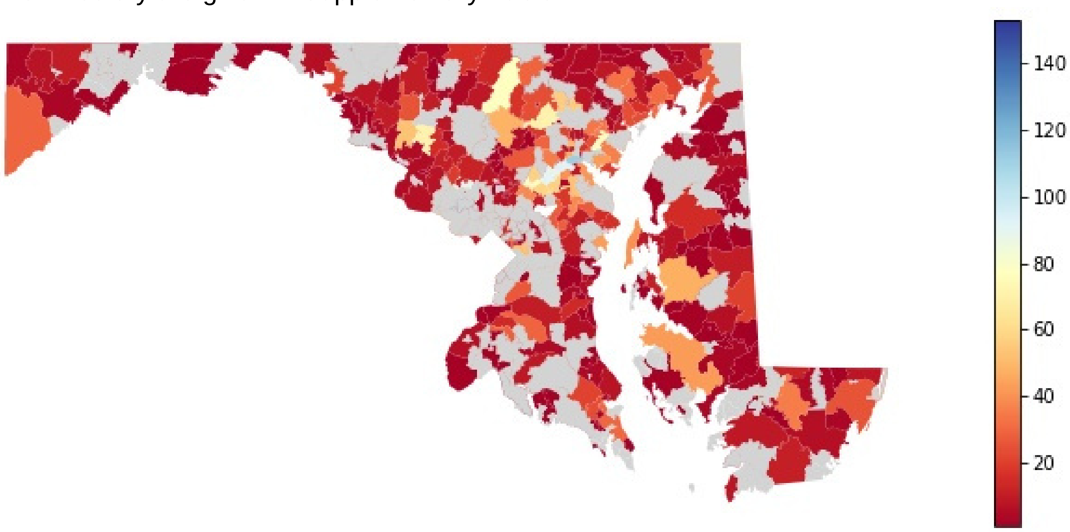
Definitions and Descriptions of Maryland Manufacturing

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.*

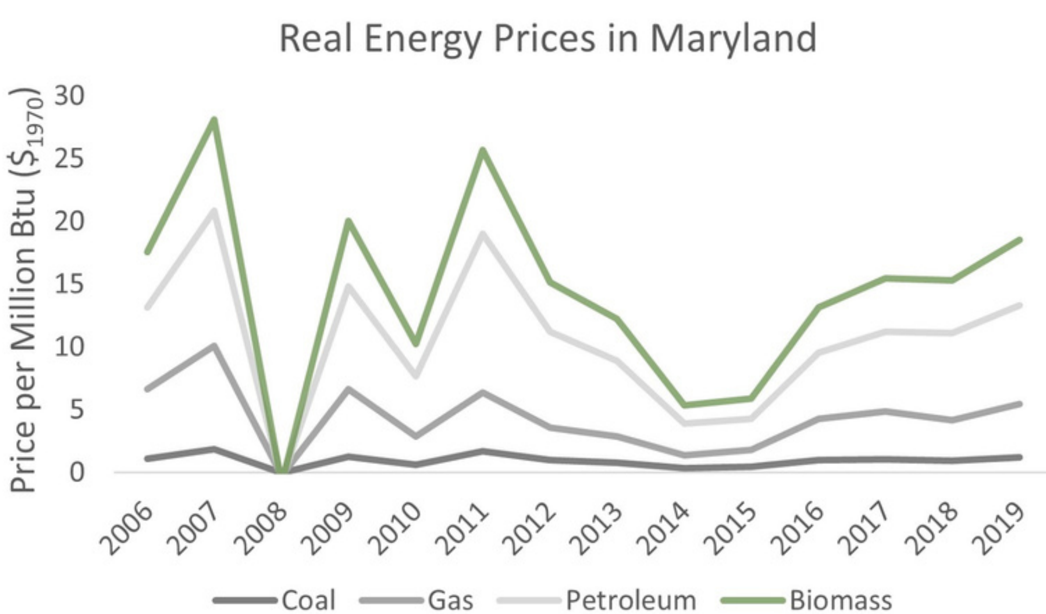
NAICS code	NAICS code description	Number of facilities
323111	Commercial Printing (except Screen and Books)	463
311811	Retail Bakeries	419
339999	All Other Miscellaneous Manufacturing	328
339950	Sign Manufacturing	277
337110	Wood Kitchen Cabinet and Countertop Manufacturing	262

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 2018Manufacturing 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.

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

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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