Coming Clean on Industrial Emissions

Challenges, Inequities, and Opportunities in U.S. Steel, Aluminum, Cement, and Coke

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For additional materials and the companion interactive map, go to https://www.sierraclub.org/trade/climate-jobs-american-industries.

Our research and analysis is based on the most recent available data as of March 2023, which is when we concluded the work.

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EXECUTIVE SUMMARY

Background on industrial facilities in the United States

Iron, steel, cement, aluminum, and metallurgical coke are foundational industries in the U.S. economy. Industry associations estimate the economic impact of America's iron and steel industry at over $500 billion, aluminum at $180 billion, and cement in the trillions of dollars per year.[1,2,3] These benefits include the value from the direct material sales, jobs, and peripheral industries that rely on iron, steel, aluminum, and cement as feedstocks. We estimate that in 2020 the iron, steel, cement, aluminum, and metallurgical coke industries employed nearly 100,000 workers directly and produced approximately 175 million tons of salable material. These figures include the 100 facilities that produced primary iron and steel, 12 merchant facilities that produced metallurgical coke for the iron and steel industry, 96 facilities that produced cement, and 7 that produced primary aluminum.

Facilities that produce iron, steel, cement, aluminum, and metallurgical coke are challenging to decarbonize and produce a range of adverse environmental and health impacts. According to the U.S. Environmental Protect Agency (EPA), these primary production facilities are responsible for approximately 2 percent of U.S. greenhouse gas emissions.[4] They also produce criteria air pollutants such as sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and particulate matter (PM), along with hundreds of other toxic materials with far-reaching effects on land, water, wildlife, and people. Further, the negative effects of these facilities often fall on fence-line communities that face socioeconomic and environmental hardship.

Managing industrial pollutants is a technological challenge that each of these industries faces and one area where government agencies can raise environmental standards. Such standards will deliver benefits to fence-line communities and other communities downwind and downstream. We estimate that eliminating the emissions of PM and its precursors from production of iron, steel, cement, aluminum, and metallurgical coke could avoid 1,250 to 2,830 deaths annually. It could also greatly reduce the incidence of respiratory and cardiac events, hospital admissions, emergency room visits, costly medical bills, and lost workdays.

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[1] American Iron and Steel Institute. 2023. "The Economic Impact of the American Iron and Steel Industry." Available at: https://www.steel.org/economicimpact/.

[2] The Alumina Association. 2020. "U.S. Aluminum's Economic Impact." Available at: https://www.aluminum.org/economy#:~:text=Today%2C%20the%20U.S.%20aluminum%20industry,%24103%20billion%20in%20economic%20output.

[3] Weinstein, B. 2010. *Economic Impacts of Cement Industry Regulations: The Proposed Portland Cement NESHAP Rule*. SMU COX Maguire Energy Institute. Available at: https://www.smu.edu/-/media/Site/Cox/CentersAndInstitutes/MaguireEnergyInstitute/Economic-Impacts-of-Cement-Industry-Regulations.pdf?la=en#:~:text=The%20economic%20footprint%20of%20the,trillion%20of%20the%20nation's%20output.

[4] Scope 1 industry emissions from U.S. EPA Greenhouse Gas Reporting Program 2020; U.S. total emissions in CO_2-equivalent from https://www.epa.gov/climate-indicators/climate-change-indicators-us-greenhouse-gas-emissions.

Given the consequential impacts of industrial facilities on the economy, environment, and populace, it is imperative to have informed industrial policymaking and action. This includes understanding the specific effects of each industry at large as well as individual facilities. Unfortunately, the industrial sector is rife with data limitations. The limitations include disparate sources of facility-level information, uncertainty in reported levels of pollutants, and missing data.

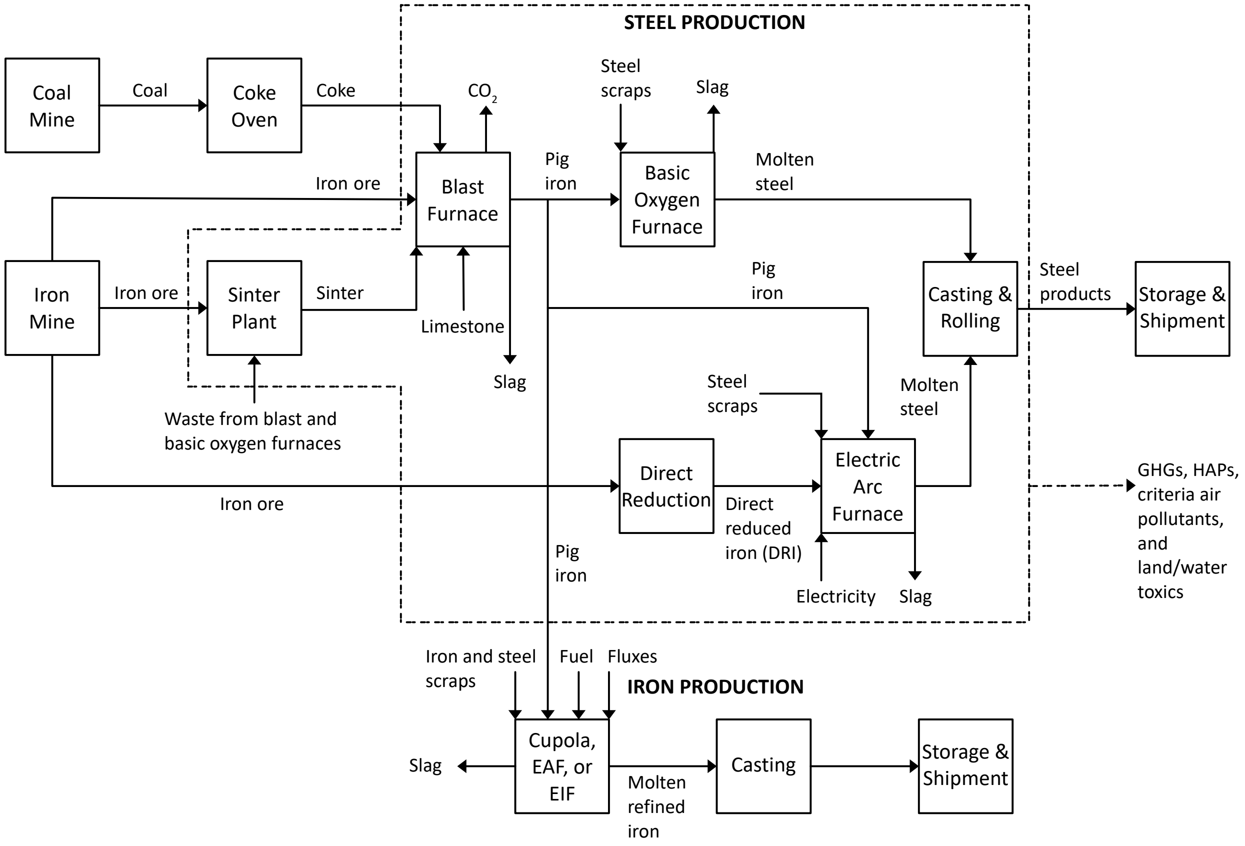
This report and the accompanying tools we provide seek to assemble all publicly available data on U.S. facility-level pollution, production, and employment from the iron, steel, metallurgical coke, aluminum, and cement industries. Additionally, we couple this information with an environmental justice analysis of fence-line communities surrounding these facilities, using a range of boundaries. We conduct a comparative analysis to identify which facilities are the greatest polluters, both in total magnitude and on a per-ton-of-production basis. We prepare a nationally consistent, easy-to-use database and interactive website to disseminate this data and inform public discourse on the challenges presented here. The results also serve to benchmark current emissions, assess uncertainty in reported data, and identify steps to improve data quality and access. Finally, we review current and emerging technologies that can reduce or eliminate GHG and toxic pollutant emissions.

Industrial processes

Iron, steel, metallurgical coke, cement, and aluminum facilities follow a similar production process. Raw, earthen material is mined, pre-processed, and delivered to an industrial facility—thus entering the scope of this analysis. Facility operators then add heat and other feedstocks to induce a chemical transformation. After that transformation, the facility processes the industrial material into a salable product and sends it off-site.

This material production emits pollutants through numerous processes in relatively large, complex facilities. Industrial electricity use also contributes to emissions indirectly by drawing on fossil-powered generators. We begin by evaluating the industrial processes at iron, steel, metallurgical coke, cement, and aluminum facilities to illuminate the stages in which specific pollutants are produced. Figure ES-1 provides an example of this for iron and steelmaking.

Figure ES-1. Steel production process diagram



Note: The dotted line shows the boundary of the facilities included in this report.

Prior studies

Industry and environmental experts have previously sought to quantify emission intensities, emissions inventories, and facility-level impacts of pollution. While several studies compare emissions at the national or international level, there is a paucity of facility-level data and robust analysis grounded in such data. Because many studies focus on greenhouse gases, especially carbon dioxide, there is also a need for more analysis of air, land, and water toxics. Notably, several of the most detailed studies are over 20 years old, so updated research is needed to reflect changes in these industries.

Our review of prior studies highlights several data limitations that hinder effective policymaking and action. We find that available information is commonly available at the national level, which conceals facility-by-facility differences in emissions, production, and jobs. Further, emissions data are often missing due to lack of regulation and protections for confidential business information. The data that are available are strewn across many public databases, with no unified repository, and have high levels of uncertainty in reported emissions.

Facility-level data collection and analysis

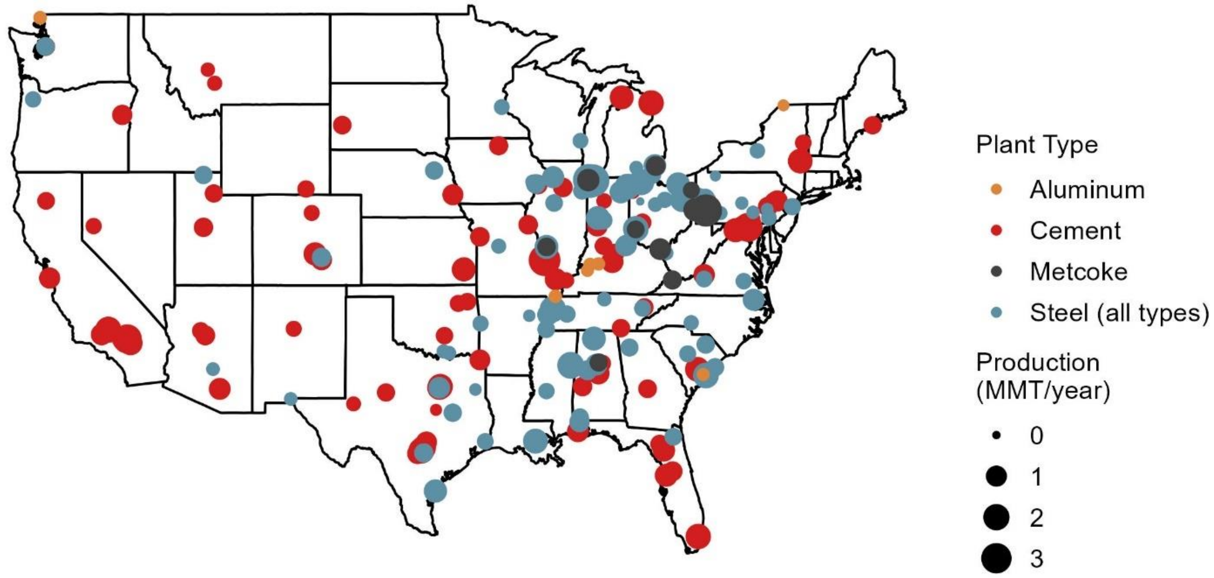
We begin to address the limitations in facility-level information for the iron, steel, metallurgical coke, aluminum, and cement industries by assembling all nationally consistent public data on U.S. facility-level pollution, production, and employment for Year 2020. We include socioeconomic and demographic information for the fence-line communities surrounding these facilities.

We assemble four databases of primary production facilities—one per industry. Each database contains a list of facilities operating in 2020, their parent companies, and their location. We compile facility-level data from EPA about emissions from greenhouse gases, air toxics, and the six criteria air pollutants (ozone, PM, carbon monoxide, lead, SO_2, NO_2). The databases also include water and land pollution data for more than 100 additional pollutants. We provide reported employment levels and facility-level production, or we estimate these where public data are not available. The databases also describe the specific manufactured products at each facility and provide environmental and socioeconomic data on the communities on the fence-line of each facility. Last, we estimate Scope 1 and Scope 1 plus Scope 2 emission intensity using reported direct emissions, industry-specific electricity usage factors, production estimates, and geographically specific electricity emission factors.

Production

Figure ES-2 shows a map of the industrial facilities with point size corresponding to production quantity. Our estimates of total industry production align closely with known industry-level data; nonetheless, our methodology for estimating facility-level production where public data are not available is a key source of uncertainty in this analysis. This study accounted for the overall effects of the COVID-19 pandemic on industry-level production using an industry-wide capacity factor, but it did not analyze effects on individual facilities.

Figure ES-2. Map of facility-level annual production



Employment

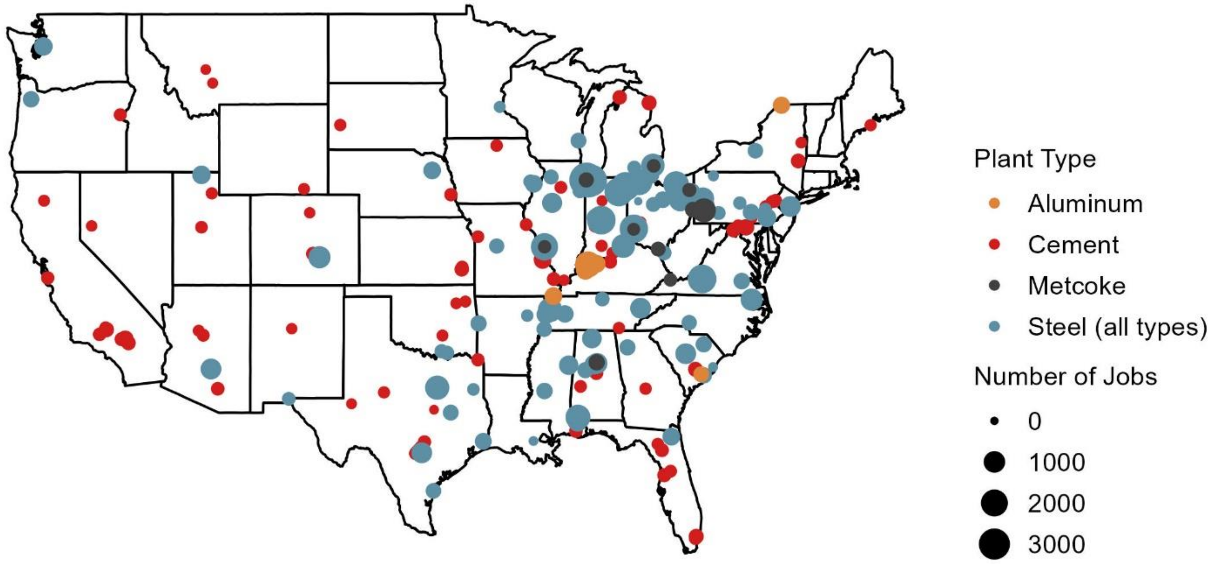
The four industries we study employ nearly 100,000 workers in total. Table ES-1 summarizes the total number of jobs in each industry. Cement plants have the lowest median jobs per facility, followed by metallurgical coke plants. Only aluminum facilities have a median jobs per facility greater than 500 people. The steel industry employs the largest total number of people, and employment per plant varies widely based on the type of steel produced. Of the 10 plants with employment greater than 2,000 people, six are basic oxygen furnace (BOF) steel plants and four are electric arc furnace (EAF) facilities. Figure ES-3 shows a map of the industrial facilities with point size corresponding to employment.

Table ES-1. Employment by facility type

Industry	Number of Facilities*	Number of Jobs	Median Jobs per Facility
Aluminum	6	4,275	520
Cement	90	12,220	115
Metallurgical coke	12	3,710	195
Iron and steel	100	74,353	388

**Only includes facilities that have jobs data available. One aluminum facility and two cement facilities are omitted.*

Figure ES-3. Map of facility-level employment



Air, land, and water pollutants

The number and identity of toxic chemicals released by each industry varies, and not every facility in each industry reported the same set of toxic releases. Table ES-2 summarizes the overall count of individual toxic chemicals reported by industry. The accompanying databases present facility-level air, land, and water releases by pollutants. We also include EPA's Risk-Screening Environmental Indicators (RSEI) scores for each facility.

Table ES-2. Summary of toxic chemical releases by industry

Industry	Number toxic chemicals reported as released on land	Number toxic chemicals reported as released into water	Number toxic chemicals reported as released into air	Total
Iron and steel	39	51	77	167
Metallurgical coke	-	28	40	68
Aluminum	17	21	42	80
Cement	26	17	139	182

Environmental and Socioeconomic Indicators

Synapse used tools available from the U.S. EPA to collect and compile relevant environmental justice indicator data for each plant and compare the plant-specific indicators to indicators for other geographic areas (state, regional, and national). We characterized the affected fence-line communities that fall within a geographic buffer zone that is centered around each facility. We selected a circular buffer radius that approximates the way pollutants disperse from a facility—for example, carried in plumes by wind or groundwater or transported by surface water. Synapse selected a 3-mile buffer based on prior analysis and recommendations of the National Association for the Advancement of Colored People (NAACP) and U.S. EPA in prior work.[5,6]

Figure ES-4 provides an example of the socioeconomic indicators—the percentage of the population that is low-income population in the community that falls within a 3-mile radius of each industrial facility. Figure ES-5 depicts the air toxics cancer risk in the 3-mile radius of industrial facilities, an example of the environmental indictors we study. We find that fence-line communities that support industrial facilities face greater socioeconomic and demographic hardship that the average community in the United States. The closer a community is to an industrial facility, the more likely it is to be disadvantaged across all 8 demographic indicators we study and 9 of 12 environmental indicators. Metcoke and iron or steel communities are the most disadvantaged, especially host communities for BOF steel plants. For example, iron or steel and metallurgical coke plants are located in communities with 6.6 percent and 8.3 percent unemployment rate, as compared to a national average of 5.0 percent.

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[5] Wilson, P., Adrian, J., Wasserman, K., Starbuck, A., Sartor, A., Hatcher, J., Fleming, J. and Fink, K. 2012. *Coal blooded: Putting profits before people*. NAACP. Available at: https://naacp.org/resources/coal-blooded-putting-profits-people.

[6] U.S. EPA. 2022. *EJScreen Technical Documentation*. Available at: https://www.epa.gov/sites/default/files/2021-04/documents/ejscreen_technical_document.pdf.

Metcoke and BOF steel communities also experience worse air quality, as measured by particulate matter and air toxics cancer risk (Figure ES-5).

Figure ES-4. Low-income population in the 3-mile radius of industrial facilities

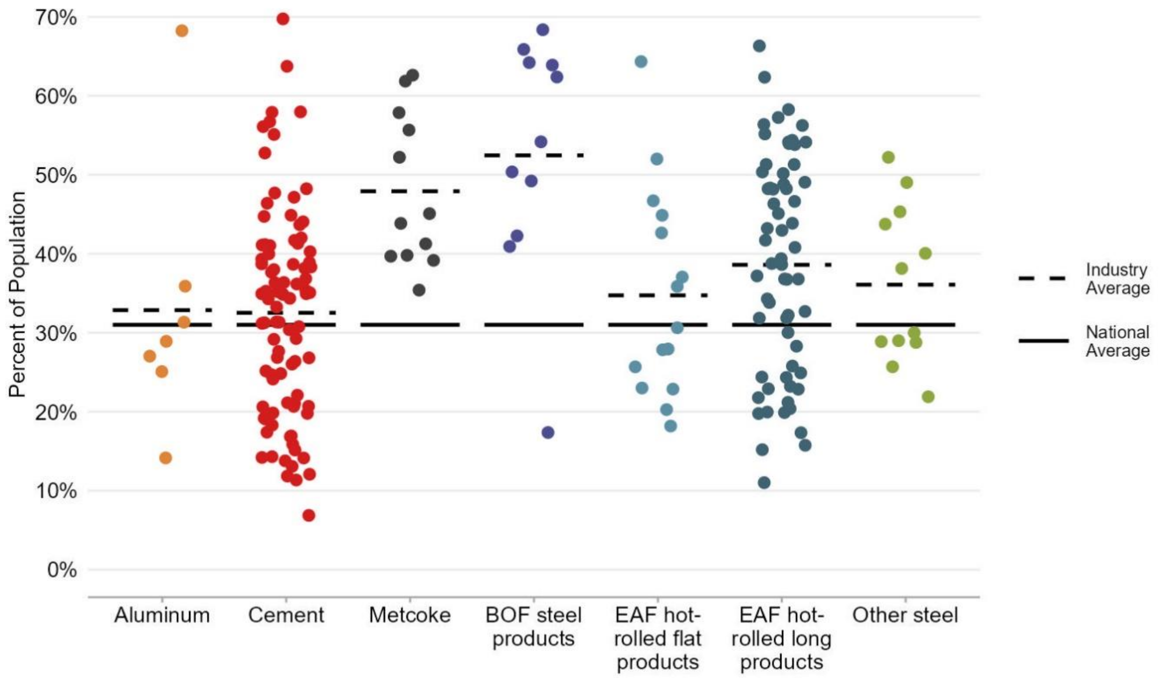
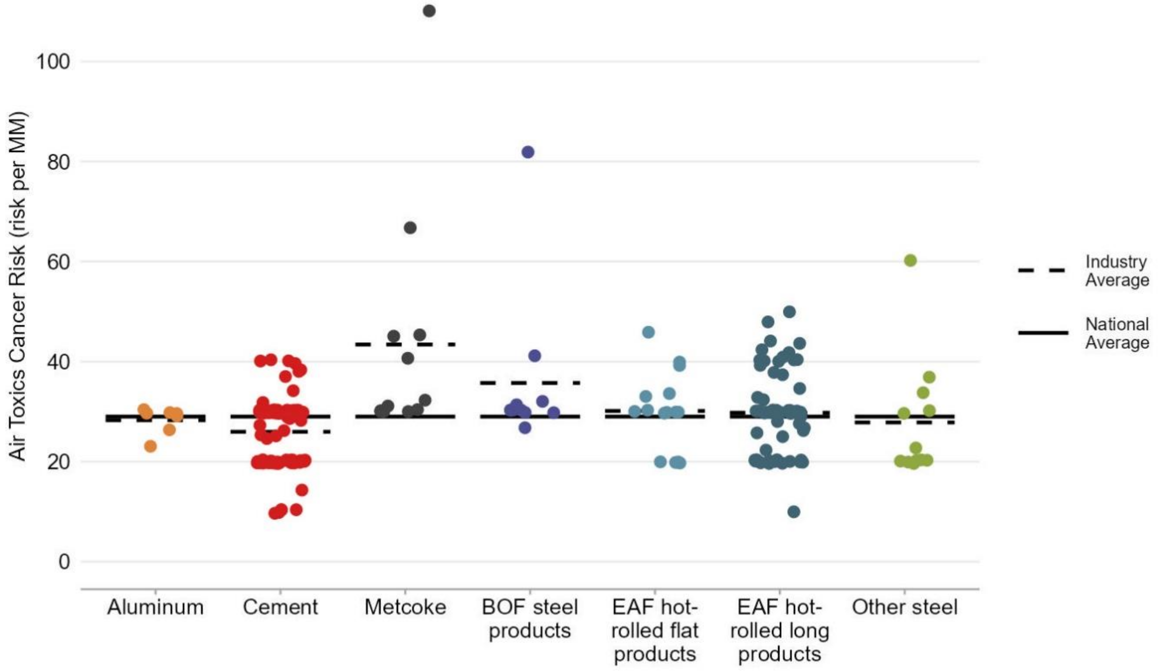


Figure ES-5. Air toxics cancer risk in the 3-mile radius of industrial facilities



Health impact analysis

Synapse evaluated the health impacts of emissions of particulate matter and its precursors using EPA's CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA).[7] Using COBRA, we estimate geographically specific changes in emissions, atmospheric dispersion, and emission concentrations across the United States. The model estimates the associated changes in the incidence of health outcomes, including premature mortality, heart attacks, asthma exacerbation, and lost workdays.

Table ES-3 shows the total potential reductions in annual incidence of each health endpoint measured by COBRA. Overall, eliminating the emissions of $PM_{2.5}$ and its precursors from production of iron, steel, cement, aluminum, and metallurgical coke could lead to 1,250–2,830 avoided deaths annually. It could also drastically reduce respiratory and cardiac events, including those that lead to hospitalization. Roughly 610 hospital admissions could be avoided annually for respiratory and cardiovascular illness, and 620 visits to the emergency room for asthma could be avoided. Beyond the health benefits of avoided illness, this would save money on costly medical bills for those affected and could keep people from missing work. In addition, 140,840 lost workdays could be avoided by eliminating these emissions.

Table ES-3. Summary of reductions in incidence of health endpoints by industry

Health Endpoint	Change in Incidence (cases, annual)							
	Iron and Steel		Cement		Aluminum		Metallurgical Coke	
	Low	High	Low	High	Low	High	Low	High
Mortality	869	1,966	179	405	35	78	170	385
Nonfatal Heart Attacks	93	860	19	181	4	36	17	153
Infant Mortality	5		1		0		1	
Hospital Admits, All Respiratory	212		45		9		37	
Hospital Admits, Cardiovascular (except heart attacks)	218		45		9		39	
Acute Bronchitis	1,072		237		42		197	
Upper Respiratory Symptoms	19,434		4,290		754		3,564	
Lower Respiratory Symptoms	13,639		3,017		530		2,503	
Emergency Room Visits, Asthma	435		92		16		81	
Asthma Exacerbation	20,194		4,485		791		3,701	
Minor Restricted Activity Days	575,241		128,610		22,792		105,725	
Work Loss Days	97,374		21,761		3,848		17,862	

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[7] We include the following precursors: sulfur dioxide, nitrogen oxides, ammonia, and volatile organic compounds.

The iron and steel industry accounts for approximately 70 percent of the total incidence reductions across all health endpoints. This is followed by the cement industry, accounting for approximately 15 percent of the total incidence reductions across all endpoints, then by the metallurgical coke industry at 13 percent. The aluminum industry has the lowest potential for reductions in adverse health outcomes, at approximately 3 percent.

Greenhouse gas emissions and emission intensity

Table ES-4 presents Scope 1 and Scope 2 emissions by industry. These primary production facilities are responsible for approximately 2 percent of the U.S. greenhouse gas emissions in 2020, with cement and iron and steel representing 90 percent of the emissions across all four industries.

Table ES-4. Scope 1 Emissions and Scope 2 Emissions by Industry (MMT CO_2e)

Industry	Scope 1 Emissions	Scope 2 Emissions
Iron and Steel	53.4	18.9
Metallurgical Coke	5.0	0.03
Aluminum	9.2	8.4
Cement	66.9	4.4

Note that in the aluminum industry, 5.3 million of the Scope 1 emissions are attributable to coal-fired electricity generation at a single facility, which was sold to the power market and not used for aluminum production. Note also that Scope 1 cement emissions includes biogenic emissions, which comprise less than 1 percent of the total Scope 1 emissions.

Table ES-5 shows total industry emissions on a per ton basis for Scope 1 and Scope 1 plus 2 emissions. On a per-ton basis, aluminum is by far the most emissions-intensive of the four industries we study. However, due to a smaller industry footprint and lower overall production, the aluminum industry's total contribution to emissions is small relative to iron, steel, and cement.

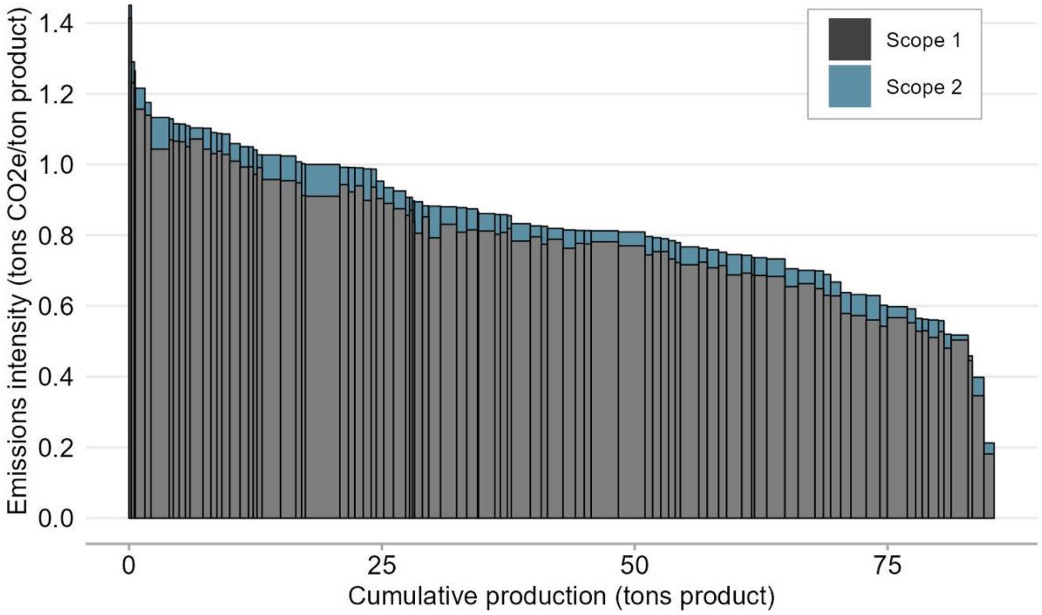
Figure ES-6 shows an example of the distribution of emissions by plant for one industry, cement. Across all four industries, we find that there is a considerable spread in how intensive individual facilities are within a particular industry. Within the iron and steel industry, blast furnace and basic-oxygen furnace facilities are, on average, about seven times as greenhouse-gas-intensive on a Scope 1 basis as EAF facilities. The metallurgical coke industry has a similar bifurcation, with non-recovery facilities more than three times as emissions-intensive as byproduct recovery facilities. For all industries, the spread of emission intensities points to the potential effectiveness of policies that seek to bring down the emissions of the worst performers. Further, lessons learned from the best performers may provide insight into opportunities to reduce GHG emissions through knowledge transfer and process improvement.

Table ES-5. Greenhouse gas emissions across industries

Industry	Total number facilities	Emissions scope	Total industry emissions (MMT CO_2e)	Production-weighted emission intensity (tons CO_2e/ton)
Iron and Steel	100	Scope 1	53.43	0.696
		Scope 1 + 2	72.36	0.943
Metallurgical Coke	12	Scope 1	4.99	0.435
		Scope 1 + 2	5.12	0.451
Cement	92	Scope 1	66.89	0.782
		Scope 1 + 2	71.29	0.833
Aluminum	7	Scope 1	3.81	3.764
		Scope 1 + 2	12.17	12.026

Note: While the production-weighted average for iron and steel is industry-wide, the calculation for facilities above average and the sum of emissions reductions were done relative to each applicable subcategory (e.g., BOFs were only compared to other BOFs). Cement averages include biogenic CO_2e emissions, which are about 2 percent of total industry emissions in 2020.

Figure ES-6. Emissions curve for cement



Emission reduction policies

Policies targeting industrial sector emissions, such as Buy Clean initiatives and industry-specific emission standards can provide economic incentives and/or regulatory mandates for facilities to reduce pollutants. We rank all facilities within each industry according to their emissions intensities on a tons-CO_2-equivalent per ton production basis and compare each facility to an industry-average emissions intensity. We also estimate what the maximum emissions intensity could be while still achieving a 50-percent reduction in industry-wide emissions. Holding domestic output constant, we assume that facilities above the threshold would reduce emissions to meet this target, while facilities below the target would not make any changes.

Figure ES-7 presents facility-level emission intensities within each industry for Scope 1 emissions, including industry average and industry-specific targets.

Figure ES-7. Scope 1 emissions intensities by industry

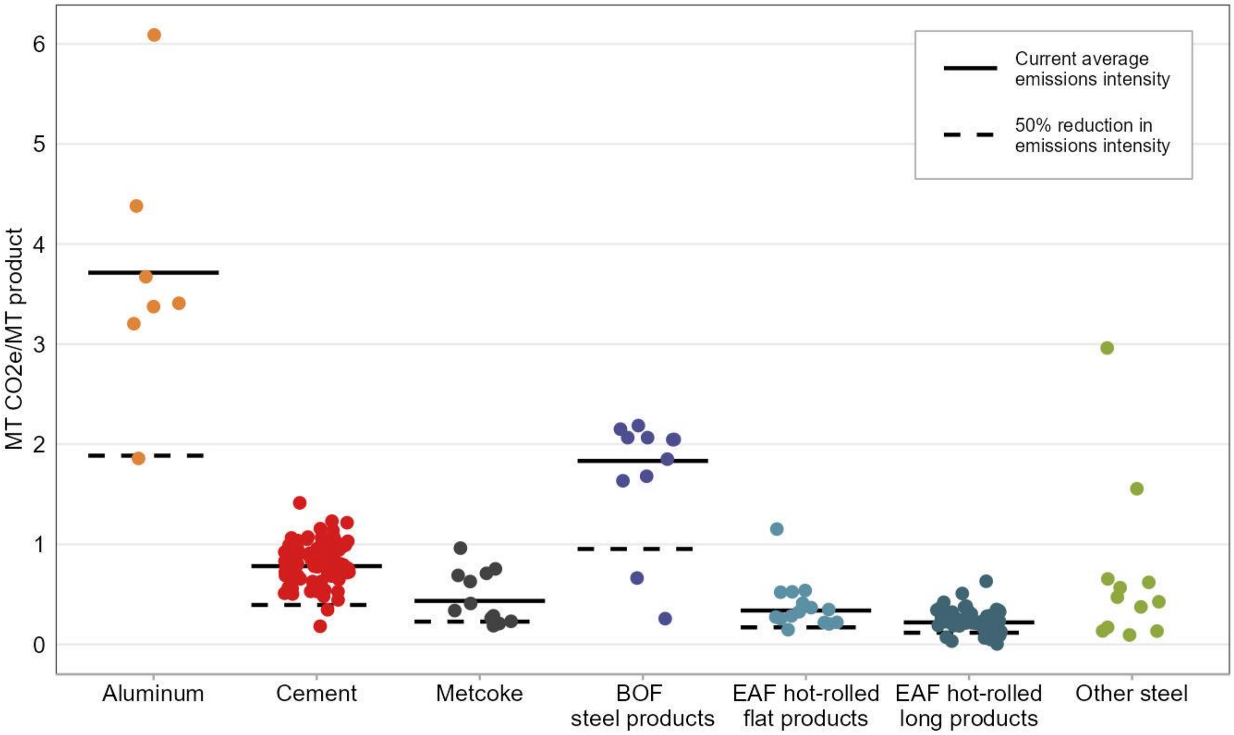


Table ES-6 shows how many facilities in each industry have an emissions intensity greater than average. The table also highlights the total emissions reduction necessary for all facilities above average to reach average in total tons CO_2e and as a percent of total industry emissions. If all facilities were to reach at least the 2020 average production-weighted emission intensity, the overall emissions reduction would be modest. Deeper emissions cuts will require a much more aggressive shift in industry emissions that comes from the current top performers in terms of emissions in addition to those that are currently the most emissions intense.

Table ES-6. Emissions reductions if every facility achieved at least the 2020 industry average emissions intensity, Scope 1

Industry	Emissions Scope	Number facilities above average	Total emissions reduction if every facility reached average emissions intensity (metric tons CO_2e)	Total emissions reduction if every facility reached average emissions intensity (% of industry emissions)
Iron and Steel	Scope 1	56	5,397,985	10%
	Scope 1+2	55	5,485,782	8%
Metallurgical Coke	Scope 1	5	1,458,531	29%
	Scope 1+2	5	1,398,456	28%
Cement	Scope 1	50	6,062,096	9%
	Scope 1+2	47	6,412,668	9%
Aluminum	Scope 1	2	442,389	12%
	Scope 1+2	3	2,255,884	19%

Table ES-7 presents intensities and reduction targets by industry to achieve 50-percent reduction for Scope 1 emissions and identifies the count of facilities that met the targets in 2020. Almost all facilities need to reduce emissions over the next decade for the United States to be on a path to net-zero industrial emissions by 2050.

Table ES-7. Emissions intensity and reduction targets by industry to achieve 50-percent reduction, Scope 1

Industry	Average 2020 emissions intensity (metric ton CO_2e/ton)	Scope 1 target emission intensity to achieve 50% reduction in greenhouse gas emissions (metric ton CO_2e/ton)	Count of facilities that meet the 50% target	Industry-wide emissions reduction (metric tons CO_2e)
Aluminum	3.76	1.89	1	1,904,517
Cement	0.78	0.39	2	33,446,381
Metcoke	0.43	0.23	2	2,480,020
BOF steel products	1.83	0.95	2	19,167,881
EAF hot-rolled flat products	0.34	0.17	1	2,363,901
EAF hot-rolled long products	0.22	0.12	8	4,071,275
Other steel	0.46	0.26	4	1,112,591

Emission reduction technologies and strategies

Numerous technologies are available today that can substantially reduce GHG emissions and hazardous pollutants from industrial facilities. Leading scientists, government agencies, and industry experts also expect an assortment of emerging technologies to reduce industrial emissions. For example, a peer-reviewed 2022 paper identifies 86 “potentially transformative” technologies for the steel and iron industry. A multitude of efficiency measures can reduce emissions as well as the use of costly energy and material inputs. A recent study of the aluminum industry, for example, identified 52 distinct energy efficiency measures.

Uncertainty in reported emissions

Facilities reporting emissions to the U.S. EPA are allowed to use a range of methods, with varying degrees of uncertainty, to estimate reported emissions. There are substantial differences in the methods used across industries, by transport medium, and by pollutant type. Reported toxic emissions are most uncertain for cement and metallurgical coke production facilities, shown in Table ES-8. Table ES-9 summarizes the certainty of greenhouse gas emissions. Greenhouse gas process emissions from aluminum and cement facilities are the most uncertain, followed by combustion emissions for all the industries except cement.

Table ES-8. Qualitative uncertainty assessment

Facility type	Air releases	Land releases	Water releases
Iron and steel	B	B	A
Aluminum	B	A	A
Cement	B	B	C
Metallurgic coke	C	D	B

Note: Rankings are ordered based on preference and accuracy ("A" represents greater certainty, "D" represents less certainty).

Table ES-9. Greenhouse gas emission calculation methodologies typical of the studied industries

Industry	Combustion emissions	Process emissions
Iron and Steel, Metcoke	Tier 1, Tier 2	Tier 4
Aluminum	Tier 1, Tier 2	Tier 1
Cement	Tier 4	Tier 1

Note: Tiers are ordered with descending preference and accuracy (Tier 4 is best, Tier 1 is worst).

Conclusions

For the industries we study, this work constitutes a first-of-its-kind effort to assemble and disseminate comprehensive, facility-level emissions and production data, assess health impacts, quantify environmental justice indicators, and evaluate approaches to reduce emissions. We conclude the following:

1. Pollutants from the facilities we study are responsible for alarming rates of premature deaths, hospital admits, lost worker productivity, and respiratory and cardiac damage.
2. Iron and steel facilities have the largest impact on human health among the facilities we study.

3. Compared to the United States on average, fence-line communities that support industrial facilities are socioeconomically and environmentally disadvantaged. Metcoke and iron and steel communities are most affected.
4. Against a backdrop of diminishing domestic manufacturing, the 211 facilities in this study employ approximately 100,000 workers and represent an important segment of local economies throughout the United States.
5. Policies that seek to bolster domestic manufacturing and reduce industrial emissions should be coupled with workforce development initiatives.
6. Industrial Buy Clean policies and emission standards are promising strategies to incentivize or require materials with low GHG emission intensities.
7. Deploying pollution control strategies at industrial facilities can provide important employment opportunities while reducing adverse health and environmental impacts.
8. A vast array of technologies that can reduce or eliminate pollutants from industrial facilities are available, and many more are under development.
9. Reducing emissions in the electricity sector is an important industrial decarbonization strategy.
10. Our review of prior studies and existing, public information highlights several data gaps that hinder effective policymaking and action.
11. The accuracy of available greenhouse gas emissions data and toxic emissions reporting data is uncertain, largely due to the range of reporting methods available to facilities.
12. This study is an important step in studying the current state of the industry and evaluating emissions reduction opportunities, but further work is needed to inform emissions reduction initiatives.

GLOSSARY

Alumina	Chemical compound of aluminum and oxygen (Al_2O_3) that is derived from bauxite and is the feedstock for aluminum smelting.
Anode	Electrode at which oxidation occurs during electrolysis.
Basic oxygen furnace (BOF)	Furnace used to produce steel using the basic oxygen process, in which oxygen is blown through molten pig iron and scrap metal to lower their carbon content and remove impurities.
Bauxite	Type of aluminum-rich sedimentary rock that is refined to produce crystalline alumina and ultimately aluminum.
Blast furnace	Smelting furnace that produces pig iron from iron ore by combusting metallurgical coke.
Byproduct recovery plant	Metallurgical coke plant that recovers and purifies organic chemical byproducts from the gas waste stream, rather than burning them.
Calcination	Process of altering the chemical composition of a substance by heating it to a high temperature, for example during the pyroprocessing stage of cement production.
Carbon capture and storage (CCS)	Act of capturing the carbon dioxide emitted during processes such as steel production and storing it long term, for example in underground geological formations.
Charging	Process of loading material into a furnace or other industrial equipment, e.g., transferring coal into a coke oven battery.
Clinker	Intermediate product in cement production composed of spherical nodules (diameter 3–25 mm) with the chemical properties of cement.
Coke oven gas	Byproduct of coke production composed of approximately 47–58 percent hydrogen and 27–32 percent methane by volume, along with smaller percentages of carbon monoxide, carbon dioxide, nitrogen, oxygen, ammonia, hydrogen sulfide, and other constituents. Generally recycled as fuel for the coking process.
Criteria air pollutant	Group of six common air pollutants that the U.S. Environmental Protection Agency (EPA) regulates under the *Clean Air Act National Ambient Air Quality Standards* (NAAQS). The criteria air pollutants are sulfur dioxide (SO_2), nitrogen dioxide (NO_2), particulate matter, ground-level ozone (O_3), carbon monoxide (CO), and lead.
Destructive distillation	Chemical decomposition of organic materials at high temperatures in the absence of oxygen, as in coke production.
Desulfurization	Removal of sulfur or sulfur compounds from a material, e.g., removal of sulfur dioxide from flue gas.
Direct reduced iron	Type of iron produced by the direct reduction of solid-state iron ore using hydrogen or carbon monoxide. Also known as sponge iron.

Electric arc furnace (EAF)	Furnace that uses high-current electric arcs to produce steel from scrap metal, direct-reduced iron, or pig iron.
Electric induction furnace	Furnace that induces electrical currents in bulk metals, creating heat through the metal's electrical resistance.
Electrolysis	Electrochemical process that uses a direct electrical current to separate chemical compounds into their constituent parts.
Embodied emissions	Sum of the emissions produced during the lifecycle of a material, from extraction to disposal.
Feedstock	Raw material used to supply an industrial process.
Fence-line community	Neighborhood immediately adjacent to one or more polluting facilities.
Flue gas	Exhaust gas from furnaces and other combustion equipment, often containing residual substances such as particulate matter, sulfur oxides, nitrogen oxides, and carbon monoxide.
Flux	Substance such as limestone introduced in the smelting process to increase fluidity and remove impurities.
Hazardous air pollutants	Pollutants that are known or suspected to cause cancer and other serious health impacts. Under the *Clean Air Act*, U.S. EPA regulates a list of 188 hazardous air pollutants in addition to the criteria air pollutants.
Metallurgical coke (metcoke)	The primary source of fuel in the blast furnace, which creates the reducing atmosphere necessary to strip oxygen atoms from ore and yield metallic iron.
Non-recovery plant	Metallurgical coke plant that burns organic chemical byproducts as fuel rather than recovering them.
Pig iron	Intermediate product in steel production that is brittle because of its high carbon content. Produced in a blast furnace.
Primary production	Production of an end-product such as aluminum from raw materials rather than by recycling scrap.
Process heat	Heat required to complete industrial processes such as smelting, destructive distillation, and calcination.
Pyroprocessing	Stage in cement production that uses heat to transform kiln feed into clinker.
Quenching	Rapid cooling of a substance to obtain the desired material properties.
Secondary production	Production of an end-product from preexisting products, such as alloys from ingots or recovered metal from scrap and salvage.
Scope 1 emissions	On-site emissions produced at a facility.
Scope 2 emissions	Emissions attributable to a facility due to its use of purchased electricity.

Scrubbing	Removal of pollutants from industrial exhaust streams.
Slag	Waste material from ore smelting and refining processes, composed of the impurities in the input raw materials and products of the refining processes. Generally used in other industrial processes, for example as road base or the aggregate in concrete.
Smelting	Process that uses heat and chemical reducing agents to extract metals from ore.
Toxic release	Introduction of a toxic chemical into the environment through emission to the air, discharge into water, or disposal on land.
Volatile organic compounds (VOC)	Diverse group of carbon compounds that evaporate easily under normal temperature and pressure conditions. When emitted indoors, some VOCs are directly harmful to human health, and outdoors, they contribute to the formation of ground-level ozone.

1. INTRODUCTION

Iron, steel, cement, and aluminum are four of the most foundational industries in a modern economy. They are also some of the most challenging to decarbonize, and like any large industry, they produce a range of adverse environmental impacts. This is also true for the metallurgical coke industry, which provides a critical input for iron and steelmaking.

Estimates of iron, steel, cement, and aluminum's economic impact vary according to a researcher's scope. In the broadest analyses, industry associations put the full economic impact of America's iron and steel industry at over $500 billion, aluminum at $180 billion, and cement in the trillions of dollars per year.[8,9,10] These benefits include the value from the direct material sales, jobs, and peripheral industries that rely on iron, steel, aluminum, and cement as feedstocks. With a more focused lens, in 2020 the primary iron, steel, cement, and aluminum industries employed an estimated 77,000 workers directly and produced approximately 175 million tons of salable material.[11] These figures include the 100 facilities that produced primary iron and steel, 12 merchant facilities that produced metallurgical coke for the iron and steel industry, 96 facilities that produced cement, and 7 that produced primary aluminum.

According to the U.S. Environmental Protect Agency (EPA), these primary production facilities are responsible for approximately 2 percent of America's 2020 greenhouse gas emissions.[12] They also produce criteria air pollutants such as sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and particulate matter (PM), along with hundreds of other toxic materials with far-reaching effects on land, water, wildlife, and people. Managing these pollutants is a technological challenge all four industries face and one area where government agencies can raise environmental standards. Such standards will deliver benefits to fence-line communities and other communities downwind and downstream.

Given the consequential impacts of industrial facilities on the economy, environment, and populace, it is imperative to have informed industrial policymaking and action. This includes understanding the specific

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[8] American Iron and Steel Institute. 2023. "The Economic Impact of the American Iron and Steel Industry." Available at: https://www.steel.org/economicimpact/.

[9] The Alumina Association. 2020. "U.S. Aluminum's Economic Impact." Available at: https://www.aluminum.org/economy#:~:text=Today%2C%20the%20U.S.%20aluminum%20industry,%24103%20billion%20in%20economic%20output.

[10] Weinstein, B. 2010. *Economic Impacts of Cement Industry Regulations: The Proposed Portland Cement NESHAP Rule*. SMU COX Maguire Energy Institute. Available at: https://www.smu.edu/-/media/Site/Cox/CentersAndInstitutes/MaguireEnergyInstitute/Economic-Impacts-of-Cement-Industry-Regulations.pdf?la=en#:~:text=The%20economic%20footprint%20of%20the,trillion%20of%20the%20nation's%20output.

[11] For methodology used to calculate these values, see Section 4, *Facility-Specific Data*.

[12] Scope 1 industry emissions from U.S. EPA Greenhouse Gas Reporting Program 2020; U.S. total emissions in CO_2-equivalent from https://www.epa.gov/climate-indicators/climate-change-indicators-us-greenhouse-gas-emissions.

effects of each industry at large as well as individual facilities. Unfortunately, the industrial sector is rife with data limitations. The limitations include disparate sources of facility-level information, uncertainty in reported levels of pollutants, and missing data due to lack of regulation and protections for confidential business information.

This report and the accompanying tools seek to assemble all publicly available data on U.S. facility-level pollution, production, and employment from the iron, steel, metallurgical coke, aluminum, and cement industries. Additionally, we couple this information with an environmental justice analysis of fence-line communities surrounding these facilities, using a range of boundaries. This two-pronged analysis helps identify which facilities are the greatest polluters, both in total magnitude and on a per-ton-of-production basis. We prepare a nationally consistent, easy-to-use database and interactive website to disseminate this data and inform public discourse on the challenges presented here. The results also serve to benchmark current emissions, assess uncertainty in reported data, and identify steps to improve data quality and access.

This report first describes the industrial processes of iron, steel, metallurgical coke, cement, and aluminum to illuminate the stages in which specific pollutants are produced. It then summarizes the “state of the data” by reviewing existing literature relating to emission intensities, emissions inventories, and other reports about facility-level pollution and impacts. Next, it analyzes facility-level emissions data in light of recent federal Buy Clean policies and identifies promising decarbonization technologies. The paper then evaluates the health impacts of the criteria air pollutant emissions. Finally, it discusses uncertainty in greenhouse gas emissions and toxic emissions data.

2. INDUSTRIAL PROCESSES

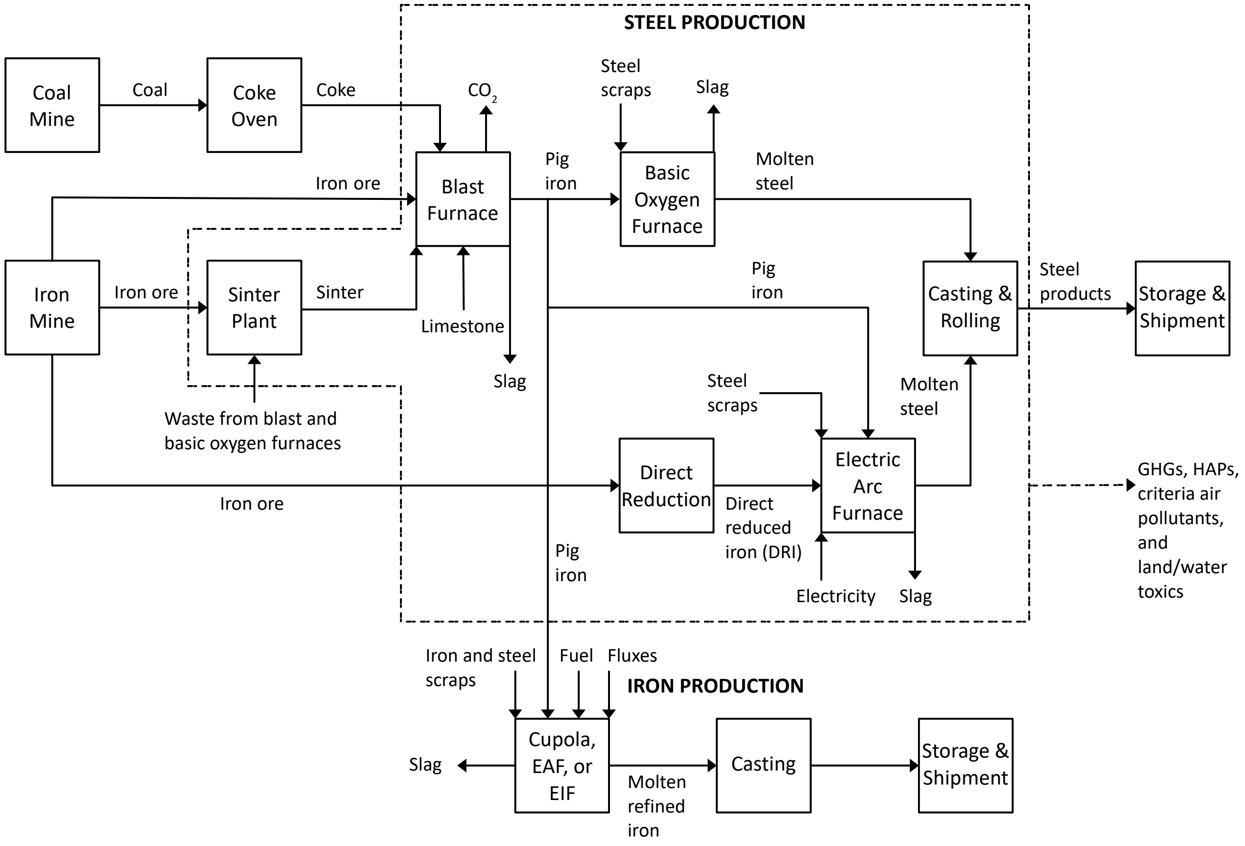
The four industries in this report follow a similar production process. Raw, earthen material is mined, pre-processed, and delivered to an industrial facility—thus entering the scope of this analysis. Facility operators then add heat and other feedstocks to induce a chemical transformation. After that transformation, the primary production facility processes the industrial material into a salable product and sends it off-site, marking the boundary of this analysis.

The four industries produce pollution by pre-processing material, by burning fossil fuels to provide the heat driving chemical transformations, and as an output of those transformations’ chemistries. Electricity usage also contributes to emissions indirectly by drawing on fossil-powered generators. As this section will outline, the relative contribution of each step to a plant’s overall release of pollution differs by industry.

2.1. Iron and Steel

Figure 1 summarizes the processes involved in iron and steel production. Production begins at a mine, which produces iron ore. That ore is then transported to a facility with a blast furnace, which is where the scope of our pollution analysis begins.

Figure 1. Steel production process diagram



Note: The dotted line shows the boundary of the facilities included in this report.

If the iron ore is the correct size for smelting, it can be used directly in a blast furnace. Otherwise, the ore is first sintered at the steel facility to fuse ore particles to the correct size for smelting.[13] The blast furnace smelts iron ore, reducing iron oxides in the ore to form pure iron. Sinter, ore pellets, coke (coal that has been heated in the absence of oxygen), and limestone react to form molten iron, slag, and carbon monoxide. The plant recycles blast furnace gas for use as fuel, and the carbon monoxide is ultimately oxidized to carbon dioxide (CO_2). Metallurgical coke (metcoke) is the primary source of fuel in the blast furnace and also creates the reducing atmosphere necessary to strip oxygen atoms from ore

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[13] Sinter plants also recycle waste material from later stages in the manufacturing process.

and yield metallic iron. (See Section 2.2 for information on metallurgical coke production.) Combustion of metcoke is another major source of carbon dioxide.

Once the plant produces metallic iron ("pig iron") in the blast furnace,[14] the next step is to produce steel. The most common method for producing steel from pig iron is the basic oxygen process. In a second furnace, an oxygen lance blasts pure oxygen through the molten metal. In conjunction with fluxes, the oxygen removes carbon and other impurities. Alternately, facilities can use electric arc furnaces (EAF) to remove impurities in primary steel production. EAFs are typically used for secondary steel production, meaning that they use scrap steel as a feedstock rather than iron. However, EAFs may also be supplied directly with pig iron or direct reduced iron (DRI).[15] After production through the basic oxygen process or in an EAF, molten steel is cast and rolled to produce a variety of final products (e.g., rails, pipes, bars, and plates).

Alternately, a facility may process pig iron directly into iron products. This process makes use of a cupola (coke-fueled furnace), EAF, or electric induction furnace which heats through electrical resistance. Pig iron and scrap metal are melted in the furnace, refined through the addition of fluxes (e.g., magnesium), and then cast in sand-based molds. Approximately 95 percent of pig iron production is used for steel production, so facilities that produce finished iron products only are not included in this report.[16]

2.2. Metallurgical Coke

Metallurgical coke (metcoke) is an industrial product used in iron and steelmaking to reduce iron ore to metallic iron. Most metallurgical coke plants in the United States are located along major waterways at or near iron and steel facilities, allowing them to sell coke to blast furnaces immediately adjacent and, often, in the local region. Four of the eleven[17] operating metcoke facilities are owned by parent companies that also own blast furnace facilities, while the rest are owned by third-party companies that produce coke alone.

Broadly, metcoke production involves heating metallurgical coal, which has specific properties and is distinct from electrical coal, to drive off lighter organic compounds. The end product is coke, a high-carbon, energy-dense material.

There are two main types of metallurgical coke plants: byproduct recovery and non-recovery, shown in Figure 2 and Figure 3, respectively. Nearly all metallurgical coke producers in the United States produce coke using the byproduct recovery process, which recovers and purifies organic chemicals from the waste gas produced by heating metallurgical coal. However, as of 2012, the three newest U.S. coke

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[14] Pig iron is brittle because of its high carbon content and must be refined further to produce useable iron. The name comes from the shape of the molds that were historically used to cast it into ingots, which resembled a litter of piglets.

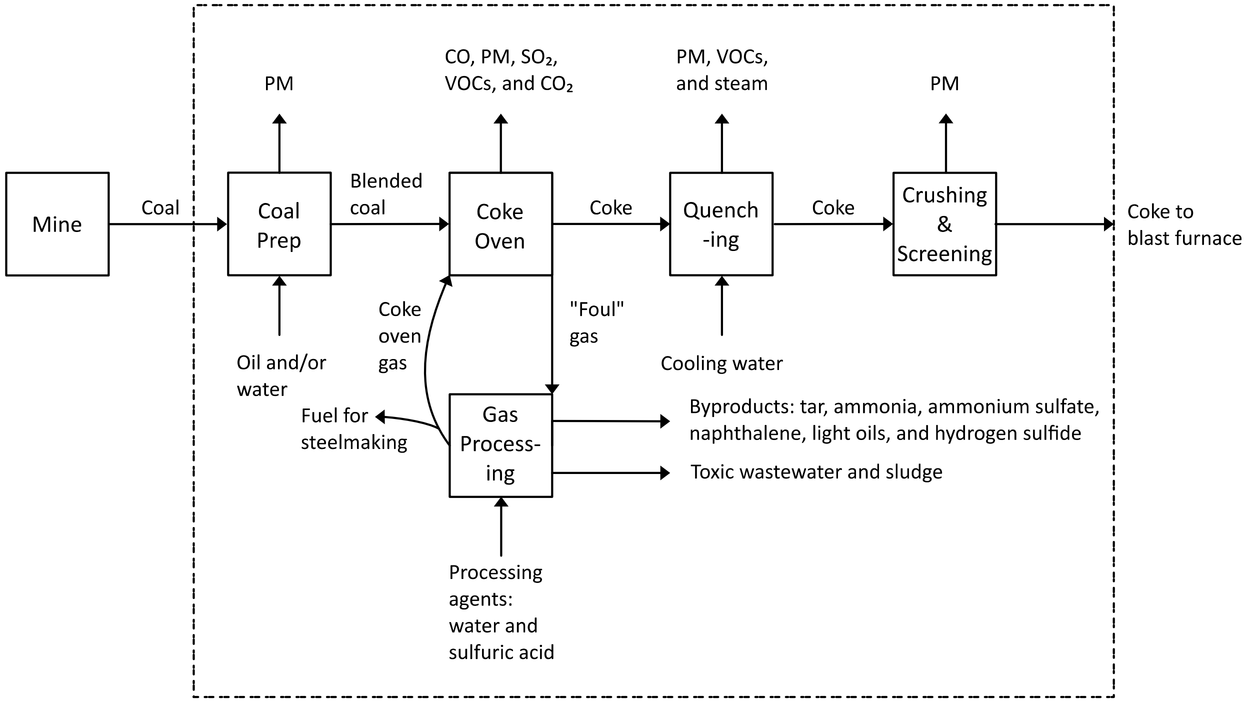
[15] Direct reduction is an alternative process to smelting in which ore is treated with a reducing gas to produce iron.

[16] U.S. Geological Survey. 2023. Mineral commodity summaries 2023. Available at: https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-iron-steel.pdf

[17] There are 12 facilities in the accompanying database, which contains 2020 data, but one closed in 2022.

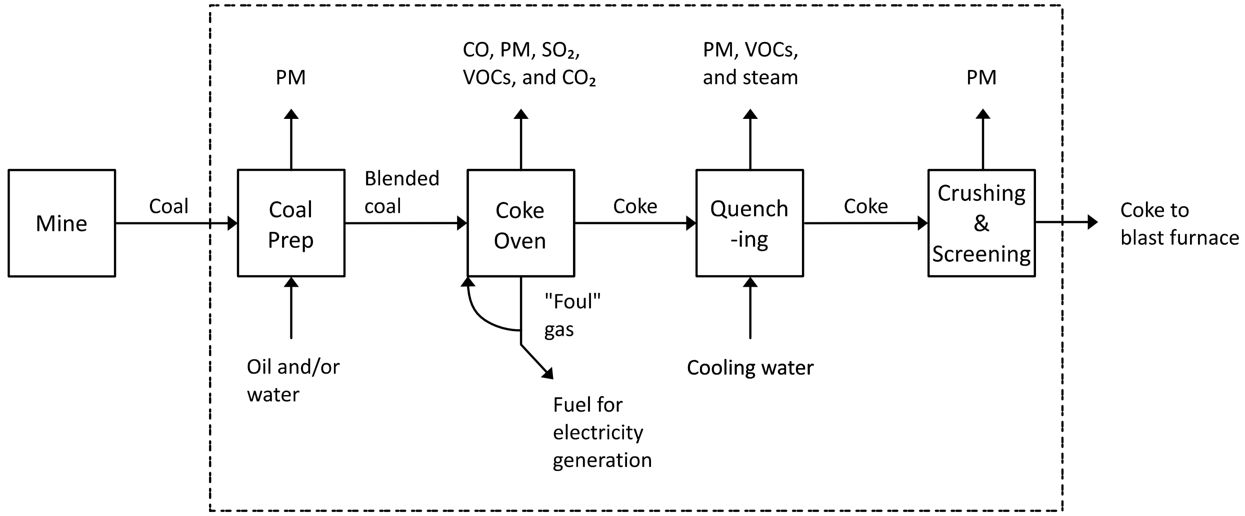
plants all use the non-recovery process, which focuses on coke production alone and burns off excess organic chemicals; these often use some of the resulting heat to generate electricity.

Figure 2. Process diagram of coke production using the byproduct recovery process



Note: The dotted line shows the boundary of the facilities included in this report. For an expanded view of the gas processing stage, see Figure 1.

Figure 3. Process diagram of coke production using the non-recovery process



The dotted line shows the boundary of the facilities included in this report. At these plants, the gas processing phase does not occur. Instead, the facilities burn "foul" gas directly as fuel and do not recover byproducts.

Within both types of coke plants, up to 100 coke ovens are arranged in groups known as batteries. Pulverized metallurgical coal is mixed with oil or water to adjust the density if necessary, and in some facilities, it is also preheated. The blended coal is then charged into the ovens, where it is heated for 12 to 20 hours at high temperatures (1,650–2,200°F). The environment inside the coking ovens is low in oxygen, causing coal to undergo destructive distillation, a process in which all volatile components evaporate and are removed as a mixture called "foul" gas.

At byproduct recovery plants, the "foul" gas is captured and purified into coke oven gas[18] through a separate series of processes, discussed below. Non-recovery plants burn the "foul" gas directly. Heat for the destructive distillation process comes from external combustion of recovered coke oven gas or "foul" gas, circulated through flues located between the ovens.

Once the destructive distillation process is complete, the coke is pushed out of the ovens with a ram and is transported to the quench tower, where it is sprayed with water (approximately 270 gallons per metric ton coke) to cool it and prevent ignition.[19] The coke then drains and is crushed and screened, at which point it is ready for use in a blast furnace. The majority of water used in quenching is lost as steam

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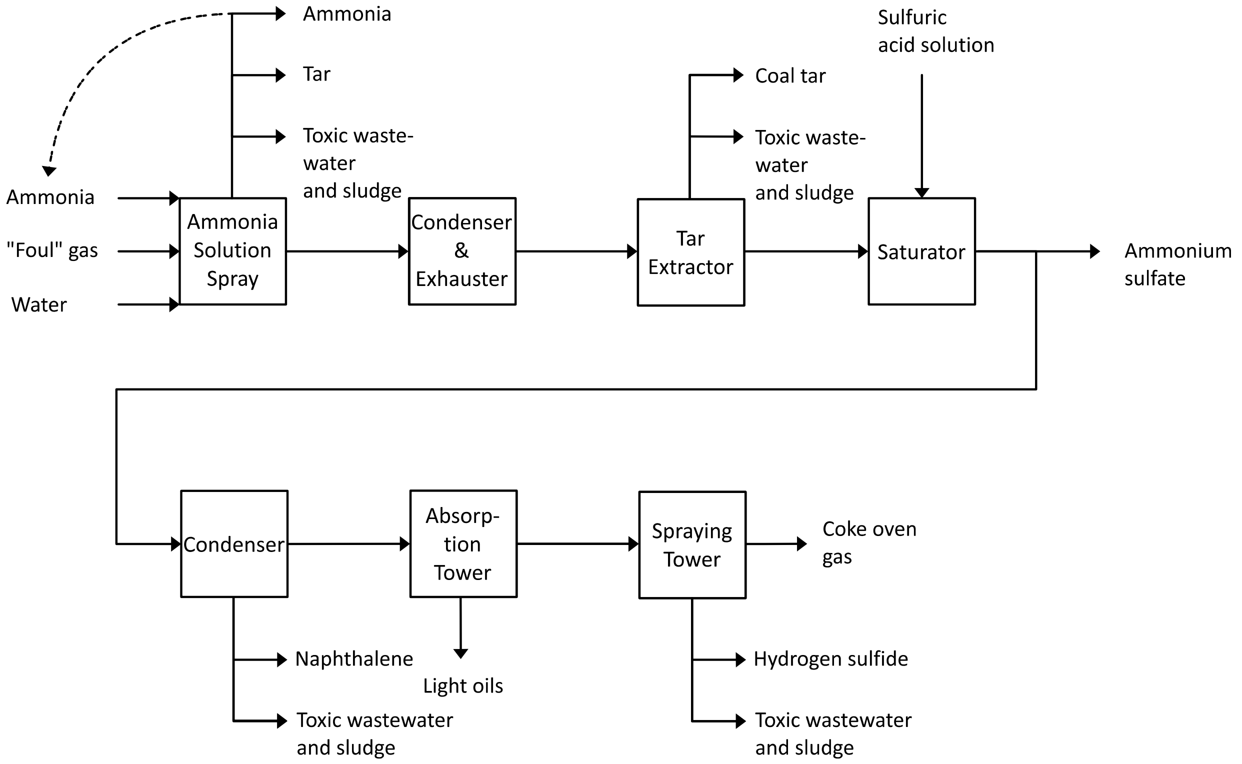
[18] Coke oven gas is the mixture that remains after processing the foul gas (Figure 2). It is composed of approximately 47–58 percent hydrogen and 27–32 percent methane by volume, along with smaller percentages of carbon monoxide, carbon dioxide, nitrogen, oxygen, ammonia, hydrogen sulfide, and other constituents. A facility can supplement coke oven gas with natural gas, or, if the facility is co-located with a blast furnace, with blast furnace gas (see Section 2.1).

[19] An alternate technique known as dry-quenching cools coke through exposure to a circulating inert gas, allowing for heat recovery and reducing pollution from the contaminated steam plume. As of 2012, no U.S. coke plants used dry quenching.

through the quench tower chimney. The steam plume also contains particulates and tar, although baffles inside the chimney help reduce this contamination.

Byproduct recovery coke facilities require an intermediate set of processes to purify the "foul" gas from the coking ovens. This gas contains all the volatile compounds removed from the coal, including water vapor, tar, light oils, solid particulate of coal dust, heavy hydrocarbons, and complex carbon compounds. The condensable materials are removed in several stages, as shown in Figure 4. These byproducts, which include tar, ammonia, ammonium sulfate, naphthalene, light oils, and hydrogen sulfide, are further processed and used in other industrial processes such as fertilizer and synthetic resin production. About 40 percent of the purified coke oven gas is used as a fuel in coking and the rest is used in steelmaking processes or power generation. Nonrecovery facilities burn the "foul" gas directly without undergoing the purification process in Figure 4, and they do not recover any organic chemical byproducts.

Figure 4. Process diagram of purification of "foul" gas to coke oven gas at a byproduct recovery plant



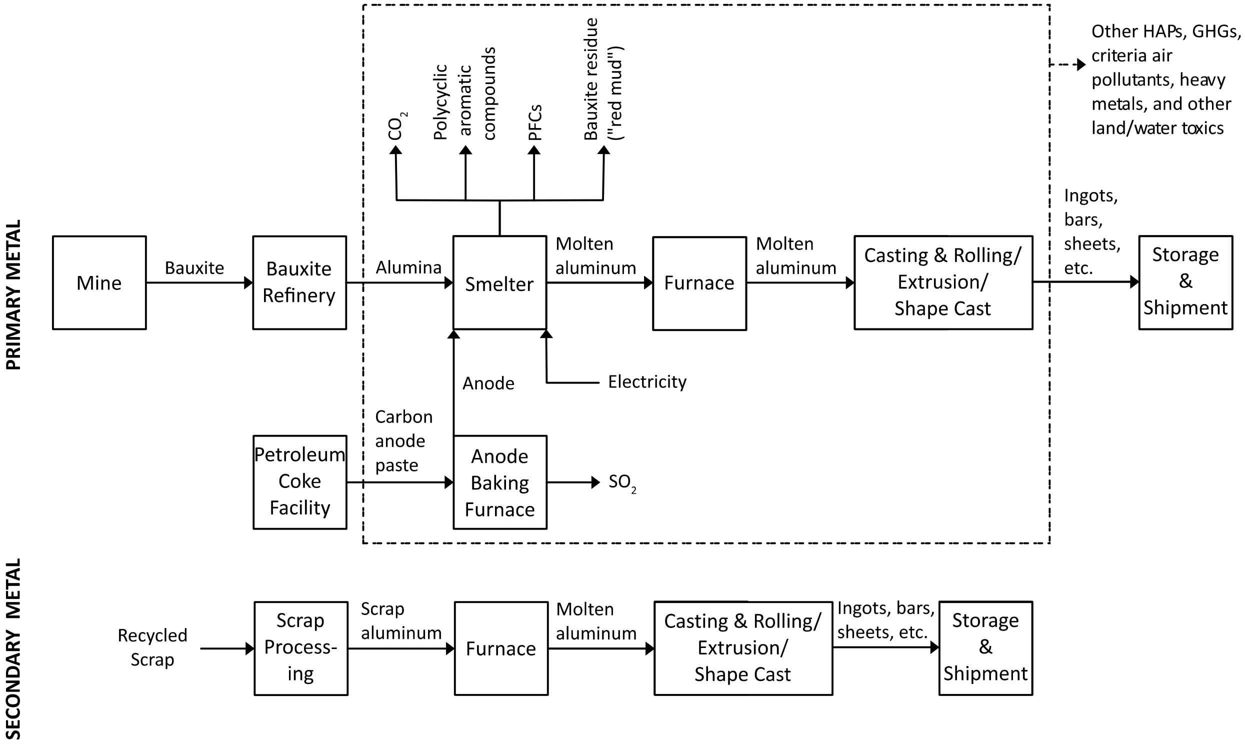
Note: The dotted line shows the boundary of the facilities included in this report.

Emissions from the coking process include greenhouse gas emissions from fuel combustion, particulate matter and other criteria air pollutants, volatile organic compounds (VOC), and toxic wastewater and sludge. Byproduct recovery facilities generally produce more benzene and organic chemical emissions, but less particulate matter, nitrogen oxides (NO_X), and CO_2. Non-recovery facilities emit less benzene and organic chemical pollution but more particulates, NO_X, and CO_2. The non-recovery process results in approximately six times higher combustion stack greenhouse gas emissions per ton of coke than the byproduct recovery process.

2.3. Aluminum

Figure 5 summarizes the processes involved in aluminum production. Production begins with bauxite, a type of sedimentary rock that is rich in aluminum. Bauxite is mined and refined through the Bayer Process to produce crystalline alumina (Al_2O_3). The alumina is then sent to a primary aluminum facility, which is where the scope of this analysis begins. The primary aluminum facility electrochemically reduces the alumina through the Hall-Héroult Process to produce molten aluminum. This process involves conducting a powerful electrical current through the molten metal, which requires a conductive carbon anode made of coke and other carbon-rich materials. The Scope 2 emissions[20] of the electricity used at this stage commonly represent the majority of the emissions attributable to a primary aluminum facility.

Figure 5. Aluminum production process diagram



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[20] Scope 2 emissions are emissions attributable to a facility due to its use of purchased electricity. Scope 1 emissions are direct, on-site emissions from the facility itself.

Note: The dotted line shows the boundary of the facilities included in this report.

In the United States, the carbon anode is typically processed onsite, by baking coke in an anode baking furnace—a process that releases CO_2. The Hall-Héroult Process itself also releases CO_2 from the oxidation of the carbon anode and perfluorochemicals (PFCs) from reactions between the anode and electrolyte bath in the reduction cell. During this "anode effect," cryolite (Na_3AlF_6), which acts as both an electrolyte and a solvent for the alumina, reacts with the anode to form two types of PFC: carbon tetrafluoride (CF_4) and hexafluoroethane (C_2F_6). Both are released in small amounts; but because they are potent greenhouse gases, they accounted for over 40 percent of Scope 1 emissions from U.S. primary aluminum facilities in 2020 (see Section 6).

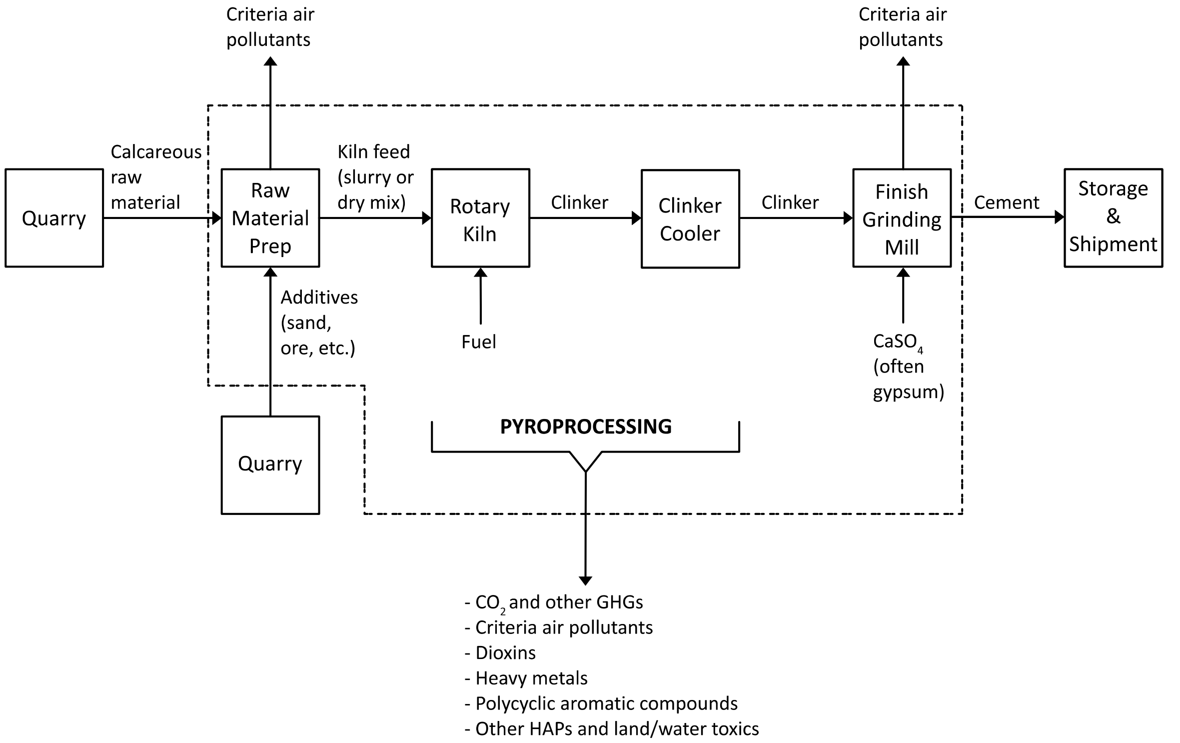
After the Hall-Héroult Process, the facility transfers the molten aluminum to a holding furnace. From there, the material is either transported to a fabricating plant or cast onsite. The facility may further process it through rolling, extrusion, or shape casting to create products such as bars and sheets.

This report only includes primary aluminum facilities, but it should be noted that secondary aluminum facilities process, melt, and cast recycled metal, thereby eliminating the most energy- and emissions-intensive steps of primary aluminum production.

2.4. Cement

The cement manufacturing process, shown in Figure 6 begins with calcareous raw materials such as limestone and chalk, which are obtained from an open-faced quarry and transported to a cement manufacturing plant. The material inputs are heavy, and the manufacturing process sheds about a third of the raw material mass as carbon dioxide. For this reason, cement plants are located near quarries to minimize transport costs. The plants crush, grind, and blend raw materials with additives onsite to produce kiln feed. Depending on the type of equipment installed, the plant either removes moisture to create a dry raw mix (dry processing) or adds moisture to create a slurry (wet processing).

Figure 6. Cement production process diagram



Notes: The dotted line shows the boundary of the facilities included in this report.

The next stage is pyroprocessing, which uses heat to chemically transform the kiln feed into clinker. Clinker is composed of spherical nodules with the chemical properties of cement. As the kiln feed moves through the rotator kiln, the temperature rises, eventually reaching 1510°C (2750°F). There are five processes that plants may use to produce clinker: dry, wet, semidry, dry with preheater, and dry with preheater/precalciner. The processes result in the same series of chemical reactions but vary in equipment setup and energy efficiency. The source of heat for kilns also varies. The most commonly used kiln fuels are coal, natural gas, oil, and coke derived from petroleum refining.[21] According to the U.S. EPA, the high temperature at which cement kilns operate also makes them an efficient technology for combusting hazardous waste.[22]

From the kiln, clinker is sent to a cooler and subsequently to a finish grinding mill, where it is blended with calcium sulfate (to control setting time) and other additives that affect the material properties of the cement. The finished product, cement, is then ready for shipping.

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[21] U.S. EPA. 1995. *Mineral Products in Industry*. Available at: https://www3.epa.gov/ttnchie1/ap42/ch11/final/c11s06.pdf.

[22] U.S. EPA. 2023. "Cement Kilns Burning Hazardous Waste as Supplemental Fuel." Available at: https://ordspub.epa.gov/ords/guideme_ext/f?p=guideme:gd:::::gd:dioxin_4_5_3.

All stages of this process release particulate matter, although the largest source is pyroprocessing. The majority of carbon dioxide emissions also occur during pyroprocessing, both from the combustion of fuel and from the calcining process (thermal decomposition of $CaCO_3$ to CaO and CO_2). Fuel burning in the kiln and precalciner (if present) can also lead to nitrous oxide emissions. Cement manufacturing also produces SO_2, carbon monoxide, and a variety of other pollutants in smaller quantities.

3. REVIEW OF PRIOR STUDIES

Primary production facilities for iron, steel, cement, aluminum, and metcoke are responsible for approximately 2 percent of America's 2020 greenhouse gas emissions.[23] They also produce substantial quantities of air, water, and land pollutants. Prior research has sought to quantify and characterize these emissions.

Table 1 through Table 4 below summarize studies of emissions in the United States. Several studies calculate the emission intensities of processes involved in iron, steel, aluminum, and cement production, often with a focus on CO_2 emissions (Table 1). Other studies inventory total emissions, capacity, or production for each industry in the United States (Table 2). Some quantify energy use at each stage of production, either for the purpose of quantifying energy-related emissions or identifying opportunities for improved energy efficiency (Table 3). Only a few studies present subnational detail, and they are generally limited in scope (Table 4). Metallurgical coke is rarely studied on its own but is often studied as a component of the iron and steel industry.

While several studies compare emissions internationally, there is a need for more disaggregated studies that compare facilities and/or regions within the United States. Because many studies focus on greenhouse gases, especially CO_2, there is also a need for more analysis of air, land, and water toxics. Finally, several of the most detailed studies are over 20 years old, so additional research is needed to reflect changes in these industries.

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[23] Scope 1 industry emissions from U.S. EPA Greenhouse Gas Reporting Program 2020; U.S. total emissions in CO_2-equivalent from https://www.epa.gov/climate-indicators/climate-change-indicators-us-greenhouse-gas-emissions.

Table 1. Studies of industry emission intensity

Name of Study	Publisher	Industries Covered	Description
AP 42	U.S. EPA	Iron and steel, aluminum, cement, metallurgical coke	Provides industry process descriptions and emission intensities of particulates, greenhouse gases, and other pollutants. The cement information was updated in 2022, but the other sections are typically decades old.
Comparison of Energy-Related Carbon Dioxide Emission intensity of the International Iron and Steel Industry: Case Studies from China, Germany, Mexico, and the United States	Lawrence Berkeley National Laboratory	Iron and steel, metallurgical coke	Compares the energy-related CO_2 emission intensity of iron and steel production in China, Germany, Mexico, and the United States. Discusses factors that contribute to the variation between countries.
Emissions Analysis Executive Summary	Steel Manufacturers Association	Steel, metallurgical coke	Compares emission intensities of basic oxygen furnace and EAF based steelmaking in the United States, broken into Scopes 1, 2, and 3.
Energy and Environmental Profiles	U.S. Department of Energy	Iron and steel and aluminum	Provides emission intensity data for a number of air emissions (SO_X, NO_X, CO_2, carbon monoxide, particulate, VOCs, etc.), both for the entire supply chain and broken out by subprocess. May be out of date.
Steel Climate Impact: An International Benchmarking of Energy and CO_2 Intensities	Global Efficiency Intelligence	Steel, metallurgical coke	Calculates energy intensity and CO_2 emission intensities of the steel (including coke production) industry in the largest steel-producing countries. For steel, the data is divided by basic oxygen furnace and EAF production routes in each country.
Aluminum Climate Impact: An International Benchmarking of Energy and CO_2 Intensities	Global Efficiency Intelligence	Aluminum	Calculates energy intensity and CO_2 emission intensities of the aluminum industry in the largest aluminum-producing countries. The data is divided into alumina production and electrolysis.
U.S. Cement Industry Carbon Intensities	U.S. EPA	Cement	Provides CO_2 emission intensities for clinker and cement produced in the United States (including low, midpoint, and high values).

Sources:
U.S. EPA. 1986. 12.5 Iron and Steel Production. AP 42, Fifth Edition, Volume 1, Chapter 12. U.S. Environmental Protection Agency. Available at: https://www.epa.gov/sites/default/files/2020-11/documents/c12s05.pdf. Also see sections 12.13 on steel foundries, 12.10 on gray iron foundries, and 12.2 on coke production.
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U.S. EPA. 2022. 11.6 Portland Cement Manufacturing. AP 42, Fifth Edition, Volume 1, Chapter 11. U.S. Environmental Protection Agency. Available at: https://www.epa.gov/system/files/documents/2022-03/c11s06_final_0.pdf.
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Energetics. 2000. Energy and Environmental Profile of the U.S. Iron and Steel Industry. Energetics for the U.S. Department of Energy Office of Industrial Technologies. Available at: https://www.energy.gov/sites/default/files/2013/11/f4/steel_profile.pdf.
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Hasanbeigi, A. 2022. Steel Climate Impact: An International Benchmarking of Energy and CO_2 Intensities. Global Efficiency Intelligence. Available at: https://static1.squarespace.com/static/5877e86f9de4bb8bce72105c/t/624ebc5e1f5e2f3078c53a07/1649327229553/Steel+climate+impact-benchmarking+report+7April2022.pdf.

Hasanbeigi, A., Springer, C., and Shi, D. 2022. Aluminum Climate Impact: An International Benchmarking of Energy and CO_2 Intensities. Global Efficiency Intelligence. Available at: https://www.globalefficiencyintel.com/aluminum-climate-impact-international-benchmarking-energy-co2-intensities.
U.S. EPA. 2021. U.S. Cement Industry Carbon Intensities. EPA 430-F-21-004. Available at: https://www.epa.gov/system/files/documents/2021-10/cement-carbon-intensities-fact-sheet.pdf.

Table 2. Studies that inventory industry emissions, capacity, and production

Name of Study	Publisher	Industries Covered	Description
Aluminum Sector Snapshot: Environmental Reporting	Aluminum Association	Aluminum	Summarizes emissions data reported to U.S. EPA and U.S. Energy Information Administration (EIA) (both greenhouse gases and toxic pollutants) since 1996.
Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2020	U.S. EPA	Iron and steel, metallurgical coke, aluminum, and cement	Reports greenhouse gas emissions from each industry in 1990, 2005, and 2016–2022 by sub-process. Also gives carbon intensities and production/consumption data for materials involved in the processes.
Mineral commodity summaries 2022	U.S. Geological Survey	Iron and steel, aluminum, and cement	Provides production, consumption, import, and export data for mineral commodities including iron, steel, aluminum, and cement.
Pedal to the Metal: It's Not Too Late to Abate Emissions From the Global Iron and Steel Sector	Global Energy Monitor	Iron and steel	Assesses the global iron and steel plant fleet based on capacity of each technology type. Reports data by country and includes both operational capacity and capacity under development. Also includes an analysis of the pace of change necessary to meet climate goals, stranded asset risk, and underreported emissions from coal mining.

Sources:
Aluminum Association. 2021. Aluminum Sector Snapshot: Environmental Reporting. Available at: https://www.aluminum.org/sites/default/files/2022-01/Aluminum_Association_Smart_Sector-Report.pdf.
U.S. EPA. 2022. Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2020: Section 4.17 Iron and Steel Production (CRF Source Category 2C1) and Metallurgical Coke Production. U.S. Environmental Protection Agency. EPA 430-R-22-003. Available at: https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-main-text.pdf#page=337*. Also see chapter 3 for information on emissions from energy consumed during processes.*
U.S. EPA. 2022. Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2020: Section 4.19 Aluminum Production (CRF Source Category 2C3). U.S. Environmental Protection Agency. EPA 430-R-22-003. Available at: https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-main-text.pdf#page=352*. Also see chapter 3 for information on emissions from energy consumed during processes.*
U.S. EPA. 2022. Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2020: Section 4.1 Cement Production (CRF Source Category 2A1). U.S. Environmental Protection Agency. EPA 430-R-22-003. Available at: https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-main-text.pdf#page=266*. Also see chapter 3 for information on emissions from energy consumed during processes.*
U.S. Geological Survey. 2022. Mineral commodity summaries 2022. Available at: https://doi.org/10.3133/mcs2022.
Swalec, C. 2022. Pedal to the Metal: It's Not Too Late to Abate Emissions From the Global Iron and Steel Sector. Global Energy Monitor. Available at: https://globalenergymonitor.org/wp-content/uploads/2022/06/GEM_SteelPlants2022.pdf.

Table 3. Studies that quantify industrial energy use

Name of Study	Publisher	Industries Covered	Description
Bandwidth Study on Energy Use and Potential Energy Savings Opportunities	U.S. Department of Energy	Steel, metallurgical coke, aluminum, cement	Quantifies current energy use by sub-process and estimates state-of-the-art energy consumption, practical minimum energy consumption, and thermodynamic minimum energy consumption.
U.S. Manufacturing Energy Use and Greenhouse Gas Emissions Analysis	Oak Ridge National Laboratory	Iron and steel, metallurgical coke	Traces energy flows, including energy used for electricity and steam generation and energy consumed through direct fuel use, both offsite and onsite. Also reports energy losses and greenhouse gas emissions.

Sources:

U.S. DOE. 2017. Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Advanced High Strength Steels Manufacturing. U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. Available at: https://www.energy.gov/sites/default/files/2019/05/f62/AHSS_bandwidth_study_2017.pdf.

DOE. 2017. Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Aluminum Manufacturing. U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. Available at: https://www.energy.gov/sites/default/files/2019/05/f62/Aluminum_bandwidth_study_2017.pdf

U.S. DOE. 2017. Bandwidth Study on Energy Use and Potential Energy Savings Opportunities in U.S. Cement Manufacturing. U.S. Department of Energy Office of Energy Efficiency and Renewable Energy. Available at: https://www.energy.gov/sites/default/files/2017/12/f46/Cement_bandwidth_study_2017.pdf

Brueske, S., Sabouni, R., Zach, C., and Andres, H. 2012. U.S. Manufacturing Energy Use and Greenhouse Gas Emissions Analysis. Energetics Incorporated for the Oak Ridge National Laboratory. Available at: https://www.energy.gov/sites/default/files/2013/11/f4/energy_use_and_loss_and_emissions.pdf#page=113.

Table 4. Subnational studies of industrial emissions

Name of Study	Publisher	Industries Covered	Description
California's Cement Industry: Failing the Climate Challenge	Global Efficiency Intelligence	Cement	Reports industry-wide and facility-level emissions and energy data for cement producers in California. Benchmarks California values against the emissions and energy intensities of cement production in other countries.
Deep Decarbonization Roadmap for the Cement and Concrete Industries in California	Global Efficiency Intelligence	Cement, concrete	Presents a follow-up study to the study above, which develops scenarios up to 2040 to study different decarbonization pathways for cement and concrete production in California.
Clean Materials Manufacturing	Clean Energy Transition Institute	Iron, steel, aluminum, cement	Provides industry descriptions, greenhouse gas footprints, and workforce information for plants in Washington state.
CO_2 Emissions Profile of the U.S. Cement Industry	U.S. EPA	Cement	Attempts bottom-up analysis of cement industry emissions in each U.S. state using average emissions rates for wet and dry processing and facility-specific capacity information.

Sources:
Hasanbeigi, A and Springer, C. 2019. California's Cement Industry: Failing the Climate Challenge. Global Efficiency Intelligence. Available at: https://static1.squarespace.com/static/5877e86f9de4bb8bce72105c/t/5c9caa6d085229a6e7b5d84c/1553771131580/CA+Cement+benchmarking+report+Rev-Final.pdf.
Hasanbeigi, A. and Springer, C. 2019. Deep Decarbonization Roadmap for the Cement and Concrete Industries in California. Global Efficiency Intelligence. Available at: https://static1.squarespace.com/static/5877e86f9de4bb8bce72105c/t/5d6743b833f508000119a3d0/1567048700971/Decarbonization+Roadmap+CA+Cement-+Final-Spet+2019.pdf
CET. 2021. Clean Materials Manufacturing. Clean Energy Transition Institute. Available at: https://www.cleanenergytransition.org/cmm.
Hanle, L, Jayaraman, K, and Smith, J. 2004. CO_2 Emissions Profile of the U.S. Cement Industry. ICF Consulting for U.S. EPA. Available at: https://www3.epa.gov/ttnchie1/conference/ei13/ghg/hanle.pdf.

Our review of prior studies highlights several data limitations that hinder effective policymaking and action. We find that available information is commonly available at the national level, which conceals facility-by-facility differences in emissions, production, and jobs. Further, emissions data are often missing due to lack of regulation and protections for confidential business information. The data that are available are strewn across many public databases, with no unified repository, and have high levels of uncertainty in reported emissions.

4. FACILITY-SPECIFIC DATA

This study addresses the limitations in facility-level information for the iron, steel, metallurgical coke, aluminum, and cement industries by assembling all nationally consistent public data on U.S. facility-level pollution, production, and employment. We also include socioeconomic and demographic information for the fence-line communities surrounding these facilities.

We assemble four databases of primary production facilities, one per industry. Each database contains a list of facilities operating in 2020, their parent companies, and their location. We compile facility-level data from U.S. EPA about emissions from greenhouse gases, air toxics, and the six criteria air pollutants (ozone, PM, carbon monoxide, lead, SO_2, NO_2). The databases also include water and land pollution data for more than 100 additional pollutants. We provide reported employment levels and facility-level production, or we estimate these where public data is not available. The databases also describe the specific manufactured products at each facility and provide environmental and socioeconomic data on the communities on the fence-line of each facility. Last, we estimate Scope 1 and Scope 1 plus Scope 2 emission intensity using reported direct emissions, industry-specific electricity usage factors, production estimates, and geographically specific electricity emission factors. This section describes these components of the industry databases in greater detail, including the methodologies we use.

4.1. Facility Identifying Information

Facility-reported U.S. EPA data is the backbone of our industrial databases. This data comes from a large number of distinct databases for various U.S. EPA programs. For example, U.S. EPA has separate databases for collecting and tracking facility-level greenhouse gas emissions, toxic releases, air pollution, environmental compliance, health impact risk, and more. Each of these programs and databases assigns a unique identification number to each plant, meaning that the same facility is identified differently in each database. The first step in data collection, therefore, was to cross-reference the identification numbers for each facility across U.S. EPA's various databases and link these identifiers to non-EPA data sources.

Data sources

- EPA Envirofacts data system
- EPA Facility Registry Service (FRS)
- EPA Greenhouse Gas Reporting Program (GHGRP) and associated Electronic Greenhouse Gas Reporting Tool (E-GGRT)
- EPA Air Facility System (AFS)
- EPA Clean Water Act National Pollutant Discharge Elimination System
- EPA Risk-Screening Environmental Indicators (RSEI) model
- EPA Safe Drinking Water Information System (SDWIS)
- EPA Resource Conservation and Recovery Act Information System (RCRAInfo)
- EPA Toxics Release Inventory (TRI)
- EPA National Emissions Inventory (NEI)
- EPA Enforcement and Compliance History Online database (ECHO)
- Facility Level Information on GreenHouse gases Tool (FLIGHT)
- Global Steel Plant Tracker (GSPT)
- BlueGreen Alliance (BGA) industrial facility databases

Methods

To develop an initial list of plants, we queried U.S. EPA's Envirofacts database for the greenhouse gas reporting system by North American Industry Classification System (NAICS) code and by the relevant subsector (i.e., iron and steel, cement, metallurgical coke, or aluminum). This type of search returns a list of facilities with basic information including facility name, location, and the ID code assigned by the FRS database. We then linked each facility to the remaining data sources using the facility IDs and other identifying information.

Results

For iron and steel, NAICS code 331110, with the subsector for iron and steel, yielded 122 unique GHGRP IDs.[24] Of these, we identified 10 as ore pellet or mining facilities and removed those, leaving 100 iron and steel production facilities and 12 metallurgical coke facilities. These 12 metallurgical coke facilities were also identified under NAICs code 324199, "All Other Petroleum and Coal Products Manufacturing." NAICS code 327310, with the subsector cement, yielded 92 facilities with unique GHGRP IDs. NAICS code 331315, with the subsector aluminum facilities, yielded 7 facilities with unique GHGRP IDs. These IDs, facility names, and location information enabled Synapse to cross reference facility-level information across various databases.

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[24] NAICS code 331110 includes facilities engaged in primary production of iron and steel as well as ferroalloys. For our analysis, we searched for the subsector iron and steel in addition to the NAICS code within GHGRP to exclude ferroalloy facilities. U.S. Census Bureau. *North American Industry Classification System.* Available at: https://www.census.gov/naics/?input=331110&year=2022&details=331110.

4.2. Production Data

To estimate the emission intensity (e.g., tons of greenhouse gas per ton of material) of a specific industrial facility requires knowing that facility's annual emissions and production. In the iron, steel, metcoke, cement, and aluminum industries, U.S. EPA collects and publishes emissions data, but it does not publish annual production data. Nor is facility-level production data publicly available at all facilities in these industries. This required developing a methodology to estimate the production at each facility in the year 2020.

Data sources

- Association for Iron & Steel Technology's (AIST) North American Blast Furnace Roundup
- BlueGreen Alliance (BGA) industrial facility databases
- Global Energy Monitor's Global Steel Plant Tracker (GSPT)
- U.S. Geological Survey (USGS) Mineral Commodity Survey
- Synapse facility-specific research

Methods

Iron and steel

We collected exact production in 2020 for 10 of the 11 extant basic oxygen furnace (BOF) facilities in the United States from the Association for Iron & Steel Technology's (AIST) 2021 North American Blast Furnace Roundup.[25] For all remaining facilities, we use the following methodology.

BlueGreen Alliance (BGA) developed production estimates for nearly every facility based on facility-specific online research. This BGA data included a raw production value for each facility that was either reported production or the estimated production capacity of the facility in a specific historical year. Global Steel Plant Tracker (GSPT), an initiative of Global Energy Monitor, also publishes a dataset that includes estimated production capacity per facility. Between these two sources, we assigned each facility in our database a raw value for capacity and/or production. Where the two sources overlapped, we used BGA's number.

The next step was to adjust historical production values to 2020 estimates, where applicable, and adjust capacity values to 2020 production. For the former step, we adjusted historical production according to the comparative difference between industry-wide production in 2020 and the historical year, as reported by the USGS. We made capacity adjustments by multiplying the industry-wide average capacity factor published by USGS in its mineral commodity summary by the specific facility's maximum production capacity. Finally, we totaled the final estimates for facility-level production and compared to

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[25] Association for Iron & Steel Technology. 2021. *2021 AIST North American Blast Furnace Roundup*, available at https://imis.aist.org/AISTPapers/Abstracts_Only_PDF/PR-RU2021-7.pdf.

industry-wide production data for 2020 available from the USGS's annual mineral commodity summaries.

In the iron and steel industry, we added product type information to the database. We sourced this data from a combination of BGA and GSPT databases and supplemented with facility-specific research where needed. To enable like-for-like facility comparisons, we grouped the products into categories, such as long products and flat products.

Cement

BGA used three types of sources to develop initial production estimates: data directly from each company, data from the media (e.g., local news articles) or other third parties, and data from the "Industry About" database, which is no longer supported online. Most plants started with two values (one from Industry About and one from either the company or media). BGA made a series of adjustments to production values. When a source provided production capacity rather than actual production, BGA adjusted downward based on the average 2018 capacity utilization to estimate actual production. For plants where a source gave a value in short tons, BGA converted the value to metric tons. Finally, for plants where a source gave a production value for clinker rather than cement, BGA adjusted upwards based on the relative production ratio between clinker and cement. To further refine these estimates, we re-adjusted capacity utilization with the 2019 value (the most recent data year available) given by the 2021 USGS Mineral Commodity Survey.

In many cases, the available data sources were ambiguous about units of measurement, capacity versus actual production, and clinker versus cement, so these adjustments may have been misapplied to some facilities. This resulted in increased data uncertainty at the facility level. For each facility, BGA chose what staff believed to be the best production value. BGA, where possible, gave priority to values from a facility's parent company. When no company value was available, BGA generally averaged the value given by the Industry About database and the media. However, there were several exceptions to these rules based on staff assessment of source quality. We totaled the final estimates for facility-level production and compared them to industry-wide production data for 2020 available from the USGS's annual mineral commodity summary.

Aluminum

For aluminum, we used facility-specific production capacity, researched for each of the seven individual plants. We allocated total primary aluminum production in 2020, available from USGS's 2021 Mineral Commodity Summary, to each facility according to the facility's share of total capacity.

Metallurgical Coke

We estimated 2020 production data for the five metcoke facilities owned by SunCoke using data from SunCoke's 2020 Form 10-k, which reports total production, facility-level production capacity, and a company-specific capacity factor of 91 percent for its facilities. For the remaining seven facilities, facility-specific online research established raw capacity values, which we converted to estimated 2020 production using the iron and steel industry's 2020 capacity factor available from USGS.

Results

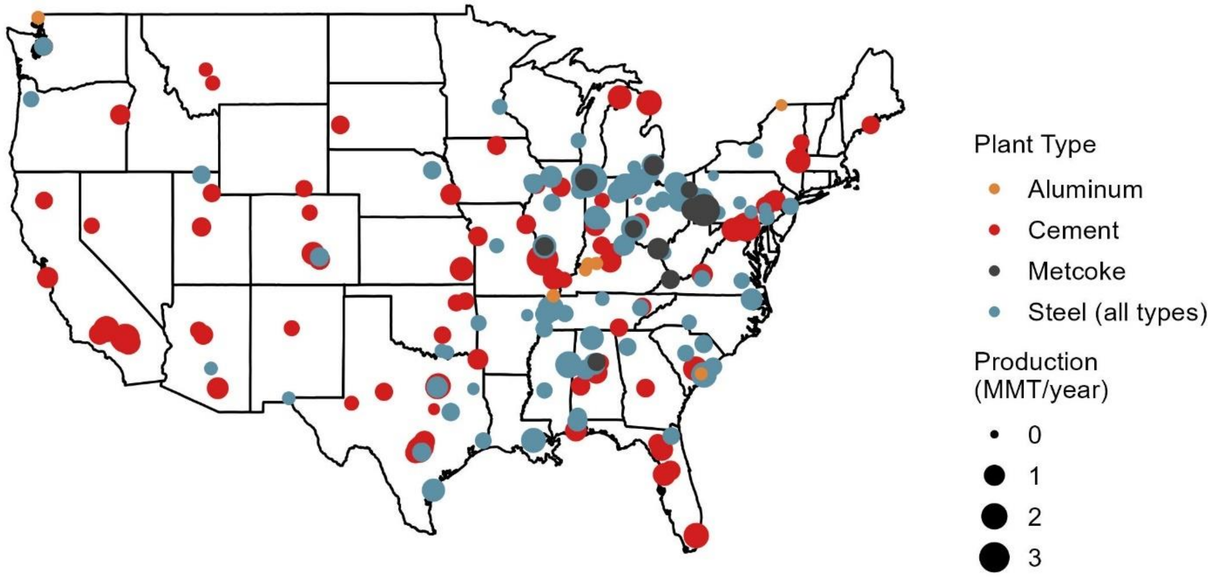
For each of the four industries, we totaled the estimated production from each facility in 2020 and compared it to a known, industry-wide production value sourced from USGS Mineral Commodity Summaries or, in the case of metallurgical coke, from EIA data. Table 5 presents the results of this analysis. Due to top-down methodology for metcoke and aluminum production, which assigned total known production to each facility, the total production in our databases matches the known value perfectly. Because we used a bottom-up approach for the cement and the iron and steel industries, our total industry production is slightly different from the known total in 2020.

Table 5. Difference between known and calculated industrial production

Industry	Known production 2020 (metric tons)	Calculated production 2020 (metric tons)	Percent difference
Iron and steel	72,700,000	76,745,894	5.3%
Metcoke	11,412,215	11,412,215	0.0%
Aluminum	1,012,000	1,012,000	0.0%
Cement	89,000,000	85,540,748	-4.0%

Figure 7 shows a map of the industrial facilities with point size corresponding to production quantity. Although our estimate of total industry production aligns closely with known industry-level data (Table 5), our methodology for estimating facility-level production still represents one of the key uncertainties of this analysis. We accounted for the overall effects of the COVID-19 pandemic on industry-level production using an industry-wide capacity factor but we did not study effects on individual facilities, and information sources may be inaccurate or out of date.

Figure 7. Map of facility-level annual production



4.3. Employment

Since 1979, domestic manufacturing employment has decreased from 22 percent of total (non-farm) U.S. employment to just 9 percent. These decreases are attributable to increases in global competition, population growth, increasing capital intensiveness, and corresponding job growth in service industries.[26] As of June 2019, domestic manufacturing accounted for about 12.8 million jobs in the United States—which was nearly 7 million jobs lower than the peak of 19.5 million in 1979, and roughly 5 million jobs lower than manufacturing employment in 2000.[27]

Manufacturing positions have historically provided middle class wages for individuals with less education.[28] In 1979, one in three men without any college education worked in a manufacturing facility. By 2018, this number had decreased to just one in eight. Over the same period for women, this number decreased from 11 percent to 6 percent.[29] Even when new manufacturing jobs have been created, they have often remained inaccessible to individuals with lower levels of education. Job postings for highly educated roles such as "engineer" have increased, while other more accessible roles have disappeared. For communities with high proportions of manufacturing workers, a decrease in manufacturing roles has

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[26] The professional and business services, education and health services, and leisure and hospitality industries grew from 25 percent of nonfarm employment in 1979 to 41 percent in 2019.

[27] Harris, Katelynn. "Forty years of falling manufacturing employment." U.S. Bureau of Labor Statistics. Available at: https://www.bls.gov/opub/btn/volume-9/forty-years-of-falling-manufacturing-employment.htm.

[28] Bonvillian., William B. "US manufacturing decline and the rise of new production innovation paradigms." Organization for Economic Co-operation and Development (OECD). Available at: https://www.oecd.org/unitedstates/us-manufacturing-decline-and-the-rise-of-new-production-innovation-paradigms.htm.

[29] Kerwin Kofi Charles, Erik Hurst & Mariel Schwartz. 2018. *The Transformation of Manufacturing and the Decline in U.S. Employment*. Available at: https://www.nber.org/system/files/working_papers/w24468/w24468.pdf pp. 63-64.

correlated with higher rates of unemployment, fewer hours worked, and lower wages.[30] Studies have also found correlations between decreased manufacturing employment and negative impacts such as increased opioid usage and overdoses in affected communities; opioid usage has also been attributed to decreased length of employment.[31]

There has recently been a national push to rebuild domestic manufacturing capacity in the United States. The 2021 *Infrastructure Investment and Jobs Act*,[32] and the 2022 *Inflation Reduction Act*[33] both include provisions that bolster domestic manufacturing and support prevailing wages. While these bills are likely to improve employment numbers and wages to some extent, more work is necessary to ensure that newly created positions are accessible to local communities.

The transition to cleaner manufacturing provides an opportunity to build employment pathways for legacy energy workers, environmental justice populations, and other historically excluded groups. Such efforts may include programs to re-train existing skilled energy workers, affordable new educational programs at local institutions (such as community colleges), and other policies and programs that focus on providing high quality jobs with sustaining wages and long-term career pathways.

The employment estimates provided in the database accompanying this study provide a snapshot of facility-level employment. These should be used as a socioeconomic indicator of the impact the facility has on its surrounding community.

Data sources

- U.S. Bureau of Labor Statistics
- U.S. Census Bureau
- Portland Cement Association
- The Congressional Research Service
- BlueGreen Alliance (BGA) industrial facility databases
- Synapse facility-specific research

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[30] Ibid.

[31] Ibid.

[32] Congress.gov. "Text - H.R.3684 - 117th Congress (2021-2022): Infrastructure Investment and Jobs Act." November 15, 2021. Available at: https://www.congress.gov/bill/117th-congress/house-bill/3684/text.

[33] Congress.gov. "Text - H.R.5376 - 117th Congress (2021-2022): Inflation Reduction Act of 2022." August 16, 2022. Available at: https://www.congress.gov/bill/117th-congress/house-bill/5376/text.

Methods

Synapse explored several methods of estimating plant-level employment for the database accompanying this study. Table 6 outlines these methods and discusses the pros and cons of each**.** Our final approach included Methods 3 and 4.

Table 6. Methods considered for estimating employment

#	Method	Pros	Cons
1	Using a jobs modeling tool, such as IMPLAN, to estimate jobs	An industry-standard way of estimating jobs	Models like IMPLAN are not designed to estimate current employment levels
2	Building a model to allocate jobs in each industry, according to NAICS codes, to each plant	Nationally recognized data based on current workforce statistics	Data is not available at a granular enough level to determine plant-level employment
3	Finding plant-level employment via public web sources	Likely the most accurate public data available	Companies do not always disclose the number of employees at a given plant on their website
4	Developing a jobs factor to estimate employment based on estimated annual production	Simple; based on national average data	May not accurately estimate employment at plants with unusually high or low employment

For aluminum and metallurgical coke, we found plant-level data available on each company's website or through other reliable public sources. The relatively small number of plants in both databases made this a feasible approach to gathering employment information.

We selected Method 4 for the cement industry because (A) data were not consistently available on each company's website and (B) feasibility given the number of plants in the industry. For the iron and steel industry, we started with GSPT data, an filled in gaps in the data with Method 4.The first step in both analyses was identifying resources that provided jobs on a per-unit of production basis. This data could then be combined with production data readily available from USGS Mineral Commodity Summaries for each year to estimate facility-level employment. For cement, we selected the 2016 U.S. Cement Industry Annual Yearbook,[34] which provides the metric "Cement Tons Per Employee." We used information from the most recent year, 2014, in our estimations of employment. For steel, we selected a national review of the industry prepared by the Congressional Research Service in 2022.[35] This report explained that steel mills generated about 1,045 tons of steel per employee.[36] We used these per-employee averages to estimate the number of employees at each cement plant and at iron and steel facilities lacking GSPT

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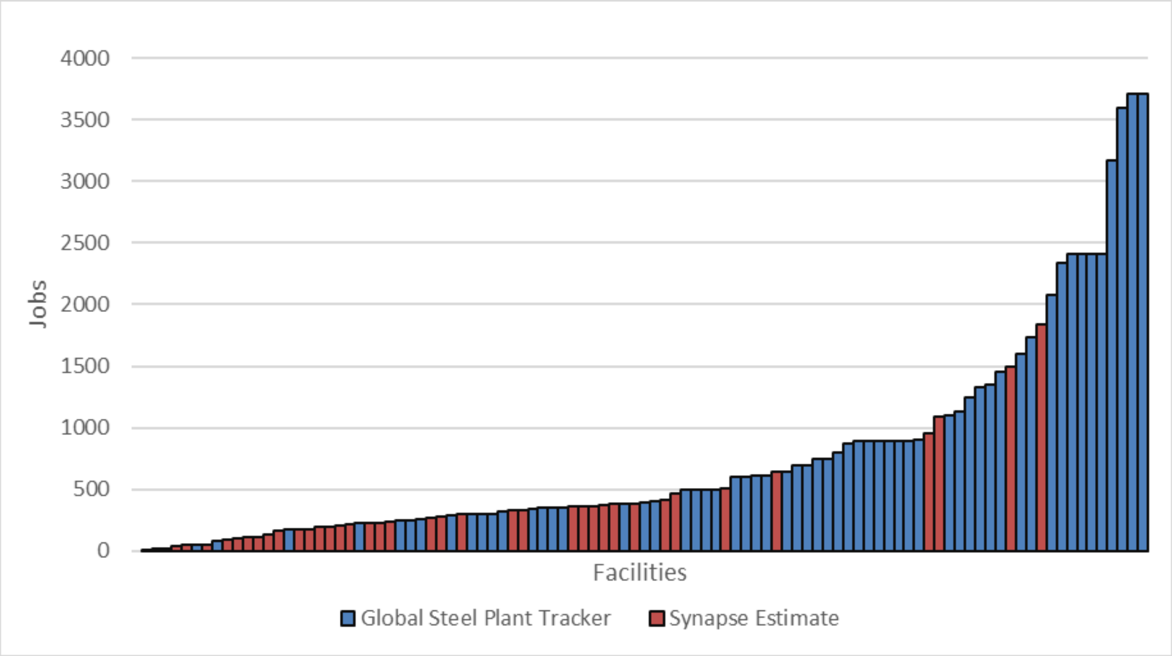
[34] Portland Cement Association. 2016. *2016 U.S. Cement Industry Annual Yearbook.* Available at: http://www2.cement.org/econ/pdf/Yearbook2016_2sided.pdf.

[35] Watson, Christopher D. May 17, 2022. *Domestic Steel Manufacturing: Overview and Prospects.* Prepared by the Congressional Research Service for Members and Committees of Congress. Available at: https://crsreports.congress.gov/product/pdf/R/R47107.

[36] Id, p. 9.

data. As shown in Figure 8, it was necessary to supplement GSPT data primarily for facilities with fewer estimated jobs.

Figure 8. Global Steel Plant Tracker employment and Synapse employment estimates



We benchmarked the accuracy of our estimates against national-level data. More granular data, such as state-level NAICS data or data from industry associations, was either not publicly available or robust enough to benchmark against. In order to confirm our methodology was reasonable, we also conducted web searches for plant-specific employment data on several of the plants to substantiate our estimates. For steel, we also compared our results to the employment data from GSPT and found that for many of the larger facilities, our employment estimation method based on tons of production alone may miss other factors that increase or decrease employment.[37]

Overall, however, our results were very close to the national industry estimates. For steel, we estimated about 74,000 jobs, compared to 78,900 estimated by a 2022 Congressional Report.[38] Similarly, for cement, we estimated 12,200 jobs, compared to 12,800 estimated by the Portland Cement Industry.[39] We recommend that our employment statistics be used as a benchmark, as they do not reflect regional, technological, or other variables that could impact employment.

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[37] We are not aware of a similar resource for cement or metallurgical coke.

[38] Watson, Christopher. *Domestic Steel Manufacturing: Overview and Prospects.* p. 8.

[39] Portland Cement Association. 2016. *2016 U.S. Cement Industry Annual Yearbook.* Available at: http://www2.cement.org/econ/pdf/Yearbook2016_2sided.pdf.

Iron and steel

In total, we estimated about 74,000 jobs for 93 iron and steel plants. We estimate that the median plant employed about 513 employees. On average, mill workers earned an annual wage of $88,325 in 2020,[40] which is about 65 percent greater than the average wage of $53,383 reported by the Social Security Administration in 2020,[41] and higher than the annual average of 76,580 for all manufacturing positions.[42]

Between 1990 and 2021, employment declined 58 percent. The U.S. government projects that this trend will reverse, and projects that employment will increase by about 1 percent between 2020 and 2030. One factor that could positively impact the steel employment is the domestic procurement provisions outlined in the *Infrastructure Investment and Jobs Act*.[43,44] The *Infrastructure Investment and Jobs Act* defines a domestic content procurement preference for iron and steel purchase by the U.S. government, which could lead to greater demand for domestic steel.

Cement

We estimated about 12,200 cement industry employees compared to 12,800 estimated by the Portland Cement Association in 2014.[45] The Portland Cement Association reported that employment had declined by 32 percent since 1991, and about 58 percent since 1980. More recently, the 2021 ACS reported total employment of 14,538 workers, including 11,526 production workers, for the cement manufacturing industry (NAICS Code 327110). The ACS also reported that the average annual wage for cement manufacturing employees is about $74,500,[46] [47] which is 28 percent higher than the average wage of $58,130 reported by the Social Security Administration for 2021,[48] and similar to the annual average of $76,580 for all manufacturing.[49]

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[40] Ibid.

[41] Social Security Administration. "National Average Wage Index." Available at: https://www.ssa.gov/oact/cola/AWI.html.

[42] Watson, Christopher D. October 26, 2022. *U.S. Aluminum Manufacturing: Industry Trends and Sustainability. p. 9.*

[43] Watson, Christopher. *Domestic Steel Manufacturing: Overview and Prospects.* p. 9.

[44] Text - H.R.3684 - 117th Congress (2021-2022): Infrastructure Investment and Jobs Act. (2021, November 15). https://www.congress.gov/bill/117th-congress/house-bill/3684/text.

[45] Portland Cement Association. 2016. *2016 U.S. Cement Industry Annual Yearbook.* Available at: http://www2.cement.org/econ/pdf/Yearbook2016_2sided.pdf.

[46] U.S. Census Bureau. AM1831BASIC01 Annual Survey of Manufactures: Summary Statistics for Industry Groups and Industries in the U.S.: 2018 – 2021. A (Filtered for NAICS code 327110). Available at: https://data.census.gov/table?n=327310.

[47] Calculated as Annual Wages divided by Annual Employment.

[48] Social Security Administration.

[49] Watson, Christopher D. October 26, 2022. *U.S. Aluminum Manufacturing: Industry Trends and Sustainability. p. 9.*

Aluminum

We used data from the Security and Exchange Commission (SEC) Form 10-k to identify employment at primary aluminum facilities in the United States operating in 2020. Where such data were missing for the seven U.S. facilities, we used facility-specific online estimates of total employment.

Overall, the primary aluminum manufacturing facilities in our database represent 4,275 jobs. This estimate is lower than the 2021 estimate of about 6,000 workers from the Congressional Research Service. Similar to the steel and cement industries, the aluminum industry as a whole has also experienced a sharp downturn in employment over the past 20 years. Between 2001 and 2021, employment fell by 38 percent, with the majority of this decline occurring between 2001 and 2008.[50]

Primary aluminum manufacturing roles also represent some of the highest paying roles in the aluminum sector with annual average wages of $84,164. This is approximately 45 percent greater than the average wage of $58,130 and much higher than the annual average of $76,580 for all manufacturing positions.[51]

Metallurgical coke

We used data from the Security and Exchange Commission (SEC) Form 10-k to identify employment at merchant metallurgical coke facilities in the United States operating in 2020. Where such data were missing for the 12 U.S. facilities, we used facility-specific online estimates of total employment.

The metallurgical coke facilities in our database represent an estimated 3,710 jobs. We did not find a national estimate against which to benchmark our results. NAICS code 324199 captures coke oven products (e.g., coke, gases, tars) made in coke oven establishments, but the same code also captures biodiesel fuels and other petroleum products. Overall, this industry accounted for 4,683 jobs in June of 2022.[52] Some steel plants also have their own metallurgical coke facilities which are not captured under this NAICS code.

Results

Table 7 summarizes the total number of jobs in each industry. Cement plants have the lowest median jobs per facility, followed by metallurgical coke plants. Only the aluminum industry has a median jobs per facility value greater than 500 people. The steel industry employs the largest total number of people, and employment per plant varies widely based on the type of steel produced, as Table 8 shows.

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[50] Watson, Christopher D. October 26, 2022. *U.S. Aluminum Manufacturing: Industry Trends and Sustainability*. Prepared by the Congressional Research Service for Members and Committees of Congress, p. 8. Available at: https://crsreports.congress.gov/product/pdf/R/R47294.

[51] Watson, Christopher D. October 26, 2022. *U.S. Aluminum Manufacturing: Industry Trends and Sustainability,* p. 9.

[52] U.S. Bureau of Labor Statistics. "Quarterly Census of Employment and Wages: Employment and Wages Data Viewer. "Available at: https://data.bls.gov/cew/apps/table_maker/v4/table_maker.htm#type=1&year=2022&qtr=2&own=5&ind=324199&supp=0.

Of the 10 plants with employment greater than 2,000 people, six are BOF steel plants and four are EAF facilities. Figure 9 shows a map of the industrial facilities with point size corresponding to employment.

Table 7. Employment by facility type

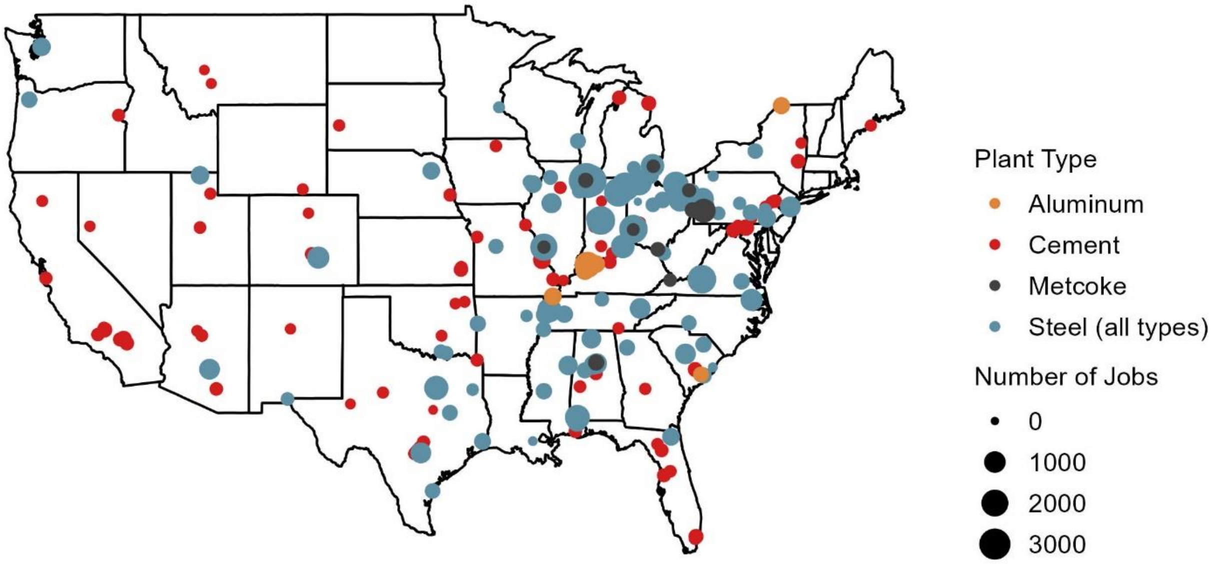
Industry	Number of Facilities*	Number of Jobs	Median Jobs per Facility
Aluminum	6	4,275	520
Cement	90	12,220	115
Metallurgical coke	12	3,710	195
Iron and steel	100	74,353	388

*Note: *Only includes facilities that have jobs data available. One aluminum facility and two cement facilities are omitted.*

Table 8. Employment in the steel industry by facility subtype

Industry	Number of Facilities	Number of Jobs	Median Jobs per Facility
BOF steel products	11	23,360	2,074
EAF hot-rolled flat products	15	11,408	607
EAF hot-rolled long products	62	37,798	378
Other steel	12	1,787	156

Figure 9. Map of facility-level employment



4.4. Greenhouse Gases

Greenhouse gas data provide insight into the most polluting facilities in an industry on an absolute and per-ton-production basis. Data that are disaggregated by industrial process also provide insight into the processes most in need of decarbonization. Our databases include Scope 1 emissions (the emissions produced by a facility itself) and Scope 2 emissions (electrical grid emissions attributable to a facility due to its electricity usage).

Data sources

U.S. EPA's Greenhouse Gas Reporting program (GHGRP)

Methods

Scope 1 emissions for all four industries were compiled from U.S. EPA's Greenhouse Gas Reporting Program (GHGRP), which collects facility-level greenhouse gas emissions data from approximately 8,000 facilities per year.[53] GHGRP data is separated by gas (e.g., CO_2, methane, N_20) and by source—that is, whether it comes from fuel combustion or process emissions (e.g., chemical reactions that yield cement, steel, or aluminum from feedstock material).

We estimate Scope 2 emissions for all four industries using an industry-wide factor for electricity usage per ton of finished product and multiplying that factor by our estimate of facility-level production. This value, in total kilowatt-hours, was then multiplied by a zip-code-specific grid emissions factor from U.S. EPA's Emissions & Generation Resource Integrated Database (eGRID) to estimate a facility-specific estimate of Scope 2 emissions.[54] Note this study considered emissions due to transmission losses to be Scope 3 and did not include them in Scope 2 estimates. Estimating electricity usage on a per-ton basis required a different methodology for each industry, as follows.

Iron and steel

We selected energy-use intensity estimates per ton of steel from BOFs versus EAFs determined in Hasanbeigi et al. (2021).[55] Next, we used 2018 USGS Mineral Commodity Survey data to find total steel production for BOFs and EAFs in 2018. By multiplying the energy intensity by production, we determined the total energy used at BOFs and EAFs. Then, we used an estimate of the percentage of energy used at BOFs and EAFs as electricity from Hasanbeigi (2011), which uses the values of 45 percent at an EAF and 5 percent at a BOF.[56] This yielded a total quantity of electricity used at BOFs and at EAFs in the United States. By dividing by production, we estimated that EAFs use about 750 kWh per metric ton of steel and BOFs use about 306 kWh per metric ton steel.

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[53] U.S. EPA. 2022. "Greenhouse Gas Reporting Program (GHGRP)." Available at: https://www.epa.gov/ghgreporting.

[54] U.S. EPA. 2022. "Emissions & Generation Resource Integrated Database (eGRID)." Available at: https://www.epa.gov/egrid.

[55] BlueGreen Alliance. 2019. *How Clean is the U.S. Steel Industry? An International Benchmarking of Energy and CO_2e Intensities*. Available at: http://www.bluegreenalliance.org/wp-content/uploads/2021/04/HowCleanistheU.S.SteelIndustry.pdf.

[56] Hasanbeigi, A., L. Price, N. Aden, Z. Chunxia, L. Xiuping, and S. Fangqin. *A Comparison of Iron and Steel Production Energy Use and Energy Intensity in China and the U.S. Department of Energy*. Available at: https://www.osti.gov/servlets/purl/1050727.

Metallurgical Coke

Our analysis assumed that metallurgical coke facilities use 4.76 kWh of electricity per metric ton of coke, purchased from the local grid. This value is based on an estimate of 3.5 kWh per short ton of coal processed and an estimated 1.5 short tons of coal processed per short ton of coke produced.[57] Refer to Section 2.2 for an overview of the metallurgical coke production process.

Cement

We used an estimate of total industry electricity usage from EIA's Manufacturing Energy Consumption Survey (MECS) for the most recent year available, 2018.[58] We then divided this value by total known production from the 2018 USGS Mineral Commodity Survey to estimate an electricity usage factor of 132 kWh/metric ton.

Aluminum

We adapted the methodology presented in Hasanbeigi (2022) to develop a bottom-up electricity use intensity.[59] This involved using a variety of literature sources to estimate the kWh/metric ton of primary aluminum production for alumina production, aluminum smelting, anode production, and primary casting.[60,61,62,63] We totaled the electricity use across these four processes. We calculated a final electrical intensity of 16,532 kWh/metric ton, which, in line with the boundaries of our analysis, includes primary casting but excludes bauxite production.

Results

Table 9 presents results for Scope 1 emissions from GHGRP and Synapse's analysis of Scope 2 emissions. Note that in the aluminum industry, one facility produced 5.3 million metric tons of additional Scope 1

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[57] Schobert International LLC. 2015. "Comparative Carbon Footprints of Metallurgical Coke and Anthracite for Blast Furnace and Electric Arc Furnace Use," pg. 70. Prepared for Blaschak Coal Corp. Available at https://www.blaschakanthracite.com/wp-content/uploads/Carbon-Footprint-Archival-Report-v-4-September-20151.pdf.

[58] U.S. EIA. 2021. "Manufacturing Energy Consumption Survey (MECS), 2018 Data." Available at: https://www.eia.gov/consumption/manufacturing/about.php.

[59] Hasanbeigi, A., C. Springer, and D. Shi. 2022. *Aluminum Climate Impact An International Benchmarking of Energy and CO_2e Intensities*. Available at: https://static1.squarespace.com/static/5877e86f9de4bb8bce72105c/t/624d11ab5a37a4341fd85a6e/1649217981897/Aluminum+benchmarking+report-+Feb2022+rev2.pdf.

[60] The Aluminium Association. 2022. "Greenhouse Gas Emissions Intensity- Primary Aluminium." Available at: https://international-aluminium.org/statistics/greenhouse-gas-emissions-intensity-primary-aluminium/.

[61] Tabereaux, A. and R. Peterson. 2013. "Aluminum Production." In Treatise on Process Metallurgy, Volume 3: Industrial Processes. Newnes.

[62] Hasanbeigi, A., C. Springer, and D. Shi. 2022. *Aluminum Climate Impact An International Benchmarking of Energy and CO_2e Intensities*. Available at: https://static1.squarespace.com/static/5877e86f9de4bb8bce72105c/t/624d11ab5a37a4341fd85a6e/1649217981897/Aluminum+benchmarking+report-+Feb2022+rev2.pdf.

[63] World Best Practice (2007) Available at: https://escholarship.org/uc/item/77n9d4sp.
US DOE (2007) Available at: https://www1.eere.energy.gov/manufacturing/resources/aluminum/pdfs/al_theoretical.pdf.

emissions attributable to coal-fired electricity, which was sold to the power market and not used for aluminum production. These Scope 1 emissions—although produced by a facility covered in this report—were not directly related to production output, so are not included in later analysis about production emissions intensity.[64] Note also that Scope 1 cement emissions from GHGRP include biogenic emissions, which comprise less than 1 percent of the total Scope 1 emissions. Due to uncertainty surrounding the source of these biogenic emissions and their carbon neutrality, these emissions are included in this analysis and attributed to facilities' Scope 1 emissions.

Table 9. Scope 1 Emissions and Scope 2 Emissions by Industry (MMT CO_2e)

Industry	Scope 1 emissions	Scope 2 emissions
Iron and Steel	53.4	18.9
Metallurgical Coke	5.0	0.03
Aluminum	3.9	8.4
Cement	66.9	4.4

Table 10 presents our estimated electrical usage factors. The accompanying databases present facility-level Scope 2 emissions. See Section 6 for additional greenhouse gas emissions results.

Table 10. Electrical use factors (kWh/metric ton)

Industry	Facility type	Electrical use factor
Iron and steel	EAF	750
	BOF	306
Cement	All	133
Aluminum	All	16,532

4.5. Criteria Air Pollutants and Hazardous Air Pollutants

The *Clean Air Act* requires U.S. EPA to track and regulate certain pollutants due to their impacts on human health and the environment. One group of these pollutants is the "criteria air pollutants," for which U.S. EPA sets National Ambient Air Quality Standards (NAAQS). These pollutants can cause harm to public health and the environment at certain levels, and U.S. EPA sets science-based criteria for these pollutants based on levels that may cause damage to human health and the environment. The criteria air pollutants include ground-level ozone, particulate matter, carbon monoxide, lead, SO_2, and nitrogen dioxide.[65] The act also requires U.S. EPA to regulate and track the emissions of "hazardous air pollutants"—those that are known to cause cancer and other serious health impacts.[66] Examples of

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[64] These emissions are, however, included and noted in our facility-level databases.

[65] U.S. EPA. 2022. "Criteria Air Pollutants." Available at: https://www.epa.gov/criteria-air-pollutants.

[66] U.S. EPA. 2022. "What are Hazardous Air Pollutants?" Available at: https://www.epa.gov/haps/what-are-hazardous-air-pollutants.

hazardous air pollutants include benzene, acetaldehyde, and chloroform. U.S. EPA tracks and regulates more than 188 individual hazardous air pollutants.[67]

Data sources

- U.S. EPA’s Toxic Releases Inventory (2020)
- U.S. EPA’s National Emissions Inventory (2017)

Methods

We obtained data on criteria air pollutants from U.S. EPA’s National Emissions Inventory from the most recent data year available, 2017. This data was then matched to each industrial facility based upon each facility’s specific GHGRP ID and National Emissions Inventory ID. As the next section will detail, in some instances pollutants tracked in the National Emissions Inventory are also tracked in the annually updated Toxic Releases Inventory. In such instances, we used Toxic Releases Inventory values because they were from a more recent year (2020 compared to 2017). Industrial facilities are required by law to report toxic releases to Toxic Releases Inventory each year. The number and selection of toxic chemicals tracked in each industry vary due to different industrial processes.

Results

Each industry’s facilities have individual values for all six criteria air pollutants, including various sizes of particulate. The data include 100 or more hazardous air pollutants for each industry. The accompanying databases present facility-level criteria air pollutant and hazardous air pollutants emissions by pollutant. Table 11 summarizes the number of toxic chemicals reported across each industry for each medium of release (land, water, and air). We do not sum the quantities of pollution (e.g., lbs. released) in the report due to differences in pollutant toxicity thresholds.

4.6. Air, Land, and Water Pollutants

In addition to tracking criteria air pollutants and hazardous air pollutants, U.S. EPA also collects information on the management of toxic chemicals released on land, into water, and into air through its Toxic Releases Inventory.

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[67] U.S. EPA. 2022. “Initial List of Hazardous Air Pollutants with Modifications.” Available at: https://www.epa.gov/haps/initial-list-hazardous-air-pollutants-modifications.

Data sources

U.S. EPA's Toxic Releases Inventory (2020)

Methods

We collected U.S. EPA's Toxic Releases Inventory data for each of our four industries using industry NAICS codes and then matched to individual facilities in our databases based upon facilities' unique GHGRP and Toxic Releases Inventory identification numbers. Where Toxic Releases Inventory data overlapped with National Emissions Inventory data, we used Toxic Releases Inventory data, which is more recent.

Results

The number and identity of toxic chemicals released by each industry varies, and not every facility in each industry reported the same set of toxic releases. Table 11 summarizes the overall count of individual toxic chemicals reported by industry to TRI. The accompanying databases present facility-level air, land, and water releases by pollutants.

Table 11. Summary of toxic chemical releases by industry

Industry	Number Toxic Chemicals Reported as Released on Land	Number Toxic Chemicals Reported as Released into Water	Number Toxic Chemicals Reported as Released into Air	Total[1]
Iron and steel	39	51	77	81
Metallurgical coke	-	28	40	46
Aluminum	17	21	42	42
Cement	26	17	139	140

[1]Note: the total number of pollutants reported for each industry is not equal to the sum of the number of chemicals reported by each medium of release because many chemicals are released across multiple media.

4.7. Equity: Environmental and Socioeconomic Indicators

Industrial facilities often contribute to environmental, socioeconomic, and health inequities because these sites are concentrated in urban areas with disadvantaged communities and disproportionately high pollution levels from industry, heavy transport, and on-site combustion of fossil fuels.[68] Industrial facilities are sited in low-income and racial minority communities with greater frequency than in white

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[68] Bell, Michelle L., & Ebisu, Keita. 2012. "Environmental Inequality in Exposures to Airborne Particulate Matter Components in the United States." *Environmental Health Perspectives*, *120*(12), 1669–1704. Available at: https://ehp.niehs.nih.gov/1205201/.

communities, in part due to neglect by policymakers.[69,70] Such polluting facilities also contribute to lower property values, which, coupled with racial discrimination, diminishes the social and economic mobility of disadvantaged households; this, in turn, can drive households to reside and remain near such facilities.[71]

Adverse air quality, such as resulting from industrial pollution, can create severe health problems in fence-line communities.[72] Some industrial decarbonization strategies can reduce releases of co-pollutants and thereby improve the health and vitality of communities that have borne the brunt of industrial facilities' pollution, but additional work is needed to understand the existing adverse impacts and quantify the potential benefits from pollution reduction.[73,74] This report advances the understanding of the environmental, health, and socioeconomic impacts of industrial facilities by presenting quantitative data on facility-level emissions of greenhouse gases, criteria air pollutants, hazardous air pollutants, and other hazardous pollutants (Sections 4.4, 4.5, and 4.6 above) as well as environmental justice indicators for the fence-line communities, presented below.

Workers in industrial facilities are also exposed to hazardous pollutants, but do not always live in fence-line or downwind communities. The analysis in this section does not capture the health impacts on workers, and thus misses the full breadth of people harmed by status quo production. Future work should seek to quantify worker exposure.

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[69] Mohai, P. and Saha, R., 2015. Which came first, people or pollution? A review of theory and evidence from longitudinal environmental justice studies. *Environmental Research Letters, 10*(12), p.125011. Available at: https://iopscience.iop.org/article/10.1088/1748-9326/10/11/115008/pdf.

[70] Paul, I., Pries, C., and Sarinsky, M. 2021. *Improving Environmental Justice Analysis: Executive Order 12,898 and Climate Change*. Institute for Policy Integrity. Available at: https://policyintegrity.org/publications/detail/improving-environmental-justice-analysis.

[71] Bullard, R.D., 1993. Race and environmental justice in the United States. *Yale J. Int'l L.*, *18*, p.319. Available at: https://openyls.law.yale.edu/bitstream/handle/20.500.13051/6282/16_18YaleJIntlL319_1993_.pdf.

[72] Nadeau, Kari, McDonald-Hyman, Cameron, Noth, Elizabeth M., Pratt, Boriana, Hammond, S. Katharine, Balmes, John, & Tager, Ira. 2010. "Ambient air pollution impairs regulatory T-cell function in asthma." *Journal of Allergy and Clinical Immunology*. Volume 126, Issue 4, Pages 845-852.e10. ISSN 0091-6749, http://dx.doi.org/10.1016/j.jaci.2010.08.008.

[73] Deason, J., Wei, M., Leventis, G., Smith, S., Schwartz, L. 2018. *Electrification of buildings and industry in the United States: Drivers, barriers, prospects, and policy approaches*. Lawrence Berkeley National Laboratory. Available at: https://eta-publications.lbl.gov/sites/default/files/electrification_of__buildings_and_industry_final_0.pdf.

[74] Hasanbeigi, A., Kirshbaum, L.A., Collison, B. and Gardiner, D. 2021. "Electrifying US Industry: A Technology and Process-Based Approach to Decarbonization." *Renewable Thermal Collaborative*.

Data sources

Synapse compiled environmental and socioeconomic indicator data from various federal agencies. Table 12 summarizes publicly available data sources from federal agencies used for this report.

Table 12. Data sources for environmental justice indicators

Indicator Type	Indicator	Source
Socioeconomic	Native American tribes and native Alaskan villages within 25 miles of the facility	U.S. EPA: Enforcement and Compliance History Online (ECHO)
	Percent people of color	U.S. Census Bureau: American Community Survey
	Percent low income	
	Percent less than high school education	
	Percent linguistically isolated	
	Percent under age 5	
	Percent over age 64	
	Unemployment rate	
	Demographic index	U.S. EPA: Environmental Justice Screening and Mapping Tool (EJScreen)
Pollution and Sources	Facility is in a non-attainment area	U.S. EPA: Enforcement and Compliance History Online (ECHO)
	Environmental enforcement and compliance history	
	Lead paint (% pre-1960s housing)	U.S. Census Bureau: American Community Survey
	Diesel particulate matter (ug/m3)	U.S. EPA: Hazardous Air Pollutants
	Air toxics cancer risk (risk per mm)	
	Air toxics respiratory hazard index	
	Traffic proximity (daily traffic count/distance to road)	U.S. DOT traffic data
	Wastewater discharge (toxicity-weighted concentration/m distance)	U.S. EPA: Risk-Screening Environmental Indicators (RSEI)
	Superfund proximity (site count/km distance)	U.S. EPA: Comprehensive Environmental Response, Compensation, and Liability Information System (CERCLIS) database
	Risk management Plan facility proximity (facility count/km distance)	U.S. EPA: Risk Management Plan (RMP) database
	Hazardous waste proximity (facility count/km distance)	U.S. EPA: Resource Conservation and Recovery Act Information (RCRAInfo) database
	Ozone (ppb)	U.S. EPA: Office of Air and Radiation (OAR) monitoring and modeling data
	Particulate matter 2.5 (ug/m3)	
	Underground storage tanks (facilities/sq km area)	U.S. EPA: Underground Storage Tank (UST) Finder

Methods

Synapse used tools available from the U.S. EPA to collect and compile relevant environmental justice indicator data for each plant and compare the plant-specific indicators to indicators for other geographic areas (state, regional, and national). Those tools include the Environmental Justice Screening and Mapping Tool (EJScreen) and Enforcement and Compliance History Online (ECHO).

Synapse used EJScreen to characterize the affected fence-line communities that fall within a geographic buffer zone that is centered around each facility. We selected a circular buffer radius that approximates the way pollutants disperse from a facility—for example, carried in plumes by wind or groundwater or transported by surface water. Synapse selected a 3-mile buffer based on prior analysis and recommendations of the National Association for the Advancement of Colored People (NAACP) and U.S. EPA in prior work.[75,76]

Results

The resulting socioeconomic and environmental indicators are available in the master databases and in the web-based data visualization tool. Figure 10 provides an example of these results—the percentage of the population that is low-income population in the community that falls within a 3-mile radius of each industrial facility. Figure 11 through Figure 16 show the results for additional metrics, with remaining results presented in Appendix B, the accompanying databases, and the interactive webtool. We summarize key findings below:

All indicators

1. **Metallurgical coke, steel, and iron communities are disadvantaged.** With few exceptions, the communities surrounding coke, steel, and iron facilities had worse environmental justice indicators than communities around cement and aluminum facilities and than the United States on average.
2. **Communities near steel plants that use basic oxygen furnaces are particularly disadvantaged.** On nearly every metric, BOF steel product plants had worse environmental justice indicators than EAF steel plants and than the other industries in the United States on average.
3. **Socioeconomic and environmental indicators vary widely on a facility-by-facility basis.** While there are environmental justice trends by facility type (discussed below), within each facility type some fence-line communities are considerably more disadvantaged than others. The worst facilities of each type have socioeconomic disadvantage 7.8 times higher, on median, than the best facilities of the same type. Pollution

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[75] Wilson, P., Adrian, J., Wasserman, K., Starbuck, A., Sartor, A., Hatcher, J., Fleming, J. and Fink, K. 2012. *Coal blooded: Putting profits before people*. NAACP. Available at: https://naacp.org/resources/coal-blooded-putting-profits-people.

[76] U.S. EPA. 2022. *EJScreen Technical Documentation*. Available at: https://www.epa.gov/sites/default/files/2021-04/documents/ejscreen_technical_document.pdf.

concentrations and health hazard indices are 2.5 higher at the worst facilities of each type, on median, than at the best facilities of the same type.

4. **Data quality declines with proximity to industrial facilities.** Data coverage is poor in areas less than 1 mile from each plant, with 11.1 percent of indicators missing on average. This is likely due to a combination of sparse population and fewer pollution monitoring facilities. At 3.0 miles and 5.0 miles, 1.1 percent and 0.2 percent of data are missing, respectively.

Socioeconomic indicators

1. **Socioeconomic disadvantage increases with proximity to industrial facilities.** The communities living 1.0 miles from the facilities we are studying are most likely to be socioeconomically disadvantaged. The rate of disadvantaged persons changes slowly with distance from the facility: –0.24 percent per mile, on average across the eight demographic indicators studied.
2. **High unemployment near iron, steel, and coke facilities.** Iron, steel, and metallurgical coke plants are located in communities with 6.6 percent and 8.3 percent unemployment rate, as compared to a national average of 5.0 percent (Figure 11). Unemployment rates are particularly high near BOF steel plants (10.5 percent). Rates near cement and aluminum facilities are consistent with the national average.
3. **Low educational attainment near iron, steel, and coke facilities.** Compared to a national average of 12.0 percent, iron, steel, and coke facilities have 13.5 percent and 16.4 percent of adults over age 25 with less than a high school education (Figure 12). Again, the percentage of adults with less than a high school education is particularly high near BOF steel plants (19.5 percent). Aluminum facilities, at 8.3 percent, are better than the national average.
4. **Greater population density near iron, steel, and coke facilities.** Iron, steel, and metallurgical coke plants are located in comparatively densely populated communities: 1,061 and 1,024 people per square mile, respectively. The communities around aluminum and cement facilities are less densely populated: 292 and 526 people per square mile, respectively. Note, these population densities are relatively low, compared to the average U.S. urban density of 2,545 people per square mile;[77] the large land area of the facilities may contribute to this lower density, as few people typically live onsite.
5. **Fewer minorities near industrial facilities.** Compared to a national population that is 40.0 percent people of color, the communities surrounding these industrial facilities have fewer minorities: 31.5 percent of the population, on average. BOF steel plants are the exception, with nearby populations that are 60.1 percent people of color. Metallurgical coke fence-line communities are close to the national average at 40.5 percent people of color (Figure 13). For additional context, see the discussion of the U.S.

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[77] U.S. Census Bureau. 2023. “Urban and Rural.” Available at: https://www.census.gov/programs-surveys/geography/guidance/geo-areas/urban-rural.html.

Census definition of minorities, which omits some races and ethnicities and is, therefore, an imperfect indicator.

6. **Low linguistic isolation near industrial facilities.** Fence-line communities have half the rate of people living in limited English-speaking households as compared to the United States as a whole: 2.5 percent versus 5.0 percent (Figure 14). Linguistic isolation surrounding BOF steel plants is close to the national average at 4.8 percent.

7. **Typical proportion of young children and elderly persons.** The rates of people under the age of 5 and over the age of 65 is virtually indistinguishable from the national average and varies little across the four types of industrial facilities.

Environmental indicators

1. **Environmental quality declines with proximity to industrial facilities.** Across 9 of the 12 indicators we study, environmental indicators worsen as distance from the facility decreases. The exceptions to this are traffic proximity, ozone concentration, and proximity to underground storage tanks.

2. **High lead-based paint risk near iron, steel, and coke facilities.** Iron, steel, and metallurgical coke plants are located in communities with 39.5 percent and 56.4 percent of housing stock built prior to 1960. The national average is 28 percent. Rates near cement and aluminum facilities are consistent with the national average.

3. **Poor air quality near metallurgical coke facilities and BOF steel facilities.** The national average concentration of $PM_{2.5}$ is 8.74 micrograms per cubic meter, compared to 9.25 micrograms per cubic meter near coke facilities and 9.92 micrograms per cubic meter near BOF steel plants (Figure 15). The air toxics cancer risk is 29.0 per million lifetimes on average in the Unites States as a whole, compared to 43.4 per million lifetimes near coke facilities and 35.7 per million lifetimes near BOF steel facilities (Figure 16). BOF steel facilities also have higher than average diesel particulate exposure (see Appendix A, Additional Environmental Justice Metrics).

4. **Average air quality near non-BOF iron, steel, aluminum, and cement facilities.** On average, fence-line communities for these three facility types have comparable air quality to the United States average for air toxics cancer risk, air toxics respiratory hazard, ozone, and particulate matter. On average at these facility types, diesel particulate matter is lower than the national average (15 percent lower for steel and iron, 44 percent lower for aluminum, and 43 percent lower for cement).

5. **Metallurgical coke communities have high proximity to sites of concern.** Fence-line communities for metallurgical coke are more likely to be located near superfund sites (proximity is 95 percent greater), Risk Management Program facilities (160 percent greater), hazardous waste facilities (30 percent greater), and underground storage tanks (49 percent greater) compared to the United States on average.

Figure 10. Low-income population in the 3-mile radius of industrial facilities

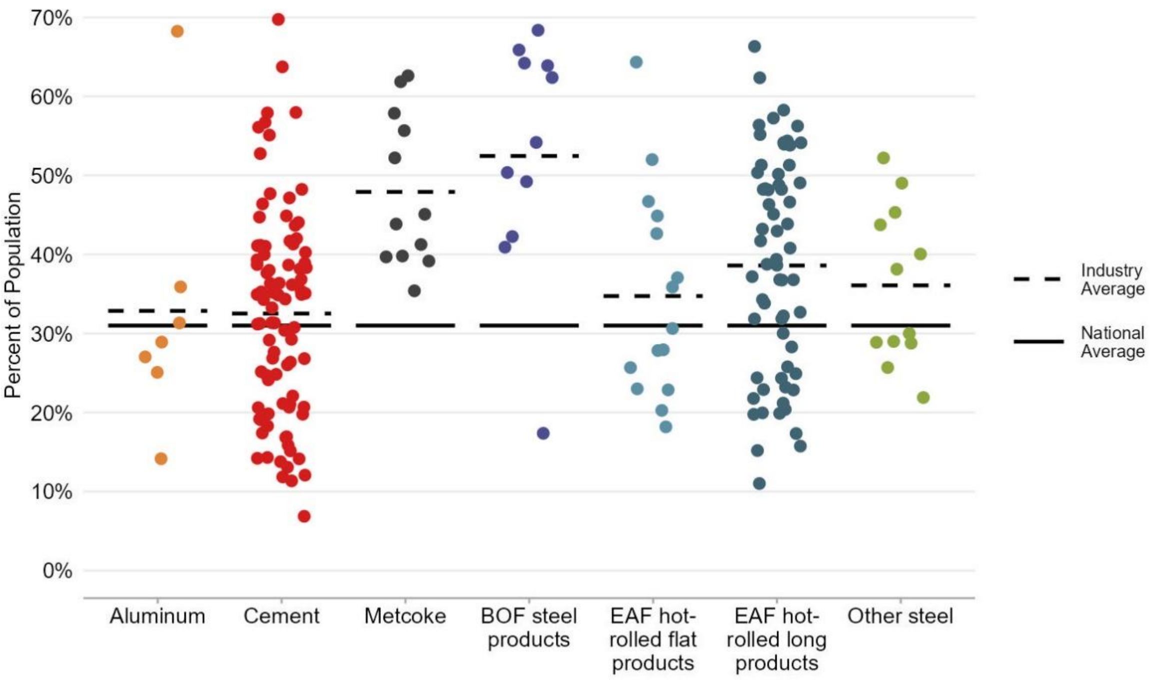


Figure 11. Unemployment rates in the 3-mile radius of industrial facilities

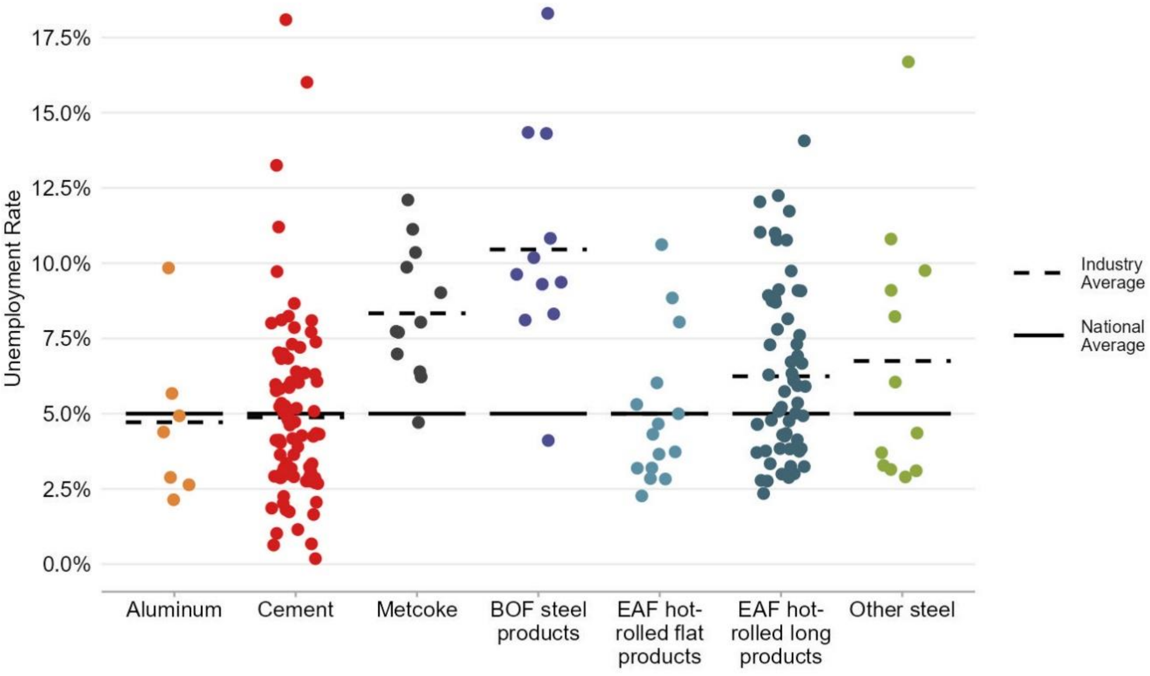


Figure 12. Educational attainment in the 3-mile radius of industrial facilities

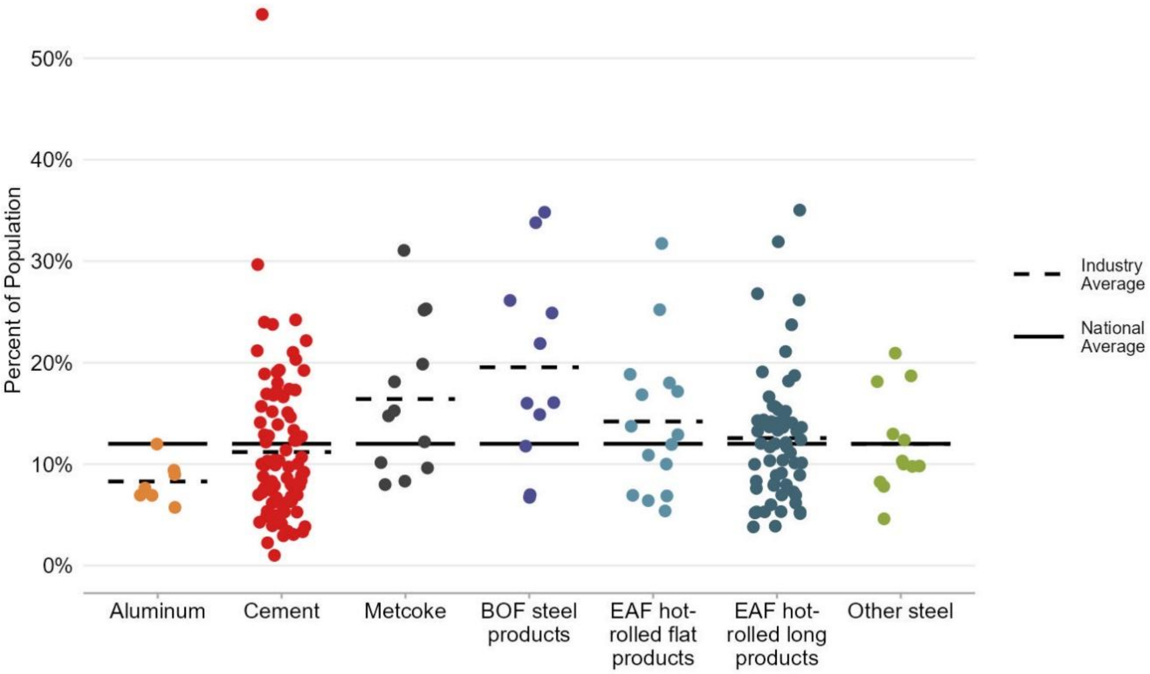


Figure 13. Minority populations in the 3-mile radius of industrial facilities

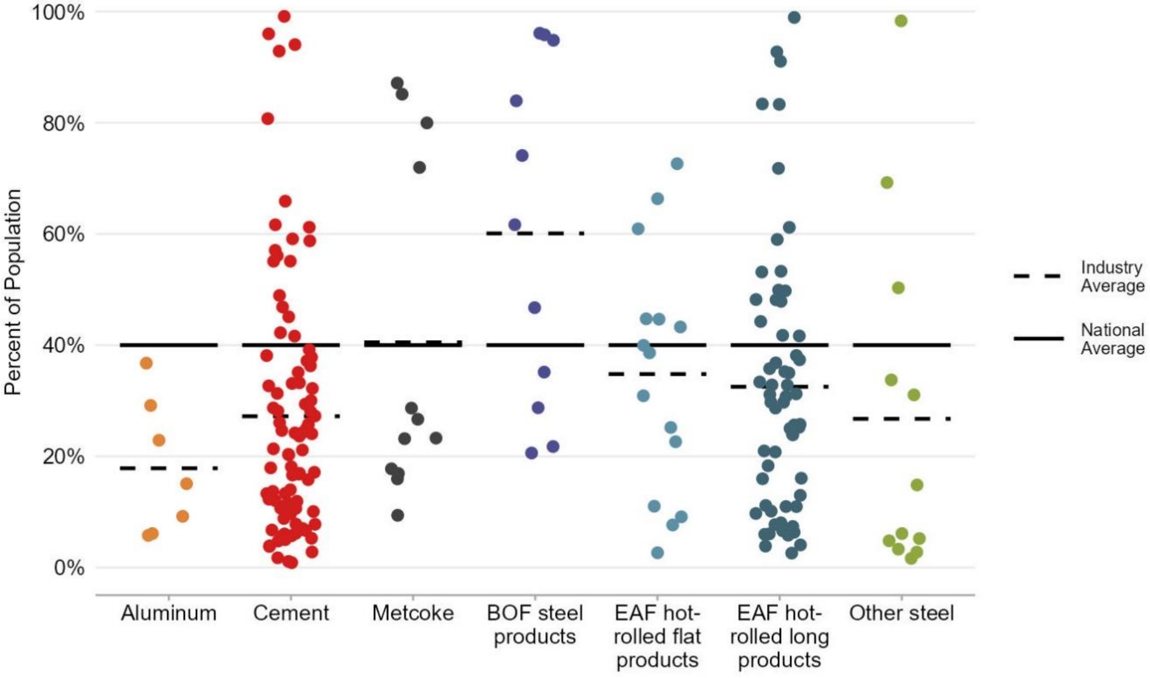


Figure 14. Linguistic isolation in the 3-mile radius of industrial facilities

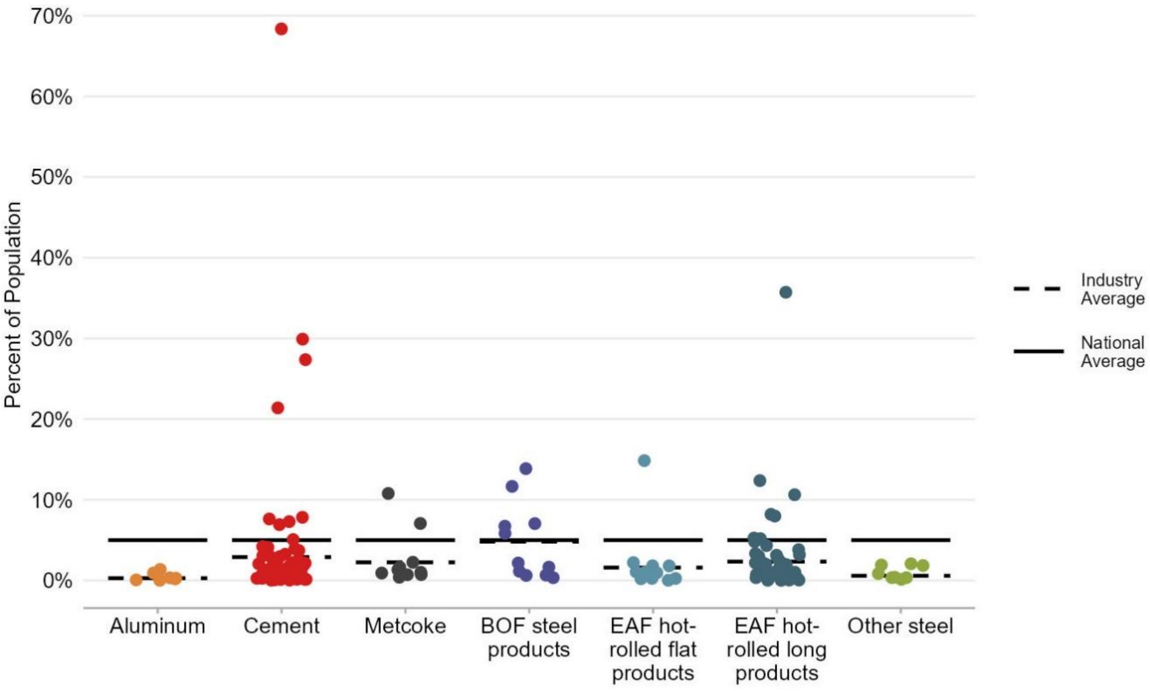


Figure 15. Fine particulate exposure in the 3-mile radius of industrial facilities

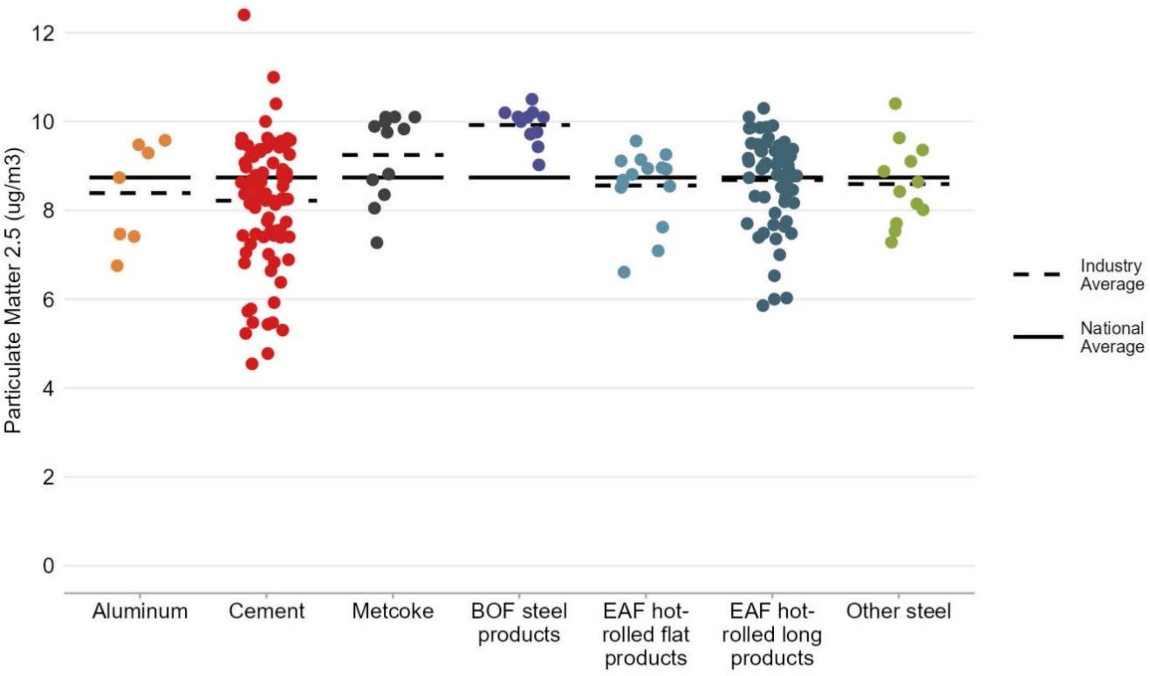
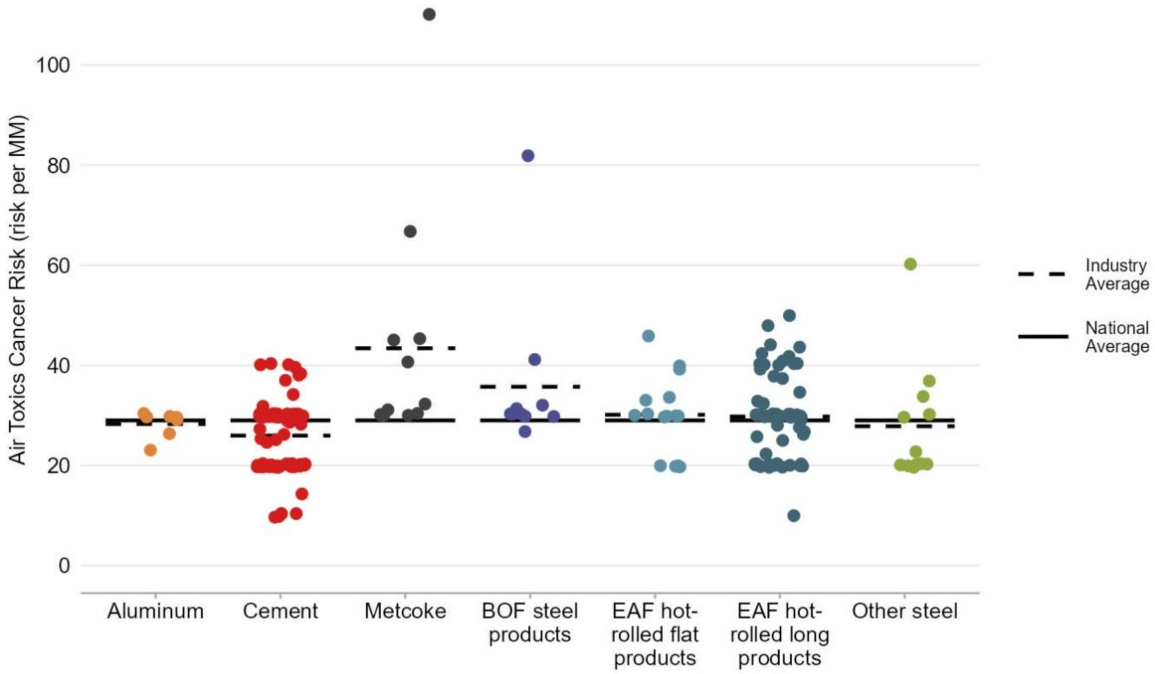


Figure 16. Air toxics cancer risk in the 3-mile radius of industrial facilities



Synapse also conducted a sensitivity analysis to characterize the differences in environmental justice indicators at various buffer distances from each facility. We varied the buffer distance from 1.0 miles to 5.0 miles in half-mile increments. See Appendix B for the sensitivity analysis results.

Limitations

There are several limitations to the underlying environmental justice data we present. Foremost among these issues is missing data. A recent analysis by the Environmental Data & Governance Initiative shows that data coverage is poor—even missing the most basic information—for facilities regulated under foundational environmental protection laws.[78] The analysis finds that the data to conduct basic environmental justice assessments, such as the percent minority population surrounding a facility or regulatory compliance information is missing in many of U.S. EPA's public records. Further, the study finds that facilities in communities where most inhabitants are minorities have worse data quality than facilities in majority-white communities.

In addition to missing data, there is also substantial uncertainty in the quantities of emissions reported by individual facilities. For a detailed review of this issue, see Section 7 on Uncertainty.

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[78] EDGI. 2022. *How Gaps and Disparities in EPA Data Undermine Climate and Environmental Justice Screening Tools.* Available at: https://envirodatagov.org/publication/how-gaps-and-disparities-in-epa-data-undermine-climate-and-environmental-justice-screening-tools/.

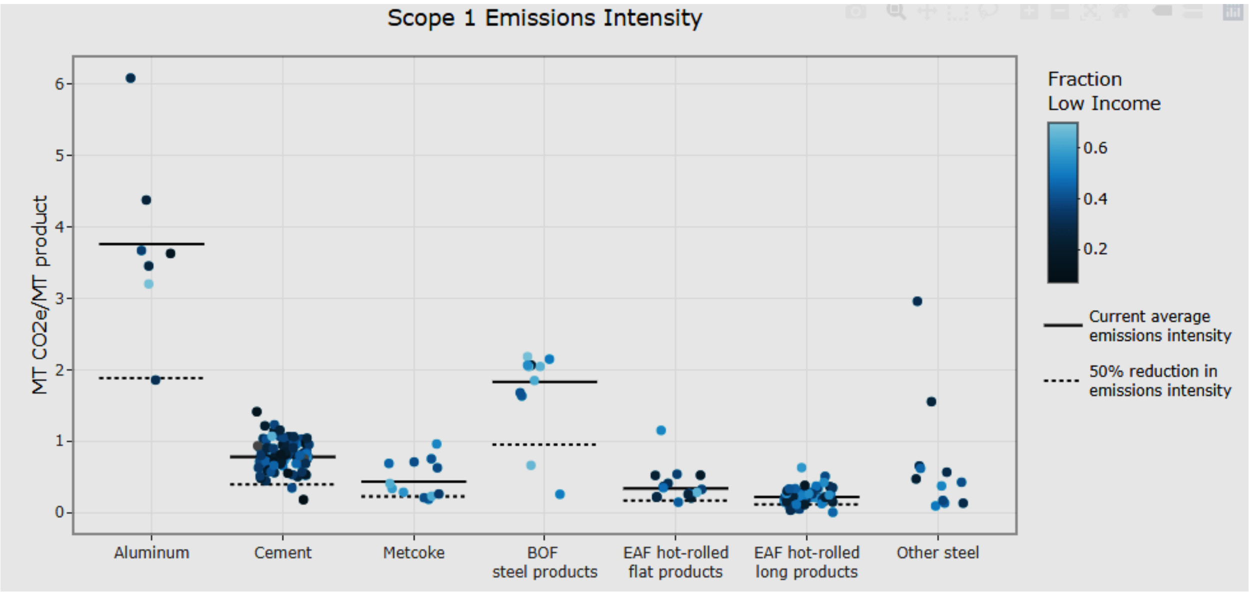
U.S. Census data has limitations to characterizing the racial or ethnic composition of a community that can conceal adverse impacts on minorities. For example, the census definition for race considers people of Middle Eastern and North African descent to be white.[79] This can hide important environmental justice communities that have been adversely impacted by industrial facilities. An example of this is the large Arab and Arab-American community in Dearborn, Michigan, which has experienced adverse impacts of local steel production.[80]

Finally, our work highlights correlations between a community's proximity to an industrial facility and environmental justice concerns. Further work is needed to identify whether the industrial facilities are a root cause of these environmental justice concerns.

4.8. Interactive Webtool

Synapse created an interactive webtool with data visualizations that allows users to explore the facility-level dataset. Hover-over features allow users to view details about each facility. Dropdown menus and data tabs allow the user to explore a range of facility-level metrics. Figure 17 provides an example of the interactive figures, specifically a tool to study plant-level emissions and environmental justice indicator data. The tool includes a map of all plants, shown in Figure 18, with navigation features. The webtool is hosted by Sierra Club and can be accessed at: https://www.sierraclub.org/trade/climate-jobs-american-industries.

Figure 17. Static view of interactive figures



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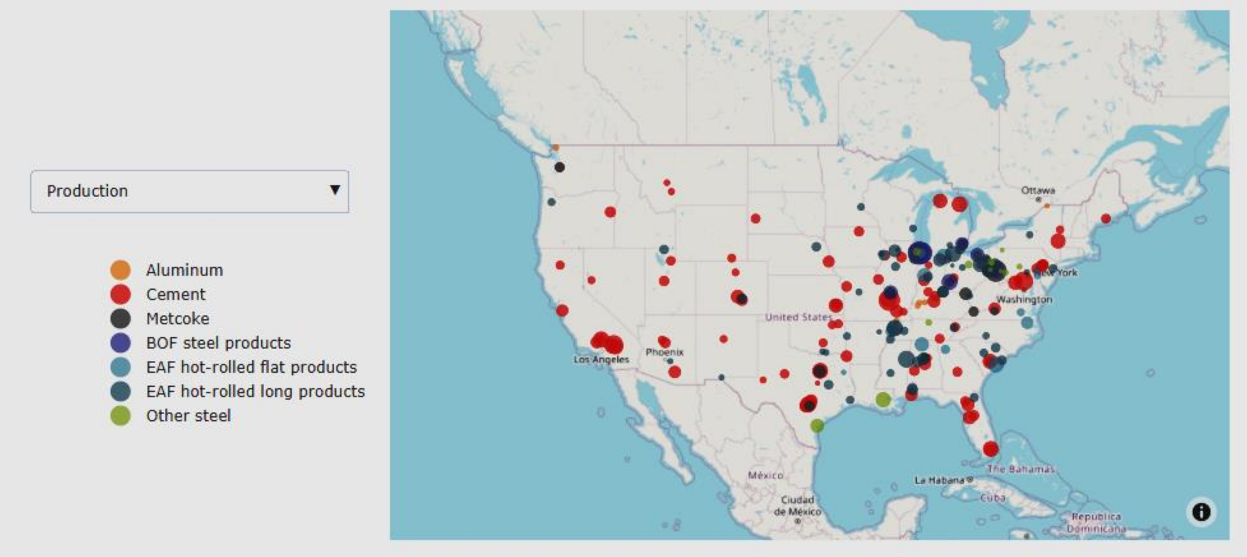
[79] U.S. Census Bureau. 2022. "About the Topic of Race." Accessed September 2, 2022. Available at: https://www.census.gov/topics/population/race/about.html.

[80] Arab American Community Center for Economic and Social Services. 1996. *Environmental Justice Case Study: The Dearborn, Michigan Arab American Community and Industrial Air Pollution*. Accessed September, 2, 2022. Available at: http://websites.umich.edu/~snre492/berry.html.

Note: Within the web page, users can hover over a point to view details about the plant. The color scale shows the percentage of the population within a 3-mile buffer around each facility who are low-income. The webtool includes similar figures for the other environmental justice indicators.

Figure 18. Static view of interactive map



Note: Within the web page, users can hover over a point to view details about the plant. The dropdown menu allows users to change the variable that determines point size.

5. HEALTH IMPACTS ANALYSIS

Many pollutants released by industrial facilities have adverse effects on human health. Air pollution exposure is associated with oxidative stress and inflammation in human cells, which, according to the National Institute of Environmental Health Sciences (NIEHS), might lead to chronic diseases and cancer. NIEHS also links air pollution to cardiovascular disease; respiratory diseases; diabetes; obesity; and reproductive, neurological, and immune system disorders.[81] Similarly, releases of industrial pollutants into water negatively impact the health of local communities. Toxins that contaminate drinking water supplies can lead to both acute and chronic health issues.[82] The release of industrial pollutants onto land also adversely impacts human health, as pollutants can leach into soil and groundwater, contaminating food and drinking water, among other impacts.[83]

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[81] National Institute of Environmental Health Sciences. 2023. "Air Pollution and Your Health." Available at: https://www.niehs.nih.gov/health/topics/agents/air-pollution/index.cfm.

[82] Natural Resources Defense Council (NRDC). 2023. "Water Pollution: Everything You Need to Know." Available at: https://www.nrdc.org/stories/water-pollution-everything-you-need-know.

[83] European Environment Agency. 2022. "Land and soil pollution — widespread, harmful and growing." Available at: https://www.eea.europa.eu/signals/signals-2020/articles/land-and-soil-pollution.

To understand the impact that the facilities in our dataset have on the health of surrounding communities, we conducted a health impacts analysis that assessed the potential health benefits that would occur if facilities completely stopped emitting primary $PM_{2.5}$ (emitted directly into the air) and precursors of secondary $PM_{2.5}$ (particles that lead to formation of $PM_{2.5}$ once in the atmosphere). These tiny inhalable particles pose the greatest risk to health of all types of particulate matter, with impacts ranging from respiratory and cardiac dysfunction and disease to premature death and increased mortality.[84] We chose to focus on these pollutants because of the availability of robust modeling tools that we could use to assess the health impacts of primary and secondary $PM_{2.5}$. While these facilities also emit many other pollutants and toxins that can harm health and the environment, we were not able to systematically assess these other health impacts in the scope of this analysis due to data limitations. More research is needed to understand the complex relationship between other pollutants and human health.

We conducted this analysis to help understand the range of possible benefits that could occur if facilities began to operate in a cleaner manner. The relationship between PM2.5 emissions and GHG emissions is complex, and this work did not seek to quantify specific reductions associated with adoption of a Buy Clean policy. These results represent the maximum potential health benefits from air quality improvements that could be expected if all facilities were to completely stop emitting $PM_{2.5}$ and its precursors. However, as discussed above, our health impacts analysis does not assess potential benefits from reductions in other air pollutants or any land or water pollutants due to limitations in modeling capabilities. Because of this, additional health benefits beyond those calculated below are possible from reductions in other types of pollutants in industrial processes.

5.1. Methods

To conduct our health impacts analysis, we used U.S. EPA's CO-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA). COBRA is a screening tool that allows users to estimate the air quality and health benefits of different emissions scenarios. COBRA users input changes in emissions of $PM_{2.5}$ and precursors of secondary $PM_{2.5}$, including SO_2, NO_X, ammonia, and VOCs. COBRA uses these changes in emissions compared to the model defined baseline and conducts air quality modeling to estimate changes in total annual ambient concentrations of $PM_{2.5}$. The air quality modeling includes atmospheric dispersion modeling to estimate how changes in one area affect $PM_{2.5}$ concentrations across the continental United States. COBRA then applies health impact functions to the changes in outdoor air quality to assess changes in the incidence of health outcomes, including premature mortality, heart attacks, asthma exacerbation, and lost workdays. Users can refine COBRA to a particular

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[84] U.S. EPA. 2022. "Health and Environmental Effects of Particulate Matter (PM)" Available at: https://www.epa.gov/pm-pollution/health-and-environmental-effects-particulate-matter-pm.

set of counties where initial emissions changes will occur and particular industries from which the changes will occur.[85]

To calculate the maximum potential health benefits from air quality improvements that could be expected if all facilities were to completely stop emitting $PM_{2.5}$ and its precursors, we created scenarios to run through COBRA for each of our four industries. For each industry, we calculated the total emissions volume of $PM_{2.5}$, SO_2, NO_X, ammonia, and VOCs in our database, using National Emissions Inventory and Toxic Releases Inventory data. We then allocate emissions as either industrial process emissions or combustion emissions. This differentiation improves the precision of the analysis because the COBRA model apportions emission reductions geographically according to county-level baseline emissions by source. Baseline data and model outputs are calibrated to county-level emissions monitoring data. This geographic apportionment is important due to the differences in county-level population density and pollution dispersion. For iron, steel, and cement facilities, we allocated emissions based on the percent of greenhouse gas emissions for each sector that were process or combustion emissions, according to GHGRP data. For example, 34 percent of greenhouse gas emissions reported to GHGRP for the iron and steel facilities in our dataset were process emissions, and 66 percent were combustion emissions. As a result, we assumed that 34 percent of the emissions of $PM_{2.5}$ and its precursors were from industrial processes and 66 percent were from combustion.

For aluminum facilities, we followed a similar methodology, except we excluded greenhouse gas emissions from power generation at the Alcoa Inc - Warrick Operations facility in Newburgh, IN as well as emissions from industrial waste landfills at the Alcoa Intalco Works facility in Ferndale, WA. Because we are not able to calculate air pollution from offsite generation or offsite waste disposal for facilities without this onsite capability, we excluded these onsite emissions to be consistent with the boundaries of this analysis. For metallurgical coke facilities, we assumed we could allocate all air pollutant emissions to combustion because metallurgical coke production is a high-temperature, combustion-heavy process.[86] Table 13 shows the volume of each pollutant allocated as combustion or process emissions for each sector.

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[85] U.S. EPA. 2021. *User's Manual for the Co-Benefits Risk Assessment Health Impacts Screening and Mapping Tool (COBRA)*. Available at: https://www.epa.gov/system/files/documents/2021-11/cobra-user-manual-nov-2021_4.1_0.pdf.

[86] See Section 2.2 for more information on the metallurgical coke production process.

Table 13. Allocation of emissions between industrial processes and combustion for each industrial sector

Pollutant	**Total Emissions (US tons)**						
	Iron and Steel		Aluminum		Cement		Metallurgical Coke
	Process	*Combustion*	*Process*	*Combustion*	*Process*	*Combustion*	*Combustion*
$PM_{2.5}$	4,156	8,111	1,115	72	6,345	140	2,582
SO_2	9,820	19,165	12,661	850	18,030	398	16,986
NO_X	10,681	20,846	549	42	68,925	1,520	8,992
Ammonia	93	182	0	0	1,355	30	151
VOCs	1,841	3,593	541	54	4,101	90	824

For each industry, we ran one COBRA scenario in the COBRA Web Edition tool for process emissions (except for metallurgical coke) and one for combustion emissions, selecting every county with a facility in it for the location of emissions reductions. For all industries, we used the COBRA sector “Fuel Combustion: Industrial” for the combustion scenarios. For iron and steel process emissions, we used the COBRA sector “Ferrous Metals Processing.” For cement process emissions, we used the COBRA sector “Mineral Products.” For aluminum process emissions, we used the COBRA sector “Metals Processing.”

5.2. Results

Table 14 shows the total potential reductions in annual incidence of each health endpoint measured by COBRA. Overall, eliminating the emissions of $PM_{2.5}$ and its precursors from production of iron, steel, cement, aluminum, and metallurgical coke could lead to 1,250–2,830 avoided deaths annually. It could also drastically reduce the incidence of respiratory and cardiac events, including those that lead to hospitalization. Modeling estimated 610 hospital admissions could be avoided annually for respiratory and cardiovascular illness, and 620 visits to the emergency room for asthma could be avoided. Beyond the health benefits of avoided illness, this would save money on costly medical bills for those affected and could keep people from missing work. An estimated 140,840 lost workdays could be avoided by eliminating these emissions.

Table 14. Summary of reductions in incidence of health endpoints for all industries

Health Endpoint	Change in Incidence (cases, annual)	
	Low	High
Mortality	1,253	2,835
Nonfatal Heart Attacks	133	1,230
Infant Mortality	7	
Hospital Admits, All Respiratory	304	
Hospital Admits, Cardiovascular (except heart attacks)	310	
Acute Bronchitis	1,548	
Upper Respiratory Symptoms	28,042	
Lower Respiratory Symptoms	19,689	
Emergency Room Visits, Asthma	624	
Asthma Exacerbation	29,171	
Minor Restricted Activity Days	832,368	
Work Loss Days	140,845	

Table 15 shows the potential reductions in annual incidence of each health endpoint measured by COBRA by industry sector. Overall, the largest potential reductions in adverse health outcomes can be made within the iron and steel industry. Reducing emissions for $PM_{2.5}$ and its precursors within the iron and steel industry accounts for approximately 70 percent of the total incidence reductions across all health endpoints. This is followed by the cement industry, accounting for approximately 15 percent of the total incidence reductions across all endpoints, then by the metallurgical coke industry at 13 percent. The aluminum industry has the lowest potential for reductions in adverse health outcomes, at approximately 3 percent of the total potential incidence reduction across all health endpoints. However, even as the smallest contributor to health endpoints, reducing air pollution from the aluminum production industry still has the potential to have substantial health benefits, including an annual reduction in 3,800 lost workdays.

Table 15. Summary of reductions in incidence of health endpoints by industry

Health Endpoint	Change in Incidence (cases, annual)							
	Iron and Steel		Cement		Aluminum		Metallurgical Coke	
	Low	High	Low	High	Low	High	Low	High
Mortality	869	1,966	179	405	35	78	170	385
Nonfatal Heart Attacks	93	860	19	181	4	36	17	153
Infant Mortality	5		1		0		1	
Hospital Admits, All Respiratory	212		45		9		37	
Hospital Admits, Cardiovascular (except heart attacks)	218		45		9		39	
Acute Bronchitis	1,072		237		42		197	
Upper Respiratory Symptoms	19,434		4,290		754		3,564	
Lower Respiratory Symptoms	13,639		3,017		530		2,503	
Emergency Room Visits, Asthma	435		92		16		81	
Asthma Exacerbation	20,194		4,485		791		3,701	
Minor Restricted Activity Days	575,241		128,610		22,792		105,725	
Work Loss Days	97,374		21,761		3,848		17,862	

6. EMISSION INTENSITY ANALYSIS

Synapse estimated the emission intensity of each facility in tons of CO_2e per ton of product. This production-normalized metric facilitates comparison of emissions across facilities within a given industry. We draw on data from Sections 4.2 on Production Data and 4.4 on Greenhouse Gases for this analysis.

6.1. Current State of Industry

Methods

We calculate Scope 1 production-weighted average emission intensities using our estimates of facility-level production in 2020 and greenhouse gas emissions data from U.S. EPA. We also calculated production-weighted emission intensities based on the sum of Scopes 1 and 2 emissions to capture the emissions impact of electricity consumption by each facility.

Results

Table 16 shows total industry emissions on a per-ton basis for Scope 1 and Scope 1 plus Scope 2 emissions. On a per-ton basis, aluminum is by far the most emissions-intensive of the four industries we study. However, due to a smaller industry footprint and lower overall production, the aluminum industry's total contribution to U.S. emissions is small relative to iron, steel, and cement. A large portion of the greenhouse gas emissions from aluminum production are PFCs created during reactions between the carbon anode and electrolyte bath: PFCs account for 43 percent of industry-wide Scope 1 emissions (measured in CO_2e). This percentage varies widely by plant, from 9 percent to 72 percent. Further, the large contribution of PFCs to aluminum's overall emission intensity makes it a target for strategies that reduce greenhouse gas emissions, which will be discussed in Section 6.2, below. Figure 19 through Figure 24 show the distribution of emissions by plant, ordered from highest emissions-intensive to lowest; the horizontal axes of each figure depicts the production capacity of each facility and in total across each industry.

Table 16. Greenhouse gas emissions across industries

Industry	Total number facilities	Emissions scope	Total industry emissions (MMT CO_2e)	Production-weighted emission intensity (tons CO_2e/ton)
Iron and Steel	100	Scope 1	53.43	0.696
		Scope 1 + 2	72.36	0.943
Metallurgical Coke	12	Scope 1	4.99	0.435
		Scope 1 + 2	5.12	0.451
Cement	92	Scope 1	66.89	0.782
		Scope 1 + 2	71.29	0.833
Aluminum	7	Scope 1	3.81	3.764
		Scope 1 + 2	12.17	12.026

Note: While the production-weighted average for iron and steel is industry-wide, the calculation for facilities above average and the sum of emissions reductions were done relative to each applicable subcategory (e.g., BOFs were only compared to other BOFs). Cement averages include biogenic CO_2e emissions, which are about 2 percent of total industry emissions in 2020.

Note that the emission intensity values in Table 16 are highly sensitive to our estimate of facility-level production in 2020, which, due to our methodology, includes some uncertainty. Scope 2 emissions are likewise sensitive to our production estimates and to our estimates of electrical intensity, plus the accuracy of a location-specific emissions factor.

Production-weighted averages on an industry scale can also obscure variation within industries by production process. As seen in Table 17, there are notable differences between facility types in the iron and steel industry.

Table 17. CO_2e emission intensities within the iron and steel industry

Facility Type	Number of Facilities	Emissions Scope	Production-weighted emission intensity (tons CO_2e/ton)
Blast furnace - BOF	11	Scope 1	1.83
		Scope 1 + 2	1.98
EAF, long products	62	Scope 1	0.22
		Scope 1 + 2	0.52
EAF, flat products	15	Scope 1	0.34
		Scope 1 + 2	0.62
EAF total	87	Scope 1	0.25
		Scope 1 + 2	0.55
Other	12	Scope 1	0.46
		Scope 1 + 2	0.64

Blast furnace - BOF facilities are, on average, about seven times as CO_2e-intense on a Scope 1 basis than EAF facilities. Including Scope 2 emissions, BOF facilities are more than 3.5 times as emissions intense as EAF facilities. Within the EAF category, whether a facility manufactures long products (e.g., rebar, I-beams) or flat products (e.g., sheet metal) also affects emission intensity. Twelve facilities categorized as "other" are either direct-reduced iron facilities or EAF facilities that make such a niche product that they could not be categorized as manufacturing flat or long products.[87]

The metallurgical coke industry has a similar bifurcation between recovery and non-recovery facilities. Table 18 shows that non-recovery metcoke facilities are more than three times as emissions-intense as byproduct recovery facilities in terms of Scope 1 emissions alone and, since electricity use is a small component of metcoke production, Scope 1 and 2 emissions. This dramatic difference is due to the greater combustion of VOCs and other byproducts that occurs in a non-recovery oven.

Table 18. Emission intensity differences between byproduct recovery and non-recovery coke facilities

Metallurgical coke facility type	Emissions scope	Production-weighted greenhouse gas emission intensity (tons CO_2e/ton production)
Byproduct recovery	Scope 1	0.231
	Scope 1 + 2	0.233
Non-recovery	Scope 1	0.778
	Scope 1 + 2	0.780

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[87] Examples include a metal powder recycler and facilities specializing in power metallurgy or military products.

Figure 19. Emissions curve for aluminum

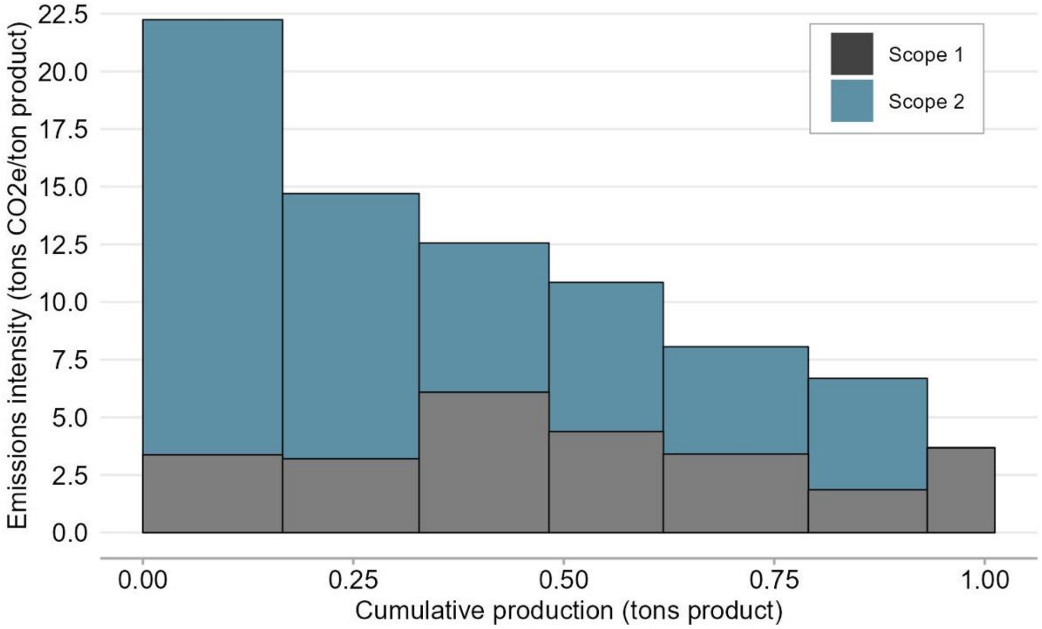


Figure 20. Emissions curve for cement

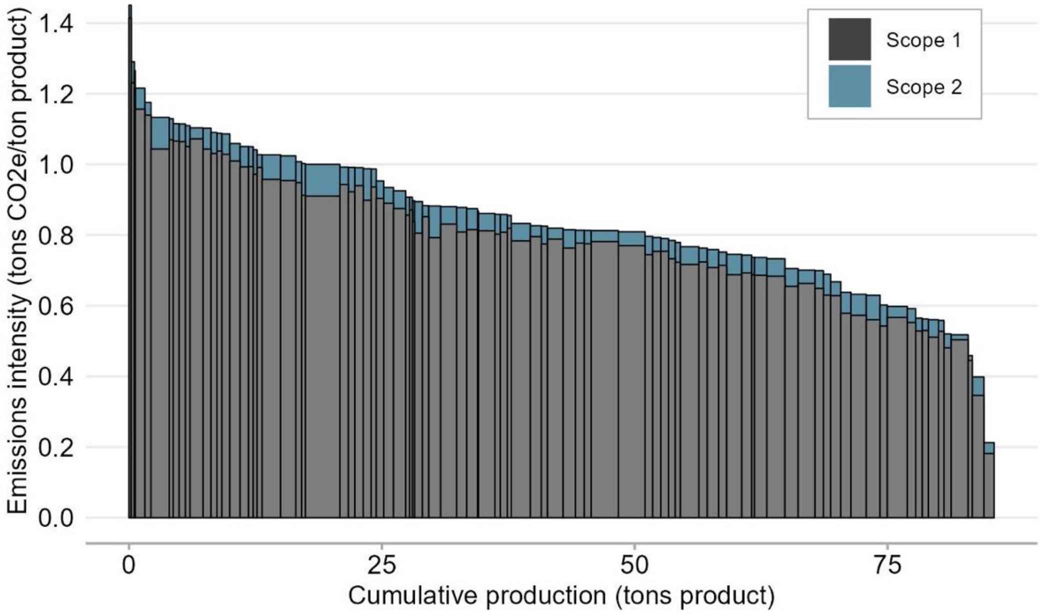


Figure 21. Emissions curve for metcoke

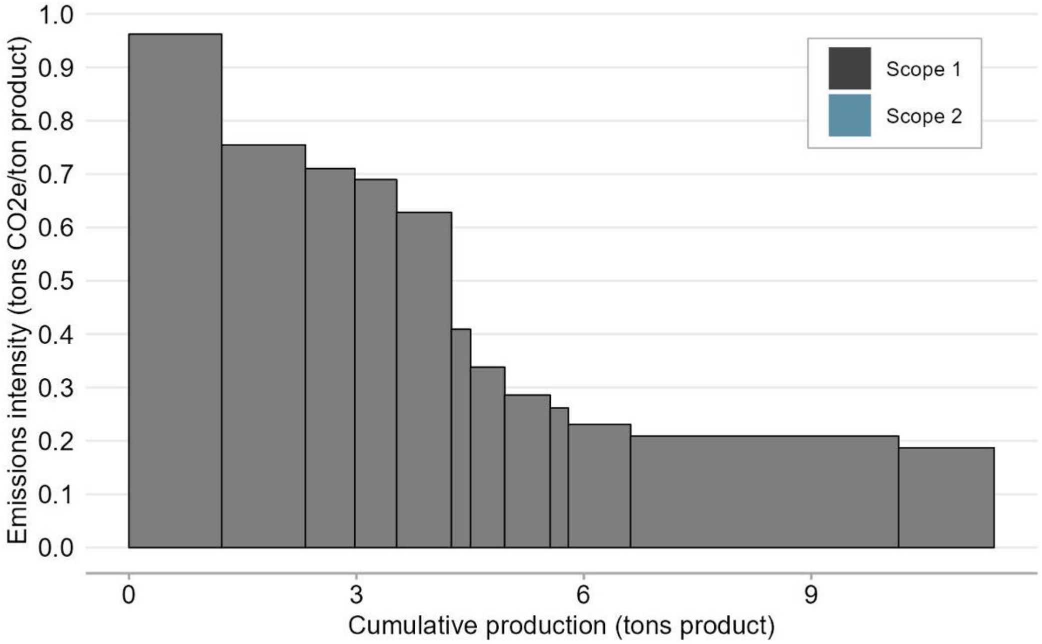


Figure 22. Emissions curve for EAF hot-rolled flat steel products

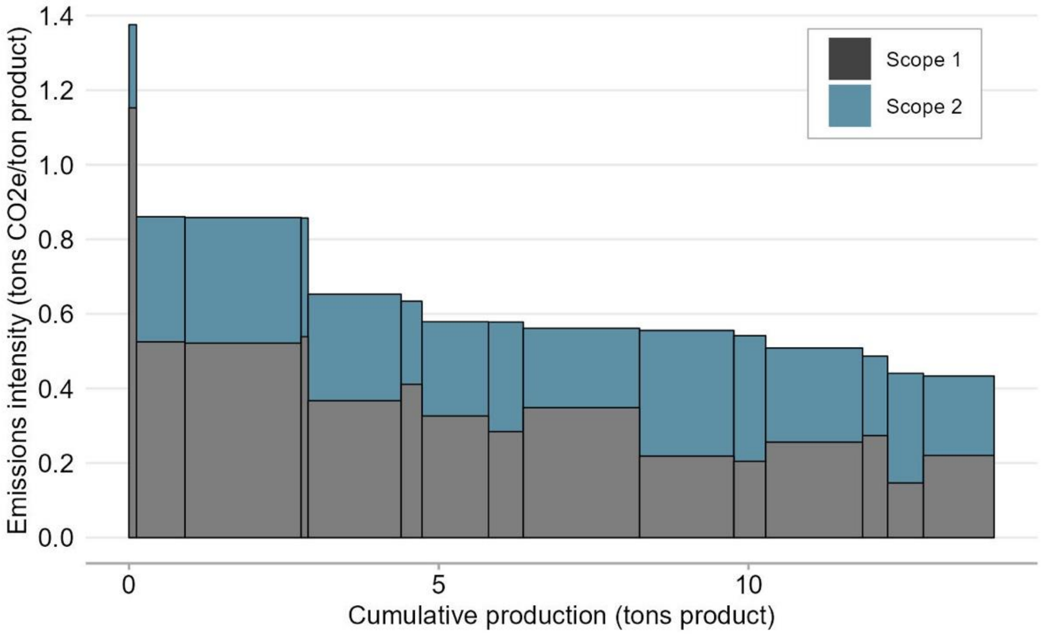


Figure 23. Emissions curve for EAF hot-rolled long steel products

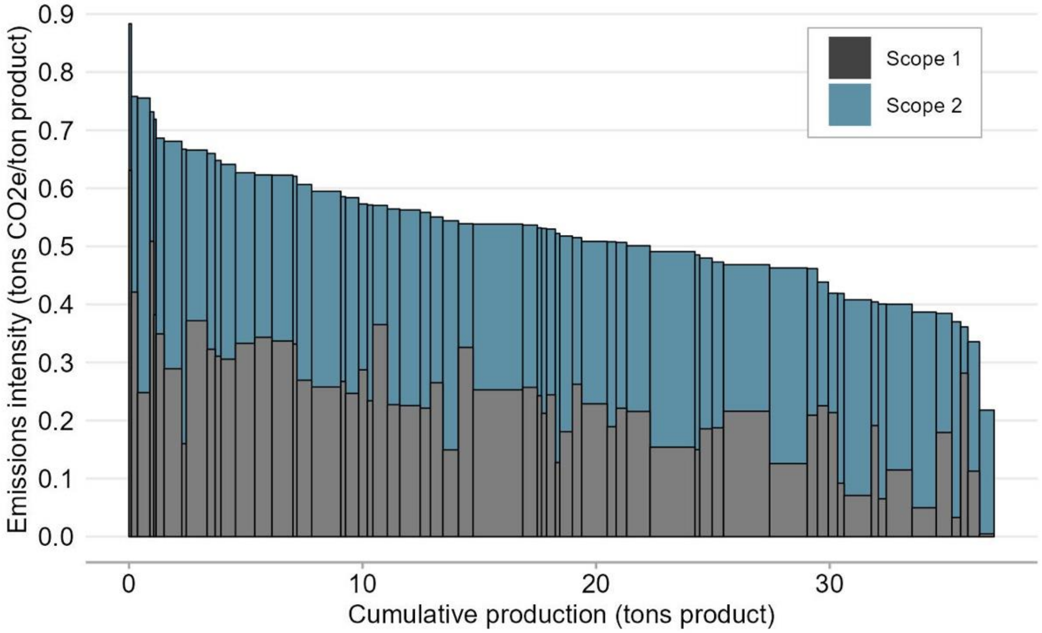
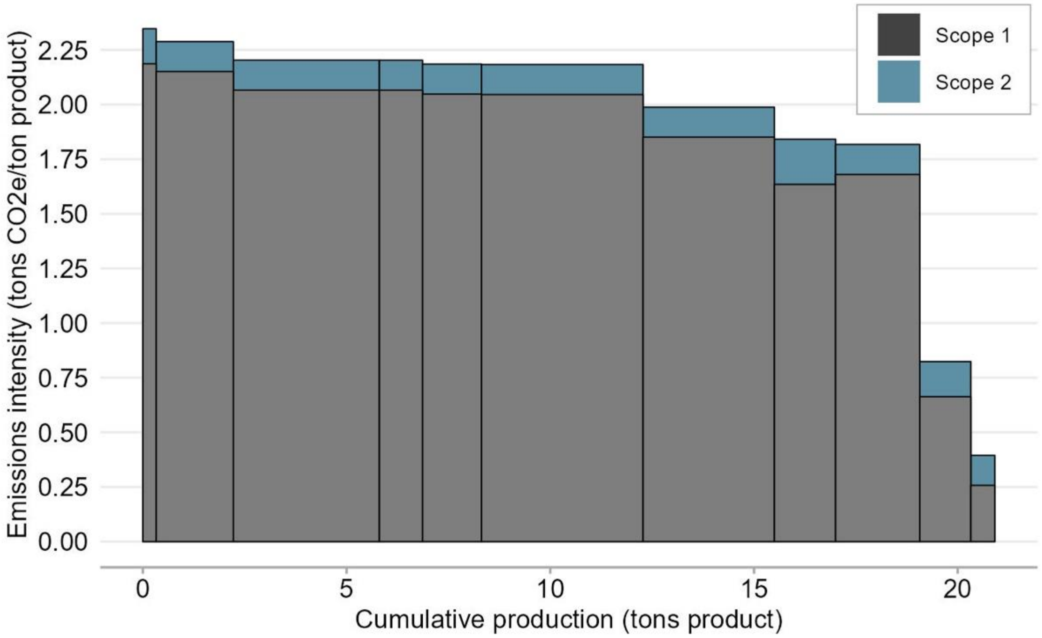


Figure 24. Emissions curve for BOF steel products



6.2. Emission-Reduction Policies and Technologies

How do the industry-wide and facility-specific emissions results help characterize the opportunity for industrial decarbonization and reduction of other harmful pollutants? This section of the report explores policy options, such as Buy Clean initiatives and industry-specific emissions targets. We also discuss technologies and strategies that can contribute to decarbonization efforts.

Federal Buy Clean Policy

As the single largest purchaser in the world with annual purchasing power over $650 billion, the U.S. federal government's procurement decisions can exert substantial leverage over suppliers.[88] In December of 2021, President Biden established the Federal Buy Clean Task Force and Initiative through Executive Order 14057 to make use of this leverage.[89] The goal of the Task Force and Initiative is to develop policies that reduce the embodied emissions in federal procurement and projects while catalyzing clean, domestic manufacturing. So far, the effort focuses on procuring low-carbon construction materials. Specifically, this includes steel, concrete, asphalt, and glass—industries that make up 98 percent of the materials purchased by the federal government.[90] The federal Buy Clean effort does not currently directly target aluminum or metallurgical coke.

In the time since Executive Order 14057, multiple federal agencies have taken steps to implement the initiative.[91] The U.S. General Services Administration (GSA), which connects federal purchasers with commercial products and services,[92] issued the first Buy Clean standards for concrete and asphalt in 2022, which set numerical limits on the embodied carbon of these products[93,94] On May 16, 2023, the

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[88] U.S. Council on Environmental Quality. 2023. "Federal Buy Clean Initiative." Available at: https://www.sustainability.gov/buyclean/.

[89] The Whitehouse. 2021. "Executive Order on Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability." Available at: https://www.whitehouse.gov/briefing-room/presidential-actions/2021/12/08/executive-order-on-catalyzing-clean-energy-industries-and-jobs-through-federal-sustainability/.

[90] The Whitehouse. 2022. "Fact Sheet: Biden-Harris Administration Announces New Buy Clean Actions to Ensure American Manufacturing Leads in the 21st Century" Available at: https://www.whitehouse.gov/briefing-room/statements-releases/2022/09/15/fact-sheet-biden-harris-administration-announces-new-Buy Clean-actions-to-ensure-american-manufacturing-leads-in-the-21st-century/.

[91] The Whitehouse. 2022. "Fact Sheet: Biden-Harris Administration Announces New Buy Clean Actions to Ensure American Manufacturing Leads in the 21st Century" Available at: https://www.whitehouse.gov/briefing-room/statements-releases/2022/09/15/fact-sheet-biden-harris-administration-announces-new-Buy Clean-actions-to-ensure-american-manufacturing-leads-in-the-21st-century/.

[92] U.S. GSA. 2023. "Purchasing Programs." Available at: https://www.gsa.gov/buy-through-us/purchasing-programs.

[93] U.S. GSA. 2022. "GSA Administrator Highlights Progress on Low-Carbon Construction Material Procurement in Ohio." Available at: https://www.gsa.gov/about-us/newsroom/news-releases/gsa-administrator-highlights-progress-on-lowcarbon-construction-material-procurement-in-ohio-09152022.

[94] U.S. GSA. 2022. "GSA Lightens the Environmental Footprint of its Building Materials."Available at: https://www.gsa.gov/about-us/newsroom/news-releases/gsa-lightens-the-environmental-footprint-of-its-building-materials-03302022

GSA also announced a six-month Buy Clean pilot program covering the procurement of the four material categories for use in eleven projects.

In a separate but parallel, collaborative effort with industry, the U.S. Department of Energy (DOE) launched the "Better Climate Challenge," through which organizations can partner with DOE to reduce portfolio-wide Scope 1 and 2 emissions by at least 50 percent within 10 years. Among more than 120 member organizations are Cleveland-Cliffs Inc, the largest producer of flat-rolled steel in America, and numerous primary-metal-consuming manufacturers including Ford Motor Company, General Motors, General Electric, and Avangrid.[95]

The *Inflation Reduction Act* also provided a boost for the Federal Buy Clean Initiative with "$4.5 billion in funding for the General Services Administration, Department of Transportation, and EPA to designate and use construction materials and products that produce substantially lower levels of greenhouse gas (GHG) emissions."[96] Beyond this funding, the *Inflation Reduction Act* also provides the EPA with $350 million for grants, technical assistance and tools, including carbon labeling, to help the measurement and reporting of embodied emissions associated with the covered materials via Environmental Product Declarations, and the Department of Energy with billions in federal grants and loans to invest in retrofitting industrial facilities.[97]

At this stage, it remains to be seen if the Initiative will expand to other materials or industries, how Buy Clean standards will affect applicable industries or how Buy Clean procurement decisions will affect specific companies or facilities versus the industry as a whole. In particular, it is unclear the degree to which Buy Clean policies will support new facilities and breakthrough technologies, or be limited to incremental emissions improvement either among the cleanest or least-clean facilities. In this context, we undertook an analysis to characterize the emission intensities of facilities in the iron, steel, cement, aluminum, and metallurgical coke industries and to describe technologies that are likely to reduce emissions in response to emerging federal policies.

Impact of Buy Clean and emission target policies

We rank all facilities within each industry according to their emission intensities on a tons-CO_2e per ton production basis and compare each facility to an industry-average emission intensity. The purpose of this analysis was to illuminate how much variability there is already within each industry, identify

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[95] U.S. DOE. 2022. "Better Climate Challenge." Available at: https://betterbuildingssolutioncenter.energy.gov/climate-challenge.

[96] U.S. GSA. 2023. "GSA pilots Buy Clean Inflation Reduction Act Requirements for low embodied carbon construction materials." Available at: :https://www.gsa.gov/about-us/newsroom/news-releases/gsa-pilots-buy-clean-inflation-reduction-act-requirements-for-low-embodied-carbon-construction-materials-05162023.

[97] The Whitehouse. 2022. "Fact Sheet: Biden-Harris Administration Announces New Buy Clean Actions to Ensure American Manufacturing Leads in the 21st Century" Available at: https://www.whitehouse.gov/briefing-room/statements-releases/2022/09/15/fact-sheet-biden-harris-administration-announces-new-Buy Clean-actions-to-ensure-american-manufacturing-leads-in-the-21st-century/.

leaders and laggards, and quantify the potential for reducing industry-wide emissions through targeted policy action.

Methods

We ranked industrial facilities according to their Scope 1 emission intensities and according to their Scope 1 plus Scope 2 greenhouse gas emission intensities (GHGEI). Both methods were used to illuminate the different contributions of Scope 2 emissions within each industry and to highlight the spread in emission intensities within each industry.

Our approach to ranking facilities based upon their GHGEI involved grouping similar facilities within industries. In the aluminum and cement industries, we assume all facilities produce substitutable products and we rank these industries together in one group each. In the iron and steel industry, in contrast, we separate BOF facilities and EAFs since they largely fulfill different market functions and are not yet entirely substitutable. Within these two production-process categories, we compare all BOFs to one another given how few facilities there are and how similar production processes are between them. Within the EAF category, however, we also separate facilities into groups by end product, to help ensure that a Buy Clean policy compares facilities that are most likely to be substitutable.[98] Apart from these categorizations, we also create an “other” iron and steel category, which contains all of the unique facilities that produce specialized, niche products, or DRI. We analyzed metallurgical coke facilities as one group given how few there are, but as will be discussed in the results section below, clear differences emerged between byproduct recovery and non-recovery facilities.

Within each of the four industries and within sub-categories, we calculate a production-weighed emission intensity. Finally, for each facility that is more emissions-intense than its industry’s average, we calculated what emissions reduction would be necessary for it to reach the industry average, which we present in the accompanying Excel database. This analysis does not represent the certain outcome of a current Buy Clean policy, but it highlights the potential emissions impact of emissions reductions in the less-clean half of each industry.

Finally, we estimate what the maximum emission intensity would need to be in order to achieve a 50-percent reduction in industry-wide emissions. Holding domestic output constant, we assume that facilities above the threshold would reduce emissions to meet this target, while facilities below the threshold would not make any changes. We select a 50-percent target that roughly aligns with the progress needed over the next decade to move these industries toward net-zero greenhouse gas emissions by 2050. This target broadly aligns with DOE’s Industrial Decarbonization Roadmap, which seeks reductions of 29 percent by 2030 and 58 percent by 2040, relative to a 2015 baseline. We then evaluate which facilities in each industry would need to adopt decarbonization strategies.

Results

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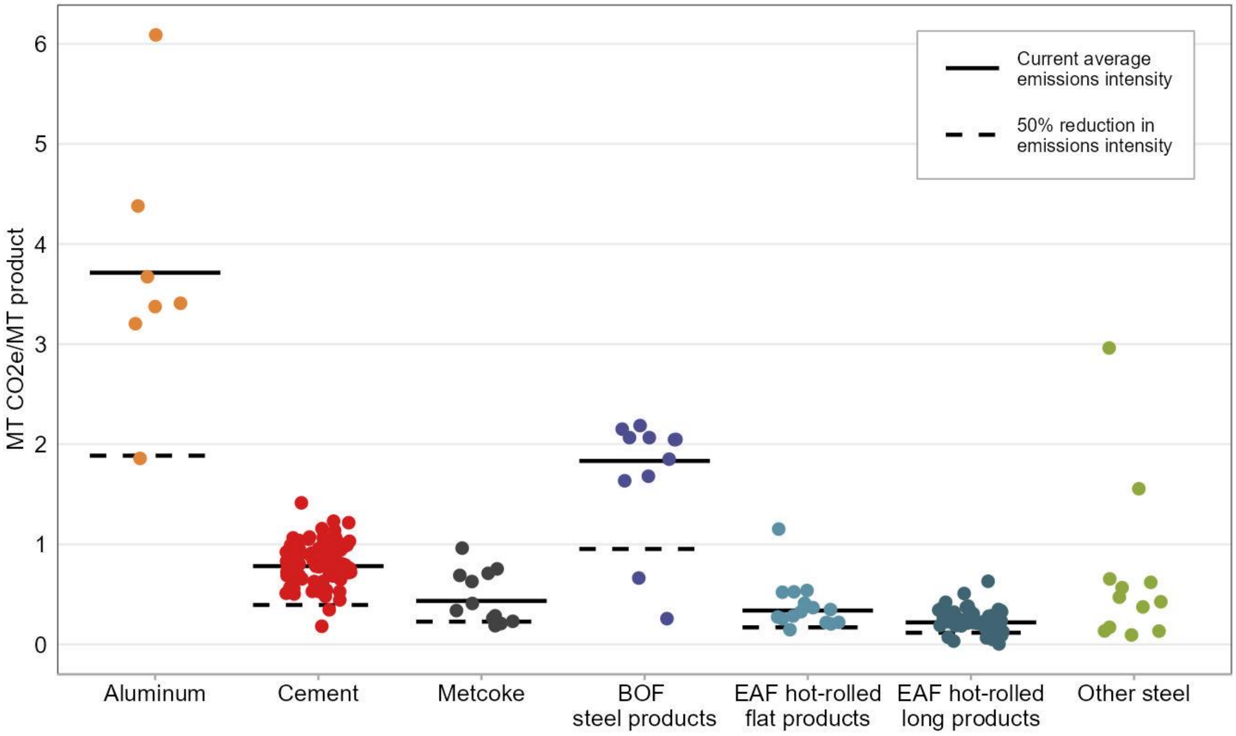
[98] This process involved simplification of end products and represents one source of error in this analysis.

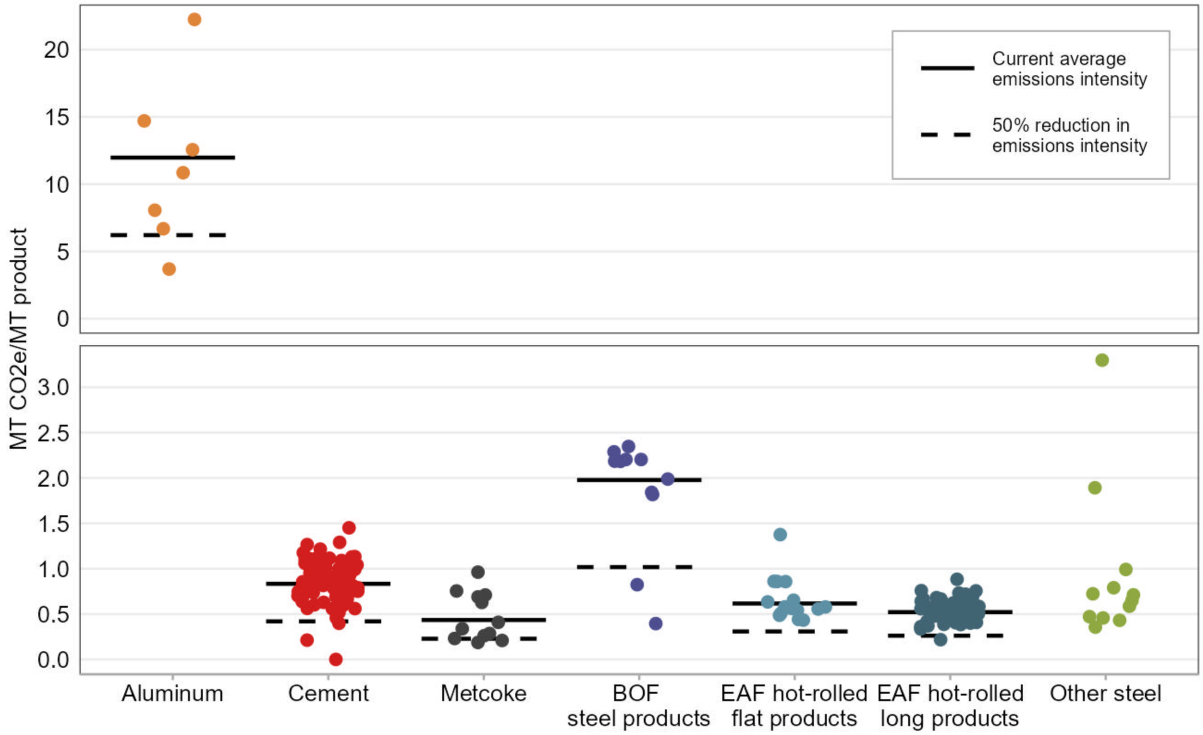
Figure 25 presents facility-level emission intensities within each industry for Scope 1 emissions, including industry-average and industry-specific targets. Similarly, Figure 26 shows Scopes 1 plus 2 emission intensities. We find that there is a considerable spread in how intensive individual facilities are within a particular industry, which points to an opportunity for knowledge transfer and process improvement to reduce greenhouse gas emissions. The divergence of emission intensities is greatest in aluminum facilities. Facility-level data on Scope 1 and Scope 1 plus Scope 2 emission intensities are also available in the databases and interactive tool.

Figure 25. Scope 1 emission intensities by industry



Note: In the figure above, the solid crossbars show each industry's current production-weighted average emission intensity, and the dashed crossbars show the emission intensity that achieves a 50-percent reduction in Scope 1 greenhouse gas emissions while holding domestic production constant.

Figure 26. Scope 1 and 2 emissions by industry



Note: The solid crossbars show each industry's current production-weighted average emission intensity, and the dashed crossbars show the emission intensity that achieves a 50-percent reduction in Scope 1 and 2 greenhouse gas emissions while holding domestic production constant.

Table 19 shows how many facilities in each industry have an emission intensity greater than average. The table also highlights the total emissions reduction necessary for all above-average facilities to reach average in total tons CO_2e and as a percent of total industry emissions. One takeaway from this table is that the emissions reduction necessary for the facilities with higher emissions intensity than the median is a relatively small percentage of overall emissions for iron, steel, cement, and aluminum. This suggests that the relatively more emissions-intense facilities also produce relatively less. Another takeaway is that if all facilities were to reach at least the 2020 average production-weighted emission intensity, the overall emissions reduction would be modest. Deeper emissions cuts will require a much more aggressive shift in industry emissions that comes from the current top performers in terms of emissions in addition to those that are currently the most emissions-intense.

Table 20 presents intensities and reduction targets by industry to achieve 50-percent reduction for Scope 1 emissions. Similarly, Table 21 shows Scope 1 plus Scope 2 emission intensities and targets. Both tables identify the count of facilities that met the targets in 2020. Consistent with the results in Table 19, this analysis shows that almost all facilities need to reduce emissions over the next decade for the United States to be on a path to net-zero industrial emissions by 2050.

Table 19. Emissions reductions if every facility above average emissions intensity achieved the 2020 industry-average emissions intensity

Industry	Emissions Scope	Number facilities above average	Total emissions reduction if every facility reached average emissions intensity (metric tons CO_2e)	Total emissions reduction if every facility reached average emissions intensity (% of industry emissions)
Iron and Steel	Scope 1	56	5,397,985	10%
	Scope 1+2	55	5,485,782	8%
Metallurgical Coke	Scope 1	5	1,458,531	29%
	Scope 1+2	5	1,398,456	28%
Cement	Scope 1	50	6,062,096	9%
	Scope 1+2	47	6,412,668	9%
Aluminum	Scope 1	2	442,389	12%
	Scope 1+2	3	2,255,884	19%

Table 20. Emissions intensity and reduction targets by industry to achieve 50-percent reduction, Scope 1

Industry	Average 2020 emissions intensity (metric ton CO_2e/ton)	Scope 1 target emission intensity to achieve 50% reduction in greenhouse gas emissions (metric ton CO_2e/ton)	Count of facilities that meet the 50% target	Industry-wide emissions reduction (metric tons CO_2e)
Aluminum	3.76	1.89	1	1,904,517
Cement	0.78	0.39	2	33,446,381
Metcoke	0.43	0.23	2	2,480,020
BOF steel products	1.83	0.95	2	19,167,881
EAF hot-rolled flat products	0.34	0.17	1	2,363,901
EAF hot-rolled long products	0.22	0.12	8	4,071,275
Other steel	0.46	0.26	4	1,112,591

Table 21. Emissions intensity and reduction targets by industry to achieve 50-percent reduction, Scopes 1 and 2

Industry	Average 2020 emission intensity (metric ton CO_2e/ton)	Scope 1 and 2 target emission intensity to achieve 50% reduction in greenhouse gas emissions (metric ton CO_2e/ton)	Count of facilities that meet target	Industry-wide emissions reduction (metric tons CO_2e)
Aluminum	12.03	6.21	1	6,085,019
Cement	0.83	0.42	3	35,645,073
Metcoke	0.44	0.23	2	2,492,597
BOF steel products	1.98	1.02	2	20,674,339
EAF hot-rolled flat products	0.62	0.31	0	4,303,313
EAF hot-rolled long products	0.52	0.26	1	9,658,316
Other steel	0.64	0.32	0	1,542,775

Emission-reduction technologies and strategies

As we have discussed so far in this report, the iron and steel, aluminum, cement, and metallurgical coke industries all consume electricity, producing Scope 2 emissions. Decarbonization of the electrical grid, therefore, is an essential component of emissions mitigation across all four of these industries. The proportion of emissions that can be reduced this way, however, varies by industry. In the aluminum industry, for example, Scope 2 emissions comprise the majority of overall emissions, so a cleaner electric grid can create a sizeable industry-level emissions reduction. In the iron and steel industry, clean electricity can also have a substantial impact on overall emissions due to the electricity-intense EAF production process. For cement and metcoke, clean electricity must still play a role, but a relatively smaller one. Even with 100 percent clean electricity, however, industrial facilities will still produce Scope 1 emissions, necessitating changes to onsite production processes as well. The remainder of this section will focus exclusively on the technologies and strategies available to reduce Scope 1 emissions.

Sources of pollutants in the iron and steel industries

Process heating accounted for 82 percent of total energy use in the U.S. steel industry in 2020 across all facilities.[99] The method of generating process heat greatly influences greenhouse gas and criteria air pollutant emission intensities at each facility. Blast furnace - BOF facilities, which produce heat by burning fossil fuels, are generally the most emissions-intense steel production pathway.

The World Steel Organization estimates that, within a blast furnace - BOF facility, 80 percent to 90 percent of the CO_2e emissions come from the blast furnace used to produce iron, in large part because iron production is what requires metallurgical coke.[100] Feedstock composition is one factor that affects the coke feeding rate. For example, when the silicon content increases by 0.1 percent, the coke rate must increase by about 0.75–0.9 percent, which has corresponding effects on emissions.[101] Combustion of metallurgical coke also releases a significant amount of particulate matter, SO_2, and NO_X.[102] Since the BF chemical process relies on carbon monoxide to reduce iron ore, leaked carbon monoxide can be another source of criteria air pollutant emissions. Within the BOF part of the blast furnace - BOF process, the type of steel produced and further downstream processing also affect elements such as industrial

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[99] Nimbalkar, S. 2022. "Potential Decarbonization Strategies and Challenges for the U.S. Iron & Steel Industry." Oak Ridge National Laboratory. Available at: https://www.energy.gov/sites/default/files/2022-02/Nimbalkar%20-%20ORNL%20-%20Decarbonizing%20US%20Steel%20Industry.pdf.

[100] Madhavan, N., Brooks, G., Rhamdhani, M.A. and Bordignon, A. 2022. "Contribution of CO_2 Emissions from Basic Oxygen Steelmaking Process." *Metals*, *12*(5), p.797. Available at: https://www.mdpi.com/2075-4701/12/5/797.

[101] This percentage is based on a 4.5 kg increase specified by Madhavan et al. (id. 89) and an average coke rate of 500–650 kg per ton of steel according to U.S. EPA's AP 42 emissions factors. U.S. EPA. 1986. 12.5 Iron and Steel Production. AP 42, Fifth Edition, Volume 1, Chapter 12. U.S. Environmental Protection Agency. Available at: https://www.epa.gov/sites/default/files/2020-11/documents/c12s05.pdf.

[102] Vasu, A. 2006. *Evaluation of PM2. 5 Emissions and Controls at Two Michigan Steel Mills and a Coke Oven Battery*. Prepared by RTI International for U.S. EPA. Available at: https://www.epa.gov/sites/default/files/2015-06/documents/aqm_detroit_steel_report_final_20060207.pdf.

process temperature, which determines the amount of fuel burned for heat.[103] The BOF emits additional iron dust (PM), SO_2, NO_X, fluoride dust, and wastewater.[104]

The EAF process, in contrast, uses electricity to generate heat and does not produce iron; so it is generally less emissions-intense. Over 90 percent of the pollution emitted from an EAF is generated during melting and refining.[105] The chemical composition of these emissions is extremely variable and depends on the following parameters:

- Composition of the base materials
- Refining process that is used (with gaseous oxygen or ore)
- Duration of melting and refining
- Grade of the steel

DRI only represents about 1 percent of domestic iron production, through a process that reduces iron ore by carbon monoxide and hydrogen often derived from natural gas or coal. The core DRI process is a furnace, and the fuel that is performing the reduction largely determines the level of pollution of DRI.[106] A coal-based process is used primarily in India, whereas in the United States, DRI relies on natural gas. This production process is cleaner, but it still produces carbon monoxide and a range of pollutants during the reduction process and handling of iron after it is produced.

Current technologies used to reduce emissions

Facilities have managed process emissions for many years using control technologies that capture exhaust gas from fuel combustion and chemical reactions within furnaces through fume hoods, exhaust pipes, and seals. Facilities can then remove pollutants by wetting, gaseous washing, centrifugal force, filters with bags, or electrostatic filters.[107,108] These technologies continue to be useful; but historically,

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[103] Madhavan, N., Brooks, G., Rhamdhani, M.A. and Bordignon, A. 2022. “Contribution of CO_2 Emissions from Basic Oxygen Steelmaking Process.” *Metals*, *12*(5), p.797. Available at: https://www.mdpi.com/2075-4701/12/5/797.

[104] Id.

[105] Ioana, A., Semenescu, A., Costoiu, M. and Marcu, D. 2017. “Elements of the electric arc furnace’s environmental management.” In AIP Conference Proceedings (Vol. 1918, No. 1, p. 020003). AIP Publishing LLC. Available at: https://aip.scitation.org/doi/pdf/10.1063/1.5018498#:~:text=The%20gaseous%20phase%20of%20the,purity%20of%20the%20base%20material.

[106] Béchara, R., Hamadeh, H., Mirgaux, O. and Patisson, F. 2020. “Carbon impact mitigation of the iron ore direct reduction process through computer-aided optimization and design changes.” *Metals*, 10(3), p.367. Available at: https://www.mdpi.com/2075-4701/10/3/367.

[107] Ioana, A., Semenescu, A., Costoiu, M. and Marcu, D. 2017. “Elements of the electric arc furnace’s environmental management.” In AIP Conference Proceedings (Vol. 1918, No. 1, p. 020003). AIP Publishing LLC. Available at: https://aip.scitation.org/doi/pdf/10.1063/1.5018498#:~:text=The%20gaseous%20phase%20of%20the,purity%20of%20the%20base%20material.

[108] Vasu, A., 2006. *Evaluation of PM2. 5 Emissions and Controls at Two Michigan Steel Mills and a Coke Oven Battery*. Prepared by RTI International for U.S. EPA. Available at: https://www.epa.gov/sites/default/files/2015-06/documents/aqm_detroit_steel_report_final_20060207.pdf.

industries have achieved greater emissions reductions with technologies that shift the industry away from processes that create emissions, rather than those that control emissions after they are created.

The most significant example is the technological advancement and proliferation of EAFs. Until 1969, essentially all U.S. steel was produced through the blast furnace - BOF pathway. That year, when Nucor opened the first EAF mill in Darlington, South Carolina, EAF product lines were limited to rebar production. By 1989, however, technology had advanced to allow EAFs to produce flat-rolled steel and other products formerly producible only by blast furnace - BOFs. Over time, blast furnace - BOF firms have specialized in higher-value products that are still difficult to produce using an EAF.[109] Nevertheless, EAFs have come to produce more than 70 percent of U.S. steel each year, a figure which is expected to grow as technology continues to improve, use of DRI increases, and EAFs penetrate further into markets once dominated by blast furnace - BOFs.

Among blast furnace - BOF operations, developments in iron feedstocks have also reduced emissions. Integrated steel mills in the United States today are predominantly fed by domestically sourced iron ore pellets—in contrast to a reliance on lower-quality sintered iron used in China and elsewhere—which has resulted in lower emissions of CO_2e (and of NO_X, SO_2, and particulate matter) compared to foreign steel.[110]

Increasing scrap use in blast furnace - BOF and EAF steelmaking has also reduced the need for iron production, thereby reducing overall emissions. In 2019, average recycled steel content in EAFs was 82 percent, and in BOFs it was 23 percent.[111] The United States recycles between 60–80 million tons of steel scrap per year, a rate that has remained fairly constant over the last 10 years.[112,113]

Lastly, iron production has just begun to shift from the BF production pathway to DRI, which is about half as CO_2-intensive.[114] DRI capacity still supplies only about 1 percent of domestic iron; but fueled by cheap natural gas, DRI capacity has grown in recent years and its output is increasingly used to

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[109] Wachs, L., McMillan, C., Boyd, G. and Doolin, M. 2022. *Exploring New Ways to Classify Industries for Energy Analysis and Modeling*. National Renewable Energy Laboratory (NREL). Available at: https://www.nrel.gov/docs/fy23osti/82957.pdf.

[110] Wu, X., Zhao, L., Zhang, Y., Zheng, C., Gao, X. and Cen, K. 2015. "Primary Air Pollutant Emissions and Future Prediction of Iron and Steel Industry in China." *Aerosol Air Qual. Res*. 15: 1422-1432. https://doi.org/10.4209/aaqr.2015.01.0029; and Mourao, Jose & Cameron, Ian & Huerta, Manuel & Patel, Nishit & Pereira, Rodrigo. 2020. *Comparison of Sinter and Pellet Usage in an Integrated Steel Plant 1*. Available at: https://www.researchgate.net/publication/341386739_COMPARISON_OF_SINTER_AND_PELLET_USAGE_IN_AN_INTEGRATED_STEEL_PLANT_1.

[111] American Iron and Steel Institute. 2021. "Determination of Steel Recycling Rates in the United States." Available at: https://www.steel.org/wp-content/uploads/2021/08/AISI-and-SMA-Steel-Recycling-Rates-Report-Final-07-27-2021.pdf.

[112] American Iron and Steel Institute. 2021. "Sustainability of the American Steel Industry." Available at: https://www.steel.org/wp-content/uploads/2021/03/Sustainability-Key-Messages.pdf.

[113] American Iron and Steel Institute. 2021. "Determination of Steel Recycling Rates in the United States." Available at: https://www.steel.org/wp-content/uploads/2021/08/AISI-and-SMA-Steel-Recycling-Rates-Report-Final-07-27-2021.pdf

[114] Voraberger et al. 2022. "Green LD (BOF) Steelmaking—Reduced CO_2 Emissions via Increased Scrap Rate." *Metals 12(3), 466.* Available at https://doi.org/10.3390/met12030466.

"sweeten" EAF feedstocks.[115] Existing facilities include Nucor Louisiana (2.5 MMT/year) and Voestalpine Texas (2 MMT/year). Cleveland Cliffs recently completed a facility in Toledo, Ohio with a capacity of 1.9 MMT/yr;[116] the plant owner intends to incorporate increased hydrogen use, for which it may pursue federal funding. Alternative ironmaking technologies exist in other parts of the world but have not yet come to the Unites States.[117]

Leading technological options to reduce pollutants in the future

There are myriad technological options available and emerging to reduce the emissions of iron and steel production. As recently as 2017, the Lawrence Berkeley National Laboratory identified 56 emerging technologies that include: new coke-making techniques and improvements; BF ironmaking; alternative ironmaking technologies; new steelmaking technologies; more advanced recycling techniques; and carbon capture.[118] A more recent paper from 2022 identifies 86 "potentially transformative" technologies.[119] As argued by the DOE, a wide range of technological options will be useful for incremental improvements to iron and steel emissions. Dramatic improvements to emissions, however, will require step-change technology advancements and abatement strategies.[120] Recent studies by the Voestalpine group, International Energy Agency (IEA), the National Renewable Energy Laboratory (NREL), and DOE broadly agree on the set of technological shifts that are likely to deliver that step change. In short, they are: electrify production, shift to clean hydrogen, and explore carbon capture and storage where needed. Each category contains a variety of sub-technologies with potential to reduce CO_2 and displace criteria-air-pollutant-intensive processes.

Electrify production

Several technologies are emerging that use electricity to eliminate the process heat and emissions involved in ironmaking. Boston Metal, for example, uses a modular, high temperature process for molten electrolysis. Another option, the Siderwin process, involves electrolysis for iron recovery at low temperature in an alkaline solution and also includes induction heating or EAF compatibility to produce

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[115] S&P Global Commodity Insights. 2019. "US Steel sector thrives as mills move up quality ladder." Available at https://www.spglobal.com/commodityinsights/en/market-insights/blogs/metals/050919-us-steel-sector-thrives-as-mills-move-up-quality-ladder.

[116] Cleveland Cliffs. 2023. "Toledo - Direct Reduction Plant." Available at: https://www.clevelandcliffs.com/operations/steelmaking/toledo-dr-plant.

[117] One example is the FINEX process, which has been in commercial operation since approximately 2004. This process combines the coking, sintering, and blast furnace processes to reduce emissions in ironmaking. https://www.primetals.com/fileadmin/user_upload/content/01_portfolio/1_ironmaking/finex/THE_FINEX_R__PROCESS.pdf.

[118] Ali Hasanbeigi. 2017. "56 Emerging Technologies for Energy-efficiency and GHG Emissions Reduction in the Iron and Steel Industry." *Global Efficiency Intelligence*. Available at: https://www.globalefficiencyintel.com/new-blog/2017/technologies-energy-emissions-steel-industry.

[119] Kim, J. et al. 2022. "Decarbonizing the iron and steel industry: A systematic review of sociotechnical systems, technological innovations, and policy options." *Energy Research & Social Science* 89. Available at: https://doi.org/10.1016/j.erss.2022.102565.

[120] Nimbalkar, Sachin. "Potential Decarbonization Strategies and Challenges for the U.S. Iron & Steel Industry." Presentation by Oak Ridge National Laboratory, February 2022. Available at: https://www.energy.gov/sites/default/files/2022-02/Nimbalkar%20-%20ORNL%20-%20Decarbonizing%20US%20Steel%20Industry.pdf.

steel. Parkinson et al. (2017) suggest a third, molten salt electrolysis process that could eliminate CO_2 and produce other marketable chemicals such as ethylene and benzene.[121] These direct-electrolysis routes, coupled with clean electricity, have the potential to reduce both ironmaking CO_2 emissions and criteria air pollutant emissions associated with fuel combustion to zero. The costs for these technologies at a commercial scale is currently unknown. Electrolysis can also be used to produce clean hydrogen, which we discuss below.

After producing low-emissions iron, the next step is to produce low-emissions steel. Globally, the main pathway to do so is the EAF; but in the Unites States, where EAFs comprise over 70 percent of steel production, additional technological advancement is needed for EAFs to increase their market share. In the nearer term, alternative process-heating pathways may be scaled up using low-carbon electricity. These pathways include electrified reheating furnaces and electric induction furnaces. Ladle and tundish heating systems, which may be involved in further steel refinement after an EAF or BOF, could also be converted to resistance, infrared, or plasma heating using electricity.[122]

Shift to clean hydrogen

Hydrogen has received increasing attention as a potential reducing agent for iron in the DRI ironmaking process. DRI ironmaking is already commercial with natural gas and is in the demonstration stage with hydrogen internationally. An alternative to the DRI process, called smelting reduction, also has the potential to use clean hydrogen for ironmaking.[123] One example is the SuSteel process, which uses hydrogen plasma as the reducing agent for zero-CO_2 ironmaking.[124] For process heating during iron and steelmaking, hydrogen may also present a low-carbon alternative to carbon-intensive fuels, since hydrogen produces a 2,100 degree Celsius flame when burned in air.[125]

IEA estimates that hydrogen will be responsible for approximately 8 percent of the cumulative direct emissions reductions from iron and steel between 2020 and 2050.[126] Key needs according to DOE's Industrial Decarbonization Roadmap include reducing the cost of clean hydrogen to $1 per kilogram and

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[121] Wachs, L. et al. 2022. "Exploring New Ways to Classify Industries for Energy Analysis and Modeling." *National Renewable Energy laboratory*. Available at: https://www.nrel.gov/docs/fy23osti/82957.pdf.

[122] U.S. DOE. 2022. *Industrial Decarbonization Roadmap.* DOE/EE-2635. Available at: https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf.

[123] According to the U.S. Department of Energy, 95 percent of hydrogen produced in the United States today is made by natural gas reforming and relies on fossil fuels. It is possible to capture carbon dioxide emissions associated with this process, but this practice is uncommon. It is also possible to make no- to low-emissions 'green hydrogen' via electrolysis, which is the process of using electricity generated by renewable sources to split water into hydrogen and oxygen.

[124] Wachs, L et al. 2022. "Exploring New Ways to Classify Industries for Energy Analysis and Modeling." National Renewable Energy laboratory. Available at: https://www.nrel.gov/docs/fy23osti/82957.pdf.

[125] U.S. DOE. 2022. *Industrial Decarbonization Roadmap.* DOE/EE-2635. Available at: https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf.

[126] International Energy Agency. 2020. *Iron and Steel Technology Roadmap.* Available at: https://iea.blob.core.windows.net/assets/eb0c8ec1-3665-4959-97d0-187ceca189a8/Iron_and_Steel_Technology_Roadmap.pdf.

improving the efficiency and durability of electrolyzers.[127] In December 2022, the Biden administration announced an additional $750 million in funding to progress toward these goals and create long-term clean hydrogen supply.[128] Hydrogen-based technologies are likely to be a longer term element of iron and steel decarbonization; according to the DOE's Near Zero GHG scenario for iron and steel, hydrogen-based DRI-EAF technologies are primarily deployed after 2040.[129]

Carbon capture, utilization, and storage

Carbon capture, with the potential for utilization or storage (CCS), is generally accepted as a potential strategy for iron and steel decarbonization. Amine-based CCS systems are already market-ready and commercially available in the power sector. Amine CCS systems rely on the unique properties of amine solvents, which either bind to CO_2 or release it depending on changes in temperature. One key impact of amine-based CCS on co-pollutants is its relationship with SO_2. Because amine solvents also have a high affinity for SO_2, its presence in flue gas can decrease the efficiency of CO_2 capture. For this reason, SO_2 must be highly controlled prior to the installation of CCS. It can be assumed that installing an amine CCS system will coincide with a near-total reduction of SO_2 in treated gas. Amine-based CCS is also expected to reduce the emissions and ground-level concentrations of PM 2.5 without significantly increasing emissions of other toxic and hazardous air pollutants.[130] It should be noted, however, that the heat and energy used to power CCS equipment may require supplemental power generation, which, if fueled by fossil energy sources, could contribute a range of additional pollutants if not properly controlled. The use of waste heat, where available, is expected to reduce capture costs by 10 to 20 USD per ton, but it is unclear whether this will be possible at all facilities.[131]

In the power sector, amine CCS systems can achieve capture rates of up to 95 percent. Because of the structure of steel plants and different emissions point sources during production, however, it is expected to be more difficult to reach capture efficiencies this high in the industry.[132] Costs are also highly uncertain; to date, CCS retrofits in the power sector are uncommon, and those that have been undertaken are infamous for budget overruns and underperformance. Capture costs are expected to fall to approximately $50 per metric ton CO_2 for coal-fired power plants by 2026, but the cost to retrofit iron

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[127] U.S. DOE. 2022. *Industrial Decarbonization Roadmap.* DOE/EE-2635. Available at: https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf.

[128] U.S. DOE. 2022. "Biden-Harris Administration Announces $750 Million To Accelerate Clean Hydrogen Technologies." *Energy.gov.* Available at: https://www.energy.gov/articles/biden-harris-administration-announces-750-million-accelerate-clean-hydrogen-technologies.

[129] U.S. DOE. 2022. *Industrial Decarbonization Roadmap.* DOE/EE-2635. Available at: https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf.

[130] Rochelle, Gary. 2022. *Air pollution impacts of amine scrubbing for CO_2 capture*. Proceedings of the 16th Greenhouse Gas Control Technologies Conference (GHGT-16) 23-24 Oct 2022, Available at SSRN: https://ssrn.com/abstract=4281826 or http://dx.doi.org/10.2139/ssrn.4281826.

[131] Kearns, D. et al. 2021. *Technology Readiness and Costs of CCS.* Prepared for the Global CCS Institute. Available at: https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf.

[132] U.S. DOE. 2022. *Industrial Decarbonization Roadmap.* DOE/EE-2635. Available at: https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf.

and steel facilities is not well characterized.[133] Pilot projects in the iron and steel industry are still uncommon or small-scale worldwide; one plant in Abu Dhabi has captured 0.8 million tons CO_2 per year since 2016 for injection into a nearby oilfield. Two plants operated in Mexico since 2008 capture 5 percent of their emissions for use in the beverage industry. Hebei Iron and Steel Group announced in 2021 its plan to build CCS demonstration projects at its steel plant by 2030.[134] A handful of other pilot projects are in development, but their timelines are often unpredictable.[135] The Athos CCS project in the Netherlands, for example, was canceled in 2021 when project partner Tata Steel decided to develop hydrogen-based DRI instead.[136] No CCS projects are currently planned for the U.S. iron and steel industry. Nevertheless, DOE's decarbonization roadmap includes CCS in all scenarios (see Table 22), and most include a significant percentage by 2050.[137]

Table 22. Percentage of iron and steel CO_2 captured by CCS in DOE's Industrial Decarbonization scenarios

Scenario	2014	2020	2030	2040	2050
BAU	0%	0%	0%	3%	5%
Moderate	0%	0%	2%	8%	15%
Advanced	0%	0%	5%	20%	40%
Near Zero GHG	0%	0%	10%	40%	85%

IEA's iron and steel technology roadmap projects a lower adoption rate for the global industry. In its sustainable development scenario, only 1 percent of iron and steel direct emissions are captured for storage by 2030—led by the United States, India, and China. By 2050, that rises to 25 percent worldwide.[138]

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[133] Kearns, D. et al. 2021. *Technology Readiness and Costs of CCS.* Prepared for the Global CCS Institute. Available at: https://www.globalccsinstitute.com/wp-content/uploads/2021/03/Technology-Readiness-and-Costs-for-CCS-2021-1.pdf.

[134] Ibid.

[135] International Energy Agency. 2020, *Iron and Steel Technology Roadmap.* Available at: https://iea.blob.core.windows.net/assets/eb0c8ec1-3665-4959-97d0-187ceca189a8/Iron_and_Steel_Technology_Roadmap.pdf.

[136] S&P Global Commodity Insights. 2021. "Dutch CCS project scrapped after Tata Steel opts for hydrogen DRI production route." Available at: https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/electric-power/092121-dutch-ccs-project-scrapped-after-tata-steel-opts-for-hydrogen-dri-production-route.

[137] U.S. DOE. 2022. *Industrial Decarbonization Roadmap.* DOE/EE-2635. Available at: https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf.

[138] International Energy Agency. 2020, *Iron and Steel Technology Roadmap.* Available at: https://iea.blob.core.windows.net/assets/eb0c8ec1-3665-4959-97d0-187ceca189a8/Iron_and_Steel_Technology_Roadmap.pdf.

Metallurgical coke

Sources of pollutants in the metallurgical coke industry

Metallurgical coke production centers on a series of ovens used to bake coal, collectively known as a battery. The heat used in the coking process is provided by burning coke oven gas—gas produced by the coking process itself. Despite scrubbing technologies, this combustion produces CO_2, particulate, and SO_2.[139] Fugitive emissions of CO_2, particulate matter, VOCs, carbon monoxide, and other criteria air pollutant emissions can be produced from other stages of metcoke production as well. These stages include coal preparation, preheating (if used), the process of loading the coke battery, leakage from the battery during coking, and coke removal from the battery.[140] For example, oven charging can produce considerable amounts of particulate and VOC emissions from coal decomposition. During coking, gaseous emissions passing through byproduct-recovery processes are one potential source of VOC emissions. The process of coke oven unloading, if the coke mass is not fully coked, can emit VOCs and combustion products such as CO_2 and other criteria air pollutants. The process of coke quenching, which involves cooling hot coke with water, also produces wastewater laden with organic compounds and other pollutants.[141]

Current technologies used to reduce pollutants

Coking facilities are equipped with a wide range of hoods, pipes, seals, and scrubbing units designed to limit or capture emissions from each step in the production process. In part, this is because of the industry's historical focus on capturing byproducts, which can be worth as much as 35 percent of the value of the feedstock coal.[142] This is also done to comply with U.S. EPA emissions regulations. Most facilities, for example, control emissions caused during coke oven unloading by using a device that sucks air through to a cleaning device—whether that is a mobile scrubber car with a fume hood, a shed enclosure, or a traveling hood with a fixed duct leading to a stationary gas cleaner.[143] At multiple points in the production process, these types of technologies are used to control SO_2, NO_X, and particulate matter emissions.

One large shift in the metcoke industry that has impacted emissions is the rise of non-recovery processing, also known as heat-recovery ovens, particularly under the company Suncoke.[144] Since these ovens incinerate organic compounds that would otherwise be recovered, they reduce VOC emissions, but they increase CO_2 emissions per unit of coke.[145] At the same time, the rise of EAF steelmaking and

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[139] U.S. EPA. 1995. *Metallurgical Industry*. Available at: https://gaftp.epa.gov/ap42/ch12/s02/final/c12s02_1995.pdf.

[140] Ibid.

[141] Ibid.

[142] Ibid.

[143] Ibid.

[144] SunCoke Energy. 2017. "Advanced Cokemaking Technology." Available at: https://www.suncoke.com/English/our-business/coke-business/advanced-cokemaking-technology/default.aspx.

[145] Schobert, H. and N. Schobert. 2015. *Comparative Carbon Footprints of Metallurgical Coke and Anthracite for Blast Furnace and Electric Arc Furnace Use.* Available at: https://www.blaschakanthracite.com/wp-content/uploads/Carbon-Footprint-Archival-Report-v-4-September-20151.pdf.

the increasing use of steel scrap in BOF steelmaking have reduced the need for metcoke through a reduction in blast-furnace ironmaking.

Leading technological options to reduce pollutants in the future

As the U.S. iron and steel industry shifts away from blast-furnace ironmaking, metcoke production will likely fall. However, as pointed out by NREL, carbon capture has the potential to preserve the blast furnace - BOF production pathway, which may have the knock-on effect of preserving demand for metcoke.[146] In the event that carbon capture is also economically deployed at metcoke facilities, CO_2 emissions could decrease dramatically. Since the efficiency of the leading CCS technology is dramatically affected by SO_2 concentrations in the exhaust gas it is likely that SO_2 emissions would also be eliminated if CCS is deployed at a metallurgical coke plant.

Additional technologies are available to further reduce metcoke emissions. One is dry quenching, a process in which coke is cooled with an inert gas instead of water. This process can substantially reduce energy use by recovering heat, particularly if paired with coal preheating, which can reduce CO_2 emissions, NO_X, and SO_2 emissions. Dry quenching is already common in Asia and Europe, but it is not currently deployed in North America.[147]

A second technology is a single-chamber-system (SCS) coking reactor. SCS coking reactors are individual, large coking ovens with rigid walls designed for high coking pressure. This design lends itself to a greater range of coal blends, which can be selected to reduce volatile matter or criteria-air-pollutant-forming content. SCS reactors are also more thermally efficient, lower cost to maintain, and have a reduced coking time, among other benefits.[148],[149] So far, this technology is at the pilot scale.

Next-generation coking technology is also available; since 2008 and 2013, respectively, Nippon Steel has operated two facilities using its proprietary "SCOPE21" process, which involves rapid coal heating and other pretreatment. This process improves process efficiency and productivity by increasing the

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[146] Wachs, L., McMillan, C., Boyd, G. and Doolin, M. 2022. *Exploring New Ways to Classify Industries for Energy Analysis and Modeling*. National Renewable Energy Laboratory (NREL). Available at: https://www.nrel.gov/docs/fy23osti/82957.pdf.

[147] UN Climate Technology Centre & Network. 2010. "Coke dry quenching for iron and steel sector." Available at: https://www.ctc-n.org/technologies/coke-dry-quenching-iron-and-steel-sector.

[148] Hasanbeigi, A., 2013. *Emerging energy-efficiency and carbon dioxide emissions-reduction technologies for the iron and steel industry*. Available at: https://eta-publications.lbl.gov/sites/default/files/6106e-steel-tech.pdf.

[149] Nashan, G., Rohde, W. and Wessiepe, K. 2004. "Transition of cokemaking from multi-chamber to single-chamber ovens-The independent module technology of the future." *Steel Times International*, 28(7), p.27. Available at: https://www.proquest.com/docview/1282506861.

blending of non- or slightly-caking coal.[150] According to the Lawrence Berkeley National Laboratory, this process can reduce NO_X emissions by up to 30 percent while more than doubling production.[151]

Aluminum

Sources of pollutants in the aluminum industry

Greenhouse gas and criteria air pollutant emissions from aluminum production primarily come from the carbon-based anode, which is necessary to conduct an electrical current during smelting, and from chemical reactions during smelting itself. Carbon anodes release emissions when they are made and when they are used. They are typically made onsite from a calcined petroleum coke, which is a residue from crude oil production and contains heavy metals and substantial amounts of sulfur. This petcoke is combined with “anode butts” left over from prior use at the aluminum plant and coal tar pitch, which acts as a binder. These are then baked in gas-fired ovens to high temperatures for up to two weeks, releasing CO_2 and criteria air pollutants.

During smelting, an electrical current flowing through the carbon anode splits alumina molecules into molten aluminum metal and oxygen. Some of this oxygen then reacts with the carbon in the anode to form CO_2 and carbon monoxide, creating process emissions and degrading the anode. Some oxygen also reacts with sulfur present in the anode, forming SO_2. The smelting process also creates perfluorocarbons (PFCs), particulate, and NO_X.[152]

Current technologies used to reduce pollutants

Aluminum smelting pits in the United States have exhaust duct collection systems that remove exhaust gases from the aluminum smelting process using fume hoods. Large fans pull exhaust gas through ducts attached to the hoods to treatment systems that remove various constituents, including criteria air pollutants. Scrubbers commonly use alumina to pull gaseous fluoride from exhaust gas, which can be fed back into the reduction process. Fabric filters and electrostatic precipitators are typically used to remove particulate matter. Technologies and strategies that help improve capture rates include a boosted suction system connected to the scrubbing system; minimizing the time spent changing anodes and other activities that open fume hoods; and using process control systems to maximize efficiency.

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[150] Uebo, K., Matsuura, M., Kubota, Y., Sasaki, M., Fujikawa, H., Nakai, H., Doi, K., Noguchi, T. and Tanizawa, K. 2020. *SCOPE21 Cokemaking Process*. Nippon Steel Technical Report No. 123. Available at: https://www.nipponsteel.com/en/tech/report/pdf/123-25.pdf.

[151] Worrell, E., Blinde, P., Neelis, M., Blomen, E. and Masanet, E., 2010. *Energy efficiency improvement and cost saving opportunities for the US iron and steel industry: an ENERGY STAR guide for energy and plant managers*. Lawrence Berkeley National Lab. Available at: https://www.osti.gov/servlets/purl/1026806.

[152] Safe, P., Russell, M. and Grass, C., 2015. SO2 emissions reduction–a new challenge for aluminium smelters. In 2*3rd International Aluminium Conference* (pp. 21-23). Available at: https://gcteng.com/wp-content/uploads/2022/07/2008_IAC_2008_SO2_Emissions_Reduction_A_New_Challenge_for_Aluminium_Smelters.pdf.

Historically, regulators have not imposed SO_2 emissions limits on aluminum smelters, which is one reason why their SO_2 emission intensity is high relative to the other industries examined in this study.[153]

The aluminum industry also uses many energy efficiency measures to varying degrees. Haraldsson and Johansson (2018) identified 52 separate energy efficiency measures used across the aluminum industry, including reducing cell voltage noise; ensuring good anode quality; pre-heating anodes; using slotted or perforated anodes; optimizing anode-rod assembly design; using graphitized cathodes; using novel structure cathodes that have different surface shapes; optimizing the cathode bar structure; reducing cell ventilation; using distributed pot suction in which the suction can be optimized at each pot; adding lithium fluoride to increase the bath conductivity; and improving electrical contact to lower contact resistance at all contact interfaces.[154]

Leading technological options to reduce pollutants in the future

One way to reduce aluminum SO_2 emissions specifically is to retrofit facilities with scrubbing technologies developed for other industries. Many different technologies exist. Due to the relatively high-volume, low-concentration gas produced by aluminum facilities, the most practical technologies are likely lime, sodium, and/or dual alkali scrubbing. Aluminum plants in Norway have also effectively demonstrated flue gas desulfurization units using seawater, providing an additional route for U.S.-based facilities with access to seawater.[155]

Strategies to prevent emissions before they occur fall into two categories: reducing anode reactivity and improving electrical efficiency. To reduce anode reactivity, gas anodes and inert anodes offer two candidate technologies. Gas anodes use porous or inert materials along with methane as a reducing agent for aluminum. This can reduce carbon anode degradation by over 40 percent and could slightly reduce CO_2 and carbon monoxide emissions while eliminating PFC emissions. One potential challenge is minimizing methane cracking at the temperatures experienced in the aluminum pot, which could cause increases in air pollution.

An inert anode, in contrast, is totally non-consumable. After years of development, these have recently been deployed for the first time under the brand name “Elysis” in Canada by a collaboration between Alcoa, Rio Tinto, the Canadian government, and Apple.[156] Elysis is the first commercial aluminum technology to claim that it can eliminate carbon monoxide and CO_2 produced during smelting, but costs

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[153] Ibid.

[154] Haraldsson, J. and Johansson, M.T., 2018. Review of measures for improved energy efficiency in production-related processes in the aluminium industry–From electrolysis to recycling. *Renewable and Sustainable Energy Reviews*, 93, pp.525-548. Available at: https://www.sciencedirect.com/science/article/abs/pii/S1364032118303915.

[155] Safe, P., Russell, M. and Grass, C., 2015. SO2 emissions reduction–a new challenge for aluminium smelters. In 2*3rd International Aluminium Conference* (pp. 21-23). Available at: https://gcteng.com/wp-content/uploads/2022/07/2008_IAC_2008_SO2_Emissions_Reduction_A_New_Challenge_for_Aluminium_Smelters.pdf.

[156] ELYSIS. 2023. “What is ELYSIS?” Available at: https://www.elysis.com/en/what-is-elysis#carbon-free-smelting.

for the technology and the ease with which facilities can be retrofitted with the technology are still unclear.

From an energy standpoint, the decomposition voltage of alumina when using inert anodes is about 1 V higher than when using carbon anodes. If the energy efficiency deteriorates due to the higher decomposition voltage, then the increased Scope 2 CO_2 associated with greater electricity consumption can offset the reduction in CO_2 at the electrolytic cell from inert, non-carbon anodes.

Various technologies are also in development to improve electrical efficiency during aluminum production. The first is lower temperature electrolytes. Sodium cryolite in use today, which provides the liquid environment for electrolysis to occur, has a very high melting temperature (around 1,000 degrees C) which is one reason why aluminum smelting is so electricity intensive. Other salts, such as potassium cryolite, offer promising alternatives but present physiochemical tradeoffs such as reduced electrical conductivity. On the horizon, room-temperature molten salts have the potential to lower operating temperatures dramatically (e.g., to less than 150 degrees C), reducing heat loss and energy demand.

A wettable cathode, another energy efficiency technology, is so-called because its surface is exposed to and wetted by molten aluminum during operation. Wettable cathodes are an important component that may be paired with the increased energy demand of an inert anode, since they enable alternative aluminum pot designs that reduce energy consumption by decreasing the distance between the anode and cathode. In a normal aluminum cell, decreasing the anode-cathode distance can result in electromagnetic forces that risk creating a short circuit. However, if the cathode is adequately wetted with a protective layer of aluminum, it can keep the cathode inert and protected against the risk of a short circuit. One leading material being developed for wettable cathode use is titanium diboride.[157]

Another on-the-horizon technology is a corrosion-resistant “sidewall refractory.” Currently, some molten sodium cryolite in the aluminum cell is allowed to freeze back to its solid state around the edges of the pot, forming what is called a “ledge” which is an essential barrier to prevent corrosion of the side of the aluminum cell. This insulates the sidewall from the extreme challenge of direct contact with oxidizing, corrosive, and reducing environments for different zones in the aluminum cell, but the process requires heat loss so that the cryolite can freeze. The input of energy needed to maintain this constant heat loss can account for up to 35 percent of electricity input into electrolysis. New composite materials are in development to improve the resilience of the sidewall and reduce the need for this ledge, which would allow for aluminum cells to be insulated better, reducing energy input.[158]

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[157] Padamata, S.K., Singh, K., Haarberg, G.M. and Saevarsdottir, G., 2022. Wettable TiB2 Cathode for Aluminum Electrolysis: A Review. *Journal of Sustainable Metallurgy*, 8(2), pp.613-624. Available at: https://link.springer.com/article/10.1007/s40831-022-00526-8.

[158] Yawei, L. and X. Yibiao. 2014. New Sidewall Materials in Aluminum Reduction Cell. *Refractories World Forum.* 6(4), pp.101-106. Available at: https://www.refractories-worldforum.com/paper?article_id=100342.

Cement

Sources of pollutants in the cement industry

The central process of the cement-making is baking feedstock materials at the high temperatures necessary for clinkering reactions. Nearly 60 percent of the CO_2e emissions of cement-making are non-energy related and result from the chemical reduction of limestone to lime during this process.[159] These emissions are not affected by which fuel is used to generate heat. Likewise, the high temperatures and oxidizing atmosphere required for cement manufacturing also favor NO_X formation, regardless of the fuel used.[160]

However, fuel type also contributes a significant component of greenhouse gases and criteria air pollutant emissions. Coal is the primary fuel for the U.S. cement industry and is the primary source of cement's SO_2 emissions.[161] Some NO_X is also formed by the oxidation of nitrogen present in fuel, though the primary source of NO_X is exposure of atmospheric nitrogen to high temperatures. Pre-and post-processing of feedstock material and clinker can also release particulate emissions in addition to particulate released by fuel combustion.

Current technologies used to reduce emissions

Today, one of the simplest ways to reduce emissions is by improving efficiency. For example, optimizing how feedstocks enter and move through kilns can help stabilize kiln temperatures and reduce heat consumption, indirectly reducing NO_X and CO_2 emissions.[162] A staged combustion calciner can also reduce NO_X by staging the introduction of fuel, combustion air, and feed material in a way that chemically reduces NO_X to nitrogen inside the kiln.[163] Facilities can also use various scrubbing technologies after NO_X has been produced. These include selective noncatalytic reduction (SNCR), which involves injecting ammonia in the form of ammonia water or urea into flue-gas, which results in safe, stable nitrogen gas and water.[164] Selective catalytic reduction (SCR), which adds a catalyst to the process, may be used instead to allow the scrubbing reaction to occur at a lower temperature.

The NO_X removal efficiency depends on the flue gas temperature, the molar ratio of ammonia to NO_X, and the amount of time that flue gas is in contact with the catalyst.[165] In general, an SNCR may increase

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[159] U.S. DOE. 2022. *Industrial Decarbonization Roadmap.* DOE/EE-2635. Available at: https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf.

[160] U.S. EPA. 2007. *Alternative Control Techniques Document Update – NOx Emissions from New Cement Kilns*. Available at: https://www3.epa.gov/ttncatc1/dir1/cement_updt_1107.pdf.

[161] U.S. DOE. 2022. *Industrial Decarbonization Roadmap.* DOE/EE-2635. Available at: https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf.

[162] U.S. EPA. 2008. 12.2 Coke Production. AP 42, Fifth Edition, Volume 1, Chapter 12. U.S. Environmental Protection Agency. Available at: https://www3.epa.gov/ttn/chief/ap42/ch12/final/c12s02_may08.pdf.

[163] Ibid.

[164] Ibid.

[165] Ibid.

the emissions of ammonia, nitrous oxide, carbon monoxide, CO_2, and particulate matter. For an SCR, particulate emissions may increase. In systems with higher SO_2 emissions due to high sulfur content of raw materials, the conversion to sulfur trioxide by SCR can also cause additional sticky deposits or acid formation. For SCR, emissions of carbon monoxide, sulfuric acid, mercury, VOCs, and dioxin/furan may also decrease.[166] These effects are not specific to the cement industry, but rather byproducts of SNCR and SCR applications across industries.

Fuel-switching, despite limited potential for deep decarbonization, has been a common method of reducing cement's emissions. In the United States in 2015, more than half of the cement industry's final energy use—about an equal amount of energy as is consumed through coal combustion—was made up of liquid waste (24.8 percent), solid waste (14.4 percent), and tires (12.4 percent), which have become substitutes for coal during production.[167]

Adjusting the quantity of clinker in the final cement mix has also yielded emission reductions by stretching the same amount of emissions-intense clinker across more tons of finished product. Clinker is the main constituent in most types of cement and is the material that reacts with water to allow cement to harden. The quantity used in cement is known as the clinker ratio and has important implications for the cement's finished properties. Blending in other materials such as slag from iron and steel production, fly ash from coal-fired power plants, limestone, and other materials is common in the cement industry as a whole; however, the specific ratio of clinker varies, particularly between nations, due to different cement certification standards. In the United States, cement producers generally adhere to the ASTM C-150 Standard set by the American Society for Testing and Materials, which defines clinker ratios and other chemical properties of U.S.-made cement varieties.[168,169]

Leading technological options to reduce pollutants in the future

Due to the large percentage of cement's emissions that are unrelated to fuel use and driven by the chemistry of cement-making, decarbonization of the industry cannot be achieved by energy efficiency or fuel-switching alone. Alternative chemistries and/or CCS will also be necessary.[170] The DOE projects that under a near-zero greenhouse gas emissions scenario, U.S. cement manufacturing greenhouse gas emissions can decrease to near zero by 2050, while cement production increases by nearly 50 percent. Around 65 percent of the total greenhouse gas emission reductions in this scenario are the result of

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[166] Ibid.

[167] U.S. DOE. 2022. *Industrial Decarbonization Roadmap.* DOE/EE-2635. Available at: https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf.

[168] Portland Cement Association. "Cement Types." Available at: https://www.cement.org/cement-concrete/concrete-materials/cement-types.

[169] World Cement. 2020. "US Cement Standards: Accelerating the green transition." Available at: https://www.worldcement.com/special-reports/16042020/us-cement-standards-accelerating-the-green-transition/.

[170] U.S. DOE. 2022. *Industrial Decarbonization Roadmap.* DOE/EE-2635. Available at: https://www.energy.gov/sites/default/files/2022-09/Industrial%20Decarbonization%20Roadmap.pdf.

CCS.[171] In the process of installing CCS, given the sensitivity of market-ready amine CCS technology to SO_2, it is very likely that further SO_2 reductions—through additional scrubbing, or more likely through fuel-switching—would also be necessary. This means that as a byproduct of installing CCS, SO_2 emissions can also be expected to be essentially eliminated. As in the iron and steel industry, the degree to which waste heat can be repurposed for CCS will be an important component of preventing emissions from auxiliary heat and power generation that would otherwise be needed.

Today, CO_2 capture in the cement sector is close to commercial demonstration. The world's largest CO_2 capture from a cement kiln's off-gas is the pilot project at Anhui Conch's Baimashan plant in China. The plant relies on amine CCS to capture roughly 3 percent of the unit's CO_2 emissions. Another amine-based demonstration plant at the Norcem cement plant in Brevik, Norway is expected to capture 50 percent of the factory's emissions using surpluses of waste heat. Dalmia Cement in India has also announced its intention to build CCS.[172] The CCS company Leilac is also leading the development of multiple pilot projects and engineering studies across the United States, Germany, Poland, and Australia. Leilac plans to deploy and scale a novel kiln that inherently produces a near-pure stream of process CO_2 that can be more easily captured.[173]

Beyond CCS, electrification may play a role in providing the process heat. VTT Decarbonate in Finland unveiled the first electric kiln prototype in 2022.[174] The unit still produces CO_2 and heat, resulting in NO_X, but it avoids all emissions related to fuel combustion. The project may also begin capturing CO_2 in the future.[175]

Alternative cement chemistries offer another path forward and have been in development for decades. In the near term, the expansion of cement varieties that offer the same building properties while reducing the clinker ratio offer one way to reduce, but not eliminate, the embedded emissions of each ton of cement. Environmental organization Project Drawdown estimates that this method can reduce cement's global emission intensity by 33 percent by 2050.[176] Alternative cement chemistries that replace limestone are in also in development and have proven capabilities to reduce emissions and cost. The U.S. EPA, for example, funded a Small Business Innovation Research project that is developing a new class of sustainable hydraulic cements. These novel cements are capable of meeting performance-based standards for hydraulic cements with 25 percent of the carbon footprint, half the energy content, and half the production cost of Portland cement. The new blend is also suitable for recycling and sequestering a range of industrial byproducts—an element that makes it suitable for use in many locales

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[171] Ibid.

[172] Rumayor, M. et al. 2022. "Deep Decarbonization of the Cement Sector: A Prospective Environmental Assessment of CO_2 Recycling to Methanol." *ACS Sustainable Chemical Engineering.* Available at: https://pubs.acs.org/doi/pdf/10.1021/acssuschemeng.1c06118.

[173] Leilac. 2023. "Leilac Projects." Available at: https://www.leilac.com/projects/.

[174] Katajisto, O. "Cement precalcination with electricity and carbon dioxide sequestration." Presentation at VTT, May 25, 2022. Available at: https://www.decarbonate.fi/wp-content/uploads/2022/05/2022-05-17-Betonitutkimusseminaari.pdf.

[175] Ibid.

[176] Project Drawdown. 2020. "Alternative Cement." Available at: https://drawdown.org/solutions/alternative-cement#:~:text=Substituting%20materials%20such%20as%20volcanic,gigatons%20between%202020%20and%202050.

where cement is already produced. Development of this new cement is a collaboration with industry partners.[177]

Multiple startups are also working on commercializing alternative chemistries. U.S.-based Brimstone has announced the development of a new process that sources lime from calcium silicate rocks instead of limestone. The process purports to eliminate emissions during the calcination process and produce a magnesium-based waste product that can be used to absorb emissions from fuel combustion. Brimstone claims that the process would be cheaper than traditional production and chemically identical to ordinary Portland cement clinker. Only about 1 kg has been produced in a lab so far, but in 2022 the company announced plans to build a demonstration plant.[178] Other alternative chemistries exist in the scientific literature, including processes that entirely replace limestone with bauxite or bauxite-rich Belterra clay.[179]

7. UNCERTAINTY IN REPORTED EPA EMISSIONS DATA

This study combines facility-level data based on our own estimates, drawn from publicly available data, and reported emissions data available from EPA. Throughout this study, we have noted that there is uncertainty associated with our estimates, primarily due to incomplete publicly available data. This means that facility-level production data, employment data, environmental justice indicators, and health impact scores for example, while informative, include a margin of error and should be updated as more accurate data becomes available.

However, Synapse's literature review and interviews with industry experts indicate that the accuracy of available greenhouse gas emissions data and toxic emissions data reported to EPA is also uncertain, largely due to the range of reporting methods available to facilities. For this reason, it is important to characterize the accuracy of reported information used in this report.

7.1. Reported Greenhouse Gas Emissions

The GHGRP program's reporting requirements introduce inherent uncertainty into the GHGRP database. According to U.S. EPA:

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[177] U.S. EPA. 2020. "Final Report: An Alternative Concrete Chemistry with Significantly Enhanced Durability, Sustainability, Economy, Safety and Strength." Available at: https://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract_id/10807/report/F.

[178] Businesswire. 2022. "Brimstone to Produce the World's First Carbon-Negative Portland Cement." *Businesswire.* Available at: https://www.businesswire.com/news/home/20220428005472/en/Brimstone-to-Produce-the-World%E2%80%99s-First-Carbon-Negative-Portland-Cement.

[179] Negrao, L. et al. 2021. "Production of low-CO_2 cements using abundant bauxite overburden "Belterra Clay." *Sustainable Materials and Technologies.* 29. Available at: https://doi.org/10.1016/j.susmat.2021.e00299.

> The Greenhouse Gas Reporting Program (GHGRP) prescribes methodologies that must be used to determine greenhouse gas (GHG) emissions from each source category. Reporters generally have the flexibility to choose among several methods for computing GHG emissions. The decision of which method to use may be influenced by the existing environmental monitoring systems in place and other factors. Reporters can change emission calculation methods from year to year, as long as they meet the requirements for use of the method selected.[180]

Emissions reported to the GHGRP are categorized as either combustion emissions, process emissions, or fugitive emissions. Combustion emissions "include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) emitted from combustion of a fossil fuel (e.g., coal, natural gas, petroleum products) or biomass feedstock (e.g., wood, landfill gas)." Process emissions, in contrast, **"**generally include emissions from chemical transformation of raw materials and fugitive emissions. The chemical transformation of raw materials often releases greenhouse gases such as CO_2, CH_4, and N_2O." These processes are prevalent in iron, steel, and cement production. Fugitive emissions refer to "emissions of gases due to leaks or other unintended or irregular releases." Fugitive emissions of fluorinated gases occur during aluminum production. These processes typically release hydrofluorocarbons (HFCs), perfluorocarbons, and sulfur hexafluoride.

GHGRP designates four tiers of emissions calculation methodologies, with descending preference and accuracy.

Tier 4: employs a continuous emission monitoring system (CEMS). The system continuously monitors both the stack gas CO_2 concentration and the stack gas flow rate. Mass CO_2 emissions are determined using these two values, along with the appropriate conversion factors. For heterogeneous fuels such as municipal solid waste, CEMS are generally considered the most accurate emissions estimation method.

Tier 3: generally uses fuel-specific data. Measured fuel characteristics, such as carbon content and molecular weight, are used in conjunction with the measured fuel quantity to calculate mass CO_2 emissions. The fuel quantity is measured with flow meters, tank drop measurements, weigh scales, or other devices.

Tier 2: methodology uses a mix of default and fuel-specific data. An emission factor and a measured high heating value are used in conjunction with the estimated fuel quantity to calculate mass CO_2 emissions. The fuel quantity estimate is based on company records (e.g., fuel purchases).

Tier 1: uses default values to calculate CO_2 mass emissions. An emission factor, default high heating value, and estimated fuel quantity are used together to calculate emissions. The fuel quantity is based on company records (e.g., fuel purchases). Table 23 shows the typical use of these methods in the industries studied herein.

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[180] U.S. EPA. 2022. "GHGRP Methodology and Verification." Available at: https://www.epa.gov/ghgreporting/ghgrp-methodology-and-verification.

Table 23. Greenhouse gas emission calculation methodologies typical of the studied industries

Industry	Combustion Emissions	Process Emissions
Iron and Steel, Metcoke	Tier 1, Tier 2	Tier 4
Aluminum	Tier 1, Tier 2	Tier 1
Cement	Tier 4 CEMs (90% of facilities)	Tier 1

Note: Tiers are ordered with descending preference and accuracy (Tier 4 is best, Tier 1 is worst).

7.2. Reported Toxic Emissions

Synapse's compiled databases incorporate data from U.S. EPA's annual Toxic Releases Inventory and U.S. EPA's periodic National Emissions Inventory. We assemble land, water, and air toxics data from U.S. EPA's Toxic Releases Inventory for the year 2020. For pollutants not included in Toxic Releases Inventory, Synapse compiled data from U.S. EPA's National Emissions Inventory using the most recent data year available, 2017. National Emissions Inventory data comes from state, local, and tribal agencies, with some augmentation from U.S. EPA datasets including Toxic Releases Inventory and the GHGRP.[181]

EPA requires facilities to use the best readily available information or to prepare reasonable estimates of releases for the Toxics Release Inventory program.[182,183] However, U.S. EPA allows facilities reporting to Toxic Releases Inventory to choose among four methods to develop estimates of chemical releases. While facilities may be able to improve the accuracy of toxic release reporting by performing direct measurement of pollutants, U.S. EPA does not require additional sampling or testing under Toxic Releases Inventory.[184] Table 24 identifies the allowable reporting methods and summarizes potential data sources for each. When reporting toxic releases to Toxic Releases Inventory, the facilities must also identify the method used to estimate each toxic release, using the codes listed in Table 25. A similar series of codes are used to categorize the estimation method for National Emissions Inventory data, shown in Table 26.

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[181] U.S. EPA. 2021. 2017 National Emissions Inventory: January 2021 Updated Release, Technical Support Document. Available at: https://www.epa.gov/sites/default/files/2021-02/documents/nei2017_tsd_full_jan2021.pdf.

[182] For example, emission factors or engineering calculations may not be the best readily available information when other data such as stack testing are available.

[183] U.S. EPA. 1999. *Section 313 of the Emergency Planning and Community Right-to-Know Act: Toxic Chemical Release Inventory*. Available at: https://ordspub.epa.gov/ords/guideme_ext/guideme_ext/guideme/file/chemical%20distribution%20facilities.pdf.

[184] Ibid.

Table 24. Allowable methods and potential data sources for estimating toxic releases

Method	Data sources	
Monitoring data or direct measurement (M)	• Stack monitoring data • Outfall monitoring data • Air permits • Industrial hygiene monitoring data • NPDES permits	• POTW pretreatment standards • Effluent limitations • RCRA permit • Hazardous waste analysis • pH for acids • Continuous emission monitoring
Mass balance (C)	• Supply records • Hazardous material inventory • Air emissions inventory	• Pollution prevention reports • Hazardous waste manifests • Spill event records
Emission factors (E)	• AP-42 or other U.S. EPA emission factors	• Published facility or trade association chemical-specific emission factors
Engineering calculations (O)	• Volatilization rates • Raoult's Law • Henry's Law • Solubilities	• Non-published emission factors • Facility or trade association non-chemical-specific emission factors (e.g., SOCMI factors)

U.S. EPA. 1999. Section 313 of the Emergency Planning and Community Right-to-Know Act: Toxic Chemical Release Inventory. Available at: https://ordspub.epa.gov/ords/guideme_ext/guideme_ext/guideme/file/chemical%20distribution%20facilities.pdf.

Table 25. Toxics Release Inventory program reporting codes

Method	Reporting code	Description
Monitoring data or direct measurement (M)	M1	Estimate is based on continuous monitoring data or measurements for the *Emergency Planning and Community Right-to-Know Act* (EPCRA) section 313 chemical. Added in reporting year 2007.
	M2	Estimate is based on periodic or random monitoring data or measurements for the EPCRA section 313 chemical. Added in reporting year 2007.
Mass balance (C)	C	Estimate is based on mass balance calculations, such as calculations of the amount of the EPCRA section 313 chemical in streams entering and leaving equipment.
Emission factors (E)	E1	Estimate is based on published emission factors, such as those relating release quantity to throughput or equipment type (e.g., air emission factors). Added in reporting year 2007.
	E2	Estimate is based on site-specific emission factors, such as those relating release quantity to throughput or equipment type (e.g., air emission factors). Added in reporting year 2007.
Engineering calculations (O)	O	Estimate is based on other approaches such as engineering calculations (e.g., estimating volatilization using published mathematical formulas) or best engineering judgment. This would include applying an estimated removal efficiency to a waste stream, even if the composition of the stream before treatment was fully identified through monitoring data.

U.S. EPA. 1999. Section 313 of the Emergency Planning and Community Right-to-Know Act: Toxic Chemical Release Inventory. Available at: https://ordspub.epa.gov/ords/guideme_ext/guideme_ext/guideme/file/chemical%20distribution%20facilities.pdf.

Table 26. National Emissions Inventory calculation codes

Code	Calculation method
1	Continuous Emission Monitoring System
2	Engineering Judgment
3	Material Balance
4	Stack Test (no Control Efficiency used)
5	USEPA Speciation Profile
6	S/L/T Speciation Profile
7	Manufacturer Specification
8	U.S. EPA Emission Factor (no Control Efficiency used)
9	S/L/T Emission Factor (no Control Efficiency used)
10	Site-Specific Emission Factor (no Control Efficiency used)
11	Vendor Emission Factor (no Control Efficiency used)
12	Trade Group Emission Factor (no Control Efficiency used)
13	Other Emission Factor (no Control Efficiency used)
24	Stack Test (pre-control) plus Control Efficiency
28	U.S. EPA Emission Factor (pre-control) plus Control Efficiency
29	S/L/T Emission Factor (pre-control) plus Control Efficiency
30	Site-Specific Emission Factor (pre-control) plus Control Efficiency
31	Vendor Emission Factor (pre-control) plus Control Efficiency
32	Trade Group Emission Factor (pre-control) plus Control Efficiency
33	Other Emission Factor (pre-control) plus Control Efficiency
40	Emission Factor based on Regional Testing Program
41	Emission Factor based on data available peer reviewed literature
42	Emission Factor based on Fire Emission Production Simulator (FEPS)

U.S. EPA. 2006. NEI Quality Assurance and Data Augmentation for Point Sources. Available at: https://www.epa.gov/sites/default/files/2015-11/documents/nei2002_qa_augmentation_0206.pdf.

Analysis of reporting methods

Synapse reviewed the methods used to estimate emissions for all steel, metcoke, aluminum, and cement facilities in the United States. For each facility, Synapse determined the method used by the facility to report each toxic release of air, land, and water pollutants. National Emissions Inventory data does not provide industry-specific methodological information, so Synapse analyzed the entire National Emissions Inventory database as a whole.

Toxic Releases Inventory uncertainty analysis

U.S. EPA implements quality control to ensure Toxic Releases Inventory data is as accurate as possible according to the methods used. U.S. EPA utilizes emissions reporting software with built-in data quality alerts and conducts data quality calls to facilities to verify the accuracy of reported information.

However, these methods are not able to fully mitigate the underlying uncertainty of each method.[185] Although each of the methods can be very accurate, the range of possible accuracies does vary within method categories.

For example, method M, direct measurement, is considered one of the least variable and most accurate methods, though U.S. EPA's technical documentation warns that vendor data on "treatment efficiencies" often represent ideal operating conditions and must be adjusted to account for downtime throughout the year. Adjustments must also be made for specific chemicals—for example, an incinerator may be 99.99 percent efficient in combusting organic chemicals, but 0 percent efficient in combusting metals.[186] Direct measurement is also not always necessary; for example, when burning a specific fuel, if the quantity of the fuel is known, an emissions factor can yield highly accurate results.

Method C, mass balance, can also be very accurate if proper site-specific data is used, but U.S. EPA warns that mass balance equations are only as accurate as each particular data element. All inputs and outputs must be included with as much precision as possible or the final estimate of a pollutant will be inaccurate.

Method E, emissions factors, may be the most variable given the quality of available emissions factors. A facility may choose to use AP-42 emissions factors, for example, which themselves contain a range of accuracy rankings from "A" (calculated using highly accurate test data) to "E" (poor).

Likewise, engineering calculations (method O) are only as accurate as the best engineering judgment of the person making the calculations or the calculation used. Engineering calculations can also include computer models. Engineering calculations are ultimately "assumptions or judgments" that rely on thorough knowledge of processes at a facility.

The accuracy rating of the method used to construct each of a facility's Toxic Releases Inventory estimates is not included in Toxic Releases Inventory, obscuring the accuracy of each reported quantity. In general, U.S. EPA leaves it up to submitters to "determine the best method for calculating quantities of each release" based on "site-specific knowledge and potential data sources available."[187] As shown in Figure 27, each industry makes use of different calculation methods relative to one another and within the separate categories of land, water, and air releases. Since different facilities report different types of releases, the number of Toxic Releases Inventory releases reported varies.

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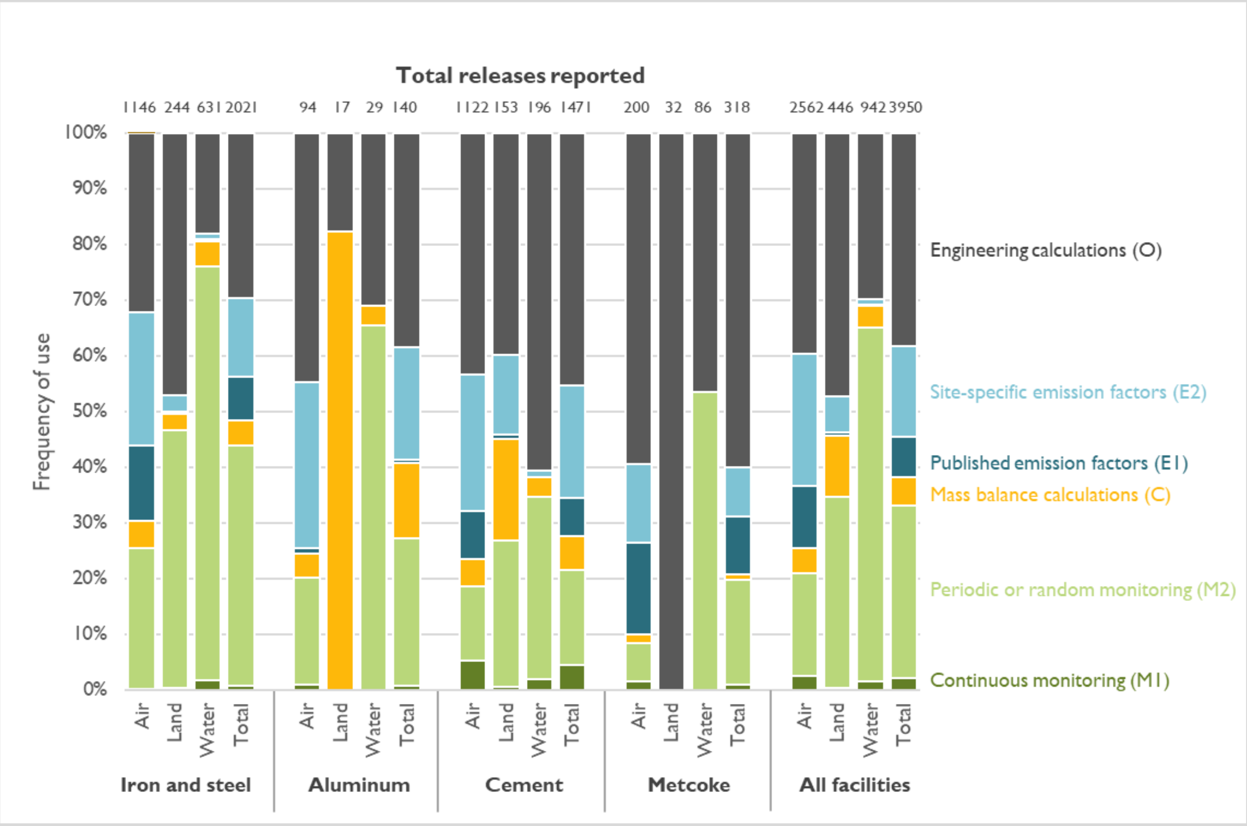
[185] U.S. EPA. 2022. *TRI Data Quality*. Available at: https://www.epa.gov/toxics-release-inventory-tri-program/tri-data-quality.

[186] U.S. EPA. 1999. Section 313 of the *Emergency Planning and Community Right-to-Know Act: Toxic Chemical Release Inventory*. Available at: https://ordspub.epa.gov/ords/guideme_ext/guideme_ext/guideme/file/chemical%20distribution%20facilities.pdf.

[187] U.S. EPA. 1999. Section 313 of the *Emergency Planning and Community Right-to-Know Act: Toxic Chemical Release Inventory*. Available at: https://ordspub.epa.gov/ords/guideme_ext/guideme_ext/guideme/file/chemical%20distribution%20facilities.pdf.

Figure 27. Toxic emissions estimation methods, frequency of use



Prevailing methods: The dominant methods used to estimate facility-level toxic emissions are "engineering calculations" (38 percent of reported methods), periodic or random monitoring (31 percent), and site-specific emission factors (16 percent). The remaining methods are used less frequently: published emission factors, mass balance calculations, and continuous emission monitoring.

Facility-type effects: There are differences in the methods employed among the facility types. Iron and steel facilities rely more heavily on periodic or random monitoring than do other facilities (43 percent). Aluminum is the only facility to use mass balance calculations with some frequency (13.6 percent). Cement facilities use periodic or random monitoring less than other facilities (17 percent). Metcoke facilities use the largest percentage of engineering calculations (60 percent).

Release medium effects: The comparative differences in reporting method by release medium are also substantial. Water releases tend to rely most heavily on periodic or random monitoring, whereas published and site-specific emission factors are used most commonly for air emissions (respectively 10.8 and 24.4 percent). Land releases employ the largest percentage of mass balance calculations of any category (11.8 percent). In the cases of aluminum and metcoke land releases, very few facilities report toxic releases, so the methods of the limited number that do determine the overall industry reporting method.

Overall Toxic Releases Inventory uncertainty rating:

The uncertainty ratings in Table 27 reflect a qualitative assessment of the calculation methods employed by each industry. In general, greater use of direct measurement and periodic or random measurements resulted in greater certainty, whereas use of engineering calculations reduced certainty. “A” represents greater certainty and “D” represents less certainty. Importantly, this assessment of uncertainty does not comment on values’ accuracy. Calculation methods with a high level of certainty may still be inaccurate if, for example, direct measurement equipment malfunctions, just as an engineering calculation may yield an extremely accurate result due to precise computer modeling or engineering experience.

Table 27. Qualitative uncertainty assessment of Toxic Releases Inventory Data

Facility Type	Air	Land	Water
Iron and steel	B	B	A
Aluminum	B	A	A
Cement	B	B	C
Metallurgic coke	C	D	B

EPA National Emissions Inventory 2017 uncertainty analysis

EPA’s National Emissions Inventory database is a combination of data submitted by state, local, and tribal (SLT) agencies and supplemental data added by U.S. EPA. SLT agencies are required to report emissions as point sources for all facilities that meet or exceed emissions thresholds specified by the Air Emissions Reporting Rule (AERR). Under the AERR, SLT agencies require facilities to report to them, and U.S. EPA requires SLT agencies to report to it.[188] SLT and U.S. EPA data are compiled in U.S. EPA’s Emissions Inventory System (EIS) in a process that includes automated and manual quality control checks.

The general approach U.S. EPA takes to building the National Emissions Inventory point source inventory, which provides the National Emissions Inventory data for our databases, is to use SLT-submitted emissions, locations, and release point parameters wherever possible. U.S. EPA gap-fills missing emissions values with U.S. EPA data where available.[189] As U.S. EPA notes, one reason that SLT data may not be available is that hazardous air pollutants are voluntarily reported, and thus some state-level data and certain pollutants are not reported.[190]

Data from SLT agencies and U.S. EPA come from a wide variety of sources and calculation methods. For SLT agencies, U.S. EPA encourages the use of National Emissions Inventory emissions estimation tools,

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[188] U.S. EPA. “What facilities are required to report to the NEI?” Available at: https://www.epa.gov/air-emissions-inventories/what-facilities-are-required-report-nei.

[189] U.S. EPA. 2021. *2017 National Emissions Inventory: January 2021 Updated Release, Technical Support Document*. Available at: https://www.epa.gov/sites/default/files/2021-02/documents/nei2017_tsd_full_jan2021.pdf .

[190] U.S. EPA. 2022. “2017 national Emissions Inventory Summary of Quality Assurance information.” Available at: https://www.epa.gov/system/files/documents/2022-01/2017-nei-qa-summary-info_1.pdf.

which include emissions factors based on U.S. EPA rule-development efforts. According to U.S. EPA, “in many cases, these factors are more recent than those in WebFire and AP-42, and agencies are encouraged to rely on these where available.”[191] However, standards differ by states. While some SLT agencies use the same emissions thresholds as the AERR, other states have lower limits or may require hazardous air pollutants to be reported.

In the 2017 National Emissions Inventory, U.S. EPA supplemented SLT data with data from 18 separate U.S. EPA datasets, one of which was the Toxic Releases Inventory for 2017. U.S. EPA ranks these datasets in an order of preference driven by the accuracy of their calculation methods and levels of uncertainty.[192] The primary purpose of these U.S. EPA datasets beyond gap-filling pollutants or sources not provided by SLT agencies is to resolve inconsistencies in SLT agency-reported pollutant submissions for particulate matter and to speciate SLT agency-reported total chromium into hexavalent and trivalent forms.[193] Which specific U.S. EPA dataset a given National Emissions Inventory data point comes from is not reported in the National Emissions Inventory.

Quality assurance

U.S. EPA’s quality approach consists of both automated quality assurance checks and manual quality assurance steps. Automated checks are applied when data enters U.S. EPA’s Emissions Inventory System. If problems are found, “then the data are not loaded into the EIS and the data submitter is notified to correct and resubmit the data. These checks are run on both the data SLTs submit as well as data EPA loads to EIS. A list of checks is available on the 2017 National Emissions Inventory website as part of the documentation. In addition, the EPA provided a QA list to SLT agencies as part of the 2017 National Emissions Inventory Process. That list provided recommended quality assurance checks for SLTs to perform in advance of submitting their data to EIS.”[194]

Calculation methods

Both SLTs and U.S. EPA report information about the calculation methods used to develop data included in the National Emissions Inventory. This information is provided according to a list of codes, which each correspond to a different method of data collection (see Table 26). The exact code describing the methods behind each piece of data reported in the National Emissions Inventory is not reported as a part of National Emissions Inventory, so the distribution of calculation methods specific to industries cannot be calculated based on the National Emissions Inventory. However, U.S. EPA has published

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[191] U.S. EPA. 2016. Emissions Inventory Guidance for Implementation of Ozone and Particulate Matter National Ambient Air Quality Standards (NAAQS) and Regional Haze Regulations. Available at:https://www.epa.gov/sites/default/files/2016-12/documents/2016_ei_guidance_for_naaqs.pdf.

[192] U.S. EPA. 2021. *2017 National Emissions Inventory: January 2021 Updated Release, Technical Support Document*. Available at: https://www.epa.gov/sites/default/files/2021-02/documents/nei2017_tsd_full_jan2021.pdf.

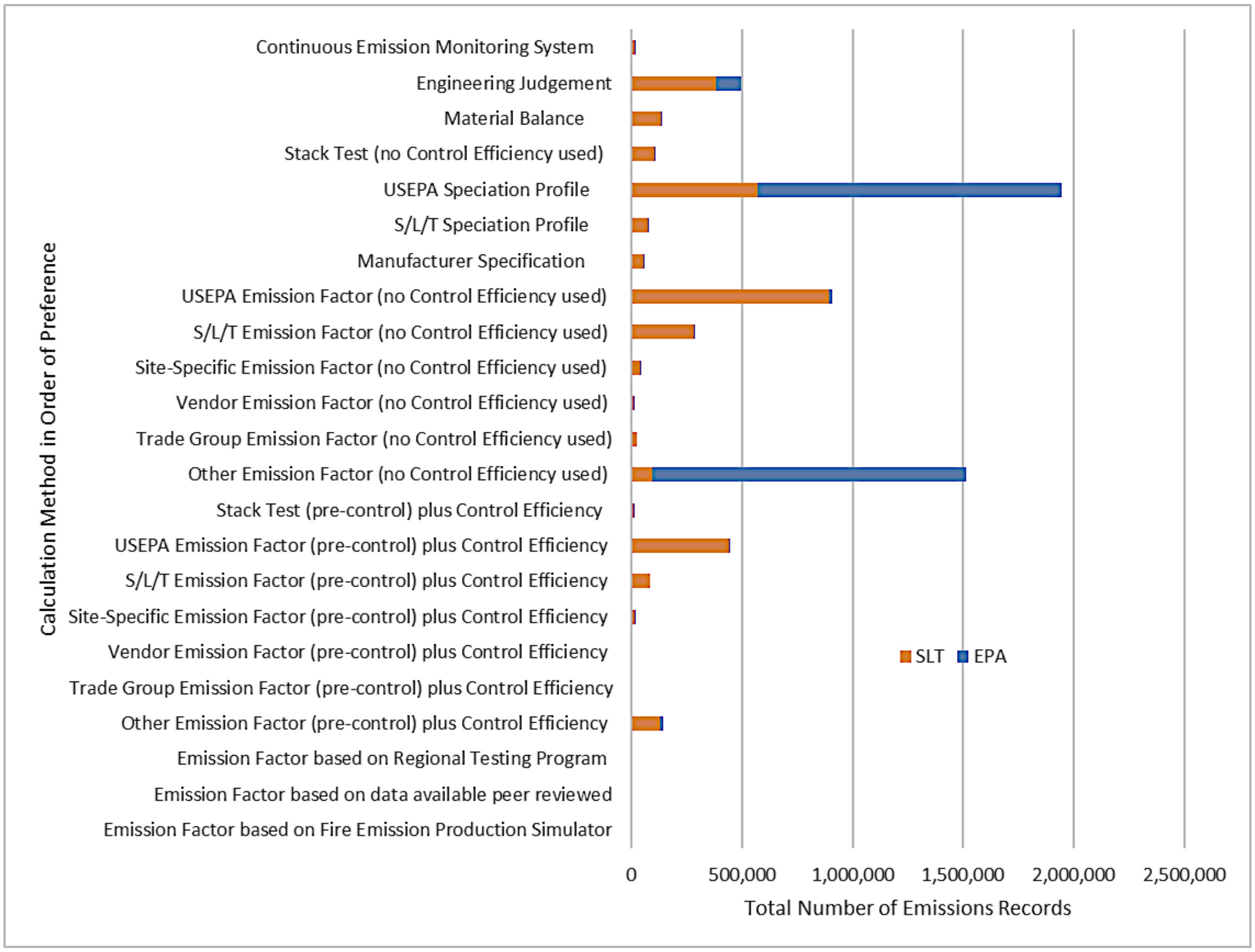
[193] Ibid.

[194] U.S. EPA. 2022. “2017 national Emissions Inventory Summary of Quality Assurance information.” Available at: https://www.epa.gov/system/files/documents/2022-01/2017-nei-qa-summary-info_1.pdf.

information describing the distribution of emissions calculation methods across all data submissions to the 2017 National Emissions Inventory from SLT agencies and from U.S. EPA.

As shown in Figure 28, SLT agencies and U.S. EPA together submitted data under 23 codes. These methods are presented in U.S. EPA's order of preference, meaning that the most preferred and accurate method is a "Continuous Emission Monitoring System."

Figure 28. Emissions calculation methods in U.S. EPA National Emissions Inventory 2017



For the 2020 National Emissions Inventory, U.S. EPA has requested that "facilities use stack test data, material balances, or other site-specific and reliable calculation methods to estimate emissions for their processes. Where such methods are not available, facilities can use the best available emission factors for similar processes."[195]

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[195] U.S. EPA. 2020. *2020 NEI Plan August 2020.* Available at: https://www.epa.gov/sites/default/files/2020-08/documents/2020_nei_plan_final.pdf.

8. CONCLUSIONS

For the industries we study, this work constitutes a first-of-a-kind effort to assemble and disseminate comprehensive, facility-level emissions and production data, assess health impacts, quantify environmental justice indicators, and evaluate approaches to reduce emissions. This section presents key findings of this effort.

Pollutants from the facilities we study are responsible for alarming rates of premature deaths, hospital admits, lost worker productivity, and respiratory and cardiac damage.

Eliminating the emissions of $PM_{2.5}$ and its precursors from production of iron, steel, cement, aluminum, and metallurgical coke could avoid 1,250–2,830 deaths annually. It could also drastically reduce the incidence of respiratory and cardiac events, including those that lead to hospitalization. An estimated 610 hospital admissions could be avoided annually for respiratory and cardiovascular illness, and 620 visits to the emergency room for asthma could be avoided. Beyond the health benefits of avoided illness, this would save money on costly medical bills for those affected and could keep people from missing work. Eliminating these emissions would avoid 140,840 lost workdays annually.

Iron and steel facilities have the largest impact on human health among the facilities we study.

Reducing emissions of $PM_{2.5}$ and its precursors within the iron and steel industry accounts for approximately 70 percent of the total incidence reductions across all health endpoints. This is followed by the cement industry, accounting for approximately 15 percent of the total incidence reductions across all endpoints, then by the metallurgical coke industry at 13 percent. The aluminum industry has the lowest potential for reductions in adverse health outcomes, at approximately 3 percent of the total potential incidence reduction across all health endpoints. However, even as the smallest contributor to health endpoints, reducing air pollution from the aluminum production industry still has the potential to have significant health benefits, including an annual reduction in 3,800 lost workdays.

Fence-line communities that support the industrial facilities we study are socioeconomically and environmentally disadvantaged, compared to the United States on average. Metcoke and iron or steel communities are most affected.

The closer a community is to an industrial facility, the more likely it is to be disadvantaged across all 8 demographic indicators and 9 of 12 environmental indicators. Metcoke and iron or steel communities are the most disadvantaged, especially host communities for BOF steel plants. For example, iron/steel and metallurgical coke plants are located in communities with 6.6 percent and 8.3 percent unemployment rate, as compared to a national average of 5.0 percent; the disparity in employment in the community adjacent to the (often) large employers may be justification for community representatives to seek community benefit agreements or local employment quotas. Metcoke and BOF steel communities also experience worse air quality, as measured by particulate matter and air toxics cancer risk.

Against a backdrop of diminishing domestic manufacturing, the 211 facilities in this study employ approximately 100,000 workers and represent an important segment of local economies throughout the United States.

Altogether, the facilities included in this database represent 1 percent of employment in domestic manufacturing. Industrywide, employment in domestic manufacturing has steadily decreased since the late 1970s, with large downward spikes occurring over the past 20 years. The decreasing number of manufacturing roles has had a devastating impact on manufacturing communities and resulted in decreased income, increased unemployment, and higher opioid addiction rates.

Policies that seek to bolster domestic manufacturing and reduce industrial emissions should be coupled with workforce development initiatives.

New federal policies, such as the *Infrastructure Investment and Jobs Act* and the *Inflation Reduction Act*, have sought to re-invigorate manufacturing communities by bolstering domestic manufacturing and its associated wages. Unfortunately, newly created manufacturing positions tend to require higher levels of education, and this can serve as a barrier to entry for legacy energy workers and other disadvantaged communities. As policymakers look to decarbonize and lessen environmental burdens on disadvantaged communities, they should recognize that manufacturing facilities have competing impacts on local communities. While the environmental impacts of such facilities may be staggering, reductions in employment can be similarly debilitating. Alongside policies that reduce industrial emissions, we recommend that that legislators consider policies that re-train existing workers and establish programs targeting legacy energy workers and other disadvantaged populations.

Industrial Buy Clean policies and emission standards are promising strategies to incentivize or require materials with low greenhouse gas emission intensities.

We find that there is a considerable spread in how pollution-intensive individual facilities are within a particular industry. The divergence of emission intensities is greatest in aluminum facilities. For all industries, the spread of emission intensities points to the potential effectiveness of policies that seek to bring down the emissions of the worst performers. Further, lessons learned from the best performers may provide insight into opportunities to reduce greenhouse gas emissions through knowledge transfer and process improvement.

Deploying pollution control strategies at industrial facilities can provide important employment opportunities while reducing adverse health and environmental impacts.

Investments in industrial decarbonization can deploy beneficial technologies in ways that provide benefits to local communities such as improved health and environment through reducing criteria air pollutants, hazardous air pollutants, and other toxic pollutants. Such investments also provide workforce development opportunities that can improve the economic vitality of local communities that host industrial facilities.

A vast array of technologies that can reduce or eliminate pollutants from industrial facilities are available, and many more are under development.

Industrial iron, steel, cement, aluminum, and metcoke production emits pollutants through numerous processes in relatively large, complex facilities. These industries produce pollution through pre-processing feedstocks, burning fossil fuels, conducting chemical processes, transformations, and as an output of those chemical changes. Industrial electricity use also contributes to emissions indirectly by drawing on fossil-powered generators. For these reasons, a variety of pollution control and fuel switching strategies are needed to mitigate the harmful impacts.

Fortunately, numerous technologies are available today that can substantially reduce greenhouse gas emissions and hazardous pollutants. Further, leading scientists, government agencies, and industry experts expect an assortment of emerging technologies will contribute to improvements in emissions. For example, a peer-reviewed 2022 paper identifies 86 “potentially transformative” technologies for the steel and iron industry. Historically, industries have achieved greater emissions reductions with technologies that shift the industry away from processes that create emissions, rather than those that control emissions after they are created.

Efficiency improvements can reduce emissions in the near term, while industries develop and deploy transformative technologies. Efficiency measures are numerous and can reduce the use of costly energy and material inputs. A recent study of the aluminum industry, for example, identified 52 distinct energy efficiency measures.

Reducing emissions in the electricity sector is an important industrial decarbonization strategy.

Indirect emissions from electricity produced offsite are a large share of the total greenhouse gas emissions for facilities that produce aluminum or iron and steel, specifically BOF and EAF flat product facilities. Transitioning these industries to low-emissions electricity sources can dramatically reduce sector-wide emissions.

Our review of prior studies and existing, public information highlights several data limitations that hinder effective policymaking and action.

Information about production, fuel and material inputs, jobs, and emissions is commonly available at the national level, while facility-level data is missing. Robust policymaking should be informed by the facility-by-facility differences, which determine the need and opportunity for various decarbonization and pollution control strategies. Further, emissions data are often missing due to lack of regulation and protections for confidential business information. The data that are available exist across many public databases, with no unified repository.

The accuracy of available greenhouse gas emissions data and toxic emissions reporting data is uncertain, largely due to the range of reporting methods available to facilities.

Facilities reporting under GHGRP, Toxic Releases Inventory, and National Emissions Inventory are allowed to use a range of methods, which have varying degrees of uncertainty, to estimate reported emissions. There are substantial differences in the methods used across industries, by transport medium and by pollutant type. Reported toxic emissions are most uncertain for cement and metallurgical coke production facilities. For greenhouse gases, process emissions from aluminum and cement facilities are the most uncertain, followed by combustion emissions for all the industries except cement.

This study is an important step in studying the current state of the industry and evaluating emissions reduction opportunities, but further work is needed to inform emission-reduction initiatives.

Topics for future research include the following:

- Evaluating the effectiveness of various decarbonization policies on industrial emissions
- Examining costs and benefits of building new, low-emission facilities
- Examining the physical and financial feasibility of adopting specific emissions-reduction technologies at industrial facilities
- Modeling public health co-benefits from adopting greenhouse-gas-reducing technologies and processes
- Evaluate health impacts of water and land pollution by each sector
- Examine worker safety and toxic exposure in industrial facilities
- Quantifying Scope 3 indirect emissions from each sector
- Conducting similar data assembly, analysis, and research for other industrial sectors responsible for large levels of emissions; examples include chemical and fertilizer production, ferroalloy production, petroleum refining, glass production, and food and beverage processing

Appendix A. ADDITIONAL ENVIRONMENTAL JUSTICE METRICS

Figure A-1. Diesel particulate matter exposure in the 3-mile radius of industrial facilities

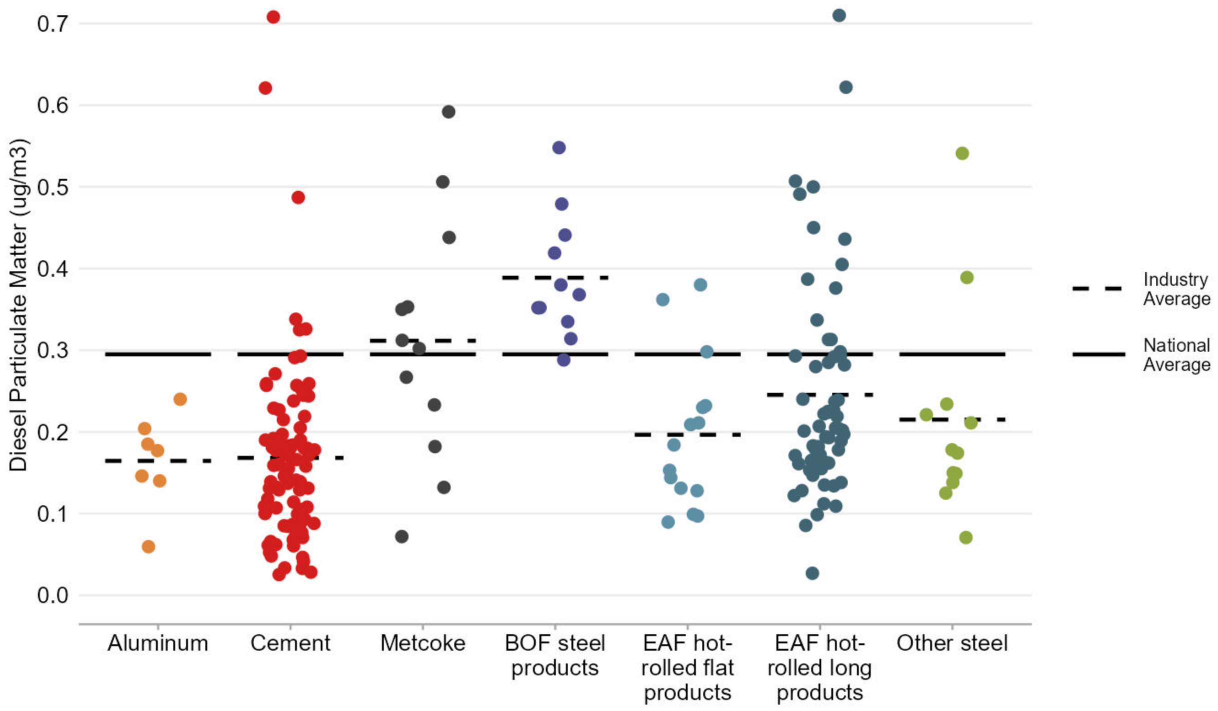


Figure A-2. Air toxics respiratory exposure in the 3-mile radius of industrial facilities

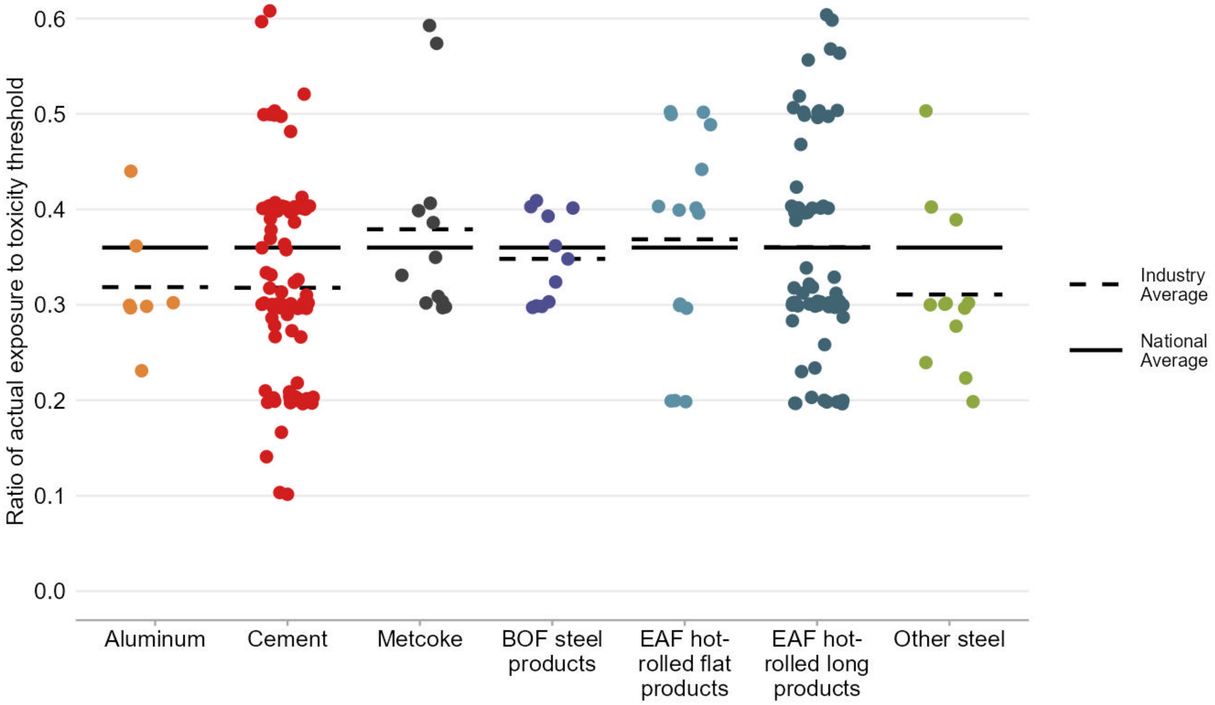
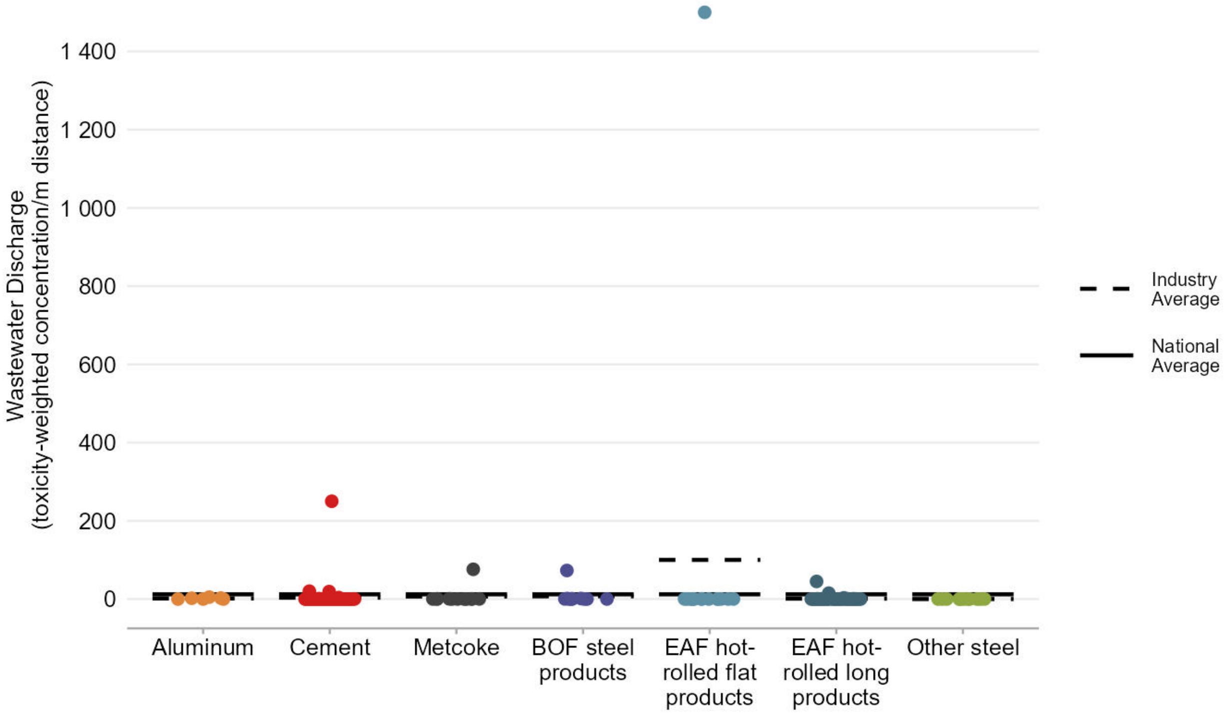


Figure A-3. Wastewater discharge exposure in the 3-mile radius of industrial facilities



Appendix B. ENVIRONMENTAL JUSTICE SENSITIVITY RESULTS

Synapse conducted a sensitivity analysis to characterize the differences in environmental justice indicators at various buffer distances from each facility. We varied the buffer distance from 1.0 miles to 5.0 miles in half-mile increments. Appendix Table 1 shows the combined sensitivity results for all plants, Appendix Table 2 shows results for iron and steel plants, Appendix Table 3 shows results for aluminum plants, Appendix Table 4 shows results for cement plants, and Appendix Table 5 shows results for metallurgical coke plants.

Appendix Table 1. Environmental justice indicators sensitivity results for all plants

Indicator	National Average	Buffer (miles)								
		1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
Socioeconomic Indicators										
Population density (people/sq mi)	94	670	760	792	797	800	794	778	759	735
People of Color	40.0%	32.3%	31.7%	31.6%	31.3%	31.5%	31.1%	31.1%	31.1%	31.1%
Low Income	31.0%	38.3%	37.7%	37.2%	37.0%	36.6%	36.1%	36.0%	35.6%	35.3%
Less Than High School Education	12.0%	13.5%	12.9%	12.9%	12.6%	12.5%	12.3%	12.3%	12.2%	12.2%
Linguistically Isolated	5.0%	2.7%	2.4%	2.4%	2.3%	2.5%	2.5%	2.5%	2.5%	2.5%
Under Age 5	6.0%	6.1%	6.0%	6.0%	6.0%	6.0%	6.1%	6.1%	6.1%	6.1%
Over Age 64	16.0%	16.6%	17.2%	17.0%	17.0%	16.9%	16.9%	17.0%	17.1%	17.2%
Unemployment Rate	5.0%	6.4%	6.3%	6.3%	6.0%	5.9%	5.9%	5.8%	5.8%	5.8%
Demographic Index	36.0%	35.1%	34.5%	34.3%	34.1%	33.9%	33.6%	33.4%	33.3%	33.1%
Environmental Indicators										
Lead Paint (% pre-1960s housing)	28.0%	38.1%	36.8%	35.9%	34.9%	34.1%	33.6%	33.3%	32.9%	32.6%
2017 Diesel Particulate Matter (ug/m3)	0.295	0.222	0.218	0.216	0.215	0.216	0.216	0.216	0.217	0.217
2017 Air Toxics Cancer Risk (risk per MM)	29.0	30.0	29.7	29.5	29.3	29.1	28.9	28.9	28.8	28.7
2017 Air Toxics Respiratory HI	0.360	0.344	0.343	0.341	0.339	0.339	0.338	0.338	0.337	0.337
Traffic Proximity (daily traffic count/distance to road)	710	307	311	323	331	337	341	345	347	344
Wastewater Discharge (toxicity-weighted concentration/m distance)	12.0	18.9	12.1	10.5	9.8	10.1	10.2	10.5	11.3	11.1
Superfund Proximity (site count/km distance)	0.130	0.164	0.149	0.142	0.131	0.129	0.123	0.120	0.121	0.120
RMP Facility Proximity (facility count/km distance)	0.750	1.119	1.053	0.990	0.943	0.906	0.872	0.838	0.809	0.786
Hazardous Waste Proximity (facility count/km distance)	2.20	1.71	1.57	1.50	1.43	1.39	1.35	1.32	1.28	1.24
Ozone (ppb)	42.6	42.7	42.6	42.8	42.9	43.0	43.1	43.1	43.1	43.1
Particulate Matter 2.5 (ug/m3)	8.74	8.61	8.59	8.58	8.56	8.56	8.55	8.55	8.55	8.53
Underground Storage Tanks (facilities/sq km area)	3.90	2.97	2.84	2.95	3.33	3.21	3.25	3.22	3.15	3.09
Data Coverage										
Percent of data available at buffer distance		88.8%	95.0%	97.3%	98.3%	98.8%	99.3%	99.3%	99.3%	99.8%

Appendix Table 2. Environmental justice indicators sensitivity results for iron and steel plants

Indicator	National Average	Buffer (miles)								
		1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
Socioeconomic Indicators										
Population density (people/sq mi)	94	988	1,090	1,089	1,074	1,061	1,039	1,010	977	937
People of Color	40.0%	37.4%	36.6%	36.2%	35.5%	35.2%	35.1%	35.0%	35.0%	34.7%
Low Income	31.0%	41.9%	41.1%	40.5%	39.9%	39.2%	38.9%	38.7%	38.2%	37.8%
Less Than High School Education	12.0%	15.4%	14.5%	14.0%	13.6%	13.5%	13.4%	13.3%	13.2%	13.0%
Linguistically Isolated	5.0%	2.7%	2.3%	2.4%	2.2%	2.3%	2.3%	2.3%	2.2%	2.2%
Under Age 5	6.0%	6.7%	6.5%	6.4%	6.4%	6.3%	6.3%	6.2%	6.2%	6.2%
Over Age 64	16.0%	15.7%	16.3%	16.1%	15.9%	15.9%	16.1%	16.1%	16.2%	16.3%
Unemployment Rate	5.0%	7.4%	7.2%	7.2%	6.9%	6.6%	6.5%	6.5%	6.4%	6.4%
Demographic Index	36.0%	39.5%	38.7%	38.4%	37.7%	37.3%	37.0%	36.9%	36.6%	36.3%
Environmental Indicators										
Lead Paint (% pre-1960s housing)	28.0%	43.3%	42.1%	41.1%	39.9%	39.5%	39.1%	38.7%	38.2%	37.7%
2017 Diesel Particulate Matter (ug/m3)	0.295	0.256	0.253	0.250	0.250	0.250	0.251	0.250	0.251	0.250
2017 Air Toxics Cancer Risk (risk per MM)	29.0	30.9	30.6	30.4	30.3	30.3	30.2	30.1	30.1	30.0
2017 Air Toxics Respiratory HI	0.360	0.357	0.356	0.355	0.354	0.354	0.354	0.353	0.353	0.354
Traffic Proximity (daily traffic count/distance to road)	710	348	366	386	400	404	409	411	414	410
Wastewater Discharge (toxicity-weighted concentration/m distance)	12.0	34.9	22.0	19.0	17.7	16.5	14.3	13.1	12.0	10.9
Superfund Proximity (site count/km distance)	0.130	0.171	0.156	0.148	0.129	0.126	0.118	0.115	0.115	0.112
RMP Facility Proximity (facility count/km distance)	0.750	1.443	1.359	1.277	1.207	1.148	1.107	1.061	1.029	0.996
Hazardous Waste Proximity (facility count/km distance)	2.20	2.40	2.18	2.05	1.93	1.87	1.80	1.73	1.68	1.62
Ozone (ppb)	42.6	42.6	42.4	42.4	42.4	42.4	42.4	42.4	42.4	42.4
Particulate Matter 2.5 (ug/m3)	8.74	8.81	8.81	8.79	8.79	8.79	8.79	8.79	8.79	8.79
Underground Storage Tanks (facilities/sq km area)	3.90	3.60	3.61	3.61	4.28	4.00	4.03	3.97	3.87	3.82
Data Coverage										
Percent of data available at buffer distance		92.0%	98.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%

Appendix Table 3. Environmental justice indicators sensitivity results for aluminum plants

Indicator	**National Average**	**Buffer (miles)**								
		1.0	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**	**4.5**	**5.0**
Socioeconomic Indicators										
Population density (people/sq mi)	94	4	82	220	269	292	284	280	284	274
People of Color	40.0%	11.3%	15.0%	15.0%	17.3%	17.9%	17.4%	17.0%	18.3%	18.3%
Low Income	31.0%	28.8%	26.0%	26.7%	31.7%	32.9%	32.4%	32.7%	32.7%	32.9%
Less Than High School Education	12.0%	6.8%	7.2%	9.0%	8.3%	8.3%	8.7%	9.4%	11.0%	11.0%
Linguistically Isolated	5.0%	0.50%	0.50%	0.43%	0.57%	0.29%	0.71%	0.86%	0.86%	0.86%
Under Age 5	6.0%	5.3%	5.2%	4.9%	5.3%	5.4%	5.6%	5.7%	5.9%	5.9%
Over Age 64	16.0%	18.8%	19.0%	18.0%	15.7%	16.0%	15.3%	15.6%	16.3%	16.3%
Unemployment Rate	5.0%	1.8%	2.3%	5.0%	5.0%	4.7%	5.3%	5.4%	5.4%	5.3%
Demographic Index	36.0%	20.3%	20.5%	21.0%	24.4%	25.4%	24.9%	24.7%	25.6%	25.6%
Environmental Indicators										
Lead Paint (% pre-1960s housing)	28.0%	46.3%	35.6%	31.7%	27.9%	26.2%	25.1%	24.8%	24.7%	25.2%
2017 Diesel Particulate Matter (ug/m3)	0.295	0.146	0.160	0.159	0.163	0.165	0.166	0.167	0.170	0.171
2017 Air Toxics Cancer Risk (risk per MM)	29.0	30.0	30.0	29.3	29.3	28.3	28.4	28.6	28.7	28.9
2017 Air Toxics Respiratory HI	0.360	0.325	0.337	0.326	0.326	0.319	0.320	0.320	0.321	0.321
Traffic Proximity (daily traffic count/distance to road)	710	214	152	108	114	108	109	112	110	112
Wastewater Discharge (toxicity-weighted concentration/m distance)	12.0	2.0	1.4	1.2	1.4	1.6	1.5	1.2	1.1	1.2
Superfund Proximity (site count/km distance)	0.130	0.059	0.053	0.049	0.051	0.051	0.051	0.052	0.053	0.053
RMP Facility Proximity (facility count/km distance)	0.750	0.930	0.708	0.591	0.554	0.533	0.519	0.497	0.474	0.467
Hazardous Waste Proximity (facility count/km distance)	2.20	1.14	1.00	0.84	0.76	0.71	0.67	0.63	0.60	0.58
Ozone (ppb)	42.6	39.1	38.9	39.7	39.7	39.6	39.6	39.6	39.6	39.7
Particulate Matter 2.5 (ug/m3)	8.74	8.30	8.36	8.40	8.41	8.39	8.38	8.38	8.39	8.39
Underground Storage Tanks (facilities/sq km area)	3.90	0.66	0.60	1.28	1.64	1.67	1.55	1.53	1.48	1.58
Data Coverage										
Percent of data available at buffer distance		86.3%	91.7%	94.0%	96.3%	97.3%	98.5%	98.5%	98.5%	99.6%

Appendix Table 4. Environmental justice indicators sensitivity results for cement plants

Indicator	National Average	Buffer (miles)								
		1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
Socioeconomic Indicators										
Population density (people/sq mi)	94	344	420	479	504	526	539	534	527	519
People of Color	40.0%	25.8%	25.9%	26.3%	26.3%	27.2%	27.0%	27.3%	27.4%	27.9%
Low Income	31.0%	32.1%	32.8%	32.5%	32.7%	32.5%	32.2%	32.1%	32.0%	32.1%
Less Than High School Education	12.0%	10.6%	10.9%	11.2%	11.2%	11.2%	11.0%	10.9%	10.9%	11.1%
Linguistically Isolated	5.0%	2.9%	2.7%	2.7%	2.6%	2.9%	2.9%	2.9%	2.9%	3.0%
Under Age 5	6.0%	5.5%	5.6%	5.6%	5.7%	5.8%	6.0%	6.0%	6.1%	6.1%
Over Age 64	16.0%	17.7%	18.1%	18.0%	18.3%	18.0%	17.8%	18.0%	18.0%	18.1%
Unemployment Rate	5.0%	5.1%	5.1%	5.1%	4.8%	4.9%	5.0%	5.0%	4.9%	5.0%
Demographic Index	36.0%	28.6%	29.0%	29.1%	29.3%	29.4%	29.4%	29.5%	29.6%	29.8%
Environmental Indicators										
Lead Paint (% pre-1960s housing)	28.0%	28.7%	27.5%	27.0%	26.7%	25.8%	25.5%	25.2%	25.1%	25.1%
2017 Diesel Particulate Matter (ug/m3)	0.295	0.173	0.169	0.168	0.166	0.168	0.170	0.171	0.172	0.172
2017 Air Toxics Cancer Risk (risk per MM)	29.0	26.7	26.5	26.3	26.0	26.0	25.8	25.9	25.9	25.8
2017 Air Toxics Respiratory HI	0.360	0.325	0.323	0.321	0.317	0.318	0.317	0.317	0.317	0.316
Traffic Proximity (daily traffic count/distance to road)	710	237	236	245	251	252	256	261	263	261
Wastewater Discharge (toxicity-weighted concentration/m distance)	12.0	0.7	0.5	0.7	1.1	3.6	6.7	8.7	12.1	13.0
Superfund Proximity (site count/km distance)	0.130	0.132	0.124	0.122	0.118	0.121	0.120	0.119	0.119	0.119
RMP Facility Proximity (facility count/km distance)	0.750	0.576	0.541	0.521	0.521	0.527	0.522	0.517	0.510	0.509
Hazardous Waste Proximity (facility count/km distance)	2.20	0.73	0.70	0.72	0.72	0.72	0.73	0.74	0.74	0.74
Ozone (ppb)	42.6	42.8	42.9	43.2	43.6	43.8	44.0	44.0	44.0	44.1
Particulate Matter 2.5 (ug/m3)	8.74	8.30	8.25	8.25	8.22	8.22	8.19	8.19	8.19	8.16
Underground Storage Tanks (facilities/sq km area)	3.90	1.55	1.59	1.86	2.01	2.10	2.21	2.22	2.20	2.13
Data Coverage										
Percent of data available at buffer distance		56.4%	85.0%	99.3%	99.3%	99.3%	99.3%	99.3%	99.3%	99.3%

Appendix Table 5. Environmental justice indicators sensitivity results for metallurgical coke plants

Indicator	National Average	Buffer (miles)								
		1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
Socioeconomic Indicators										
Population density (people/sq mi)	94	905	1,003	1,045	1,051	1,024	1,011	998	994	987
People of Color	40.0%	43.8%	42.0%	41.8%	40.9%	40.5%	38.0%	36.1%	34.5%	33.9%
Low Income	31.0%	55.1%	50.7%	48.8%	48.3%	47.9%	45.4%	44.1%	42.7%	41.4%
Less Than High School Education	12.0%	20.4%	17.2%	17.2%	16.9%	16.4%	15.5%	14.9%	14.3%	13.9%
Linguistically Isolated	5.0%	2.0%	1.5%	1.8%	2.3%	2.3%	2.3%	2.3%	2.2%	2.0%
Under Age 5	6.0%	6.2%	6.2%	5.8%	5.8%	5.7%	5.8%	5.6%	5.6%	5.6%
Over Age 64	16.0%	15.4%	16.6%	16.8%	16.8%	16.8%	17.2%	17.2%	17.7%	17.8%
Unemployment Rate	5.0%	9.2%	8.8%	8.4%	8.3%	8.3%	7.7%	7.2%	7.2%	6.9%
Demographic Index	36.0%	49.6%	46.5%	45.3%	44.8%	44.5%	42.0%	40.2%	38.7%	37.8%
Environmental Indicators										
Lead Paint (% pre-1960s housing)	28.0%	57.7%	60.4%	59.9%	58.3%	56.4%	54.6%	53.8%	52.3%	51.4%
2017 Diesel Particulate Matter (ug/m3)	0.295	0.303	0.302	0.305	0.310	0.312	0.310	0.308	0.306	0.307
2017 Air Toxics Cancer Risk (risk per MM)	29.0	45.2	44.3	44.9	45.1	43.4	42.1	41.6	41.1	40.5
2017 Air Toxics Respiratory HI	0.360	0.385	0.383	0.381	0.381	0.379	0.378	0.377	0.372	0.372
Traffic Proximity (daily traffic count/distance to road)	710	475	453	481	475	535	558	574	566	574
Wastewater Discharge (toxicity-weighted concentration/m distance)	12.0	10.2	9.3	8.5	7.8	6.5	5.8	5.3	4.8	3.9
Superfund Proximity (site count/km distance)	0.130	0.352	0.311	0.294	0.281	0.253	0.230	0.223	0.226	0.225
RMP Facility Proximity (facility count/km distance)	0.750	2.330	2.359	2.222	2.104	1.951	1.772	1.603	1.444	1.340
Hazardous Waste Proximity (facility count/km distance)	2.20	3.10	3.00	2.92	2.95	2.85	2.74	2.62	2.46	2.33
Ozone (ppb)	42.6	43.8	43.8	43.8	43.8	43.8	43.8	43.8	43.8	43.8
Particulate Matter 2.5 (ug/m3)	8.74	9.25	9.25	9.25	9.25	9.25	9.25	9.25	9.24	9.25
Underground Storage Tanks (facilities/sq km area)	3.90	8.41	6.50	6.29	6.15	5.80	5.64	5.53	5.33	5.31
Data Coverage										
Percent of data available at buffer distance		100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%