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REPORT

LIGHTENING EMISSIONS IN HEAVY INDUSTRY:

REDUCING CO_2 IN CEMENT, CONCRETE, STEEL, AND ALUMINUM CAN HELP KEEP US ON A PATH TO 1.5 DEGREES

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Executive Summary

The industrial sector produces many of the products and materials we rely on. It takes mined inputs like limestone, iron ore, and alumina and turns them into vital raw materials like cement, steel, aluminum, glass, and paper, as well as basic chemicals that are used elsewhere in the economy. At the same time, industry is responsible for 30 percent of U.S. economy-wide greenhouse gas (GHG) emissions.[1] Without strong measures to switch to clean technologies, that percentage is expected to increase through 2050.[2] This is the timeframe by which scientists tell us the global economy must achieve net-zero emissions if we are to avoid the worst consequences of climate change. Globally, the proportion of GHG emissions from industry is even larger.[3] If we want to meet our climate goals, the United States and governments around the world that are committed to climate action must immediately enact policies aimed at decarbonizing the industrial sector.

However, in the United States, industry has been both technically challenging to decarbonize and politically challenging to regulate. The manufacturing processes by which many heavy industrial materials are made require very high temperatures and large amounts of energy.[4] Today, these processes depend primarily on burning fossil fuels in applications that are difficult to electrify.[5] Further, a large proportion of GHG emissions in the sector are from "process emissions"—those resulting from certain unavoidable chemical reactions necessary to produce goods from raw materials.[6] Finally, many industrial subsectors operate on thin profit margins and are sensitive to foreign competition.[7] As a result, climate action has at times been positioned as a threat to U.S. jobs, with some leaders arguing that any policies that raise operating costs would shift emissions offshore instead of reducing them.[8]

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A cement plant in Tehachapi Pass, California.

"On the industry side, both investing in R&D and in the deployment of new technologies that will help U.S. industry lead in creating low-carbon or zero-carbon industrial applications to the future, whether that's low carbon materials, steel, cement, or in zero-carbon areas like CCS and hydrogen. Those are places where you need public investment to actually help unlock new breakthroughs. And we have a big stake in having that innovation happen in the United States and then having the manufacturing happen co-located with the innovation."

—BRIAN DEESE, DIRECTOR OF THE NATIONAL ECONOMIC COUNCIL

For most other carbon-intensive sectors—electricity, transportation, buildings—the path to decarbonization primarily involves transitioning from reliance on fossil fuels to machines and processes that generate or run on clean, renewable electricity. In heavy industry, however, off-the-shelf technologies and measures alone, such as energy efficiency improvements, can reduce GHG emissions to some degree but cannot eliminate them.[9] The technologies necessary to reach deeper levels of decarbonization (50 percent and greater) are in early stages of development and deployment.[10] Further, for the chemicals sector to transform to a safe and sustainable industry that does not harm people, the environment, or the climate requires fundamental and comprehensive reform beyond decarbonization.[a]

In this issue brief, we present the results of new NRDC modeling, conducted with Evolved Energy Research, that assesses an ambitious but realistic economy-wide decarbonization scenario for the United States to stay on a 1.5 °C aligned pathway.[b] In our modeling, the U.S. industrial sector achieves a 70 percent reduction in GHG emissions compared with 2005 levels by 2050. A broad uptake of existing solutions like energy efficiency and electrification (where available) can deliver modest but important near-term GHG emissions reductions of roughly 35 percent below 2005 levels by 2030. However, our analysis shows that the U.S. industrial sector cannot achieve deeper levels of decarbonization without more investment in advanced technologies like industrial electrification, the use of hydrogen in steel manufacturing, and carbon capture and storage to abate emissions from cement manufacturing, all of which will require significant further innovation to unlock.[c]

These results have important implications for climate policies aimed at driving deep reductions in industrial GHG emissions. Many industrial facilities are expected to stay online for decades, and for those, 2050 is one investment cycle away.[11]

Given the long horizons for building or retrofitting industrial sites, it is critical that policymakers advance policies now to jump-start investments and plans. Low- and zero-emissions industrial processes must also become scalable and widely available in the next decade for less industrialized nations to meet expected growth without increasing emissions.

After presenting our results, we dive deep on four specific industrial subsectors: cement, concrete, steel, and aluminum. For each, we provide an overview of the subsector, including global CO_2 footprint, primary production methods, and key technologies and measures for reducing GHG emissions. As our discussion demonstrates, the pathway to decarbonization for these industries runs through innovation, not obsolescence. That's because these products will continue to form the foundation of our modern built environment for decades to come; all four are necessary for critical infrastructure like roads, schools, hospitals, and clean water systems. These industrial materials are also critical to our clean energy transition: Providing electricity and mobility in a carbon-constrained world will require a lot of cement, concrete, steel, and aluminum to build wind turbines, solar panels, and electric vehicles. Further, global demand for these products is growing, not shrinking—global cement production increased in 2020 despite the economic downturn caused by the pandemic, and global crude steel production dropped just 1 percent.[12] Yet there are few, if any, viable alternatives at scale.

Finally, we provide important policy tools for delivering climate progress over this critical decade and by midcentury.

Cleaning up the U.S. industrial sector is imperative to meeting our nation's climate goals. Moreover, it will bolster the global competitiveness of domestic industrial manufacturing and help retain and create high-quality jobs. U.S. policymakers have the tools they need and must take immediate steps to ensure that this vital sector is part of our zero-carbon future.

a NRDC advocates reforming the chemical industry according to the road map laid out in the Louisville Charter for Safer Chemicals, available at https://comingcleaninc.org/louisville-charter/read.

b This modeling, which used Evolved Energy's PATHWAYS+RIO model to assess potential technological pathways to a net-zero economy by 2050, will be released in an NRDC report later this year. In the context of this modeling analysis, we account for all industrial emissions, aligning with the U.S. Environmental Protection Agency's GHG Inventory. While the chemicals sector is included in this modeling, it is important to note that the modeled decarbonization interventions are insufficient to address the additional significant environmental and health harms of this sector. For chemicals, more comprehensive reform is needed, such as phasing out fossil fuel feedstocks and eliminating the production of toxic chemicals and harmful plastics. Documentation on the EnergyPATHWAYS model used for NRDC's analysis can be found on the Evolved Energy website, https://www.evolved.energy/about. For the industrial subsectors included in NRDC's modeling, see Table 12 in the Evolved Energy report *Net Zero by 2050 Technical Supplement*, at https://a35761c6-b61b-4a48-81d2-fa0a879c476a.usrfiles.com/ugd/a35761_4129edd3b6be4274adff581fc361ca2a.pdf.

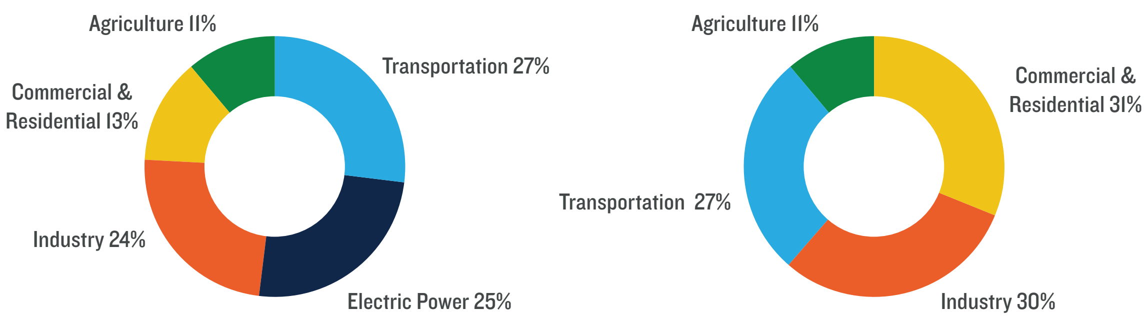
c NRDC's modeling also considered other measures, like the elimination of fossil feedstocks in industrial production. However, even under this scenario, our results indicate that the industrial sector will still need to invest in technologies like electrification, hydrogen, and carbon capture for certain processes like cement to achieve deep decarbonization. The full set of modeled scenarios will be discussed in forthcoming NRDC reports.

Reducing GHG Emissions in the U.S. Industrial Sector

When emissions from electricity generation are included in the calculation, industrial activities accounted for nearly one-third of total U.S. GHG emissions by economic sector in 2020, as shown in Figure 1.[13] Under current policy efforts in the United States, which focus largely on decarbonizing the power and transportation sectors and give little attention to curbing industrial emissions, industry will become the largest source of U.S. GHG emissions within the decade.[14] Decarbonizing heavy industry is challenging. The sector is heterogeneous and heavily dependent on fossil fuels in applications that are not yet candidates for electrification, and many products have complex supply chains. Despite these challenges, cleaning up these industries offers an enormous opportunity to reduce emissions and help meet our near- and long-term climate targets.

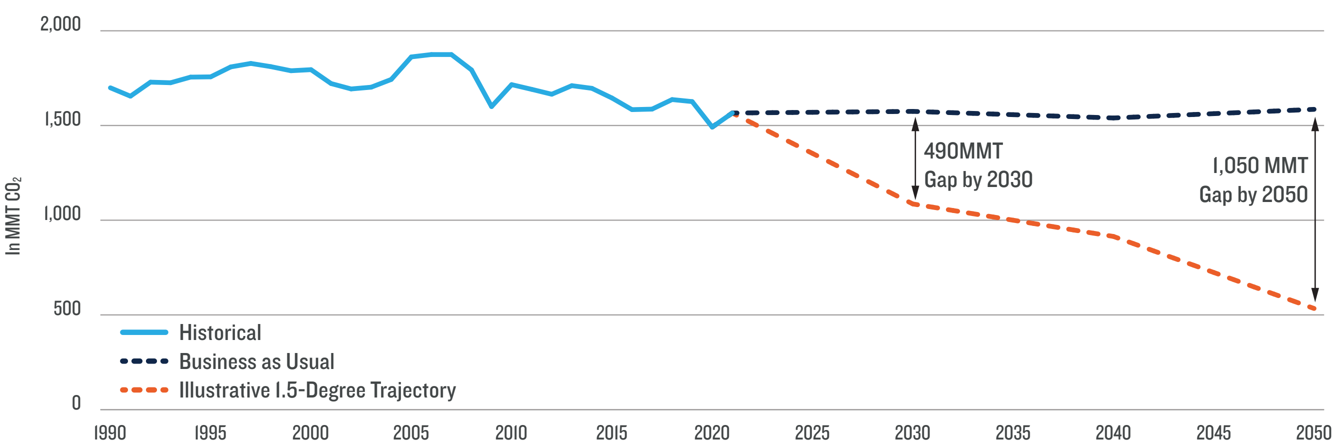
NRDC recently modeled the economy-wide decarbonization efforts necessary to meet President Biden's pledge to slash U.S. GHGs at least 50 percent below 2005 levels by 2030, and to align the country with international efforts to limit global warming to 1.5 °C. These projections indicate that the industrial sector is not on track to deliver the necessary emissions reductions. As shown in Figure 2, the gap between the sector's existing emissions trajectory and what is necessary to protect the climate is only set to widen by 2050. At that point, massive and difficult reductions in industrial GHGs will be necessary to stay on a 1.5 °C warming pathway—and avoid severe harm to people and communities, major loss of species, and social and economic upheaval around the world.

Figure 1: GHG Emissions From U.S. Industry With and Without Emissions From Electricity (2020)



Source: EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020.

Figure 2: U.S. Industrial CO_2 Emissions (Including Electricity-Related): 1990–2050



U.S. industrial CO_2 emissions shown under the sector's existing emissions trajectory compared with NRDC's modeled deep decarbonization pathway aligned with a 1.5 °C warming trajectory.
Source of historic trend line: U.S. Energy Information Administration, *Monthly Energy Review*, October 2022, Table 11.4: Carbon Dioxide Emissions From Energy Consumption: Industrial Sector.

Prior NRDC analysis found that to achieve the upcoming U.S. target of at least 50 percent economy-wide GHG savings by 2030, industrial emissions must fall by roughly one-third below 2005 levels.[15] If undertaken promptly and at scale, this can be achieved with existing technologies and measures like energy efficiency and electric boilers to supply low-temperature steam for industrial processes, alongside demand reduction and better materials recycling.

Now, our new modeling analysis finds that beyond 2030, deeper cuts will require developing and scaling new technologies that could prove transformational in decarbonizing sectors like cement and steel manufacturing. These include carbon capture and storage (CCS), the process of capturing CO_2 before it enters the atmosphere and storing it permanently underground, and green hydrogen, a carbon-free fuel made by using electricity generated from renewable sources like solar and wind to split water into hydrogen and oxygen.

LOWERING GHG EMISSIONS IN THE U.S. INDUSTRIAL SECTOR WILL REQUIRE BOTH EXISTING TECHNOLOGIES AND RAPID INNOVATION

NRDC's modeling analysis shows that cleaning up heavy industry is one of our key opportunities to cut CO_2 pollution on the scale needed to address climate change, as captured in Figure 3. GHG emissions reductions in the U.S. industrial sector are highlighted by the gray box.

According to the modeled results, four key solutions together slash U.S. industrial emissions by 70 percent in 2050 (Figure 4). The largest driver of these emissions reductions is cleaning up already electrified industrial end uses by investing in renewables like solar and wind and energy efficiency, represented by the light blue wedge. Electricity is used in multiple industrial subsectors such as aluminum, steel, and other fabricated metals manufacturing, as well as in the food industry, which consumes large amounts of electricity, predominantly for process cooling and refrigeration.[16] These solutions are effectively available to industrial facilities today but may require additional incentives to ensure widespread adoption across facilities of all types and sizes.

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Steel being produced at the HYBRIT fossil-free steel pilot plant in Lulea, Sweden.

Figure 3: U.S. GHG Emissions Reductions in 2050 by End-Use Sector (Compared With 2005 Levels, in MMT CO_2e)

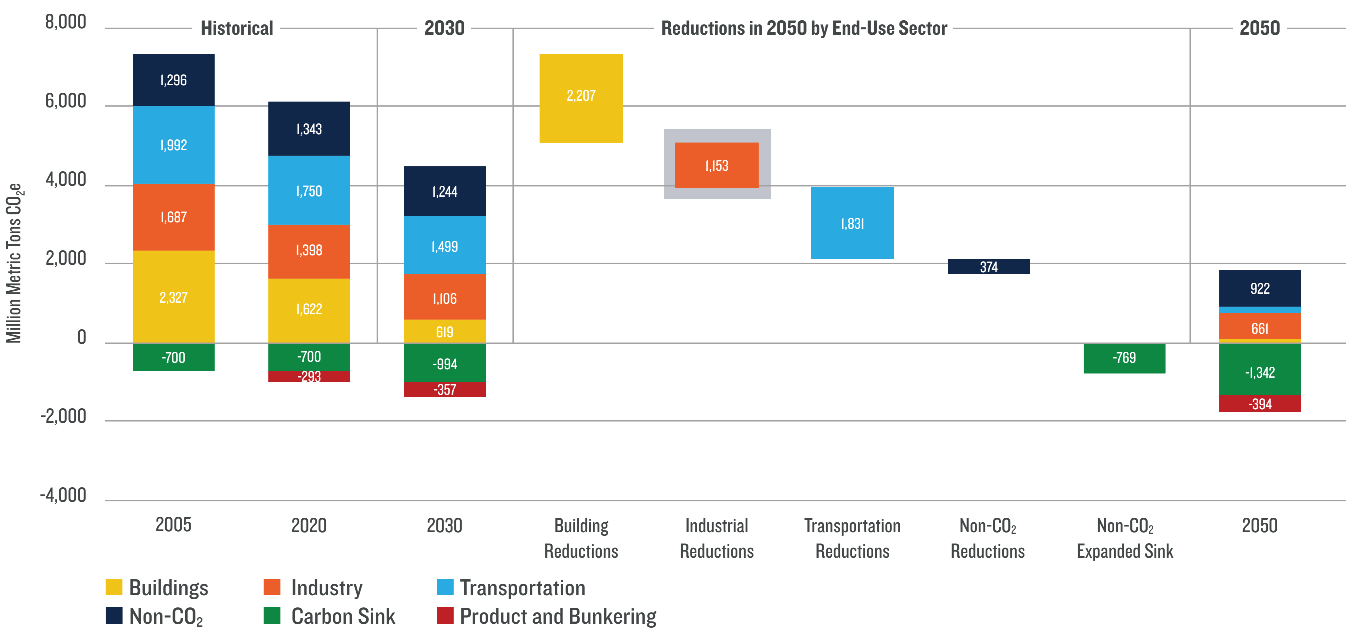
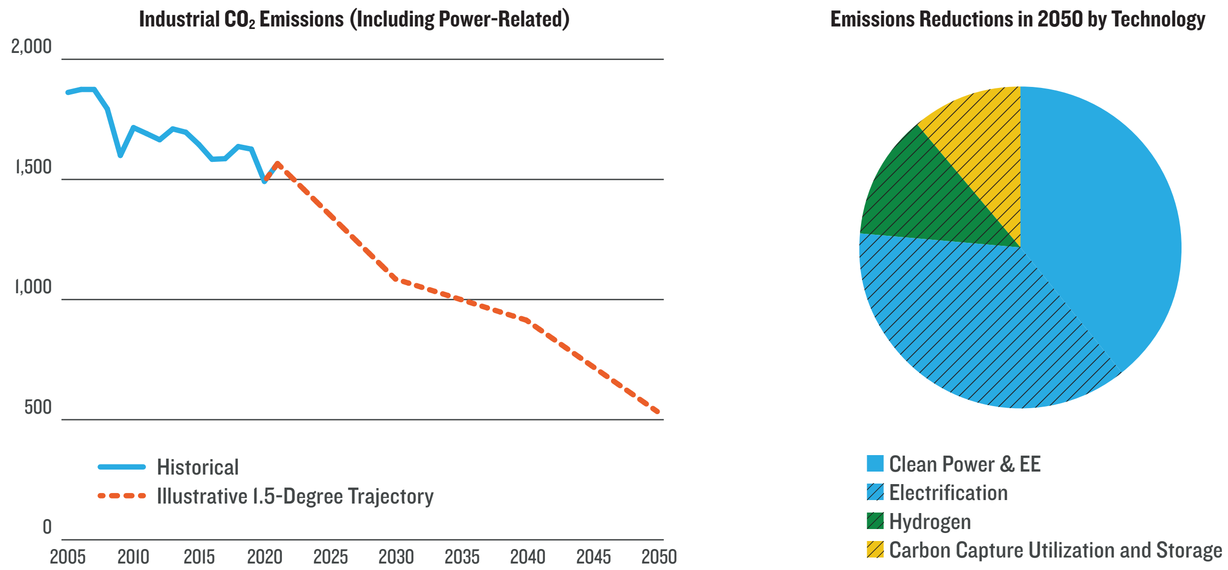


Figure 4: U.S. Industrial CO_2 Emissions (2005–2050) and CO_2 Reductions in 2050 by Technology Driver



In NRDC's modeled emissions reduction trajectory for the U.S. industrial sector through 2050, we assume energy productivity gains of 2 percent per year; while ambitious, this is lower than the historical maximum of roughly 3 percent per year.[17] To achieve deep U.S. industrial emissions cuts of 70 percent relative to a 2005 baseline, green hydrogen is deployed in steel manufacturing and CCS in the lime and cement sectors. Outside the industrial sector, CO_2 is also captured directly from the atmosphere via direct air capture (DAC) and utilized to produce synthetic fuels, which displace fossil fuels in hard-to-electrify applications, such as jet fuels and shipping. Some CO_2 captured from cement plants may also be used for this purpose.

Source: Preliminary PATHWAYS modeling by Evolved Energy for NRDC.

Additional GHG cuts in the sector are driven by the massive transition of currently non-electrified industrial processes to efficient, electric options run on clean power. For example, in NRDC's core modeled scenario, 90 percent of pipeline gas and diesel energy used for irrigation is converted to electricity.[18] These powerful emissions reduction strategies are followed by using green hydrogen in key industrial sectors like steel manufacturing, and finally, by deploying CCS in the cement and lime sectors.[19] These solutions are represented by the hatched blue, green, and yellow wedges, respectively, and will require significant additional investment in technological innovation and industrial transformation to unlock.

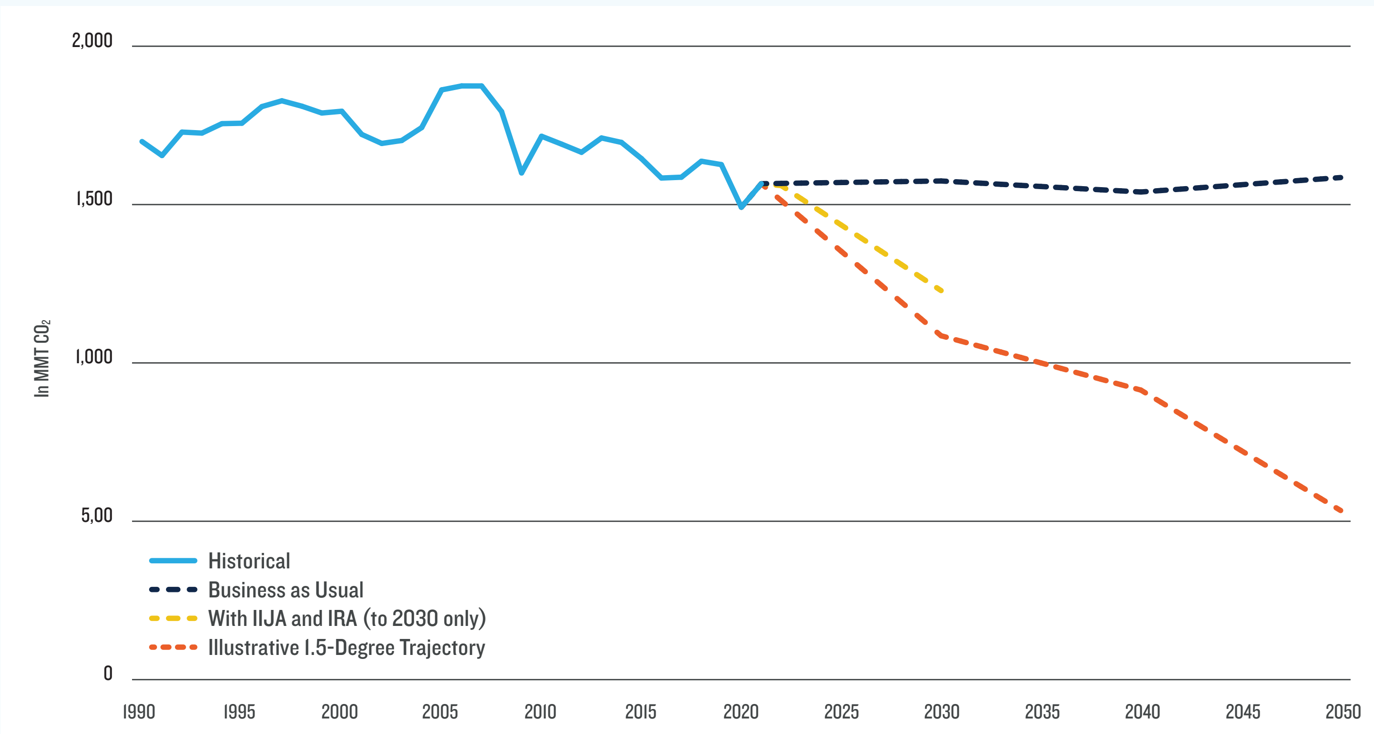
Success in decarbonizing U.S. industry will thus require near-term action on two parallel tracks. First, the sector needs to widely deploy existing solutions across industrial facilities of all sizes and classes. Second, the United States needs to rapidly reduce the risk of adopting the advanced technologies integral to deeper decarbonization, including by demonstrating commercial viability for these technologies; lowering barriers to their adoption, such as permitting and financing; building first- through third-of-a-kind projects; and ensuring that policies are in place to drive technological deployment at scale by midcentury.

NEW CLIMATE LAW IS A GAME-CHANGER FOR THE U.S. INDUSTRIAL SECTOR

The Inflation Reduction Act (IRA), passed by Congress and signed into law by President Biden in August 2022, includes billions in direct funding to help the most energy-intensive industrial sectors like cement, steel, and aluminum install transformational technologies to deeply decarbonize their plants, as well as tax credits and incentives for advanced manufacturing and low-carbon technology adoption.[20] If well implemented, these provisions will help spur investments in clean electrified processes, efficiency, green hydrogen for clean steel manufacturing, installation of carbon capture technology at cement plants, and other advanced technologies. The IRA also funds low-carbon industrial materials disclosure and labeling and contains billions for federal agencies to procure low-carbon concrete, steel, and other clean building materials for infrastructure projects. Together, these programs will provide manufacturers with the incentives to equip their facilities with decarbonization technologies, making U.S. industry cleaner, more efficient, and more competitive globally. Investments in low-carbon industrial processes and upgrades also have the potential to reduce many types of pollution, improving the health and air quality of communities near industrial plants.[21] Coupled with the Infrastructure Investment and Jobs Act (IIJA), enacted in 2021, this major federal legislative package contains game-changing investments and incentives for industrial decarbonization.[22]

While NRDC's modeled assessment of the impact of the IRA and IIJA extends only through 2030, the policies in these bills have the potential to dramatically bend the industrial GHG emissions curve in the current decade toward the trajectory we need to be aligned with a 1.5 °C warming pathway, as shown in Figure 5.

Figure 5: U.S. Industrial CO_2 Emissions (Including Power-Related Emissions): 1990–2050



Source: Preliminary NRDC assessment of IIJA and IRA.

Cement, Concrete, Steel, and Aluminum are GHG-Intensive—But Vital to Modern Life

This section provides a high-level primer on cement, concrete, steel, and aluminum. These four industrial subsectors are necessary to critical infrastructure and a clean energy economy but face unique challenges to decarbonization. We present an overview of each subsector, including global CO_2 footprint, primary production methods, and key technologies and measures for reducing emissions.

CEMENT AND CONCRETE

Worldwide emissions of CO_2 from making cement for buildings, roads, and other infrastructure totaled nearly 2.6 billion metric tons in 2021, reflecting a more than threefold increase over the prior three decades.[23] Globally, CO_2 emissions from cement production now account for 7 to 8 percent of global emissions.[24] That means that if cement were a country, it would be the world's fourth-largest emitter of CO_2, behind China, the United States, and India.[25] In the United States, the 92 largest cement plants reported emissions of 67 million metric tons of carbon dioxide equivalent (CO_2e) to the U.S. Environmental Protection Agency (EPA) in 2019—alone equal to 10 percent of direct reported emissions from the U.S. industrial sector.[26]

The cement industry has such a large climate footprint in no small part because it is used throughout our built environment. Cement is the binding agent in concrete, the most widely used material on earth. Cement typically makes up roughly 10 percent of concrete by mass yet accounts for upwards of 80 percent of the GHG emissions linked to concrete production (Figure 6).[27] Demand for cement is growing with urbanization and the need to replace aging infrastructure, and it will remain a major global construction material into the future.

Roughly 60 percent of the emissions from cement production are associated with the chemical process of calcination, in which raw materials like limestone are heated at high

A worker pouring concrete during construction of a sidewalk in Washington, DC.

temperatures to release CO_2 from the rock and produce clinker, a stony residue that is ground and combined with other ingredients to make cement.[28] Nearly all the remaining emissions come from burning fossil fuels to heat the large kilns where this reaction occurs to approximately 1400 °C, as shown in Figure 7.[29]

Near-term solutions like improving plant energy efficiency, switching from fossil fuels to cleaner energy sources, and partially replacing traditional cement with low-carbon alternatives (known as supplementary cementitious materials, or SCMs) in ready-mix concrete, as well as pursuing material and design efficiency strategies that reduce the amount of concrete used in construction and improving end-of-life reuse of materials, can make a significant contribution to curbing emissions. An especially promising near-term decarbonization lever for the cement industry is the use of limestone calcined clay cement (LC3). This is a group of blended cements produced by substituting up to half

Figure 6: Emissions From Concrete

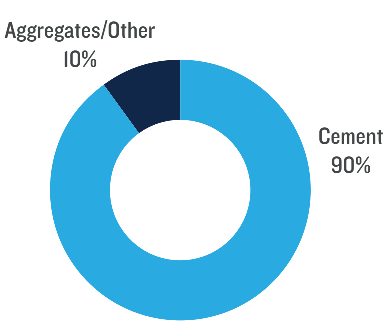
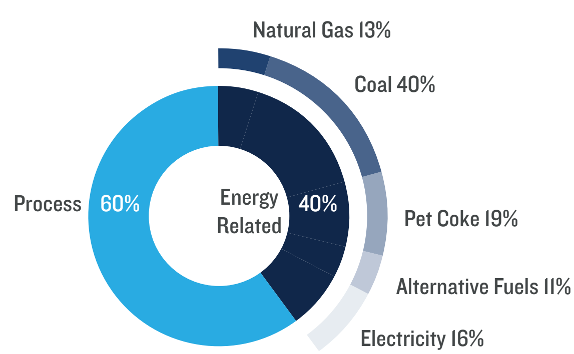


Figure 7: Sources of CO_2 Emissions From U.S. Cement Manufacturing (2019)



of traditional clinker with a mix of calcined clay, limestone, and gypsum, which can reduce cement emissions by up to 40 percent.[30]

However, even in combination, these solutions cannot completely eliminate emissions from cement production. At least 30 percent of a cement plant's emissions (and sometimes more)—the portion associated with the chemical decomposition of limestone, as described above—will remain unaffected and continue to be emitted to the atmosphere. Full decarbonization of existing cement plants will require the additional deployment of advanced technologies, such as CCS, alongside these other strategies. However, we must be clear that carbon capture in cement is not a way to prolong the use of dirty fossil fuels that can be replaced. Instead, it is a way to address emissions that cannot otherwise be abated for a material we rely on.

Emerging technologies also have the potential to become game-changers in the cement sector. One such innovative technology is Brimstone's cement alternative, which uses ground-up calcium silicate rocks instead of heating limestone. While Brimstone is currently a pre-commercial technology, it opens the possibility of producing ordinary Portland cement without the process emissions.[31] Elsewhere, Australian-based Calix is developing another pre-commercial yet highly innovative technology called LEILAC (Low Emissions Intensity Lime and Cement), which captures pure CO_2 as it is released from heated limestone. LEILAC uses a novel kiln design that heats limestone in the absence of other gases, producing a purer CO_2 stream that is cheaper to capture than the CO_2 in traditional kiln flue gas. Calix completed a two-year pilot test of its kiln at a Heidelberg Cement plant in Belgium and has now entered an agreement with the European Union for a scaled-up trial in Germany.[32]

STEEL

In industry, cement emissions are rivaled only by those from iron and steel production, which accounts for roughly another 7 to 8 percent of global CO_2 emissions. Steel is the most used metal in the world by mass. The combination of increasing steel demand in developing countries and fairly stable demand in advanced economies means global steel production is projected to increase from about 1,880 million tonnes in 2020 to as much as 2,500 million tonnes in 2050.[33] Building the wind turbines, transmission towers, and other infrastructure we need for economy-wide decarbonization will require a lot of steel.

In today's steel industry, iron ore is processed into steel by one of two principal routes. In primary steelmaking, carbon-rich pig iron is melted using an integrated blast furnace (BF) or basic oxygen furnace (BOF), a process that depends on burning coke (a fuel derived from coal) to chemically reduce iron ores at temperatures of up to 2300 °C.[34] In secondary steelmaking, an electric arc furnace (EAF) is used to melt primarily steel scrap, which results in less energy used to produce a ton of steel and substantially fewer emissions.[35]

The Essar Steel plant on St. Mary's River in Sault Sainte Marie, Michigan.

TABLE 1: STEEL PRODUCTION BY FACILITY TYPE FOR MAJOR STEEL-PRODUCING COUNTRIES AND REGIONS (2020)					
	Million tonnes, crude steel production	BOF %	EAF %	Other %	Total %
European Union (28)	139.2	58	42		100
Other Europe	40	33	68		100
Commonwealth of Independent States (Russia, Ukraine, Other)	100.2	67	28	5	100
United States	72.7	29	71		100
Canada	11	54	46		100
Mexico	16.8	17	83		100
Central and South America	38.8	68	31	1	100
Africa	17.4	15	85		100
Middle East	45.4	6	94		100
China	1,064.8	91	9		100
India	100.3	45	56		100
Japan	83.2	75	25		100
South Korea	67.1	69	31		100
Taiwan	21	60.6	39.4		100
Other Asia	52.4	28.2	66	5.7	100
Australia	5.5	74	26		100
New Zealand	0.6	100			100
Total	**1,876.4**	**73.2**	**26.3**	**0.5**	**100**

Source: 2021 World Steel in Figures, World Steel Association, April 2021.

While globally more than 70 percent of steel is produced using blast furnaces, the ratio is roughly the inverse in the United States, where EAF facilities dominate the industry, as shown in Table 1.[36]

Recycling of steel can mitigate some of the sector's emissions provided that the electric arc furnaces used to melt steel scrap in secondary steelmaking run on zero-carbon electricity. However, recycling alone will not suffice to meet global steel demand because of the limitations in scrap metal availability and the accumulation of impurities in secondary steel.[37] Instead, zeroing out emissions from primary steelmaking can be achieved by replacing a blast furnace with an electric arc furnace powered by zero-carbon electricity, paired with the use of direct reduced iron, which is the product of the direct reduction of iron ore into iron, via a process that runs on 100 percent hydrogen.[38] To the extent that the hydrogen is "green"—produced from water in a process powered by 100 percent (or near 100 percent) renewable electricity—the process would result in nearly emissions-free steel (see the section below on green hydrogen for greater detail on this technology). The use of green hydrogen in steelmaking is a technically proven production method, and all major European steel players have received government support to build or test the technology.[39] The United States is now poised to join and even lead this transition, owing to major green hydrogen incentives available via the IRA.[40]

An alternative technology, developed by Boston Metal, is molten oxide electrolysis (MOE), which replaces fossil fuel–intensive processing in blast furnaces with clean electricity to convert iron ore directly into steel within a modular cell. While the technology is at a pre-commercial stage, the MOE process could be transformative in the steel industry by eliminating the need for coal in steel production.[41] Alternatively, emissions from blast furnace steelmaking can potentially be abated by capturing the CO_2 emitted at steel facilities and storing it permanently underground, but this application of CCS faces high technical and economic hurdles.[42]

© SSAB

The HYBRIT fossil-free steel pilot plant in Lulea, Sweden.

A worker uses a crane to lift a cask of molten aluminum along a potline at a Century Aluminum Company plant in Hawesville, Kentucky.

ALUMINUM

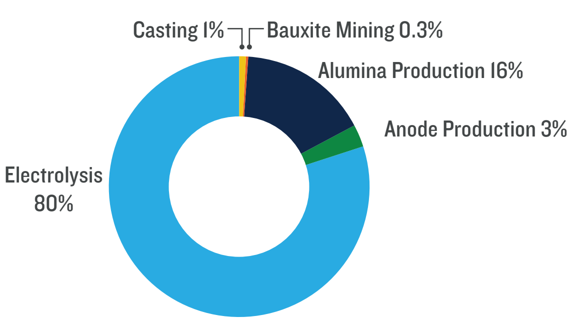
After steel, aluminum is the second most used metal in the world by mass and is integral to construction, transport, and power transmission. The aluminum industry is currently responsible for 2 percent of global GHG emissions, and demand for the material is growing significantly. Absent action, aluminum demand is projected to rise 80 percent by 2050. Strategies to improve material efficiency and ensure that aluminum is used effectively have the potential to limit that growth in demand to 50 percent.[43]

Nearly all of the sector's emissions (96 percent) come from first turning aluminum ore (known as bauxite) into alumina (mostly from burning fuel on-site) and then reducing that alumina into aluminum via electrolysis, a process that relies heavily on electricity. Aluminum smelting also results in direct process emissions, in which CO_2 is the product of aluminum electrolysis (Figure 8).[44]

Globally, the aluminum industry has in the past two decades built a greater reliance on dirty coal power, primarily because of coal-fired power plants built specifically to provide a local source of power to aluminum smelters in China.[45] Meanwhile, U.S. aluminum production has plummeted as smelters have closed, even as domestic demand for aluminum and aluminum imports have grown. In effect, the United States has sent aluminum production and its associated GHG emissions offshore.

Deep decarbonization of aluminum manufacturing is heavily dependent on the type of electricity available to aluminum smelters. Increasing the amount of electricity generated with renewable, zero-carbon resources is a key pathway to decarbonize aluminum manufacturing, alongside measures to improve recycling of aluminum scrap.

Figure 8: Share of GHG Emissions by Aluminum Production Phase (2019)



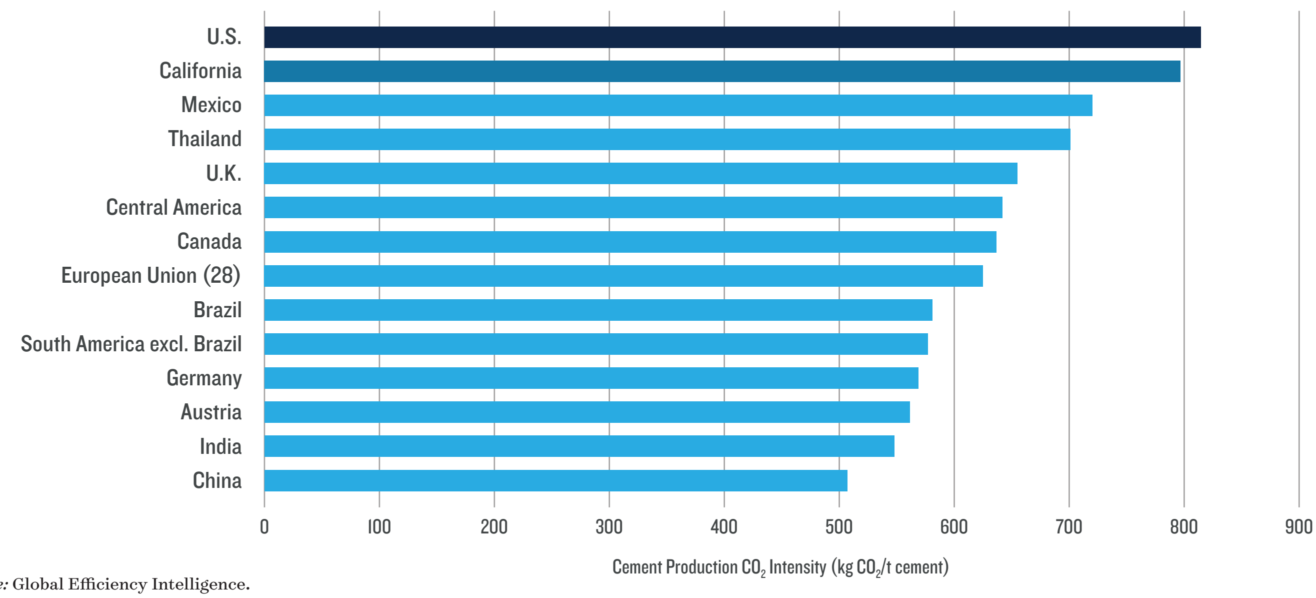
Source: Hasanbeigi, A., Springer, C., Shi, D. 2021. Aluminum Climate Impact—An International Benchmarking of Energy and CO_2 Intensities. Global Efficiency Intelligence. Florida, United States.

Beyond these strategies, adoption of advanced technology like the ELYSIS process developed by Alcoa, one of the world's largest manufacturers of aluminum, and Rio Tinto, the world's second-largest metals and mining corporation, could prove transformational in zeroing out process emissions from aluminum smelting.[46] ELYSIS, which is still a pre-commercial technology, replaces the carbon anodes used in traditional aluminum smelting with inert anodes, eliminating the direct CO_2 emissions from the aluminum smelter and instead emitting pure oxygen.[47]

TRADE EXPOSURE AND COMPETITIVENESS

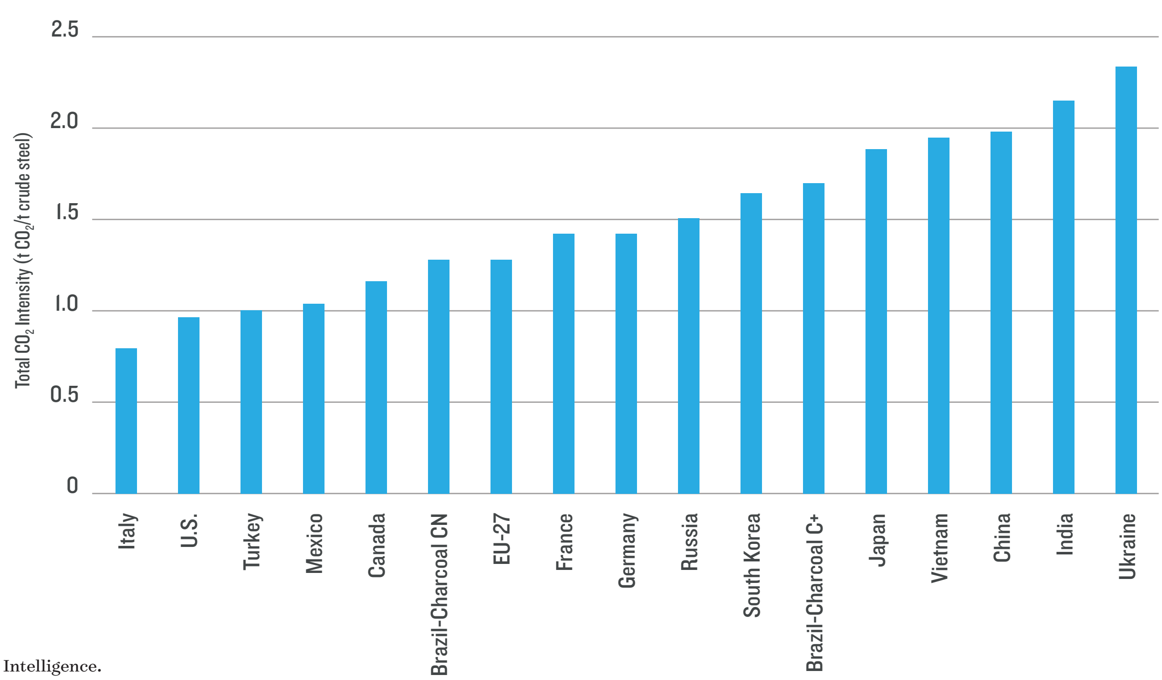
Industrial subsectors like cement, steel, and aluminum manufacturing are energy-intensive industries that operate on thin profit margins and are particularly vulnerable to global competition. Historically, this has prompted U.S. industry leaders to portray climate policy as a threat to jobs and to argue that policies to decarbonize domestic industry would only drive emissions offshore as industrial facilities relocate.[48]

Figure 9: International Comparison of Cement Production CO_2 Intensity (2015)



Source: Global Efficiency Intelligence.

Figure 10: CO_2 Intensity of Steel Manufactured in Top Steel-Producing Countries (2019)



Source: Global Efficiency Intelligence.

However, those arguments ignore the nuances facing each industrial subsector. For example, U.S. cement plants tend to be more fuel and emissions intensive than plants in India and China, partly because they were built earlier and have not adopted state-of-the-art technologies (Figure 9).[49]

U.S. steel plants, on the other hand, have a competitive advantage relative to their foreign counterparts in terms of CO_2 emissions. Among the six largest steel producers—China, India, Japan, the United States, Russia, and South Korea—which together account for 75 percent of global steel production, the United States has the lowest CO_2 intensity (Figure 10).[50] However, this is in large part because unlike many other steel-producing countries, domestic steel production in the United States is predominantly secondary production or recycling using electric arc furnaces, which are much lower-emitting than primary production.[51] At the same time, the United States is a top global importer of steel, which suggests that a large share of GHG emissions associated with U.S. steel consumption are effectively being exported abroad.

Given this, U.S. climate policies should cover both the emissions from domestic production and the emissions embodied (or embedded) in imported products. (Embodied carbon emissions are those associated with a final product that occur during raw material extraction, upstream production, transportation, and manufacturing stages before the material is used.[52]) Such policies not only can ensure global emissions reductions but can bolster the competitiveness of cleaner domestic manufacturers.

One approach is to use carbon border adjustment mechanisms (CBAMs).[53] CBAM proposals vary. Many add a fee onto imported goods based on their embodied CO_2 that is equivalent to the fee imposed on domestic carbon pollution.[54] The goal is to reduce global GHG emissions and level the playing field for domestic manufacturers subject to emissions standards or other climate policies that may raise their costs relative to foreign competitors. This avoids the emergence of trade advantages and disadvantages as governments enact climate policies with different levels of ambition, potentially requiring industrial manufacturers in energy-intensive and trade-exposed sectors, such as steel, aluminum, and cement, to spend money on new technologies in some countries but not in others.[55]

The Solutions: Technologies and Measures

A suite of industry measures and technologies exist to reduce carbon emissions in the industrial sector, including energy efficiency, electrification, and use of renewable energy sources (solar and wind) alongside emerging technologies such as green hydrogen and CCS. As industrial decarbonization accelerates, these technologies must be deployed under strict environmental, social, and climate considerations and in a manner consistent with 1.5 °C pathways.

As advocates, policymakers, and industry consider decarbonization strategies, it is important to recognize that there can be tension between incremental and deeper emissions reductions. Incremental, near-term GHG reductions can be achieved through investments in energy efficiency and other measures at existing facilities. Dramatically reducing emissions in heavy industry, however, will require fundamental changes in production processes, including either deep retrofits or the construction of new facilities, and will generally take longer. While NRDC does not propose a simple rule to distinguish which near-term investments make sense and which might slow the transition to the fundamental process changes we ultimately need, it is incumbent upon stakeholders to continue to evaluate how to maximize both near-term reductions and the shift to deeply decarbonized industrial production. Critically, the United States must aim to ensure that favored approaches do not lock in incremental improvements to the status quo at the expense of deep decarbonization of the sector.

ENERGY EFFICIENCY

Because the processes used to make industrial materials like cement, steel, and aluminum are so energy intensive and most energy used in the sector is fossil fuel–based, energy savings mean less fossil fuel burning and fewer GHG emissions. The potential for energy savings across the industrial sector has been estimated at upwards of 15 percent.[56] It is almost

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The ArcelorMittal steel mill in Cleveland, Ohio.

certainly much larger, however.[57] The lack of plant-specific data hampers the ability of researchers to demonstrate the potential for deeper savings based on whole-plant integrated performance and on process engineering improvements. Moreover, improvements in operations and maintenance, which also have the potential to reduce energy usage, are seldom analyzed in efficiency studies.

There are various ways to reduce on-site energy use, including on-site energy efficiency, waste heat recovery, and advancing innovation of products and services. One promising approach to slash energy usage is strategic energy management (SEM), a rigorous method by which a company can set ambitious energy performance improvement goals and regularly measure its success at achieving them. SEM focuses on continual energy efficiency improvements at industrial facilities—and often on their suppliers as well. It takes a comprehensive look at reducing facility energy use, including via both capital upgrades and improved operations and maintenance—for example, actions such as turning off an air compressor during lunch break that managers of industrial sites can take to continually reduce energy use, increase efficiency, and improve environmental performance. SEM can be promoted through utility incentive programs and potentially a well-designed federal tax incentive.[58]

Additionally, there are energy efficiency upgrade opportunities to improve equipment within industrial processes, as well as within the industrial buildings themselves. On-site energy efficiency programs can include any combination of measures, such as improvements to motors, fans, furnaces, compressors, and process loads.

MATERIALS EFFICIENCY

There are opportunities across the value chain to increase industrial materials efficiency—that is, reduce the volume of materials consumed and thus reduce GHG emissions. For example, recirculating residual materials back into the manufacturing process can reduce use of virgin raw materials in the cement and steelmaking processes. Further, recycling of materials at the end of their useful life—such as the use of scrap steel as an input in the EAF steelmaking process—also contributes to fewer emissions and smaller burdens on landfills.[59]

In the cement and concrete industries, readily available technologies can help reduce the amount of emissions-intensive clinker in the final cement product. For example, mixing in lower-carbon materials like limestone and calcined clay can partially replace traditional clinker in the final cement mixture and significantly reduce associated emissions.[60] Farther down the value chain, materials efficiency strategies like substitution of SCMs can reduce the amount of cement mixed into ready-mix concrete, as can using crushed concrete from demolition in lieu of newly mined aggregate materials in concrete mixes.[61] Finally, a variety of building design and construction strategies can reduce the amount of concrete (and other common construction materials, such as steel) used in buildings and thus significantly lower their embodied CO_2 emissions.[62]

ELECTRIFICATION WITH RENEWABLES

It is critical to decarbonize low- to mid-temperature process heat applications in the industrial sector by replacing carbon-intensive fossil fuels with zero-carbon electricity. Advancements in industrial heat pump technology have the potential to significantly reduce energy consumption and GHG emissions. Currently, a few types of industrial heat pumps can provide heat up to about 160 °C and cover roughly 44 percent of industrial process heat needs, and products are in development to raise this temperature ceiling to about 200 °C, covering roughly 55 percent of industrial process heat needs.[63] Examples of industrial processes that can use these heat pumps include food and beverage production, pulp and paper manufacturing, and chemicals manufacturing.[64] Some industries have also electrified high-temperature processes, the leading example being the steel industry and its use of electric arc furnaces, which can reach 1760 °C.[65]

Many industry sectors are already heavily reliant on electricity, and converting more industrial processes to use electricity will only increase this demand. Transitioning to renewable energy sources like solar and wind will thus dramatically reduce industrial GHG emissions. However, widening the scale and accelerating the pace of the renewable energy resource buildout necessary to power heavy industrial processes remains a major challenge.

Because of how electricity intensive processes like aluminum and steel making are, these heavy industries have the potential to become supporters of increased 24/7 carbon free electricity generation and influential voices in advocating for the distribution system to deliver renewable energy where it is needed. This is critical, as generating the very large amount of solar and wind energy necessary to meet the needs of the industrial sector may not be feasible (politically or geographically) within any one state.

GREEN HYDROGEN

The unique needs of many industrial processes—for example, the need for a chemical reaction to reduce iron ore into steel—means electrification cannot carry us all the way to our decarbonization goals. A carbon-free, high-energy source like green hydrogen is also necessary. Green hydrogen, produced by splitting water in electrolyzers in a process powered by renewable electricity, can replace coal and gas as a feedstock for this chemical reaction in steel manufacturing. The process represents a major technological breakthrough; replacing fossil fuels in the direct reduction of iron with hydrogen produced with renewable energy enables the manufacturing of nearly emissions-free steel.

The IRA includes a generous 10-year hydrogen production tax credit that is now the largest hydrogen subsidy in the world. The tax credit is available for “clean” hydrogen, which the law defines as a hydrogen source that delivers a GHG reduction of at least 60 percent relative to the unabated fossil hydrogen, or “gray” hydrogen, that comes from natural gas.

With this incentive, green hydrogen can begin to compete with dirty, incumbent hydrogen in some parts of the United States today, and in most places by the end of this decade, years ahead of previous projections.[66]

This rapid shift has major implications for U.S. industrial manufacturing; with these incentives in place, replacing highly emitting blast furnace steel mills that run on coal with clean, green hydrogen–based steel plants may be financially viable for the first time in the United States. Early estimates even suggest that in some cases, green steel can now be cheaper than traditional, coal-based steel. This means that the United States now has the potential to produce the world's most competitive low- and zero-carbon steel, which would revitalize the domestic steel industry.[67] It also offers an opportunity for the United States to lead on and bolster global efforts to decarbonize the steel sector and, along with other major economies such as Britain, India, China, and the European Union, and others, meet their recently announced goal of ensuring that "near-zero emission steel production" is "established and growing in every region by 2030."[68]

CARBON UTILIZATION AND MINERALIZATION

The most common form of carbon utilization uses CO_2 from industrial sources—including CO_2 captured during cement production—as an input in concrete production. CO_2 is injected into the concrete, making it stronger and reducing how much cement is needed. Today's methods can sequester up to 5 percent of CO_2 emissions from production, but newer technologies could sequester up to 30 percent.[69]

Another promising form of carbon utilization in concrete is called carbon mineralization. This process involves making or enhancing common high-volume concrete inputs, such as aggregate and SCMs, with CO_2, turning the concrete into a carbon sink. (Aggregate, typically a granular material like sand, gravel, or crushed stone, makes up roughly 80 percent of most concrete mixes by mass.) U.S.-based Blue Planet and U.K.-based Carbon8 have already developed commercial products that produce carbon-mineralized aggregate.[70]

CARBON CAPTURE AND STORAGE

In addition to the challenges of decarbonizing their energy sources, industrial subsectors like cement, aluminum, and others must address process emissions (emissions from chemical reactions inherent in creating their products). In some cases, such as existing cement manufacturing, the only retrofit solution available to achieve very low- or zero-emission production is CCS, the process of capturing CO_2 before it enters the atmosphere, transporting it, and storing it permanently underground in geologic formations or saline aquifers.[71]

Industrial CCS is still at a nascent stage, and additional public investments in research, development, and deployment are needed. For CCS to become available at scale in sectors like cement, investments in pilots and larger-scale demonstrations must start now to bring down its costs and risks. The IRA increased the tax credit for CCS at cement plants to $85 per ton of CO_2 captured and stored securely in geologic formations (and not used for enhanced oil recovery). At its prior value of $50 per ton, the tax credit was not high enough to make such projects viable. Analysis shows that the IRA's enhancement will change that, allowing CCS projects at industrial facilities like cement plants to move forward for the first time.[72]

Carbon capture in industrial subsectors like cement is not a way to prolong reliance on dirty fossil fuels that can be replaced, but rather a necessary tool to address a large share of emissions that cannot otherwise be abated for a material we rely on. It may also be needed to decarbonize parts of other industrial subsectors. However, CCS is not a blanket solution. It should be selectively deployed as an additional tool to reach climate goals that cannot be met through other measures, such as material adjustments, energy efficiency improvements, fuel switching, and electrification.

Key Policy Tools

NRDC's modeling shows that getting to deep levels of decarbonization in U.S. heavy industry will require both widespread adoption of off-the-shelf solutions like investments in energy efficiency and electric boilers and the development and scaling of new, transformational technologies including high levels of electrification of more industrial processes, use of green hydrogen in steel manufacturing, and use of CCS in the cement sector. Additionally, the average life span of U.S. industrial plants in sectors like cement can reach 50 years, and most existing plants have not been designed with state-of-the-art technologies and process integration. This makes retrofit options vital to decarbonization domestically. It is also critical that industrial decarbonization efforts avoid locking in technologies or infrastructure that deliver incremental GHG emissions reductions but not the deeper cuts that the sector needs.

The following sets of policy tools—research, development, and demonstration funding; deployment and procurement incentives; and standards—can help the United States achieve the necessary deep reductions in industrial GHG emissions.

RESEARCH, DEVELOPMENT, AND DEMONSTRATION

Technologies to decarbonize industrial facilities like steel mills and cement plants are critical to addressing the climate crisis, and we have only a short window of time to develop the necessary solutions to meet our climate goals. This challenge requires strategic research and development (R&D) prioritization and focus in this decade on technologies that will support the most efficient pathways to a net-zero GHG economy by 2050 while delivering the most economic and public health benefits to Americans.

R&D aimed at developing deep decarbonization technologies in the industrial sector has long been underfunded at the U.S. Department of Energy (DOE). It is critical that the federal government significantly ramp up funding for clean energy R&D aimed specifically at decarbonizing heavy industry. It must also redress long-standing imbalances whereby energy end uses, such as industry, have been highly underfunded relative to energy production (e.g., renewable energy and fuels) as well as relative to their contribution to economy-wide GHG emissions. Large funding increases are needed

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Workers pouring concrete onto an elevated section of a high-speed rail line near Fresno, California.

for DOE's Advanced Manufacturing Office and for industrial decarbonization work within the department's Office of Clean Energy Demonstrations.

Moreover, those offices must seamlessly coordinate to support early-stage and later-stage demonstrations at industrial facilities, which help reduce the risk associated with being an early adopter of new technologies and encourages widespread deployment. In addition, DOE should expand its efforts on industrial electrification, green hydrogen, materials efficiency and recycling, novel cements, and other processes, as well as industrial carbon capture and storage.

DEPLOYMENT INCENTIVES

The biggest barrier to deep decarbonization is often the fact that advanced technologies are in a nascent development stage and very costly, and industrial manufacturers are limited in their ability to pass costs on to their customers. Industries like cement operate with low profit margins and face substantial capital costs in implementing key decarbonization levers.[73] Further, deep decarbonization is unlikely to happen incrementally; instead it will require high-risk investments in the near term, either to retool existing industrial facilities or to build first-in-class commercial-scale facilities producing ultra-low-emission steel, cement, and other building and construction materials.

Encouraging these investments in this decade will require leveraging federal tax policy, grants, and loans to provide a mix of incentives. As discussed above, the IRA's enhanced federal tax credit for CCS now provides a large incentive for industrial applications in sectors like cement. Also needed is a deployment tax incentive like those already existing in the clean energy sector, such as an industrial decarbonization tax credit or combination of multiple tax incentives matched on a cost-per-ton of CO_2 basis.

PROCUREMENT INCENTIVES

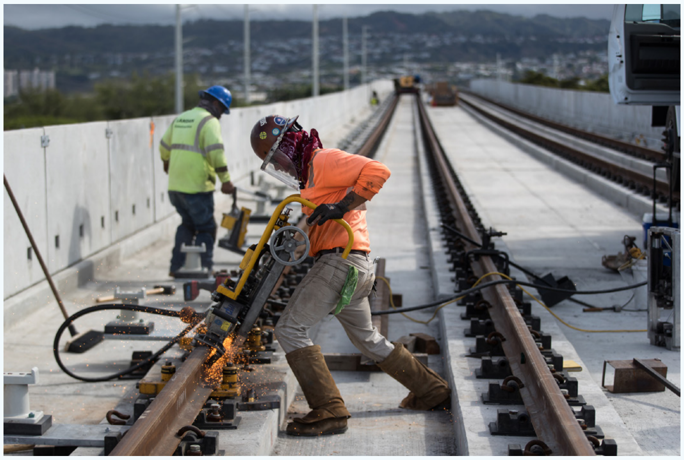
Federal and state government agencies are major purchasers of industrial building materials like concrete, cement, and steel for the construction of railways, buildings, roads, and bridges. This makes government procurement policies an immensely powerful tool in creating a market for lower-emission materials and helping to jump-start needed innovation.

Procurement policies like Buy Clean are popular, have the potential to deliver major GHG savings, and can do so in a way that supports domestic industrial manufacturing.[74] Buy Clean sets embodied carbon labeling requirements for a range of products and requires the government to take climate pollution (and labor protection) into account when awarding contracts. As more companies adopt technologies and practices to reduce their climate impact, the government can require lower and lower embodied carbon in the industrial building materials it purchases, tightening standards over time. Buy Clean policies not only directly reduce the carbon footprint of public works projects but can drive significant indirect spillover benefits. That's because as more companies adopt cleaner manufacturing processes to compete for the large pool of government-funded construction business, those same manufacturers will be selling low-carbon materials to buyers in the private market alongside the public sector.

Buy Clean can be an especially powerful policy tool because it can help governments account for and address pollution upstream in the supply chain and beyond their own borders—helping close the loophole wherein products like steel and cement are produced in places (other states or countries) with relatively weak regulations and consumed in places with stronger pollution standards.[75] Additionally, Buy Clean works in conjunction with RD&D and various types of deployment incentives. For example, by creating demand for decarbonized industrial products, Buy Clean can accelerate uptake of industrial decarbonization tax credits and other incentives offered in the IRA. Federal agencies like the General Services Administration, under the auspices of the Buy Clean Task Force, have already taken important initial steps to set standards for lower-carbon concrete and environmentally friendly asphalt used for federally funded construction projects.[76]

One area where public procurement can be especially helpful in spurring market transformation is in decarbonizing concrete, since nearly one-third of all concrete used for construction in the United States is purchased by governments (federal, state, and local).[77] And because of how ubiquitously concrete is used in our building environment, even relatively modest reductions in embodied CO_2 emissions can add up to big climate impacts. However, public procurement policies can do more than encourage incremental reductions in emissions; they can also expand what is possible in climate performance by encouraging continuous innovation in the sector—for example, by awarding performance-based bonuses or other types of incentives to high performers.[78] In 2022 NRDC published a guide to using public procurement to curb emissions associated with concrete, create a market for cleaner alternatives, and incentivize concrete makers to adopt innovative technologies and production techniques.[79] These recommendations have been incorporated into multiple state policy initiatives.[80]

BUY CLEAN POLICY TAKES CENTER STAGE



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A worker at a construction site for the Honolulu Rail Project in Honolulu, Hawai'i.

Following a December 2021 executive order, the Biden administration's Buy Clean Task Force announced in September 2022 that the federal government would use its enormous purchasing power to prioritize low-carbon procurement across four major materials categories—steel, concrete, asphalt, and flat glass, which together represent 98 percent of the materials purchased by the federal government.[81] Critically, the initiative will extend beyond direct federal purchasing to federally funded projects, notably including projects using funds passed through from the U.S. Department of Transportation to individual states.

The Buy Clean Task Force's recommendations come at a critical time, as federal and state agencies move forward with implementation of the 2021 Infrastructure Investment and Jobs Act, which includes historic levels of funding for infrastructure projects. Whether federal agencies are looking to construct high-performance green buildings; build new railways, highways, and bridges; rebuild a road or school after a natural disaster; or make a community more climate resilient, they should seek to use low-carbon concrete, steel, and other construction materials. Doing so would not only help these industries decarbonize and the nation meet its climate goals, but also support high-quality jobs and strengthen our manufacturing base.

Key implementing agencies like the Federal Highway Administration (FHWA) have a unique opportunity to ensure that billions in infrastructure investments are coupled with programs to purchase clean materials. Because so many transportation infrastructure projects are built using federal funds passed through to states and metropolitan planning organizations, the role of state departments of transportation in implementation will also be critical. FHWA and other agencies can help catalyze market transformation in carbon-intensive sectors like concrete (and, by extension, cement) and steel by:

- Requiring or encouraging use of environmental product declarations—a best-practice reporting document for measuring the embodied emissions generated during the production of industrial building materials and products;
- Establishing preferences for low-carbon bidders, giving suppliers offering industrial building materials with verifiably superior climate performance a selection advantage within certain cost parameters;
- Establishing a carbon intensity ceiling for commonly used construction materials in federally funded projects; and
- Awarding performance-based bonuses or other types of financial incentives for high performers, and/or creating a "super performer" tier or a set-aside pool of funding to encourage bids from suppliers that significantly outperform their competitors or meet an exceptional level of GHG emissions reduction.

Where possible, federal and state agencies should also explore opportunities to make advance purchase commitments for breakthrough innovations, such as zero-emission steel or cement.

FEDERAL AND STATE POLLUTION STANDARDS

Federal pollution standards

Federal pollution standards for industrial facilities could help mandate deployment of decarbonization solutions once other policies and innovations bring those solutions to market. The Clean Air Act authorizes EPA to set strong GHG emission standards for a wide variety of industrial sources once emission-reducing technologies have been adequately demonstrated. In some instances, there may also be opportunities to employ Clean Air Act authority to require reductions in traditional and hazardous air pollutants (e.g., nitrous oxide, sulfur dioxide, benzene) from industrial facilities, which could result in process changes that have the co-benefit of reducing GHG emissions.

State regulations

Federal regulations and other types of federal policies ultimately have far-reaching impact and can raise the floor on all production, including in states that refuse to act. However, leading states are increasingly serving as laboratories for climate policy in the industrial sector.

States can play a major role in establishing model regulatory policies that can then be exported to other jurisdictions as well as extended to other products. For example, California recently passed SB 596, which requires the state to achieve net-zero carbon emissions for cement used in the state by 2045. Such policies can also catalyze early commercial-scale decarbonization projects that help lower barriers to wider adoption of critical advanced technologies, such as industrial carbon capture technologies, across the United States and globally.

Clean product standards

Clean product standards are sector-specific, market-based performance standards that establish the maximum amount of GHGs per unit of material produced that can be emitted in the production of covered industrial products sold in the United States.[82] Standards can ratchet up over time, ideally on a known trajectory that helps to create regulatory certainty for industry. Such standards are also typically technology neutral, meaning that manufacturers of covered products can adopt whatever decarbonization technologies or measures they choose, singly or in combination, to meet GHG emissions limits. Unlike Buy Clean standards, a clean product standard for cement, steel, or any other industrial materials sector would apply to the entire market for that material, not just government purchases.

Building codes

There is opportunity for building codes at the state and local levels to start incorporating upfront requirements for embodied carbon in concrete, cement, steel, and other widely used construction materials. With this inclusion, building codes can complement other efforts to decarbonize buildings, such as through reductions in energy use.

Trade policies

The industrial sector faces significant exposure to global competition, and it is critical to design industrial climate policies in a way that preserves the competitiveness of domestic manufacturers and avoids potential shifts of emissions or jobs abroad. Policy advocates and decision makers can combine GHG emissions standards with innovation incentives into a package that enhances job security. This includes policies and provisions to minimize and mitigate potential emissions leakage, wherein industrial production simply moves abroad, and account for embedded GHGs in imported industrial materials, such as a CBAM. Other ways to integrate climate action with trade policy are being explored through bilateral agreements like the EU–US Global Arrangement on Sustainable Steel and Aluminum and the Clean Energy Ministerial, and as part of an international “Climate Club,” which has been a focus of Germany’s G7 presidency.[83]

MUTUALLY REINFORCING POLICY TOOLS

These three policy tools—research, development, and demonstration; deployment and procurement incentives; and federal and state standards—can and must work in tandem. For example, public procurement programs like Buy Clean, which are designed to boost early demand for decarbonized industrial products, will have the greatest impact when paired with direct public investments in helping industrial facilities slash their climate emissions.[84] (Adding a well-designed carbon border adjustment mechanism will ensure that domestic manufacturers of cement, steel, and other energy-intensive and trade-exposed products can make the necessary investments in decarbonization without risking being outcompeted by dirtier producers abroad.) Similarly, state regulations that elevate and accelerate investments focused on getting first- through third-of-a-kind commercial scale deep decarbonization projects built in the near term help prove the commercial viability of cleaner production models and thus lay groundwork for federal emissions standards—and other climate policies—to lock in adoption of solutions industry-wide. For the best results, U.S. policymakers must use these policy tools together.

Conclusion

Manufacturing the cement, concrete, steel, and aluminum we rely on results in heavy climate pollution in the United States and around the world. Alongside national and global climate action to decarbonize the power sector, transportation, and buildings, decarbonizing heavy industry is critical to meeting our “North Star” climate goals. Governments committed to tackling climate change must have plans to address industrial emissions.

There is no one-size-fits-all technological or policy solution to getting GHG emissions out of the industrial sector. To transform heavy industry in the United States, policymakers will need to enact a package of policies that can at once encourage far greater adoption of existing solutions; deliver necessary innovation; and get early commercial scale projects built featuring the advanced technologies necessary for deep decarbonization. Developing and deploying these technologies for cement, steel, and other types of industrial plants can help commercialize game-changing climate solutions, akin to the innovation breakthroughs represented by electric vehicles in the transportation sector or heat pumps in home heating.

At the same time, in addition to GHGs, the U.S. industrial sector as a whole is also a major source of other air and water pollution, such as smog, toxic chemicals, and soot, as well as lead and mercury.[85] Where industrial facilities are clustered in already-overburdened communities, they add to longstanding public health and economic challenges.[86] Policies that reduce GHG pollution from industrial subsectors like cement, concrete, steel, and aluminum must not come at the expense of exacerbating local pollution.

In this decade, successful industrial decarbonization will look like the widespread deployment of existing technologies and measures like energy efficiency and electric boilers to supply low-temperature steam for industrial processes, including much greater penetration across small and medium-size facilities; greater materials efficiency, driven, for example, by improved design and construction practices and ultimately by codes and standards; and much higher recycling rates for materials like concrete, steel, and aluminum. At the same time, by 2030 success will also be defined by the demonstration and early commercial deployment of nascent but transformational technologies like green hydrogen and industrial CCS, allowing a clearer view of deep decarbonization pathways over the subsequent decades through midcentury. If successful, this vision can deliver not only major benefits to our climate and environment, but economic development, jobs, and investments in American competitiveness in a carbon-constrained global economy.

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