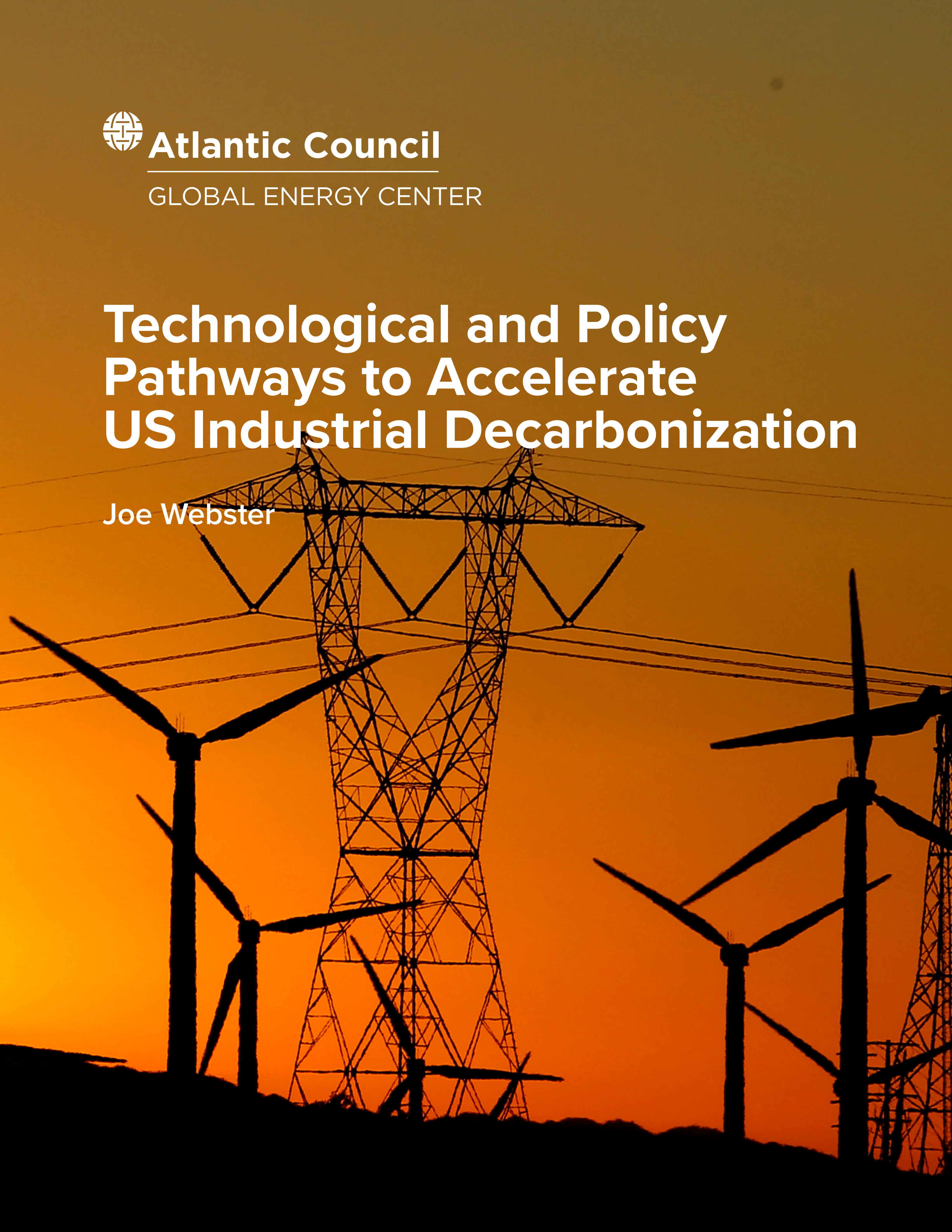

Atlantic Council

GLOBAL ENERGY CENTER

Technological and Policy Pathways to Accelerate US Industrial Decarbonization

Joe Webster

The Atlantic Council Global Energy Center develops and promotes pragmatic and nonpartisan policy solutions designed to advance global energy security, enhance economic opportunity, and accelerate pathways to net-zero emissions.

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Cover photo: The sun rises behind windmills at a wind farm in Palm Springs, California, February 9, 2011. REUTERS/Lucy Nicholson.

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Executive Summary

With global industrial carbon emissions reaching nearly 9.4 gigatons in 2021, decarbonizing the sector is critical if the world is to reach net-zero emissions and avert the worst impacts of climate change.[1] Industry has long been a major contributor to rising worldwide emissions, which climbed at a compound annual rate of 2.6 percent from 2000 to 2021, as industrial emissions accounted for about a quarter of the world's total carbon releases in 2021.[2] Growth in world CO_2 industrial emissions has nearly crawled to a halt in recent years, but industrial sector emissions must fall if the world is to effectively mitigate climate change.

Industrial decarbonization in the United States will be an important element in lowering global emissions. US industry released 1.4 gigatons of carbon in 2021, about 28 percent of all US emissions.[3] Lowering these greenhouse gas contributions and modeling effective strategies to achieve reductions will go a long way toward leading global decarbonization efforts.

To accelerate US industrial decarbonization, policymakers should start with the lowest hanging fruit and then expand to more difficult areas. Greening the electricity sector, for example, would sharply curtail emissions from electricity-intensive industries, while switching to clean hydrogen in refineries will likely accelerate hydrogen's relevance for other promising use cases, such as in steelmaking. By targeting these "easy" challenges, policymakers can achieve decarbonization gains as quickly as possible.

The United States is already pursuing a highly pragmatic industrial decarbonization policy. The Inflation Reduction Act (IRA) aims to support the nation's burgeoning clean hydrogen sector, particularly for green hydrogen, which is produced from renewables. The IRA provides significant fiscal support for every point of the green hydrogen value chain, including mining and manufacturing, renewables generation, and hydrogen production, potentially driving green hydrogen prices below competing natural gas-produced gray hydrogen costs. This program will provide significant environmental benefits for areas where hydrogen is already embedded in production, such as refineries and fertilizers. Over time, widespread clean hydrogen adoption could lead to economies of scale and learning by doing, further driving down costs and leading to increasing hydrogen introduction into harder-to-decarbonize processes, such as interseasonal storage and high-temperature industrial heat.

In addition to its provisions for clean energy and clean hydrogen, IRA also provides important incentives for carbon storage and sequestration, which will prove vital for industrial decarbonization objectives. Carbon capture can help reduce emissions from many industrial applications that cannot be eliminated by hydrogen or electrification. Notably, cement's reliance on limestone processing, which emits carbon dioxide, means emissions will need to be captured. Carbon storage technologies will require some continued level of fiscal and policy support if the United States is to achieve its decarbonization goals.

US policymakers should take additional actions to mitigate industrial sector emissions. This report recommends the following steps:

- Accelerate electricity sector decarbonization. Not only is grid decarbonization relatively easy, but it will also sharply reduce emissions associated with the industrial sector. As the overwhelming majority of highly polluting coal is burned for the

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[1] International Energy Agency (IEA), "Direct CO_2 Emissions from Industry in the Net Zero Scenario, 2000-2030–Charts–Data & Statistics," *World Energy Outlook 2022*, October 26, 2022, https://www.iea.org/data-and-statistics/charts/direct-co2-emissions-from-industry-in-the-net-zero-scenario-2000-2030.

[2] IEA, "Direct CO_2 Emissions from Industry in the Net Zero Scenario; and IEA, "Global CO_2 Emissions Rebounded to Their Highest Level in History in 2021–News," in *World Energy Outlook 2022*, IEA, March 1, 2022, https://www.iea.org/news/global-co2-emissions-rebounded-to-their-highest-level-in-history-in-2021.

[3] "Total Energy: Table 11.4 Carbon Dioxide Emissions from Energy Consumption: Industrial Sector," Data, US Energy Information Administration (EIA), Accessed November 6, 2022, https://www.eia.gov/totalenergy/data/browser/index.php?tbl=T11.04#/?f=A&start=2000&end=2021&charted=0-2-12-13.

electricity sector—not industry—a cleaner grid would sharply curtail emissions.

- Reform the permitting process to accelerate the deployment of clean electricity generation and construction of new long-distance transmission and distribution infrastructure. Massive increases in clean energy generation will prove critically important for industrial decarbonization: first, through supporting grid decarbonization and, later, by improving green hydrogen economics.
- Fund research for nuclear energy, with a focus on studies examining grid flexibility and pink hydrogen production. In the future, nuclear reactors with flexible ramping, or the ability to dispatch electricity to the grid, could replace today's "peaker" natural gas and coal plants that power on to meet peak demand. While today's peaker power plants run at low-capacity utilization rates, nuclear power plants could theoretically continuously operate. When not providing electricity to the grid, the plants can send electrons unneeded for the grid to produce pink hydrogen. Given that nuclear energy can also aid industrial decarbonization by powering industrial processes, the technology deserves attention and funding.

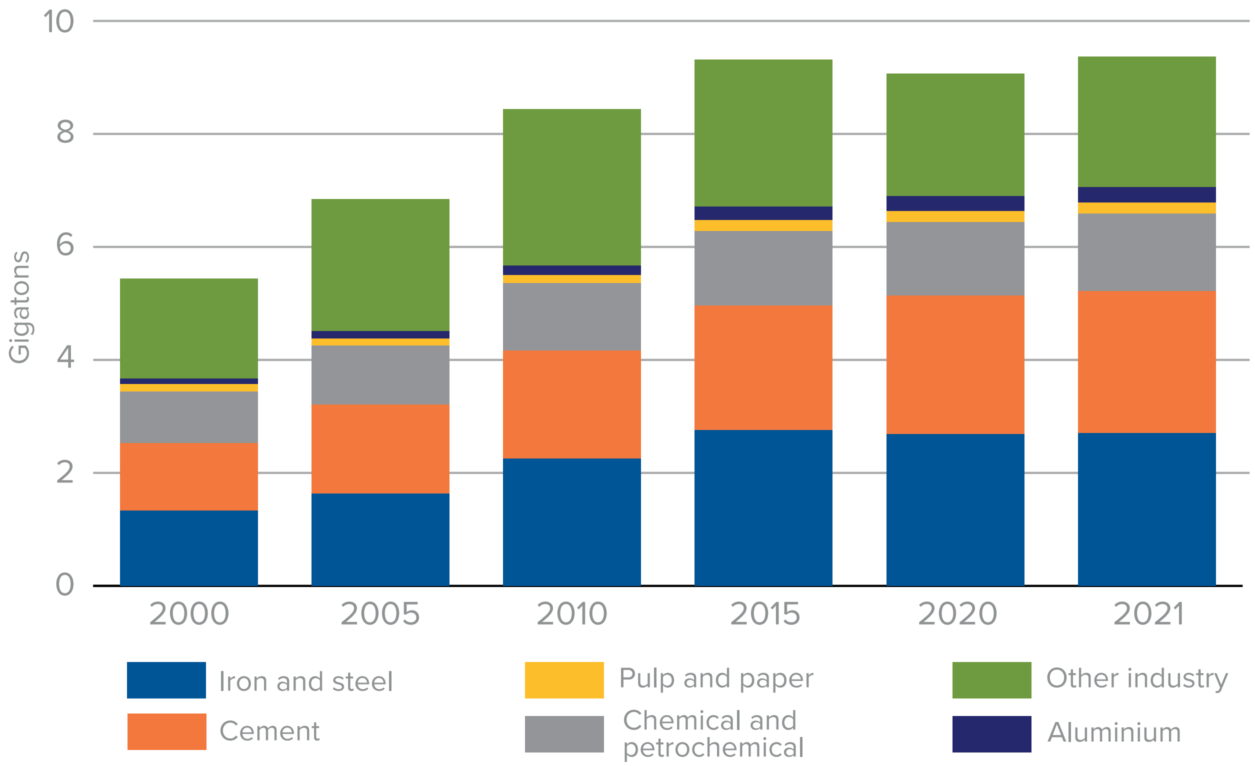
US Industrial Emissions in Global Context

The largest industrial emitters by CO_2 levels in the United States and globally include the steel, cement, and chemicals/petrochemicals sectors. As seen in Figure 1, these three industries accounted for 70 percent of all world industrial emissions in 2021. In the United States, steel, aluminum, and cement contribute 10 percent of all US industrial emissions; chemicals/petrochemicals and other industries account for the remaining 90 percent, as seen in Figure 2. Global industrial carbon emissions have been steadily rising, while US levels overall have largely been declining due to a few major factors outlined below.

Emissions Intensity Is Down – but More Must Be Done

Overall US carbon and energy intensity fell almost continuously from 2008 to 2021 (Figure 3), as cleaner-burning natural gas replaced coal, and more renewables entered the grid. These shifts allowed US industry to begin decarbonizing. At the same time, US industrial production is higher than it was immediately before the Great Recession (Figure 4).[4] Thus, although US industrial emissions fell from 1999 to 2009, reductions stalled at above 1,400 million metric tons of CO_2. The Great Financial Crisis of 2008 caused temporary but steep declines in both output and emissions.

Figure 1: World Direct CO_2 Emissions from Industry



Source: David Hodgson et al., “Direct CO_2 Emissions from Industry in the Net Zero Scenario, 2000-2030–Charts,” Data and Statistics, International Energy Agency (IEA), October 26, 2022, https://www.iea.org/data-and-statistics/charts/direct-co2-emissions-from-industry-in-the-net-zero-scenario-2000-2030.

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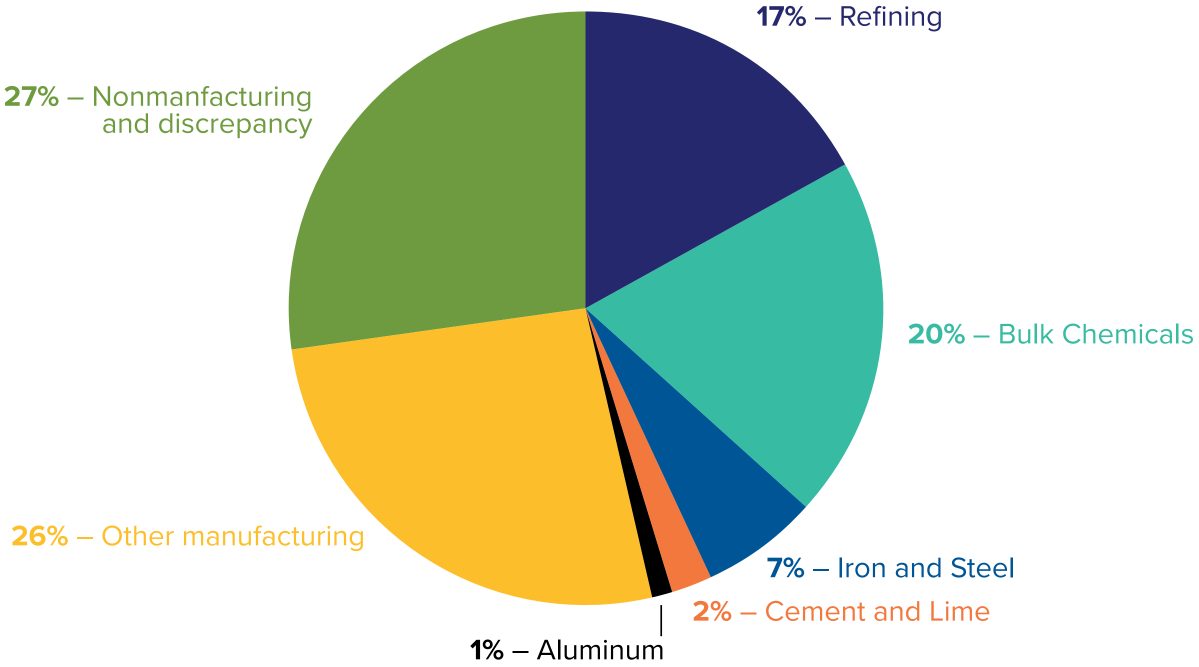
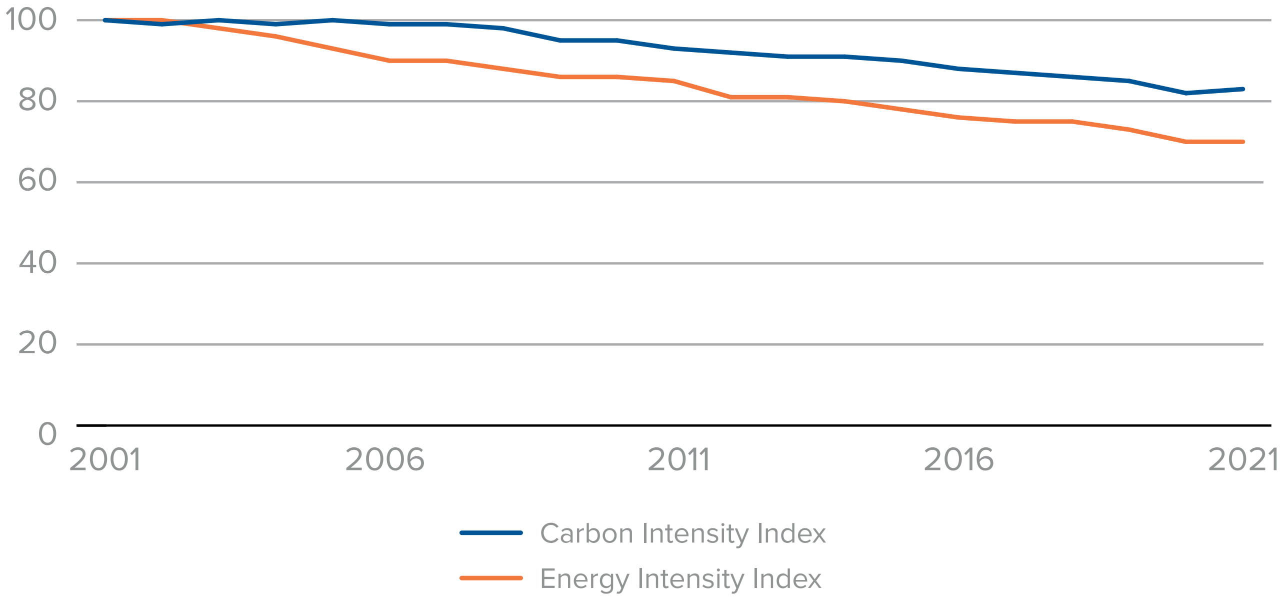
[4] Industrial Production: Total Index,” Federal Reserve Economic Data (FRED), St. Louis Federal Reserve Bank (website), August 26, 2022, https://fred.stlouisfed.org/series/IPB50001A.

Figure 2: US Industrial Sector CO_2 Emissions, 2022



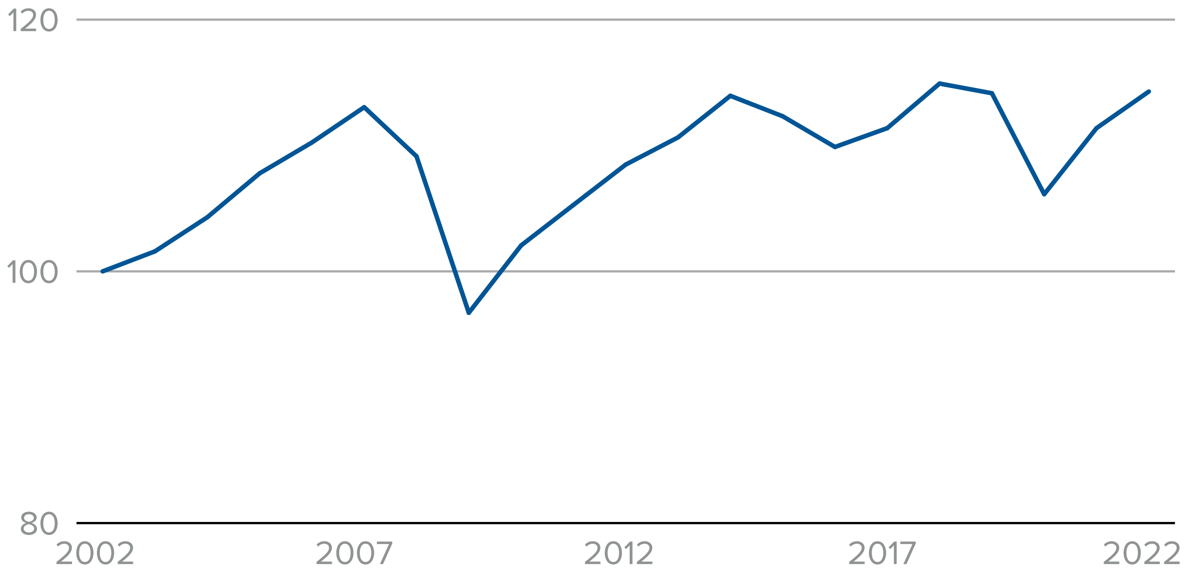
Source: "Table 19: Energy-Related Carbon Dioxide Emissions by End Use," US Energy Information Administration (EIA) (homepage), March 3, 2022, https://www.eia.gov/outlooks/aeo/data/browser/#/?id=22-AEO2022&cases=ref2022&sourcekey=0.

Figure 3: US Carbon and Energy Intensity Index, 2001 = 100



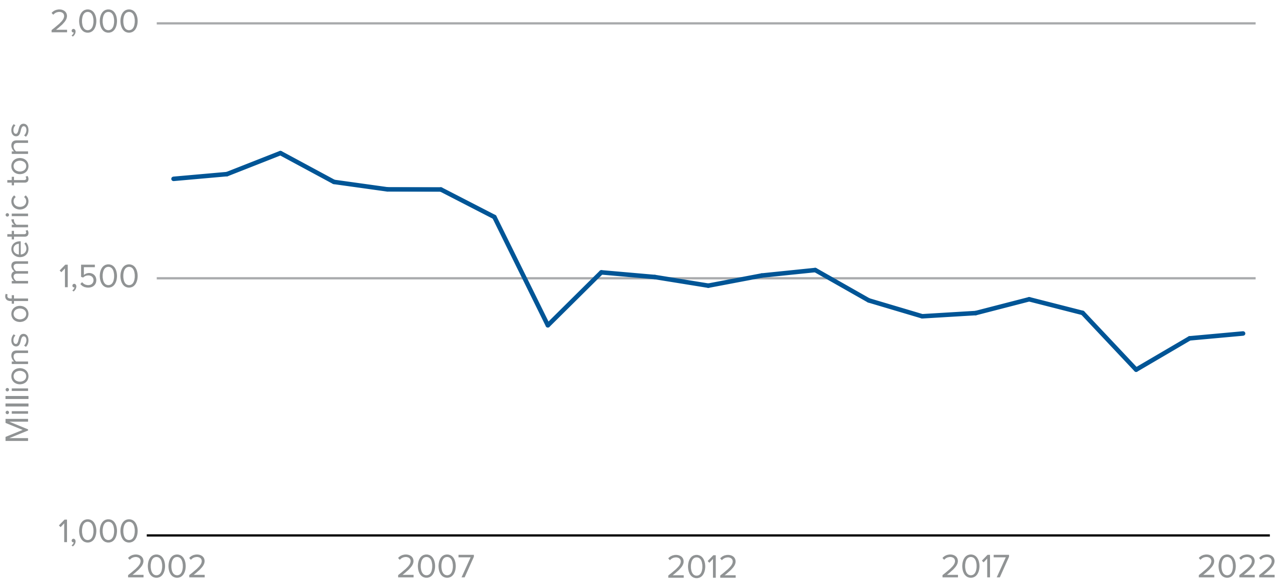
Source: "US Energy-Related Carbon Dioxide Emissions, 2020," Independent Statistics and Analysis, US Energy Information Administration, December 22, 2021. https://www.eia.gov/environment/emissions/carbon/.

Figure 4: US Industrial Production Index, 2002 = 100



Note: Annual, not seasonally adjusted.
Source: "Industrial Production: Total Index," Federal Reserve Economic Data (FRED), St. Louis Federal Reserve Bank, August 26, 2022, https://fred.stlouisfed.org/series/IPB50001A.

Figure 5: US Industrial Sector CO_2 Emissions

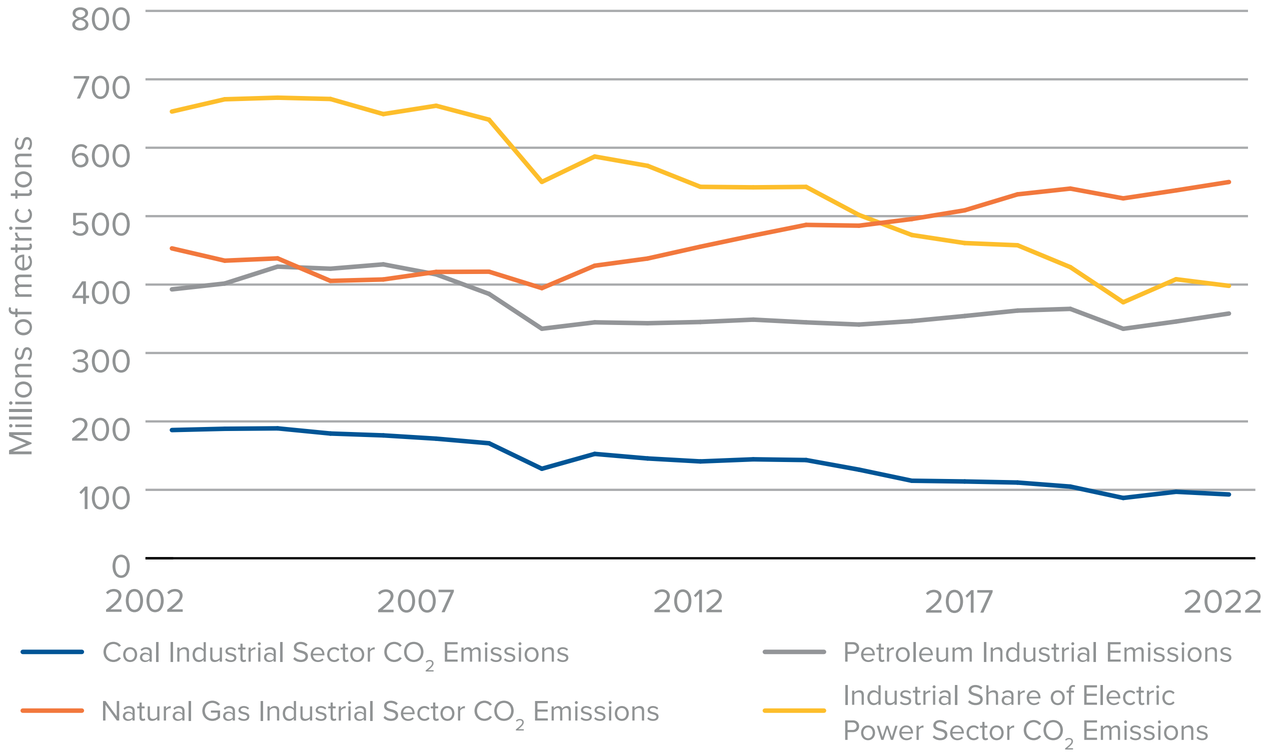


Source: "Table 11.4 Carbon Dioxide Emissions from Energy Consumption: Industrial Sector," Total Energy (page), Data, US (EIA), accessed November 6, 2022, https://www.eia.gov/totalenergy/data/browser/index.

Industrial emissions drifted downwards in the late 2010s (Figure 5), largely due to declining coal industrial emissions and, importantly, a decline in the industrial share of electric power sector emissions. As natural gas and renewables increasingly supplanted coal-fired electricity generation on the US grid, industrial emissions from electricity use declined (Figure 6).

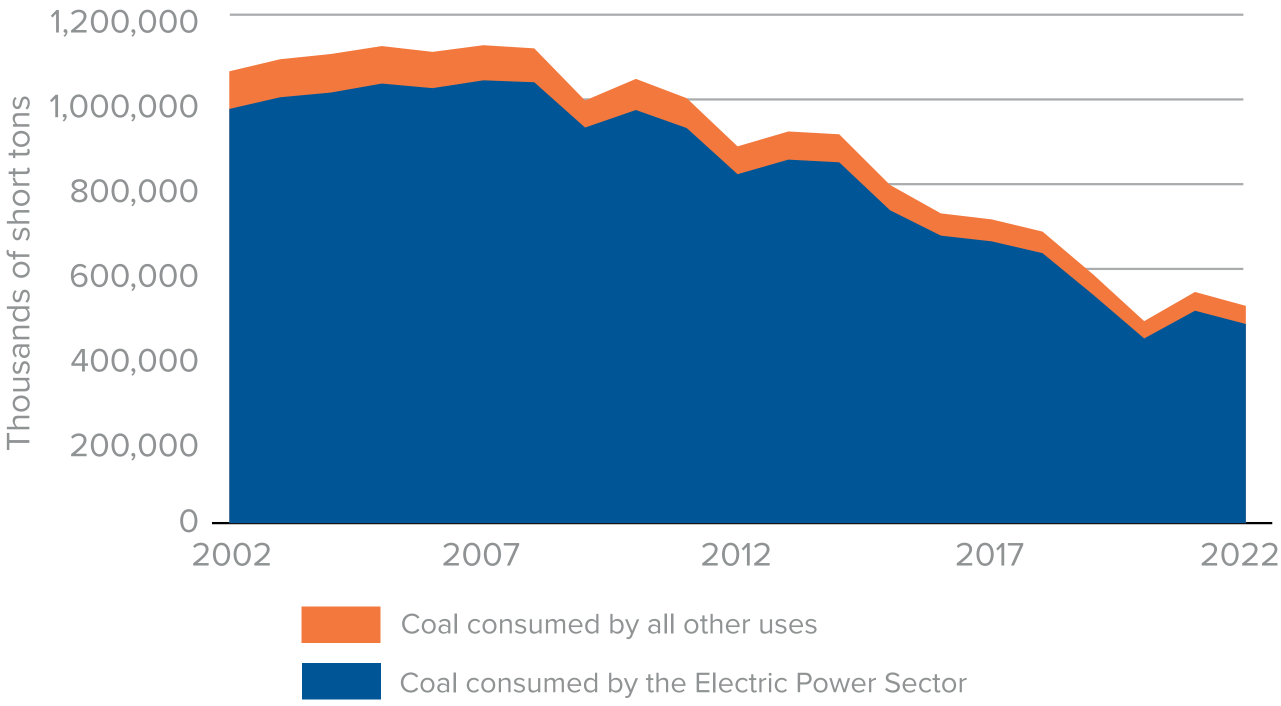
As seen in Figure 7, the electric power sector accounts for the overwhelming majority (nearly 92 percent) of US coal consumption. Removing coal from the electricity grid would dramatically reduce emissions, including the industrial share of electric power sector CO_2 emissions.

Figure 6: US Industrial CO_2 Emissions by Sector



Source: “Table 11.4 Carbon Dioxide Emissions from Energy Consumption: Industrial Sector,” US EIA. https://www.eia.gov/totalenergy/data/browser/index.php?tbl=T11.04#/?f=A&start=1973&end=2022&charted=0-2-12-13.

Figure 7: US Coal Consumption by Sector



Source: Total Energy Monthly Data: US EIA [coal consumption by sector], accessed March 5, 2023, https://www.eia.gov/totalenergy/data/monthly/.

Industry Fundamentals and Decarbonization Pathways

While the United States is already decarbonizing its industry, progress must accelerate to meaningfully curb climate change. Strategies to accelerate the pace of carbon cuts among industry largely focus on steel, cement, and aluminum, as decarbonizing these sectors entails relatively straightforward approaches. The chemical/petrochemicals industry is a heavy emitter, but its heterogeneity requires a much more complex decarbonization strategy.

Steel

Steel is a vital element of the world economy. It is a building block for new buildings and materials, with end uses ranging from infrastructure, construction, mechanical equipment, automotives, metal products, and more. Indeed, a recent study found that the direct economic impacts of world steel production include employment for about six million people.[5] When the supply chain and steel-using sectors are incorporated in estimates of the industry's economic effects, its impact extends to about 95 million people employed, or about 3 percent of world employment.[6] Steel is a relatively carbon-intensive sector, however, and is responsible for 7 percent of energy sector CO_2 emissions and about 8 percent of global final energy demand.[7]

World crude steel production totaled 1,951 million metric tons in 2021, up from 850 million metric tons in 2000.[8] Astonishingly, steel production has grown nearly every year since 2000; only 2008 and 2009 saw declining output amid the financial crisis. Notably, global steel production rose in 2020 despite wide-scale COVID-19 lockdowns and a sharp global recession.

The steel industry's growth reflects trends in China (Figure 8), the world's largest and most important steel consumer and producer. China also accounts for most steel-sector carbon emissions, producing about 53 percent of world crude steel and over 60 percent of the sector's emissions.[9] This high carbon intensity is largely due to China's use of Blast Furnace–Basic Oxygen Furnace (BF-BOF) technology, which relies on coal for 90 percent of its production. BF-BOF processes produce about 2.2 tons of CO_2 in direct and indirect emissions, according to the International Energy Agency.[10] In the United States, about 31 percent of all steel output is produced by BF-BOF technology, while the iron and steel sector accounted for about 89 million tons of CO_2 emissions, or under 2 percent of total US CO_2 emissions.[11]

Decarbonizing Steel

Reducing US steel emissions is possible through the implementation and development of new and existing processes and technologies. Wider adoption of lower-emitting manufacturing techniques currently available can lead to near-term carbon reductions. In the longer term, industry will need to develop and deploy new technologies, including hydrogen, to make deeper cuts in carbon emissions.

To start, efficiency programs can limit near-term emissions of steelmakers using BF-BOF. BF-BOF's direct emissions, which comprise about 55 percent of its emissions, come from coal injections; its

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[5] Edwin Basson, "Stakeholders–Global Forum on Steel Excess Capacity," World Steel Association, March 17, 2020, https://www.steelforum.org/stakeholders/gfsec-march-2020-worldsteel.pdf.

[6] Basson, "Stakeholders–Global Forum on Steel Excess Capacity."

[7] Sara Budinis et al., "Iron and Steel Technology Roadmap–Analysis," International Energy Agency, October 21, 2020, 35, https://www.iea.org/reports/iron-and-steel-technology-roadmap.

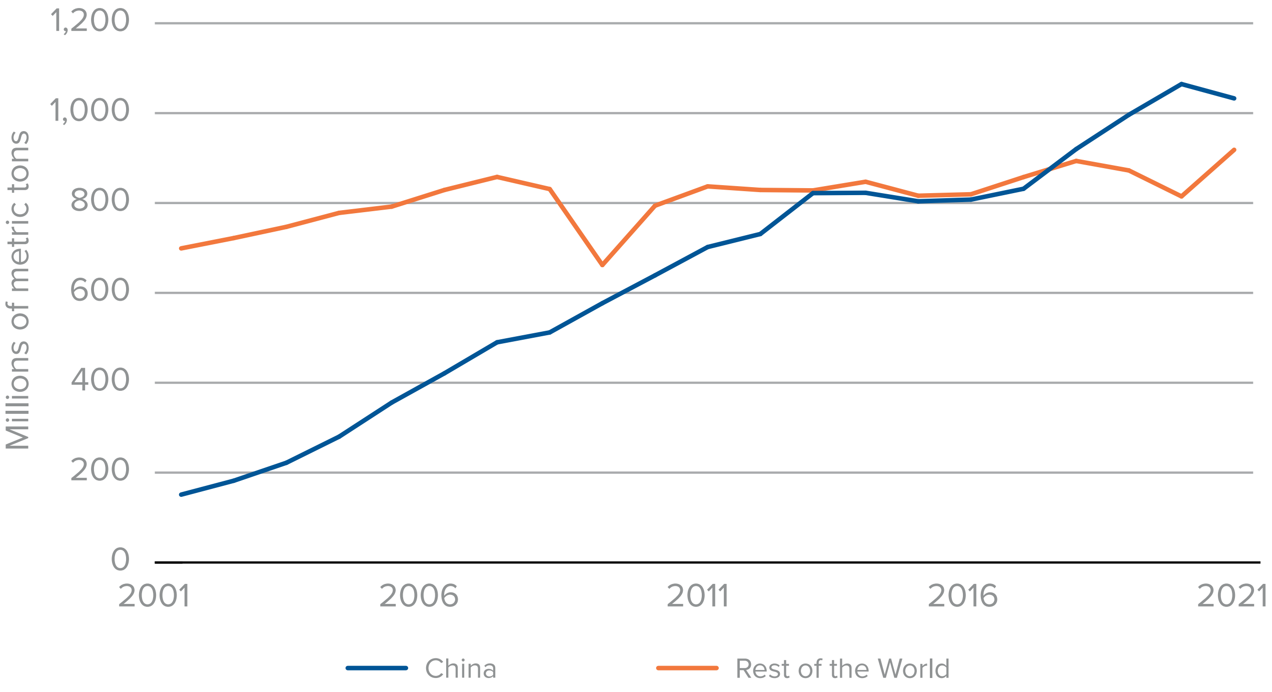
[8] "World Steel in Figures 2022," World Steel Association, August 4, 2022, https://worldsteel.org/steel-topics/statistics/world-steel-in-figures-2022/.

[9] World Steel in Figures 2022," World Steel Association; and Min Zhang and Dominique Patton, "Steel Industry Carbon Emissions to Drop Nearly 1/3 by 2050–Woodmac," Reuters, May 16, 2022, https://www.reuters.com/business/environment/steel-industry-carbon-emissions-drop-nearly-13-by-2050-woodmac-2022-05-16/#:~:text=5%20months%20ago-,Steel%20industry%20carbon%20emissions%20to,1%2F3%20by%202050%20%2D%20Woodmac&text=BEIJING%2C%20May%2017%20(Reuters),in%20a%20study%20on%20Tuesday.

[10] Budinis et al., "Iron and Steel Technology Roadmap."

[11] Budinis et al., "Iron and Steel Technology Roadmap;" and "Table 19. Energy-Related Carbon Dioxide Emissions by End Use," US EIA (homepage), March 3, 2022, https://www.eia.gov/outlooks/aeo/data/browser/#/?id=22-AEO2022&cases=ref2022&sourcekey=0.

Figure 8: World Crude Steel Production



Source: "Steel Statistical Yearbook," World Steel Association, September 7, 2022, https://worldsteel.org/steel-topics/statistics/steel-statistical-yearbook/.

indirect emissions are attributable to steel off-gases, imported generation, and imported electricity and heat. Efficiency programs include minimizing the use of coal as a reductant, increasing fuel injection, or using coke-oven gas as an energy source, among other options.[12]

In addition to reducing emissions from existing BF-BOF facilities, new mills should rely on electric arc furnaces (EAF), rather than blast furnaces. EAF technology relies on steel scrap and direct reduced iron (DRI), and are less carbon-intensive than the BF-BOF alternative. This is especially true when they use natural gas or even cleaner chemicals, such as clean hydrogen. DRI-EAF natural gas-produced steel has substantially lower indirect emissions than BF-BOF, producing about 0.4 tons of CO_2 in indirect emissions for every ton of steel produced, on average, largely due to emissions from electricity generation.[13] As the electricity grid becomes greener, indirect pollution from the DRI-EAF method will fall even further. The outlook for new US steel capacity is uncertain, but there is interest in new mills, including a new EAF facility in Arkansas.[14] Accordingly, EAF technology should be prioritized for all new plants—or, potentially, mandated.

While the US steel industry's predominant use of EAF has limited its emissions, newer technologies can achieve even deeper reductions. In the near term, carbon capture and storage (CCS) and carbon capture utilization and storage (CCUS) will be important options for domestic-market steel decarbonization, due to the relatively low costs involved.[15] Bioenergy,

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[12] Christian Hoffmann, Michel Van Hoey, and Benedikt Zeumer, "Decarbonization Challenge for Steel: Hydrogen as a Solution in Europe," McKinsey & Company," April 2020, https://www.mckinsey.com/~/media/McKinsey/Industries/Metals%20and%20Mining/Our%20Insights/Decarbonization%20challenge%20for%20steel/Decarbonization-challenge-for-steel.pdf.

[13] Budinis et al., "Iron and Steel Technology Roadmap."

[14] John Ambler, "U.S. Steel Selects Osceola, Arkansas as Location for Most Advanced Steelmaking Facility in North America," United States Steel Corp., January 11, 2022, https://investors.ussteel.com/news/news-details/2022/U.-S.-Steel-Selects-Osceola-Arkansas-as-Location-for-Most-Advanced-Steelmaking-Facility-in-North-America/default.aspx.

[15] Industrial Decarbonization Roundtable, Atlantic Council, June 1, 2022, (closed event).

or renewable energy derived from recently living organic materials, could also be part of a solution set. Industry experts suggest that bioenergy with CCUS or bioenergy with carbon capture and storage (BECCS) may be the most attractive near-term option due to its limited cost.[16]

Over the long term, however, net-zero steel decarbonization goals will overwhelmingly rely on hydrogen, which can be produced with near-zero emissions from renewables or from natural gas with emissions captured. Moreover, since hydrogen-based steel production can be implemented at either greenfield or brownfield sites, and directly reduces emissions, clean hydrogen would nearly eliminate emissions from steel production and is arguably the desired end state for the US domestic steel industry.[17] Policies to unleash US clean hydrogen are explored in a section III.

While decarbonizing steel will rely largely on domestic policy, including the development of a clean hydrogen industry, international coordination also is crucial. A failure to coordinate with international partners while raising US environmental standards could lead to a flood of lower-cost imports, which could eviscerate the US steel industry, generate political backlash, and drain support for steel decarbonization. Fortunately, the United States and its international partners have taken steps to increase cooperation, including through the Joint EU-US Statement on a Global Arrangement on Sustainable Steel and Aluminum.[18] Relatedly, an emerging voluntary market in "green steel" could provide important, if limited, decarbonization benefits. While certification and, most fundamentally, a lack of market incentives will constrain uptake, a voluntary green steel market could enable learning-by-doing, ultimately accelerating cost reductions.

Aluminum

Aluminum is used widely for both industrial and consumer purposes. The metal and its alloys have applications not only in building materials, but also in durable consumer goods such as large and small appliances, and more. Aluminum is also a major source of carbon emissions. Global direct emissions from the sector total about 275 million tons of CO_2 in 2021; if indirect emissions are included, the figure rises to about 1.1 gigatons.[19]

Decarbonizing Aluminum

The aluminum industry will prove relatively straightforward to decarbonize, fortunately, as most emissions are attributable to its electricity consumption. Electricity accounted for 70 percent of total direct and indirect aluminum production emissions globally in 2021.[20] The United States' aluminum-related emissions were estimated to be around 16 million metric tons in 2022.[21] To decarbonize the grid and thus the aluminum industry, policymakers should seek to build out clean energy generation as fast as possible, expand long-distance transmission, build out diurnal and interseasonal storage, and remove coal generation units as quickly as possible.

Aluminum's remaining, nonelectricity emissions come from processing steps requiring heat, which is primarily generated by burning fossil fuels. Heating-related emissions could largely be eliminated by replacing the fossil fuels with clean hydrogen.[22] Furthermore, the United States could strengthen aluminum scrap-recycling incentives, as the World Economic Forum estimates that increased collection and recovery of postconsumer scrap could lower primary aluminum requirements by up to 15 percent.[23]

US aluminum and broader industrial decarbonization efforts should prioritize electricity decarbonization and hydrogen in that order. Electrification will prove vastly simpler and lower cost than large-scale hydrogen adoption. This straightforward path makes aluminum an intriguing sector for industrial decarbonization since most of its emissions could theoretically be lowered quickly.

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[16] Industrial Decarbonization Roundtable, Atlantic Council, June 1, 2022, (closed event).

[17] Hoffmann, Van Hoey, and Zeumer, "Decarbonization Challenge for Steel."

[18] "Joint EU-US Statement on a Global Arrangement on Sustainable Steel and Aluminium," European Commission, October 31, 2021, https://ec.europa.eu/commission/presscorner/detail/en/IP_21_5724.

[19] David Hodgson and Tiffany Vass, "Aluminium–Analysis," IEA, September 1, 2022, https://www.iea.org/reports/aluminium.

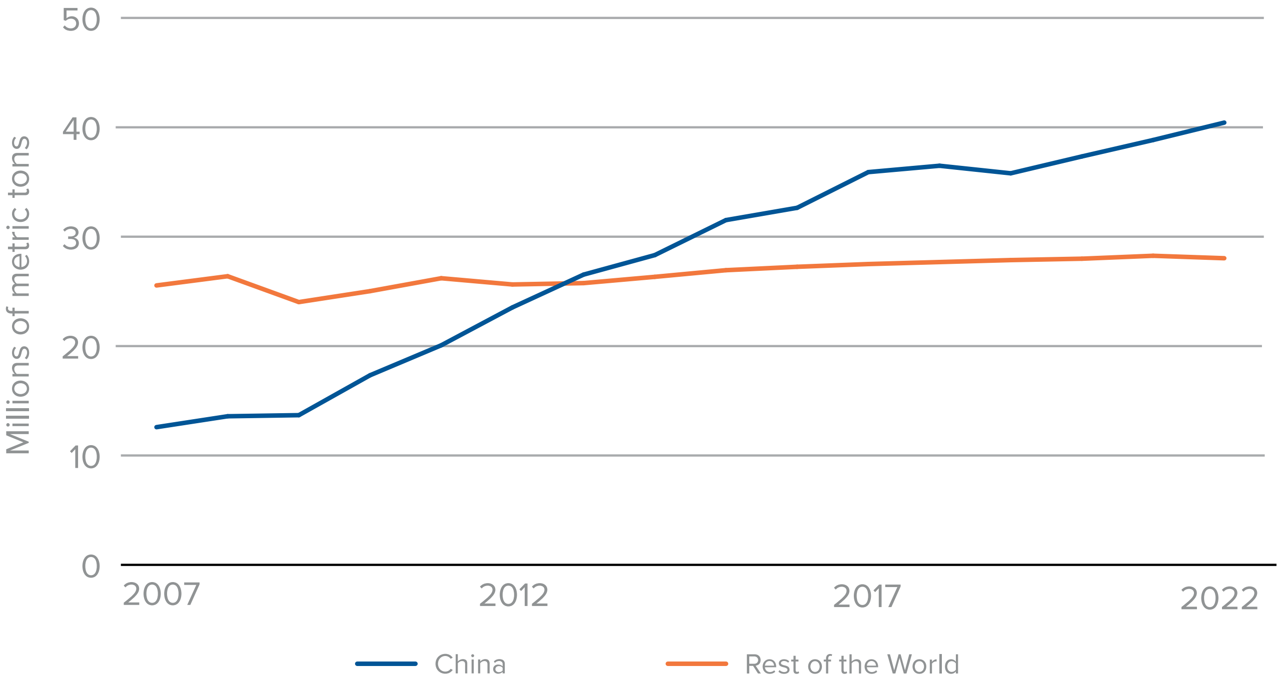
[20] IEA 2022, "Aluminium–Analysis," Tracking Report, https://www.iea.org/reports/aluminium, License: CC BY 4.0.

[21] "Table 19. Energy-Related Carbon Dioxide Emissions by End Use," US EIA.

[22] Jörgen Sandström and Renée van Heusden, *Aluminium for Climate: Exploring Pathways to Decarbonize the Aluminium Industry*, Community Report, World Economic Forum, November 2020, https://www3.weforum.org/docs/WEF_Aluminium_for_Climate_2020.pdf.

[23] Sandström and van Heusden, *Aluminium for Climate*.

Figure 9: World Primary Aluminum Production



Source: "Primary Aluminium Production," International Aluminium Institute, August 2, 2022, https://international-aluminium.org/statistics/primary-aluminium-production/.

Cement

Cement is a highly emissions-intensive but critical construction material used extensively in plastering, joints, laying floors, foundations, and more. Cement accounted for more than 2.5 gigatons of global CO_2 emissions in 2021, with production and emissions concentrated in China.[24] While US production and consumption of cement accounts for only about 2 percent of world production, apparent cement consumption rose by over 20 percent from 2018 to 2022.[25] Amid growing domestic cement consumption, US policymakers must devise policies to abate emissions in this sector.

Decarbonizing Cement

Some industry participants maintain that electrifying cement making with on-site hydrogen could eliminate 25 percent of CO_2 emissions.[26] This shift could be facilitated by the availability of land near cement plants, which often have large land-use needs for limestone quarries and buffer zones. Adjoining vacant land could potentially be used for renewable electricity generation, which could in turn be used to produce green hydrogen via electrolysis.[27] On-site hydrogen (H_2) production would substantially lower its transportation costs, particularly where local solar and/or wind potential is high.

Half of cement's emissions are extremely challenging to avoid, making carbon capture and storage important for decarbonizing the cement industry—more specifically, BECCS, with emissions captured in the processing stages. BECCS will require an overhaul of existing infrastructure, however, requiring between $170 billion and $230 billion in capital

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[24] David Hodgson, Paul Hugues, and Tiffany Vass, "Cement–Analysis," IEA, September 2022, https://www.iea.org/reports/cement.

[25] "Cement," US Geological Survey, Mineral Commodity Summaries, January 2023, https://pubs.usgs.gov/periodicals/mcs2023/mcs2023-cement.pdf.

[26] Industrial Decarbonization Roundtable, Atlantic Council, June 1, 2022, (closed event).

[27] Industrial Decarbonization Roundtable, Atlantic Council, June 1, 2022, (closed event).

costs along with more than 100,000 kilometers of new CO_2 pipelines across the entire United States.[28] Additionally, the technology would require retrofitting existing bioenergy facilities, retrofitting larger coal plants to accept biomass, or building new biomass facilities.[29]

International climate cooperation is especially vital for decarbonizing the cement industry, as there is relatively little international trade in cement due to its unfavorable value-to-weight and volume ratio. In 2021, the United States produced approximately 2 percent of the world's cement.[30] It must lead by example on cement industrial decarbonization by reducing its own emissions and work to ensure that other countries are responsible climate partners.

Refineries

While not a major focus of this paper, petroleum refining is worth mentioning, as it accounted for nearly 18 percent of US industrial sector emissions in 2021.[31] Refineries are major existing users of hydrogen produced from natural gas. In the very near future, however, they may consume clean hydrogen, due to the provisions of the Inflation Reduction Act (IRA), which have dramatically and permanently altered hydrogen economics. The focal point of initial hydrogen decarbonization efforts for refineries will likely include facilities in Texas and Louisiana that process highly sulfuric crudes, which require H_2 for sulfur removal, and are sited near potential clean hydrogen production nodes.

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[28] E. Larson et al., *Net-Zero America: Potential Pathways, Infrastructure, and Impacts*, Final Report Summary, Princeton University, October 29, 2021.

[29] Mathilde Fajardy and Nasim Pour, "Bioenergy with Carbon Capture and Storage–Analysis," IEA, September 2022, https://www.iea.org/reports/bioenergy-with-carbon-capture-and-storage.

[30] "Key Facts," Global Cement and Concrete Association, November 3, 2022, https://gccassociation.org/key-facts/.

[31] "Table 19. Energy-Related Carbon Dioxide Emissions by End Use," US EIA.

Industrial Decarbonization Technologies: Hydrogen and Nuclear Energy

Industrial decarbonization will require cutting-edge new energy technologies and updated versions of existing technologies. As referenced several times above, hydrogen will be a critical part of this strategy. Clean hydrogen produced with power from renewables or from nuclear energy, or by natural gas with carbon capture, could decarbonize high-temperature processes in steelmaking and cement manufacturing. Additionally, future nuclear power plants could play an important role in industrial and electricity-sector decarbonization. They can provide peaking electricity-generation services and, when not supplying electricity to the grid, they can power the production of pink hydrogen. To reach a point where industry and the energy sector can deploy these tools, they must fill in knowledge gaps that will chart the optimal path forward.

Developing the US Clean Hydrogen Industry

Hydrogen is critical for decarbonizing the steel, cement, and refineries sectors. Accordingly, policymakers should consider several policies to speed up the development of the clean hydrogen industry.

The most effective proposal for advancing decarbonization and clean hydrogen would be to set a price on carbon emissions, whether through an emissions fee or through an emissions trading system, which caps total emission levels but allows the price of the fee to fluctuate.[32] This policy would, over time, help stimulate clean forms of energy—including clean hydrogen for industrial decarbonization. Policymakers have initiated discussions on introducing a tariff on carbon-intensive imports.[33] Regional efforts, such as the Regional Greenhouse Gas Initiative, hold some promise, but also risk unintentionally shifting production to states with less rigorous standards.

Aside from a price on carbon, policymakers created incentives for clean hydrogen through the IRA. Blue hydrogen, produced from natural gas feedstock and with emissions abated via carbon capture and storage, is eligible for either a hydrogen production tax credit or a carbon capture credit, but not both.[34] Conversely, green hydrogen receives more fiscal support along all parts of the value chain. IRA provisions for green hydrogen include fiscal support for mining of critical minerals, manufacturing of renewables components, credits for clean electricity generation, and a tax credit for hydrogen production of to $3/kilogram.[35]

Hydrogen Transportation Cost Considerations

For industry to take advantage of the decarbonizing benefits of clean hydrogen, its generation and transmission must be viable. One of the biggest outstanding cost determinants in this equation revolves around where hydrogen production will take place. While blue hydrogen transportation would clearly require either dedicated hydrogen pipelines (or, potentially, repurposed existing natural gas pipelines), the optimal mode of green hydrogen transportation is more unsettled. Two models are under consideration. In one approach, a company would produce green hydrogen at the same site where renewable electricity is generated. Pipelines would then transport hydrogen to demand centers. In the other approach, hydrogen would be produced at the point of use, and the green electricity needed to generate the hydrogen would be carried via long-distance transmission wires.

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[32] "What Is Carbon Pricing?," Carbon Pricing Dashboard, World Bank, accessed November 6, 2022, https://carbonpricingdashboard.worldbank.org/what-carbon-pricing.

[33] Emma Dumain, "Senate Chatter Grows Louder on Carbon Tariff," *E&E News*, March 14, 2023, https://www.eenews.net/articles/senate-chatter-grows-louder-on-carbon-tariff/.

[34] Joe Webster, "The Inflation Reduction Act Will Accelerate Clean Hydrogen Adoption," *Energy Source* (blog), Atlantic Council, September 28, 2022, https://www.atlanticcouncil.org/blogs/energysource/the-inflation-reduction-act-will-accelerate-clean-hydrogen-adoption/.

[35] Webster, "The Inflation Reduction Act Will Accelerate Clean Hydrogen Adoption."

Air Liquide opens its North Las Vegas Hydrogen Production facility in Las Vegas, Nevada, May 24, 2022. REUTERS/Bridget Bennett

Research thus far does not provide a decisive direction on siting hydrogen. Some studies have found that the pipeline model is more economical.[36] Other industry economists say that hydrogen pipelines are three times as expensive to build as power lines, thereby making the pipeline model less affordable.[37] To get a clearer picture of costs, federal policymakers should fund more studies on options for long-distance hydrogen transmission, although market actors may ultimately have to learn by doing. Cost considerations must weigh several factors, including geography, local real estate markets, and perhaps most importantly, right-of-way authorities and permitting challenges—the latter of which will be discussed in section IV.

Key routes for hydrogen should be a particular focus in efforts to understand transmission siting and costs. Notably, policymakers and industry must understand how best to ship green hydrogen from West Texas to industrial locations along the Gulf Coast—namely, the Houston Ship Channel and Port Arthur. West Texas enjoys abundant colocated solar and wind resources—and thus superior electrolyzer economics to support green hydrogen development. Refineries in Houston and Port Arthur are natural offtakers of green hydrogen, and several refineries have already signed green hydrogen agreements. Transmission of hydrogen via pipelines, or by electricity lines tied to electrolyzers, could reach industrial locations across the South and the Midwest. While market actors will ultimately find the most fruitful midstream option, policymakers should seek to bring as much transparency to the market for both transmission options.

Flexible Nuclear Energy as a Decarbonization Tool

Over the long term, nuclear energy and particularly micro and small modular reactors will have the capacity to help decarbonize US industry in critical

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[36] Joshua D. Rhodes et al., “Renewable Electrolysis in Texas: Pipelines Versus Power Lines,” H2 White Paper, H2@UT (research cluster), University of Texas, August 2021, https://sites.utexas.edu/h2/files/2021/08/H2-White-Paper_Hydrogen-Pipelines-versus-Power-Lines.pdf.

[37] Michael Liebreich, “Liebreich: Separating Hype from Hydrogen–Part Two: The Demand Side,” BloombergNEF blog, October 16, 2020, https://about.bnef.com/blog/liebreich-separating-hype-from-hydrogen-part-two-the-demand-side/.

ways. Nuclear energy has a unique ability to provide clean, firm power that could make the grid more resilient in the face of increasingly extreme weather from climate events and, to a lesser degree, renewable energy's intermittency. This resiliency, in turn, will minimize disruptions to consumers' lives, bolstering support for nuclear energy and thus industrial decarbonization. Another advantage of nuclear energy is that it can provide flexible generation: it can ramp down electricity supply for the grid during times of peak renewables output, and ramp up generation when needed. Moreover, nuclear power plants could theoretically produce hydrogen and operate nearly continuously when not providing electricity to the grid.

Nuclear energy production of clean electricity and hydrogen would reduce industrial emissions attributable to the power sector and elsewhere. Indeed, nuclear power plants of the future could play a role akin to today's natural gas "peakers," or combustion gas turbines. Peakers have notoriously low utilization rates: just 12.1 percent in 2021, according to the EIA.[38] In contrast, nuclear energy's capacity utilization rate reached 93 percent in 2021.[39] If nuclear power plants could "toggle" between balancing renewables' intermittency and electricity for electrolyzers, they could provide pink hydrogen about 70 to 80 percent of the time, after subtracting nuclear energy current capacity utilization rates by expected demand for peaker services.

Nuclear power plants that can toggle between electricity generation for the grid and hydrogen production could enjoy utilization rates greater than found in green hydrogen that is produced with renewable energy. Electrolyzers running on renewables with excellent colocated wind and solar resources will have utilization challenges, as US solar and onshore wind have overall capacity factors of 23 percent and 36 percent, respectively.[40] Still, generating pink hydrogen on-site at a nuclear power plant would require installing dedicated pipelines from the facility to end users.

Using incremental electricity generation from new nuclear energy plants for flexible power (while maintaining elevated capacity factors via hydrogen and high-heat industrial process offtakers) could be a game-changer, but the business model would be challenging and may require a price on carbon, or other carbon offset market. Potential hydrogen offtakers such as cement facilities and steel plants will require reliable supplies of hydrogen and will therefore be reluctant to enter into agreements for variable amounts of production. The same is true for other potential industrial offtakers, such as high-heat industrial process users. Finding additional potential offtakers, such as long-duration storage, will also be challenging and may require policy refinements.

It's worth emphasizing that flexible nuclear energy is part of a long-term solution. Additional at-scale nuclear energy generation capacity will only come online by the mid-2030s at the earliest. Still, given that the electricity sector is highly important to industrial decarbonization, but relatively straightforward to decarbonize, longer-term efforts like reenvisioning nuclear power plants' roles should be pursued in tandem with grid decarbonization.

The US Midwest and Decarbonization Technologies: Illustrating the Challenge

When considering how to deploy the industrial decarbonization tools already described, region-specific conditions must be taken into account. The Midwest in particular should be a focus of industrial decarbonization in the United States due to its high concentration of heavy industry. Indiana has historically been the largest steel producer, accounting for about a quarter of the nation's output.[41] In the greater Midwest region, there are currently three primary aluminum producers.[42] Additionally, several refineries are in the Midwest's

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[38] "Table 6.07.A. Capacity Factors for Utility Scale Generators Primarily Using Fossil Fuels," Electric Power Monthly (website), US EIA, accessed November 6, 2022, https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_a.

[39] "Table 6.07.B. Capacity Factors for Utility Scale Generators Primarily Using Non-Fossil Fuels," Electric Power Monthly (website), US EIA, accessed November 6, 2022, https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_6_07_b.

[40] Table 6.07.A. Capacity Factors for Utility Scale Generators Primarily Using Fossil Fuels."

[41] Alex Brown, "Indiana Again Tops US in Steel Production," *Inside Indiana Business*, April 28, 2021, https://www.insideindianabusiness.com/articles/indiana-again-tops-us-in-steel-production.

[42] "Aluminum Statistics and Information," US Geological Survey, Advance Data Release of the 2020 Annual Tables, August 17, 2021, https://www.usgs.gov/centers/national-minerals-information-center/aluminum-statistics-and-information.

PADD-2 region,[43] with operable capacity of about 4.2 million barrels per day.[44] Furthermore, with regional refineries relying on heavily sulfuric Canadian crude, there is substantial hydrogen consumption in the Midwest.[45] A consequential fraction of US cement production also takes place in the Midwest.

While the region is an important industrial producer and emitter in the United States, it lacks requisite decarbonization infrastructure and renewable resources. The Midwest faces hurdles for developing both carbon storage to offset cement emissions and renewable energy to power hydrogen production. Like most regions of the country, the Midwest has marginal geological resources that could be used to store carbon.[46] Midwestern industrial producers in a net-zero world would therefore have to use pipelines to transport CO_2 to the Gulf Coast. For hydrogen production, unfavorable solar economics constrain the business case for regional green hydrogen electrolyzers, thus regional industry may need to rely on blue hydrogen from natural gas feedstocks in the medium term to replace fossil fuels in heating processes.

In any of these scenarios, the Midwest will require substantial new infrastructure. The United States will not succeed in decarbonizing its industry unless it can build new solar panels, wind turbines, transmission lines, batteries, electrolyzers, pipelines, and more. A consideration of Midwestern decarbonization illustrates how important permitting and transmission reform are for US industrial decarbonization efforts more broadly.

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[43] PADD stands for Petroleum Administration for Defense Districts, and the United States has five such geographic aggregations. See “Today in Energy,” US EIA, accessed March 27, 2023, https://www.eia.gov/todayinenergy/detail.php?id=4890#:~:text=The%20Petroleum%20Administration%20for%20Defense,PADD%205%20the%20West%20Coast.

[44] “Refinery Utilization and Capacity (PADD-2),” Midwest (PADD-2) Refinery Utilization and Capacity, US EIA, October 31, 2022, https://www.eia.gov/dnav/pet/PET_PNP_UNC_DCU_R20_M.htm.

[45] US Gulf Coast Refinery Demand for Hydrogen Increasingly Met by Merchant Suppliers,” US EIA (homepage), March 15, 2019, https://www.eia.gov/todayinenergy/detail.php?id=38712.

[46] “US Gulf Coast Refinery Demand for Hydrogen,” US EIA.

Permitting Reforms and Building New Infrastructure

Electrification is US decarbonization's lowest hanging fruit, offering immediate emissions reduction potential in the steel, aluminum, cement, and refining sectors. Yet achieving a green grid will require two separate elements: funding for clean energy, provided either directly through fiscal support or, preferably, via market mechanisms, and the legal authority to rapidly build clean energy and other decarbonization projects. The United States has taken a major step toward commercializing clean energy through IRA, but will fall short of its objectives if it cannot build and deploy new infrastructure.

While permitting reforms for the deployment of clean energy have not been a traditional focus of industrial decarbonization efforts, it is difficult to overstate their significance. Permitting processes regularly stall projects for months to years and are routinely identified as a primary challenge for clean energy project developers. Speeding up permitting will keep clean energy costs manageable, allow stalled projects to move forward, encourage companies to propose new ones, and add clean energy to the grid.

Examples of these permitting challenges abound. Substantive reviews of solar projects under the National Environmental Policy Act (NEPA) required projects to undertake a review process that would often take two years or longer.[47] Slow review times extend across other clean energy sectors; no new nuclear power generation capacity was brought online in the United States from 1996 to 2016.[48] Additionally, transmission lines connecting renewables generation with demand centers are routinely tied up in permitting disputes for years.[49] For these reasons and more, analysts believe that permitting delays could block clean energy targets.[50]

To clear the red tape, policymakers at the local, state, and national levels must pass policies to improve permitting with a focus on two key issues that balance safety concerns and community inputs. A priority must be to ameliorate what political scientist Francis Fukuyama calls "vetocracy," or rule by veto.[51] Well-organized "not in my backyard" interest groups and other anti-infrastructure organizations are able to veto new infrastructure in defiance of the broader public interest, the will of relevant majorities, or often both. Policymakers should strive to reduce veto points or unnecessary delays, while still striving for community buy-in and maintaining rigorous safety standards.

Additionally, all levels of government—from the local, state, and national levels—should prioritize funding for regulatory bodies and staffing them appropriately. Proper funding will support the enactment of creative proposals such as "proactive permitting," or identifying lands where solar or wind farms could be located with little to no environmental review.[52] This proposal could dramatically accelerate clean energy deployment, and, encouragingly, there are some signs of progress, as the Interior Department is seeking to identify special zones for solar projects that will receive expedited permitting.[53] Still, speed and scale matter, and for proactive permitting to be successful, all levels of government must have appropriate staffing and accelerate permitting review times.

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[47] Arthur G. Fraas, "Reforms to Federal Permitting Can Speed Solar Energy Deployment," Resources for the Future, May 12, 2021, https://www.resources.org/common-resources/reforms-to-federal-permitting-can-speed-solar-energy-deployment/.

[48] "Nuclear Explained: U.S. Nuclear Industry," US EIA (website), April 18, 2022, https://www.eia.gov/energyexplained/nuclear/us-nuclear-industry.php.

[49] Emma Penrod, "Why the Energy Transition Broke the U.S. Interconnection System," *Utility Dive*, August 22, 2022, https://www.utilitydive.com/news/energy-transition-interconnection-reform-ferc-qcells/628822/.

[50] DJ Gribbin, "Environmental Permitting Might Block Biden's Clean Energy Targets," *The Avenue* (blog), Brookings Institution, May 13, 2021, https://www.brookings.edu/blog/the-avenue/2021/05/13/environmental-permitting-might-block-bidens-clean-energy-targets/.

[51] Francis Fukuyama, "America in Decay," *Foreign Affairs*, January 30, 2023, https://www.foreignaffairs.com/united-states/america-decay.

[52] Fraas, "Reforms to Federal Permitting Can Speed Solar Energy Deployment."

[53] Nicola Groom, "U.S. Will Consider New Priority Areas for Solar Energy on Public Lands," ed. Leslie Adler, Reuters, December 6, 2022, https://www.reuters.com/business/environment/us-will-consider-new-priority-areas-solar-energy-public-lands-2022-12-06/.

Conclusion and Recommendations

Whether it comes to green hydrogen, blue hydrogen, running next-generation nuclear power facilities as peaker plants, or building a carbon capture and storage network, policymakers will have to maintain flexibility and adjust to changing techno-economic realities. Indeed, one of the most important steps in US industrial decarbonization is to fund research and development to support innovative solutions, such as advanced nuclear reactors, and identify the most efficient path forward.

Decarbonizing US industrial emissions will require an all-of-the-above solution, leading policymakers to assist in domestic technological deployment.

Generating new clean energy technologies for industrial decarbonization will hinge on macro policies. Several steps will prove enormously vital for the industrial decarbonization agenda including easing permitting burdens; accelerating the siting of new, long-distance transmission lines; building out the US grid; and reducing inflation and interest rates.

“Greening the grid” and electrification must be prioritized whenever possible. Key industrial processes in aluminum, steel, and other sectors run on electricity, so moving toward a zero-carbon grid will decrease industrial emissions. While many of the lowest-hanging fruit for electrification have already been plucked, considerable opportunities to further reduce electricity-related emissions remain. About 90 percent of coal is used for electricity, which means bringing additional clean energy to the grid to replace coal will rapidly decrease overall emissions and further industrial decarbonization.

The United States should continue to provide fiscal support for the development of clean technologies, including hydrogen. New technologies, including clean hydrogen, must resolve the “chicken-and-egg” problem by sending powerful market signals to both suppliers and consumers. The Infrastructure Investment and Jobs Act (IIJA) provides billions for “hydrogen hubs,” which will establish at least four regional hubs, while the IRA provides support along the entire clean hydrogen supply chain, especially for green hydrogen. Given hydrogen’s importance for US industrial decarbonization efforts, the United States should continue to prioritize this technology. At the same time, hydrogen’s importance should not be overstated: additional clean electricity generation is of higher—arguably the highest—importance for decarbonization, especially in the aluminum sector. Adding more clean electricity to the grid could reduce electricity prices and lower the costs of electrolysis, ultimately benefitting the hydrogen sector.

The US government should fund the research needed to understand basic hydrogen market fundamentals and adequately resource key regulatory bodies. While market participants will have to learn by doing to a certain degree, the federal government can help reduce uncertainty surrounding hydrogen infrastructure by funding research to determine the relative costs of long-distance hydrogen transmission via pipelines or wires. Research in this area would prove relatively inexpensive and could provide significant economic and climate benefits. The US federal and state governments should also begin preparing for what is expected to be a massive surge in hydrogen activity and deployment. Regulatory agencies will need to begin considering what resources, processes, and personnel will be required to provide timely oversight and approval.

Finally, policymakers should fund research to support the use of nuclear energy for grid flexibility and pink hydrogen production, which could revolutionize future electricity and hydrogen markets. Nuclear reactors with flexible ramping could, over the long term, replace natural gas and coal plants that power on to meet peak demand. Indeed, nuclear peaker plants may be instrumental to a carbon-free grid. Moreover, these facilities could run continuously, providing electrons for pink hydrogen when not supplying power to the grid. This model would theoretically lead to much higher utilization rates for peaking power plants, solve the intermittency problem for renewable assets such as wind and solar, and lead to steady production of hydrogen. Given the potential decarbonization benefits of nuclear peaker power plants—especially for US regions with less favorable green hydrogen economics, such as the Midwest—policymakers should fund research in this promising area.

The United States has made strides in reducing industrial emissions, mostly thanks to reducing coal usage in the electricity sector. This is a good start, but more is needed—and quickly. Absent additional efforts as recommended in this paper, the pace of carbon emission reductions could slow or even plateau.

The most effective paths to accelerate industrial decarbonization entail permitting reform and pursuing a comprehensive understanding of clean energy deployment. While the United States has enhanced fiscal support for clean energy development, policymakers across the country at all levels of government should reduce permitting review times and ensure that projects are not stuck in regulatory limbo indefinitely. The United States should also research methods of decarbonization, including nuclear energy development, and wires-vs-pipeline transportation costs for green hydrogen. The United States must urgently advance these efforts to guarantee the domestic and international industrial-emissions reductions the world needs.

About the Author

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