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INDUSTRY EMISSIONS: PROCESS CHANGES AND POLICY OPTIONS ON THE ROAD TO NET ZERO

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Reducing greenhouse gas (GHG) emissions from industrial operations poses a significant challenge due to heat needs ranging from 50–1,600°C (122–2,912°F) as well as process-based emissions. The Paris Agreement emphasizes maintaining a global temperature increase "well below 2°C and toward 1.5°C" from preindustrial levels. This requires industry to reach net-zero carbon dioxide (CO_2) by 2050 or pay for expensive additive, verifiable, and permanent offsets. Given this and the 15–25-year lifespan of major process equipment, all new industrial production investments will need to be near-zero emissions by the early 2030s[1] or be offset. This will require sectorally and regionally tailored mixes of more material efficiency, a higher volume and quality of recycling, electrification of existing processes, process changes that allow switching to ultra-low GHG emission fuel and feedstock, and carbon management. These strategies also lead to greatly improved local air quality.

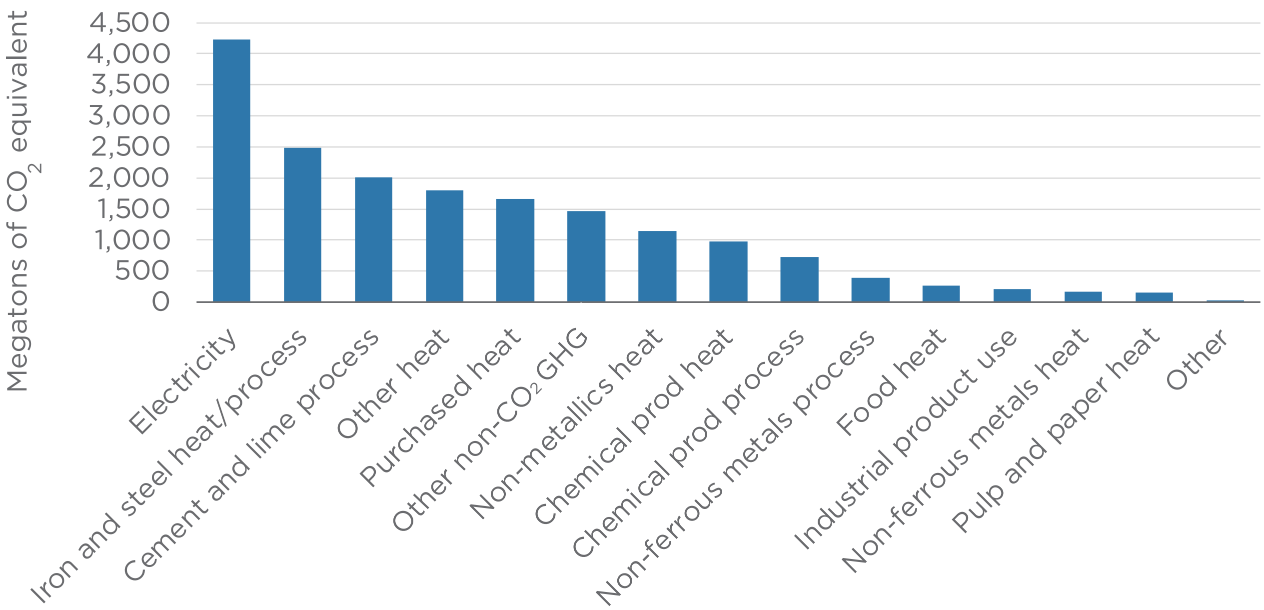
This commentary explains the necessity and challenge of decarbonizing industry, details technical areas that will need to be addressed, and provides policy recommendations based on those. Facilitating such a massive transformation will require a variety of strategies and incentives, such as encouraging expansion of very low GHG electricity, innovating for uptake of near-zero emissions processes, and establishing industrial clusters for efficiency and cost reduction. Coordinating efforts across the country, regionally, and globally will help ensure green procurement, GHG accounting, and trade policies are adequate to the task ahead.

Necessity and Challenge of Decarbonizing Industry

Industry's greenhouse gas (GHG) emissions are a big and growing problem that has historically received little attention. Electricity use, heat needs (ranging from 50–1,600°C [122–2,912°F]), and chemical process carbon dioxide (CO_2) (e.g., from cement, lime, hydrogen, and other chemical production) create the largest amount of such emissions, as shown in Figure 1. Direct combustion of coal, natural gas, and refined petroleum products for industrial heat emitted 7.0 gigatons of CO_2 equivalent (Gt CO_2e) in 2019, or 11.9 percent of all global

GHG emissions that year (which totaled 58.9 Gt CO_2e).[2] Once process emissions (3.1 Gt CO_2e) are added, such as for cement, this rises to 17.2 percent. When adding purchased heat (1.7 Gt CO_2e), purchased and self-generated electricity (4.3 Gt CO_2e), product use (0.2 Gt CO_2e), and non-CO_2 GHGs (1.5 Gt CO_2e), the total rises to 30.1 percent. Industry's emissions have grown more since 2000 than any other sector, at 2.7 percent per year.

Figure 1: Global industrial greenhouse gas sources by sector, 2019



Source: IPCC, Climate Change 2022: Mitigation of Climate Change*, April 4, 2022, ch. 11, https://www.ipcc.ch/report/ar6/wg3/.*

Before the Paris Agreement was adopted in 2015, industrial GHG mitigation was focused on energy efficiency, coal-to-gas or electricity fuel switching, and carbon capture and storage (CCS). In projections simulated by global models, industry was allowed to maintain roughly half its emissions in 2050, compensated by negative emissions from bioenergy combined with CCS in the power sector.[3]

Energy costs can be significant in some heavy industry sectors, leading these sectors to pursue energy intensity reductions over the decades, typically 1–2 percent per year. Continued improvements are getting harder to find, however, as use of best available current technology in steel, cement, and other facilities becomes more common. Size and systems integration is the remaining option for further efficiency improvements.

Coal and natural gas are still considerably cheaper than electrification in most places, limiting its adoption. Meanwhile progress with CCS has been largely confined to natural gas processing with a smattering of ethanol and hydrogen production facilities and a single steel plant, with all sharing the characteristic of producing a concentrated stream of waste CO_2, bypassing the most challenging step of separating the CO_2 from nitrogen in waste flue gases.[4]

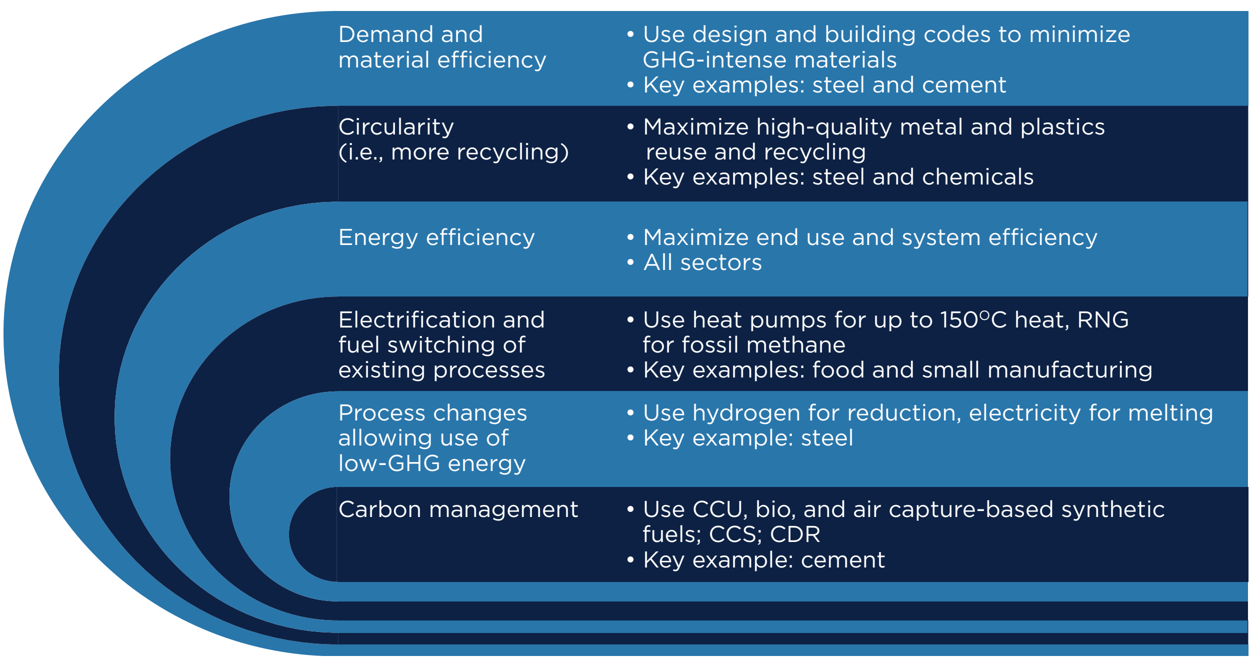
In sum, industry has been widely regarded as "hard to abate," none the less because major process equipment, like furnaces and boilers, lasts 15–25 years between major renovations, and industrial commodities trade in global markets, making carbon leakage from one region with strong climate policy to one with weaker or absent policy a distinct possibility.

The Paris Agreement utterly changed the industrial mitigation discussion. Under the new targets, any industrial facility still emitting CO_2 in 2050 will likely have to pay for permanent, additive, verifiable, and expensive atmospheric carbon dioxide removal (CDR) offsets, projected to cost $200–600 in the near term, and at least $100–300 per ton in the 2030–2050 period.[5] This change in framing sent analysts, modelers, engineers, and companies back to the drawing board. What emerged in the 2018[6] and 2022[7] Intergovernmental Panel on Climate Change (IPCC) reports was that Paris Agreement compliant mitigation will require considerable process changes, as detailed in the next section. Most of the technology involved already exists at the pilot to near commercial level but requires both a fundamental change in the approach to industrial demand and production and a systemic uplift in policy stringency.

Technical, Behavioral, and Systems Solutions

A systemic, multi-strategy approach to decarbonizing industrial electricity and heat use as well as eliminating process emissions is illustrated in Figure 2, as advanced in the Industry chapter of the latest IPCC report.[8] Below the figure the author explains the technical strategies, sector applications, and policies needed to drive the changes.

Figure 2: Strategies for decarbonizing industry



Source: Author configuration based on IPCC, Climate Change 2022: Mitigation of Climate Change*, April 4, 2022, ch. 11, fig. 11.9, https://www.ipcc.ch/report/ar6/wg3/.*

Material efficiency through better design and building codes could reduce cement use by up to 26 percent globally and steel by 40 percent.[9] Achieving this revised procurement will require architectural and engineering education and building codes that encourage material efficiency. While results will be extremely jurisdiction-specific, a building in Chicago was recently built with 27 percent less concrete and 8 percent less steel using known and already approved techniques.[10]

More circularity, initially through much more and higher quality recycling, will be central to reducing emissions from most metals and plastics. Recycled metals and plastics are far less energy and carbon intense. While most iron is recycled today, more at higher quality levels could be recovered with effort and design to minimize contamination, especially with copper.[11] Only about a quarter of aluminum is recovered, and recycling of all metals could improve.[12] Only about 5 percent of polyethylene is recycled.

Energy efficiency should be maximized. While firms should invest in electrification and near-zero emissions processes as soon as they are available, and participate in programs to commercialize them, where near-zero emissions versions aren't available the highest efficiency fossil fuel versions will help reduce cumulative emissions. There are also substantial remaining efficiencies in process and integrated system refinement, often through digital monitoring and modelling of plant processes.[13]

Electrification and other fuel switching of existing processes can lessen GHG emissions. Where technically and economically feasible, most coal-to-gas switching has already occurred. A significant GHG benefit can be derived from reducing upstream fugitive methane to less than 0.5 percent,[14] but the next big jump is clean electrification for heat, with some interim replacement of fossil methane gas with low GHG bio or synthetic methane, also known as "renewable natural gas." Many forms of electrification for industry are possible today, directly through electrothermal or induction heating or indirectly through industrial heat pumps, which can reach up to 150°C (302°F) and efficiencies of 400 percent at lower temperatures.[15] The affordability of heat pumps, however, is highly sensitive to relative regional natural gas and electricity prices, as well as access to a heat source to concentrate (e.g., industrial waste heat). They are generally more expensive than using natural gas or coal directly for low heat levels without significant carbon pricing, and electrification at higher heat levels than those achievable by heat pumps imposes challenging time-specific capacity needs on the electricity grid.

Industrial process changes can allow the use of zero-emissions fuels and feedstocks. Fundamental changes to steel, chemical, and other material production are being commercially piloted that will allow use of electricity, hydrogen, ammonia, low GHG carbon, or derivatives to be used as chemical feedstocks and replacement for methane and coal for delivering heat at all levels. Several hydrogen-based technologies have emerged to replace the use of coal as the reductant in blast furnaces for making steel,[16] and electro heated[17] and electrocatalytic chemical processes are being explored.[18] Synthetic net-zero liquid and gaseous fuels and feedstocks are commercially feasible with biomass or direct air capture carbon sources, but are considerably more expensive than today's fossil fuels. Low GHG hydrogen is a key element of many strategies and will be needed for process heat and chemical feedstocks.[19] Some regions will start with hydrogen made from methane and

CCS (“blue” hydrogen),[20] while others will go directly to hydrogen made from electrolysis (“green”).[21] Low GHG hydrogen may allow global trade in ammonia or methanol as an energy carrier. Green hydrogen production also produces oxygen, which is useful for oxy-combustion—which makes CCS easier—and as a feedstock for synthetic net-zero hydrocarbon and alcohol fuels and feedstocks.

Carbon management (i.e., flue gas CO_2 capture, utilization of waste CO_2, sourcing of lower GHG carbon sources like biomass and direct air capture, and permanent geological storage) will be necessary for several sectors and legacy assets. The first applications will likely focus on the capture of concentrated flows of CO_2 from formation gas cleaning, hydrogen production, refining, and cement production. A breakthrough in post combustion capture would allow wider use (e.g., for blast furnace steel made with coal, glass, or ceramics).[22] Combined with low GHG hydrogen and oxygen, low GHG carbon sources may also allow some continued use of synthetic net-zero methane for legacy buildings and industry, as well as methanol, ethanol, ethane, and ethylene for chemical production. Taken to its logical conclusion, with ever less CO_2 in the atmosphere, ever more recycled, and ever more underground, carbon management could lead to net-negative CO_2 flows from the atmosphere back into the earth, also known as carbon dioxide removal (CDR).[23]

Another strategy for decarbonizing industry would involve physical facility clustering. Carbon capture and use (CCU), CCS, blue and green hydrogen, electrification, and waste heat cascading and reuse with heat pumps will all be cheaper and easier if facilities are located closer together, sharing infrastructure, possibly in preplanned and approved net-zero industrial clusters.[24] While hydrogen production and storage as well as carbon collection, transport, and disposal are already commonly discussed, industrial heat pumps will also be far more economic if they have access to 40–50°C (104-122°F) industrial waste heat sharing systems as opposed to 0–25°C (32-77°F) ambient heat. The International Energy Agency (IEA) has suggested that industrial seaports with existing hydrogen production for refineries could be key catalysts for such clusters.[25]

These strategies translate to the following actions by sector in near-zero emissions scenarios for industry[26]:

- **Steel** production will maximize use of recycled scrap processed in electric arc furnaces, with quality and volume top ups of new primary iron made using processes that use hydrogen (direct reduction) or electricity (molten oxide electrolysis) instead of coal to separate elemental iron from iron ore.[27] If there is a breakthrough in post combustion carbon capture, purpose-built, coal-based blast furnaces may be chosen. Another related possibility, if gasification of biomass can be mastered, is using sustainable biomass combined with CCS to replace fossil fuel coal to get near net negative.[28]
- **Cement and concrete** production will maximize use of cementitious material substitutes (e.g., slags, ground limestone, and calcined clays), and some combination of CCS and clean process heat will be used for making clinker.[29]
- **Chemicals** production, combined with intensive plastics recycling, switches to near-zero GHG hydrogen, oxygen, and eventually carbon (through CCU, biogenic sources,

and direct air capture) with low GHG process heat and eventually electrocatalytic processes that directly use electricity to make chemicals.[30]

- **Aluminum** production fully switches to ultra-low GHG electricity and inert anodes with no process emissions.[31]
- **Pulp and paper** switches to fully biogenic energy sources or clean electricity and eventually becomes a supplier of biogenic carbon to the chemicals industry for fuels and feedstocks.
- **Light manufacturing, food processing, and some chemicals** use direct electrification, industrial heat pumps, bioenergy, direct solar energy, hydrogen, and synthetic net-zero fuels depending on the heat needs.[32]

If accomplished, decarbonization of industry will lead to several benefits besides slower climate change. Along with personal transport and building electrification, it can help lead to dramatically improved air quality, helping reduce some of the five to nine million early deaths globally due to poor local air quality.[33] While less studied, it is expected that water use will fall and less toxics associated with hydrocarbons will be emitted.

Policy and Industry Recommendations

Policy makers and industry leaders seeking pathways toward industrial decarbonization could consider the following actions:

Create policies to ensure a large, growing, reliable, and relatively inexpensive supply of very low GHG electricity. This is for direct electrification, making hydrogen, and generally powering the overall industrial ecosystem (e.g., heat pumps, electrolyzers, and CCS separation and compression units). Industry can help by reducing demand during peak periods and adding the capability to absorb off-peak electricity by transforming it into hydrogen and storing several days' capacity underground to meet daily fuel and feedstock needs.[34] Also, in regions with sufficient resources, industrial players may be able to reduce strain on the grid by building their own dedicated variable and firm clean power sources[35] and transmitting and sharing those on the grid as necessary.

Speed up the process of innovation and early-to-late commercialization for near-zero emissions, with a focus on intensive staged research and development followed by development of public and private lead markets to reduce risk. Funding needs to be boosted for the entire innovation supply chain, but mostly for early-to-late commercialization. Government and private green procurement and instruments like contracts for difference could create lead/niche markets to bridge the early commercialization valley of death and reduce risk, and therefore capital costs.

Establish industrial clusters to reduce the cost of blue and green hydrogen and CCS and to allow waste heat reuse with industrial heat pumps. This requires national and regional governments, and perhaps coalitions of firms, to map existing industry (especially where hydrogen is made and used today), renewable energy supplies, CCS geology, and transport networks. The IEA[36] indicated that industrial seaports near good sun, offshore wind, and CCS geology are likely early candidates, such as Rotterdam in the Netherlands; Galveston, Texas, in the US; and Teesside in the UK. A case study by Friedmann et al. considered Houston, Texas.[37] Heat sharing systems could capture waste heat from heavy industry and make it reusable for lighter industry using industrial heat pumps, improving their economics in turn.

Drive broad market uptake of near-zero industrial options by enacting policies including low-interest loans and tax credits to overcome capital-expenditure-intense investments like heat pumps, heat and steam GHG standards, carbon pricing, and performance regulations. These could influence the next big investment cycle from 2025 onward, and especially after 2030, but the policies need to be sufficiently strong to make near-zero emissions technologies the default for all new retrofits, renovations, and new builds.

Establish international coordination with regard to green procurement, GHG accounting, and trade policies (e.g., border carbon adjustment and standards). Green procurement will have faster transformative effects if countries work together to demand it and fund it, and sharing the risk will reduce the individual country's risk. All climate policies pertaining to industrial commodities require robust and relatively easy-to-use GHG accounting, even if a traded good or commodity is sequentially processed in several regions. Most industrial commodities are highly traded, and strong but expensive efforts to decarbonize in one region could lead to leakage of dirty production to regions without climate policy. This circumstance has already led the EU to announce it will impose a carbon border adjustment mechanism for steel, aluminum, cement, and electricity.[38] Trade policies could be structured to reshape supply chains to allow the processing of commodities (e.g., reduction of iron ore)[39] in regions with low-cost renewables or CCS geology for shipment to demand regions for final processing (e.g., making steel in electric arc furnaces).

Conclusion

Given the 15–25-year lifespan of major process equipment, all new industrial production investments will need to be near-zero emissions by the early 2030s to keep the global temperature rise below 1.5–2°C, a key Paris Agreement target. Industrial decarbonization is often framed as decarbonization of heat, or hydrogen, or CCS. Though all of these strategies will be part of the transition, a whole range of other options exist. These include sectorally and regionally tailored mixes of more material efficiency, circularity/recycling, electrification using existing processes, fundamental process changes to allow ultra-low GHG fuel and feedstock switching, and carbon management. Incorporating these process changes will require a systemic, multi-strategy approach, including the following:

- Regional and national governments crafting policies that ensure an adequate and affordable supply of very low GHG electricity for direct use and for making hydrogen and derivatives.
- Governments working with industry to speed the process of innovation and early-to-late commercialization for near-zero emissions, with a focus on developing public and private lead markets to reduce risk.
- National and regional governments establishing preplanned and zoned industrial

clusters to reduce the cost of blue and green hydrogen and CCS and to physically allow waste heat reuse with industrial heat pumps.

- Policy makers encouraging broad market uptake of near-zero industrial options through loans and tax credits to overcome capital-expenditure-intense investments like heat pumps, standards for heat and steam GHG intensity, pricing of carbon, and regulations governing performance.
- Like-minded, ambitious national governments working together to establish international coordination of green procurement, lifecycle material GHG accounting, and trade policies.

Key future research directions could include investigation of rules of thumb for investment in new process equipment and facilities by industrial firms and for policy formation. These investment and policy benchmarks would be sector-, region- and jurisdiction-specific, and would require dynamic conversations with all key stakeholders.[40]

Notes

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About the Author

Dr. Chris Bataille has been involved in energy and climate policy analysis for 26 years as a researcher, energy systems and economic modeler, analyst, writer, project manager, managing consultant, and founding partner. His career has been focused on the transition to a globally sustainable energy system, more recently technology and policy pathways to net-zero GHG emissions by all sectors by 2050-70 to meet the Paris Agreement goals. He is an Associate Researcher at the Institute for Sustainable Development and International Relations (IDDRI.org) in Paris working on the Deep Decarbonization Pathways project (DDPinitiative.org), and an Adjunct Professor at Simon Fraser University. Chris was a Lead Author for the Industry Chapter of the 6th cycle of the IPCC Assessment Report 2019-2022, as well as the Summary for Policy Makers and Technical Summary. He manages an ongoing global project to review technology and policy options for net-zero decarbonization of heavy industrial sectors, including the global Net Zero Steel project (netzerosteel.org), which has produced facility level, geospatial net zero pathways for the global steel industry. Chris is continuing his focus on industrial decarbonization at CGEP.

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