Foreign Policy at BROOKINGS

THE CHALLENGE OF DECARBONIZING HEAVY INDUSTRY

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EXECUTIVE SUMMARY

Heavy industry makes products that are central to our modern way of life but is also responsible for nearly 40% of global carbon dioxide (CO_2) emissions. Steel, cement, and chemicals are the top three emitting industries and are among the most difficult to decarbonize, owing to technical factors like the need for very high heat and process emissions of carbon dioxide, and economic factors including low profit margins, capital intensity, long asset life, and trade exposure.

Steelmaking uses coal both as a source of heat and as part of the chemical process of converting iron ore to elemental iron. Both of these uses produce carbon dioxide. Eliminating CO_2 emissions from steelmaking requires a change in process. Using hydrogen as the heat source and the chemical reducing agent can eliminate CO_2 emissions, or carbon capture can remove them. Steel can also be recycled without CO_2 emissions, but demand for steel is too large to be met with recycled steel alone.

Cement production also releases CO_2 as part of the chemical process, in this case when limestone is heated to very high temperature to produce calcium oxide "clinker," the cement's primary component. Other substances can be mixed with clinker while still maintaining cement quality, but the primary method of decarbonizing the sector is to capture the CO_2 and store or find a use for it.

The chemical industry is different from the other two, encompassing many thousands of processes and products. However, more than 90% of "organic," or carbon-containing, chemicals are derived from just a few building blocks, which are produced in large quantities and traded internationally. The chemical industry is also unique in that it uses coal, oil, and natural gas as feedstocks that are transformed into final products, not just sources of energy. Fossil fuels will likely still be feedstocks in a zero-carbon world, with process electrification and zero-carbon hydrogen as methods of removing CO_2 emissions. Ammonia is crucial for fertilizer and although it does not contain carbon, hydrogen needed for its production is today made from natural gas, with carbon dioxide as a by-product.

These industries and others share technical challenges in common, including process emissions of carbon dioxide, the need for high heat, and use or potential use of hydrogen. A number of technical solutions can be shared across the sectors as well, which are interrelated and synergistic in some cases. Carbon dioxide capture and utilization or storage (CCUS) is an option for emissions that cannot be eliminated or where elimination is prohibitively expensive.

Despite their emissions and energy intensity, the steel, cement, and chemical industries are with us to stay. Much of the infrastructure needed to build a low-carbon economy will be made of steel and cement. Reductions in single-use plastics could help reduce organic chemical demand, but plastics have useful qualities that are hard to replace, such as their light weight and durability. Policy will be crucial to achieving industrial decarbonization, since it will require large capital investments in low-margin industries, not something that most companies will be able to do on their own. Governments can assist with the investment cost, provide demand pull for low-carbon products, and use trade policy to protect domestic low-carbon industries from cheaper but higher-carbon products from abroad. These policies use different levers to spur action, and industry may need all of them to make such extensive changes.

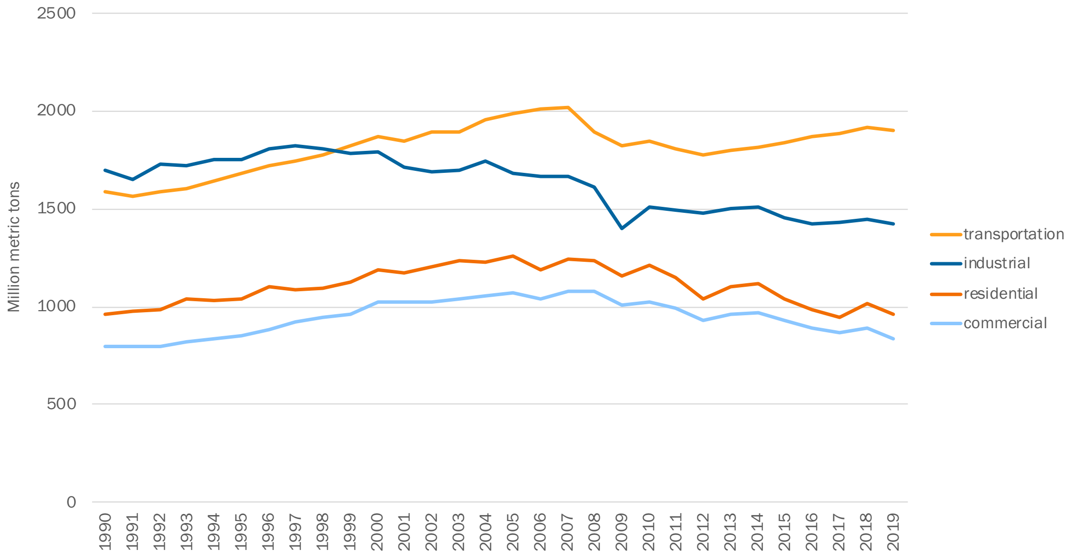
CENTRAL TO MODERN LIFE, BUT AN IMPORTANT EMISSIONS SOURCE

Industrial raw materials are key to our modern life. They are the building blocks of many products we use constantly, from buildings and infrastructure to ubiquitous plastic goods. Continuing economic growth, especially in the developing world, will only increase demand for these goods. Since 1971, global demand for steel has increased by a factor of three, cement by nearly seven, and plastics by more than 10. At the same time, the global population has doubled and GDP has grown nearly fivefold.[1] At the same time, global CO_2 emissions have increased by a factor of 2.3.[2]

The industrial sector is an important source of greenhouse gas (GHG) emissions, responsible for nearly one-quarter of direct CO_2 emissions in 2017. It encompasses a range of sources, including manufacturing, mining, and construction. When also accounting for indirect emissions — those resulting from offsite power generation — the industrial sector is responsible for nearly 40% of global CO_2 emissions.[3] Industrial emissions made up 28% of U.S. CO_2 emissions in 2019, and the Rhodium Group estimates that industry will overtake transportation as the largest source of U.S. greenhouse gas emissions within the next 10 years.[4] Reducing industrial CO_2 emissions is crucial to achieving deep decarbonization goals, such as reaching the U.S. and European Union goals of net-zero GHG emissions by 2050.

“When accounting for indirect emissions — those resulting from offsite power generation — the industrial sector is responsible for nearly 40% of global CO_2 emissions.

FIGURE 1: U.S. CO_2 EMISSIONS BY SECTOR

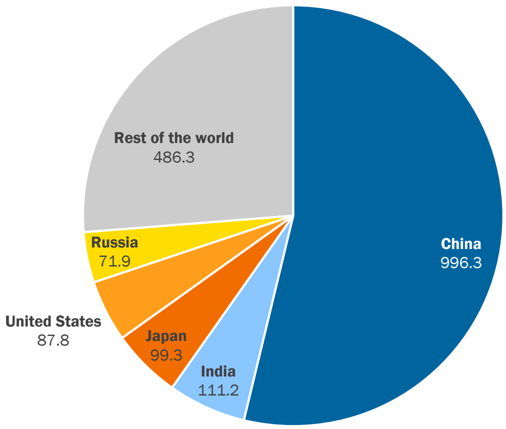


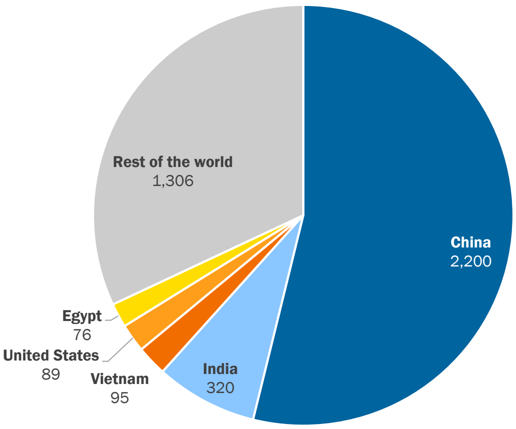
Source: U.S. Energy Information Administration[5]

This paper focuses on iron and steel, cement, and chemicals. They are crucial materials produced around the world, but are also among the largest sources of industrial emissions and the most difficult to abate. These three sectors account for more than half of industrial energy use and approximately 70% of industrial CO_2 emissions.[6] Coal is the most important fuel source in iron and steel (75%) and cement (60%) production. Natural gas and oil dominate the petrochemical sector, as both fuels and feedstocks.[7]

China is the world's largest producer of steel and cement, accounting for more than 50% of both (see Figure 2) as its industries support rapid urbanization and infrastructure buildout.[8] China's chemical industry accounts for nearly 40% of global revenue, a better measure than volume for such a diverse industry.[9] China is responsible for nearly half of global industrial GHG emissions, while the rest of the Asia-Pacific region contributes another 21%.[10] Expansion in heavy industry was an important driver of China's rapid economic growth from 2000 through 2010. In contrast, heavy industry is a smaller share of Organisation for Economic Co-operation and Development (OECD) economies and emissions.

FIGURES 2: TOP FIVE STEEL-PRODUCING AND TOP FIVE CEMENT-PRODUCING NATIONS, 2019 (MILLION METRIC TONS)





Source: World Steel Association[11]; U.S. Geological Survey[12]

Two important technical factors make these industries difficult to decarbonize. First, many processes need a level of heat that is difficult to achieve without combustion. One third of industrial energy demand is for high-temperature heat, and there are few alternatives today to the direct use of fossil fuels.[13]

Second, each of these industries includes processes that produce CO_2 as part of a chemical reaction, rather than as a combustion product. For these processes, eliminating CO_2 emissions requires either finding another chemical process that does not produce CO_2 or capturing the CO_2 produced and either using or storing it, a method known as CCUS. These process emissions constitute one quarter of emissions from the industrial sector, and much greater in certain industries.[14]

Economic factors also make these industries difficult to decarbonize. Steel, cement, and bulk chemicals are crucial products, but are also difficult businesses in which to make a profit. They are very capital intensive with minimal differentiation among products and producers. Profit margins tend to be low and cyclical, varying according to the cost of raw materials and the rate of economic growth. Economies of scale and low raw material and energy prices are crucial to profitability. There is little room in budgets for investment in new technology. Because the product is perceived to be the same across suppliers, buyers focus primarily on price.

Furthermore, production of these materials requires large capital investments in production facilities that can be used for as long as 50 years, potentially "locking in" emissions over the long term. The lock-in effect in the industrial sector is longer than for the power generation, transport, and building sectors.[15]

In addition to the technical and economic challenges with abating industrial emissions, trade raises additional challenges. Materials that produce large emissions are often traded internationally. This means that regulating emissions in one area may push production and emissions into another market, rather than eliminating them, an effect known as carbon leakage. High-emissions, trade-exposed commodities include steel, chemicals, and aluminum.

AN INTRODUCTION TO THE INDUSTRIES AND THEIR EMISSIONS

Steelmaking

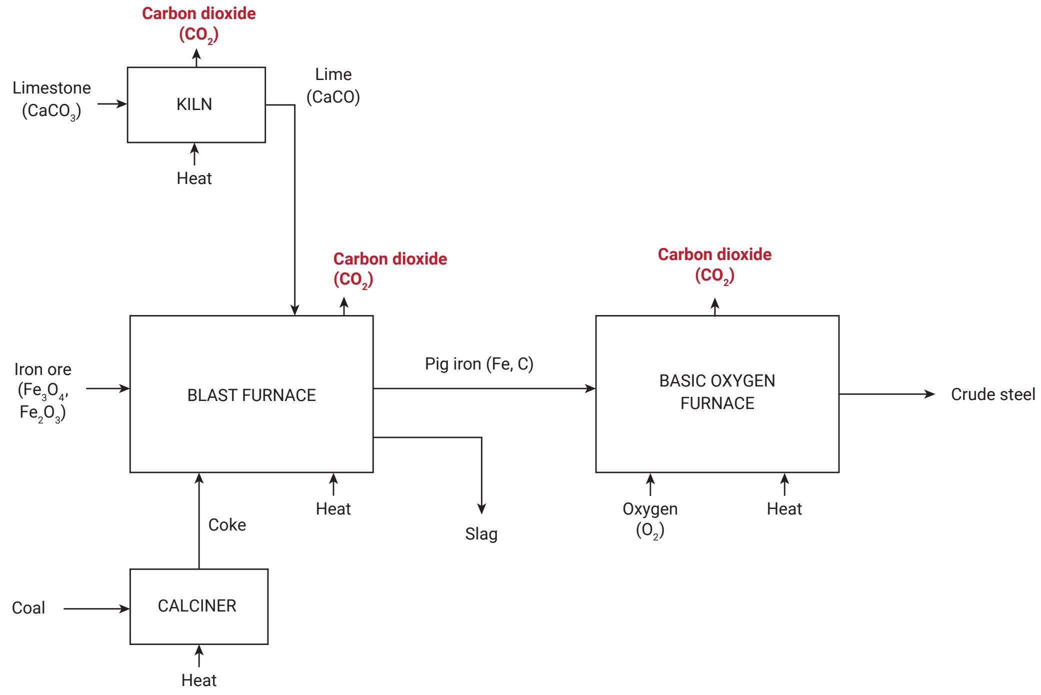
Steel is the world's most traded commodity after oil.[16] Globally, the steel industry accounted for 8% of the world's energy use in 2019.[17] About three-quarters of the sector's energy needs are met by coal — including coke produced from coal, which is also an important part of the chemical process.[18]

Steel is mostly iron, with other metals and carbon added to improve strength, hardness, and malleability. The iron is produced from iron ore — minerals consisting of iron and oxygen, mostly magnetite (Fe_3O_4) and hematite (Fe_2O_3). Although improvements over time have made it more efficient, the most common way that iron ore is processed to produce steel hasn't fundamentally changed in the 150 years since steel came into use.[19]

The first step in producing virgin steel (that made from iron ore) in an integrated steel mill is to convert the iron ore to elemental iron, breaking the chemical bond between the iron and oxygen in a blast furnace at a temperature of 1000°C or greater. The chemical process requires a reducing agent, a substance to take on the oxygen from the iron. In steelmaking, the reducing agent is usually carbon, added to the furnace in the form of coke, a form of refined coal that has been heated to remove impurities and increase the content of pure carbon. Iron oxides and coke enter the blast furnace (along with a small amount of lime, calcium oxide or CaO, "flux" to remove impurities); molten "pig iron" and CO_2 exit the furnace (along with molten slag containing impurities). The CO_2 produced in this process comes from two sources — fuel combustion to heat the furnace and the chemical output of the reaction. Approximately 80% of the CO_2 from the process of making virgin steel occurs at this stage.[20]

The pig iron produced in the blast furnace contains more carbon than finished steel and is brittle and difficult to work. The second stage in an integrated steel mill is the basic oxygen furnace, which removes excess carbon by heating the pig iron, along with a small amount of scrap steel, with pure oxygen to drive off the excess carbon and other impurities. This process also creates CO_2, although less than the blast furnace. Small amounts of other metals can be added at this stage to produce desirable properties. This process produces liquid steel, which is then formed or rolled into its final shape.

FIGURE 3: SIMPLIFIED PROCESS DIAGRAM FOR BLAST FURNACE



Steel is completely recyclable and recycling steel uses 74% less energy than creating virgin steel from iron ore.[21] Recycled steel is processed for reuse in electric arc furnaces in so-called "mini mills." Scrap metal, along with small amounts of other materials to help remove impurities, is loaded into a furnace, then electrodes are lowered onto the material. An electric arc forms between the electrodes and the scrap metal, which melts the material and oxidizes impurities in the scrap at temperature up to 1800 °C.[22] Molten steel and slag containing impurities are the final products.

Recycled steel is cost-effective, energy efficient, and relies on electricity rather than coal as its energy source, meaning that it can use renewable electricity. Additionally, unlike in virgin steel production, it does not produce process emissions of CO_2. However, there is not enough scrap steel to meet global demand. Two-thirds of U.S. steel production is recycled steel from electric arc furnaces. However, in developing markets with much greater appetite for steel than steel available for recycling, virgin steel produced from iron ore dominates. Forecasts suggest that there will continue to be high demand for virgin steel made from iron ore, meaning that process changes or carbon capture and storage are needed to deal with the CO_2 emissions from iron ore processing.[23]

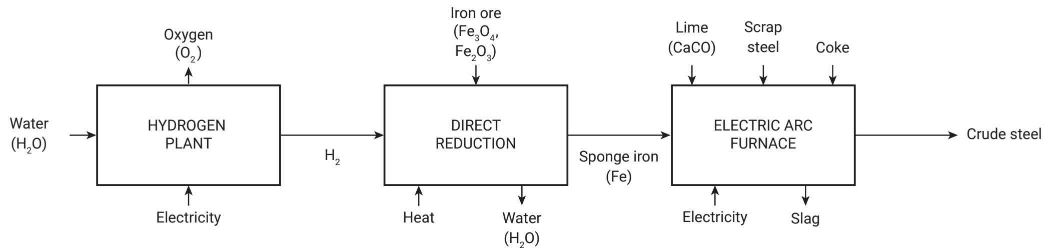
Clearly, increasing the recovery of steel for recycling can reduce energy use and CO_2 emissions. Reinforcing steel (rebar) and packaging currently have the lowest collection rates for recycling, so targeted efforts in these sectors will be helpful. Other important steps include designing steel-containing products with recycling in mind and improving processes for separating metals for recycling (especially copper and steel).[24]

Given that there will be continued demand for steel produced from iron ore, improvements in virgin steel production are needed to achieve deep decarbonization. Production has become more efficient and lower emissions over time, through optimizing the individual parts of the process and through using waste heat and waste materials. However, the most efficient producers are now reaching the thermodynamic limits of efficiency, meaning that further improvements in greenhouse gas emissions need to come from process changes.[25]

Biocarbon is a potential replacement for carbon from coal as the reducing agent in the blast furnace. The process still emits CO_2, but some of this CO_2 was taken in by the plants as they grew, resulting in lower net emissions. This method requires little change in the blast furnace process, and thus offers a near-term opportunity to reduce CO_2 emissions from virgin steel production without building new facilities. Raw biomass must be converted into charcoal through pyrolysis (heating to very high temperatures in the absence of oxygen), similar to the process that converts coal into coke, removing impurities and greatly increasing the content of pure carbon. The heat for this process typically comes from burning a portion of the biomass used. Conditions in the pyrolysis process can be controlled to produce charcoal appropriate for different types of steelmaking.[26] Potential sources of biomass include waste products from the lumber, pulp and paper, and biofuel industries. This process has the potential to reduce emissions from virgin steel production by around 20%.[27] However, there is competition for biomass and its price is often higher than fossil fuels.

One potential game changer is using hydrogen rather than carbon as the reducing agent in producing iron and as the furnace fuel, in a process called hydrogen direct reduction. The oxygen in the iron ore combines with the hydrogen to produce water (instead of with carbon to produce CO_2), eliminating the CO_2 emissions from this part of the process. The “sponge iron” product is then processed in an electric arc furnace to produce steel.[28] Since the arc furnace runs on electricity, this part of the process can be readily decarbonized as well.

FIGURE 4: SIMPLIFIED PROCESS DIAGRAM FOR HYDROGEN DIRECT REDUCTION



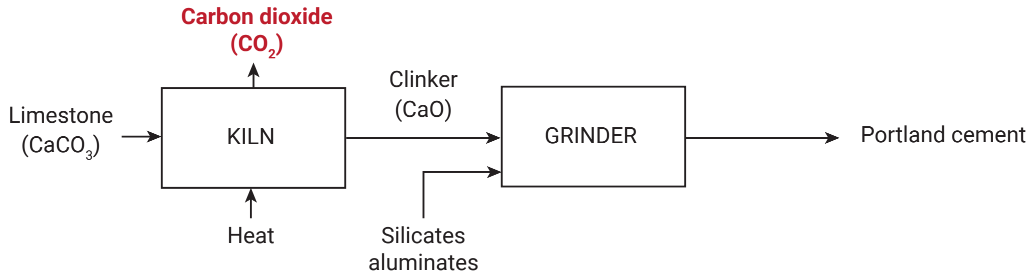
No steelmaker is using this process at a commercial scale today, but a consortium of companies in Sweden is planning to start construction on an industrial-scale demonstration plant in 2023, with production beginning in 2025.[29] They estimate that this process will produce steel at a cost premium of 20 to 30% above standard blast furnace technology,[30] a price which corresponds to a carbon price of $70 to $100 per ton of CO_2.[31] Additionally, research shows that hydrogen can be substituted into existing blast furnace processes to meet up to 30% of process energy requirements without major changes to existing equipment, allowing emissions reductions in existing plants before deployment of completely new, all-hydrogen technology.[32] Such technology is undergoing testing now in Germany.

Cement and concrete

Cement is the most widely used man-made material in existence and cement manufacture is the second-largest industrial emitter of greenhouse gases behind iron and steel. Cement is a key ingredient in concrete — the glue that holds it together. Cement forms a paste with water that binds together the sand and gravel components of concrete, then hardens as it dries. Concrete is typically 10 to 15% cement.[33] Concrete and cement are key materials in buildings, roads, and other infrastructure. Use has been growing rapidly; between 2000 and 2014, more cement was produced globally than during the entire 20th century.[34]

Portland cement, the most common type, was patented nearly 200 years ago and its production has changed little since then. Like steel, production of cement involves a chemical reaction that produces CO_2, apart from and in addition to emissions from energy use in the process. The fundamental reaction to produce cement involves heating limestone (calcium carbonate, $CaCO_3$) in a kiln to a temperature of 1400° to 1500°C to produce CaO and CO_2. The CO_2 from this chemical reaction makes up an average of 60% of GHG emissions from today's cement production, with the remainder of emissions from fossil fuel used to heat the kiln.[35] The resulting product is known as "clinker," which is ground to a powder and combined with other compounds (silicates and aluminates) to produce cement.

FIGURE 5: SIMPLIFIED PROCESS DIAGRAM FOR CEMENT PRODUCTION



CCUS will be an important technology for reducing emissions from cement production, since the majority of CO_2 emissions come from the process of producing clinker and thus cannot be abated. Recent studies of deep decarbonization in cement industry found that nearly half of potential reductions would be achieved by CCUS.[36] However, the technology is only beginning to be implemented at an industrial scale. The largest pilot-scale carbon capture plant in the industry today is at the Anhui Conch Cement Company's Wuhu Plant in China, which captures 50,000 tons of the 1.5 million tons of CO_2 produced per year by a single kiln line.[37] The captured CO_2 is sold to local industrial customers. Heidelberg Cement Company plans the first industrial-scale CCUS at its plant in Brevik, Norway, capturing 400,000 tons of CO_2 annually for geologic storage.[38]

Replacement of some clinker with other materials is another potential pathway to emissions reductions. "Supplementary cementitious materials" that can be substituted for clinker in Portland cement include industrial by-products like fly ash from coal-fired power generation or ground-granulated blast furnace slag from steel production, or natural substances like gypsum, ground limestone, calcined clay, or pozzolans (natural volcanic ash).[39] Recent studies suggest that clinker substitution could account for 27% of emissions reductions in California's cement industry and 37% of emissions globally.[40] However, the vital importance of finished concrete performance means that the cement industry is very cautious about changes in the composition of their product. Procurement criteria and quality concerns are important barriers to changes in cement composition. Additionally, the supply of industrial byproducts may decline over time as coal-fired power plants and virgin steel production are replaced by more efficient and lower-emitting processes.

The remaining potential reductions in emissions from cement production come through reductions in CO_2 production from energy, mostly from fuel switching. Coal and coke are the most common fuels for cement production today. Emissions reductions can be achieved through substitution with natural gas or with bio-based fuels or wastes. Biofuels and wastes will be in shorter supply over time, however, as many industries that need combustion for process heat or carbon building blocks for products turn to biomass and waste as fossil fuel substitutes.

Chemicals

Unlike the steel and cement sectors, the chemical industry encompasses a large variety of processes to create products that we use every day. For example, polyester accounts for 60% of fiber used globally, greater than natural fibers like wool or cotton.[41] Demand for chemicals is growing very rapidly. For example, global plastic demand has nearly doubled since 2000.[42] Demand for nitrogen fertilizer has largely plateaued in developed countries, but is growing rapidly in the developing world. On a per capita basis, the wealthy world uses up to 20 times as much plastic and 10 times as much fertilizer as countries like India or Indonesia.[43]

The industry can be broadly divided into organic chemicals that are based on carbon, including alcohols, plastics and fibers, and inorganics that do not contain carbon, such as ammonia, caustic soda, and industrial gases like chlorine. Carbon dioxide is a common ingredient or byproduct of the production of both organic and inorganic chemicals.

Because the industry is so diverse, this paper will focus on the most important industrial chemicals that are the building blocks for other products: methanol, olefins, aromatics, and ammonia. The products discussed below account for more than two-thirds of chemical sector energy consumption. Beyond these bulk chemicals, the industry is wildly complex around the edges; the European Chemicals Agency tracks 100,000 unique substances.

Organic chemicals

Organic chemicals typically use fossil fuels as the source of the carbon that forms the backbone of the final chemical. Organic chemical manufacturing absorbs 14% of oil and 8% of gas production globally.[44] The chemical industry uses as much fossil fuel as the steel and cement sectors combined, but emits less CO_2 than those industries because it has fewer process-related CO_2 emissions and because some of the fossil fuel inputs are converted into final products, rather than being combusted.

Which fossil fuels are used by the industry varies by local availability and price. In Europe chemicals use 73% oil and 16% natural gas,[45] while natural gas liquids are a more common feedstock in North America and coal is used in many processes in China.[46] Biomass can also be a source of carbon to be processed into industrial chemicals. Methanol is produced from sugar cane in Brazil, but it is used primarily as a motor fuel rather than an industrial feedstock.

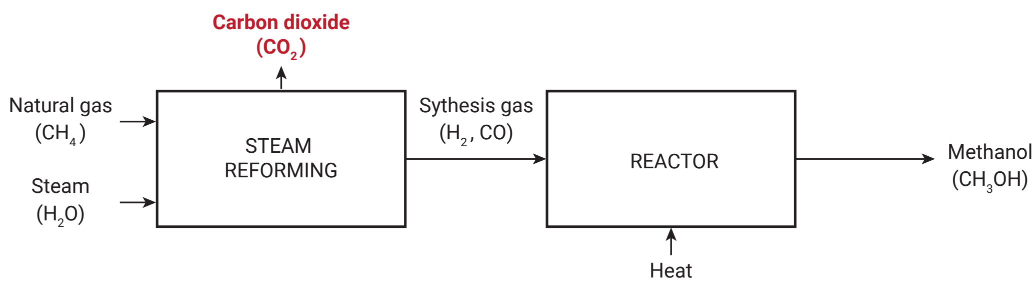
More than 90% of organic chemicals are derived from seven "primary chemicals" or building blocks: methanol; the olefins ethylene, propylene, and butadiene; and the aromatic compounds benzene, toluene, and xylene.[47] These chemicals are ultimately used in the manufacture of large-volume products like plastic resins, synthetic rubber, dyes and pigments, and fibers like polyester, along with small-volume specialty chemicals like additives for food or cosmetics or chemicals used in electronics manufacturing. These primary chemicals are responsible for about two-thirds of the sectors' energy consumption. Their low-margin, high-volume nature makes them challenging, but important, to decarbonize.

An important consideration for all chemical manufacturing is the high process heat needed. For example, a steam cracker used to produce olefins and aromatics operates near 1000 °C.[48] No mature technology can generate this level of heat without combustion.[49]

Methanol. Methanol is a key precursor to important chemicals, including formaldehyde and acetic acid, which are further processed into products like adhesives, solvents, and resins. Additionally, about one-third of methanol produced today is used directly as a fuel or in the production of fuel additives.[50]

Methanol today is mostly produced from natural gas feedstock by steam reforming the gas to produce "synthesis gas," a mixture of mostly hydrogen and carbon monoxide. This gas mixture is then converted to methanol at elevated temperature and pressure. However, synthesis gas can be produced from any carbon-containing material, including coal and oil, agricultural waste and forestry residues, and municipal solid waste. The methanol industry in China mostly uses coal as a feedstock. The coal must be gasified before it can be used to generate synthesis gas, with twice the energy consumption and five times the CO_2 intensity of production from natural gas.[51]

FIGURE 6: SIMPLIFIED PROCESS DIAGRAM FOR MENTHANOL PRODUCTION



Although coal and oil are higher-emissions ways of producing synthesis gas, wastes and plant material feedstocks provide pathways for removing fossil fuels and CO_2 emissions from the synthesis gas production process. Producing methanol from such feedstocks can reduce process CO_2 emissions by as much as 95%.[52] For example, Enerkem operates a plant in Edmonton, Alberta that converts more than 100,000 metric tons per year of non-recyclable, non-compostable municipal waste into methanol.[53] Another low-carbon pathway for methanol production uses CO_2 emissions from industrial processes or fossil fuel use and hydrogen produced through electrolysis, preferably powered by renewable electricity. Carbon Recycling International operates such a plant in Iceland, which uses 5,600 metric tons of CO_2 from a geothermal power station each year.[54] (Geothermal power is renewable, but often the underground liquid pumped to the surface contains some CO_2.)

Olefins and aromatics. The olefins ethylene, propylene, and butadiene are monomers. The double bonds in these "unsaturated" hydrocarbons allow them to react chemically to form very long chains called polymers, which become plastics, fibers, and other materials.[55] Ethylene is produced in larger quantities than any other chemical, as it is the precursor to many common products, including polyethylene used in bags, films, and other forms of packaging; polyethylene terephthalate (PET) used in water and soda bottles; and polyvinyl chloride (PVC) used in pipes and other construction materials.

Unlike methanol, olefins are generally produced from natural gas liquids or oil, rather than natural gas. Olefins are primarily produced by steam cracking, a process in which chemical bonds between atoms are broken and saturated hydrocarbons are broken down into unsaturated hydrocarbons. The inputs to the process are primarily ethane or propane, from natural gas liquids, and naphtha, a portion of refined crude oil that contains compounds with roughly five to 10 carbon atoms. The mix of outputs depends on the feedstock used. Ethylene is produced mostly by steam cracking ethane in chemical-specific facilities, whereas propylene and butadiene are primarily produced from naphtha in oil refineries along with fuels.[56] These processes do not produce CO_2 as part of the chemistry. They do produce hydrogen, which is used in other processes within the chemical plant or refinery.

FIGURE 7: EXAMPLE CHEMICAL REACTIONS IN STEAM CRACKING

C_2H_6	→	C_2H_4	+	H_2
ethane		ethylene		hydrogen
C_3H_8	→	C_3H_6	+	H_2
propane		propylene		hydrogen
C_6H_{14}	→	$2\ C_3H_6$	+	H_2
hexane		propylene		hydrogen

In China, methanol is converted to olefins on a large scale, allowing coal to be transformed into final products that are produced from natural gas liquids or oil in other parts of the world, with a high environmental cost in the form of greater CO_2 emissions.

Aromatics are a particular type of unsaturated hydrocarbons, based on a ring of six carbon atoms. Aromatics can be produced along with olefins during the steam cracking of naphtha or heavier crude fractions, or through catalytic reforming of naphtha, which rearranges straight chains of carbon molecules into the ring structure characteristic of aromatics. This process also creates high octane blending components for gasoline.[57] More than 80% of global aromatics production occurs at refineries along with fuel production.[58] As in steam cracking, catalytic cracking reactions generally produce hydrogen.

FIGURE 8: EXAMPLE CHEMICAL REACTIONS IN CATALYTIC CRACKING

C_7H_{14}	$\rightarrow$ C_7H_8	+	$3H_2$
heptane	toluene		hydrogen
C_6H_{12}	$\rightarrow$ C_6H_6	+	$3H_2$
cyclohexane	benzene		hydrogen

In 2019, six chemical companies launched the Cracker of the Future Consortium, agreeing to invest and share knowledge as they explore the use of renewable electricity to run naphtha or gas steam crackers. The companies aim to have a pilot plant in operation by 2030 and widespread commercial operation by 2050.[59] A challenge for this and all industrial electrification will be the amount of electricity required. Replacing fossil fuels at Europe's 40 steam cracker sites would require around 171 terawatt hours a year of electricity.[60] This is a staggering amount of power, equal to 30% of Europe's entire generation of renewable electricity in 2019.[61]

Another pathway to decarbonization is to use biomass-derived feedstocks instead of petroleum. Several refineries in the western United States are converting from crude oil feedstocks to waste oils and fats and soybean oil.[62] These plants are primarily focused on producing renewable diesel fuel that can qualify for lucrative credits under California's Low Carbon Fuel Standard and the federal Renewable Fuels Standard. However, these refineries produce a slate of other products as well, including renewable jet fuel and products in the naphtha range. This "renewable naphtha" can be used as a gasoline blending stock, but it is also well-suited to be cracked into olefins and aromatics, just like its fossil equivalent. In the United States, biofuel policy supports using this material as fuel rather than feedstock, but European refiners are beginning to use renewable naphtha to make chemicals. For example, a refinery owned by Total in France is shifting to processing oils and fats into renewable jet fuel, diesel, and naphtha for bioplastics.[63]

Plastic Recycling

Recycling is one way to reduce the energy and raw material use of the plastics industry. Plastics are ubiquitous in our modern world, with wealthy countries using more than 60 kilograms per capita annually. Developing country use is lower; per capita demand in China is 45 kg and in India is nine kg.[64] However, plastic recycling is often chemically and economically challenging, and in 2017 only around 16% of available plastic waste was recycled.[65] In the United States, plastic recycling is far below levels achieved for paper, metal, and glass.[66]

Plastics recycling takes two main forms: mechanical and chemical recycling.

Mechanical recycling involves sorting, cleaning, shredding, and melting plastic materials for molding into new products. The chemical makeup of the plastic does not change during the process. PET beverage bottles (plastic #1) and polyethylene bottles for products like milk and detergent (plastic #2) are most commonly recycled in this way. Mechanical recycling emits less CO_2 than producing virgin plastic.[67]

Plastics from mechanical recycling are typically of lower quality than virgin plastic. Color additives are a particular challenge to mechanical recycling. Separating plastics by color is difficult, meaning that products made from post-consumer recycled plastic are often dark in color. PET degrades each time it is re-processed.[68] Some processes "downcycle" into new products that are not themselves recyclable, for instance, turning drink bottles into polyester fibers for clothing or carpet.

Chemical recycling takes the recycled material back to the monomer level (olefins) and offers the possibility of a circular economy for plastics. Depolymerization can break down some plastics into their raw materials, for conversion into new products with quality equal to virgin plastics. The process can remove colors and impurities that reduce the quality of mechanically recycled plastic.

Another method of chemically recycling plastics is pyrolysis, which can turn mixed plastic waste into naphtha, going one step further back in the production process than depolymerization. Pyrolysis can be used for mixed plastic waste and plastics that are difficult to recycle any other way, like polypropylene yogurt cups (plastic #5) and multilayered plastic pouches.[69]

However, both methods of chemical recycling are capital intensive and more expensive today than virgin plastic production, and thus are not used on an industrial scale. Very large plants are needed to achieve economies of scale. Additionally, the GHG emissions savings created are lower for chemical recycling than for mechanical recycling. A study from the Netherlands of recycling PET trays (such as those as used for meats in grocery stores) found that depolymerization could result in a 60% reduction in CO_2 while mechanical recycling could result in an emissions reduction greater than 90%, both compared to producing virgin plastic.[70] For these reasons, chemical recycling is likely to be a complement to mechanical recycling, rather than a replacement.

In general, recycling reduces GHG emissions and demand for fossil fuel feedstocks, but is not an overall solution to emissions from plastic production. Recycling is still energy intensive and demand for plastics is growing rapidly, far exceeding the availability of material to recycle. Gathering recyclables and moving them to recycling centers add to the cost and energy use of the process. Nonetheless, designing packaging and materials to make recycling easier could increase recycling rates and reduce demand for virgin plastic.

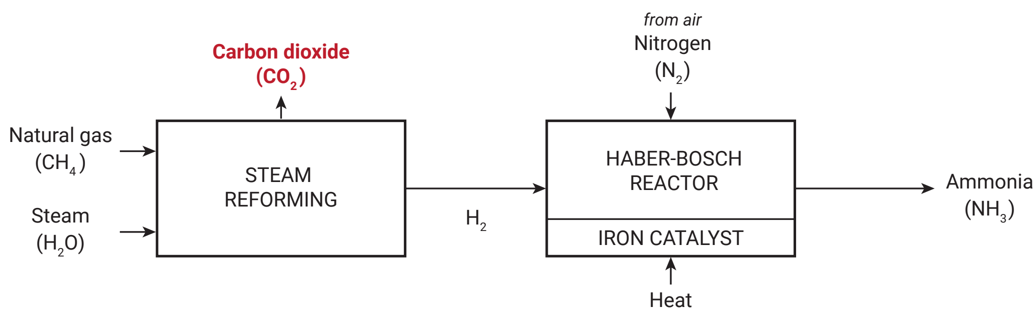
Inorganic chemicals — ammonia

Inorganic chemicals are those not based on carbon. Ammonia is the most important inorganic chemical in the economy, in terms of amount produced and CO_2 emissions.

Nearly 90% of ammonia production is used in fertilizer manufacturing.[71] Ammonia-based fertilizer has been crucial to feeding the world's growing population; about half of global food production relies on it.[72] The remainder of production is used in the manufacturing of nearly every chemical that contains nitrogen, including pharmaceuticals, plastics, and textiles.

Ammonia production is a significant source of CO_2 emissions. Like many industrial chemicals, the fundamental process for making ammonia has changed little since it was commercialized in 1913. The process begins with steam reforming natural gas to produce hydrogen-rich synthesis gas and CO_2, in a process similar to that used in methanol production. About 90% of the CO_2 produced occurs at this stage.[73] The Haber-Bosch process then combines this hydrogen with nitrogen gas separated from air at a temperature of 400° to 500°C and high pressure over an iron catalyst to produce ammonia gas (NH_3).[74] Process efficiency has improved over time from such improvements as waste heat recovery and more efficient compressors.[75] The heat required for ammonia production is lower than for such products as steel or cement, making it amenable to electrification. As in methanol production, Chinese ammonia production uses coal as the source for hydrogen, with similar increases in energy use and CO_2 emissions.

FIGURE 9: SIMPLIFIED PROCESS DIAGRAM FOR AMMONIA PRODUCTION



In many facilities, ammonia is combined with the CO_2 released during synthesis gas production to create urea, a solid, more easily transportable form of nitrogen-based fertilizer. However, the CO_2 is released again to the atmosphere when the fertilizer is used, meaning that this use does not change the net emissions of CO_2 to the atmosphere. In fact, decarbonizing ammonia use in fertilizer will require a shift away from urea toward forms of nitrogen fertilizer that do not contain carbon.

The key to low-carbon ammonia production is producing hydrogen without CO_2 emissions, a common challenge across industrial processes discussed in the next section. Steam reforming of natural gas with CCUS or electrolysis of water are the two most commonly discussed methods of producing zero-carbon hydrogen, and plants using these processes are in operation. However, a new plant in Nebraska is following a different path. The process uses methane pyrolysis to produce hydrogen and carbon black, a product used in the manufacturing of tires and other rubber goods, plastics, and printing ink. A demonstration plant is in operation today and the new plant will produce 275,000 metric tons of ammonia a year with zero CO_2 emissions.[76]

Unique among the products discussed in this paper, ammonia could play an additional, completely different role in a zero-carbon economy. In addition to its use as fertilizer and in the production of nitrogen-containing chemicals, ammonia could also act as a zero-carbon energy carrier and storage method, similar to the role envisioned for hydrogen. The ammonia molecule contains no carbon and thus does not emit CO_2 when it is burned or used in a fuel cell. Ammonia could be produced using excess renewable electricity and stored for later use in power generation or transportation. In September

2020, Saudi Arabia sent a pilot shipment of 40 tonnes of low-carbon ammonia to Japan for power generation.[77] A discussion of the potential for ammonia as a fuel is beyond the scope of this paper, but the fact that decarbonization of ammonia is so possible that it could be used as a low-carbon fuel makes it unique among industrial chemicals.[78]

COMMON CHALLENGES AND SOLUTIONS ACROSS THE SECTORS

The three industrial sectors have several technical challenges in common, including process emissions of CO_2, the need for high heat, and use or potential use of hydrogen. Therefore, a number of technical solutions can be shared across the sectors as well. In some cases, these solutions are interrelated and synergistic.

Carbon dioxide capture and utilization or storage (CCUS)

Removing CO_2 from an exhaust stream is an option when eliminating the emission is impossible or prohibitively expensive. The CO_2 can then be used in an industrial process or permanently stored in geological formations deep underground. In the IEA Clean Technology Scenario, designed to keep global temperature rise well below 2°C, CCUS accounts for nearly 20% of the emissions reductions in the industrial sector, most of these in the iron and steel, cement, and chemicals industries.[79] However, as of mid-2020, only 19 CCUS projects were in operation globally in the industry and refining sectors.[80]

Although capturing CO_2 and compressing it for storage or use is an energy-intensive and expensive process, the use of CCUS as a tool for emissions mitigation can reduce the overall cost of decarbonizing energy-intensive industries.[81] Process emissions from the steel and cement industries are good candidates for carbon capture, since they are difficult to eliminate without drastically changing the underlying production process.

A consistent challenge in carbon capture is that it involves separating CO_2 from other substances in the effluent gas stream, generally using a solvent. The solvent must then be regenerated, releasing the CO_2 for storage or use and allowing the solvent to be used again. This process tends to be energy intensive. It is also more efficient with effluent streams that contain higher concentrations of CO_2. For combustion processes, burning the fuel in an atmosphere of pure oxygen, rather than air containing 78% nitrogen, increases the concentration of CO_2 in the effluent and the efficiency of carbon capture. Generating pure oxygen for the process is also expensive, but the gain in carbon capture efficiency may reduce costs overall.

> **Although CCUS is likely to play an important role in deep decarbonization of the economy, the most environmentally-minded citizens are least supportive of the technology.**

In addition to the technical and economic challenges for CCUS, public perception can raise challenges. Studies show that the public views CCUS more negatively when it is seen as a delaying tactic or a substitute for implementing cleaner energy technologies.[82] Paradoxically, although CCUS is likely to play an important role in deep decarbonization of the economy, the most environmentally-minded citizens are least supportive of the technology since they often view it as a way to avoid the "real" solution of a societal shift away from fossil fuels.[83] Better framing of the technology and its usefulness in eliminating emissions that are difficult to abate any other way could help, along with more demonstrations of the safety of the technology and its ability to keep CO_2 out of the atmosphere over the long term.

Carbon capture in steelmaking is focused on the blast furnace, where the majority of plant emissions takes place. Technologies that can be retrofit onto existing furnaces can remove 50% to 75% of emissions at a cost of $50 to $90 per ton of CO_2 removed.[84] Retrofits can allow significant emissions reductions without the expense of retiring facilities before the end of their useful life. However, retrofits have not yet occurred, largely because policy change is needed to make them economically viable.

The first industrial-scale CCUS project at a new steel mill began operation in 2017 at an Emirates Steel facility in Abu Dhabi, capturing 800,000 tons per year of CO_2 to be used in enhanced oil recovery in nearby oil fields.[85] The plant uses hydrogen and carbon monoxide produced from natural gas as the reducing agents in the furnace, producing a very high concentration of CO_2 in the effluent, making recovery of CO_2 with a solvent more efficient.[86]

Calcium-looping technology is an interesting candidate for carbon capture in both the cement and steel industries. Both industries have kilns onsite to convert limestone into lime (CaO) — in cement to produce clinker and in steel to produce lime for use as impurity-removing flux in the blast furnace. Calcium looping uses some of the lime produced as the absorbent for CO_2, capturing both CO_2 from the calcined limestone and the fuel used for combustion.[87] This process uses materials already onsite and familiar to operators, rather than the liquid solvents used in some other carbon capture processes. Fuel in the kiln can be burned in an oxygen-rich environment to minimize the amount of nitrogen in the flue gas, making a more concentrated stream of CO_2 and improving CO_2 capture efficiency. This technology has been demonstrated at several pilot-scale power plants and the synergy with cement production is considered a bonus.[88]

The most common use for captured CO_2 today is in enhanced oil recovery, where it is pumped into underground reservoirs to increase the pressure and allow more oil production. This may seem backwards, but enhanced oil recovery can provide a significant volume of secure CO_2 storage while helping to produce oil that the economy will still need for many years.[89] Other potential uses, now and in the future, include use in greenhouses to increase plant growth, in cement and building materials, and as a carbon source for synthetic chemicals and fuels.

High-temperature processes

Process heating is a primary component of industrial energy demand. One of the common challenges in heavy industry is the need for processes to operate at high temperatures. Beyond around 400 °C, direct use of renewable heat or electricity for heating, with such equipment as heat pumps or resistance heaters, is impractical.[90] Such temperatures are necessary in the steel, cement, and chemicals industries. Electric arc furnaces can provide very high heat, but they work only in applications where the materials being heated conduct electricity, such as melting steel for recycling. For other applications, combustion is needed.

Zero-carbon sources of heat will be a key component of decarbonizing heavy industry. Renewable hydrogen is a potential solution that can produce high heat through combustion. It is an especially attractive option in industries that currently use natural gas, where hydrogen could be used with little process change. Hydrogen could even be blended into the existing natural gas fuel as an interim emissions-reducing step with little or no change to existing equipment.[91] Combustion of biomass is another high-temperature option, through direct combustion or by transforming biomass to methane through gasification or anaerobic digestion.[92] However, supply of sustainable biomass is a challenge, especially as the call on biomass and arable land for other uses (agriculture for a growing population, carbon raw materials for chemicals, carbon offsets through forest preservation) grows in a carbon-constrained world. Solar thermal technologies are a non-combustion way to provide heat, but today are practical only at temperatures less than 400°C.[93] However, research is underway to use solar energy to provide heat for a cement kiln, a much higher temperature process.[94]

Another potential future technology is modular nuclear reactors. These reactors are much smaller than today's utility-scale models and are designed to be mass-manufactured at much lower cost. These reactors are not yet commercial, but they are one of few non-combustion technologies that can produce heat of 1000°C or more.[95] Like any form of nuclear power, however, public opinion will be a challenge.

Hydrogen production and use

Hydrogen is a common component across industrial sectors: as a potential reducing agent in steel blast furnaces; as a raw material in the production of many chemicals, including methanol and ammonia; and as a potential zero-carbon fuel in many industries.

The greenhouse gas implications of hydrogen use depend on how it is produced. Today, hydrogen is generally produced by steam reforming natural gas, to produce hydrogen and CO_2. If the CO_2 from this process is captured and stored or used, the product is known as "blue" hydrogen. Another hydrogen production method is using renewable electricity to split water into its components of hydrogen and oxygen, producing so-called "green" hydrogen.

Green and blue hydrogen have the potential to be important components of a zero-carbon economy, as an industrial fuel and raw material and, for green hydrogen, as a way of balancing the production and use of renewable electricity. The choice between green and blue hydrogen in a particular location or process will depend on the relative costs of renewable electricity and natural gas, the availability of geological storage or use for CO_2, and the acceptability of CCUS to local citizens. Infrastructure for storing and transporting hydrogen would be needed for both technologies. Electrolysis for green hydrogen is a relatively mature technology, but economies of scale in producing large-scale equipment would help bring down costs.[96] This raises a chicken and egg problem since you need demand to build large facilities, but demand can't develop until hydrogen is available. Large projects are under consideration in Australia and in Saudi Arabia, in areas with excellent renewable electricity potential, but how and where the resulting hydrogen will be used is still unclear.[97]

Must we wait for the widespread availability of blue or green hydrogen to gain the benefits of substituting hydrogen in industrial processes? Perhaps not. A study from the Rocky Mountain Institute shows that benefits can be achieved from using hydrogen as the reducing agent (instead of coal) in a steel mill even before the electricity sector is completely decarbonized.[98] A hydrogen direct reduction steel mill that creates hydrogen by water electrolysis using today's global average electricity supply would have about equal greenhouse gas emissions to a standard blast furnace integrated mill. And in countries with greener electricity, the hydrogen mills would produce lower emissions today, for example 19% lower in the United States and 38% lower in the European Union. These results are encouraging, as they mean that conversion of processes to hydrogen in parallel with electricity decarbonization is a viable path forward.

Trade exposure and industrial products

Not all the shared challenges across industries are technical. The trade exposure of the steel and chemical industries raises challenges for establishing decarbonization policy. Regulating emissions in one country or region would likely require protection from cheaper, higher-emissions product made elsewhere, for both imports and exports. Conversely, only about 7% of cement is traded on the international market, because it is low value compared to its weight and volume and because its raw materials are widely available geographically.

“The trade exposure of the steel and chemical industries raises challenges for establishing decarbonization policy. Regulating emissions in one country or region would likely require protection from cheaper, higher-emissions product made elsewhere.

In 2019, 25% of steel intermediate products (like wire, tube, ingots, and unworked castings and forgings) were traded internationally.[99] Therefore customers have the ability to search for lower-cost materials produced abroad. Additionally, the steel industry today is suffering from global overcapacity, making competition even more fierce. The economics of steel production are very sensitive to local energy costs.[100] Nonetheless, the cost of steel is often a small part of the cost of the finished product or project. For this reason, an increase in steel prices to achieve decarbonization goals would not result in a significant increase in product costs or overall cost to the economy, even though the steel industry is trade-exposed.

The United States is the world's largest steel importer, importing about 29% of its total steel supply in 2019.[101] Construction is the most important use of steel in the United States, making up 44% of the total, followed by the automotive industry at 28% and machinery and equipment at 9%.[102] Most steel used in construction in the United States is recycled steel produced in electric arc furnaces.[103] For a large building with structural steel, the cost of steel is approximately 15% of total building cost.[104] Steel makes up a much smaller portion of costs for wood or masonry construction.

The automotive and machinery sectors primarily use new steel produced from iron ore,[105] for which decarbonization is more difficult. The average car contains nearly 2,000 pounds of steel.[106] However, the cost to the consumer of low-emissions steel might only add 0.2% to the cost of a car.[107]

For chemicals, trade tends to happen further down the value chain, not in the primary chemicals discussed in this paper. The derivative products are higher value and often easier to transport than their building blocks. For example, only 7% of global ammonia gas production was traded internationally in 2016, but trade in easier-to-transport urea was three times larger.[108] The same is true of organic chemicals — polyethylene is much more traded than ethylene itself. However, the primary chemicals are still trade-exposed through their derivatives, as the entire value chain can be moved to a different country. Production of primary chemicals and their derivatives tends to occur in areas with low raw materials costs. For example, since the U.S. revolution in oil and gas production began in the mid-2000s, the United States has become an important low-cost chemicals producer, especially of those based on natural gas liquids.

Since the world is unlikely to decarbonize at the same rate, early movers in trade-exposed industries are likely to need protection from international competition. Two primary methods are under consideration. In the European Union, border carbon adjustment mechanisms are being considered as part of the implementation of the European Green Deal. Such taxes would ensure that imported goods pay the same for their embodied emissions as products produced within the EU, while exported goods would be relieved of their necessity to pay for their embodied emissions when they are traded to nations that do not require such payment for domestic goods. This scheme is easy to understand and appealing, but very difficult to design and implement in practice.[109] In particular, determining the point of compliance is challenging, such as how to account for the steel or chemicals included in imported finished products.

The United States is today more focused on encouraging innovation through direct government funding of research and support for innovative technologies through tax breaks and other methods to decrease costs. Such policies can reduce the cost of low-emissions technologies, especially for first movers. Additionally, procurement standards can be created to require the purchase of lower-carbon goods. Parts of the U.S. federal government have green procurement standards for some items, including vehicles, appliances, and office equipment, but no standards for steel or cement. The California Buy Clean program sets standards for infrastructure materials, including many steel products. Compliance is required in July 2021.[110] A bill was introduced in the California State Assembly to require compliance in the cement sector as well.[111] A bill introduced in the New York State Assembly would advantage bids from low-carbon cement producers.[112] However, government demand is likely not enough to incentivize new facility construction or upgrade of existing facilities. Policy, not just government procurement, will be needed to provide greater incentive for modernization and decarbonization.

Border measures and mechanisms to reduce the costs of lower-carbon technologies can certainly move emissions in the right direction but are likely not enough to achieve the complete transformation needed to reach the net-zero by 2050 goals set by a number of entities, including the EU. Such goals generally require complete transformation in industries, with capital expenditure for all new production facilities and, in many cases, higher operating expenses as well. Policies that tweak the relative competitiveness of different production methods are not enough to bring about this level of rapid, wholesale change. Achieving mid-century decarbonization goals will require industrial policy that works with industry to bring about change and establishes mechanisms to keep industry competitive. This sort of industrial policy hasn't been seen outside of centrally planned economies and requires a very different approach to markets than is seen in the EU and United States today. Such discussions are still at an early stage but need to advance rapidly if mid-century goals are to be achieved.

A discussion of the pros, cons, and World Trade Organization compliance issues involved in protecting trade-exposed low-carbon industry could be the subject of a book. But in this context, recognizing the nature of trade exposure and some mechanisms to alleviate it is the point.

CONCLUSION: A LOW-CARBON ECONOMY NEEDS INDUSTRIAL RAW MATERIALS

> Can we reduce emissions by reducing demand for these products? Especially for steel and cement, the answer is largely no.

This paper has primarily focused on how to reduce emissions from the steel, cement, and chemicals industry. But a question remains — can we reduce emissions by reducing demand for these products? Especially for steel and cement, the answer is largely no. Many technologies that will be important parts of a net zero-energy system, such as transportation infrastructure, renewable power generation and transmission infrastructure, CCUS equipment, and CO_2 or hydrogen pipelines will consume large amounts of steel and cement. The International Energy Agency's Sustainable Development Scenario envisions a pathway to net-zero global greenhouse gas emissions by 2070. In this scenario, global steel production rises slightly between now and 2060, despite the adoption of a number of strategies to increase the efficiency of steel use.[113] Plastics and other materials derived from basic chemicals will also play an important role in a low-carbon economy, including providing lightweight materials for cars and other modes of transport and insulation for efficient buildings. Additionally, developing countries will require steel, cement, and chemicals to support their growing populations and increasing prosperity.

Future growth in chemical demand could be impacted by the push to eliminate single-use plastics in some parts of the world. However, for some uses there are not suitable substitutes, and plastics provide advantages such as their low weight and their ability to reduce spoilage and damage to products in transit. Additionally, plastics only make up one-third of chemical demand and other uses continue to grow.[114] Sustainable farming practices and reductions in food waste can dampen demand for ammonia as fertilizer, but demand is still likely to grow as the world's population grows and developing countries adopt more intensive agricultural practices.

The COVID-19 crisis raises both challenges and opportunities for decarbonizing heavy industry. Demand for high-emissions industrial products declined globally, by 6% for cement, 5% for steel, and 2% for chemicals, in the first half of 2020 as the pandemic took hold.[115] These industries will recover as the economy does, but if infrastructure projects, with their large demand for steel and cement, are important parts of wider economic recovery, that could pose a challenge for decarbonization. Wise use of infrastructure investment could increase countries' resilience to climate change, but construction of such infrastructure could be an important source of emissions itself. Ideally, recovery packages will include infrastructure investments and programs to green the industries that produce the raw materials for infrastructure construction. It's too early for green procurement standards in most cases, but assistance with pilot projects and new technology implementation would be a good use of recovery funding, as well as attention to green building practices in the projects themselves.

Since key industrial raw materials aren't going away, policymakers must focus on how to decarbonize their production. For these industries, policymakers face choices on how to accelerate technologies that are not yet commercial, a very different problem than encouraging more mature technologies like renewable power generation or electric vehicles. Industries will need support for capital expenditures to retool their production.

Several new low-carbon processes, like hydrogen direct reduction for virgin steel production, will also have higher operating costs than the processes they replace. In fiercely competitive, low-margin industries, policy is the only way to make these changes happen. Demonstration projects for new technologies are underway, but in steel, cement, and chemicals, the race for “winning” low-carbon technologies is still underway. Local considerations, like availability of low-cost renewable power and attitudes toward CCUS, will be important considerations in which technologies are adopted.

The competition for winning ideas isn’t just taking place in technology. Governments are trying out different policy mechanisms as well. Europe’s focus on carbon border adjustments will be challenging to implement in an environment where other countries, especially the United States, are focused on the carrot of subsidizing and encouraging new technology, rather than the stick of keeping higher-carbon products out. As with technologies, local politics will be important in which policy mechanisms are adopted in which areas. However, unlike for technology, policy mechanisms with the same goals can work at cross purposes. For example, carbon border adjustment mechanisms can penalize low-carbon products that do not face carbon prices at home. Conversely, the technology subsidy in one country can exceed the carbon price benefit offered in another. Both of these possibilities are barriers to trade in low-carbon products. Completely avoiding these outcomes is likely impossible, but trade policies and policy harmonization are more important for low-carbon industry than for other sectors, adding another wrinkle to an already difficult climate challenge.

Finally, any discussion of decarbonization of heavy industry must have a special focus on China. Many processes in the chemical industry that in other countries use oil or gas as fuel and raw material— including in the production of ammonia, methanol, and olefins — in China use local, inexpensive coal. And as Figure 2 shows, China is the world’s largest producer of both steel and cement, by a large margin. Global mechanisms to reduce industrial emissions must find a way to reach these Chinese products, including those that are not traded outside China. Research, development, and deployment of low-carbon technologies will be needed globally to achieve the low-carbon transformation the world needs.

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