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BATTEN REPORT
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PATH TO 2060:

Decarbonizing the Industrial Sector

A Long Road Ahead for Low-Carbon Manufacturing

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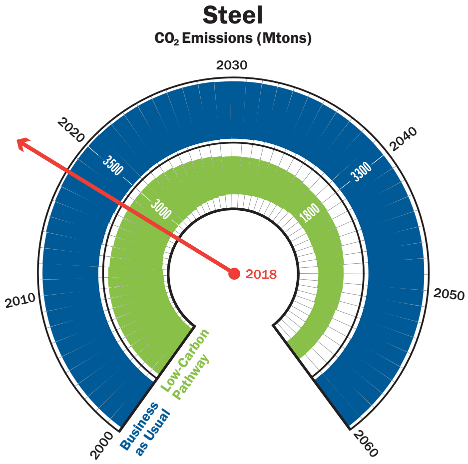
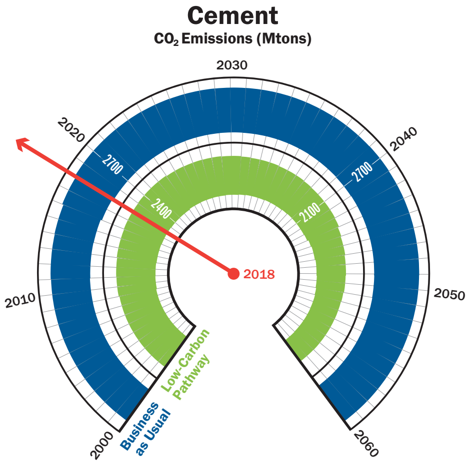
SNAPSHOT

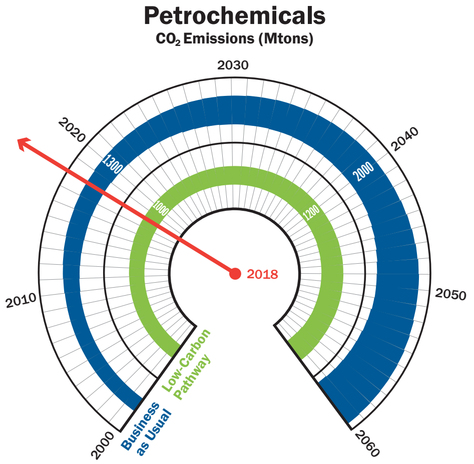
Scientists say that global warming must be kept below two degrees Celsius to avoid significant global disruptions. Getting there will require near total ***decarbonization of all economic activity by 2060****.*

Industrials are critical to economic growth but contribute ***21% of global greenhouse gas emissions****. Steel, cement, and petrochemicals are some of the most carbon-intensive manufacturing processes.*

Improvements in energy efficiency have greatly reduced the carbon intensity of these industries, but to decarbonize, ***fossil-fuel and feedstock substitutions are essential****.*







The **Business as Usual** scenario represents the IEA 6 degree baseline, where no new policies are introduced and technologies progress as they would normally. The **Low-Carbon Pathway** represents the IEA 2 degree scenario, which considers available and known technologies, including CCS adoption that ramps up in 2030. For petrochemicals, low-carbon pathway captures emerging technologies that are in the later R&D stages, in demonstration or could realistically be commercialized (e.g. steam cracking substitute). To completely decarbonize these industries, we will need significant innovation supported by low-carbon policies.

Sources: Bas J. van Ruijven et al, "Long-term model-based projections of energy use and CO_2 emissions from the global steel and cement industries", Science Direct, Resources, Conservation, and Recycling, vol. 112 (2016), p. 15–36, IEA Technology Roadmap: Low-Carbon Transition in the Cement Industry, IEA Technology Roadmap: Energy and GHG Reductions in the Chemical Industry via Catalytic Processes.

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WHY 2060?

In the 2015 Paris climate agreement, 175 countries pledged to commit to greenhouse gas emission reductions in order to limit global warming to no more than two degrees Celsius from preindustrial levels. According to the atmospheric scientists, achieving this goal requires limiting total cumulative global emissions to 2,900 gigatons of CO_2. Since the Industrial Revolution, global CO_2 emissions have reached 2,100 gigatons; this leaves a carbon "budget" of 800 gigatons. Assuming the continued emission of greenhouse gases in the near future, staying within this carbon budget will require near-total decarbonization of global economic activity by 2060.[1]

IN THIS REPORT, WE ASSESS the potential for complete decarbonization of the industrial sector by 2060. Industrials refers to a broad array of industries that mine, refine, and manufacture many of the materials and products in the global economy.[2] Today, the industrial sector accounts for 22% of greenhouse gas emissions in the United States and 21% globally.[3] Given the breadth and diversity of this sector, we focus on three industries: steel, cement, and petrochemicals. These industries were chosen because they represent the largest share of "Scope 1" industrial carbon emissions, which are those produced *in situ* as opposed to those created through the use of electricity supplied from an electric utility (referred to as "Scope 2" emissions). Manufacturing operations are complex, and there are innumerable areas where improvements in energy efficiency and raw material choice can help to reduce the carbon footprint of a facility. As such, we target the largest sources of carbon emissions within the manufacturing process where technology substitution would have the biggest impact.

For each of the three industry-specific discussions in this report, we: **(1)** review the history of production, **(2)** describe the production process, focusing on the decarbonization opportunity, **(3)** characterize the US and global markets, and **(4)** explore the zero-carbon technologies and innovations that offer disruptive potential. We then assess the levers that could determine the rate of clean technology adoption moving forward and conclude with some thoughts on the timing of decarbonization, as well as the accelerators and roadblocks to meeting the 2060 goal.

UVA DARDEN'S BUSINESS INNOVATION AND CLIMATE CHANGE INITIATIVE

The Business Innovation and Climate Change Initiative at the University of Virginia Darden School of Business facilitates a dialogue across a diverse set of stakeholders in business, non-profits, government, and academia about the role of innovation in addressing climate change. In support of this initiative, the Batten Institute for Entrepreneurship and Innovation is publishing a series of reports that explore technology innovation and the drivers behind the market disruption needed to decarbonize our economy. These reports synthesize research regarding industry sectors that hold the most promise for innovation and significant reductions in carbon-dioxide emissions, including: transportation, energy, and industrials.

Visit **www.darden.virginia.edu/innovation-climate** to learn more about the Business Innovation and Climate Change Initiative and to hear a podcast discussing the findings of this report.

INDUSTRIALS: THE ROAD TO DECARBONIZATION

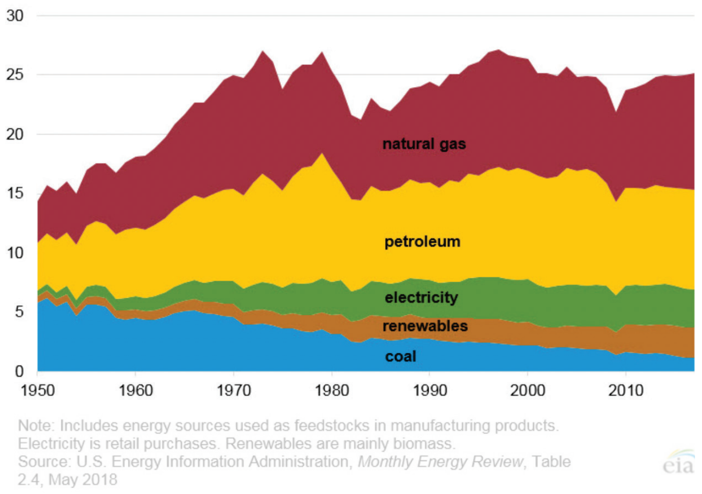
INDUSTRIALIZATION HAS BEEN CRITICAL to economic growth. Nowhere was this better demonstrated than during the second Industrial Revolution (1870–1914). Steel and cement manufacturing, along with railroad expansion, provided the means for mass production and delivery of lower-cost goods, giving rise to urbanization and improving quality of life.

Yet this industrialization has come at a cost. Cumulative worldwide carbon emissions have risen from 34 billion metric tons in 1894 to 1.3 trillion metric tons by 2014.[4] The industrial sector has contributed greatly to the rise in these emissions. Manufacturing requires significant amounts of thermal energy, and for decades, fossil fuels have served as the primary energy source.

Energy represents the highest operating cost of industrial production. Companies already have a natural incentive to reduce these costs, which has the added benefit of lower energy intensities (energy used for every unit produced) and reduced carbon emissions. A flattening out of emissions is being observed in developed countries[5] as a result of energy efficiency improvements and fuel-switching from coal to natural gas.[6] Figure 1 shows the shift of US manufacturing away from coal and toward other fuel sources. Moving forward, developing countries led by China and India, who continue to rely heavily on coal, will determine the rate of decarbonization.

Carbon emissions have been linked to economic growth for decades. The argument is that global economies cannot continue to thrive and grow without some level of pollution. The industrial sector is seen as a key driver to this economic growth. More recently we have seen a decoupling of GDP and carbon emissions (see Figure 2) and, according to the International Energy Agency (IEA), "market forces, technology cost reductions, and concerns about climate change and air pollution" are behind this phenomenon. What does this mean for the industrial sector? No longer can industrials hide behind the "necessary evil" argument and ignore the call for action with regard to climate change.

Figure 1: U.S. Industrial Sector Energy Use by Source, 1950–2017
in quadrillion British thermal units



Note: Includes energy sources used as feedstocks in manufacturing products.
Electricity is retail purchases. Renewables are mainly biomass.
Source: U.S. Energy Information Administration, *Monthly Energy Review*, Table 2.4, May 2018

Source: US EIA, Use of Energy in the United States Explained (accessed Oct. 2018)

Figure 2: CO_2 emissions and global economy growth rates
World Energy Outlook

Source: IEA Energy Snapshot

Industrials, such as steel, cement, and petrochemicals, are beholden to commercial customers that demand cheap, reliable, and readily available products. Profit margins are often slim and investment in new innovation is risky. Clean technologies exist, but many are far from commercialization or face barriers to scaling. Most of the energy savings observed to date have been the result of optimizing operations and reducing cost. There has been little incentive for manufacturers to innovate or adopt low-carbon technologies. While the 2060 goal seems far away, shifting a sector this big and diverse will be challenging.

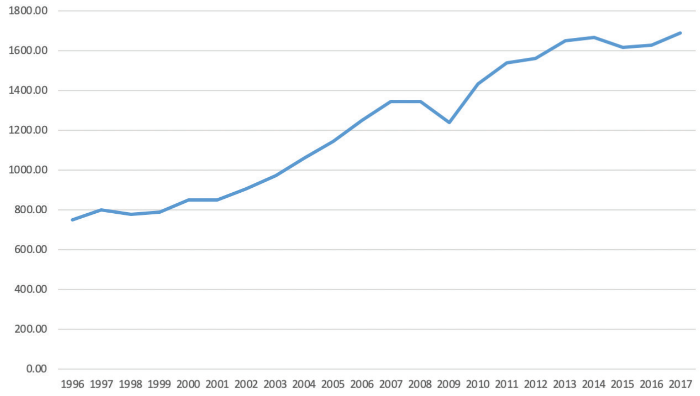
For industrials, decarbonization by 2060 seems unlikely. At the same time, the opportunity for disruptive innovation is vast and technology breakthroughs could have a ripple effect. What are the levers that need to be pulled to facilitate meaningful change?

STEEL MANUFACTURING

STEEL IS A CRITICAL INDUSTRY in the global economy, serving as an important input to everything from buildings to autos to appliances. Steel production dates back to the 13th century BC, but came into broad commercial fabrication with the invention of the Bessemer process. Inventor Henry Bessemer developed the novel steelmaking process that blew air into the molten iron, thereby removing impurities through oxidation. Variations of the Bessemer design were introduced over the next 100 years, addressing concerns around purity of the steel, fuel consumption, and productivity. The basic oxygen furnace (BOF), introduced in Europe and commercialized in the 1950s, continues to dominate global production today.

Nearly 1.7 billion tons of steel were produced in 2017[7] (see Figure 3) by more than 100 steel manufacturing companies around the world. With the exception of the 2008 recession, worldwide steel production has steadily increased over the last 20 years, driven largely by China's rise (see Figure 4). According to the World Steel Association, China alone represented 86% of global steel-production growth between 2002 and 2016, and accounted for 70% of steel consumption.[8] In the United States, steel production has seen a steady decline over the last 10 years, which was driven partly by competitive foreign pricing, increases in imports,[9] and a reluctance of US manufacturers to innovate (see inset, "The Fall of American Steel").

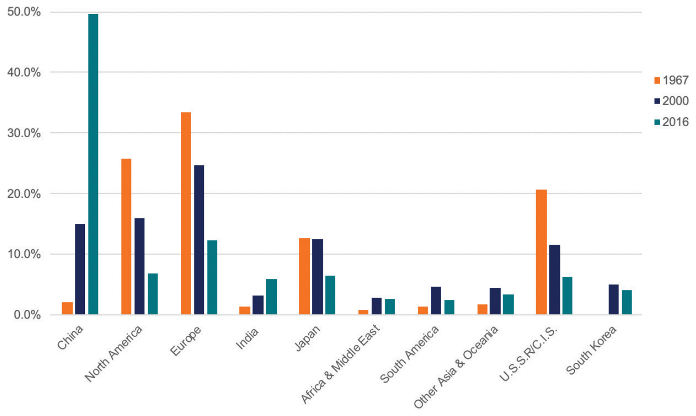
Figure 3: Worldwide Steel Production
(Millions of Tonnes)



Source: World Steel Association

With $1 trillion in 2016 revenue, and employment of 6 million people around the world,[10] steel companies are an important contributor to the global economy.[11] The top five steel producers worldwide are: ArcelorMittal (Germany), China Baowu Steel Group (China), NSSMC Group (Japan), HBIS Group (China), and POSCO (South Korea).[12] The top ten companies represent a quarter of production globally.[13] Nucor Corporation, the largest US steel manufacturing company, ranks 11th globally.[14] Other US manufacturers include US Steel (ranked 26), Steel Dynamics (ranked 47), and AK Steel. Once the leader in steel production, the United States today represents only about 5% of global steel production and sits fourth behind China (49%), Japan (6%), and India (6%).[15]

Figure 4: Global Share of World Crude Steel Production



Source: World Steel Association

THE FALL OF AMERICAN STEEL: *Following World War II, European and Asian steel industries began to rebuild, embracing new BOF steelmaking. US steelmakers, instead of exploring new technologies, continued to use open-hearth furnaces to produce steel. It wasn't until the 1960s that the big three US manufacturers—US Steel, Bethlehem Steel, and Republic Steel—began building BOF plants. By that time, it was too late. Europe, Japan, and China were growing by leaps and bounds in production, utilizing not only BOF but also a new technology, the electric arc furnace (EAF). US manufacturing had lost its foothold. By 1991, US Steel was dropped from the Dow Jones Industrial Index and Bethlehem Steel followed in 1999. As other steel companies went out of business, US Steel survived, accompanied by a newcomer to the industry, Nucor Steel. In the 1960s Nucor embraced EAFs and mini-mills and today, it is ranked 11th in the world in global steel production.*

The US tariff imposed on imported steel in 2018 seeks to level the playing field for US steel with foreign competition. The US Department of Commerce notes that the tariff is aimed at increasing domestic steel production to an 80% operating rate from the current 73%.[16] *The United States presently imports steel from Canada, Brazil, South Korea, and Mexico. While the tariff would allow US steelmakers to overcome cheaper foreign pricing by encouraging greater domestic consumption, it could have unintended consequences. Some imports are for specialty steel, and companies will be penalized for using foreign steel that is not available in the United States; also, the countries affected by the US tariffs would likely retaliate with higher prices.*[17] *Trade negotiations are ongoing, but in the short term, US steel manufacturers are already reporting growth in sales while steel consumers scramble to adjust their supply chains to avoid cost increases.*

Today, two steelmaking processes have risen to dominance around the world: BOF and EAF. The BOF is the key component of an integrated steel mill that transforms iron ore into finished steel products. Iron ore is placed into a blast furnace along with coke (a reducing agent), and flux (materials, such as limestone, to collect impurities). The resulting hot metal, or pig iron, is transferred to the BOF along with a small amount of steel scrap and flux and the iron ore is reduced to liquid steel.[18] The final step is casting and rolling the steel into specialty products. Today, the BOF process is used to produce 75% of global steel.[19]

The EAF process emerged in the 1960s. Initially developed for the production of small-batch specialty steels, EAFs were able to meet the thermal demand needed for steel production by running electricity through charged material. Using scrap metal exclusively, EAF manufacturing bypasses the iron-ore processing step in BOF integrated mills. Steel scrap is introduced into the EAF and melted using electrodes that deliver an electric arc through the scrap, raising the temperature to 1,600 degrees Celsius to make steel.[20] Once the molten steel comes out of the furnace, the finishing steps are the same as in BOF operations: transfer to secondary refining to adjust chemistry; casting; and rolling. Further processing may occur during these steps that requires reheating, usually provided by natural gas boilers and furnaces.[21] EAF mini-mills tend to be smaller than integrated mills and can be started and stopped on short notice. This offers operators more flexibility in terms of locating the mills and varying production based on demand. Today, the EAF process represents 25% of global steel production.[22]

CARBON EMISSIONS

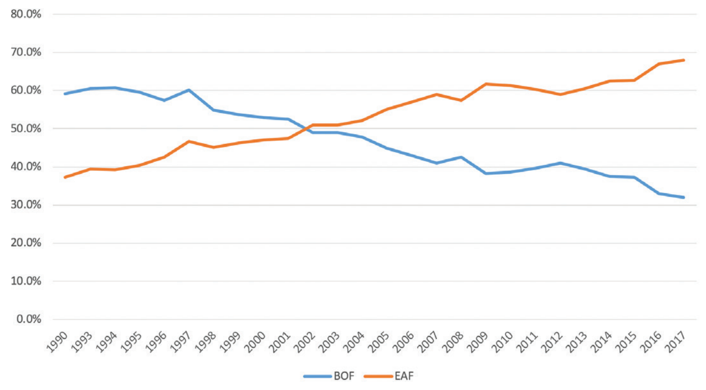
Steel production contributes approximately 6.7% of global CO_2 emissions.[23] Most of this is from BOF-integrated steel mills. The iron-making process alone represents 70% to 80% of CO_2 emissions from BOF steel manufacturing,[24] with most of those emissions coming from the coke used as feedstock.[25] There are also emissions from fuel combustion, as the blast furnace is typically heated by natural gas, oil, or coal.[26] Lastly, the chemical process within the BOF produces CO_2 emissions when the oxygen removes carbon from the molten iron and steel scrap, either mixing it with incoming air at the furnace's mouth or flaring it after gas cleaning.[27]

In contrast, minimal CO_2 emissions from EAFs and mini-mills come from the melting and refining processes, as carbon is driven off the charged material and carbon electrodes. Some EAF plants use oxy-fuel burners that burn natural gas and oxygen, transferring additional heat to the scrap metal. The largest emissions from EAF mini-mills come from the fuel used to produce electricity for the furnace, especially if that fuel is coal.

EAFs require a significant amount of electricity to operate. On average, the total energy required to produce molten steel in an EAF is 425 kWh/ton,[28] or 127 million kWh/year, which is equivalent to the electricity needed to power nearly 12,000 homes in the United States. However, this is also one of the great advantages of EAF mini-mills, as coal and other fossil fuels could be replaced by renewable energy sources such as solar and wind power, thereby greatly reducing net emissions from EAF plants.

In the United States, the shift from BOF to EAF has largely happened already, with the share of EAF production close to 70% today (see Figure 5). Lower capital costs, flexibility in operation in response to market demand, and favorable scrap pricing has driven this transition.[29] The difference in cost between BOF and EAF mills comes down to raw/scrap material prices and capital expenditures. Iron ore and coal represent most of the cost to operate BOF mills, but these are variable. Similarly, steel scrap represents most of the cost to operate an EAF mill, and this price is also variable. However, when comparing fixed capital costs, those of EAF are about half those of BOF.[30] In 2016, 108 out of the 119 steel mills operating in the United States used EAF technology.[31]

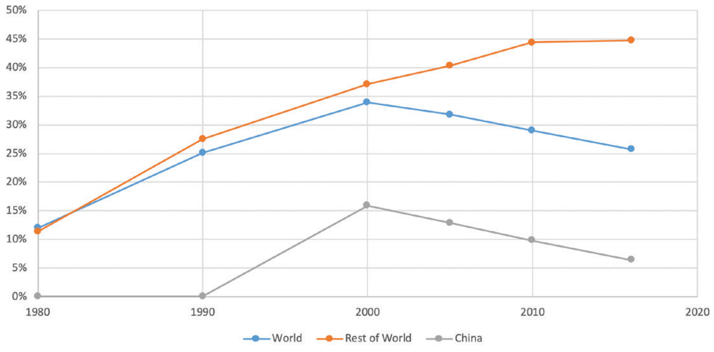
Figure 5: U.S. Steel Production. BOF vs. EAF Process



Source: USGS Minerals Information: Iron and Steel 1990–2017

It's a different story in China, where BOFs represent 91% of steel production (see Figure 6).[32] With an estimated 50% share of worldwide steel production,[33] and continued reliance on coal as a dominant fuel source, China has heavily influenced the global carbon footprint of steel and could influence the pace at which the global shift to cleaner steel manufacturing will happen.

Figure 6: Production Share of EAFs Worldwide



Source: World Steel Association

Rapid expansion of BOF integrated mills in China reduced EAF's share of the global market starting in 2000, driven largely by tight supplies of power and scrap.[34] According to some industry experts, this is expected to change with the increased access to electricity and domestic scrap supply resulting from the rapid growth in Chinese steel consumption over the last two decades, as well as stricter environmental regulations and a looming national carbon trading scheme.[35] Amid concerns about oversupply and its ability to meet domestic emissions targets in 2018, China has announced a reduction in steel production.[36] Market analysts have long predicted a slowing of China's explosive economic growth in the coming years and a resulting slowdown in new steel production. As infrastructure ages, this could open up the scrap market in China. EAF growth will depend on the creation of a more efficient and robust network of scrap suppliers in the country.[37] This increase in scrap availability will likely have an impact on the larger global market.[38] However, China's shift away from existing BOF mills will be slow due to the fact that more than half of the facilities were built in the last 10 to 15 years. Closing the doors of these facilities and building new EAF plants has to be economically feasible.[39]

OPTIONS TO DECARBONIZE

So how can 100% decarbonization in global steel production be achieved by 2060? The World Steel Association reports that the steel industry has reduced its energy intensity per ton of steel produced by 60% over the last 50 years. The 2016 carbon intensity average was reported at 20.3 GJ/ton.[40] Modern integrated steel mills, employing best practices using currently available technologies, are operating near maximum energy efficiency.[41] According to the IEA, the absolute minimum energy needed to produce steel using pig iron is 9.8 GJ/ton of steel. Current state-of-the-art blast furnaces use 12.0 GJ/ton.[42] The differential between state-of-the-art and global-average carbon intensity suggests an opportunity for continuous improvement; yet, even if new technologies are adopted, we will not get to zero emissions with BOFs.

Decarbonization opportunities are limited because the pig iron used in the BOF process contains 4% to 5% carbon by weight due to the inclusion of coal/coke as a reducing agent. The US Department of Energy (DOE) is currently working on several alternatives to the blast furnace and BOF processes, which promise to reduce the steelmaking carbon footprint but won't eliminate carbon emissions completely as long as molten iron continues to be a critical part of the process.[43]

One possibility for decarbonization is to substitute charcoal for coking coal. The coal used in iron-making acts as a reducing agent, an energy source to drive the process, and a carbon source that remains with the steel. Charcoal, made from wood or other biomass, could serve as an alternative renewable fuel source that would meet all of these needs. In fact, charcoal was the first fuel used in early steelmaking. Steel manufacturers are experimenting with the idea once again. ArcelorMittal's company, BioFlorestas, is growing and maintaining a forest of eucalyptus for charcoal use in one of its Brazil plants, supporting the small amount of pig iron needed to supplement the EAF-dominant steelmaking operation.[44]

However, while biomass is renewable, it continues to emit carbon dioxide when processed and burned. In addition, the growing demands for steel production would need to be balanced with the impacts to forests as well as the challenges in transporting biomass to the mills. Deforestation is already a hot-button issue around the world because, among other reasons, it contributes to global warming by removing carbon sinks (natural environments that absorb CO_2 from the atmosphere). Biomass as a fuel is only zero-carbon if the ratio of trees burned to trees planted is 1:1. The BioFlorestas eucalyptus forest serves as a case study in effectively balancing production needs with sustainability, but it is only for one operation. The question is: Can it be scaled? Substituting biomass for coal as an input to the steel industry will likely do little to reduce its global carbon footprint.

One technology that holds promise is hydrogen flash smelting. Technology R&D is currently being funded by the US DOE in partnership with ArcelorMittal, US Steel, and others. With flash smelting, hydrogen (or natural gas) can be used as the reducing agent instead of coal and is applied directly to the iron ore. When compared to the average blast furnace, hydrogen flash smelting reduces CO_2 emissions by 96%[45] and avoids the coke-making and sintering[46] processes needed for iron-making. Scientists in Europe are exploring a similar process called hydrogen direct reduction, which is similar to natural-gas direct reduction iron (DRI) methods.[47] DRI uses natural gas or hydrogen to react with iron oxide, without melting it, producing sponge iron nuggets or briquettes to be used primarily in EAF processes.

However, these technologies are still in the scale-up and demonstration phases[48] and would require the hydrogen to be produced by electrolysis, with electricity provided by a zero-carbon energy source, to truly decarbonize the process.

A better option for more quickly decarbonizing steel production would be to accelerate the adoption of EAF mini-mills. However, a complete shift to 100% EAF steel production is challenged by: (1) steel quality, due to the continued demand for high-quality specialized applications that cannot be met by EAF steel because of steel scrap contamination; (2) access to large sources of electricity to power EAFs, which is particularly challenging for developing countries; and (3) continued economic growth, creating demand for steel that outstrips the supply of scrap. The end-of-life recycling rate for iron and steel is encouraging, with a global range of 70% to 90% suggested by the United Nations Environment Programme (UNEP) in its 2011 Recycling Rates of Metals report.[49] Yet a sufficient supply of scrap steel remains a significant barrier to broader EAF adoption.

EAFs cannot currently satisfy demand for infrastructure expansion without adding virgin steel into the mix. The quality of steel scrap and the steel produced in EAFs has improved over time, yet there are some specialty steels that require a purer iron-sourced steel. To broaden the range of products produced in EAFs, and to adjust to the availability of scrap metal and variable pricing, US manufacturers are incorporating DRI into their steelmaking processes.[50] DRI-enhanced EAFs offer a cleaner source of iron, lowering the residual elements and improving the quality of steel produced, while avoiding the more carbon-intensive iron-making process by replacing coke with natural gas. DRI-EAFs are allowing these mills to more directly compete with BOF mills that use pig iron. In the future, hydrogen sourced from electrolysis using renewables could replace natural gas.

Even if we could produce 100% of the steel needed using EAFs, the electricity must be provided by clean-energy sources to decarbonize. In China, most of the EAF steel mills are powered by coal plants.[51] In the United States, the availability of electricity from renewable sources depends largely on where mills sit geographically. The large amounts of electricity needed to power EAF mini-mills are a barrier to on-site renewable energy and could challenge the electric grid if sourced from a local provider. In our previous report, *Path to 2060: Decarbonizing Electric Utilities*, we provide thoughts on the potential to decarbonize electricity generation and associated timing.

CEMENT MANUFACTURING

CEMENT IS THE SECOND KEY industrial process that will require significant decarbonization in order to achieve global carbon emission targets by 2060. The production and use of cement dates back to the time of the ancient Egyptians, but Portland cement, used widely today, wasn't invented until 1924 when Joseph Aspdin filed a patent for the process, which used finely ground clay and limestone in calcination. Twenty years later, Isaac Johnson improved upon Aspdin's formula, mixing chalk and clay at much higher temperatures to create the clinker needed to make modern Portland cement.[52] Clinker is the result of sintering limestone and other minerals into lumps or nodules, which then forms cement paste with the addition of water. Aspdin named the combination Portland cement after limestone found in Portland, England.[53]

Today, Portland cement is the most commonly used cement globally for concrete, mortar, stucco, and nonspecialty grout. This is due to the high availability of low-cost limestone, shale, and other naturally occurring materials used in Portland cement.[54]

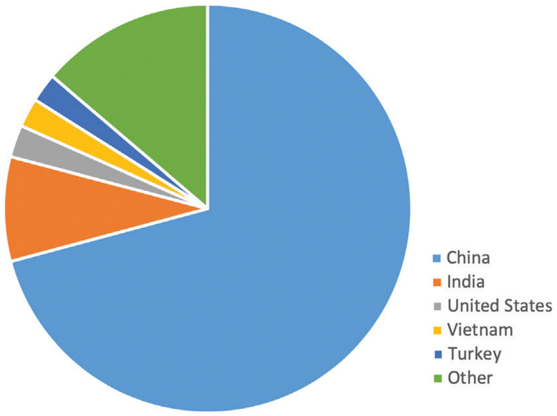
The cement manufacturing process begins with the quarrying of limestone, clay, and other materials. The rocks are then crushed to a size of 2–5 cm, fed into a rotary kiln, and heated to about 2,500 degrees Fahrenheit. As the material travels through the kiln, elements are released in the form of gas, namely CO_2. The remaining materials bond together to make clinker. To achieve the temperatures needed for the kiln-heating process, cement plants have traditionally burned coal, natural gas, or oil. The hot clinker is transferred to coolers prior to being mixed with gypsum, which slows the set time of the cement, and ground into fine powder. The heated air collected in the coolers is sent back to the kiln in an effort to improve burning efficiency and reduce fuel combustion.

Cement can be made using either a dry or wet process. In the wet process, the clay is washed first to remove adhering organic matter. The resulting slurry, which can contain up to 40% water, provides for a more homogeneously blended material. However, adding moisture to the materials then requires more energy to drive off the water, in addition to the elements, within the kiln—specifically, 350 kg of coal per ton of cement produced.[55] The dry process grinds the materials separately then mixes them according to the required proportions. Compared to the "wet" process, the dry process uses only 100 kg of coal per ton of cement produced.[56] Modern dry cement plants incorporate suspension preheaters that use the hot gas from the kiln and hot air from the coolers to preheat the raw materials, thus reducing the energy needed for clinker production. Newer plants also incorporate a precalciner kiln, which further heats the raw materials to 85% to 95% decarbonation prior to entering the rotary kiln.[57] Upgrading to a precalciner generally offers plant operators increased capacity while reducing fuel consumption and thermal nitrogen oxide (NO_x) emissions.[58]

Fuel savings influenced the shift to dry process manufacturing in the United States, which increased from 38% market share in 1975 to 70% by 2001.[59] Today, 93% of US cement is manufactured using the dry process.[60] Similar trends have been seen worldwide. In Europe, the use of dry production increased from 78% in 1997 to 90% by 2007.[61] Dry production plants dominate the industries in the top five producing countries including the United States, China,[62] India,[63] Vietnam,[64] and Turkey.[65] While the shift to dry production appears to have largely happened globally, there are cases where wet plants continue to contribute significantly to production. For example, in Russia, wet process plants hold a significant share of production capacity, nearly 83% in 2009.[66]

Due to the high cost of shipping and other transportation, the US cement distribution channel is largely limited to domestic customers.[67] However, the US market also depends heavily on imports, as domestic production is insufficient to cover demand. Canada provides the bulk of US imports given its close proximity.[68] US exports are predominantly to Canada and Mexico, again due to close proximity to operations, but revenues are less than 2%.[69] Concrete is mostly used in construction-related activities, including infrastructure, utilities, public works, residential and private nonresidential construction projects. As such, growth of the cement industry relies on the health of the construction market.[70] In the last 10 years, with exception of the 2008 recession, the US market has seen limited growth (Figure 8). Market analysts predict that growth in the industry will continue in the United States, albeit slowly, with support from publicly and privately funded infrastructure improvements.[71]

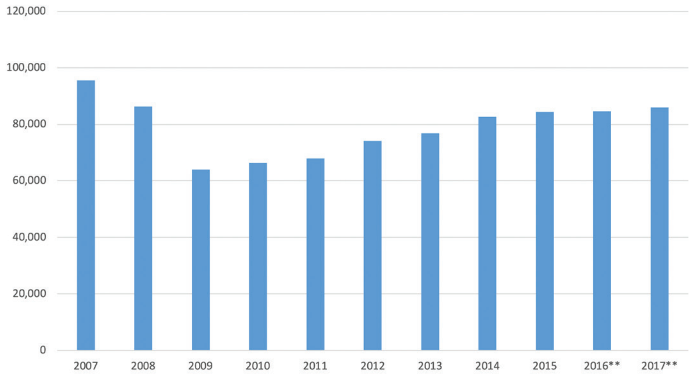
Figure 7: Global Cement Production Share 2017



Source: Statista

We see similar industry dynamics around the world in terms of new infrastructure driving production. In the last 10 years, China has seen a significant increase in production in response to rising domestic demand for concrete to support urbanization. In 2017, China held a significant share of cement production worldwide (Figure 7). With 20 million people moving into cities every year, there are estimates that half of China's infrastructure has been built since 2000.[72] Production is slowing, however, and according to industry sources, this trend is expected to continue over the next few years, eventually flattening out at a level similar to production in developed countries. Industry analysts predict continued growth worldwide, though at a slower rate, largely due to China's slowdown.[73]

Figure 8: U.S. Cement Production. Portland and Masonry (1,000 metric tons)



Source: USGS

Global companies are expanding their operations in an effort to increase revenues and profits outside the domestic market. Cement is largely a commodity product, with little differentiation, which results in a highly competitive market. Expanding the customer base requires global companies to establish operations in other countries. In the United States, acquisition of domestic operations has been the path forward for global expansion. An estimated 76.7% of US clinker capacity is owned by companies headquartered outside of the country,[74] with CRH (Ireland), Cemex (Mexico), LafargeHolcim (Switzerland), and HeidelbergCement (Germany) leading in revenues.[75]

In terms of total global cement capacity, LafargeHolcim is the largest producer, operating in 80 countries. HeidelbergCement, Cemex, UltraTech Cement (India), and Votorantim (Brazil) round out the top five global companies.[76]

CARBON EMISSIONS

Cement accounts for 7% of global CO_2 emissions,[77] the majority of which arise from the chemical reactions involved in converting limestone to calcium oxide. The bulk of the remaining emissions are from on-site fossil fuel combustion, with a smaller share from electricity consumption.[78] The carbon intensity of global cement manufacturing has declined over the years due largely to reduced clinker factor (the proportion of Portland clinker in the cement mix) and energy-efficiency improvements.[79] According to a 2016 report issued by the PBL Netherlands Environmental Assessment Agency and the European Union's Joint Research Centre, decreasing average clinker factor resulted in a 20% decrease in carbon emissions per ton of cement produced compared to that made in the 1980s.[80] Progress has been made to reduce the energy intensity of cement manufacturing through the reduction of Portland cement used in concrete but research into low-carbon substitutes is still nascent.

Coal continues to be the fuel of choice for most cement plants in the United States. According to the Portland Cement Association, coal and coke represent nearly 70% of the fuels consumed on-site, followed by alternative fuels (15%), electricity (11%), and natural gas (6%).[81] Coal is also the dominant fuel source globally (70%), while oil (16%), natural gas (8%), and alternative fuels, including biomass (6%), account for smaller portions of the energy mix.[82]

OPTIONS TO DECARBONIZE

Opportunities for decarbonizing cement manufacturing lie largely in the kiln-heating process (i.e., fossil fuel combustion and limestone calcination) and the grinding and milling processes (electricity).[83] The electricity used in cement manufacturing is a small portion (roughly 10%[84]) of its energy consumption. Manufacturers are incorporating state-of-the-art technologies, such as high-pressure grinding rolls and vertical rolling mills (used to grind materials to a fine powder); these offer 50% to 70% electricity savings relative to the current practice of using ball roller mills.[85] To decarbonize this industry, the focus needs to be on fossil fuels and raw materials.

Since coal is still a significant share of fuel consumption globally, we first look at the potential for fuel-switching to a less carbon-intense, fossil fuel source. The US EPA estimates that switching from coal to natural gas could reduce CO_2 emissions in the United States as much as 40%.[86] A global shift to natural gas for clinker production would have a significant impact, but it won't get us to zero carbon.

Alternative fuels, including biomass and waste, have great potential in this industry, with many companies already using them for clinker production. Caloric content must be taken into account when assessing biomass for fossil fuel substitution. Most organic materials have caloric contents of 9–16 GJ/ton of cement, and 18–20 GJ/ton of cement is required for cement kiln firing.[87] Some blending of other materials is needed to meet the thermal needs of the kiln. In the European Union, plastics, mixed industrial waste, and tires represent nearly 70% of alternative fuels used in plants.[88] Many cement plants in the United States are also using tires and other waste fuels in their manufacturing process. According to industry sources, tires are the closest substitute for coal with regard to the energy required to sufficiently heat the kiln.

Using waste fuel for cement manufacturing has the added benefit of addressing growing waste-management issues. In Poland, taxes imposed on landfills forced waste-management companies to look for other options. Faced with potentially high incinerator construction and operation costs, waste-management companies saw an opportunity in cement manufacturing and entered into long-term contracts to process alternative waste. Today, Poland's alternative fuel substitution rate is above 60%, with several cement plants reaching 85%.[89] In the United States, average landfill costs are still relatively cheap at $50/ton. However, this average has risen every year since 2010 and in the Northeast, the cost to landfill reached $79/ton in 2017.[90] As these prices continue to rise, and landfill space become scarce, similar partnerships could form between waste management companies and cement plants.

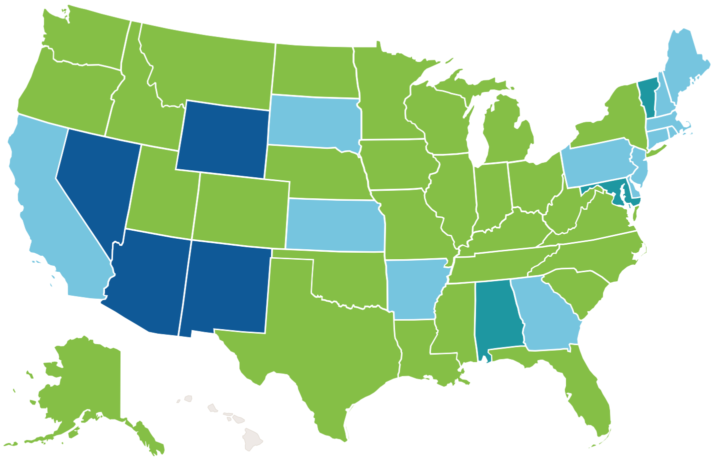
Alternative fuel use in cement plants faces other barriers, including: public acceptance; local regulations; complex permitting processes; and costs of collection, transportation, and processing. Supply chains would also need to be established; in the United States, waste streams are often provided through individual partnerships as opposed to a network of distribution. And, to be clear, while biomass is renewable and waste-to-energy supports a circular economy, using them as fuel still emits CO_2 in the production process. These alternatives may reduce carbon emissions but will not entirely eliminate them.

Even if the thermal process is decarbonized, the CO_2 emissions coming from the chemical reaction to make Portland cement need to be addressed. Given the direct relationship between clinker factor and CO_2 emissions, lowering the clinker-to-cement ratio can go a long way toward decarbonization.

Ordinary Portland cement can contain up to 95% clinker, with gypsum making up the remainder. Manufacturers have been adding other materials to lower the clinker factor, making sure that strength and durability are not threatened by lowering that ratio. According to the IEA, the average global clinker-to-cement ratio is 66%.[91]

Clinker substitutes include: natural pozzolans (silicon-based materials that react with hydraulic lime at room temperature) such as clays, shale, and sedimentary rocks; finely ground (unheated) limestone; silica fume (a pozzolanic material and by-product of silicon or ferrosilicon alloy production); granulated blast furnace slag (a by-product of steel and iron production); and fly ash (dust-like particles from coal-fired power plants).[92] Blended cements also offer other performance benefits, such as increased strength and durability.

Figure 9: Acceptances of Portland-Limestone Cement
Tentative Data March 2018



🟩 Accepting
🟦 Planning to Accept
🟦 Considering
🟦 Type II market
⬜ not considering or no information

Source: Portland Cement Association

However, there are limits to the quantity of substitute materials used in concrete. For example, the American Concrete Institute (ACI) establishes limits for the use of supplementary cementitious materials, which range from 25% to 50% of total material mass, depending on the substitute materials used.[93] The limits established are based on ASTM International standards for cement, concrete, and aggregates.

One alternative that is gaining momentum in the United States is Portland-limestone cements (PLCs), known as Type 1L cements. PLCs offer similar performance to Portland Type I (general use) cements with a 10% savings in carbon emissions. Finely ground limestone is blended with the Portland cement in the final milling stage. ASTM standards were revised in 2012 to define PLCs as having 5% to 15% limestone by mass (compared to the previous 5% requirement).[94] Considered a new technology in the United States, PLCs have been used for decades in Europe, which caps limestone addition at 35%.[95]

This is a step in the right direction, but according to industry sources, it has taken years of meeting with state officials, in particular US Department of Transportation (DOT) representatives, to build acceptance of PLCs, and some states are still not on board (Figure 9).

According to a 2016 report by Allied Market Research, green cement (defined by Allied as cementious materials made from industrial waste) represented less than 5% of total global production.[96] North America, Europe, and Asia-Pacific represented 86% of this market.[97] According to industry-supplied data, PLC sales are growing in the United States but represented only 1% of total production in 2016.

Widespread adoption of supplemental cementious materials can greatly reduce cement's carbon footprint, but the regulatory and performance constraints around Portland substitution will limit their potential impact. To achieve total decarbonization, we need a drop-in replacement for Portland cement.

NOVEL APPROACHES TO MATERIAL SUBSTITUTION

While still in the very early stages of R&D and demonstration, low-carbon cements and concretes offer significant disruptive potential. These alternatives must offer the same strength, durability, and consistency as Portland varieties but without the carbon emissions associated with their manufacturing.

Efforts to create substitutes to Portland cement are underway, and some are commercially available today. Solidia Cement uses the same raw materials, manufacturing equipment, and processes as Portland cement, but its chemistry requires less limestone. As a result, the raw materials are heated at lower kiln temperatures, reducing CO_2 emissions associated with fuel burning and limestone calcination; the company estimates a 30% reduction in greenhouse gases and other pollutants compared to ordinary Portland.[98] In addition, Solidia concrete sequesters CO_2 equal to 5% of its weight during the curing process. Combined, the company estimates that the Solidia cement and concrete solution can reduce the carbon footprint of construction products by 70%.[99]

Carbon sequestration, or the capture and long-term storage of CO_2, holds promise for the cement industry. In addition to Solidia, several companies are looking at the potential for using CO_2 to enhance or replace cement and concrete products while lowering carbon footprints. CarbonCure Technologies offers a solution that injects captured CO_2 into the ready-mix concrete process, replacing some of the Portland cement needed for the mix. The company estimates a 5% reduction in cement binder.[100] Carbicrete replaces Portland cement with steel slag, adding CO_2 to the wet concrete to strengthen the mix during the curing process. A cement plant that substitutes a cement-based process with Carbicrete could see 13,000 tons of CO_2 emissions avoided or sequestered.[101] Carbon Capture Machine and Carbon Upcycling UCLA (CO2NCRETE™) are researching the use of CO_2 to create novel binding materials to replace Portland cement.[102]

One group of concretes, geopolymers, are leading alternatives into commercialization. Geopolymer concretes use silicon and aluminum found in thermally activated natural materials, such as fly ash and blast furnace slag, with an activating solution to create a hardened binder with performance similar to Portland cement concretes. Zeobond's E-Crete and Wagner's Earth Friendly Concrete are both commercially available and can reduce carbon emissions by 60% and 80%–90%, respectively, compared to ordinary Portland cement.[103]

In most cases, low-carbon cements and concretes perform better than Portland cement in terms of durability, fire resistance, and other industry metrics. However, these novel alternatives do not yet have the long-term performance data needed for an industry-wide shift away from Portland cement. For example, the first geopolymer concrete building, the University of Queensland's Global Change Institute, was built in 2013.[104]

Alternatives to Portland cement show promise, but the cement industry is large, and adoption of new technologies requires years of rigorous testing. Performance must be proven not only in a lab setting but also in the field with decades of data. Based on industry discussions, alternatives that are commercially available are cost-prohibitive; without a significant increase in customer demand and changes to ASTM and state DOT specifications that allow for these alternatives, adoption will be slow.

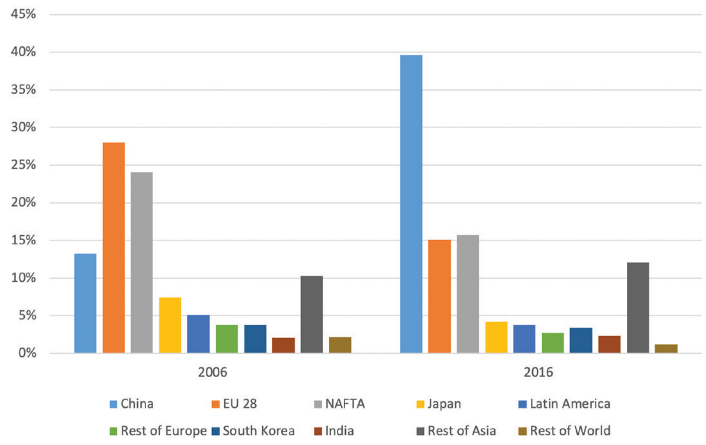
PETROCHEMICAL MANUFACTURING

PETROCHEMICALS ARE UBIQUITOUS in modern life. Decarbonizing this rapidly growing industry will be challenging, yet critical to significantly reducing carbon emissions in this sector. Petrochemicals and their derivatives are used to make plastics, rubber, detergents, insulation, solvents, fertilizer, furniture, clothes, and electronic equipment, to name just a few applications. Scientific discoveries around polymer chemistry in the 1920s laid the groundwork for today's petrochemical industry, and World War II created initial demand for large-scale petrochemical production. Two decades later, the fast pace of economic growth in the United States provided consumers with new wealth, and petrochemicals offered an opportunity to achieve a higher standard of living at low cost.

By the 1960s, petrochemical manufacturing expanded to Europe and other parts of the world, led by companies such as ExxonMobil and BP, which built facilities in close proximity to their oil refineries.[105] The oil price shock of the 1970s slowed consumer demand for products made with petrochemicals in western economies and shifted production to developing countries with access to oil production such as in the Middle East. By the 1970s, most of the technological advances in polymer chemistry had been achieved. The 1980s brought the discovery of linear low-density polyethylene (LLDPE), a stronger, more versatile, and lower-cost bulk polymer. R&D efforts then shifted from product innovation and focused instead on improving processes to reduce energy consumption and increase yields and efficiencies.[106]

The 2008 global recession resulted in a significant decrease in petrochemical production in developed countries, but growth continued in emerging countries such as China and India. China shifted from the region's biggest importer to the world's largest producer by 2016 (see Figure 10).[107] Over the last 15 years, the petrochemical industry has seen significant growth, led by ethylene production, which increased by 50 million metric tons,[108] growing 4% to 5% annually[109] between 2000 and 2016.

Figure 10: Share of Global Chemical $ Sales



Source: CEFIC Facts and Figures 2017

In the United States, 99% of petrochemicals are manufactured using crude oil or natural gas as feedstock, and more than 60% of petrochemicals are bought by plastic, resin, and synthetic rubber manufacturers.[110] The shale-oil boom in 2010 revived US production of petrochemicals, and low natural gas pricing will continue to pave the way for growth over the next five years, according to industry analysts. New capacity growth in the United States is expected to outpace the Middle East and China, which rely on naphtha (a liquid rich with hydrocarbons distilled from oil refining) and coal for petrochemical production.[111] Downstream demand over the next five years largely from the new construction and packaging industries is expected to drive production of petrochemicals.

The petrochemical industry is mostly regional in terms of trade and distribution, but it is heading toward globalization. In 2000, only 5% of petrochemicals were traded overseas, compared to 10% today and 20% predicted by 2020.[112] ICIS Chemical Business reports that 212 new producers entered the global petrochemical market over the last 10 years (a 20% increase), and at least 51 more are expected in the next five years based on company announcements.[113]

CARBON EMISSIONS

Petrochemical manufacturing represents approximately 7% of global CO_2 emissions.[114] According to the US EPA, carbon emissions from petrochemical production have increased by 33% in the United States since 1990.[115] The most common classes of petrochemicals are olefins, aromatics, and synthesis gases. The primary petrochemicals within these classes are ethylene, propylene, butadiene (olefins), benzene, toluene, xylene (aromatics), and ammonia and methanol (synthesis gases). The most energy- and carbon-intensive, high-volume chemicals are ammonia, ethylene, and propylene.[116]

Olefins are derived primarily from oil and natural gas. Oil refineries heat crude oil at high temperatures, distilling it in a chamber where hydrocarbon products are boiled off and recovered at varying temperatures. The lighter hydrocarbon chains, including naphtha and ethane, are recovered at lower temperatures and fed into a steam cracker for further processing to make ethylene and propylene. Ethane may also be sourced from natural gas processing plants and fed into the steam cracking process.

The steam cracking chamber breaks, or "cracks," the carbon-carbon bonds within the hydrocarbon chains by briefly heating the products in a furnace at 1,500 degrees Fahrenheit, without the presence of oxygen, creating the intermediate chemicals needed to make useful products. The furnace, or pyrolysis, section of the steam cracking process represents as much as 73% of total energy use and is responsible for the majority of carbon emissions generated on-site.[117]

Synthesis gases are produced through a steam reforming process (ammonia) or coal gasification (methanol). The basic chemical reaction needed to make ammonia isn't thermal driven, avoiding the need for cracking. However, significant amounts of heat energy are required to source the hydrogen needed for the reaction, which is done through steam methane reforming using natural gas. The currently practiced thermochemical Haber-Bosch process requires high temperatures and pressures that call for large-scale, centralized reactions to make economic sense. Fossil fuels provide the thermal energy needed for this process, resulting in significant carbon emissions.[118]

China is the only country producing olefins and aromatics from coal gasification, a thermo-chemical process that breaks it down into its chemical properties. This is largely due to the country's access to abundant, low cost coal.

OPTIONS FOR DECARBONIZATION

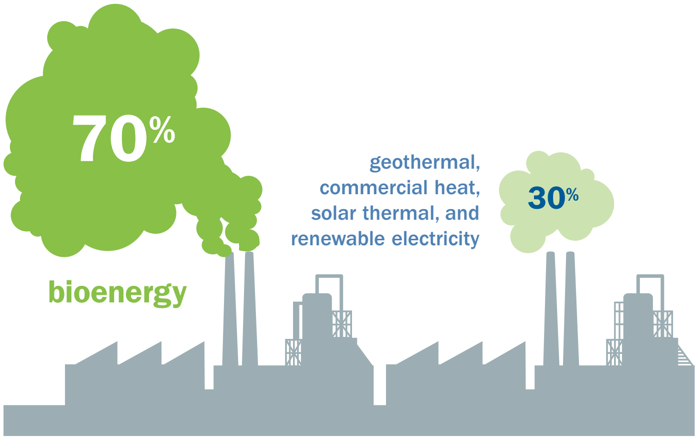
Efforts in the petrochemical industry to reduce energy intensity and carbon emissions have slowed the growth of emissions. According to the IEA, energy intensity of the US chemical sector improved by 39% and greenhouse gas intensity was reduced by 10% between 1997 and 2007.[119] As the global market for plastics continues to grow, more significant reductions will be needed to offset the increase in emissions inherent in industry expansion.

Overall, energy consumed in petrochemical plants can be broken down to three sources: fuel combustion, 60%; steam energy consumption, 35%; and power consumption, 5%.[120] Steam cracking is the largest single point of opportunity for carbon emission reduction. Naphtha steam cracking is more energy intensive than gas (e.g. ethane) and therefore produces more carbon emissions. Yet substituting one for the other isn't that easy. While gas crackers are less complex, less costly, and less energy intensive, their production is largely limited to ethylene. Naphtha crackers also produce by-products like propylene that are important constituents of consumer products today.[121]

State-of-the-art steam cracking furnaces have thermal efficiencies around 94%.[122] There is little to be gained from further efficiency measures. To truly have an impact on carbon emissions, either the energy source for steam cracking needs to shift to alternative fuels or the thermal-driven cracking process needs to be replaced altogether by an electrochemical one.

Biomass could serve as a substitute for fossil fuel energy sources and feedstock. Sugars from sugarcane, sugar beets, grain starches (e.g., corn and wheat), and lignocellulose (plant dry matter), along with vegetable oils from palm, soybean, and oilseeds offer promise. For industrials overall, biomass represented 70% of renewable energy consumption globally in 2015 (see Figure 11).[123] Industries where biomass waste is produced as a by-product of operations (e.g., pulp and paper) are best positioned to adopt bioenergy technologies, creating a "waste to energy" closed-loop industrial process.[124]

Figure 11: Renewable Energy Consumption for Heat 2015
Note: the provision of heat for industrial processes was the largest end user (63%)



Source: IEA Technology Roadmap, Delivering Sustainable Bioenergy, 2017

In the case of petrochemicals, biomass is up against the highly integrated relationship between petrochemicals and the oil and gas industry, as well as low fossil fuel prices. Harvesting and transporting crop waste to make petrochemicals is expensive as well as logistically challenging. Furthermore, use of biomass at an industrial scale could negatively impact the global food supply.

Another approach to reducing carbon emissions is substituting existing chemical processes and feedstocks. Looking at the most carbon-intensive petrochemicals—ammonia, ethylene, and propylene—two areas of research offer promise: electrolysis and oxidative dehydrogenation.

For ammonia, the opportunity for decarbonization comes at the hydrogen-sourcing stage. Hydrogen, which reacts with nitrogen to produce ammonia, is currently derived from natural-gas reforming. This is a process through which methane reacts with high pressure steam to produce hydrogen and CO_2. Another way to make hydrogen is electrolysis, where electricity is used to split water into hydrogen and oxygen. The process could thus be powered by renewable energy sources, eliminating all carbon emissions. Electrolysis is not a new technology, but it is expensive and far from commercialization. According to the IEA, producing hydrogen from electrolysis is twice the cost of gas steam reforming.[125] More promising is hydrogen's potential role across several critical industries, including the transportation and energy sectors, which may help to support further R&D and drive down the price of the technology.

For ethylene and propylene, avoiding the steam-cracking step would eliminate a significant share of carbon emissions. Oxidative dehydrogenation is a chemical process where oxygen is introduced to react with ethane and propane to make ethylene and propylene, with water as a by-product. This seems simple enough, but a catalyst is needed to control the reaction, and while there has been research in this area, one has yet to be identified.

Bioplastics, or plastics derived from plant feedstock instead of petroleum, are a viable substitute for ethylene and propylene and offer the added benefit of being biodegradable. Research published by Carnegie Mellon in 2017 suggests that carbon emissions could be reduced by 25% through a shift from traditional plastics to corn-based bioplastics.[126] Yet there might be some unintended consequences for agriculture and the environment if bioplastic manufacturing were scaled up. There are also cross-contamination challenges with the traditional plastics recycling stream and higher costs to consider, which can be 20% to 50% more expensive due to the complexity of processing the plant feedstock.[127]

Compared to cement and steel, the focus of the relatively new petrochemical industry has been on rapid growth and streamlining processes to reduce production costs. Expansion of the US industry provides an opportunity to more cost effectively incorporate new, clean technologies that will prove more costly down the road in retrofitting existing plants. Yet as long as oil and gas prices are low, and regulatory pressures absent, there is little incentive for change.

MORE DISRUPTION: THE FOURTH INDUSTRIAL REVOLUTION

MANY EXPERTS BELIEVE we are in the midst of a fourth Industrial Revolution, defined by the fusion of technologies that blurs the lines between the physical and digital worlds. The World Economic Forum's Klaus Schwab characterized this new phase as one that will disrupt almost every industry at unprecedented speeds.[128] New technology developments in data analytics, artificial intelligence (AI), advanced robotics, and the Internet of Things (IoT) have the potential to optimize resources and increase manufacturing productivity.

IBM uses the term "cognitive" when describing the manufacturing plant of the future, with a vision of real-time data analytics to maximize throughput, reduce equipment downtime, and minimize energy costs.[129] Some studies have suggested emissions reductions of 25% resulting from digitization of processes, real-time monitoring of equipment and systems, and advanced data analytics.[130]

For manufacturing, waste—of both energy and materials—impacts profitability. Focused investments continue to be in improving operations and increasing productivity. Consumer pressure on companies to be more transparent and environmentally conscious when making products is also influencing change on the factory floor and in supply chains. These technologies could assist companies in addressing these challenges, but they could also make problems worse if not implemented responsibly.

One example is additive manufacturing (AM), or 3D printing, which uses digital information to apply successive layers of raw material to produce a product. A benefit of AM is the ability to place printers close to customers, reducing the transportation needed to ship products and thus, emissions associated with the supply chain. AM also reduces material waste compared to conventional processes that start larger and subtract material through cutting.

AM has the potential to replace current thermal-driven manufacturing processes for industries such as steel and cement, driving down carbon emissions. However, some industry analysts caution that AM can be more energy intensive than conventional manufacturing. If the electricity is supplied by clean energy sources, then the emission gains will be realized. Today, AM is limited to smaller, specialized applications and it is not yet known whether it is capable of replacing mass-produced industrial processes. As 3D printer prices drop and applications scale, we could see significant disruption across the industrial sector. Whether this will help or hurt efforts to reduce carbon emissions is yet to be determined.[131]

More broadly, as the industrial sector adopts smarter manufacturing technologies and systems, the need for additional computing power will grow. Data collection, housing, and analytics, along with sensors and digitalization of processes, could actually increase the industrial sector's impact on the electric grid at the same time that core functions are being decarbonized. As industries look to streamline and electrify operations, companies should be mindful of impacts outside of factory walls.

Governments can play a critical role in creating the standards and incentives that need to be put in place to ensure that the expansion of fourth Industrial Revolution technologies doesn't negate the strides being made to reduce carbon emissions by the industrial sector.

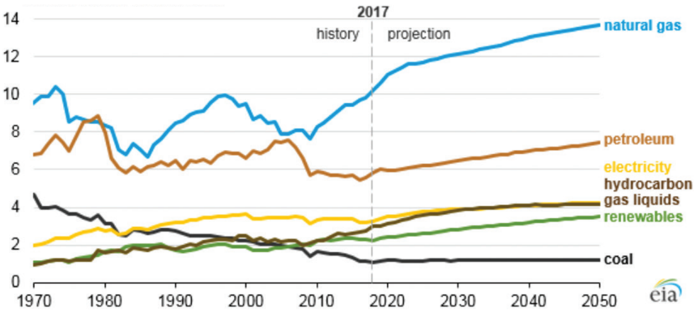
LEVERS FOR DECARBONIZATION

WHILE EACH INDUSTRY within the industrial sector may face different decarbonization challenges, there is a common thread across all of them. Industrial manufacturers are producing commodity products destined for use by downstream market actors that drive price and volume, which is driven by consumer demand. This consumer demand has more recently included preferences for greener products, influencing the choice of materials used in manufacturing. Private companies looking to establish themselves as good environmental stewards are asking more from their supply chains and have the buying power to influence change. Apple's efforts to decarbonize the aluminum industry is a great example (see Demand Pull section). This is only one of several levers that need to be pulled for industrials to have a chance of meeting the 2060 decarbonization goal. We explore each of the potential influencers below and discuss the opportunities and barriers to their success.

R&D INVESTMENT

Today, industrials consume more natural gas than any other sector, and the US EIA predicts that natural gas consumption will continue to grow faster than any other fuel source to 2050 due to continued economic growth and low prices (see Figure 12).[132]

Figure 12: Industrial energy consumption in AEO2018 Reference case (1970–2050)
in quadrillion British thermal units



Source: EIA Annual Industry Outlook 2018

What would it take to shift the sector to electrification, similar to what we have seen in the US steel industry? For steel, it took investment by an industry outsider, Nucor, using a radically different steelmaking process, which was being applied in Europe but yet to be explored in the United States. At the time, electricity was cheap and scrap metal was a fraction of the cost of iron ore, and as a result Nucor was able to undercut other US steelmakers on price. Today, Nucor is the largest manufacturer of US steel, and electrified steel represents the majority of steel produced in the country. Similar disruption is needed across dozens of industries within the industrial sector, each contending with its own market dynamics and challenges.

Often it's too risky for private companies, particularly incumbents, to invest significantly in R&D within highly competitive commodity markets. Many low-carbon solutions are in the early stages of technology development for several industries, including cement and petrochemicals, and public investment could provide the funding and expertise (e.g., national labs) needed to pilot solutions, perfect designs, and drive down the cost of these new technologies. Once these technologies are cost-competitive, private industry can more easily deploy and scale the solutions. This type of government intervention has proven to be successful in the past. For example, US government investment in early wind and solar energy development and demonstration projects paved the way for commercialization. Today, clean energy is increasingly becoming cost-competitive with coal and natural gas on the electric grid.

Yet clean technology R&D is precisely the area of research proposed to be cut by the Trump administration. The Office of Energy Efficiency & Renewable Energy (EERE), where much of this research takes place, was in danger of receiving 70% less funding compared to 2017.[133] As a result of bipartisan support and decision to raise the spending cap, EERE's FY18 budget landed 11% higher than FY17.[134] Looking forward, the FY19 budget brings EERE back in-line with its FY17 spending.[135]

Even with federal R&D support, the timing to commercialization can be slow. Private sector actors with a keen interest in climate change and technology innovation can accelerate the path to commercialization. An example is the Breakthrough Energy Coalition, led by Microsoft's Bill Gates, which has brought together a group of private investors, global corporations, financial institutions, and academic institutions to support innovative clean technologies at every stage of development, from discovery to development to deployment. Manufacturing is one of the "grand challenges" identified by the coalition, and targeted technology solutions include: low-greenhouse-gas (GHG) chemicals and steel, low/negative-GHG cement, and low-GHG industrial thermal processing.[136]

POWER ELECTRIFICATION BY RENEWABLES

Electrification is only clean if the electricity generation is carbon-free. Industrials have two choices: (1) purchase green electricity off the electric grid through a third-party power producer located near the plant, or (2) install clean energy on-site, where the plant fully owns and operates the power-producing asset. For this report we focus on the second option. Given their flexibility in siting, wind and solar are best positioned to support industrials. Yet, deploying wind and solar to meet the energy-intensive demands of industries such as steel, cement, and petrochemicals is fraught with challenges.

The temperatures demanded by energy-intensive industries are too high for wind and solar, at least in the immediate future. According to IEA's 2017 Renewable Energy for Industrials report,[137] the majority of plants implementing solar projects use nonconcentrating technologies, which do not deliver useable heat over 100 degrees Celsius. Today, the max-tech designs, or those that are technically feasible, only reach 160 degrees Celsius. Concentrated solar technologies have the potential to reach temperatures up to 400 degrees Celsius, which can support medium- to high-heating processes. However, concentrated solar arrays are geographically limited to areas with good direct normal irradiance (the amount of solar energy falling perpendicular to the panel, measured in watts/m2). Solar towers can reach higher temperatures but have been deployed only in the electric power sector to date.

R&D efforts are underway to create thermal solar solutions that can better serve the industrial sector. For example, through the SOLPART initiative, funded by the European Union and several cement companies, scientists are working to develop a new solar technology that can produce a high-temperature concentrating solar process suitable for particle calcination in energy-intensive industries. However, the 950 degrees Celsius targeted by the researchers would not reach the 1,500 degrees Celsius needed to make clinker.[138] Raw material substitution might be necessary to lower the thermal demand of these processes and bring it within concentrated solar's reach.

Yet, focusing on energy-intensive industries alone would be a mistake. There is a shift happening within the industrial sector that merits consideration when setting the path to decarbonization. Data provided by the IEA suggests that while industries with high-temperature heat demand, such as the three covered in this report, drove thermal industrial demand in the past, industries with low- and medium-temperature heat demand (operations requiring thermal sources under 400 degrees Celsius) will propel 75% of industrial growth between now and 2040.[139] While efforts should continue to address the high demands of industries like steel, cement, and petrochemicals, clean energy technologies available today could be deployed in less-demanding industries (e.g., computer and electronic products, pharmaceuticals, machinery).

Even if renewables could meet 100% of industrial thermal and electricity needs, these energy sources are further challenged by location, scale, and land availability. A petrochemical company operating a plant built on the Gulf Coast to be in close proximity to oil refineries would be hard-pressed to find a sufficiently large site conducive to solar within the region. Industrial facilities require large amounts of power to operate. The US DOE National Renewable Energy Laboratory estimates that it takes 2.8 acres of land to generate 1GWh of solar per year, and 3.5 acres for concentrated solar.[140] To give a sense of scale, Xcel Energy recently announced a deal with steel manufacturer EVRAZ to build a 240 MW solar plant that will provide electricity directly to their Rocky Mountain steel plant in Colorado.[141]

PUT A PRICE ON CARBON

For industrials, carbon capture and storage (CCS) is a critical piece to decarbonizing the sector. Yet adoption of CCS technologies has been slow, largely due to the fact that there are no market incentives or regulatory pressures to incorporate them into industrial operations. Reductions in carbon emissions over the years are attributed to efficiency improvements or fuel-switching from coal to natural gas, driven by an interest in reducing energy costs, which make up the largest share of operational expense. For these industries to consider CCS, we need to place a price on carbon; otherwise there is no economic incentive to adopt it.

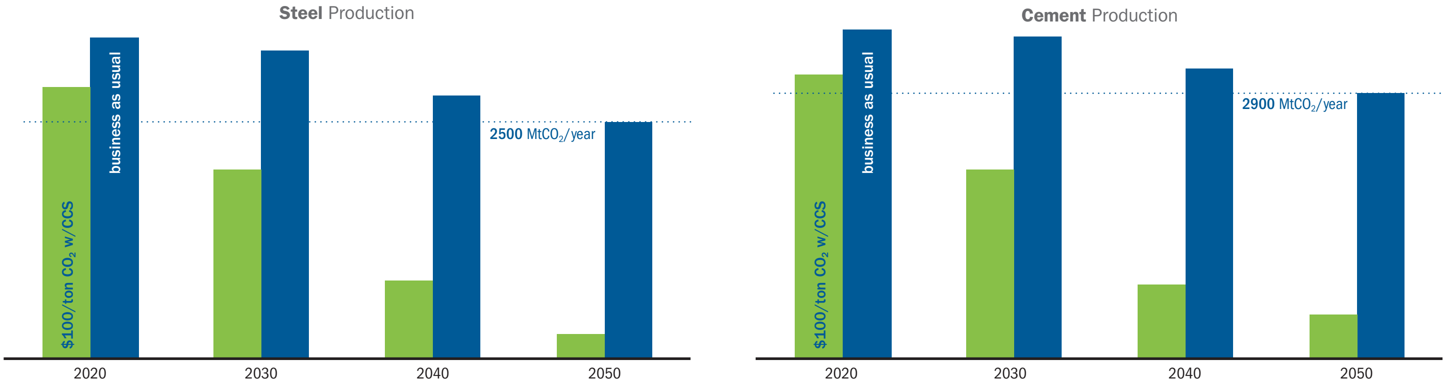
There is a significant additional cost to incorporating CCS technologies into industrial operations. Industries in this sector are very familiar with the idea of capturing by-products, such as heat and steam, and putting those back into the process to increase efficiencies and reduce costs. Carbon emissions don't offer the same efficiency improvements for the plants emitting them, nor do they provide a means for recovering the capital expense. Modeling by PBL Netherlands Environmental Assessment Agency and other contributors suggests a carbon tax of \$100/ton CO_2 combined with CCS technologies could significantly decarbonize steel and cement industries (see Figure 13). What are the most viable options for creating a demand for CO_2 and motivating manufacturers to adopt CCS technologies?

Carbon Emission Trading Schemes can create a market for carbon where companies buy and sell emissions permits and credits, motivating industrial manufacturers to explore clean technologies. While there are two existing cap-and-trade programs in the United States, only California's covers industrial facilities.

California's cap-and-trade system includes industrial plants that emit 25,000 metric tons or more of CO_2-equivalent. In addition to selling credits at auction, California also provides some allowances for free, although that will phase out over time. While overall the state has observed declining carbon emissions under the program, some industries are emitting more than their baseline through the purchase of offsets. According to one study, cement plants increased their carbon emissions by 75% in the first three years (2013–16).[142] Emissions offsets pay for forestry and agriculture projects, a requirement meant to increase investment in land conservation. Unfortunately, many of these offset investments are going to projects in other states, suggesting that the program is either poorly designed or, perhaps, just requires more time to mature.

The carbon emission trading market in the European Union has benefited from time, learning from early mistakes. Initially, prices soared between 2006 and 2008 only to then plunge 90% following the global recession. Ten years later, carbon prices are again increasing, inviting investors and creating financial hardship for companies reluctant to shift to clean-energy

Figure 13: impact of \$100/ton CO_2 tax
(with 4% annual increase, 2021–2050)



Source: Bas J. van Ruijven, et al, "Long-Term Model-Based Projections of Energy Use and CO_2 Emissions from the Global Steel and Cement Industries," Science Direct (2016), https://www.sciencedirect.com/science/article/pii/S0921344916301008.

sources. Governments have recently shifted their free permit support away from power companies to other industries, like steel. Strong messaging from country leaders of their intention to phase out coal within the next decade has helped create a demand for new technologies.[143]

By October 2018, carbon prices in the European Union for the first time in a decade had surpassed $20/ton, which is encouraging but still well below the price needed to achieve the Paris climate goals. According to the World Bank, carbon prices need to be between $40/ton and $80/ton to significantly move the needle on climate change.[144]

Federal Tax Incentives can defray the initial cost of purchasing and installing a CCS system. Increasing the demand for CCS technologies could create new markets for CO_2 and lower the cost for deployment. Congress recently extended tax credits to carbon-capture projects that begin construction in the next six years. Along with an extension, Congress increased the credit amounts. The previous measure offered credits of $10/ton of carbon captured and used for enhanced oil recovery and $20/ton of carbon captured and put in geological storage or used in other ways. The new measure increases these credits to $35/ton and $50/ton, respectively.[145]

For some industries, the new tax credit will greatly reduce the cost of carbon capture. In the energy sector, carbon-capture costs are about $60/ton for coal plants and $70/ton for natural gas plants. In the industrial sector, plants that manufacture petrochemicals like ethanol and fertilizers, where carbon capture costs $9/ton to $30/ton, will benefit the most from these credits.[146] For steel and cement plants, these incentives will do little to sway decision-making. Carbon-capture costs for these industries are estimated to be closer to $100/ton.[147] Also, there are other costs to consider, including transportation and storage costs, that are an additional $11/ton of carbon.[148]

Tax credits alone won't be enough to accelerate the adoption of carbon-capture technologies sector-wide. Customer demand for CO_2, however, could provide the catalyst needed for industrial manufacturers to embrace CCS. There are many ways in which CO_2 could be used to enhance and substitute other manufacturing processes. The largest application of captured CO_2 today is enhanced oil recovery (EOR), where the CO_2 is injected into the ground to facilitate oil and gas extraction. Of course, the longer-term profitability of EOR will depend on oil and gas pricing.

Other potential applications include turning CO_2 into chemicals, fuels, and products. Selling CO_2 as an input to other industries holds promise, particularly if consumer demand for greener products continues to grow. We already see some examples of this happening across several industries. One example is HeidelbergCement's plant in Germany that uses algae to absorb its CO_2 emissions, then sells the algae as a food additive to agricultural companies. Another example is Newlight Technologies, which uses carbon from greenhouse gases and converts it into plastics. Carbicrete, mentioned earlier in this report, uses CO_2 with steel slag during the concrete curing process.

Yet CO_2-enhanced products are only viable if there is demand downstream for greener products.

DEMAND PULL FOR GREEN PRODUCTS

The manufacturing of industrial components is driven by demand for the finished products in which they are used. More than 60% of steel made in the United States is sold to companies in the nonresidential construction and automobile industries.[149] For cement, 70% of the volume produced is sold to ready-mix concrete companies, while 10% is sold to precast-concrete manufacturers,[150] both of which are influenced by the demand for new construction. For petrochemicals, demand comes from dozens of industries from healthcare to IT to automobiles, many of which sell consumer-facing products.

In the building industry, construction companies are beholden to building codes and standards. These standards can drive demand for new technologies, such as more effective and efficient insulation and lighting, but can also stifle innovation if too prescriptive, as in the case of cement where Portland is often specifically cited. This makes it difficult for new low-carbon cements to enter the market. Voluntary certification and labeling programs, such as LEED for buildings, can also drive demand for greener materials. For example, slag cement used in new construction can contribute to 13 LEED points.[151]

Shifts in the automobile industry have had a significant impact on steel innovation. As car manufacturers work toward more fuel-efficient designs to meet new federal standards, steel has met some competition from aluminum, carbon fiber, and other lightweight materials. This has motivated research into lighter-weight steel alloys reducing the amount of steel needed. Through innovation, steel has been able to reduce its carbon footprint while retaining its leading spot as the most common metal used in automobile manufacturing today.[152]

The buying power and influence of global corporations has the potential to shift entire industries. One example is Apple. In May 2018, aluminum manufacturers Alcoa and Rio Tinto launched a joint venture, Elysis, to further develop and scale a new smelting process that replaces carbon material with an advanced conductive material. The new process releases oxygen instead of carbon dioxide. This unlikely partnership between two aluminum giants was facilitated by Apple, which was looking for opportunities to further reduce its own carbon footprint. Apple will continue to provide technical support and funding to the development process, along with financial contributions from Alcoa, Rio Tinto, and the governments of Canada and Quebec.

Growing concerns among consumers around plastics could impact future demand for petrochemicals. While it is unlikely that consumers will have insight into the manufacturing process and thus influence the chemistry used to make these products, an increased demand for higher recycled content or product substitution (e.g., wooden toys instead of plastic) could have a direct impact on petrochemical manufacturing. Companies such as Green Toys, Pilot, and Trex are selling toys, ballpoint pens, and deck materials using recycled plastics. Certification and labeling programs could make it easier for customers to identify, and trust, green products.

INDUSTRIAL DECARBONIZATION IS UNLIKELY BY 2060 WITHOUT INTERVENTIONS

INDUSTRIALIZATION HAS CONTRIBUTED to the environmental challenges we face today. As we progress into the fourth Industrial Revolution, the industrial sector has an opportunity to reverse these impacts, by harnessing existing (and innovating new) technologies that use resources more efficiently and reduce reliance on fossil fuels. Data and automation also could help facilitate a shift toward more efficient operations in general. As the IT and industrial worlds collide, will industries within this sector be able to reinvent themselves and stay cost-competitive? Without public intervention, will carbon emissions ever become more than a reporting requirement? Can these industries continue to grow sustainably?

GROWING NEEDS, GROWTH IN PRODUCTION

According to the IEA, increasing population and urbanization patterns, coupled with infrastructure development needs, will drive new demand for cement and concrete. Demand for green cement (blends) is expected to grow significantly over the next decade due to several factors, including increased demand from governments to reduce carbon emissions. Analysts' predictions range from 10% to 15% CAGR[153] increase in green cement global production. In comparison, CAGR growth of the overall global cement industry is estimated at 7% to 8%.[154] This is encouraging, but doesn't go far enough to decarbonize this industry without novel low-carbon cements.

The steel industry has always claimed to be green because of the high percentage of recycled steel used in the manufacturing process. More recently, it has experienced an increase in demand due to clean technologies such as electric vehicles, wind turbines, and solar panels. Increasing demand from growing automobile and construction industries will help to sustain demand for steel in the next five years, although slowing production out of China will decelerate overall growth, according to the World Steel Association. With any growth in demand comes the need for iron ore-supplied steel, which is more carbon-intensive than EAF produced steel. Yet, reports of overproduction and oversupply as well as expected new sources of recycled steel from developing economies bode well for EAFs. Market analysts expect that there will be a trend toward higher EAF production worldwide.[155]

Expanding economies such as China have helped to drive demand for plastics, and thus petrochemicals. Consumers in developed countries such as the United States are acquiring more goods and devices that incorporate plastics. Even clean technologies like lightweight vehicles, wind turbines, and solar panels are creating a brand-new market segment for plastics. Low oil and natural-gas prices are boosting new petrochemical plant construction in the United States and the Middle East. Global demand for petrochemicals is expected to grow in the near term, but then slow as economies mature. According to McKinsey & Company, the industry will go from 3.6% growth today to as low as 2% by 2030.[156]

THE CHALLENGE AHEAD

Substituting for steel, cement, and plastics will be difficult. These industries and the products they produce are the backbone of global infrastructure growth and new product development. The sector overall is challenged by the fact that it is made up of dozens of industries, all requiring different inputs and feedstocks. Even within each industry there can be hundreds of different methods used for manufacturing. For example, there are 130 different industrial processes that can be used to manufacture the 18 most carbon-intensive chemicals.[157] Carbon pricing could provide industry-wide incentives to innovate and adopt low carbon technologies without being prescriptive, but many political hurdles face its implementation in the United States. Electrification of manufacturing processes could eliminate the need for fossil fuel heating across the sector but is challenged by the scale of the demand. The key to industrial decarbonization may be found in basic chemistry and material substitution.

Focusing primarily on the steel, cement, and petrochemical industries, which represent more than 70% of industrial carbon emissions in the United States, is a good start. Of course, this does not negate the need to address carbon-intensive operations within other industries that collectively could present a growing problem. Developing industry-specific strategies could enable customized solutions based on operational needs and be more effective. For example, IEA is moving the dialogue forward through its technology roadmap series on key industries, such as steel and cement, which identifies the priority actions that governments, industry, financial partners, and civil society need to take to advance clean technologies in these areas in support of achieving international climate goals. Support from the US government in the form of R&D investment would lower the cost of market entry and remove some of the risk otherwise taken on by private companies. Yet, the speed at which these solutions need to be commercialized may ultimately require private sector leadership or at the very least, public-private partnerships.

This will take time, and while some industries, like steel, have technologies at the ready, others, such as petrochemicals, have yet to identify alternatives. The road is long for industrial decarbonization, and unfortunately it appears to stretch beyond our 2060 target. For many of these industries, downstream influencers could make the difference.

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ENDNOTES

[1] Climate Interactive and MIT Sloan carbon reduction scenario tool, http://www.climateinteractive.org (accessed Oct. 2018).

[2] We separate transportation, energy, and agriculture from the industrial sector. See previous Batten Path to 2060 reports for these other sectors: https://www.darden.virginia.edu/innovation-climate/research/.

[3] US Environmental Protection Agency, Global Greenhouse Gas Emissions Data, https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data (accessed Aug. 2018). The share provided here represents direct emissions, or those generated on-site to support industrial operations. Electricity generated off-site is covered by the previous report, *Path to 2060: Decarbonizing the Electric Utility Industry.*

[4] Statista, "Cumulative Carbon Dioxide Emissions Worldwide from 1814 to 2014," https://www.statista.com/statistics/500146/worldwide-carbon-dioxide-emissions-cumulative/ (accessed Oct. 2018).

[5] Center for Climate and Energy Solutions, Climate Basics: Energy/Emissions Data, Global Emissions, "Greenhouse Gas Emissions for Major Economies 1990–2020," https://www.c2es.org/content/international-emissions/ (accessed Oct. 2018).

[6] US Energy Information Adminstration, Environment: Analysis and Projections, "US Energy-Related Carbon Dioxide Emissions, 2017," September 25, 2018, https://www.eia.gov/environment/emissions/carbon/.

[7] World Steel Association, "World Steel in Figures 2018," https://www.worldsteel.org/en/dam/jcr:f9359dff-9546-4d6b-bed0-996201185b12/World+Steel+in+Figures+2018.pdf (accessed Aug. 2018).

[8] Frank Zhong, World Steel Association, "The Chinese Steel Industry at a Crossroads," presentation at the China Iron Ore 2018 conference, Beijing, https://www.worldsteel.org/en/dam/jcr:295ce643-fff1-4a23-8db8-d24bf3b154f2/PPT%2520for%2520MB%2520iron%2520ore%2520conference%25202018_EN_final.pdf (accessed Sept. 2018).

[9] Jonathan Hadad, "Iron & Steel Manufacturing in the US," IBISWorld Industry Report 33111, October 2018, www.ibisworld.com. Note: The US iron and steel manufacturing industry has operated at a trade deficit, with imports exceeding exports by a factor of three.

[10] World Steel Association, World Steel in Figures 2018.

[11] Ibid.

[12] Ibid.

[13] Ibid.

[14] Ibid.

[15] Ibid.

[16] Zacks Equity Research, "Here's How the Steel Industry's Getting Hot," Nasdaq, May 8, 2018, https://www.nasdaq.com/article/heres-how-the-steel-industrys-getting-hot-cm960556.

[17] Hadad, "Iron & Steel Manufacturing in the US."

[18] World Coal Association, Coal: Uses of Coal, "How Is Steel Produced?," https://www.worldcoal.org/coal/uses-coal/how-steel-produced (accessed July 2018).

[19] World Steel Association, World Steel in Figures 2018.

[20] World Coal Association, How is Steel Produced?

[21] US Environmental Protection Agency, Office of Air and Radiation, "Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Iron and Steel Industry," September 2012, https://www.epa.gov/sites/production/files/2015-12/documents/ironsteel.pdf.

[22] World Steel Association, World Steel in Figures 2018.

[23] World Steel Association, Publications: Position Papers, "Steel's Contribution to a Low Carbon Future," https://www.worldsteel.org/publications/position-papers/steel-s-contribution-to-a-low-carbon-future.html (accessed July 2018).

[24] Global CCS Institute, Insights, "CCS for Iron and Steel Production," August 23, 2013, https://www.globalccsinstitute.com/insights/authors/dennisvanpuyvelde/2013/08/23/ccs-iron-and-steel-production.

[25] US EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Iron and Steel Industry, p. 4.

[26] Global CCS Institute, CCS for Iron and Steel Production.

[27] US EPA, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Iron and Steel Industry, p. 4.

[28] The Institute for Industrial Productivity, Industrial Efficiency Technology Database, "Electric Arc Furnace," http://ietd.iipnetwork.org/content/electric-arc-furnace (accessed July 2018).

[29] Luke Hickman, "The Rise of EAFs Provides Flexibility to Steel Producers," Freedonia Focus Reports, April 3, 2017, https://www.freedoniafocusreports.com/Content/Blog/2017/04/03/The-Rise-of-EAFs-Provides-Flexibility-to-Steel-Producers.

[30] Steelonthenet.com, "Electric Arc Furnace Steelmaking Costs 2018," https://www.steelonthenet.com/cost-eaf.html, and "Basic Oxygen Furnace Route Steelmaking Costs 2018," https://www.steelonthenet.com/cost-bof.html (both accessed Sept. 2018).

[31] Ibid.

[32] World Steel Association, World Steel in Figures 2018.

[33] World Steel Association, Press Releases, 2018, "World Crude Steel Output Increases by 5.3% in 2017," January 24, 2018, https://www.worldsteel.org/media-centre/press-releases/2018/World-crude-steel-output-increases-by-5.3--in-2017.html.

[34] Frank Zhong, The Chinese steel industry at a crossroads.

[35] Frank Zhong, "Is It Time for China to Switch to Electric Arc Furnace Steelmaking?," World Steel Association (blog), February 13, 2018, https://www.worldsteel.org/media-centre/blog/2018/Is-it-time-for-China-to-switch-to-EAF-steelmaking.html.

[36] Muyu Xu and Tom Daly, "China to Cut More Coal, Steel Output to Defend 'Blue Skies,'" *Reuters*, March 4, 2018, https://www.reuters.com/article/us-china-parliament-steel-coal/china-to-cut-more-coal-steel-output-to-defend-blue-skies-idUSKBN1GH034.

[37] Steven Vercammen, Avetik Chalabyan, Oliver Ramsbottom, Junjie Ma, and Charlie Tsai, "Tsunami, Spring Tide, or High Tide? The Growing Importance of Steel Scrap in China," McKinsey & Company, March 2017, https://www.mckinsey.com/~/media/mckinsey/industries/metals%20and%20mining/our%20insights/the%20growing%20importance%20of%20steel%20scrap%20in%20china/the-growing-importance-of-steel-scrap-in-china.ashx.

[38] Ibid.

[39] Ibid.

[40] World Steel Association, World Steel in Figures 2018. Note that GJ = gigajoule, which is equivalent to 1 billion joules or 277 kWh of energy.

[41] World Steel Association, Fact Sheet: "Climate Change Mitigation by Technology, Innovation and Best Practice Transfer," February 2018, https://www.worldsteel.org/en/dam/jcr:0191b72f-987c-4057-a104-6c06af8fbc2b/fact_technology%2520transfer_2018.pdf.

[42] Simone Landolina and Araceli Fernandez, "Global Iron & Steel Technology Roadmap," presentation at the IEA Kick-Off Workshop, November 20, 2017, https://www.iea.org/media/workshops/2017/ieaglobalironsteeltechnologyroadmap/ISTRM_Session0_IEA_201117.pdf.

[43] Based on information provided by US Department of Energy, Energy Efficiency and Renewable Energy Office, July 2018.

[44] ArcelorMittal, "Charcoal from Renewable Forests for Carbon-Neutral Steel," News and Media: Our Stories https://corporate.arcelormittal.com/news-and-media/our-stories/charcoal-from-renewable (accessed Oct. 2018).

[45] Cédric Philibert, "Renewable Energy for Industry: From Green Energy to Green Materials and Fuels," IEA Insights Series 2017, https://www.iea.org/publications/insights/insightpublications/Renewable_Energy_for_Industry.pdf.

[46] Sintering is the compacting of iron ore and added minerals, using a combination of high heat and pressure, to prepare iron ore fines for the blast furnace stage.

[47] Cédric Philbert, "Renewable Energy for Industry: From Green Energy to Green Materials and Fuels," IEA Insight Series 2017, https://www.iea.org/publications/insights/insightpublications/Renewable_Energy_for_Industry.pdf.

[48] Hong Yong Sohn, "Novel Flash Ironmaking Technology (FIT)," presentation at US DOE H2@Scale workshop, November 2017, https://www.energy.gov/sites/prod/files/2016/12/f34/fcto_h2atscale_workshop_sohn.pdf.

[49] Thomas Graedel, A. Dubreuil, Michael Gerst, Seiji Hashimoto, Yuichi Moriguchi, Daniel Müller, Claudia Pena, Jason Rauch, Barbara Reck, Thompson Sinkala, Guido Sonnemann, Christian Hagelucken, UNEP International Resource Panel, "Recycling Rates of Metals: A Status Report," World Resources Forum, 2011, https://www.wrforum.org/uneppublicationspdf/recycling-rates-of-metals.

[50] US Department of Energy, Energy Efficiency & Renewable Energy Office, "Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in US Iron and Steel Manufacturing," June 2015, https://www.energy.gov/sites/prod/files/2015/08/f26/iron_and_steel_bandwidth_report_0.pdf, p. 12.

[51] Steven Vercammen, et al, Tsunami, spring tide, or high tide? The growing importance of steel scrap in China.

[52] Understanding Cement, "Cement History," https://www.understanding-cement.com/history.html (accessed June 2018).

[53] Today in Science History, "Joseph Aspdin's Portland Cement," https://todayinsci.com/A/Aspdin_Joseph/AspdinJoseph-Cement.htm (accessed June 2018).

[54] Cement and concrete often are used interchangeably. Concrete is a mixture of aggregates and paste. The aggregates are sand and gravel or crushed stone; the paste is water and Portland cement (the binder for the concrete).

[55] Kishan Mudavath, "Difference between Wet and Dry Process of Cement," *We Civil Engineers* (blog), March 28, 2018, https://wecivilengineers.wordpress.com/2018/03/28/difference-between-wet-and-dry-process-of-cement/.

[56] Ibid.

[57] Understanding Cement, "Manufacturing – The Cement Kiln," https://www.understanding-cement.com/kiln.html# (accessed June 2018).

[58] Ernst Worrell and Christina Galitsky, "Energy Efficiency Improvement and Cost Saving Opportunities for Cement Making: An ENERGY STAR Guide for Energy and Plant Managers," sponsored by the US EPA, March 2008, https://www.energystar.gov/ia/business/industry/LBNL-54036.pdf?5d92-a6b3.

[59] Lisa J. Hanle, Kamala R. Jayaraman, and Joshua S. Smith, “CO2 Emissions Profile of the US Cement Industry,” US Environmental Protection Agency, https://www3.epa.gov/ttnchie1/conference/ei13/ghg/hanle.pdf (accessed Oct. 2018).

[60] Portland Cement Association, Cement Industry Overview, “Economics of the US Cement Industry,” http://www.cement.org/structures/manufacturing/Cement-Industry-Overview (accessed July 2018).

[61] Joint Research Centre of the European Commission, 2013 Technology Map of the European Strategic Energy Technology Plan (SET-Plan): Technology Descriptions, Chapter 20:1 “The Cement Industry,” April 9, 2014, http://hub.globalccsinstitute.com/publications/2013-technology-map-european-strategic-energy-technology-plan-set-plan-technology-descriptions/201-cement-industry.

[62] Global Cement, “China: First in Cement,” July 23, 2013, http://www.globalcement.com/magazine/articles/796-china-first-in-cement.

[63] Burange, L.G., “Performance of Indian Cement Industry: The Competitive Landscape”, Table 3, Sept. 2008.

[64] PR Newswire, “Vietnam Cement Report 2015,” April 20, 2016, https://www.prnewswire.com/news-releases/vietnam-cement-report-2015-300254887.html.

[65] Global Cement, “Turkish Cement Focus,” March 12, 2013, http://www.globalcement.com/magazine/articles/766-turkish-cement-focus.

[66] Galina Peshkova, Alexei Cherepovitsyn, and Pavel Tcvetkov, “Prospects of the Environmental Technologies Implementation in the Cement Industry in Russia,” *Journal of Ecological Engineering* 17, no. 4 (Sept. 2016): 17–24, 10.12911/22998993/64607, p. 20.

[67] Dylan Miller, “Cement Manufacturing in the US,” IBISWorld Industry Report 32731, June 2018, www.ibisworld.com.

[68] Ibid.

[69] Ibid.

[70] Ibid.

[71] Ibid.

[72] Ana Swanson, “How China Used More Cement in 3 Years than the U.S. did in the Entire 20th Century,” *Washington Post*, March 24, 2015, https://www.washingtonpost.com/news/wonk/wp/2015/03/24/how-china-used-more-cement-in-3-years-than-the-u-s-did-in-the-entire-20th-century/?utm_term=.8e38808da6b6.

[73] Marketline, Global Construction Materials report, 2017, www.marketline.com.

[74] Portland Cement Association, Cement Industry Overview.

[75] Statista, “Ranking of Selected Cement Manufacturers in FY 2017, Based on North American Revenue,” https://www.statista.com/statistics/235293/leading-us-cement-manufacturers/ (accessed Sept. 2018).

[76] Peter Edwards, “Global Cement Top 100 Report 2017–2018,” *Global Cement*, December 4, 2017, http://www.globalcement.com/magazine/articles/1054-global-cement-top-100-report-2017-2018.

[77] Araceli Fernandez and Yvonne Leung, “Technology Roadmap: Low-Carbon Transition in the Cement Industry,” International Energy Agency and the Cement Sustainability Initiative of the World Business Council for Sustainable Development, April 6, 2018, https://webstore.iea.org/technology-roadmap-low-carbon-transition-in-the-cement-industry, p. 12.

[78] N. A. Madlool, R. Saidur, M. S. Hossain, and N. A. Rahim, “A Critical Review on Energy Use and Savings in the Cement Industries,” *Renewable and Sustainable Energy Reviews* 15, no 4 (May 2011): 2042–60, https://www.sciencedirect.com/science/article/pii/S1364032111000207.

[79] Jos G. J. Olivier, Greet Janssens-Maenhout, Marilena Muntean, and Jeroen A. H. W. Peters, “Trends in Global CO2 Emissions: 2016 Report,” PBL Netherlands Environmental Assessment Agency and EU Joint Research Centre, 2016, http://edgar.jrc.ec.europa.eu/news_docs/jrc-2016-trends-in-global-co2-emissions-2016-report-103425.pdf.

[80] Ibid.

[81] Portland Cement Association, “2016 U.S. Cement Industry Annual Yearbook,” Table 50: Plant Fuel Mix, http://www2.cement.org/econ/pdf/Yearbook2016_2sided.pdf .

[82] International Energy Agency, “Cement: Tracking Clean Energy Progress” (updated May 23, 2018), https://www.iea.org/tcep/industry/cement/.

[83] Araceli Fernandez and Yvonne Leung, Technology Roadmap: Low-Carbon Transition in the Cement Industry, p. 14, Figure 2.

[84] Ernst Worrell, Katerina Kermeli, and Christina Galitsky, “Energy Efficiency Improvement and Cost Saving Opportunities for Cement Making: An ENERGY STAR Guide for Energy and Plant Managers,” sponsored by the US EPA, August 2013, https://www.energystar.gov/sites/default/files/buildings/tools/ENERGY%20STAR%20Guide%20for%20the%20Cement%20Industry%2028_08_2013%20Final.pdf.

[85] Ibid.

[86] US Environmental Protection Agency, Office of Air and Radiation, “Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Portland Cement Industry,” October 2010, https://www.epa.gov/sites/production/files/2015-12/documents/cement.pdf.

[87] US Environmental Protection Agency, Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Portland Cement Industry, p.39.

[88] International Finance Corporation (World Bank Group), “Increasing the Use of Alternative Fuels at Cement Plants: International Best Practice,” 2017, https://www.ifc.org/wps/wcm/connect/cb361035-1872-4566-a7e7-d3d1441ad3ac/Alternative_Fuels_08+04.pdf?MOD=AJPERES.

[89] Ibid.

[90] Rob Watson, "The Cost to Landfill MSW in the US Continues to Rise Despite Soft Demand", July 10, 2017, https://nrra.net/sweep/the-cost-to-landfill-msw-in-the-us-continues-to-rise-despite-soft-demand/.

[91] IEA, Cement: Tracking Clean Energy Progress.

[92] Cembureau, Clinker Substitution, "Five Parallel Routes: Resource Efficiency" http://lowcarboneconomy.cembureau.eu/index.php?page=clinker-substitution (accessed July 2018),.

[93] NRMCA Research Engineering and Standards Committee, "SIP 1 – Limits on Quantity of Supplementary Cementitious Materials," Specification in Practice, National Ready Mixed Concrete Association, 2015, https://www.nrmca.org/aboutconcrete/downloads/SIP1.pdf.

[94] Based on industry discussions.

[95] Claude Goguen, "Portland-Limestone Cement," *Precast Inc. Magazine*, National Precast Concrete Association, June 2, 2014, https://precast.org/2014/06/portland-limestone-cement/.

[96] Allied Market Research, "Global Green Cement Market 2017–2018," www.alliedmarketresearch.com and Statista, "Cement Production Globally and in the U.S. from 2010 to 2017," https://www.statista.com/statistics/219343/cement-production-worldwide/. Note that cementitious material made from industrial waste includes fly ash, steel slag, recycled aggregates, and others.

[97] Ibid.

[98] Solidia Technologies, Solidia Cement™, http://solidiatech.com/applications/adoptions/cement/ (accessed Sept. 2018).

[99] Solidia Technologies, The Patented Process Behind Solidia Cement™ & Solidia Concrete™, http://solidiatech.com/applications/patented-process/ (accessed Sept. 2018).

[100] Sean Monkman and Mark MacDonald, "Making Concrete with Carbon Dioxide," *Concrete Construction*, May 15, 2017, https://www.concreteconstruction.net/concrete-production-precast/making-concrete-with-carbon-dioxide_o.

[101] Carbicrete, "Technology," http://carbicrete.com/technology/ (accessed July 2018).

[102] Carbon Capture Machine, "About Us," https://ccmuk.com/ and Carbon Upcycling UCLA, http://www.co2upcycling.com/ (both accessed Sept. 2018).

[103] The Zeobond Group, E-Crete™, http://www.zeobond.com/products-e-crete.html and Wagners, Earth Friendly Concrete, https://www.wagner.com.au/main/what-we-do/earth-friendly-concrete/efc-home

[104] Geopolymer Instutute, "World's First Public Building with Structural Geopolymer Concrete," October 18, 2013, https://www.geopolymer.org/news/worlds-first-public-building-with-structural-geopolymer-concrete/.

[105] European Petrochemical Association, Petrochemicals and EPCA: A Passionate Journey, https://epca.eu/ebooks/history/index.html#1/z (accessed Aug. 2018).

[106] Ibid.

[107] Ibid.

[108] Eren Cetinkaya, Nathan Liu, Theo Jan Simons, and Jeremy Wallach, "Petrochemicals 2030: Reinventing the Way to Win in a Changing Industry," McKinsey & Company Chemicals, February 2018, https://www.mckinsey.com/industries/chemicals/our-insights/petrochemicals-2030-reinventing-the-way-to-win-in-a-changing-industry.

[109] Tayeb Benchaita, "Greenhouse Gas Emissions from New Petrochemical Plants," Inter-American Development Bank, Environmental Safeguards Unit,Technical Note No. IDB - TN – 562, https://publications.iadb.org/bitstream/handle/11319/5962/Greenhouse%20Gas%20Emissions%20from%20New%20Petrochemical%20Plants%20.pdf;sequence=1.

[110] Darshan Kalyani, "Petrochemical Manufacturing in the US," IBISWorld Industry Report 32511, December 2017, www.ibisworld.com.

[111] Heather Doyle, "US Chemical Capacity to Increase by More than 50 Million Tonnes," P*etrochemical Update*, May 18, 2018, http://analysis.petchem-update.com/engineering-and-construction/us-chemical-capacity-increase-more-50-million-tonnes.

[112] EPCA, Petrochemicals and EPCA: A Pasionate Journey.

[113] Paul Bjacek, "Global Petrochemical Ownership Changes Bring Risk," ICIS Chemical Business, September 27, 2017, https://www.icis.com/resources/news/2017/09/27/10147168/global-petrochemical-ownership-changes-bring-risk/.

[114] IEA, "Technology Roadmap: Energy and GHG Reductions in the Chemical Industry via Catalyic Processes," International Energy Agency, International Council of Chemical Associations, and DECHEMA, May 2013, https://webstore.iea.org/technology-roadmap-energy-and-ghg-reductions-in-the-chemical-industry-via-catalytic-processes, p. 1.

[115] US Environmental Protection Agency, "Inventory of US Greenhouse Gas Emissions and Sinks: 1990–2016," April 12, 2018, https://www.epa.gov/sites/production/files/2018-01/documents/2018_complete_report.pdf.

[116] Zachary J. Schiffer and Karthish Manthiram, "Electrification and Decarbonization of the Chemical Industry," *Joule* 1, nos. 10–14, September 6, 2017, https://www.cell.com/joule/pdf/S2542-4351(17)30015-6.pdf.

[117] Tayeb Benchaita, Greenhouse Gas Emissions from New Petrochemical Plants.

[118] Zachary J. Schiffer et al, Electrification and Decarbonization of the Chemical Industry.

[119] IEA, Technology Roadmap: Energy and GHG Reductions in the Chemical Industry via Catalyic Processes.

[120] Tayeb Benchaita, Greenhouse Gas Emissions from New Petrochemical Plants.

[121] Ibid.

[122] Ibid.

[123] Adam Brown and Pharoah Le Feuvre, "Technology Roadmap: Delivering Sustainable Bioenergy, 2017," International Energy Agency, 2017, p. 19, http://www.iea.org/publications/freepublications/publication/Technology_Roadmap_Delivering_Sustainable_Bioenergy.pdf.

[124] Ibid.

[125] IEA, Technology Roadmap: Energy and GHG Reductions in the Chemical Industry via Catalytic Processes.

[126] Daniel Posen, Paulina Jaramillo, Amy E. Landis, and W. Michael Griffin, "Greenhouse Gas Mitigation for U.S. Plastics Production: Energy First, Feedstocks Later," *IOP Science, Environmental Research Letters* 12, no. 3 (March 16, 2017), http://iopscience.iop.org/article/10.1088/1748-9326/aa60a7.

[127] Renee Cho, "The Truth about Bioplastics," *State of the Planet: Sustainability* (blog), Earth Institute, Columbia University, December 13, 2017, https://blogs.ei.columbia.edu/2017/12/13/the-truth-about-bioplastics/.

[128] Bernard Marr, "The 4th Industrial Revolution Is Here - Are You Ready?," *Forbes*, August 13, 2018, https://www.forbes.com/sites/bernardmarr/2018/08/13/the-4th-industrial-revolution-is-here-are-you-ready/#22297bc9628b.

[129] Binny Samuel, "What Does a Manufacturing Plant of the Future Look Like? (Part 1)," Internet of Things (blog), IBM, November 21, 2017, https://www.ibm.com/blogs/internet-of-things/iot-plant-future-part-1/.

[130] World Economic Forum, "Impact of the Fourth Industrial Revolution on Supply Chains," October 2017, http://www3.weforum.org/docs/WEF_Impact_of_the_Fourth_Industrial_Revolution_on_Supply_Chains_.pdf.

[131] Avetik Chalabyan, Elena Jänsch, Tom Niemann, Tobias Otto, Benedikt Zeumer, and Ksenia Zhuravleva, "How 3-D Printing Will Transform the Metals Industry," McKinsey & Company Metals and Mining, August 2017, https://www.mckinsey.com/industries/metals-and-mining/our-insights/how-3d-printing-will-transform-the-metals-industry; Jason Bordoff, "How 3-D Printing Could Decrease Carbon Emissions. Or Maybe Increase Them," Leadership (blog), *Wall Street Journal*, June 8, 2016, https://blogs.wsj.com/experts/2016/06/08/how-3-d-printing-could-decrease-carbon-emissions-or-maybe-increase-them/.

[132] US Energy Information Administration, "Natural Gas Expected to Remain Most-Consumed Fuel in the U.S. Industrial Sector," Today in Energy, March 1, 2018, https://www.eia.gov/todayinenergy/detail.php?id=35152 .

[133] American Institute of Physics, Federal Science Budget Tracker, Fiscal Year 2018. https://www.aip.org/fyi/federal-science-budget-tracker/FY2018#tabs-section-doe-applied-energy (accessed October 20, 2018).

[134] American Institute of Physics, Final FY18 Appropriations: DOE Applied Energy R&D, April 10, 2018 (43), https://www.aip.org/fyi/2018/final-fy18-appropriations-doe-applied-energy-rd.

[135] American Institute of Physics, Federal Science Budget Tracker, Fiscal Year 2019.

[136] Breakthrough Energy, Manufacturing a Brighter Tomorrow http://www.b-t.energy/ (accessed Aug. 2018).

[137] Cedric Philbert, Renewable Energy for Industry, From Green Energy to Green Materials and Fuels.

[138] SOLPART Project, www.solpart-project.eu.

[139] Elie Bellevrat and Kira West, "Clean and Efficient Heat for Industry," International Energy Agency, January 23, 2018, https://www.iea.org/newsroom/news/2018/january/commentary-clean-and-efficient-heat-for-industry.html.

[140] Linda Hardesty, "It Takes 2.8 Acres of Land to Generate 1GWh of Solar Energy Per Year, Says NREL," *Energy Manager Today*, August 1, 2013, https://www.energymanagertoday.com/it-takes-2-8-acres-of-land-to-generate-1gwh-of-solar-energy-per-year-says-nrel-094185/.

[141] Christian Roselund, "Big steel goes big solar in the US", *PV Magazine*, August 20, 2018, https://www.pv-magazine.com/2018/08/20/big-steel-goes-big-solar-in-the-us/.

[142] Amel Ahmed, "California Cap-and-Trade Is Working — For Other States," *PBS News Hour*, July 15, 2018, https://www.pbs.org/newshour/science/california-cap-and-trade-is-working-for-other-states.

[143] Jeremy Hodges, Ewa Krukowska, and Mathew Carr, "Europe's $38 Billion Carbon Market Is Finally Doing Its Job," *Bloomberg*, March 26, 2018, https://www.bloomberg.com/news/articles/2018-03-26/europe-s-38-billion-carbon-market-is-finally-starting-to-work.

[144] "Most CO2 Prices Are Insufficient, World Bank Says," Bloomberg Weekly Brief: Sustainable Finance, January 3, 2018, https://newsletters.briefs.bloomberg.com/document/TxrTRyZlQqupLKg4W7J22w--_9ez2hhvxnqgzbspk5q/year-ahead.

[145] Emma Foehringer Merchant, "Can Updated Tax Credits Bring Carbon Capture into the Mainstream?," Greentech Media, February 22, 2018, https://www.greentechmedia.com/articles/read/can-updated-tax-credits-make-carbon-capture-mainstream#gs.wljfACQ.

[146] James Temple, "The Carbon-Capture Era May Finally Be Starting," *MIT Technology Review*, February 20, 2018, https://www.technologyreview.com/s/610296/the-carbon-capture-era-may-finally-be-starting/.

[147] Ibid.

[148] Ibid.

[149] Hadad, Iron & Steel Manufacturing in the US.

[150] Miller, Cement Manufacturing in the US.

[151] Slag Cement Association, LEED Certification, https://www.slagcement.org/sustainability/leedcertification.aspx (accessed Oct. 2018).

[152] WorldSteel Association, Steel in Automotive (accessed September 2018), https://www.worldsteel.org/steel-by-topic/steel-markets/automotive.html.

[153] Compund Annual Growth Rate (CAGR) is defined as the mean annual growth rate of an investment over a specified period of time longer than one year.

[154] IEA Technology Roadmap: Low-Carbon Transition in the Cement Industry (summary).

[155] Hadad, Iron & Steel Manufacturing in the US.

[156] Eren Cetinkaya et al Petrochemicals 2030: Reinventing the Way to Win in a Changing Industry.

[157] IEA, Technology Roadmap Energy and GHG Reductions in the Chemical Industry via Catalytic Processes.