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Decarbonization of industrial sectors: the next frontier

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Preface

The industrial sector is a vital source of wealth, prosperity, and social value on a global scale. Industrial companies produce about one-quarter of global GDP and employment, and make materials and goods that are integral to our daily lives, such as fertilizer to feed the growing global population, steel and plastics for the cars we drive, and cement for the buildings we live and work in.

Industry also emits about 28 percent of global greenhouse gas (GHG) emissions, of which 90 percent are carbon dioxide (CO_2) emissions. Between 1990 and 2014, GHG emissions from major sectors such as buildings, power, and transport increased by 23 percent (0.9 percent per year), while emissions from the industrial sector increased by 69 percent (2.2 percent per year). Over the last decades, the outlines of energy transition pathways have emerged in the buildings, power and transport sectors. These have been driven by technological breakthroughs and cost reduction. For industrial processes, such pathways are less well-defined.

The energy transition in industry should be viewed in the context of global trends that will impact the demand for and preferred production routes of industrial products. There is an expected growth in resource demand, driven by an increase in middle class consumers of ~3 billion in the coming 20 years, as well as rapid urbanization. This coincides with growing constraints on key resources, such as copper and zinc, and environmental degradation, for instance from air pollution. On top of that, there are technological breakthroughs. Rapid cost reduction in renewable power generation is driving further electrification. New digital technologies are improving productivity. In the light of these demographic, resource, and technological developments, industrial players should reconsider their strategies.

This report provides a global perspective on the energy transition in industry, with a focus on reducing CO_2 emissions from industrial processes in cement, steel, ammonia, and ethylene production. It shows that decarbonization of industry is technically possible through a combination of technical solutions, the optimum mix of which will vary widely between sectors and regions. It also shows that in many cases decarbonized production processes are currently not cost competitive with conventional production technology. In cases such as these, where there is currently an absence of an economic driver, decarbonization would require technological breakthroughs, a further lowering of zero-carbon energy prices, changing customer preferences (willingness to pay) and/or a regulatory push.

This should not be seen as a ground to delay action. We believe that starting now with the decarbonization of industry would lead to better outcomes for individual companies. The long time horizons involved in building or retrofitting industrial sites mean that significant emission reductions can be achieved more efficiently through investment and plans initiated now, with an eye on capitalizing on future developments.

This report offers industrial executives, policy makers, and others a menu of options for decarbonization, along with ideas for how to prioritize and pursue them. We describe the industrial sector's role in the climate challenge and explain how a range of innovative technologies and processes could cut CO_2 emissions from the production of four major industrial commodities: cement, steel, ethylene, and ammonia. We present our analyses of how companies in the four focus sectors might assemble portfolios of decarbonization options that reflect their growth strategies and local conditions near their production sites. Based on these outcomes, we assess the (industrial) investments and changes to the energy system that are required to decarbonize these industrial processes. The report concludes with recommendations for how executives and policy makers can position themselves as industrial decarbonization progresses.

The findings in this report would not have been possible without the valuable input of many industry and energy experts. We are especially grateful to the leaders and members of the Energy Transitions Commission for sharing their views with us, and to Cedric Philibert (IEA), Marco Mensink (Cefic) and Andy Read (Uniper) for sharing their insights. We would also like to thank Energy Insights, McKinsey's global energy market intelligence and analytics group, and a number of colleagues for their support and insights: Peter Berg, Nicolas Denis, Dirk Durinck, Michel van Hoey, Maria Kolobova, Nathan Lash, Timo Leenman, Carlos Mendes, Joris van Niel, and Theo Jan Simons.

The findings presented here represent our own, independent perspective. We share them in the hope of informing public discussion about the decarbonization challenge and helping industrial companies develop effective approaches to decarbonizing their operations.

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Executive summary

In the Paris Agreement of 2015, member states agreed to limit global warming to 2 °C versus pre-industrial levels. This would imply reducing greenhouse gas (GHG) emissions by 80 to 95 percent of the 1990 level by 2050. As industry accounted for about 28 percent of global greenhouse gas emissions in 2014, it follows that these targets cannot be reached without decarbonizing industrial activities. Industrial sites have long lifetimes; therefore, upgrading or replacing these facilities to lower carbon emissions requires that planning and investments start well in advance.

In this report, we investigate options to decarbonize industrial processes, especially in the cement, steel, ethylene, and ammonia sectors. We selected these sectors because they are hard to abate, due to their relatively high share of emissions from feedstocks and high-temperature heat compared to other sectors. We conclude that decarbonizing industry is technically possible, even though technical and economical hurdles arise. We also identify the drivers of costs associated with decarbonization and the impact it will have on the broader energy system.

The industrial sector is both a global economic powerhouse and a major emitter of GHG emissions

The industrial sector is a vital source of wealth, prosperity, and social value on a global scale. Industrial companies produce about one-quarter of global GDP and employment, and make materials and goods that are integral to our daily lives, such as fertilizer to feed the growing global population, steel and plastics for the cars we drive, and cement for the buildings we live and work in.

In 2014, direct GHG emissions from industrial processes and indirect GHG emissions from generating the electricity used in industry made up ~15 Gton CO_2e (~28 percent) of global GHG emissions. CO_2 comprises over 90 percent of direct and indirect GHG emissions from industrial processes. Between 1990 and 2014, GHG emissions from the industrial sector increased by 69 percent (2.2 percent per year),[1] while emissions from other sectors such as power, transport, and buildings increased by 23 percent (0.9 percent per year).[2]

Almost 45 percent of industry's CO_2 emissions result from the manufacturing of cement (3 Gton CO_2), steel (2.9 Gton CO_2), ammonia (0.5 Gton CO_2), and ethylene (0.2 Gton CO_2)—the four sectors that are the focus of this report. In these four production processes, about 45 percent of CO_2 emissions come from feedstocks, which are the raw materials that companies process into industrial products (for example, limestone in cement production and natural gas in ammonia production). Another 35 percent of CO_2 emissions come from burning fuel to generate high-temperature heat. The remaining 20 percent of CO_2 emissions are the result of other energy requirements: either the onsite burning of fossil fuels to produce medium- or low-temperature heat, and other uses on the industrial site (about 13 percent) or machine drive (about 7 percent).[3]

1 Feedstocks are the raw materials that companies process into industrial products. High-temperature heat is defined in this report as a temperature requirement above 500 °C.

2 Based on IEA data from the World Emissions Database © OECD/IEA 2018, IEA Publishing; modified by McKinsey.

3 Breakdown of emissions is defined by the use of various reports and datasets, most importantly IEA, Enerdata, heat and cooling demand, market perspective (JRC 2012), and sector energy consumption flow charts by the US Department of Energy combined with input from experts. Activities up and down the value chain are not included in these numbers and could lead to additional emissions, e.g., transportation of fuel to the production site or incineration of ethylene-based plastics at end of product life.

After breakthroughs in the power, transport, and buildings sectors, industrial decarbonization is the next frontier

Global efforts have driven innovation and the scaling up of decarbonization technologies for the power, buildings, and transport sectors. This has led to major reductions in the costs of these technologies. Examples are the recent reductions in the costs of solar photovoltaic modules and electric vehicles. Less innovation and cost reduction have taken place for industrial decarbonization technologies. This makes the pathways for reducing industrial CO_2 emissions less clear than they are for other sectors.

Besides that, CO_2 emissions in the four focus sectors are hard to abate for four technical reasons. First, the 45 percent of CO_2 emissions that result from feedstocks cannot be abated by a change in fuels, only by changes to processes. Second, 35 percent of emissions come from burning fossil fuels to generate high-temperature heat (in the focus sectors, process temperatures can reach 700 °C to over 1,600 °C). Abating these emissions by switching to alternative fuels such as zero-carbon electricity would be difficult, because this would require significant changes to the furnace design. Third, industrial processes are highly integrated, so any change to one part of a process must be accompanied by changes to other parts of that process. Finally, production facilities have long lifetimes, typically exceeding 50 years (with regular maintenance). Changing processes at existing sites requires costly rebuilds or retrofits.

Economic factors add to the challenge. Cement, steel, ammonia, and ethylene are commodity products for which cost is the decisive consideration in purchasing decisions. With the exception of cement, these products are traded globally. Generally, across all four sectors, externalities are not priced in and the willingness to pay more for a sustainable or decarbonized product is not yet there. Therefore, companies that increase their production costs by adopting low-carbon processes and technologies will find themselves at an economic disadvantage to industrial producers that do not.

Industrial companies can reduce CO_2 emissions in various ways, with the optimum local mix depending on the availability of biomass, carbon-storage capacity and low-cost zero-carbon electricity and hydrogen, as well as projected changes in production capacity

A combination of decarbonization technologies could bring industry emissions close to zero: demand-side measures, energy efficiency improvements, electrification of heat, using hydrogen (made with zero-carbon electricity) as feedstock or fuel, using biomass as feedstock or fuel, carbon capture and storage (CCS), and other innovations.[4]

The optimum mix of decarbonization options depends greatly on local factors. The most important factors are access to low-cost zero-carbon electricity and access to a suitable kind of sustainably produced biomass, because most processes in the focus sectors have significant energy- and energy-carrier-related feedstock requirements that could be replaced by one or both of these alternatives. The local availability of carbon storage capacity and public and regulatory support for carbon storage determine whether CCS is an option. The regional growth outlook for the four focus sectors matters, too, because certain decarbonization options are cost effective for use at existing (brownfield) industrial facilities while others are more economical for newly built (greenfield) facilities.

[4] Other innovations can be non-fossil-fuel feedstock change (e.g., alternatives for limestone feedstock in cement production) and other innovative processes (e.g., reduction of iron ore with electrolysis).

Since the optimum combination of decarbonization options will vary greatly from one facility to the next, companies will need to evaluate their options on a site-specific basis. To help industrial companies narrow down their options and focus on the most promising ones, we offer the following observations, which account for current commodity prices and technologies:

- **Energy efficiency improvements can reduce carbon emissions competitively, but cannot lead to deep decarbonization on their own.** Energy efficiency improvements that lower fuel consumption by 15 to 20 percent can be economical in the long run. However, depending on the payback times on energy efficiency required by companies (sometimes less than two years), implementation can be less than the potential of 15 to 20 percent.

- **Where carbon-storage sites are available, CCS is the lowest-cost decarbonization option at current commodity prices.** However, CCS is not necessarily a straightforward option for decarbonization. CCS imposes an additional operational cost on industrial companies, whereas further innovation could make alternative decarbonization options (for example, electrification of heat) cost competitive vis-à-vis conventional production technology. CCS can only be implemented in regions with adequate carbon-storage locations, and supportive local regulations and public opinion. CCS has the distinction of being the only technology that can currently fully abate process-related CO_2 emissions from cement production.[5]

- **At zero-carbon electricity prices below ~USD 50/MWh, using zero-carbon electricity[6] for heat or using hydrogen based on zero-carbon electricity becomes more economical than CCS.** Electricity prices below USD 50/MWh have already been achieved locally (e.g., hydro and nuclear based power-system of Sweden) and could be achieved in more places with the current downward cost trend in renewable electricity generation. The minimum price that makes it less expensive to switch to zero-carbon electricity than to apply CCS for decarbonization depends strongly on the sector, local fossil fuel and other commodity prices and the state of the production site.
  - » At electricity prices below ~USD 50/MWh, electrifying heat production at greenfield cement plants is more cost-competitive than applying CCS to the emissions from fuel consumption, provided that very-high-temperature electric furnaces are available.[7,8]
  - » At electricity prices below ~USD 35/MWh, hydrogen use for greenfield ammonia and steel production sites is more cost-competitive than applying CCS to conventional production processes.
  - » At electricity prices below ~USD 25/MWh, electrification of heat in greenfield ethylene production and in brownfield cement production and usage of hydrogen for brownfield steel production are more cost-competitive than applying CCS to conventional production processes.
  - » Finally, below an electricity price of ~USD 15/MWh, usage of hydrogen for brownfield ammonia production and electrification of heat for ethylene production are more cost-competitive

[5] At the current state of technology, process emissions from cement production can only be abated by a change in feedstock. Alternatives for the conventional feedstock (limestone) are not available (yet) at scale. Hence, decarbonizing cement production currently relies on CCS.

[6] The zero-carbon electricity price should be the average wholesale industrial end user price,so including, e.g., transmission, distribution, and storage costs.

[7] Electrification of very-high-temperature heat (>1,600 °C) required in cement production would require research, as these temperatures are not yet reached in electric furnaces.

[8] Process emissions from cement production cannot be abated by a fuel change and therefore require CCS, irrespective of electricity prices.

than applying CCS to conventional production processes. This means that electric heat production and usage of electricity to make hydrogen are more economical approaches to decarbonization than CCS in all four focus sectors at this electricity price level.

Lower costs for capital equipment or process innovations could make electrification or the use of zero-carbon electricity based hydrogen economical at higher electricity prices.

- Using biomass as a fuel or feedstock is financially more attractive than the electrification of heat or the use of hydrogen in cement production and at electricity prices above ~USD 20/MWh in steel production. Mature technologies are available for using biomass as fuel and feedstock in steel and as fuel in cement production. These technologies reduce emissions more economically than CCS on the conventional process. Biomass can also replace fossil fuel feedstocks for ethylene and ammonia production. Though this approach costs more than electrification or hydrogen usage, it also abates emissions in both the process and at end-of-life of the product, such as the emissions from incineration of plastics made from ethylene. The global supply of sustainably produced biomass, however, is deemed limited at the global level. Additionally, re-forestation to generate offsets might be a counter use of biomass rather than the shipping and usage in industrial processes.

- Demand-side measures are effective for decarbonization but were not a focus of this report. Replacing conventional industrial products with lower-emission alternatives (e.g., replacement of cement with wood for construction) would result in significant reductions in CO_2 emissions from the four focus sectors. Radical changes in consumption patterns driven by technology changes could further offset demand, such as reduced build-out of roads (and therefore cement) through autonomous driving, or reduced demand for ammonia through precision agriculture. Moreover increasing the circularity of products, by e.g., recycling or reusing them can also cut CO_2 emissions. Producing material based on recycled products generally consumes less energy and feedstock than production of virgin materials. As an example, producing steel from steel scrap requires only about a quarter of the energy required to produce virgin steel.

Industrial decarbonization will require increased investment in industrial sites and has to go hand in hand with an accelerated build-out of zero-carbon electricity generation

Completely decarbonizing the energy-intensive industrial processes in the four focus sectors will have a major impact on the energy system. It is estimated that it would require ~25 EJ to 55 EJ per year of low-cost zero-carbon electricity. In a business-as-usual world, only 6 EJ per year would be needed, indicating that, regardless of the mix of decarbonization options chosen, electricity consumption will go up significantly. The transition in the power and industrial sectors should thus go hand in hand. The industrial sector might be able to lower the costs of the power sector transition, e.g., by providing grid balancing, while being a large off-taker that can support increased build-out of generation capacity.

The total costs of fully decarbonizing these four sectors globally are estimated to be ~USD 21 trillion between today and 2050. This can be lowered to ~USD 11 trillion if zero-carbon electricity prices come down further compared to fossil fuel prices.[9] These estimates are based on cost assumptions that do not allow for process innovations or significant reductions in the costs of capital equipment. Furthermore, they heavily depend on the emission reduction target, local commodity prices, the

[9] These total costs include all capital and operational costs on industrial sites, but exclude other costs, e.g., build-out of zero-carbon electricity generation capacity.

selected mix of decarbonization options, and the current state of the production site. The estimated costs for complete decarbonization of the four focus sectors are equivalent to a yearly cost of ~0.4 to 0.8 percent of global GDP (USD 78 trillion). According to the estimations in this report, about 50 to 60 percent of these costs consists of operating expenses and the remainder consists of capital expenditures, mainly for cement decarbonization.

An analysis of the effects of different electricity prices suggests that decarbonization would have an upward impact on the costs of the industrial products: cement doubling in price, ethylene seeing a price increase of ~40 to 50 percent, and steel and ammonia experiencing a ~5 to 35 percent increase in price.[10]

Advance planning and timely action could drive technological maturation, lower the cost of industrial decarbonization and ensure the industry energy transition advances in parallel with required changes in energy supply

- Governments can develop roadmaps for industrial decarbonization on local and regional levels. Setting such a longer-term direction for decarbonization could support planning for decarbonization by other parties, including industrial companies, utilities and owners of key infrastructure (such as the electricity grid or hydrogen pipelines), and unlock investments with long payback times. Such a roadmap should take a perspective, e.g., on the production outlook, resource availability (including carbon-storage sites), additional resources required (zero-carbon electricity generation, etc.), coordinated roll-out of infrastructure and demand-side measures, as well as the role government would play (e.g., in the development of critical infrastructure).

- Adjust regulation and incentives in line with decarbonization roadmaps. Various policy mechanisms could support industrial decarbonization. These might include direct incentives for companies to decarbonize, or adjustments to the financial requirements placed on utilities and other companies involved in energy generation and distribution.

- Industrial companies should prepare for decarbonization by conducting a detailed review of each facility in their portfolio. Such a review should include the availability of low-cost zero-carbon electricity, zero-carbon hydrogen, biomass, and carbon-storage capacity near the facility as these will differ on a country-by-country basis. Interaction with other stakeholders, such as governments, utilities, and other industrial companies, could help to identify synergies between industrial decarbonization and decarbonization in other sectors or companies, driving targeted innovation and driving down costs. For example, companies in an industrial cluster might benefit from shared carbon-storage infrastructure.

- Governments, industrial companies, and research institutions can support innovation and the scale up of promising decarbonization technologies, which is required to reach full decarbonization of the industrial sector. Innovative decarbonization technologies could potentially lower the costs of the industry transition. Governments can support the development of innovative decarbonization options, including the scale up of global markets, e.g., in certain types of biomass, or the introduction of innovative processes to lower implementation costs. Overall, decarbonizing industrial sectors requires collaboration across governments, industrial players, and research institutes, similar to the effort that led to the cost reduction and scale up of renewable energy generation.

[10] Conventional prices assumed are: cement USD 120/ton, steel USD 700/ton, ammonia USD 300/ton and ethylene USD 1,000/ton.

1 Industry’s role in the climate challenge

The industrial sector's GHG emissions are commensurate with its contributions to global well-being. Industry produces about one-quarter of global GDP and employment, along with roughly one-quarter of the world's GHG emissions. CO_2 is the most significant GHG emitted as a result of industrial activity. Almost half of this CO_2 comes from the production of four commodities: cement, steel, ammonia, and ethylene. These four sectors are the focus of this report.

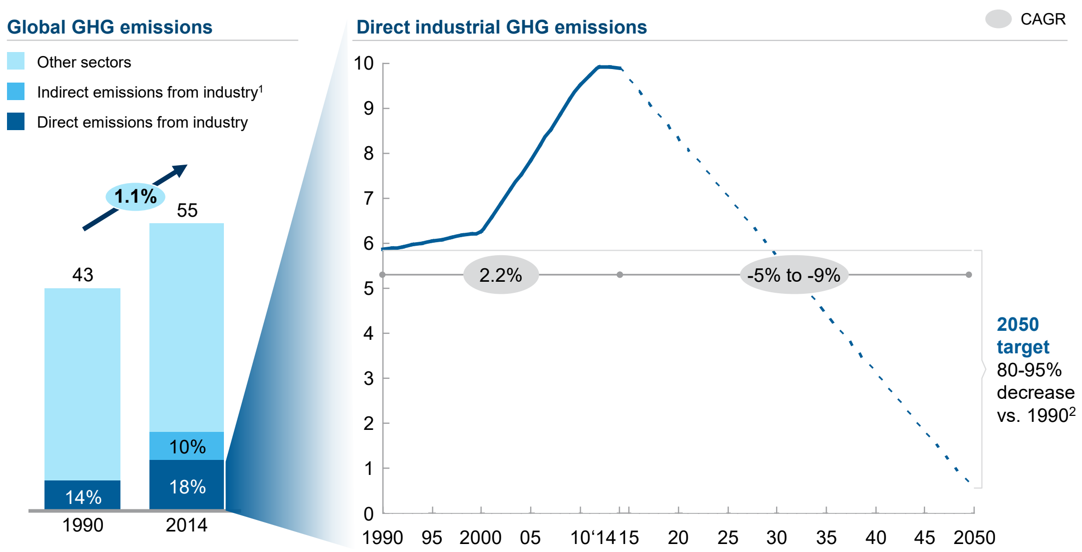
Industrial emissions in a global context

The industrial sector accounts for a significant share of global GHG emissions. From 1990 to 2014, industry's direct GHG emissions increased about 70 percent, or 2.2 percent per year on average. This was faster than global GHG emissions, which increased by 30 percent, or 1.1 percent per year on average.[11] During the same period, industry's economic output increased slightly faster than its GHG emissions, resulting in a 5 percent reduction of direct GHG emissions per unit of economic output from 1995 to 2014. Direct GHG emissions from industrial processes, along with indirect GHG emissions resulting from the generation of electricity used by industry, accounted for 28 percent (~15 Gton CO_2e) of global GHG emissions in 2014 (Exhibit 1).[12]

Exhibit 1

Direct and indirect industrial emissions (28 percent of global CO_2e emissions) require turnaround from growth to a steep decline to reach 2050 targets

Gton CO_2e/yr



NOTE: CO_2 emission from fuel combustion in manufacturing industries and construction included, as well as industrial process emissions. Data available until 2014

1 Indirect emissions from industry are emissions related to central power generation for electricity used in the industrial sector

2 Implied by 2015 Paris agreement targets

SOURCE: IEA World CO_2 Emissions from Fuel Combustion © OECD/IEA 2017 IEA Publishing

[11] Up-to-date GHG emissions data are not available yet. 2016 emissions data are expected to be released by the IEA after the publication of this report. 2014 is therefore used in this report as a base year for GHG emissions from industry.

[12] This includes ~10 Gton CO_2e direct emissions and ~5 Gton CO_2e indirect emissions. Indirect emissions are based on 31 EJ electricity consumption in industrial sectors and the average carbon intensity of electricity generation. This excludes GHG emissions from adjacent activities, such as transportation of industrial feedstocks and products.

Because industrial output is projected to grow until 2050, the sector could face challenges in simultaneously meeting the emission reduction targets implied by the Paris Agreement of 2015. The agreement among 195 UN member states calls for preventing average global temperatures from rising 2 °C, and ideally limiting the average temperature rise to 1.5 °C. Achieving these goals would require an 80 to 95 percent reduction of global GHG emissions by 2050, as compared to 1990 levels.

Bringing about emission reductions on this scale will be a large undertaking for both the industrial sector and the energy system as a whole. It will require a massive reconfiguration of industrial activity, affecting the energy and resources that companies require for production, the production processes they use, and the controls they place on their facilities.

We have focused this report on opportunities to mitigate industry's largest flows of GHG emissions, which are CO_2 emissions from the production of cement, steel, ammonia, and ethylene. In this chapter, the breakdown of current industrial energy use and emissions is described. In Chapter 2, the challenges regarding decarbonizing industrial sectors are discussed. In Chapter 3, technological options for decarbonization are outlined, including related costs and (technical) limitations. In Chapter 4, these options are specified by sector. In Chapter 5, the implications of the deep decarbonization of industrial sectors on investments and energy demand are analyzed. Finally, in Chapter 6, a way forward is discussed, describing the roles that industrial companies, governments, innovative players, and utilities can take in the effort to decarbonize industrial sectors.

CO_2 emissions in industrial sectors

CO_2 is the most significant GHG emitted as a result of industrial activity

CO_2 comprised more than 90 percent (~10 Gton CO_2) of direct GHG emissions from industrial processes in 2014. Less than 10 percent of industry's direct emissions consist of GHGs other than CO_2: methane (e.g., from black carbon production), fluorinated gases (used in refrigeration), and nitrous oxide (e.g., from the production of glyoxylic acid and nitric acid).

Since the vast majority of industry's direct GHG emissions come in the form of CO_2, and the reduction options for non-CO_2 emissions are very specific to industrial activities (e.g., refrigeration), this document will focus on options for reducing CO_2 emissions. The largest sectors in terms of CO_2 emissions and energy consumption are non-metallic minerals, iron and steel, and chemicals. Both because of the relative size of these sectors and for several technical reasons that will be explained in Chapter 2, this report will focus on decarbonizing the production processes of four key commodities in these sectors: cement, steel, ammonia, and ethylene.

Cement, steel, ammonia, and ethylene are the industrial commodities whose production generates almost 45 percent of industry's direct and indirect CO_2 emissions

Production of cement, steel, ammonia, and ethylene emitted 6.5 Gton CO_2 globally in 2015, which equates to ~15 percent of global CO_2 emissions. Cement production (~80 percent of non-metallic mineral sector emissions) is the largest source of CO_2 emissions (~3 Gton CO_2/yr), followed by production of iron and steel (~2.9 Gton CO_2/yr). In the chemicals sector (~2.1 Gton CO_2/yr), significant amounts of CO_2 emissions result from the production of ammonia (~0.5 Gton CO_2/yr) and ethylene (~0.2 Gton CO_2/yr).[13]

[13] Ethylene production also yields other chemicals, such as propylene and aromatics. When ethylene production is discussed in this report, the emissions and energy/feedstock demand from the production of other products in the same process (e.g., propylene, aromatics) are included as well.

In these subsectors, about 45 percent of direct and indirect CO_2 emissions come from the processing of feedstocks

Feedstocks are the raw materials that industrial companies process into products. In certain production processes, the processing of certain feedstocks will lead to CO_2 emissions. For example, the calcination of a feedstock mineral, limestone, is a production step in cement fabrication that produces CO_2 emissions. Some feedstocks are energy carriers, such as natural gas, a feedstock for ammonia production that emits CO_2 during production. Some feedstocks do not emit CO_2 during processing. An example is the oil-based feedstock that is used for ethylene production. In that process, called steam cracking, there are no process emissions. The carbon present in the feedstock mostly ends up in the products, monomers, which are the raw materials for plastic production.

Another 35 percent of direct and indirect CO_2 emissions in these subsectors come from fuels that are combusted to generate high-temperature heat

Two-thirds of energy-related emissions come from producing high-temperature heat (above 500 °C). High-temperature heat is needed for specific processes such as steam cracking to produce ethylene (~800 °C), the melting of iron ore[14] for producing steel or the rolling of steel (~1,200 °C),[15] and the calcination of limestone (~1,400 °C).

The remaining 20 percent of emissions from these production processes are generated by other modes of energy consumption

Medium-temperature heat (100-500 °C) is generally produced using gas- or coal-fired steam or heating oil boilers. Low-temperature heat (below 100 °C) is either derived from the waste heat from higher temperature processes or produced using boilers. Together with other modes of energy consumption, such as the heating and cooling of buildings, these account for 13 percent of emissions. The remaining emissions are in machine drive e.g., for grinding feedstocks in cement production or running compressors.

Emissions from feedstock or fuel production and from the handling of industrial products at end-of-life are not included in direct or indirect industry emissions

The production of feedstocks and fuels generates emissions, such as those stemming from the transportation of fuel and feedstock to the industrial site. There are also emissions from products during use or at end-of-life. For example, up to ~0.6 Gton CO_2 is emitted each year by the incineration of goods (mostly plastics) made from ethylene. Neither emissions up or down the value chain nor end-of-life emissions are included in direct or indirect industry emissions, although these emissions can be reduced by changing the fuel or feedstocks used in industrial processes.

[14] Iron ore is Fe_2O_3.

[15] In the most common process used to produce steel from iron ore (blast furnace-blast oxygen furnace or BF-BOF), coal is both a fuel for high-temperature heat and a feedstock. In the blast furnace, coal is transformed from C to CO, which produces heat. Then part of the CO is transformed into CO_2 by reducing the iron ore (Fe_2O_3) to iron (Fe). Not all of the CO is used for reduction or iron ore in the blast furnace. Some is used elsewhere on the steel production site, mostly for high-temperature process heating and some for on-site power production. On top of its use as feedstock and fuel, coal is required for the stability of the content of the blast furnace. It is assumed that 40 percent of emissions in the blast furnace are from coal use as a feedstock (so as a reductant), and the remainder are from coal use for high-temperature heat.

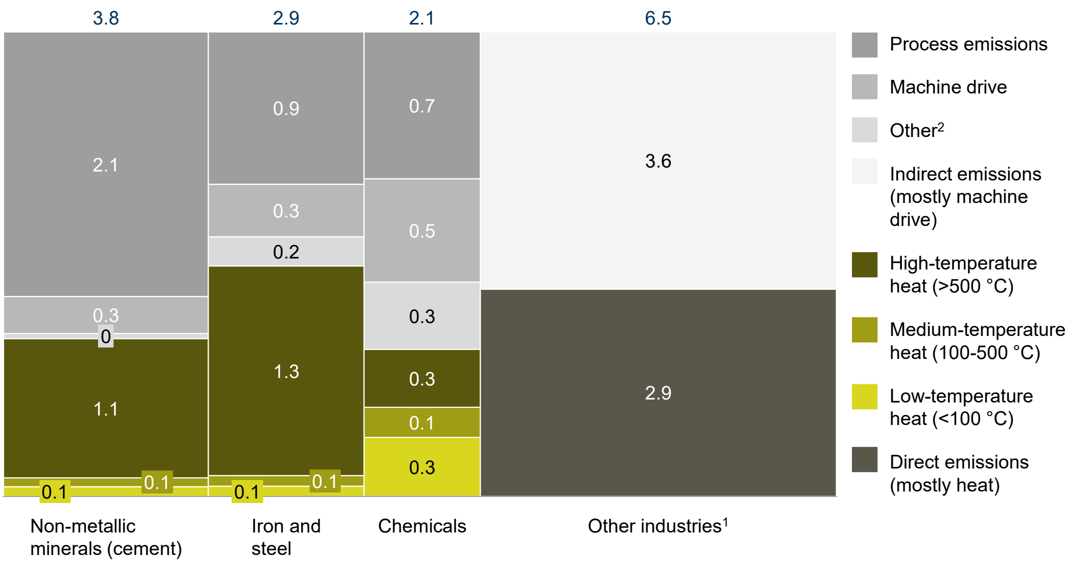
In other industrial sectors, about a third of energy used is electricity, and the remainder of energy consumption is mostly for low- and medium-temperature heat

Besides non-metallic minerals, iron and steel, and chemicals, other industrial sectors also have an impact on global GHG emissions. The largest of these in terms of energy consumption are: food and tobacco; paper, pulp, and print; and nonferrous metals. In all other industrial sectors, about a third of energy consumption and almost 55 percent of CO_2 emissions are from the consumption of centrally produced electricity (indirect emissions). Furthermore, most energy consumed is (and hence most emissions stem from) natural gas and coal for low- (0 to 100 °C) and medium- (100 to 500 °C) temperature heat demand. There are exceptions, such as the high-temperature heat demand in the nonferrous metals sector, which is supplied by electricity. The majority of biomass energy used in other industrial sectors is in the paper and pulp and food and tobacco sectors. (Exhibit 2)

Exhibit 2

40% of emissions in industry are related to fuel combustion for heat

Gton CO_2/yr per emission source, 2014



NOTE: Differences in totals due to rounding
1 Includes food and tobacco, construction, mining, machinery, nonferrous metals, paper and pulp, transport equipment, textiles and leather, wood and miscellaneous industry
2 Includes emissions related to electrochemical processes, process refrigeration and cooling, and all emissions from nonprocess energy use, such as on-site transport and facility HVAC
3 This graph does not differentiate in emissions source for other industries

SOURCE: IEA data from World Energy Statistics © OECD/IEA 2017 IEA Publishing; Enerdata: global energy and CO_2 data; expert interviews

Coal is a major industrial fuel and feedstock

Coal is the source of a third of the energy used in industry globally. It provides 70 percent of the energy used in steel and cement production. In the steel sector, coal is used both as a feedstock (reductant of iron ore to steel) and as a fuel (e.g., for melting iron ore and producing on-site power).[16] In the cement sector, coal provides fuel for cement kilns and on-site power production.

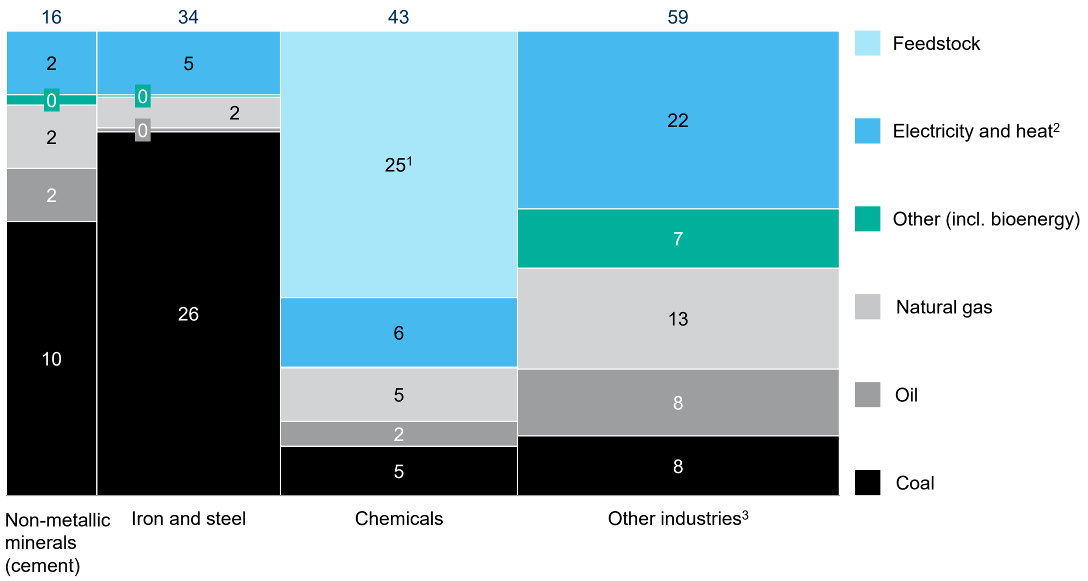
[16] In China, coal is used as feedstock for ammonia and methanol production (instead of natural gas). As a first step in those production processes, coal is converted into syngas (a mix of hydrogen and CO) in a process called coal gasification.

In the production of chemicals, most fuels are used as feedstocks. Ethylene production consumes 18 EJ worth of energy-carrier feedstocks per year, mostly in the form of petroleum- or natural gas-based products such as naphtha, ethane, and LPG. Methanol and ammonia production takes up 7 EJ worth of energy-carrier feedstocks per year, mostly natural gas. (Exhibit 3)

Exhibit 3

Coal use accounts for 44% of energy consumption in non-metallic minerals, iron and steel, and chemicals

EJ/yr final energy consumption, 2015



NOTE: Differences in totals due to rounding
1 Feedstock consists of oil (18 EJ) and natural gas (7 EJ) 2 Electricity sourced from the power grid. Heat from an external source
3 Nonferrous metals; transport equipment; machinery, mining, and quarrying; food and tobacco; paper, pulp and print; wood and wood products; textile and leather, construction, non-specified industry

SOURCE: Based on IEA data from World Energy Statistics © OECD/IEA 2017 IEA Publishing; McKinsey analysis

A regional perspective on reducing industrial CO_2 emissions

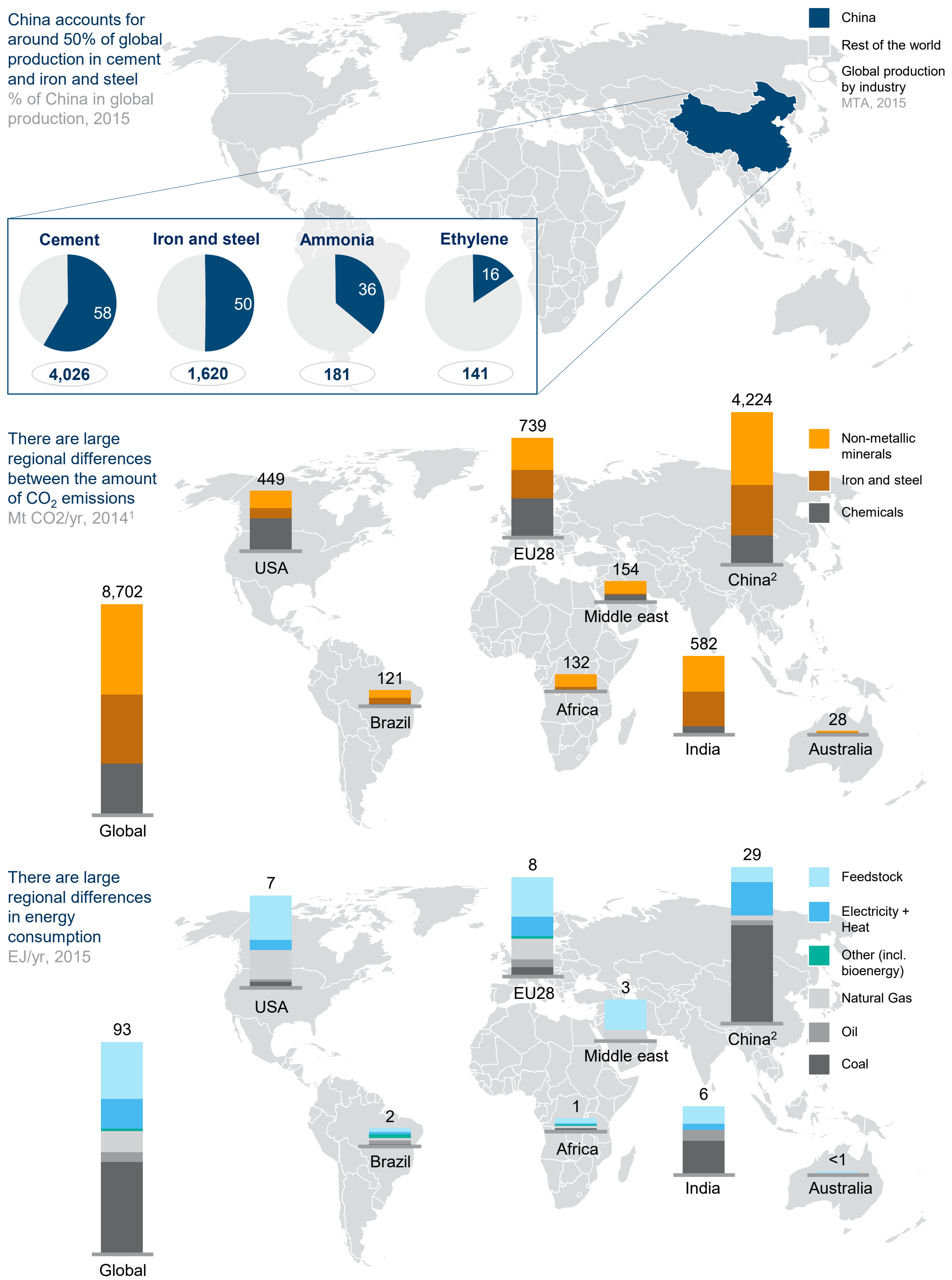
Industry decarbonization will play out differently in different regions. China will play a pivotal part in the effort to reduce industrial emissions, as it accounts for a large share of production and CO_2 emissions in the four focus sectors. According to McKinsey's Basic Materials Institute, facilities in China produce half of the world's cement, iron, and steel and small but still significant shares of ethylene (16 percent) and ammonia (36 percent). While Chinese facilities account for only 30 percent of the energy used in these sectors, their extensive use of coal as a primary source of energy enlarges their emissions footprint. Producers in other countries, who rely more on gas for heat production, produce 55 percent less CO_2 emissions per unit of energy consumed for heat. Also, 60 percent of cement emissions are process emissions, which are not related to energy consumption.

Looking forward, this picture should change somewhat. China will remain the largest producer of cement, steel, and ammonia, but its share of global production will be smaller. China's steel and cement production is expected to decline through 2050, as the rate of construction slows. Ammonia and ethylene production by Chinese facilities is expected to almost double until 2050, in line with the country's projected increases in GDP and population.

The largest increases in industrial production are expected to occur in India and Africa. Projected increases for these regions include a tripling of production capacity in cement and steel by 2050 and similar growth (though from a smaller base) for ammonia and ethylene.

Efforts to decarbonize the four focus sectors will therefore need to include existing and new production sites in China and new production sites in Africa and India. Besides this, existing sites in developed regions should also participate to a significant extent in decarbonization. (Exhibit 4)

Exhibit 4



1 2014: Africa, Australia, Middle East, EU28; 2015: Brazil, China, India, USA
2 Global and China bar graph not on same scale as other regions/countries

SOURCE: Based on IEA data from World Energy Statistics © OECD/IEA 2017, IEA Publishing; Enerdata: Global Energy and CO_2 Data, McKinsey Basic Materials institute, ICIS, IFDC

2 The next frontier

Global efforts have driven innovation and the scaling up of decarbonization-technology usage in buildings, power, and transport sectors. In turn, these developments have led to major reductions in the costs of associated technologies, such as those recently seen in solar photovoltaic modules, wind turbines, and electric vehicles. Less innovation and cost reduction have taken place for industrial decarbonization technologies. This makes the pathways for reducing industrial CO_2 emissions less clear than they are for other sectors. Therefore, both the technological and the broader economic challenges of decarbonization seem bigger for industry.

Cost decreases in zero-carbon electricity generation drives energy transition pathways in power, buildings and transport sectors, making industry the next frontier

In the power, buildings, and transport sectors, economical options for decarbonization exist or are being developed. Equipment costs for generating energy from renewable sources have fallen significantly in the last five years: by around 80 percent for solar PV installations, and by about 40 percent for onshore wind installations. This was kick-started by targeted governmental support schemes and has led to rapid growth, and therefore further cost reductions.

As a result, electrification is becoming a viable option for decarbonizing some activities in the buildings and transport sectors in addition to other energy efficiency improvements such as insulation of buildings and lower energy use by appliances. In both of these sectors, electric equipment is more energy efficient than equipment powered with hydrocarbon fuels. In buildings, for example, a heat pump for low-temperature space heating can have an efficiency of ~200 to 400 percent versus a fossil-fuel boiler efficiency of only ~95 percent. This means that from an operational perspective electrification is usually economical even at higher electricity prices.

This also holds for the transport sector. Electric drivetrains are more efficient than conventional internal-combustion engines for passenger vehicles. The total cost of ownership of an electric passenger vehicle and for a vehicle powered by an internal-combustion engine should be nearly the same within the next five years. Before 2030, even electric long-haul heavy-duty trucks could reach cost parity with internal-combustion-engine models, and hydrogen-powered vehicles could be viable for the same segment.

This is different in industrial applications. Industry can in principle benefit from the zero-carbon electricity price decline just as the other sectors do. However, industrial electrification generally does not see the efficiency gains that are driving the technology uptake in other sectors and therefore requires lower electricity versus fossil fuel prices to be economical. For example, electric boilers and furnaces for industrial use are expected to have a similar efficiency as hydrocarbon-fueled boilers and furnaces. Also, the capital costs of these types of electrical equipment are similar or higher than the conventional alternative. Hence, electrification of heat production in industry is only economical when electricity costs the same, per unit of energy, as the conventional fossil fuel alternative.

Several technical and economical factors currently inhibit the reduction of CO_2 emissions in the focus sectors

It is difficult to abate CO_2 emissions from cement, steel, ammonia, and ethylene production for four technical reasons: (Exhibit 5)

1. The processing of feedstocks generates about 45 percent of CO_2 emissions in the focus sectors. These emissions can only be reduced by changing feedstocks or processes, rather than changing to low-carbon energy sources. Feedstocks can be related to fossil fuels (such as natural gas for ammonia production), but in other cases (such as limestone feedstock for cement production), they are not.

2. These sectors have a large demand for high-temperature heat (in the focus sectors the high-temperature heat demand ranges from 700 °C to over 1,600 °C which generates 35 percent of CO_2 emissions). To replace the fossil fuel for heat generation with electricity or hydrogen requires a significant change in the production process and development of alternative furnace designs. Up to ~1,000 °C, adaptation and scale up of electric furnace technology is needed. For temperatures above ~1,000 °C, such as required for cement production, research is required to develop industrial-scale electric furnaces.

   The use of hydrogen fuel for high-temperature heat also poses technical challenges. For industrial-scale, very-high-temperature applications such as cement production (>1,600 °C) in particular, safety considerations and a differen ce in heat transfer from hydrogen burners versus fossil fuel burners require a redesign of furnaces and/or mixing of hydrogen with steam or heating oil.

3. Given the deep integration of these industrial processes, any change to one part of the process will have to be accompanied by changes to other parts of the process. For example, if an ethylene steam cracking furnace is electrified, this will eliminate some of the excess heat that is now used to make high-pressure steam to drive compressors and turbines later in the production process. Electrification of the furnace therefore necessitates adjustments to other stages of ethylene production.

4. Industrial production sites, especially in the four focus sectors, typically have lifetimes exceeding 50 years, with regular maintenance. ArcelorMittal's steel plant in Ghent, for example, has operated for some 50 years and is not expected to reach end-of-life in the foreseeable future. Changes in the equipment or processes at existing sites require capital-intensive rebuilds or retrofits, whereas new sites can more economically implement these decarbonization measures.

The economics of the four focus sector industries adds to the challenge of reducing their CO_2 emissions. The most significant economic factors are the following:

5. Ammonia, ethylene, and steel are traded globally (cement is not). Companies or countries that increase their costs of production by adopting low-carbon processes and technologies will find themselves at a cost disadvantage to industrial producers that do not.

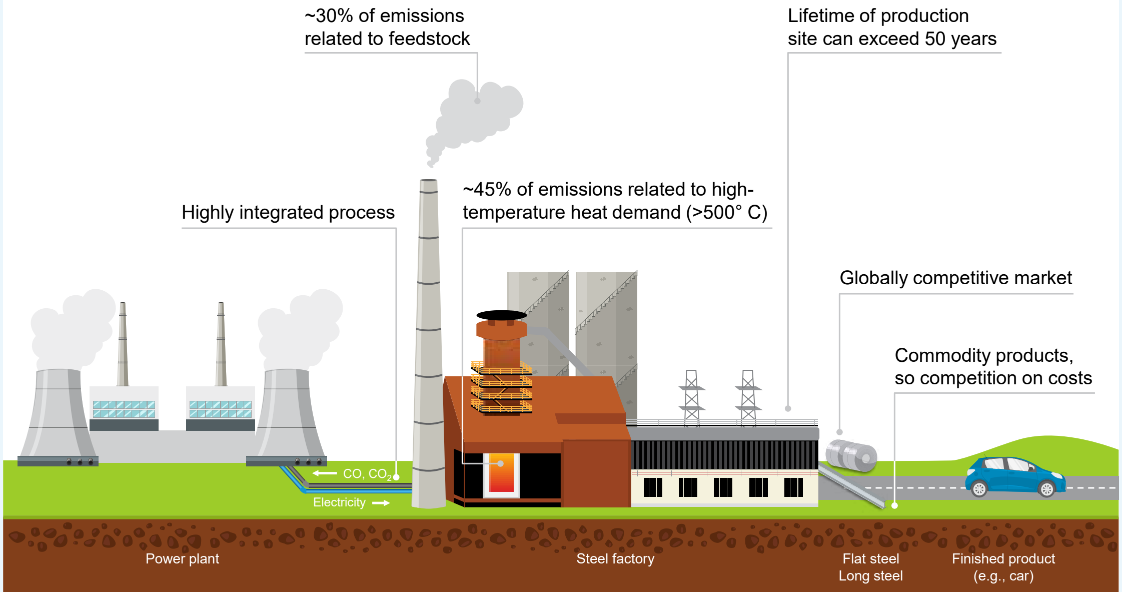
6. The products made in the four focus sectors are commodities, for which cost is the decisive consideration in purchasing decisions. Companies in the four focus sectors therefore compete mainly on price, so implementing decarbonization options that increase the cost of production will put them at a disadvantage.

On the positive side, compared to other sectors such as transport or buildings, there is a relatively small number of point emitters in the four focus sectors. This means that a large decarbonization effort can be carried out with a smaller, more focused group of stakeholders and sites.

Exhibit 5

Why are the steel, cement, ammonia, and ethylene sectors hard to abate?

Steel process example



SOURCE: IEA data from World Energy Statistics © OECD/IEA 2017 IEA Publishing; Enerdata: global energy and CO_2 data; expert interviews

3 Options for decarbonizing industry

Industrial companies can reduce their CO_2 emissions in various ways. Their decarbonization options span demand-side measures, energy-efficiency improvements, the substitution of fuels and feedstocks, carbon capture, and innovation. Whether these options will be effective and economical will depend on the cost of decarbonized versus conventional commodities, the (local) availability of the resources they require (such as biomass or geological storage space for captured CO_2), and the feasibility of applying them at both new and older facilities.

In this chapter, seven categories of options for the decarbonization of industrial sectors are described, followed by a short overview of the application of these option in sectors. Then, the impact of local conditions on the application of the categories of options is discussed. Lastly, the costs of options per sector are considered.

Decarbonization options

Decarbonization options for the four focus sectors can be grouped into the following categories: (Exhibit 6)

- **Demand-side measures.** Decreasing the demand for an industrial product should lead to lower production and CO_2 emissions. For example, light-weighting can reduce the demand for steel, and cement could be replaced by materials such as wood. In addition, increasing the circularity of products, e.g., by increasing recycling or reuse of plastics and steel, would lessen CO_2 emissions by reducing the production of virgin materials.

- **Energy-efficiency improvements.** Increases in energy efficiency can economically cut fuel consumption for energy use by 15 to 20 percent across sectors.[17] Potential gains in energy efficiency will differ between sectors and facilities. Generally speaking, developed regions will tend to be closer to the low end of that range, and developing regions closer to the high end. Using less fossil energy to make industrial products will lower CO_2 emissions.

- **Electrification of heat.** Emissions from the use of fossil fuels to generate heat can be abated by switching to furnaces, boilers, and heat pumps that run on zero-carbon electricity. Electrifying heat can involve a change in the production processes. For example, to electrify ethylene production, companies need to install both electric furnaces and electrically driven compressors.

- **Hydrogen usage.** Emissions from the consumption of fossil fuel for heat and emissions from certain feedstocks can be abated by changing them for zero-carbon hydrogen. In this report it is assumed that hydrogen is generated by using zero-carbon electricity for the electrolysis of water. For example, ammonia production can be decarbonized by replacing the natural gas feedstock with zero-carbon hydrogen.

[17] Assuming that all NPV-positive options are implemented. Energy efficiency measures can require substantial capex investments. Industrial companies can face tight constraints on deploying capital for non-core purposes and can refrain from pursuing energy efficiency investments if the payback time exceeds two years.

- Biomass usage. Like hydrogen, sustainably produced biomass can be used in place of some fuels and feedstocks. Depending on the fuel or feedstock required, biomass in a solid (wood, charcoal), liquid (biodiesel, bioethanol), or gaseous (biogas) form can be used. For example, steel producers in Brazil use charcoal as a fuel and feedstock instead of coal, and chemical producers in several European countries experiment with bionaphtha in chemicals production.

- Carbon capture. With carbon-capture technology, CO_2 can be collected from the exhaust gases produced by an industrial process and prevented from entering the atmosphere. The CO_2 can be stored underground (CCS) or used as a feedstock in other processes through carbon capture and usage (CCU).

- Other innovations. Besides the decarbonization options listed above, other techniques for carrying out industrial processes could lead to CO_2 emission reductions. For example, alternatives to limestone feedstock could reduce process emissions in cement production. High-temperature chemical processes can also be replaced by electrochemical processes, in which electricity, rather than heat, drives reduction and oxidation reactions.

Exhibit 6

Decarbonization of industry through a "menu" of options that together lead to substantial CO_2 emission reduction

Demand-side measures

Lower the demand for primary resources by increasing circularity (reuse, recycling, or replacement of products)

Energy efficiency

Adapt production equipment to lower energy use per produced volume

Electrification of heat

Replace fossil fuel for heating with renewable electricity, e.g., in ethylene production

Hydrogen as fuel or feedstock

Replace feedstock or fuel with carbon neutral hydrogen, e.g., in ammonia production

Biomass as fuel or feedstock

Replace feedstock or fuel with sustainably produced biomass to reduce CO_2 emissions, e.g., use bio-based feedstock in chemicals production

CCS/CCU

Capture the CO_2 emitted and store (CCS) or use (CCU)

Other innovation

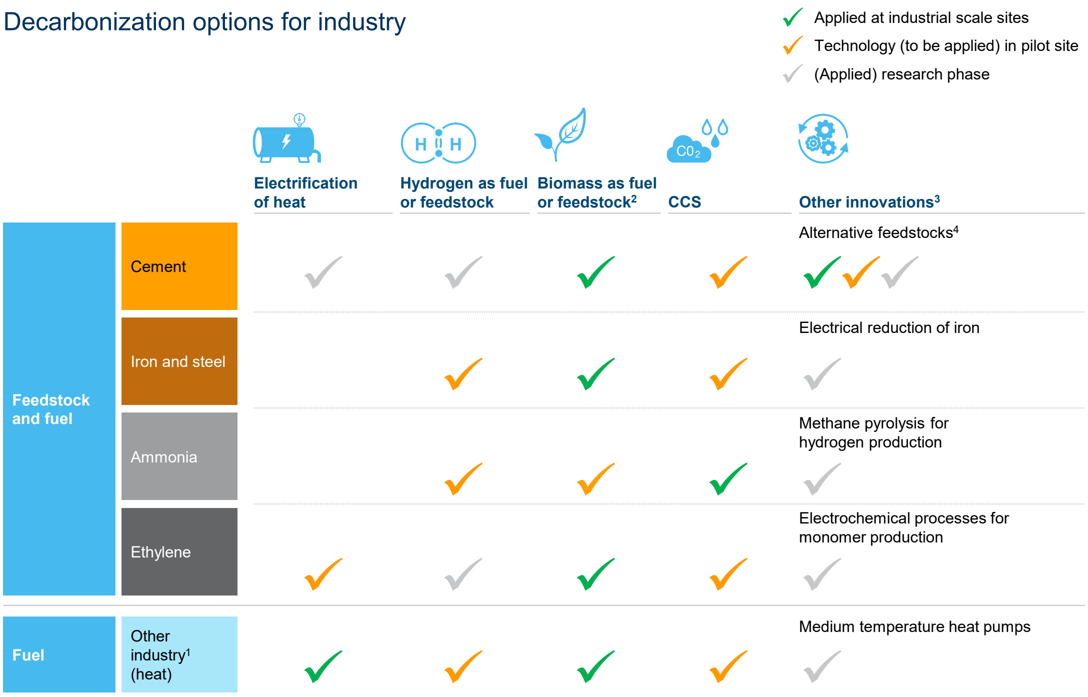
- Innovative processes, e.g., electrochemical production process
- Non-fossil fuel feedstock change, e.g., change in cement feedstock

The range of possible decarbonization options differs for each sector

While biomass and CCS can be used to decarbonize virtually every industrial sector, electrification of heat cannot. In the next chapter, the options for each sector will be specified in more detail. (Exhibit 7)

Exhibit 7

Decarbonization options for industry



1 Includes heat demand in other sectors, such as manufacturing, construction, food and tobacco, etc.
2 Type of biomass depends on the sector and process: Cement (mostly solid or gaseous biomass), Iron and steel (charcoal or biogas), ammonia (biogas), ethylene (biodiesel, sugar, bioethanol)
3 Not exhaustive
4 Technological maturity depends on the type of alternative feedstock

Local characteristics affect the feasibility of decarbonization options

The availability of low-cost zero-carbon electricity, biomass, and carbon-storage locations influences the feasibility of decarbonization options that are based on electrification of heat or hydrogen use, the use of biomass, and carbon storage. Availability varies greatly between locations and therefore between production sites. (Exhibit 8)

Regions that lack CO_2 storage locations, do not have biomass resources, and have electricity prices above USD 50/MWh will likely need to pursue decarbonization options that rely on imported low-carbon resources, such as renewable biomass, hydrogen, or renewable electricity transmitted over long distances. Projected changes in local production volumes for cement, steel, ethylene, and ammonia also influence the feasibility of various decarbonization options within a region.

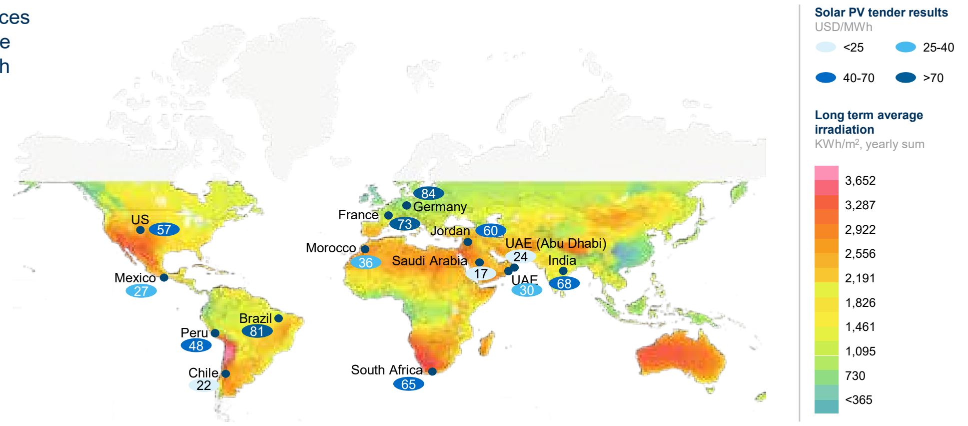
Availability and associated cost of zero-carbon electricity for direct electrification and hydrogen production

The cost of zero-carbon electricity versus the cost of fossil fuel alternatives heavily influences the cost and therefore the attractiveness of decarbonization via electrification or hydrogen (as will be discussed in more detail later in this chapter).

Exhibit 8

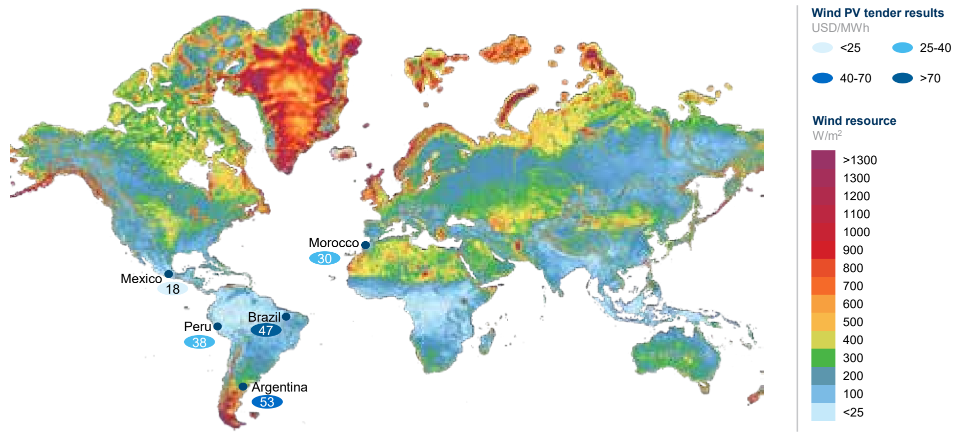
Very low electricity prices for solar PV energy are reached in regions with high insolation

SOURCE: WorldBank



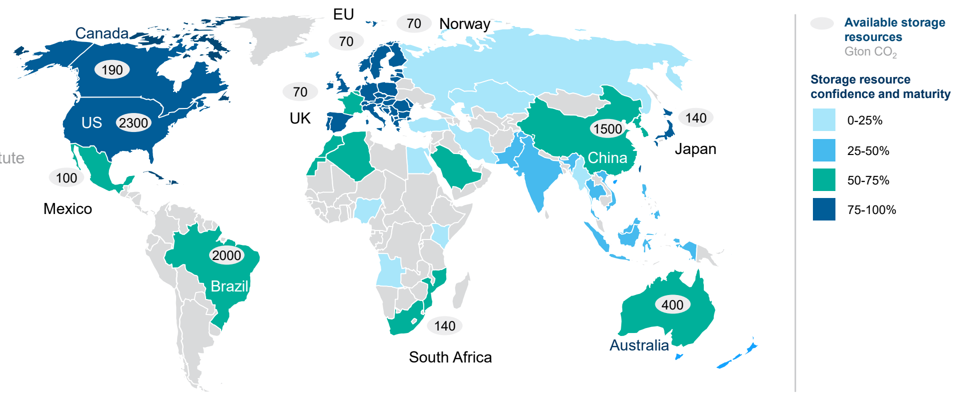
Very low electricity prices for wind energy are reached in highly specific locations

SOURCE: WorldBank



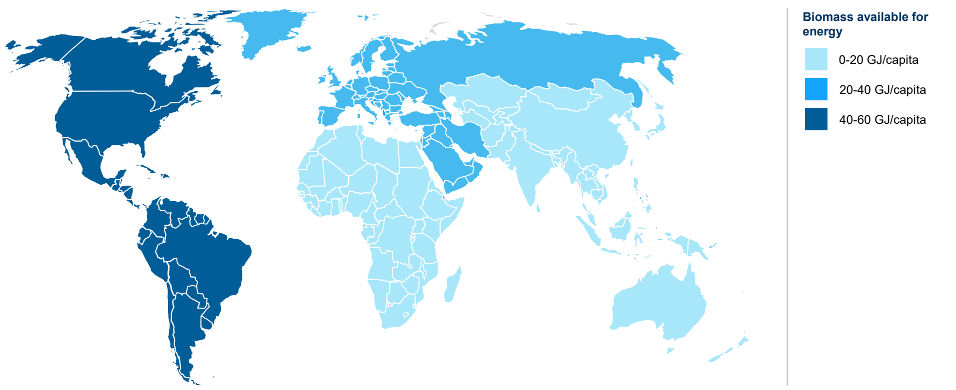
Availability of CO_2 storage resources differs locally

SOURCE: Global CCS Institute



Availability of biomass differs per region

SOURCE: IRENA; UN



In most regions, average prices for zero-carbon electricity for industrial consumers currently exceed USD 50/MWh. However, costs vary greatly between locations. Low zero-carbon electricity prices, sometimes even below USD 50/MWh, tend to be found in regions with extensive hydroelectric resources (such as Scandinavia and Quebec), high onshore wind speeds (such as the central United States), or high levels of solar irradiation (such as Australia, the Middle East, and Chile). Zero-carbon electricity prices are also affected by the costs of transmission and distribution, interconnectivity, backup production capacity, and storage.

Besides average electricity prices, other local factors such as the intermittency and the reliability of the electricity supply will determine if electrification is an attractive decarbonization option for industrial players. When zero-carbon power sources are intermittent (e.g., solar PV) or the power supply is unreliable, power storage could be required. The costs of storing electricity vary with the storage technologies used and the on-site requirements of the production process. Processes that can be started and stopped without much loss of efficiency (for example, low-temperature processes such as hydrogen electrolysis) can be tuned to run only when zero-carbon electricity is abundant and inexpensive. Some processes have enough flexibility in their production rate, and therefore electricity consumption, to be able to adjust production to fluctuating electricity prices or a fluctuating availability. These processes can hence achieve an average electricity price that is lower than processes that should run continuously (for example, high-temperature processes like ethylene steam cracking, or high-pressure processes like the Haber-Bosch process in ammonia production).

Availability and the associated costs of sustainably produced biomass

Sustainably produced biomass can serve as a fuel in all sectors, and as a feedstock for the production of steel (charcoal), ethylene (bioethanol or biodiesel), and ammonia (biogas). By 2030, it is estimated that biomass could supply ~100 to 150 EJ of energy.[18] Therefore, in theory, enough biomass is available to fulfill demand for both feedstocks and fuels in the four focus sectors (estimated to be maximum 90 EJ in 2050). (Exhibit 9)

If the focus sectors were allocated a 'fair share' of the world's biomass, i.e., in proportion to their share of global CO_2 emissions, this would satisfy approximately 15 to 20 percent of their energy and feedstock demand in 2050. This percentage can be higher if the efficiency of biomass consumption is increased. Charcoal-based steel production, for example, has on average ~60 percent of the efficiency of coal-based steel production due to the smaller furnaces required in this process.[19] If efficiency were raised to a similar level to coal-based steel production, this would reduce the maximum biomass consumption for virgin steel production from 31 to 18 EJ per year in 2050.

Biomass might be reserved for industrial sectors where alternative options cannot decarbonize the full product lifecycle, such as the ethylene/plastics value chain and the ammonia/urea value chain. However, cement and steel producers might be most willing to use biomass as a fuel (cement) or feedstock (steel) because it is a mature technology that is more economical than other decarbonization options.

The availability of biomass also differs between regions. Transporting biomass from one region to another is only economical for certain types of biomass. Liquid biomass (e.g., biodiesel) can be transported around the world at low cost. Solid biomass or intermediates (e.g., wood pellets, sugar) are more expensive to transport due to lack of scale, and are therefore currently only practical to

[18] IRENA – global bioenergy supply and demand projections (2014).

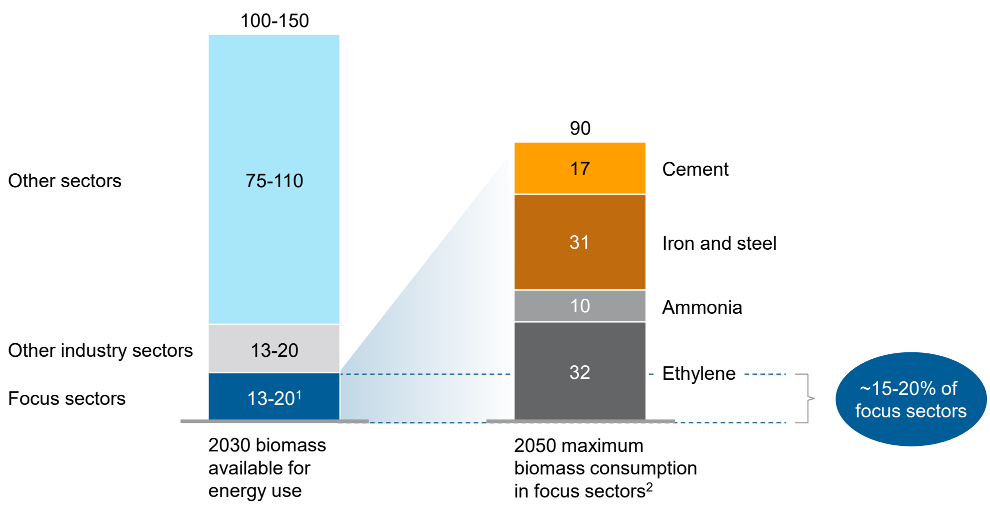
[19] IEA – Tracking industrial energy efficiency and CO_2 emissions (2007).

transport and use within a region.[20] Gaseous biomass is most difficult to transport and is therefore likely to be used locally.

Exhibit 9

Fair share of biomass for the focus sectors is ~15-20% of the energy consumption in these sectors in 2030

EJ/yr, estimated sustainable biomass availability for industry based on fair share of decarbonization



NOTE: Differences in totals due to rounding

1 Based on fair share of emissions from industry. Non industry sectors are 75% of emissions. Focus sectors are 50% of the industry emissions

2 Sectors require different types of biomass. Iron and steel (charcoal), cement (biomass), ammonia (biogas), ethylene (bioethanol, biodiesel, sugar). Estimated for 2050 based on production outlook for 2050 and maximum biomass consumption per ton produced in each sector

SOURCE: IPCC; World Bioenergy Association; IRENA

Geological storage capacity for captured CO_2

Although globally there seems to be plenty of CO_2 storage capacity available, available capacity differs widely between regions. The potential for CCS is greater in regions where CO_2 storage locations are near industrial sites, since CO_2 transport adds cost. Suitable CO_2 storage locations can be depleted gas or oil fields, mature oil fields (where CO_2 can be injected for enhanced oil recovery), deep saline aquifers, and deep unminable coal seams. Besides the availability of carbon-storage locations, CCS requires both a regulatory framework and supportive public opinion before it can be developed. Measures to offset carbon emissions, such as reforestation, could be an option in some locations and sectors. In this report, only geological storage was included in the cost and energy assessments.

Existing production sites and future production volumes

The growth outlook for each of the four focus industries matters, too. Certain decarbonization options are more cost-effective to use at newly built industrial facilities than at existing ones.

Where production in the four focus sectors is expected to grow, decarbonization measures can be implemented in forthcoming (greenfield) sites. New plants can be readily optimized for

[20] Global trade in solid biomass for industrial heat production is currently mostly driven by local feed-in tariffs or other subsidy schemes.

decarbonization. In regions with many production sites and no strong production growth, the majority of sites to be decarbonized will be existing (brownfield) facilities. Since existing sites are generally not optimized for decarbonization, they require existing equipment to be retrofitted or might require the site to be completely rebuilt in order to implement a decarbonized production process. Both approaches add cost: retrofitting requires downtime and investment, and rebuilding necessitates the existing site to be written off before end-of-life. For example, using hydrogen as a fuel in steelmaking would require a nearly complete overhaul of the steel production process at existing facilities. Hence, hydrogen-based steel production processes will generally be more economical for regions where new facilities are being built.

The relevance of greenfield or brownfield decarbonization depends on production and demand developments. For example, total demand for virgin steel is expected to stay almost flat at 1,200 MTA until 2050. However, based on predictions from McKinsey's Basic Materials Institute, demand for virgin steel in 2050 is expected to decrease by half in China—where much of the world's steel is now made—triple in India, and multiply by almost ten in Africa. This could lead to an increase in global trade and decarbonization of existing (brownfield) sites. Alternatively, this could also lead to the closure of existing sites and the construction of new sites elsewhere, and hence increased decarbonization of greenfield sites.

Carbon capture and usage

Whereas CCS involves sequestering captured CO_2, carbon capture and usage (CCU) keeps captured CO_2 out of the atmosphere by using it, e.g., as a feedstock for industrial processes such as chemical production and fuel production. Examples are production of methane, polymers, or novel materials such as carbon fiber. As a result, CCU can increase the circularity of carbon.

One expected benefit of CCU, compared to CCS, is that it will make carbon capture more economical by generating revenue from the sale of captured CO_2. However, a recent study by CO_2 Sciences and The Global CO_2 Initiative indicates that certain challenges are currently impeding the development and commercial application of CCU.[21] The most important challenge is that converting CO_2 into useful chemicals consumes a great deal of energy, most prominently hydrogen, leading to high costs and strong demand for zero-carbon electricity. Improvements in catalysts and process technology, together with an increase in the supply of low-cost zero-carbon electricity, could improve the prospect of CCU.

An integrated look at the costs of decarbonization options

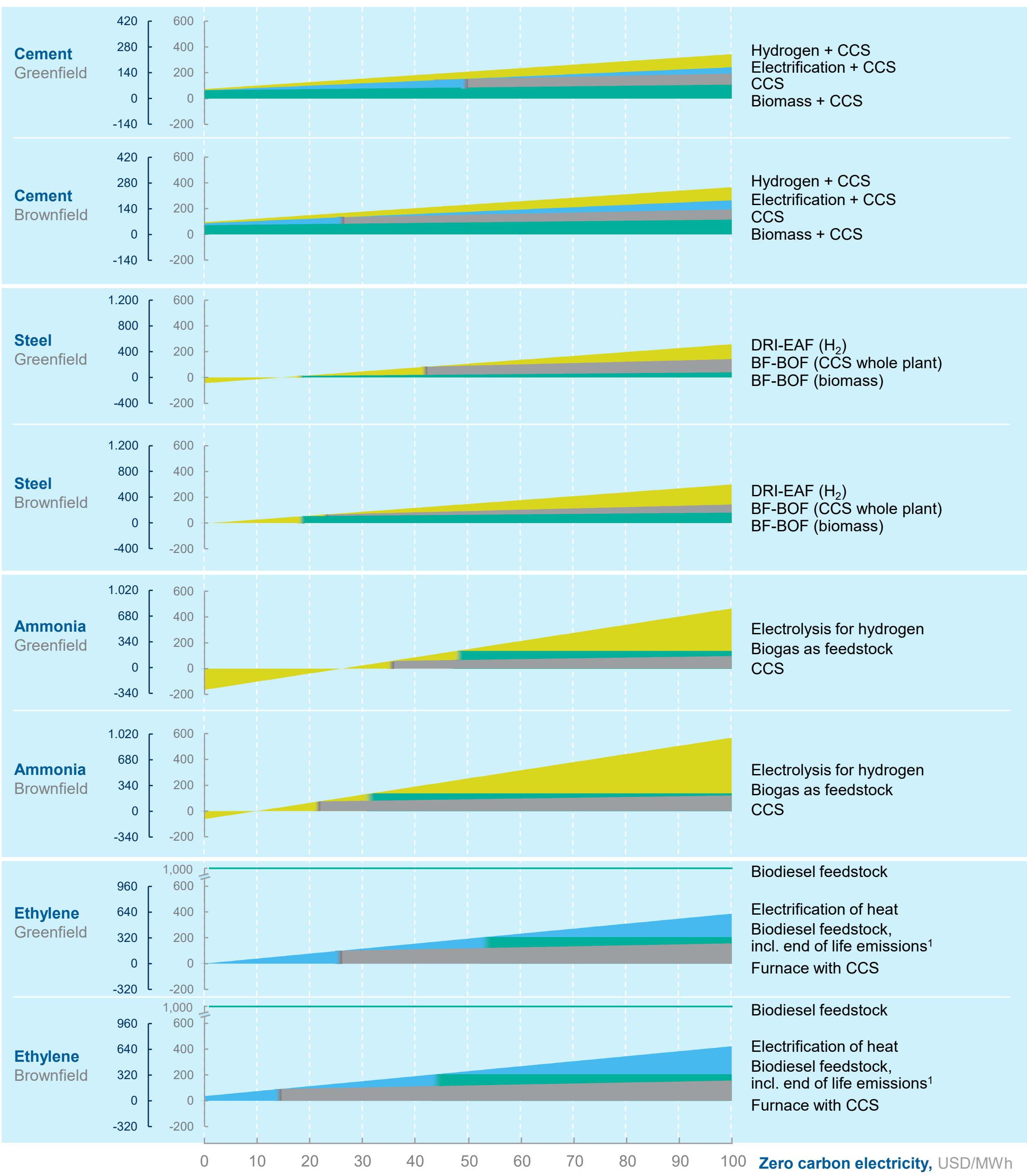
The costs of decarbonization options in the four focus sectors are largely determined by the prices of primary resources because the energy intensive processes in these sectors require significant amounts of fuel and feedstocks. By comparison, the costs of the capital equipment required by each decarbonization option are relatively modest, with the exception of CCS and some options that require extensive retrofits of existing sites. Overall, the region-to-region variability in commodity availability and price means that optimal decarbonization pathways are highly region- and location-specific.

[21] Global Roadmap for Implementing CO_2 Utilization (2016).

Exhibit 10

At electricity prices below USD ~50/MWh, electrification or hydrogen becomes a more attractive option than CCS

Selected options based on global average commodity prices



NOTE: Costs based on average commodity prices (see technical appendix). Greenfield decarbonization costs are calculated as the sum of delta capex and delta opex between conventional and decarbonized processes, divided by the tons of CO_2 abated. Brownfield decarbonization costs are calculated as the delta in opex between conventional and decarbonized processes plus the capex required for retrofit or rebuild of the existing site, divided by the tons of CO_2 abated. Hydrogen from electrolysis of zero carbon electricity based on capex of USD 450/MWh, 30% installation costs, and 70% efficiency. Capex estimates have been annualized using an annuity formula with a real terms discount rate of 8.5%. Costs of innovative option estimated on a best effort basis.

1 Decarbonization costs divided by both production emissions and end of life emissions

SOURCE: Enerdata – Global Energy and CO_2 data; DECHEMA 2017 – Low carbon energy and feedstock; IEA 2009 – The chemical and petrochemical sector; IEA 2009 Cement technology roadmap, IETD IITD network, Berkeley National Laboratory, US Department of Energy, US EPA, Global CCS Institute, CSI – Development of State of the Art techniques in Cement Manufacturing 2017; Expert interviews

In most cases, the costs of decarbonized industrial production are higher than the costs of conventional production. In Exhibit 10, the horizontal axis represents the zero-carbon electricity price and the vertical axis the costs of decarbonization per ton of CO_2 or per ton of product. The decarbonization option is competitive with conventional production only if these have negative values. The estimates are based on current prices for natural gas, petroleum products, coal, and biomass (see Technical appendix) and do not account for potential decreases in the costs of capital equipment or the costs of innovative processes, both of which are difficult to project. A detailed overview of decarbonization options for each sector and assumed commodity prices can be found in Chapter 4 and the Technical appendix respectively.

Energy-efficiency improvements can reduce carbon emissions competitively but cannot lead to deep decarbonization on their own

Energy-efficiency improvements that lower fuel consumption by 15 to 20 percent can be economical in the long run. Sites in developed countries typically have already seen improvements and can thus be expected to be at the low end of the range, whereas sites in developing countries may be at the high end. However, the potential of energy-efficiency improvements is very site specific. Depending on the payback times of energy efficiency required by companies (sometimes less than two years), the energy-efficiency improvement that is achieved can be less than 15 to 20 percent.

CCS is the lowest-cost decarbonization option at current commodity prices where carbon-storage sites are available

CCS appears to be the lowest-cost decarbonization option for the four focus sectors at current commodity prices, but CCS is not a mature technology: no large-scale, post-combustion carbon-capture plants now operate at industrial sites. Nonetheless, based on CCS plants on other facilities, CSS appears to be an economically attractive option when the price of zero-carbon electricity exceeds USD 50/MWh.

The total cost of CCS, which can range from USD 25/ton CO_2 to USD 190/ton CO_2, includes the costs of capturing CO_2 from exhaust gases, transporting captured CO_2 to a storage site, and storing it. Some CO_2 emissions occur as a pure flow of CO_2; these are inexpensive to capture. If CO_2 needs to be separated from a mix of exhaust gases, then the capture process will make up the majority of the CCS costs. The lower the percentage of CO_2 in an exhaust-gas stream, the more it costs to extract. The capture process typically requires heat (~120 °C), although the heat can be produced with electricity or can be supplied by waste heat from an industrial process.

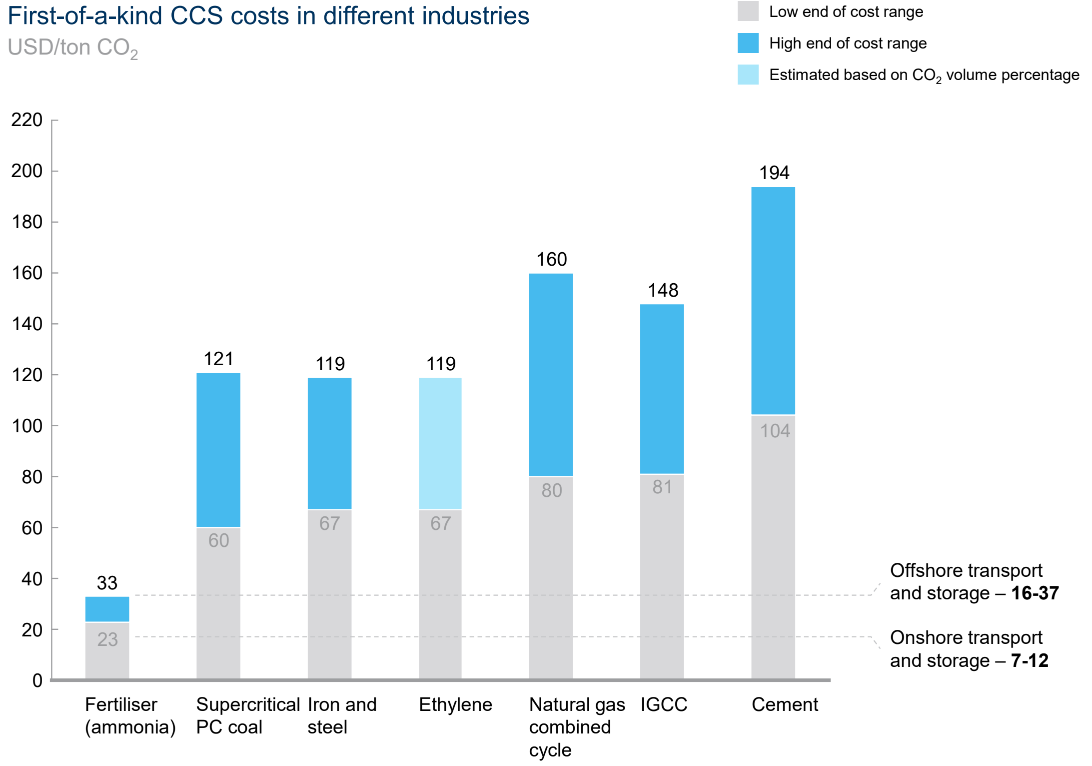
According to the Global CCS Institute, the costs of transporting and storing captured CO_2 range from USD 7/ton CO_2 to USD 35/ton CO_2, depending on the distance from the site where the CO_2 is captured to the storage location, the type of storage location, and the availability of existing storage infrastructure (as might be found at natural gas production sites, for example). Compressing the CO_2 for transport and storage requires the use of electricity.

Most captured CO_2 is currently pumped into mature oil fields to force out the remaining oil in a process known as enhanced oil recovery. Other storage sites can be depleted gas fields or saline aquifers. If the characteristics of a storage location are not well understood (as is usually the case with saline aquifers), then costly, time-consuming explorations must be performed to ensure that CO_2 can be safely stored in the location. Onshore CO_2 storage generally costs less than offshore CO_2 storage. (Exhibit 11)

Exhibit 11

First-of-a-kind CCS costs in different industries

USD/ton CO_2



SOURCE: Global CCS Institute (2017)

At zero-carbon electricity prices below ~USD 50/MWh, using zero-carbon electricity for heat or hydrogen based on zero-carbon electricity becomes more economical than CCS

The zero-carbon electricity price as used here is the average wholesale industrial end user price, so including, e.g., transmission, distribution, and storage costs. Electricity prices below USD 50/MWh have already been achieved locally (e.g., hydropower) and could be achieved in more places with the current downward cost trend in renewable electricity generation. The minimum price that makes it less expensive to switch to zero-carbon electricity than to apply CCS for decarbonization depends strongly on the sector, local fossil fuel and other commodity prices, and the state of the production site. As can be seen in Exhibit 10:

- At electricity prices below ~USD 50/MWh, electrifying heat production at greenfield cement plants is more cost-competitive than applying CCS to the emissions from fuel consumption, provided that very-high-temperature electric furnaces are available. (Process emissions from cement production cannot be abated by a fuel change and therefore require CCS.)

- At electricity prices below ~USD 35/MWh, hydrogen use for greenfield ammonia and steel production sites is more cost-competitive than applying CCS to conventional production processes.

- At electricity prices below ~USD 25/MWh, electrification of heat in greenfield ethylene production and in brownfield cement production and usage of hydrogen for brownfield steel production are more cost-competitive than applying CCS to conventional production processes.

- Finally, below an electricity price of ~USD 15/MWh, usage of hydrogen for brownfield ammonia production and electrification of heat for ethylene production are more cost-competitive than applying CCS to conventional production processes. This means that electric heat production and usage of electricity to make hydrogen are more economical approaches to decarbonization than CCS in all four focus sectors.

Lower costs for capital equipment or process innovations could make electrification or the use of zero-carbon electricity based hydrogen economical at higher electricity prices.

Although industrial-scale high-temperature electric furnaces are not yet commercially available, small-scale versions do exist that can be scaled up for most high-temperature applications. Furnaces for cement production need to reach very high temperatures (well above 1,600 °C) and require research to become available. It is expected that the capital costs of electric furnaces could eventually be similar to those of conventional furnaces. High-temperature nuclear reactors or concentrated solar power (CSP) could also supply heat, although they have not yet been used to meet the high-temperature heat demands (>700 °C) in the four focus sectors.

The cost comparisons for hydrogen-based technologies assume the use of an electrolyzer with a capital cost of USD 305/ton hydrogen (including installation costs, but excluding maintenance costs) and an efficiency of 70 percent, as can currently be achieved in large alkaline electrolyzers.[22]

Using biomass as fuel or feedstock is financially more attractive than electrification of heat or the use of hydrogen in cement production and at electricity prices above ~USD 20/MWh in steel production

Mature technologies are available for using biomass as fuel and feedstock in virgin steel production and as fuel in cement production. In greenfield steel sites and cement production, biomass is more economical than CCS to reduce emissions. Biomass can also replace hydrocarbon feedstocks for ethylene and ammonia production. Although this costs more per ton of abated on-site CO_2 emissions than electrification or hydrogen usage, it abates both the emissions on site and the emissions of the produced commodities downstream, such as the emissions from incineration of plastics made from ethylene. As discussed earlier in this chapter, there are constraints to the use of biomass due to the limited global supply of sustainably produced biomass and competition with other sectors for the biomass supply.

[22] IEA – Renewable energy for industry (2017). Capex and efficiency assumptions in this report are based on the assumptions in the IEA publication, except for those on WACC and availability. Assumptions for electrolyzers are: capex of USD 450/kW installed, installation costs of 30 percent of capex, a lifetime of 30 years, 70% efficiency, 50% availability, and 8.5 percent WACC.

4 Application of decarbonization options in the four focus sectors

The economic applicability of decarbonization options varies considerably from one sector to the next, from region to region, and among industrial facilities. Research and development could expand decarbonization options in all sectors.

Summary of decarbonization options per sector

In general, these are the most promising options for each of the four focus sectors:

- Cement production (3 Gton CO_2) can be decarbonized by using zero-carbon fuels to fire cement kilns (40 percent of CO_2 emissions). Decarbonization by replacing fossil fuels with biomass is a mature technology. Using electricity or hydrogen as a fuel will require innovation. Abating CO_2 emissions from cement feedstock (limestone) (60 percent of CO_2 emissions) requires either CCS (which can also be used to eliminate fuel emissions) or innovation in alternative feedstocks.

- Steel production (2.9 Gton CO_2) can be decarbonized by mature production processes: replacing coal with charcoal in blast furnace-blast oxygen furnaces (BF-BOF), powering electric arc furnaces (EAF) with electricity from renewable sources, or replacing natural gas used to make direct reduced iron (DRI) with biogas. Replacing natural gas with hydrogen in the DRI process is in the pilot phase. CCS can also be applied to exhaust gases from conventional, coal-based steelmaking facilities. Innovations could include electrical reduction of iron ore, HIsarna, or top gas recycling. The latter two lower CO_2 emissions from virgin steel production but require CCS for deep decarbonization.

- Ammonia production (0.5 Gton CO_2) yields a nearly pure flow of CO_2 (two-thirds of emissions) that could be captured and stored at low costs, but which is now often used to make urea, a common type of fertilizer based on CO_2 and ammonia (the CO_2 is almost immediately released upon use of the fertilizer). Changing the process to hydrogen made by electrolysis rather than hydrogen made from natural gas would eliminate these emissions. This works well in concert with demand-side measures, such as using MAP, DAP, or nitrate-based fertilizers instead of urea, as these are produced from ammonia without requiring CO_2. Innovative processes that use bio-based feedstocks and fuels, such as biogas, would decarbonize the emissions from both the ammonia production process and the urea production and use.

- Ethylene production (0.2 Gton CO_2) only has CO_2 emissions from fuel for high-temperature heat required in the steam cracking process. These fuels are partly or completely sourced from gases produced in the same steam cracking process. Switching to zero-carbon fuel sources or applying CCS could mitigate these emissions. Producing ethylene from bio-based feedstocks, such as biodiesel or sugar, or increasing the recycling of plastics would reduce end-of-life emissions as well as on-site emissions. Advances in the field could also lead to the introduction of new polymer types based on alternative bio-based processes or electrochemical production processes.

- Heat demand in other industrial sectors can be decarbonized by changing the fuel for heat production in heat pumps, boilers, or furnaces. Alternative fuels can be electricity, hydrogen or biomass. CCS can also be applied to heat production with conventional fuels.

Decarbonization options for each sector

Below is a description of the production outlook, CO_2 emissions in conventional production processes, and the application of decarbonization options for each of the four focus sectors. Only (nearly) available technologies are highlighted. Innovative decarbonization options have been described when enough information was available. More detail can be found in the Technical appendix. Also, a high-level description of the decarbonization pathways in other industrial sectors is given.

Cement

Global cement production was approximately 4,000 MTA in 2015.[23] About 80 percent of cement is used as a binder in concrete, which is a mixture of aggregate (sand or gravel), cement, and water. Cement production is expected to increase 25 percent by 2050, with most of the new production occurring in developing regions. Although some cement companies are global, the cement trade is highly localized. As a bulky, low-value product, cement is seldom economical to transport more than 250 kilometers from the production site to the user.

The worldwide production of cement emitted approximately 3.0 Gton CO_2 in 2014 (about 7 percent of the global total). Nearly all of the CO_2 emissions from making cement result from two activities. One is the combustion of fuel to heat cement kilns where calcination takes place to above 1,600 °C. This accounts for 40 percent of CO_2 emissions. Today, cement producers fire kilns with a wide variety of fuels, such as coal, petcoke, biomass, or waste, which they choose based on availability and price.

The calcination of calcium carbonate into calcium oxide produces about 60 percent of the CO_2 emissions from cement production. Calcination involves heating ground limestone, the main feedstock for cement, to temperatures of more than 1,600 °C in a kiln so that the calcium carbonate ($CaCO_3$) in the limestone turns into calcium oxide and CO_2 ($CaO + CO_2$). The substance that results from the kiln firing process, known as clinker, is ground and sometimes blended with other minerals to form cement. Generally, cement made in this manner, known as Portland cement, consists of 65 percent clinker. Few options exist for abating the CO_2 emissions from calcination, and they have limitations. A very small share of emissions comes from generating the electricity needed to grind the feedstock and clinker. (Figure 1)

Options for decarbonizing cement production:

- **Switching to a zero-carbon fuel** would mitigate CO_2 emissions from fuel combustion. At cement production sites, changing to biogas or biomass would require a modest retrofit of the kiln. Replacing conventional fuel with hydrogen would require redesign of the furnace given the differences in heat transfer from hydrogen burners vis-à-vis fossil fuel burners and safety considerations. Industrial-scale electric cement kilns are also not yet available, so further research and development will be needed. Installing an electric or hydrogen furnace at existing cement plants would likely require extensive retrofitting of these sites.

[23] GNR, McKinsey Basic Materials Institute.

- **Applying CCS to the exhaust gases of cement kilns** would prevent CO_2 emissions resulting from both fuel combustion and limestone calcination. At conventionally equipped cement plants, CO_2 would have to be captured from the combined stream of exhaust gases from fuel combustion and calcination, which contains a low percentage of CO_2. However, exhaust gases that are low in CO_2 are more expensive to capture. An innovative kiln design could separate exhaust gases of fuel combustion (low in CO_2) from the exhaust gases of calcination (nearly pure CO_2) so that CO_2 can be captured at lower cost. This approach is being piloted in an innovative project known as LEILAC. Burning fossil fuels for heat in an environment with pure oxygen rather than air, a process called oxy fuel combustion, would increase the percentage of CO_2 in the exhaust gasses from fuel combustion as well. In any case, CCS can only be used at cement sites which are near carbon-storage locations.

- **Replacing limestone or clinker with other minerals** could help reduce process emissions. Alternative minerals could replace limestone as a feedstock in the kiln or replace a large portion of the clinker in cement. Some of these substitutes are in wide use; for example, fly ash and slag are routinely mixed with clinker. Other substitutes are being tested, such as magnesium oxide, which would eliminate the use of limestone. These alternatives to limestone are not yet practical to use on a large scale because they are scarce locally, they result from CO_2-emitting processes, or they could endow the finished cement with different and undesirable properties. In some jurisdictions, regulations limit or prevent the use of alternative cement rather than conventional Portland cement.

- **Capturing CO_2 in concrete** that is produced from cement represents an innovative method of CCU. In this process, the CO_2 gas from clinker production is captured in concrete while the concrete is setting.

Figure 1

Steel

Global steel production, which was approximately 1,600 MTA in 2015, is projected to grow 30 percent to 2,100 MTA by 2050, with virgin steel production expected to remain near 1,200 MTA while recycled steel production is expected to more than double.[24] Significant turnover of existing structures in developed markets, resulting in the recovery of large amounts of steel, largely accounts for the large expected increase in recycled steel production. Some steel is traded on a global market. In 2016, 31 percent of steel was exported from the country in which it was made, and two-thirds of that was exported beyond its region of origin.[25] Flat steel, which is of higher quality, tends to be traded globally, while lower-quality long steel such as beams and rods is mostly sold locally.

Production of both virgin steel and recycled steel emitted approximately 2.9 Gton CO_2 in 2014, which is equivalent to about 7 percent of global emissions. Steel companies follow two main production processes for steel. The blast furnace-blast oxygen furnace (BF-BOF) process is used to make over 95 percent of the world's virgin steel. BF-BOF production is a coal-powered process by which iron ore is reduced and melted at temperatures around 1,200 °C.[26] The excess heat made during BF-BOF production allows steelmakers to use up to 20 to 30 percent scrap steel as a feedstock, which increases steel output without a corresponding increase in the use of coal.

The second steelmaking process is employed to produce recycled steel and the remaining fraction of virgin steel. In this process, electric arc furnaces (EAF) are either fed with scrap steel to make recycled steel or fed with direct-reduced iron (DRI) to produce virgin steel. The DRI needed to make virgin steel uses syngas produced from natural gas to reduce iron ore at temperatures below the melting point of steel. Recycled steel produced in an EAF tends to be of lower quality than virgin steel because it retains whatever contaminants that were present in the scrap steel, such as copper. DRI-EAF and EAF have much lower CO_2 emissions per produced ton of steel than the coal-based BF-BOF production route. (Figure 2)

In an integrated steel plant, steel is processed further (e.g., rolling, coating) to make goods such as steel rolls that are used in manufacturing final products.[27]

Options for decarbonizing steel production:

- Applying CCS at existing BF-BOF production sites does not necessarily require altering the conventional production process. However, there are innovative technologies that could optimize the BF-BOF process for CCS. These lessen the use of coal and increase the percentage of CO_2 in the exhaust gases and thereby lower the carbon-capture costs. Examples are top gas recycling and HIsarna. Applications of these CCS-optimized steel production methods are being piloted with the aim of addressing such challenges as preheating the recycled gas needed for top gas recycling and scaling up the technology.

[24] WSA 2016, McKinsey Basic Materials Institute.

[25] WSA 2016.

[26] In Brazil, charcoal is used in BF-BOF instead of coal.

[27] In the cost estimates of decarbonized steel production, it is assumed that the energy for machinery and heat in steel processing is electrified.

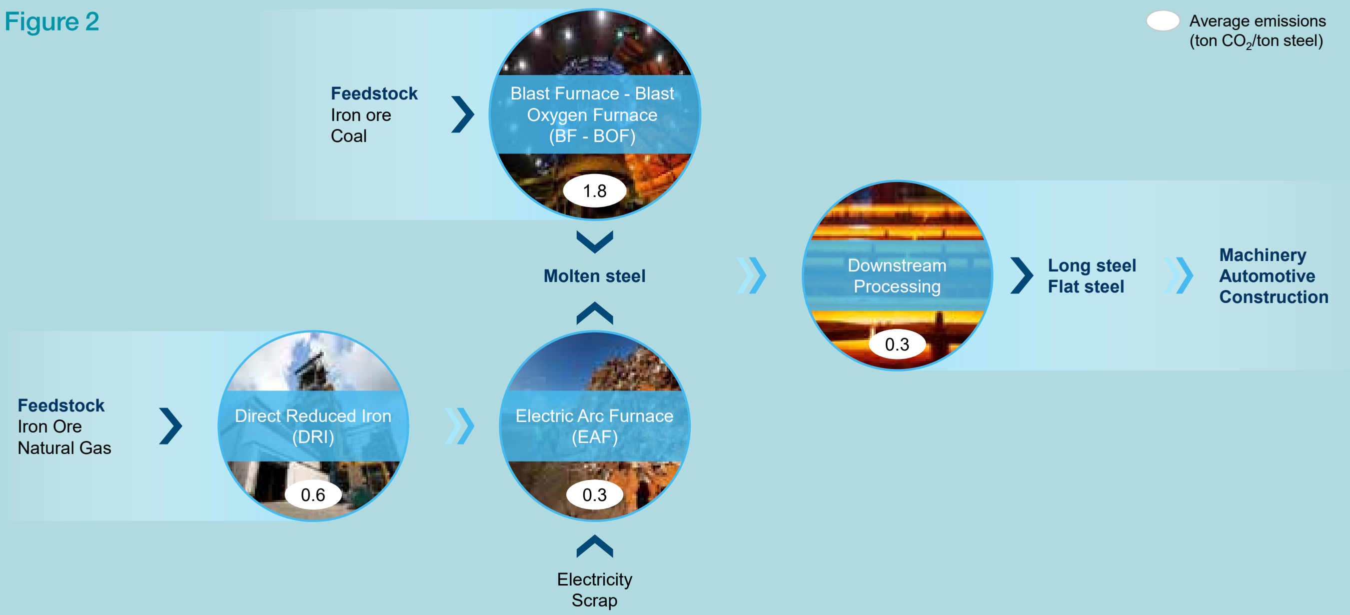
- **Using charcoal instead of coal as a feedstock and fuel in BF-BOF production** is a mature technology. Steelmakers in Brazil have found it profitable to use charcoal instead of coal in virgin steel production. Using charcoal instead of coal requires smaller furnaces and is less efficient, though.[28] BF-BOF facilities that use coal now would have to rebuild their blast furnaces if they were to switch to charcoal.

- **Using biogas or hydrogen instead of natural gas in DRI production** can reduce CO_2 emissions as well. The idea is either to make syngas from biogas or to replace syngas with hydrogen in the DRI process. SSAB is piloting the latter process. While this switch does not require a large retrofit when implemented at existing DRI-EAF facilities, existing BF-BOF sites would mostly have to be rebuilt as DRI-EAF facilities.

- **Using zero-carbon electricity in an EAF** would eliminate the CO_2 emissions associated with generating electricity to power EAFs for production of either recycled steel or virgin steel (the latter in combination with DRI).

- **Using iron electrolysis with zero-carbon electricity is an innovative process** that uses an electricity based reduction method. In one of the processes researched, the iron ore is dissolved in a mixture of calcium oxide, aluminum oxide, and magnesium oxide at temperatures around 1,600 °C and an electric current is passed through it. The reduced iron is captured at the cathode; the oxygen in the iron ore is collected at the anode. Especially the solvent, temperature and anode material are subjects of laboratory research.[29]

Figure 2



[28] IEA – Tracking industrial energy efficiency and CO_2 emissions (2007).

[29] To eliminate emissions (in high temperature electrolysis), the anode should be from a heat resistant material that does not contain carbon, as carbon in the anode could combine with the oxygen and lead to CO2 emissions (similar to emissions from conventional aluminum reduction).

Ammonia

Production of ammonia, which now totals 181 MTA, is expected to grow 65 percent by 2050, driven by population growth.[30] About 55 percent of ammonia is used as a base chemical to produce urea, a key ingredient in nitrogenous fertilizer. Both ammonia and urea are globally traded.

Producing ammonia emits approximately 0.5 Gton CO_2 per year, an amount equivalent to about one-quarter of the CO_2 emissions from the chemical industry. Conventional methods of making ammonia yield process emissions which are an almost pure flow of CO_2. These emissions account for approximately two-thirds of all CO_2 emissions from ammonia production. The other one-third of emissions result from the combustion of fuel for heat and compression.

Making hydrogen is the first step in ammonia production. It is usually done by steam methane reforming (SMR). SMR uses high-temperature steam to make hydrogen from natural gas. Only in China do ammonia producers use coal instead of natural gas as a feedstock to produce hydrogen via coal gasification. The water gas shift is the next step, in which air is added to the mix of CO and steam to make CO_2 and hydrogen. The CO_2 is then eliminated, yielding the nearly pure stream of CO_2 noted above, along with a mixture of nitrogen and hydrogen. That mixture is then used for ammonia synthesis at high pressure in the Haber-Bosch process.[31] (Figure 3)

The CO_2 emitted during the water-gas shift is combined with ammonia to produce urea in ~55 percent of produced ammonia. Urea-based fertilizer releases CO_2 into the atmosphere, most of it within a week of application, while the nitrogen remains in the soil. Therefore, to decarbonize the complete ammonia/urea value chain requires sourcing the CO_2 in the urea (which is now obtained from natural gas, the hydrogen production feedstock) from a biobased source.

Options for decarbonizing ammonia production:

- **Using alternatives to urea-based fertilizer** represents a demand-side measure for reducing emissions throughout the fertilizer value chain. Cyanobacteria, or blue-green algae, can be used as a nitrogenous fertilizer. Nitrate-based fertilizers are another option. Nitrate-based fertilizers include MAP, DAP, and ammonium nitrate. Unlike urea, these substances require no CO_2 and can therefore be used in a decarbonized production process such as electrolysis or CCS (see options below). Nitrate-based fertilizers are used today. The applicability of alternatives to urea-based fertilizer varies throughout crops, soil conditions, and growing climates.

- **Switching to electrolysis-derived hydrogen as a feedstock** eliminates the emissions associated with making hydrogen via SMR and the water gas shift reaction. It would allow ammonia production from water, air, and zero-carbon electricity. Hydrogen is produced from water and electricity in electrolyzers. A nitrogen separation train provides nitrogen from air so the nitrogen can be combined with hydrogen for ammonia synthesis in the Haber-Bosch process.

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[30] IFDC, IFA, McKinsey Energy Insights Global Energy Perspectives.

[31] In the Haber-Bosch process, ammonia is produced from hydrogen and nitrogen at 200-300 bar. In the cost estimates of decarbonized ammonia production, it is assumed that the Haber-Bosch unit is electrified.

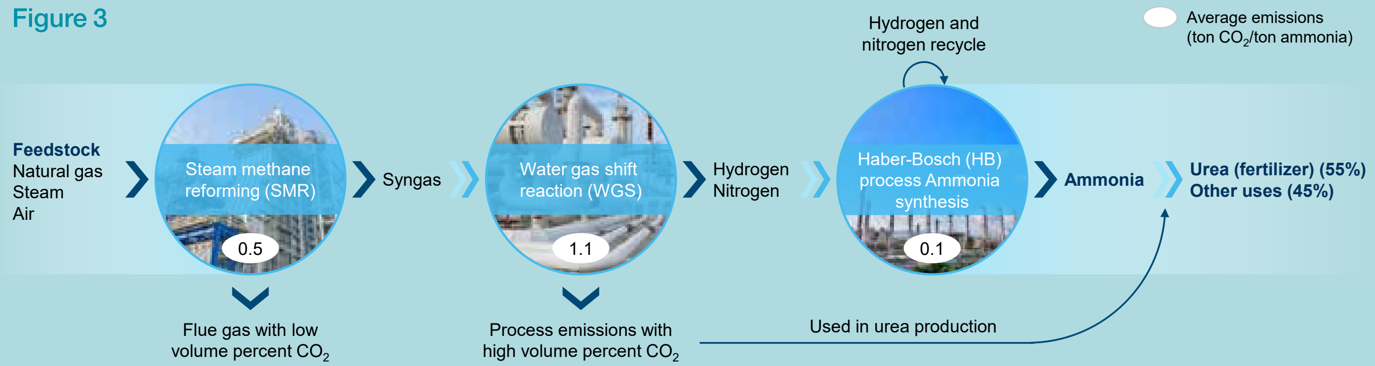
An alternative source of CO_2 would be then required for urea production, since the CO_2 that is now obtained from the water gas shift in the conventional process would no longer be made.

- **Applying CCS** could reduce emissions from ammonia production. The nearly pure stream of CO_2 from the water gas shift reaction can be captured at low cost. The emissions from the natural gas used for heat in the conventional process have a low percentage of CO_2 and so they cost more to capture. Ammonia producers may therefore benefit from switching to autothermal reforming (ATR) of natural gas to produce hydrogen. This would ensure that all emissions consist of pure CO_2, which can be captured at low cost. ATR increases natural gas consumption compared with the conventional SMR based process.

- **Using biomass as a feedstock** would decarbonize the full ammonia/urea value chain. Pyrolyzing dry biomass results in hydrogen and CO. The hydrogen can be converted into ammonia, which can then be combined with CO_2 to form urea. Wet biomass can also be gasified to make methane and CO_2, and the methane can be transformed into urea via SMR. This use of biomethane would not require modifications to existing ammonia production sites.

- **Applying innovative methods, such as methane splitting and high-temperature electrolysis,** is conceivable, but these methods are still in the research phase. Methane splitting would yield hydrogen and solid carbon rather than the hydrogen and CO_2 that are produced in the SMR-water gas shift process. High-temperature electrolysis could result in more economical hydrogen production than conventional room-temperature electrolysis, because it is done at elevated temperatures (which makes the reaction more efficient) and some of the energy for electrolysis comes from a heat source (which generally costs less than electricity e.g., heat from high-temperature nuclear reactors).

Figure 3



Ethylene

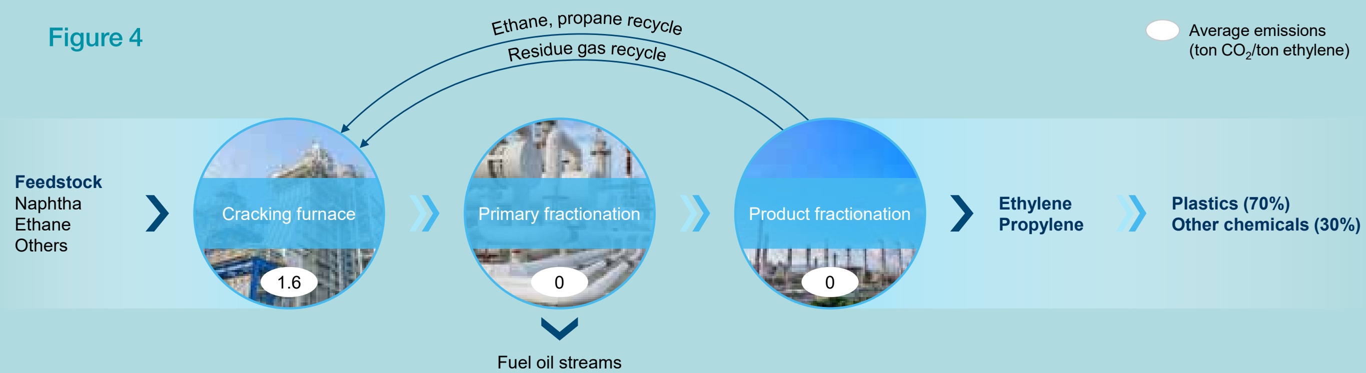
Global production of ethylene amounted to 144 MTA in 2015, including the equivalent of 3 MTA ethylene from recycling plastics.[32] Ethylene is mostly used as a base chemical for making plastics. Ethylene demand is expected to triple by 2050—so a growth faster than GDP, in line with historical trends. By that year, production of virgin ethylene is projected to account for about two-thirds of the world's supply, while the remaining one-third will come from the recycling of plastics.

Virgin ethylene can be produced from various hydrocarbon feedstocks. Naphtha is used to make about 43 percent of ethylene; ethane is used to make 35 percent; and other feedstocks account for the remainder of ethylene production. The use of these feedstocks varies from region to region. In the United States and the Middle East, for example, ethane is the most common feedstock, for it is widely available as a by-product of wet- or shale-gas production.

Ethylene production causes some 0.2 Gton of CO_2 emissions per year, which is about 10 percent of emissions from the chemical industry. These emissions come from the combustion of fuel to heat pyrolysis furnaces, which produce ethylene (along with propylene and other base chemicals) in a high-temperature process known as steam cracking. Steam cracking is the only step in conventional ethylene production at which fuel is burned and CO_2 is generated. Some of the substances created during ethylene production, such as hydrogen and methane, are burned in the pyrolysis furnace for heat. In the case of naphtha-based ethylene production, all the fuel burned in the furnace consists of gases made during steam cracking. (Figure 4)

The compounds created in the steam cracking process are separated (fractionation), which is driven by the steam generated using excess heat from the pyrolysis furnace. Most compounds are monomers, (e.g., ethylene and propylene). These can be polymerized into several types of plastics, such as polyethylene, polypropylene, and PET.

Figure 4



[32] ICIS, McKinsey Energy Insights Global Energy Perspectives.

Production-related CO_2 emissions are only a small fraction of the emissions that occur over the entire lifecycle of ethylene-based products. The incineration of virgin ethylene (or goods made from virgin ethylene) emits three to four times more CO_2 than the amount emitted during the production. Decarbonizing ethylene production will therefore only have a modest effect on the CO_2 emissions in the ethylene value chain.

Options for decarbonizing ethylene production:

- Recycling of used plastics is a demand-side measure that would not only lower the end-of-life emissions associated with ethylene, but would also lessen the need for production of virgin ethylene. Mechanical plastic recycling is now practiced on a large scale. For polymers other than PET, mechanical recycling usually does not produce plastic of quality comparable to virgin plastic. Chemical recycling, which turns plastics back into monomers, could yield virgin-quality recycled polymers, but chemical recycling currently only works with selected polymer types (e.g., nylon). Other options include using pyrolyzed plastic waste as feedstock in steam crackers; these are still in the applied-research phase. Recycled ethylene is unlikely to replace all virgin ethylene, because recycling typically causes the loss of some material and generally produces plastic of lesser quality than virgin plastic.

- Switching fuels for heat production to zero-carbon hydrogen or biomass can mitigate emissions with limited alterations to the furnace design and production setup. Changing fuels means that the methane and hydrogen conventionally burned in the pyrolysis furnance for heat, are replaced. The methane and hydrogen could be separated from the production gasses and valorized.[33]

- Switching fuels for heat production to zero-carbon electricity would require significant changes to production equipment. High-temperature electric furnaces for ethylene steam-cracking are not commercially available, although they have been tested in laboratories and in other applications. Electric pyrolysis furnaces are expected to have higher efficiency, but they also generate less excess heat. Therefore, the downstream processes now driven by steam generated with excess furnace heat would have to be electrified as well. All in all, this would lead to a more energy-efficient production process. Similar to other fuel changes, the produced methane and hydrogen that is currently burned in the furnace can be sold.[33]

- Applying CCS to the exhaust gases from the pyrolysis furnace can eliminate CO_2 emissions from ethylene production, since on-site emissions are only produced by the pyrolysis furnaces in the conventional process.

- Switching to biobased feedstocks in the conventional steam-cracking process could reduce emissions from ethylene production as well as end-of-life emissions. Biodiesel can be converted to bio-naphtha and used in existing steam-cracking furnaces, in the conventional steam cracking process.

[33] In the cost estimates of a fuel switch to decarbonize ethylene production, the costs of separating out the products in the production gasses that are now used as fuel nor the revenues of valorization of these gasses are included.

- **Switching to an alternative process based on bioethanol feedstock** produces ethylene via ethanol dehydration. This process produces only ethylene, instead of the wide range of compounds that come from conventional steam cracking. Bioethanol dehydration is used to turn sugar into polymers on an industrial scale in Brazil.

- **Applying alternative biobased processes to make alternative monomers** are now in the pilot phase of development. In these processes, alternative monomers, which resemble the molecules in bio-based feedstocks more closely than ethylene molecules, are produced at lower temperatures than steam cracking, thereby producing fewer emissions from fuel combustion and abating end-of-life emissions.

- **Applying electrochemical processes to make monomers** would use electricity from zero-carbon sources to drive chemical reactions. Electrochemical processes are expected to provide greater yield and precision in the compounds produced, and can be designed based various feedstocks, including CO_2. These processes are currently being developed in laboratory settings.

A few remarks on other industrial processes

Most emissions from industrial processes outside the four focus sectors are from low-temperature or medium-temperature heat demand or electricity consumption.[34] Processes in the food and beverages sector, such as evaporation and pasteurization, mostly occur at temperatures below 200 °C, as do processes in the pulp and paper sector. Therefore, decarbonization options for these sectors largely involve changing fuels for low- or medium-temperature heat or applying CCS to heat-production units. Note: Some sectors do have feedstock emissions and high-temperature heat demand, such as aluminum production in the nonferrous metals sector, or refining, and therefore require decarbonization measures more similar to those in the focus sectors.

In addition, electricity provides a larger proportion of the energy required by processes outside the four focus sectors. Automotive-equipment factories, for example, use electricity to drive the machines on their assembly lines. These factories can switch from conventional to zero-carbon electricity without a change in equipment. This is in contrast to production sites in the four focus sectors that have to convert their equipment so they can run on different fuels.

Given these conditions, the following options exist for decarbonizing industrial heat outside the four focus sectors:

- **Low-temperature heat (below 100 °C) can be provided by electric heat pumps,** which are two to three times more efficient than boilers. Other heat sources can also be used, such as geothermal heat or waste heat (from industrial sites). Heat pumps can reach temperatures up to ~100 °C, and ongoing research and development should widen their performance range.

[34] These sectors are: nonferrous metals, transport equipment, machinery, mining and quarrying, food and tobacco, paper, pulp and print, wood and wood products, textile and leather, construction and miscellaneous industries.

- Medium-temperature heat (100 °C to 500 °C) can be produced with less CO_2 emissions if companies switch to boilers that run on biomass, biogas, zero-carbon electricity, or hydrogen produced with zero-carbon electricity. With hybrid boilers, which can instantly switch between electricity and natural gas, companies can take advantage of fluctuating electricity prices. Hybrid boilers can support inclusion of more intermittent renewables to the grid by balancing capacity. Therefore, they can support the energy transition in the power sector as well as enable a gradual shift from fossil fuels to renewable electricity for industrial players.

- High-temperature heat (above 500 °C) could also be decarbonized if companies switch with furnaces powered by biomass, biogas, zero-carbon electricity, or hydrogen produced with zero-carbon electricity. This is much like changing the fuel used in ethylene steam-cracking furnaces. Industrial-scale, electric, high-temperature furnaces are not yet commercially available.

5 The investment and energy requirements for industrial decarbonization

Large investments in industrial equipment and changes in the energy system will be required to decarbonize industrial sectors. After testing the effects of varied electricity prices on the cost of decarbonization options, we estimate that decarbonization of the four focus sectors could cost between USD 11 trillion and USD 21 trillion through 2050, an amount equivalent to between 0.4 and 0.8 percent of global GDP (USD 78 trillion) per year. About 50 to 60 percent of that consists of operating expenses, and the remainder consists of capital expenditures. The selected mix of decarbonization options creates additional demand for between 25 EJ and 55 EJ of zero-carbon electricity per year by 2050.

Sensitivities of the mix of options with the zero-carbon electricity price

In this chapter, we build on Chapter 3's comparison of the costs of individual decarbonization options at different zero-carbon electricity prices to explore how the price of zero-carbon electricity affects the overall cost of decarbonization in the four focus sectors and those sectors' requirements for additional zero-carbon energy. From our analyses, it appears that the decarbonization challenge in the four focus sectors can only be met with large investments in equipment and operating costs and should be accompanied by a major transition within the energy system.

Our analysis is based on three sensitivities for how the price of electricity will change by 2050. For each sensitivity, we have identified a mix of decarbonization options that minimizes the cost of attaining the target emissions reductions and the corresponding impact on the energy system. None of our calculations includes assumptions on the local availability of zero-carbon/renewable power generation, or carbon-storage locations that were discussed earlier. The commodity price assumptions can be found in the Technical appendix.

The sensitivities otherwise incorporate the same set of assumptions, which are intended to make our estimates of the costs and energy system impact conservative (that is, the costs and energy system impact are expected to be on the high end of the expected range). The main assumptions are as follows: Firstly, we designed the sensitivities so that the four focus sectors achieve a complete reduction of CO_2 emissions rather than the 80 to 95 percent reduction required to achieve the temperature increase targets of the Paris Agreement, and secondly the scenarios assume that no breakthroughs will occur in process innovation (such as changes in the feedstocks used for cement production or electrochemical production processes) or in reduced costs for capital equipment (e.g., in CCS). And, again, no demand-side measures are included, while these could prove to significantly impact the choice for decarbonization options and related costs. Finally, the sensitivities all envision that 20 percent of virgin production of the focus sectors will be produced with biomass (e.g., biogas, bionaphtha, charcoal). This is industry's fair share of sustainably produced biomass, an amount proportional to industry's contribution to global emissions, as discussed in Chapter 3.

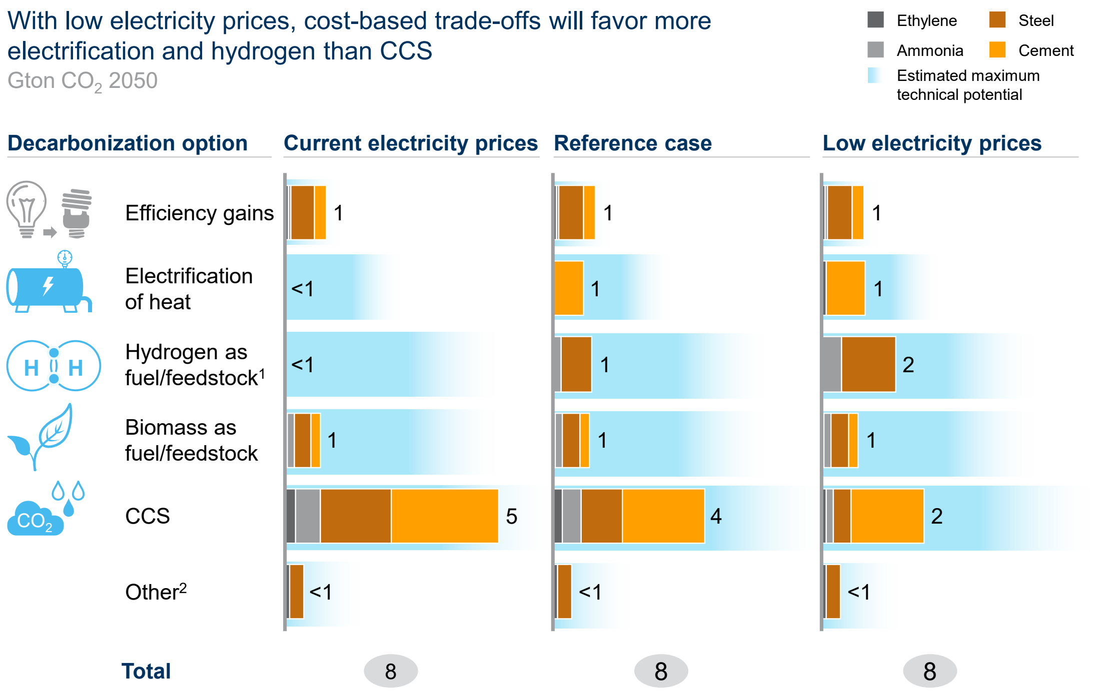
The three sensitivities are as follows: (Exhibit 12)

- Current electricity prices, in which the current electricity prices of more than USD 50/MWh in all regions persist into the future.

- A reference case, in which electricity costs USD 20/MWh in regions with high exposure to solar radiation (e.g., Australia, Middle East, India, Africa) and USD 40/MWh elsewhere.

- Low electricity prices, in which global zero-carbon electricity prices are at USD 20/MWh.

Exhibit 12



NOTE: Differences in totals due to rounding. Options selected based on lowest greenfield/brownfield decarbonization cost for each region, and 20% decarbonization with biomass in each sector. Current electricity prices capped at USD 100/MWh. Reference case with USD 20/MWh in the Middle East, Africa, India, and Australia, and USD 40/MWh in Europe, US, Brazil, and China. Low electricity prices USD 20/MWh; zero-carbon electricity prices in all regions

1 Hydrogen produced from zero-carbon electricity via electrolysis

2 Other includes the projected increase in recycling in ethylene and steel production

CCS is the most economical option for industrial decarbonization at current electricity prices. As expected, lower electricity prices lead to a higher percentage of electrification and hydrogen-based decarbonization options and less CCS. A large share of CCS remains in all sensitivities as it is the sole decarbonization option that reduces cement process emissions.

Estimating the cost of decarbonization and related changes in industrial commodity prices

We measure the cost of decarbonizing the four focus sectors as the difference between the cost of conventional industrial operations and the cost of zero emissions industrial operations.[35] In the three sensitivities, the cost of decarbonization ranges from USD 11 trillion (approximately 50 percent of which is operating expenses) to USD 21 trillion (approximately 60 percent of which is operating expenses). These amounts are equivalent to 0.4 to 0.8 percent of global GDP (USD 78 trillion) per year through 2050. (Exhibit 13 and 14)

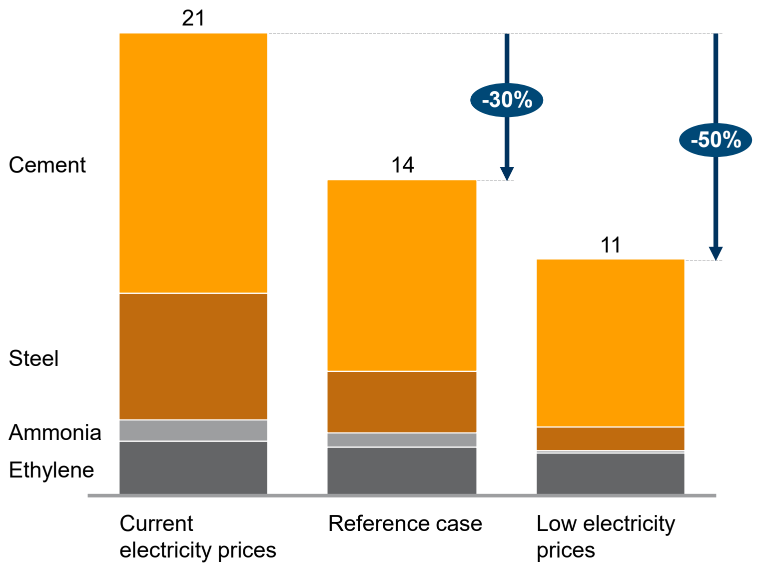
Much of the cost of decarbonization occurs in the cement sector. This is because decarbonizing cement production will depend heavily on CCS, a relatively costly option (~100 to 190 USD/ton CO_2) that is capex intensive and only partially driven by electricity costs. While innovative alternatives for cement feedstocks and fuels could dramatically alter this situation, our assumptions exclude these technological breakthroughs.

[35] At newly built greenfield facilities, we calculate the differences in both capital expenditures and operating expenses. At existing brownfield facilities, we calculate the difference in operating expenses and add the costs of retrofitting the existing facility.

Exhibit 13

The total costs of decarbonization are highly dependent on the electricity price

Cumulative USD 2015-50, trillions

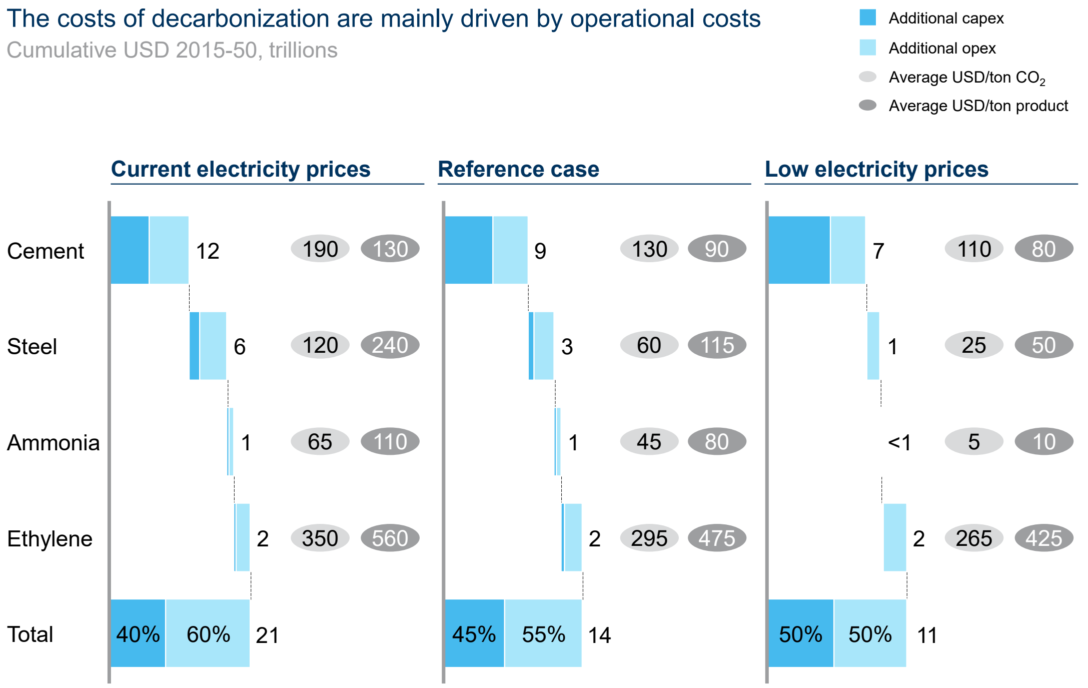


NOTE: Capex estimates have been annualized using an annuity formula, with a real-terms discount rate of 8.5%. Options selected based on lowest greenfield/brownfield decarbonization cost in each region, and 20% decarbonization with biomass in each sector. Current electricity prices capped at USD 100/MWh. Reference case with USD 20/MWh in the Middle East, Africa, India, and Australia, and USD 40/MWh in Europe, US, Brazil, and China. Low electricity prices USD 20/MWh renewable electricity prices in all regions

Exhibit 14

The costs of decarbonization are mainly driven by operational costs

Cumulative USD 2015-50, trillions



NOTE: Capex estimates have been annualized using an annuity formula, with a real-terms discount rate of 8.5%. Options selected based on lowest greenfield/brownfield decarbonization cost in each region, and 20% decarbonization with biomass in each sector. Current electricity prices capped at USD 100/MWh. Reference case with USD 20/MWh in the Middle East, Africa, India, and Australia, and USD 40/MWh in Europe, US, Brazil, and China. Low electricity prices USD 20/MWh; renewable electricity prices in all regions. Difference in totals due to rounding

The production costs of cement, steel, ammonia, and ethylene are expected to increase in all three sensitivities compared to conventional production. The cost of cement, now approximately USD 120/ton, could increase by 70 to 110 percent. Both steel and ammonia could experience a cost increase of 5 to 35 percent above the current level of approximately USD 700/ton steel and USD 300/ton ammonia, while ethylene's cost could increase by 40 to 50 percent from USD 1,000/ton.

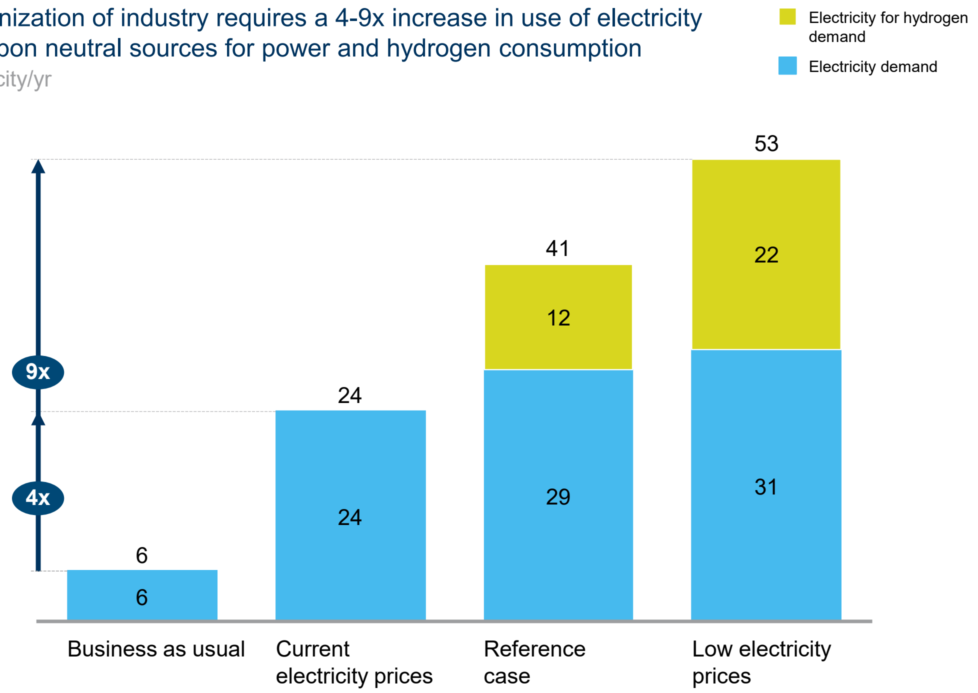
Estimating the need for additional renewable energy capacity

In all three sensitivities, decarbonizing the four focus sectors would increase zero-carbon electricity demand compared to a business-as-usual case. Except for energy-efficiency improvements, each decarbonization option increases electricity demand. Even in the base scenario with relatively little application of direct electrification and hydrogen, the electricity demand increases four fold. For example, CCS installations are expected to require ~1-4 GJ/ton CO_2 of electricity for compressors and heating of amines. Hence, zero-carbon electricity consumption in the industrial sectors in 2050 increases from 6 EJ per year in a business as usual case to ~25 to 55 EJ per year in a decarbonization case. To illustrate what that would mean in terms of generation capacity, we calculated that this supply of electricity could come from installing another ~2,000 GW to ~4,000 GW of wind capacity,[36] or by adding ~3,000 GW to ~7,000 GW of solar PV.[37] Either addition would represent a enormous expansion of the world's renewable electricity generation capacity, which currently includes 350 GW of solar PV capacity and 500 GW of wind power capacity. (Exhibit 15)

Exhibit 15

Decarbonization of industry requires a 4-9x increase in use of electricity from carbon neutral sources for power and hydrogen consumption

EJ electricity/yr



NOTE: Options selected based on lowest greenfield/brownfield decarbonization cost in each region, and 20% decarbonization with biomass in each sector. Current electricity prices capped at USD 100/MWh. Reference case with USD 20/MWh in the Middle East, Africa, India, and Australia, and USD 40/MWh in Europe, US, Brazil, and China. Low electricity prices USD 20/MWh; renewable electricity prices in all regions. Difference in totals due to rounding

[36] Assuming an average capacity factor of 40 percent.

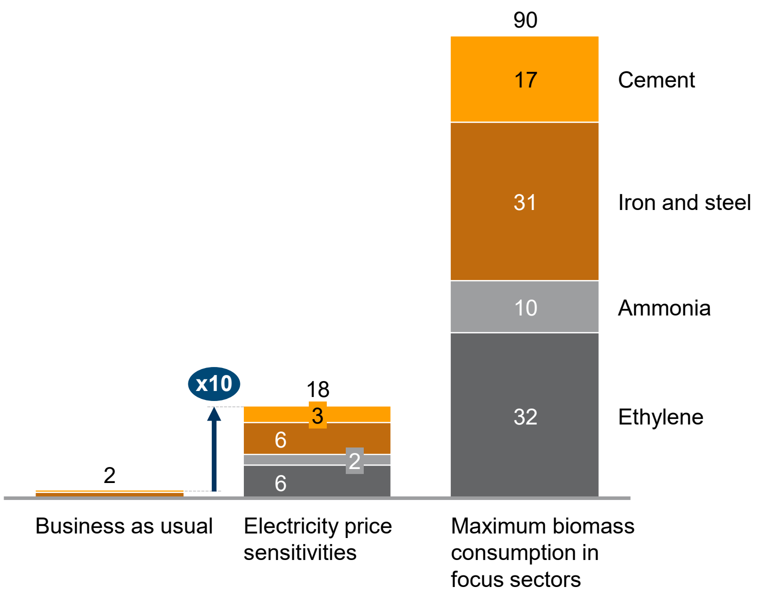
[37] Assuming an average capacity factor of 25 percent.

In all our electricity price sensitivities, we assume a 'fair share' of biomass is used for decarbonization. As a result, about ten times as much biomass is used compared to a business-as-usual scenario. This requires a scale up of both biomass production and (likely) transportation of various kinds of biomass, e.g., biogas, charcoal, bioethanol, biodiesel. (Exhibit 16)

Exhibit 16

Decarbonization of industry could require a large increase in the use of biomass in industrial processes

2050, EJ biomass/yr



NOTE: Electricity price sensitivities assumes 20% decarbonization of virgin production in each sector with biomass. Maximum biomass consumption based on 2050 production numbers and maximum biomass consumption per ton of product produced. Difference in totals due to rounding

6 Charting a way forward

Companies and regulators can prepare for decarbonization by facilitating the availability of resources, investing in transforming production sites, and making targeted investments in innovation. Companies would do well to anticipate the industry transition and begin making the medium- and long-term investments that will position them to compete in a low-carbon economy. Governments and regulators can ease the transition by planning carefully, investing in research and infrastructure, and developing decarbonization options.

By any measure, mitigating CO_2 emissions from the four sectors considered in this report will require tremendous effort and investment in multiple areas at once, such as a huge expansion of the world's zero-carbon energy supply (zero-carbon electricity and hydrogen, biomass), and extensive retrofitting of existing industrial facilities.

As discussed in Chapter 3, application of decarbonization options today is in most cases not competitive with conventional production processes. As there is currently an absence of an economic driver, decarbonization of these processes would require technological breakthroughs, a further lowering of zero-carbon energy prices, changing consumer preferences (willingness to pay) and/or a regulatory push. It is uncertain if one or all of these will materialize, and if they do, in which locations. However, as industrial sites have lifetimes exceeding 50 years and often have investment planning horizons of 30 years, we believe that preparation for these uncertainties should already start in the short term.

In this chapter, we offer some guidelines for planning and managing the transition effectively. This includes an overview of innovation, piloting, scale up and implementation of (innovative) low-carbon technologies and steps that can be taken by governments and individual companies.

Developing decarbonization technologies

Industrial companies will need a full menu of decarbonization options to meet the emissions reduction goals implied by the Paris Agreement. Some decarbonization options, such as energy efficiency and use of biomass, are already mature technology (e.g., charcoal-based steel production). Hence, other options will be required to reach full decarbonization. These can be options that require research (e.g., hydrogen fueled furnaces for cement production) or development (e.g., CCS on industrial sites) before they can be implemented on a commercial scale. In the Technical appendix a detailed overview of the technical maturity of industrial decarbonization options is given.

Today, decarbonization options fall into one of the following three categories: (Exhibit 17)

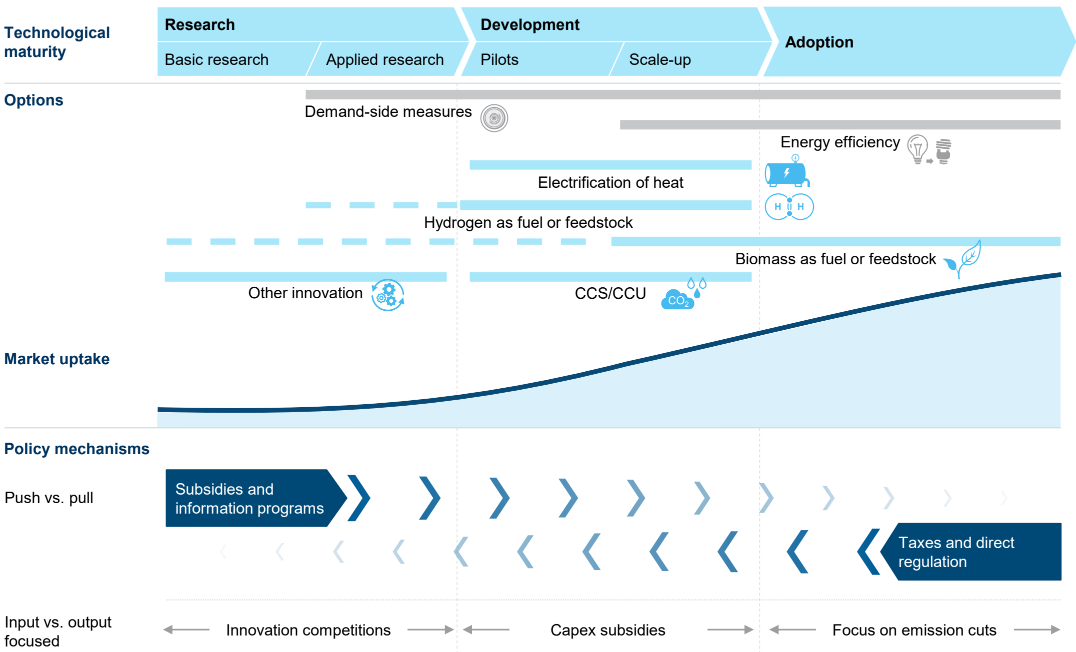
- Research phase options. Though these are not yet commercial and have an uncertain future, they have the potential to decarbonize industry at a lower cost than more mature options because they can be developed for the express purpose of industrial decarbonization. Examples include using innovative electrochemical-based, lower-temperature processes to make monomers and polymers from biomass as an alternative to conventional ethylene production, or the electrification of heat in cement production.

- Development phase options. These still have uncertain costs and should prove their decarbonization potential at the industrial scale. For example, electrical steam-cracking furnaces have yet to be developed for commercial use in ethylene production.

- Adoption phase options. These are ready to apply with only minor changes to processes that are widely used or carried out in specific regions. Existing production sites can accommodate biogas in ammonia production or biomass in cement kilns with little or no retrofitting. Also, electric boilers can replace gas or coal fired boilers for medium temperature heat demand.

Exhibit 17

Innovation is required to ensure the full menu of decarbonization options is available



Preparing for industrial decarbonization

Advance planning and timely action could drive technological maturation, lower the cost of industrial decarbonization and ensure the industry energy transition advances in parallel with required changes in energy supply.

To accelerate the shift to a low-emissions future, industrial companies can take the following steps:

- Review portfolio of assets at the level of individual facilities to understand their access to low-cost zero-carbon electricity, hydrogen, biomass, and CCS. This review should be done for both existing sites and for yet to be developed facilities, on a country-by-country basis. The expected access and costs of available resources, including disruptive scenarios, would have to be taken into account. A first outcome of such a review would be an understanding of the current and future attractiveness of each site in the broader portfolio, in light of these different scenarios. This might already lead to a shift in resource allocation over time.

As a next step, we then typically see a portfolio of activities evolve to improve an asset's or portfolio's resilience against these scenarios. Given the uncertainties, players would develop a portfolio of actions in line with the decarbonization options mentioned in this report. These would range from options to 'sure bets', taking into account the state of technology mentioned above.

- Identify those decarbonization options for which the industrial player is uniquely positioned to take a leading role. This could also lead to strategic investments in innovation or investments and/or set-up of partnerships, also in relation to securing a renewable energy supply.

- Pursue energy efficiency opportunities in the short term as a way of kickstarting decarbonization of production sites. Especially, using new technology, digitization and data analytics can provide an opportunity to capture untapped potential.

Governments and regulators can consider improving local conditions for industry decarbonization in the following ways:

- Develop a roadmap for industry decarbonization based on local access to resources. What we have seen from the analysis in this report is that the link between the industry sector and the power sector would need to be significantly strengthened, given the interdependencies both ways. A roadmap should therefore include a strategy for development and scale up of carbon storage infrastructure, biomass resources, low-cost renewable electricity, and/or hydrogen production or import. The roadmap could help set out a plan-based approach in the roll-out of associated infrastructure, such as carbon storage and (hydrogen) transport pipelines, and extension of the electricity grid to ensure timely connection to sites with newly developed decarbonized production facilities. Setting such a longer-term direction for decarbonization could support planning for decarbonization by other parties, including industrial companies, utilities and owners of key infrastructure (such as the electricity grid or hydrogen pipelines), and unlock investments with long payback times.

- Review the potential decarbonization pathways not only on costs, but especially on 'country-value-add' (such as jobs, competitive position). Such a review would typically lead to other mechanisms to support development and scale up of innovative decarbonization options, especially those which would provide local additional benefits, such as the strengthening of an existing industrial cluster, or increase in jobs.

- Align regulations with the decarbonization initiative and remove barriers by, e.g., creating policies to increase the reuse and recycling of plastics and steel or steering sustainable biomass to sectors that would reap the most benefits from it.

Technical appendix

Commodity price assumptions

In all cost estimations in this document, the global average commodity prices shown in the table below are used. This is done for the purposes of making the costs of decarbonization comparable across sectors. Commodity costs will differ between countries and regions, which impacts the local trade-off between decarbonization options as described in Chapter 3.

Global commodity price assumptions, as used in cost calculations

Product	Price, USD/GJ	Product	Price, USD/GJ
Natural gas	7	Charcoal	7
Coal	2	Solid biomass	3
Coking coal	3	Biodiesel	25
Naphtha	10	Biogas	14
Ethane	2	Bioethanol	16
Electricity[1]	21	Hydrogen	33

1 Depends on sensitivity

Decarbonization options and costs

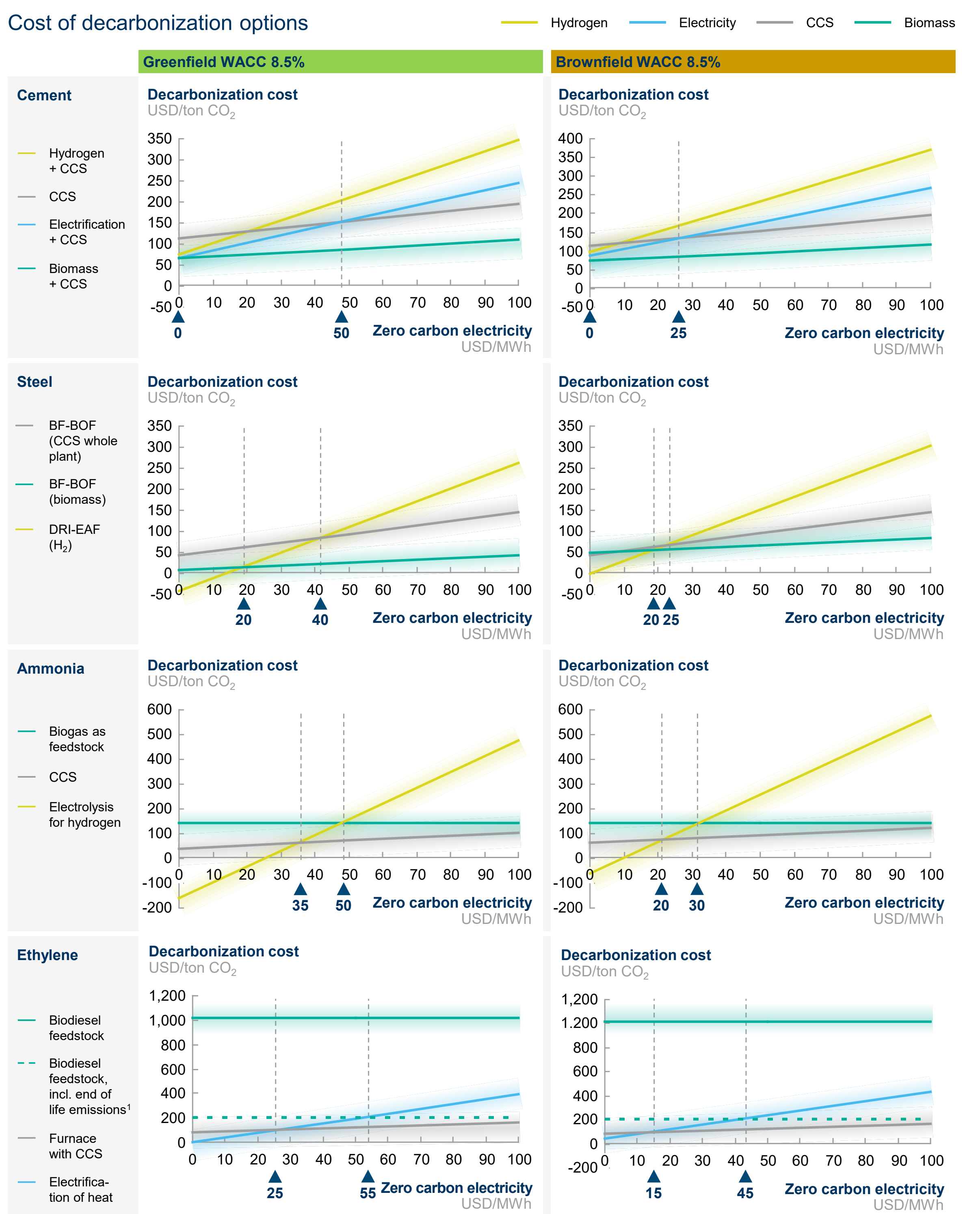
Impact of zero-carbon electricity prices and cost of capital on trade-off between decarbonization options

The local prices of electricity and other energy sources largely determine which decarbonization options are financially advantageous for new (greenfield) and existing (brownfield) production sites. Exhibit 18 on the following page shows the variation in costs with the zero-carbon electricity price. Other commodity prices are held constant.

Impact of WACC assumptions on cost of decarbonization options

The financing of industrial decarbonization will also influence which option will be most economical. In Exhibit 19, a sensitivity of WACC on the costs of decarbonization is shown for greenfield ammonia production. A higher WACC increases costs and hence reduces the attractiveness for capital intensive decarbonization options, such as electrolysis and CCS.

Exhibit 18



NOTE: Costs based on average commodity prices (see technical appendix). Greenfield decarbonization costs are calculated as the sum of delta capex and delta opex between conventional and decarbonized processes, divided by the tons of CO_2 abated. Brownfield decarbonization costs are calculated as the delta in opex between conventional and decarbonized processes plus the capex required for retrofit or rebuild of the existing site, divided by the tons of CO_2 abated. Hydrogen from electrolysis of zero carbon electricity based on capex of USD 450/MWh, 30% installation costs, and 70% efficiency. Capex estimates have been annualized using an annuity formula with a real terms discount rate of 8.5%. Research phase technology costs have been estimated on a best effort basis.

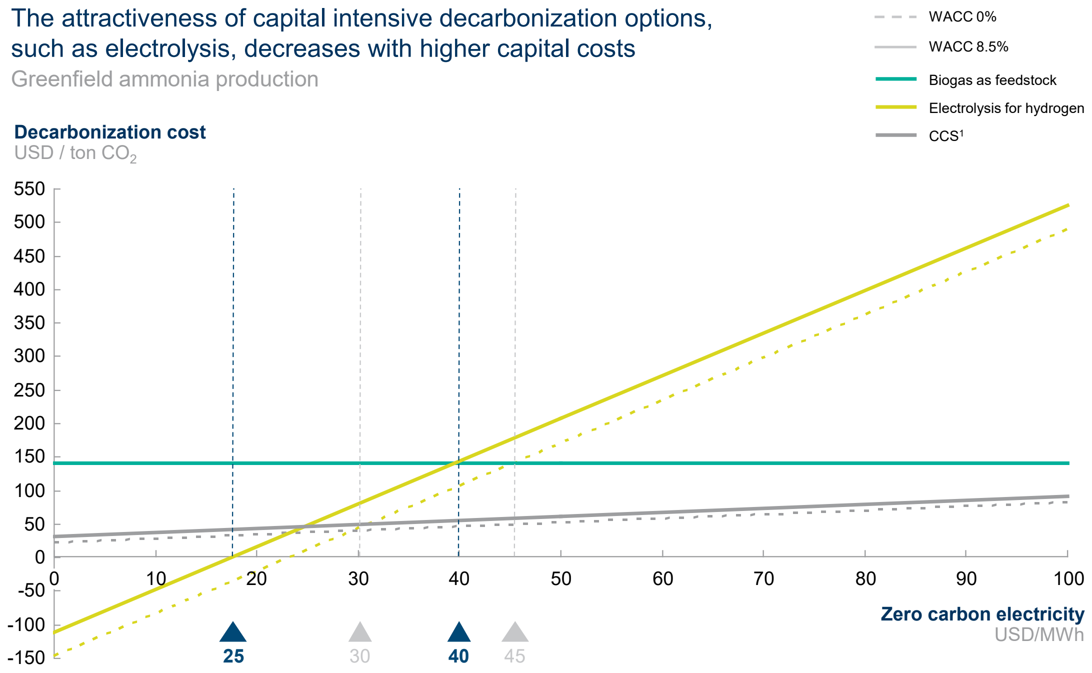
1 Decarbonization costs divided by both production emissions and end of life emissions

SOURCE: Enerdata – Global Energy and CO_2 data; DECHEMA 2017 – Low carbon energy and feedstock; IEA 2009 – The chemical and petrochemical sector; IEA 2009 – Cement technology roadmap; IETD IITD network; Berkeley National Laboratory; US Department of Energy; US EPA; Global CCS Institute; CSI – Development of State of the Art techniques in Cement Manufacturing 2017; Expert interviews

Exhibit 19

The attractiveness of capital intensive decarbonization options, such as electrolysis, decreases with higher capital costs

Greenfield ammonia production



NOTE: Capex estimates have been annualized using an annuity formula, with a real terms discount rate of 8.5%. Commodity prices are based on global averages and held constant. Natural gas prices assumed of USD 6.6 /MmBTu. Hydrogen is tied to electricity prices through the electrolyzer process. Electrolyzer availability of 50%, efficiency of 70% and capex cost of 450 USD/kW plus 30% installation costs. Electrified Haber-Bosch equipment assumed to have same efficiency as natural gas fired equipment

1 CCS abatement cost is electricity-price-dependent because CCS consumes power and Haber-Bosch process is electrified

SOURCE: DECHEMA 2017 – Low carbon energy and feedstock; IEA 2009 – The chemical and petrochemical sector; Industry efficiency technology database; Enerdata; Expert interviews

Technological maturity of decarbonization options

There are decarbonization options beyond those shown in the graphs in this report. Most options were not selected for trade-off graphs as they are technically less mature, making cost estimates less robust. Technological maturation of these and the other decarbonization options is required to increase the number of options available and reduce the cost. On the next page an extended list of decarbonization options is given, including their technological maturity. (Exhibit 20)

Exhibit 20

Overview of assessed decarbonization options for industry

		Electrification of heat	Hydrogen as fuel or feedstock	Biomass as fuel or feedstock
Feedstock and fuel	Cement	✓ *Conventional process with electricity as fuel*	✓ *Conventional process with hydrogen as fuel*	✓ *Conventional process with biomass as fuel*
	Iron and steel[1]		✓ DRI-EAF with hydrogen as feedstock	✓ BF-BOF with charcoal as fuel and feedstock ✓ DRI-EAF with biogas as feedstock
	Ammonia		✓ Electrolysis and Haber-Bosch process with electricity as fuel	✓ SMR with biogas feed-stock (from gasification of wet biomass) and Haber-Bosch process with biogas fuel
	Ethylene	✓ Conventional process with electricity as fuel in furnace and electrification of separation steps	✓ Conventional process with hydrogen as fuel In furnace	✓ Conventional process with biogas as fuel in furnace ✓ Conventional process with biodiesel as feedstock ✓ Dehydration of bioethanol
Fuel	Other industry[2] (heat)	✓ Electric heat pump for low-temperature heat ✓ Electric boiler for low- and medium-temperature heat ✓ *Hybrid boiler with electricity or natural gas for low- and medium-temperature heat* ✓ Electric furnace for high-temperature heat	✓ Boiler for low- and medium-temperature heat with hydrogen as fuel ✓ Furnace for high-temperature heat with hydrogen as fuel	✓ Boiler for low- and medium-temperature heat with biogas or other biomass as fuel ✓ Furnace for high-temperature heat with biogas or other biomass as fuel

1 Decarbonization options include electrification of downstream processing
2 Includes manufacturing, construction, food and tobacco, etc.

SOURCE: Enerdata – Global Energy and CO_2 data; DECHEMA 2017 – Low carbon energy and feedstock; IEA 2009 – The chemical and petrochemical sector; IEA 2009 – Cement technology roadmap; IETD IITD network; Berkeley National Laboratory; US Department of Energy; US EPA; Global CCS Institute; CSI – Development of State of the Art techniques in Cement Manufacturing 2017; Expert interviews; McKinsey analysis

✓ Applied at industrial-scale sites ✓ Technology (to be applied) in pilot site ✓ (Applied) research phase

Italics – carbon emissions reduction potential is less than 100% **Bold –** conventional option used in decarbonization cost calculations

CCS	Other innovations	Conventional option
✓ Conventional process with CCS on both process and fuel emissions ✓ *Adjusted process with CCS on a pure flow of process emissions* ✓ *Conventional process with CCS on oxy-fuel combustion emissions*	Alternatives for conventional lime-stone feedstock ✓ Blending of clinker with slag/fly ash ✓ Blending of clinker with other minerals ✓ Replacement of limestone feedstock ✓ Conventional process with CO_2 absorption in setting concrete	▪ **Coal as fuel and limestone as feedstock** ▪ Petcoke as fuel and limestone as feedstock ▪ Natural gas as fuel and limestone as feedstock
✓ Conventional BF-BOF with CCS on all exhaust gases ✓ BF-BOF with HIsarna technology and CCS on all exhaust gases ✓ BF-BOF with top-gas recycling, coke oven gas rerouting, and CCS on all exhaust gases	✓ Electrolysis for iron ore reduction	▪ **BF-BOF with coal as fuel and feedstock** ▪ DRI-EAF with natural gas as feedstock
✓ Conventional process with CCS on process emissions ✓ Conventional process with CCS on process and fuel emissions ✓ Autothermal reforming for hydrogen production with CCS on emissions	✓ Methane pyrolysis for hydrogen production ✓ High temperature electrolysis for hydrogen production ✓ Haber-Bosch process with hydrogen from biomass pyrolysis	▪ **SMR with natural gas feedstock and Haber-Bosch process with natural gas fuel** ▪ Haber-Bosch process with hydrogen feedstock from coal gasification
✓ Conventional process with CCS on furnace exhaust gases	✓ Alternative bio-based polymers made in a tailored production process ✓ Electrochemical processes for monomer production	▪ **Ethylene steam-cracking with naphtha feedstock** ▪ Ethylene steam-cracking with ethane or other fossil-fuel-based feedstock
✓ Conventional boiler for low- and medium-temperature heat with CCS ✓ Conventional furnace for high-temperature heat with CCS	✓ Electric heat pumps for medium-temperature heat ✓ Solar thermal for medium-tempera-ture heat ✓ High temperature nuclear for medium- to high-temperature heat	▪ Boiler for low- and medium-temperature heat with fossil fuel (e.g., coal, natural gas) ▪ Furnace for high-temperature heat with fossil fuel (e.g., coal, natural gas)

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