Transforming Industry through CCUS

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Abstract

Industry is the basis for prospering societies and central to economic development. As the source of almost one-quarter of CO_2 emissions, it must also be a central part of the clean energy transition. Emissions from industry can be among the hardest to abate in the energy system, in particular due to process emissions that result from chemical or physical reactions and the need for high-temperature heat. A portfolio of technologies and approaches will be needed to address the decarbonisation challenge while supporting sustainable and competitive industries.

Carbon capture, utilisation and storage (CCUS) is expected to play a critical role in this sustainable transformation. For some industrial and fuel transformation processes, CCUS is one of the most cost-effective solutions available for large-scale emissions reductions. In the IEA Clean Technology Scenario (CTS), which sets out a pathway consistent with the Paris Agreement climate ambition, CCUS contributes almost one-fifth of the emissions reductions needed across the industry sector. More than 28 gigatonnes of carbon dioxide ($GtCO_2$) is captured from industrial processes in the period to 2060, the majority of it from the cement, steel and chemical subsectors.

A strengthened and tailored policy response will be needed to support the transformation of industry consistent with climate goals while preserving competitiveness. The development of CO_2 transport and storage networks for industrial CCUS hubs can reduce unit costs through economies of scale and facilitate investment in CO_2 capture facilities. Establishing markets for premium lower-carbon materials – such as cement, steel and chemicals – through public and private procurement can also accelerate the adoption of CCUS and other lower-carbon industrial processes.

Highlights

- **Industrial production must be transformed to meet global climate goals.** Industry today accounts for one-quarter of CO_2 emissions from energy and industrial processes and 40% of global energy demand. Demand for cement, steel and chemicals will remain strong to support a growing and increasingly urbanised global population. The future production of these materials must be more efficient and emit much less CO_2 if climate goals are to be met.

- **Emissions from cement, iron and steel, and chemical production are among the most challenging to abate.** One-third of industry energy demand is for high-temperature heat, for which there are few mature alternatives to the direct use of fossil fuels. Process emissions, which result from chemical reactions and therefore cannot be avoided by switching to alternative fuels, account for one-quarter (almost 2 gigatonnes of carbon dioxide [$GtCO_2$]) of industrial emissions. Industrial facilities are also long-lived assets, leading to potential "lock-in" of CO_2 emissions.

- **Carbon capture, utilisation and storage (CCUS) is a critical part of the industrial technology portfolio.** In the Clean Technology Scenario (CTS), which sets out an energy system pathway consistent with the Paris Agreement, more than 28 $GtCO_2$ is captured from industrial facilities in the period to 2060. CCUS delivers 38% of the emissions reductions needed in the chemical subsector and 15% in both cement and iron and steel.

- **CCUS reduces the cost and complexity of industry sector transformation.** CCUS is already a competitive decarbonisation solution for some industrial processes, such as ammonia production, which produce a relatively pure stream of CO_2. Limiting CO_2 storage deployment would require a shift to nascent technology options and result in a doubling of the marginal abatement cost for industry in 2060.

- **Developing CCUS hubs can support new investment opportunities.** Investing in shared CO_2 transport and storage infrastructure can reduce unit costs through economies of scale as well as enable – and attract – investment in CO_2 capture for existing and new industrial facilities. The long timeframes associated with developing this infrastructure requires urgent action.

- **Establishing a market for premium lower-carbon materials can minimise competitiveness impacts.** Public and private procurement for lower-carbon cement, steel and chemicals can accelerate the adoption of CCUS and other lower-carbon processes. The large size of contracts for these materials could help establish significant and sustainable markets worldwide.

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Executive summary

Industrial production must be transformed to meet climate goals

Industry is the basis for prospering societies and central to economic development. The materials produced by the industry sector make up the buildings, infrastructure, equipment and goods that underpin modern lifestyles.

Today, industry accounts for almost one-quarter of CO_2 emissions from the combustion of fossil fuels and industrial processes and 40% of global energy demand. Continued economic growth and urbanisation, particularly in developing economies, will spur strong demand for cement, steel and chemicals. The future production of these materials must be more efficient and emit much less CO_2 if climate goals are to be met.

Emissions from industry are among the most challenging to abate

The challenge to reduce CO_2 emissions is formidable. Industry sector emissions are among the hardest to abate in the energy system, from both a technical and financial perspective.

One-quarter of industry emissions are non-combustion **process emissions** that result from chemical or physical reactions, and therefore cannot be avoided by a switch to alternative fuels. This presents a particular challenge for the cement subsector, where 65% of emissions result from the calcination of limestone, a chemical process underlying cement production.

Furthermore, one-third of the sector's energy demand is used to provide **high-temperature heat**. Switching from fossil to low-carbon fuels or electricity to generate this heat would require facility modifications and substantially increase electricity requirements.

Industrial facilities are **long-lived assets** – of up to 50 years – so have the potential to "lock in" emissions for decades. Exposure to highly competitive, low-margin international **commodity markets** accentuates the challenges faced by firms and policy makers.

Carbon capture, utilisation and storage is critical for industry decarbonisation

A portfolio of technologies and approaches will be needed to address the decarbonisation challenge while supporting industry sustainability and competitiveness. Carbon capture, utilisation and storage (CCUS) technologies can play a critical role in reducing industry sector CO_2 emissions.

For some industrial and fuel transformation processes, CCUS is one of the most cost-effective solutions available to reduce emissions; in some cases as low as USD 15-25 (United States dollars) per tonne of CO_2. In the IEA Clean Technology Scenario (CTS), which maps out a pathway consistent with the Paris Agreement, CCUS contributes almost one-fifth of the emissions reductions needed across the industry sector.

In the CTS, more than 28 gigatonnes of carbon dioxide (GtCO2) is captured from industrial processes in the period to 2060, the vast majority of it from the cement, iron and steel and chemical subsectors. CCUS makes significant inroads in these three subsectors in the 2020s, growing to 0.3 GtCO2 captured in 2030, with rapid expansion thereafter to reach almost 1.3 GtCo2 capture in 2060.

With increasing ambition in the pursuit of net zero emissions from the energy system, the role of CCUS becomes even more pronounced. In particular, greater deployment of CCUS is required to decarbonise industry and to support negative emissions through bioenergy with CCS.

Policy action is urgently needed to advance CCUS and support industry transformation

It is critical that CCUS application in industry accelerates and that opportunities for increased investment be identified. A strong and tailored policy response is needed, requiring partnerships between and across governments, industry, financial services and stakeholders. This report highlights several key priorities and strategies to support investment in CCUS for industry decarbonisation.

- Facilitating the development of CCUS hubs in industrial areas with shared CO2 transport and storage infrastructure reduces costs for facilities incorporating carbon capture into their production processes. This could attract new investments while maintaining existing facilities under increasingly climate-constrained conditions.
- Establishing a market for low-carbon materials, including steel and cement, through public and private procurement measures would provide a strong signal for firms to shift to low-carbon production.
- Identifying and facilitating early investment in competitive and lower-cost CCUS applications in industry could provide important lessons and support infrastructure development.

Findings and recommendations

Policy recommendations

- Support the development and deployment of carbon capture, utilisation and storage (CCUS) in industry as part of a least-cost portfolio of technologies needed to achieve climate and energy goals.
- Identify and prioritise competitive and lower-cost CCUS investment opportunities in industry to provide learnings and support infrastructure development.
- Facilitate the development of CCUS "hubs" in industrial areas with shared transport and storage infrastructure to reduce costs for facilities incorporating carbon capture into production processes.
- Implement policy frameworks that support significant emissions reductions across industrial facilities while addressing possible competitiveness impacts.
- Establish a market for low-carbon materials, including steel and cement, through public and private procurement measures.

CCUS can support sustainable and competitive industry

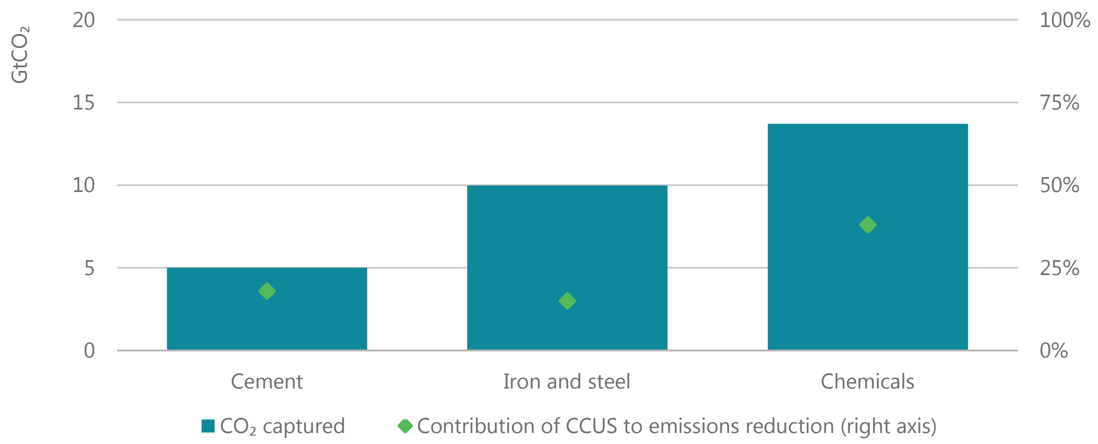
Carbon capture, utilisation and storage (CCUS) technologies are expected to play a critical role in the sustainable transformation of the industry sector. Today, 16 large-scale CCUS applications at industrial facilities are capturing more than 30 million tonnes (Mt) of CO_2 emissions each year from fertiliser (ammonia), steel and hydrogen production, and from natural gas processing.

CCUS is one of the most cost-effective solutions available to reduce emissions from some industrial and fuel transformation processes – especially those that inherently produce a relatively pure stream of CO_2, such as natural gas and coal-to-liquids processing, hydrogen production from fossil fuels and ammonia production. CCUS can be applied to these facilities at a cost as low as USD 15-25 (United States dollars) per tonne of CO_2 in some cases, and provides an opportunity to reduce CO_2 emissions by avoiding the current practice of venting CO_2 to the atmosphere.

CCUS can also play a key role in reducing emissions from the hardest-to-abate industry subsectors, particularly cement, iron and steel, and chemicals. Alongside energy efficiency, electrification (including electrolytic hydrogen) and the increased direct use of renewable energy, CCUS is part of a portfolio of technologies and measures that can deliver deep emissions reductions at least cost in these subsectors.

In the International Energy Agency (IEA) Clean Technology Scenario (CTS), which maps out a pathway consistent with the Paris Agreement climate ambition, CCUS contributes almost one-fifth of the emissions reductions needed across the industry sector. More than 28 gigatonnes of carbon dioxide ($GtCO_2$) is captured from industrial processes by 2060, mostly from the cement, iron and steel and chemical subsectors (Figure 1). A further 31 $GtCO_2$ is captured from fuel transformation, and 56 $GtCO_2$ from the power sector.

Figure 1. CCUS emissions reductions by subsector in the CTS, 2017-60



Source: IEA (2019). All rights reserved.

CCUS significantly reduces cement, iron and steel and chemical emissions in the CTS.

As ambition increases in the pursuit of net-zero energy system emissions, the role of CCUS becomes even more pronounced (IEA, 2017). Wider deployment of CCUS is especially important to decarbonise industry and support the generation of negative emissions through bioenergy with CCS (BECCS).

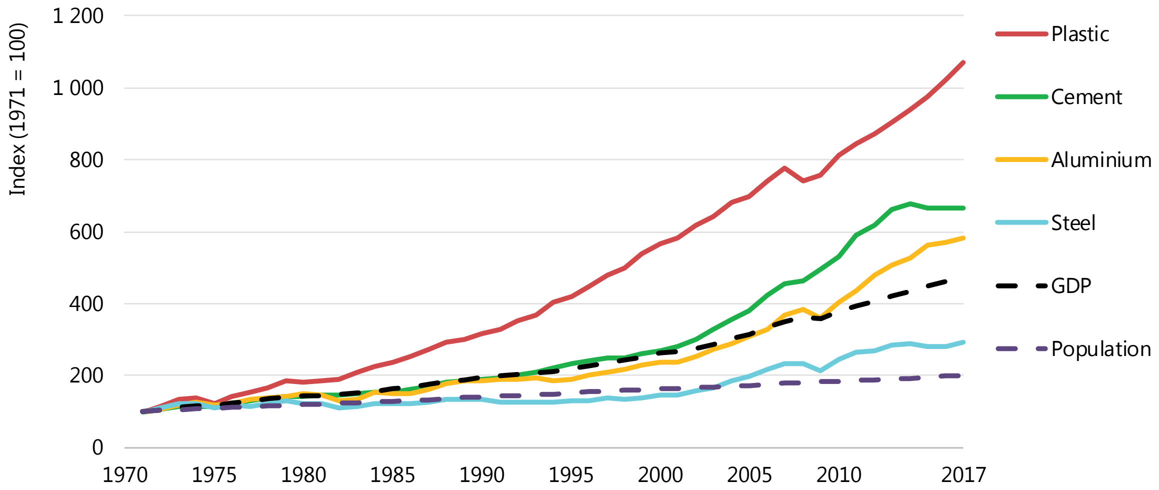
In recommending that the United Kingdom (UK) adopt a target of net-zero greenhouse gas (GHG) emissions by 2050, the UK Climate Change Committee recognised that "CCS is a necessity, not an option", and noted that early action to meet international demand for low-carbon materials could give UK firms a competitive advantage (CCC, 2019). Furthermore, early development of CO_2 transport and storage infrastructure could attract new industry investments while maintaining existing facilities in an increasingly climate constrained world.

Industry drives economic growth and development

Industry is the basis for prospering societies, central to economic development and the source of about one-quarter of global gross domestic product (GDP) and employment. The materials and goods produced by industrial sectors make up the buildings, infrastructure, equipment and goods that enable businesses and people to carry out their daily activities.

Increasing demand for cement, steel and plastics has historically coincided with economic and population growth. Since 1971, global demand for steel has increased by a factor of three, cement by nearly seven, primary aluminium by nearly six and plastics by over ten. At the same time, the global population has doubled and GDP has grown nearly fivefold (Figure 2).

Figure 2. Global trends in the production of major industrial products, GDP and population over the previous four decades



Source: IEA (2019).

Demand for industrial products is closely linked with GDP growth.

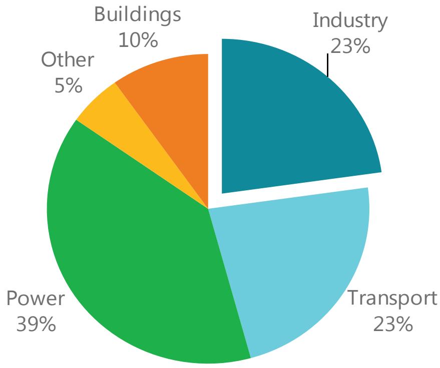
Global population expansion, increased urbanisation, and economic and social development will underpin continued strong demand for these key materials. Advanced economies currently use up to 20 times more plastic and 10 times more fertiliser per capita than developing economies (IEA, 2018a), and global demand for cement is expected to increase 12-23% by 2050 (IEA, 2018b).

One-quarter of CO_2 emissions are from industry

Industry is the second-largest source of CO_2 emissions from energy and industrial processes (equal with transport) after the power sector (Figure 3). It accounted for nearly 40% of total final energy consumption and nearly one-quarter (8 $GtCO_2$) of direct CO_2 emissions in 2017. If indirect emissions (i.e. emissions resulting from industrial power and heat demand) are also taken into account, the sector is responsible for nearly 40% of CO_2 emissions.

Steel and cement are the two highest-emitting industry subsectors. Together they accounted for 12% of total direct global CO_2 emissions in 2017: 2.2 $GtCO_2$ from cement and 2.1 $GtCO_2$ from iron and steel. The chemical subsector was the third-largest emitter at 1.1 $GtCO_2$.

Figure 3. Direct CO_2 emissions by sector, 2017



Source: IEA (2019).

Industry and transport are the second-largest sources of emissions behind the power sector.

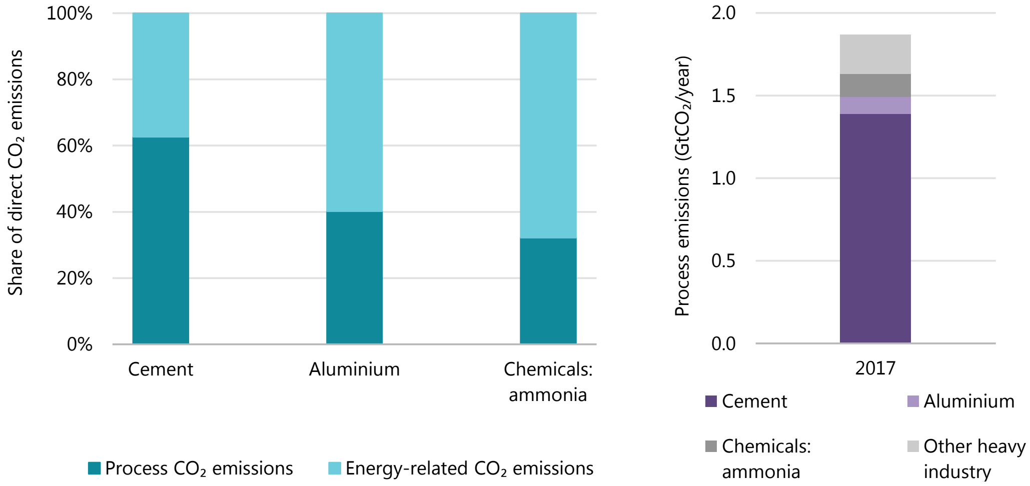
Industry emissions are among the most challenging to mitigate

Industry sector emissions are among the hardest to abate in the energy system, from both a technical and financial perspective.

Many industrial processes require **high-temperature heat**, which accounts for one third of the sector's final energy consumption. Switching from fossil to alternative fuels for processes that require temperatures as high as 1 600 degrees Celsius (°C) is difficult and costly, necessitating facility modifications and electricity requirements that may be prohibitively expensive.

Almost one-quarter of industrial emissions are **process emissions** that result from chemical or physical reactions and therefore cannot be avoided by switching to alternative fuels. Process emissions are a particular feature of cement production, accounting for 65% of emissions, but they are also significant in iron and steel, aluminium and ammonia production (Figure 4).

Figure 4. Process emissions from selected industry subsectors

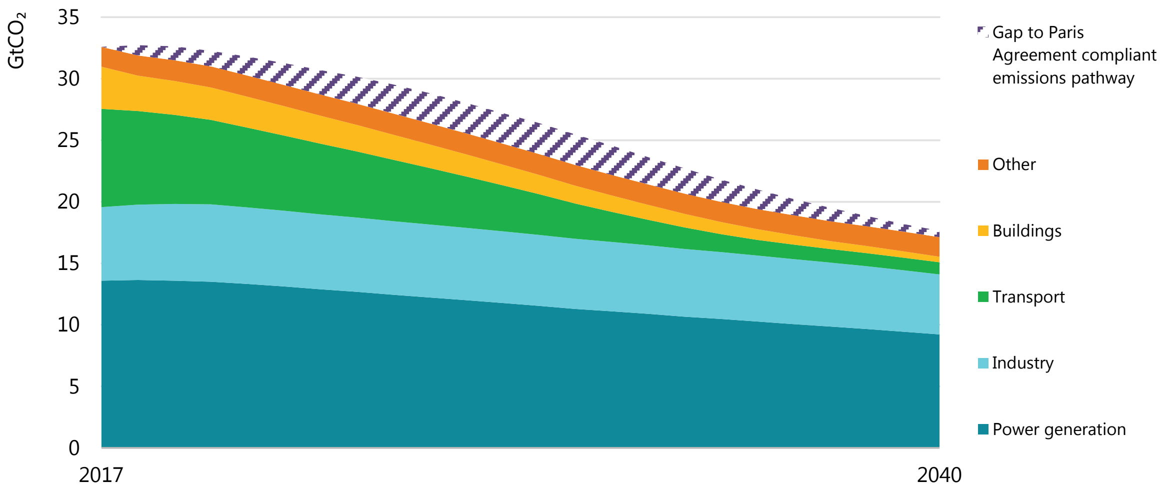


Source: IEA (2019).

Process emissions account for about two-thirds of cement and one-quarter of total industrial emissions.

Industrial facilities are **long-lived assets** – of up to 50 years – and these assets have the potential to "lock in" emissions for decades. The global production capacity of both clinker (the main component of cement) and steel has doubled since 2000, suggesting that at least half of the current production capacity is less than 20 years old. The *World Energy Outlook 2018* analysis shows that emissions from existing industrial infrastructure alone could account for some 25% of the carbon emissions allowable in a pathway compatible with the Paris Agreement until 2040 (Figure 5). The lock-in effect from the industry sector lasts longer than those from power generation, transport and building sectors.

Figure 5. Lock-in of current infrastructure



Source: IEA (2019).

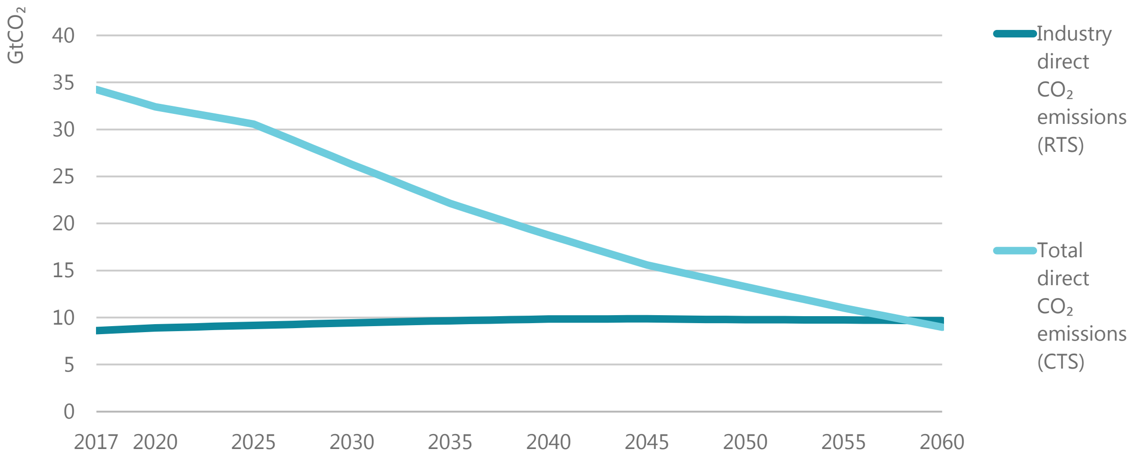
Industrial infrastructure already in place and currently being built will lock in one-quarter of the CO_2 emissions allowable in a pathway consistent with the Paris Agreement.

Beyond the technical challenges for industry decarbonisation, highly competitive, low-margin commodity markets for key industrial products can provide limited room for facilities to invest in innovation or low-carbon production routes where this increases costs. Except for cement, products are traded globally and are price-takers in international markets; companies that increase production costs by adopting low-carbon processes and technologies will therefore be at an economic disadvantage. This is especially the case where there is no carbon price or CO_2 emissions are not regulated.

Without action, industry emissions could derail climate goals

A trajectory following current trends for emissions reductions in the industry sector falls far short of the cuts needed to address the climate change challenge. Without substantial action soon, the share of emissions from industry will rise significantly and would absorb 45% of the cumulative CO_2 emissions allowable in the CTS to 2060. By 2060, industry sector emissions would be greater than total annual emissions in the CTS, which keeps CO_2 emissions within a pathway consistent with the Paris Agreement (Figure 6).

Figure 6. Industry emissions pathway in the RTS compared with overall CTS emissions



Notes: The Reference Technology Scenario (RTS) includes current country commitments to limit emissions and improve energy efficiency, including Nationally Determined Contributions (NDCs).
Source: IEA (2019).

Without large-scale deployment of new technologies such as CCUS, industry emissions in the Reference Technology Scenario (RTS) exceed total emissions in the CTS by 2060.

CCUS is central to the industry decarbonisation portfolio

A portfolio of technologies is deployed in the CTS to reduce emissions from the cement, iron and steel, and chemical subsectors. CCUS is the third most-important lever for emissions reductions in these subsectors, contributing a cumulative 27% (21 $GtCO_2$) of emissions reductions by 2060 relative to the RTS (Figure 7).

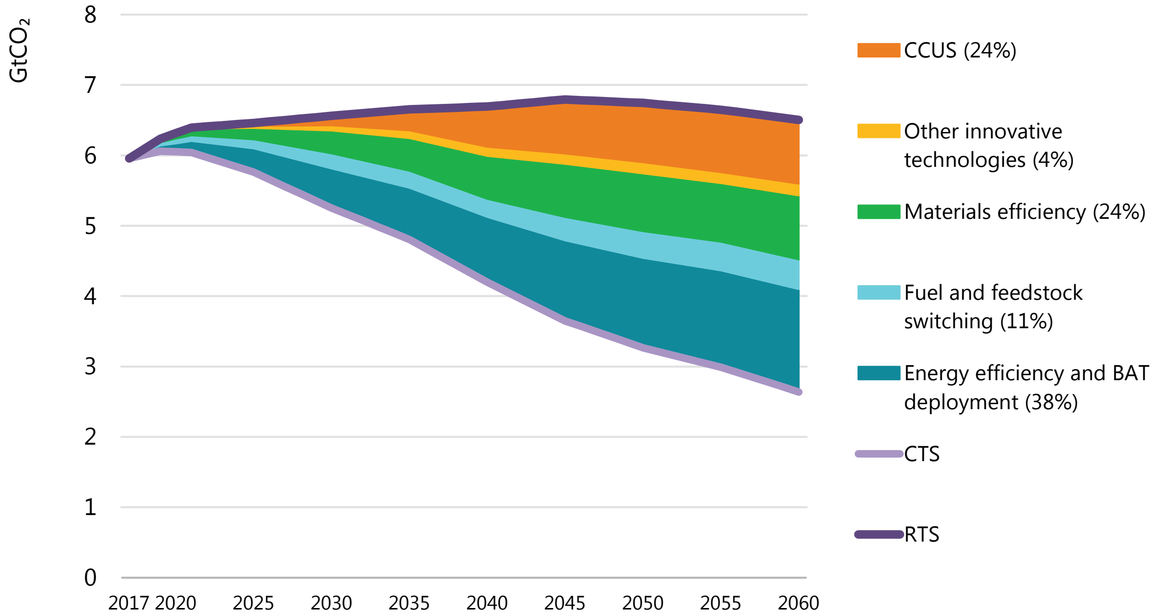
The quantity of CO_2 captured with CCUS and its relative contribution to abatement varies for each industry subsector (Figure 8).

Cement: CCUS contributes 18% to emissions reductions between 2017 and 2060, capturing 5 $GtCO_2$ by 2060.

Iron and steel: While the relative contribution of CCUS to emissions reductions is slightly lower in the iron and steel subsector (15%), cumulative capture of 10 $GtCO_2$ by 2060 is nearly double that for cement.

Chemicals: CCUS is the most important contributor to chemical sector decarbonisation, accounting for 38% of overall emissions reductions. CO_2 capture in chemicals is also the highest (14 $GtCO_2$) owing to several production processes that yield relatively pure streams of CO_2 that are relatively inexpensive to capture.

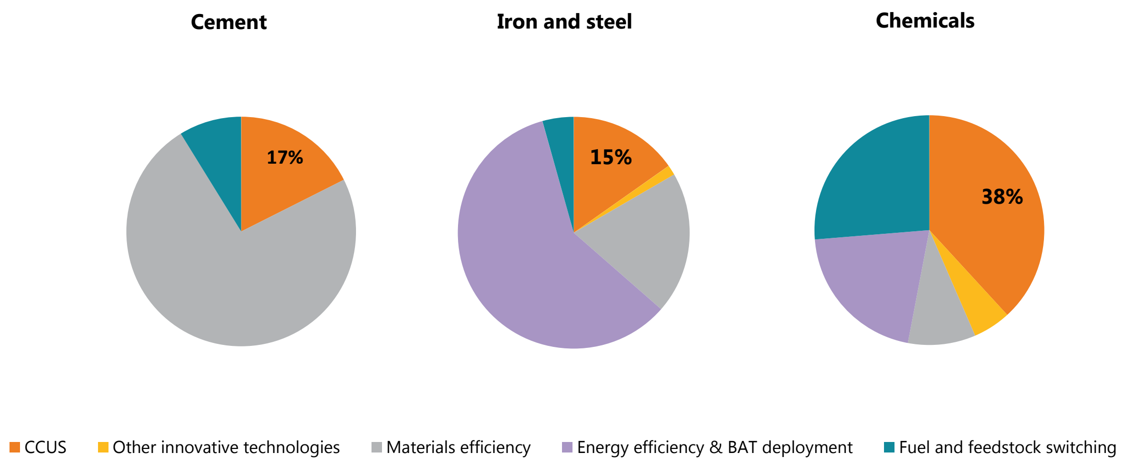
Figure 7. Emissions reductions for key industry subsectors (cement, iron and steel, chemicals) by mitigation strategy, CTS compared with RTS, 2017-60



Note: BAT = best available technology.
Source: IEA (2019).

CCUS contributes 24% of the cumulative emissions reductions from the RTS to the CTS.

Figure 8. Global cumulative direct CO_2 emissions reductions in cement, iron and steel, and chemicals in the CTS, 2017-60



Notes: Materials efficiency includes opportunities that exist throughout value chains, such as designing for long life, lightweighting, reducing material losses during manufacturing and construction, lifetime extension, more intensive use, reuse and recycling, and in the case of cement, it notably includes reduction in the clinker-to-cement ratio; BAT = best available technology.
Source: IEA (2019).

CCUS is the third-largest decarbonisation mechanism in the iron and steel subsector under the CTS, accounting for 15% of emissions reductions, and the most important lever in chemical production.

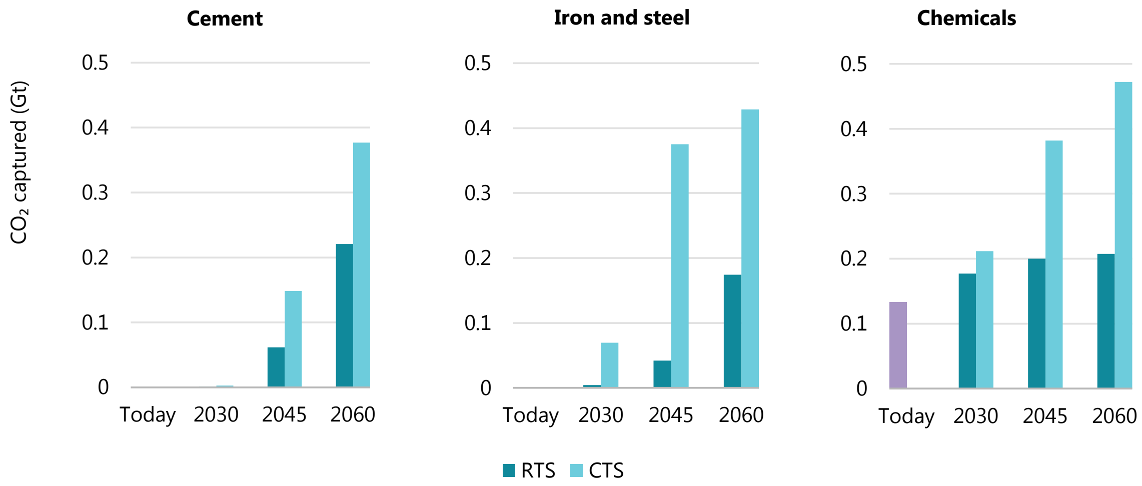
CO_2 management becomes integral to industrial production

The need for deep emissions reductions in the CTS results in large volumes of CO_2 being captured from industrial production and transported for use or storage (Figure 9). The chemicals subsector already has significant CO_2 capture today, with more than 0.1 $GtCO_2$ annually captured from ammonia production for use as a raw material in fertiliser manufacture. In the CTS, CO_2 capture from chemical production would triple to nearly 0.5 $GtCO_2$ by 2060, with most of the additional CO_2 permanently stored. Iron and steel sees significant implementation of CCUS by 2030, with deployment accelerating after 2030 as CCUS becomes an increasingly competitive and important decarbonisation option for the sector.

In the cement sector, implementation of strong material efficiency measures in the CTS leads to a 5% reduction in global cement demand in 2030 compared to RTS levels, which contributes to relatively slow CCUS uptake over the coming decade. However, a rapid increase in CO_2 capture levels occurs from 2030, to reach 0.4 $GtCO_2$ by 2060. This future scale-up in the cement sector is dependent on significant investment in CO_2 capture demonstration projects and infrastructure development prior to 2030.

Effective management of large volumes of CO_2 from industrial production will require planning and development of CO_2 transport and storage infrastructure in the near term. These investments can have lead-times of several years, particularly for pipelines and for greenfield CO_2 storage sites, and could become a limiting factor for CCUS uptake without timely action.

Figure 9. CO_2 capture in cement, iron and steel and chemical subsectors in the RTS and CTS, today through 2060



There is a significant ramp up in CO2 capture in industry to 2060, reaching nearly 1.3 GtCO2 captured across cement, iron and steel, and chemical production in the CTS.

CCUS cuts the cost and complexity of industry transformation

The importance and value of CCUS to the industry sector is revealed in IEA scenario analysis that considers the implications of a failure to develop CO_2 storage at scale (the Limited CO_2 Storage scenario variant, or LCS). In the LCS, CO_2 storage availability across the whole energy system is assumed to be restricted to 10 $GtCO_2$ in the period to 2060, compared with 107 $GtCO_2$ of storage in the CTS (IEA, forthcoming).

For industry, limiting the availability of CCUS as a mitigation option would require a shift to alternative strategies and novel technologies that often are at an earlier stage of development and in some cases have yet to be tested at scale. In the cement sector in particular, the paucity of alternatives to address emissions means that it would not be able to reduce its emissions at the scale of the CTS, even though it would secure almost half of the available CO_2 storage capacity that is assumed to be available in LCS.

In the LCS, the limited availability of CO_2 storage would result in a doubling of the marginal CO_2 abatement cost by 2060 relative to the CTS where CCUS is widely available.

References

CCC (Committee on Climate Change) (2019), *Net Zero: The UK's Contribution to Stopping Global Warming*, CCC, London.

IEA (International Energy Agency) (forthcoming), *Exploring Clean Energy Pathways: The Role of CO_2 Storage*, Paris.

IEA (2018a), *The Future of Petrochemicals*, Paris.

IEA (2018b), *Technology Roadmap: Low-Carbon Transition in the Cement Industry*, Paris.

IEA (2017), Energy Technology Perspectives 2017, Paris.

A spotlight on the industry sector

The industrial sector provides the foundation for prosperous societies and is central to global economic development. This analysis focuses in particular on the cement, iron and steel, and chemicals[1] sectors, which are fundamental to our modern lifestyle in providing buildings and infrastructure as well as pharmaceuticals, fertilisers and plastics. Demand for these industrial products is expected to remain strong for decades to come, particularly in emerging economies and to support increased urbanisation. For example, the world's building stock is projected to double by 2060 — the equivalent of adding another New York City every month between now and then (IEA, 2017). This will underpin significant future demand for cement and steel.

The industry sector presents a major carbon dioxide (CO_2) emissions reduction challenge, especially since it already accounts for almost one-quarter of global CO_2 emissions. The cement, iron and steel and chemicals subsectors, which contribute nearly 70% of these industrial emissions, are among the most difficult to decarbonise, due in part to the requirement for high temperature heat and inherent process emissions that cannot be avoided with a switch to renewable energy sources.

A portfolio of technologies and approaches will be needed to address the challenges of decarbonising these industries while maintaining global economic growth and development. Carbon capture, utilisation and storage (CCUS) could be particularly useful because it is one of the few technological solutions able to cut emissions significantly while supporting a least-cost industrial transition consistent with the goals of the Paris Agreement.

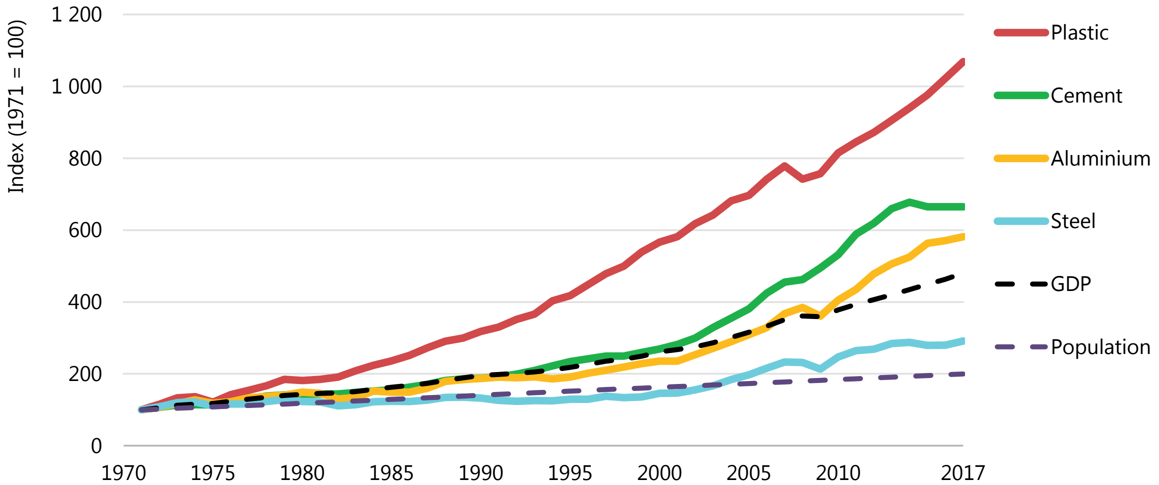
Industry central to economic growth and development

Industry is the basis for prospering societies, central to economic development and the source of about one-quarter of global GDP and employment. The materials produced by industrial sectors make up the infrastructure, equipment and goods that enable businesses and people to carry out their daily activities. Cement and steel provide the buildings we live in and the infrastructure our societies require to function; fertiliser production is essential to feed the growing global population, and plastics are ubiquitous in our daily lives.

Increasing demand for cement, steel and plastics has historically coincided with economic and population growth. Since 1971, global demand for steel has increased by a factor of three, cement by nearly seven, primary aluminium by nearly six and plastics by over ten (Figure 10). In the same period, global population doubled, while GDP has grown fivefold.

[1] Includes petrochemicals.

Figure 10. Global trends in the production of major industrial products, GDP and population over the previous four decades

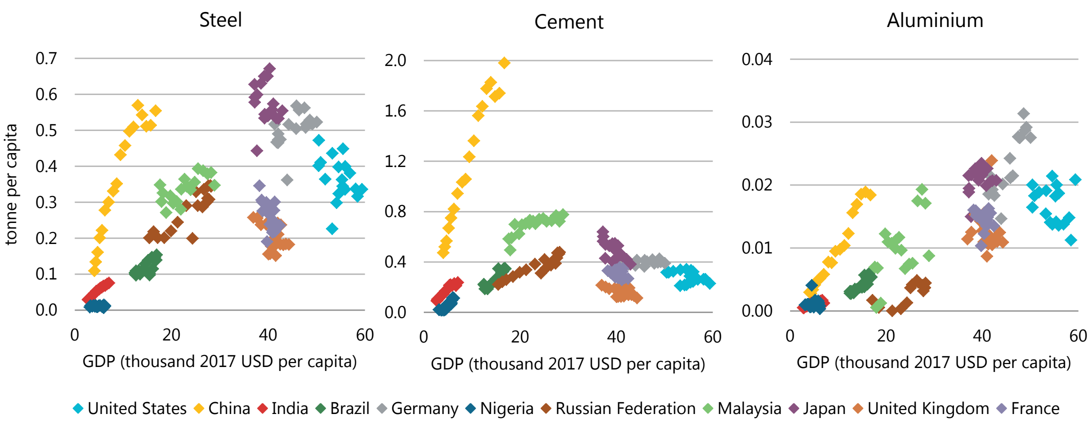


Notes: Outputs of the industry subsectors are indexed to 1971 levels. *Aluminium* refers to primary aluminium production only. *Steel* refers to crude steel production. *Plastics* includes a subset of the main thermoplastic resins.

Sources: IEA (2019), *Material Efficiency in Clean Energy Transitions*, https://www.iea.org/publications/reports/MaterialEfficiencyinCleanEnergyTransitions/.

Demand for industrial products is closely linked with GDP growth.

Figure 11. Apparent per-capita material consumption and per-capita GDP for selected countries, 2000-17



Notes: USD = United States dollars. For cement, apparent consumption is assumed to equal production, given limited international trade; 2016 is an estimate and 2017 is an extrapolation of trends since 2000. For steel, apparent consumption is that reported by Worldsteel. For aluminium, apparent consumption is primary production reported by the USGS (United States Geological Survey), adjusted for exports and imports as reported by UN Comtrade (the United Nations Commodity Trade Statistics Database); 2017 is an extrapolation of trends since 2000. Apparent aluminium consumption does not include secondary production, as historical secondary production statistics are limited. Apparent consumption refers to bulk materials as opposed to manufactured components.

Sources: IEA (2019), *Material Efficiency in Clean Energy Transitions*, https://www.iea.org/publications/reports/MaterialEfficiencyinCleanEnergyTransitions/.

Economic development generally leads to higher per-capita demand for materials.

While the relationship between industrial output and macroeconomic and social development is complex,[2] demand for materials is set to continue climbing, due primarily to strong growth in emerging economies transitioning towards the lifestyle of today's advanced economies. While per-capita demand for materials tends to be relatively weak in less economically developed economies, as economies advance, urbanise, consume more goods and build more infrastructure (e.g. high-rise buildings, roads and electricity generation equipment), material demand tends to rise significantly (Figure 11). Once an economy is more developed and infrastructure is in place, demand for materials – particularly cement – levels off.

Industrial emissions and energy demand

Converting raw materials into useable ones results in substantial energy consumption and CO_2 emissions. Therefore, while the industry sector undoubtedly benefits societies by offering employment and better living conditions, it is also a major source of energy demand and emissions.

Box 1. Categorising industrial CO_2 emissions

This report groups emissions according to how and where they are produced:

- **Energy-related emissions** result from the combustion of coal, oil and natural gas.[3]
- **Process emissions** occur during chemical or physical reactions other than combustion. They include emissions generated in the production of primary aluminium, ferroalloys, clinker and fuels through coal- and gas-to-liquid processes; in the production and use of lime and soda ash; and in the use of lubricants and paraffins.
- **Direct emissions** are emissions from industrial production, but not those embodied in purchased electricity, heat and steam. This category includes both energy-related and process emissions.
- **Indirect emissions** are produced by entities separate from the production facility and include those embodied in purchased electricity, heat and steam.

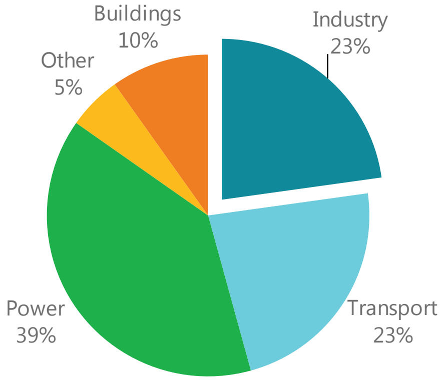
After the power sector, industry is the second-largest source of emissions (equal with transport) (Figure 12). Industry accounted for nearly 40% of total final energy consumption and nearly one-quarter (8 gigatonnes of carbon dioxide [$GtCO_2$]) of direct CO_2 emissions in 2017 (nearly 40% of emissions when indirect emissions are also considered). Over 90% of direct greenhouse gas (GHG) emissions from industrial production is CO_2, and the highest CO_2-emitting subsectors are steel and cement.[4] Together, they accounted for 12% of total direct CO_2 emissions globally in 2017: 2.2 $GtCO_2$ from cement and 2.1 $GtCO_2$ from iron and steel. The chemical subsector was the third-largest industrial emitter at 1.1 $GtCO_2$.

[2] See IEA (2019).

[3] Although biomass emits CO_2 in combustion, since it is carbon neutral over its lifecycle, it is assumed to have an emissions factor of zero.

[4] This report will consider CO_2 emissions only.

Figure 12. CO_2 emissions by sector, 2017

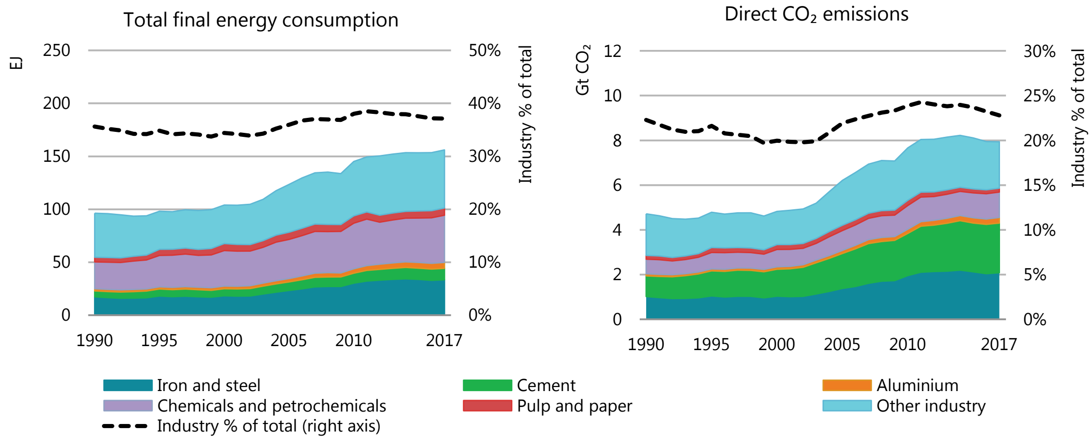


Source: IEA (2019).

Industry is the second-largest source of emissions after the power sector.

Alongside 60% growth in global industrial final energy demand since 1990, direct emissions have increased a substantial 70% (Figure 13). Notably, when indirect emissions are included, CO_2 emissions from industry are found to have risen more than CO_2 emissions from the transport and buildings sectors between 1990 and 2017. Although the cement subsector consumes relatively little energy, it is a large CO_2 emitter because a considerable share of its direct emissions are process rather than energy-related emissions.

Figure 13. Industry subsector final energy demand and direct CO_2 emissions, 1990-2017



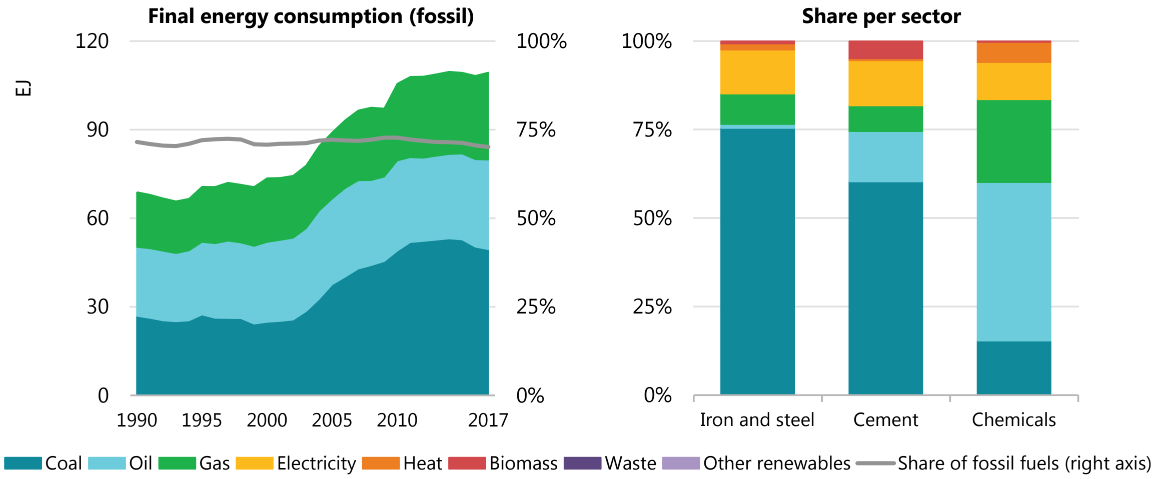
Notes: EJ = exajoule; total final energy consumption includes electricity consumption; direct CO_2 emissions do not include indirect emissions from producing the electricity consumed.

Sources: IEA (2019), *Material Efficiency in Clean Energy Transitions*, https://www.iea.org/publications/reports/MaterialEfficiencyinCleanEnergyTransitions/.

Industrial CO_2 emissions increased 70% between 1990 and 2017, mainly in cement, iron and steel, and chemicals.

Fossil fuels continue to satisfy the majority of industrial final energy demand. Their share (70%) has not changed substantially since 1990 as industry's reliance on fossil fuels continues. In absolute terms, however, fossil fuel consumption in industry has risen nearly 60% since 1990, driven mainly by industrial expansion in the People's Republic of China ("China") during 2000-10. Coal continues to be the main fuel source in iron and steel (75%) and cement (60%), while natural gas and especially oil dominate the petrochemical subsector; in fact, more than 80% of the energy consumed in all three sectors comes directly from fossil fuels (Figure 14). Furthermore, fossil fuels typically play a substantial role in the production of electricity and heat, which accounts for most of the remaining energy consumption in industry.

Figure 14. Fossil fuels in global industrial final energy demand, 1990-2017 (left), and final energy demand by fuel for selected industry subsectors, 2017 (right)



Source: IEA (2019).

70% of industrial energy needs are met by fossil fuels.

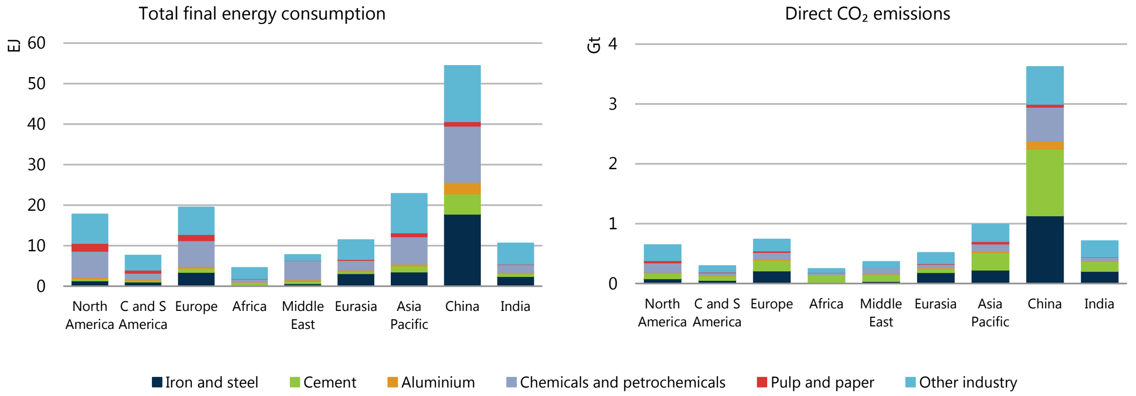
China leads the industrial growth story

Industrial energy consumption and emissions patterns vary substantially by region (Figure 15). China currently has the largest shares of global industrial energy consumption (35%) and industrial CO_2 emissions (nearly 50%) due to its dominance in global materials manufacturing.

The next-largest key contributors are the Asia-Pacific region excluding China and India (15% of energy consumption and 12% of emissions), Europe (12% of energy consumption and 9% of emissions), North America (11% of energy consumption and 8% of emissions) and India (7% of energy consumption and 9% of emissions).

China's economic growth from 2000 to 2010 resulted largely from an unprecedented expansion of industrial production. While the economy has since shifted away from heavily industry-based growth, industry-supported infrastructure expansion remains a policy priority and employment in the sector is also an important consideration. China is the world's largest producer of steel and cement, accounting for almost 60% of cement production and 50% of iron and steel (Figure 16). Further, a significant share of global petrochemical production takes place in China.

Figure 15. Industry subsector final energy consumption and direct CO_2 emissions by region, 2017

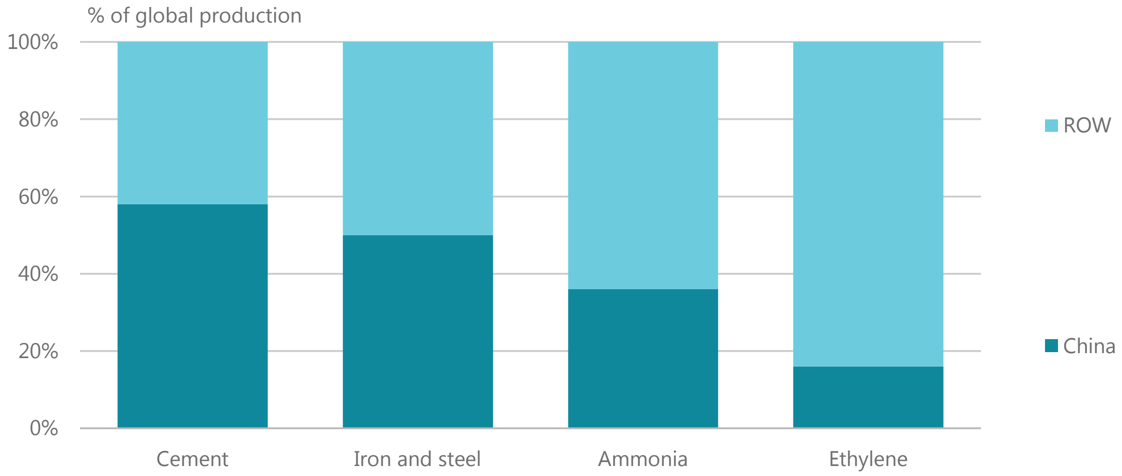


Notes: Gt = gigatonnes. Sizes are proportional by area to total regional energy consumption and emissions. *Other industry* refers to less energy-intensive industrial subsectors, such as equipment manufacturing and food and beverages. C and S America = Central and South America.

Source: IEA (2019).

China accounts for more than one-third of global industrial energy consumption and almost half of industrial CO_2 emissions.

Figure 16. China's production of iron and steel, cement and selected petrochemicals, 2017



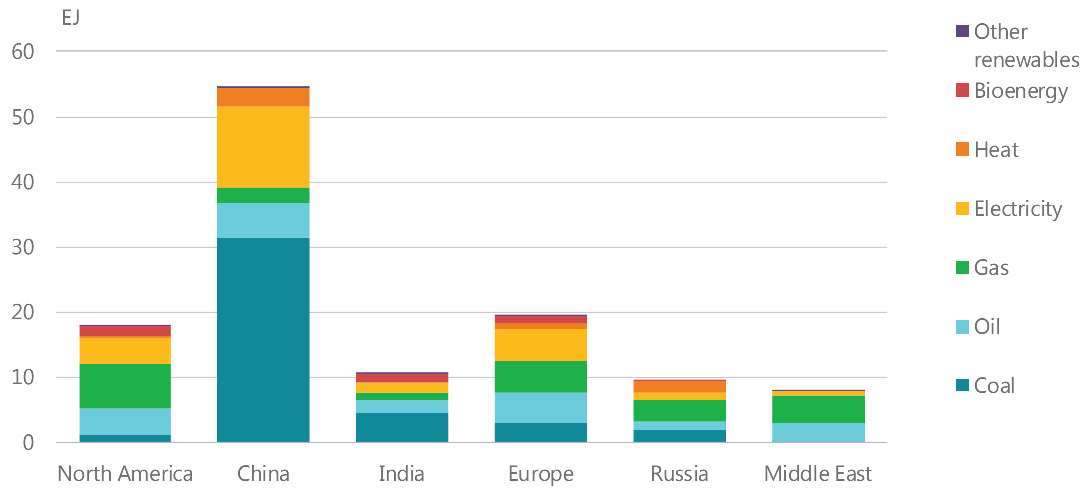
Note: ROW = rest of world.

Source: IEA (2019).

China dominates global industrial production.

The industry sector fuel mix varies markedly across regions (Figure 17). In China, industrial energy consumption is based heavily on domestic coal. Although coal is the dominant feedstock for China's methanol and ammonia production owing to its abundance and accessibility, gas is the more common feedstock in most other countries. In North America, coal is the basis for iron and steel production, whereas readily available gas and oil dominate the other industry subsectors.

Figure 17. Industry fuel use in selected regions, 2017



Source: IEA (2019).

Industry sector fuel mixes vary significantly from one region to another.

These differences in sector composition and fuel mix imply that decarbonisation pathways for industry will also differ from one region to another. Among other considerations, fuel endowment and current production are important in determining the best decarbonisation plan for each country and region.[5]

The CO_2 emissions abatement challenge

Industry is considered one of the hardest-to-abate sectors in the energy system, together with certain transport subsectors (heavy-duty road transport, shipping and aviation). Hard-to-abate sectors generally have relatively higher abatement costs or other constraints (e.g. economic or social considerations) that hinder decarbonisation. To date, the step-change innovations and abatement cost reductions that have stimulated decarbonisation in the power generation sector have not yet reached effective levels for cement, iron and steel, and chemical production. Furthermore, highly competitive commodity markets do not encourage investment in lower-carbon product alternatives.

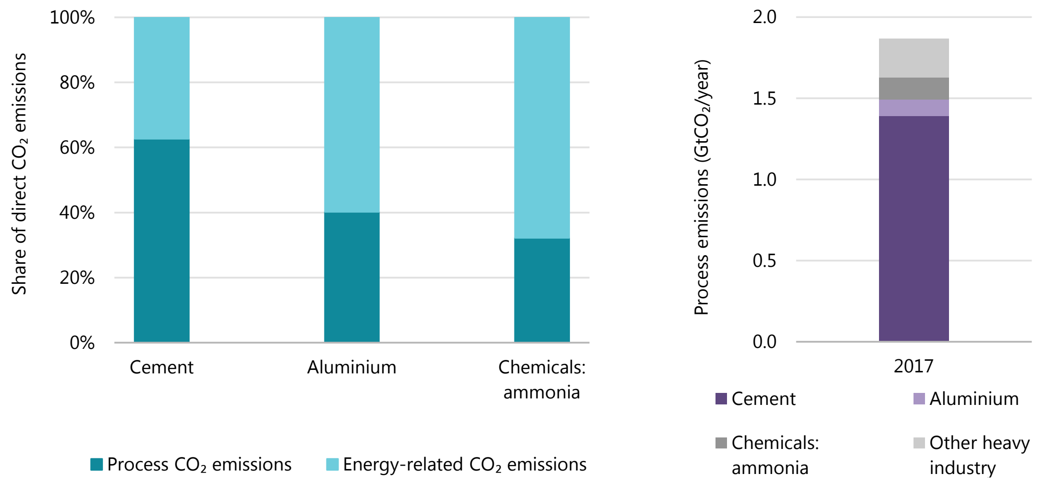
The numerous technical and economic challenges associated with industrial production processes also differentiate this sector from other parts of the energy system. Process emissions are inherent and cannot be avoided through fuel-switching; the demand for high-temperature heat has resulted in continued reliance on fossil fuels; and equipment with a long lifetime results in infrastructure lock-in.

Process emissions: About one-quarter of industrial emissions are process emissions, i.e. emissions resulting from chemical reactions occurring in industrial processes rather than from the combustion of fuels (see Box 1 and Figure 18). Emissions associated with the calcination of limestone in cement production or those arising from the oxidation of carbon contained in

[5] More details on the regional dimension of industry decarbonisation can be found in the International Energy Agency (IEA) *Technology Roadmap* series as well as in its "The Future of" publication series which illuminate important blind spots in the energy transition.

feedstocks used in chemical production are prime examples. It can be costly to avoid these emissions, as this often requires process modifications.

Figure 18. Process emissions from selected industry subsectors

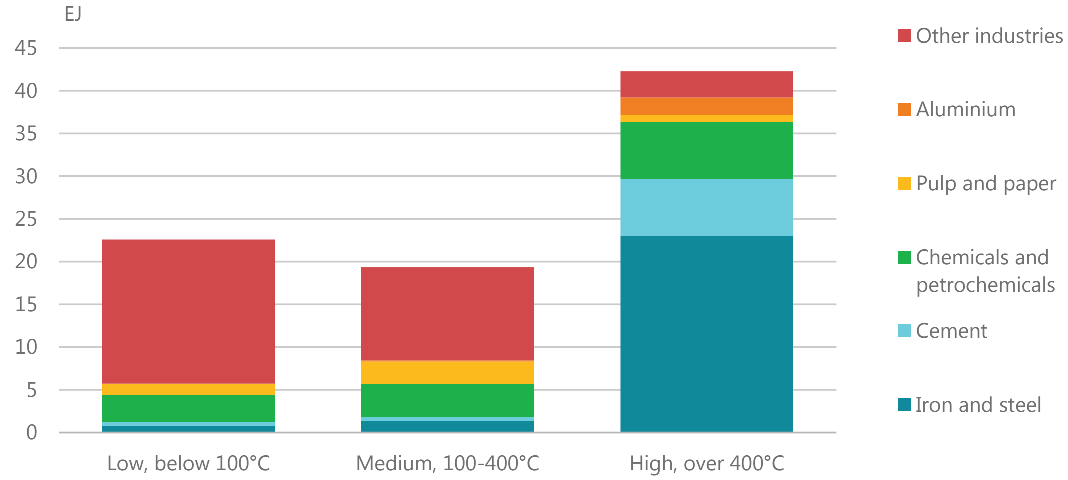


Source: IEA (2019).

Process emissions account for about two-thirds of cement and one-quarter of total industrial emissions.

High-temperature heat: A significant share of industrial CO_2 emissions comes from burning fuel to generate high-temperature heat (Figure 19). High-temperature heat demand in iron and steel, cement and chemicals totals roughly 35 EJ – more than 20% of the industry sector's total final energy consumption. Process temperatures range from 700 degrees Celsius (°C) to over 1 600°C, and abating these emissions by switching to alternative fuels or zero-carbon electricity is difficult and costly. Production facilities would also need to be modified, and the electricity requirements could be prohibitively high.

Figure 19. Heat demand by industry and temperature level



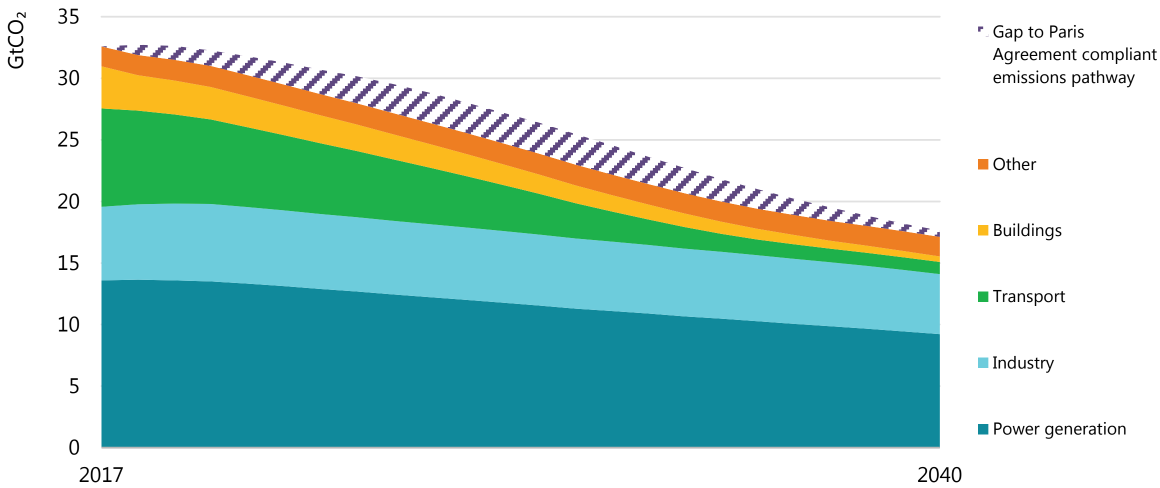
Source: IEA (2019).

Industry sectors such as iron and steel and cement require high-temperature heat, which is a major cause of fossil-fuel reliance.

A range of low-emissions technologies exist that could provide the necessary high-temperature heat,[6] but the economic and technological feasibility of wide-scale deployment and substitution across the industry sector is highly uncertain. For example, induction and microwave heating could be used to electrify high-temperature heat, but for many applications it is still at the research and development stage.

Lock-in of emissions-intensive infrastructure: A further challenge to decarbonising industry is the lock-in of emissions from existing production facilities. The global production capacity of both clinker (the main component of cement) and steel has doubled since 2000, suggesting that the production facilities are relatively young (the typical lifetime of a cement plant is 30 to 50 years with regular maintenance). According to IEA analysis, existing industrial infrastructure and facilities currently under construction would lock in around one-quarter of the total emissions allowable in the IEA Sustainable Development Scenario (SDS)[7] (IEA, 2018). Industry is therefore the second-largest source of potentially locked-in emissions after the power sector, which accounts for around half of all locked-in emissions (Figure 20).

Figure 20. Lock-in of current infrastructure



Source: IEA (2019).

Today's industrial facilities and those under construction would lock in one-quarter of the CO_2 emissions allowable to 2040 in a pathway consistent with the Paris Agreement.

Highly competitive commodity markets: The cement, steel and many chemical industries typically operate at very narrow profit margins, so cost minimisation is a decisive factor in choice of production method. Except for cement, these products are traded globally and are price-takers[8] in highly competitive international markets; companies that increase production costs by adopting low-carbon processes and technologies will therefore be at an economic disadvantage. This is especially the case when the costs of carbon emissions are not priced in or regulated and consumers are unwilling to pay more for sustainable or premium lower-carbon

[6] See IEA (2017b).

[7] The IEA's SDS is fully aligned with the Paris Agreement goal of "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C". The SDS emissions reduction pathway is comparable with that of the IEA's Clean Technology Scenario (CTS).

[8] i.e. the companies are unable to influence the market so must accept prevailing prices.

products. Further, market exposure could cause production to shift to countries or regions with less stringent emissions reduction policies, and the resulting "carbon leakage" could undermine decarbonisation efforts in industry (see discussion in Chapter 3).

Rising to the challenge: The role of CCUS

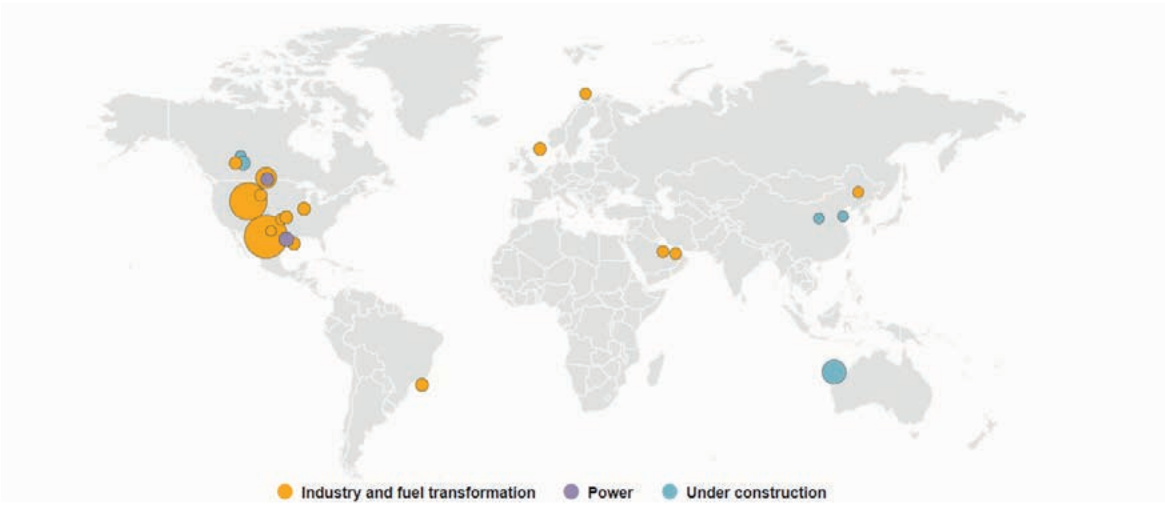
Several key strategies may be used to reduce CO_2 emissions in the industry sector: schemes to raise material efficiency and energy efficiency; deployment of best available technologies (BAT); fuel and feedstock switching; process innovation; and CCUS. The most cost-effective decarbonisation pathways will involve multiple strategies and will vary by sector and region, but among these key strategies, CCUS stands out because it directly addresses key challenges related to process emissions, the combustion of fossil fuels for high-temperature heat, and the lock-in of existing infrastructure.

Further, with increasing ambition in the pursuit of net zero emissions from the energy system, the role of CCUS becomes even more pronounced (IEA, 2017a). In particular, increased deployment of CCUS is needed to tackle the most challenging industrial emissions and to support negative emissions through bioenergy with CCS (BECCS).

CCUS is being applied in industry today

CO_2 capture and separation has been applied to industry and fuel transformation (e.g. refining and fuel processing) for many decades already, and it is even an inherent part of some industrial processes. Plus, experience with full-chain industrial CCUS deployment has broadened over the past decade, with large-scale projects now operating at fertiliser, steel and hydrogen plants.

Figure 21. Large-scale CCUS projects worldwide



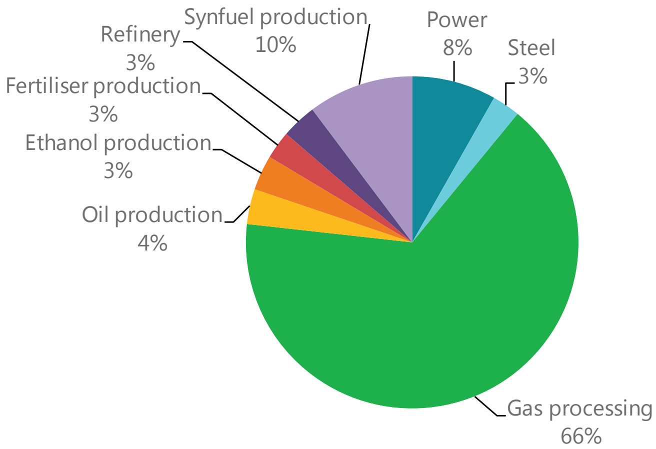
Note: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries, and to the name of any territory, city or area.

Source: IEA (2019).

16 large-scale industrial CCUS projects were in operation at the end of 2018, mostly involving hydrogen production, natural gas processing and ethanol production.

Today, 18 large-scale CCUS projects are in operation globally, capturing around 33 million tonnes of carbon dioxide ($MtCO_2$) each year, with 16 of these projects in industry or fuel transformation[9] (Figure 21). Three-quarters of the CO_2 capture capacity built since 2010 is currently operating in processes related to hydrogen production from fossil fuels, natural gas processing and biomass fermentation for ethanol production (Figure 22). These applications represent almost half of all CCUS investment in the last decade.

Figure 22. CO_2 captured at large-scale CCUS facilities globally by sector



Source: IEA (2019).

CCUS deployment has so far been concentrated on low-cost opportunities such as gas processing rather than the hardest-to-abate industry sectors.

The profile of current facilities and investment highlights that the costs of CO2 capture vary greatly by point source and by capture technology (Table 1). Fuel transformation applications which produce a concentrated CO2 stream and/or which required CO2 to be separated as an inherent part of the process (such as in natural gas processing) have been favoured. Costs range from USD 15 per tonne of carbon dioxide (/tCO2) to USD 60/tCO2 for concentrated CO2 streams (e.g. natural gas processing and bioethanol production through fermentation), to USD 40/tCO2 to USD 80/tCO2 for coal- and gas-fired power plants, to over USD 100/tCO2 for smaller or more dilute point sources (e.g. industrial furnaces).

Table 1. Selected CO2 capture cost ranges for industrial production

CO_2 source/industry	CO_2 concentration (%)	Capture cost (USD/tCO_2)
Natural gas processing	96 - 100	15 - 25
Coal to chemicals (gasification)	98 - 100	15 - 25
Ammonia	98 - 100	25 - 35

[9] While some definitions include fuel transformation subsectors (such as refining) as part of industry, the sectoral boundary in the IEA is set to include iron and steel, aluminium, pulp and paper, cement, petrochemicals, and the less emissions-intensive manufacturing subsectors.

CO_2 source/industry	CO_2 concentration (%)	Capture cost (USD/tCO_2)
Bioethanol	98 - 100	25 - 35
Ethylene oxide	98 - 100	25 - 35
Hydrogen (SMR)	30 - 100	15 - 60
Iron and steel	21 - 27	60 - 100
Cement	15 - 30	60 - 120

Notes: Some cost estimates refer to chemical sector and fuel transformation processes that generate relatively pure CO_2 streams, for which emissions capture costs are lower; in these cases, capture costs are mostly related to further purification and compression of CO_2 required for transport. Depending on the product, dilute energy-related emissions, which can have substantially higher capture costs, can still make up an important share of overall direct emissions. Costs estimates are based on capture in the United States. Hydrogen refers to production via steam reforming; the broad cost range reflects varying levels of CO_2 concentration: the lower end of the CO_2 concentration range applies to CO_2 capture from the pressure swing adsorption off-gas, while the higher end applies to hydrogen manufacturing processes in which CO_2 is inherently separated as part of the production process. Iron and steel and cement capture costs are based on 'Nth of a kind' plants, reflecting projected cost reductions as technology is applied more broadly. Iron and steel and cement costs are based on capture using existing production routes—however, innovative industry sector technologies under development have the potential to allow for reduced costs in the long term. The low end of the cost range for cement production applies to CO_2 capture from precalciner emissions, while the high end refers to capture of all plant CO_2 emissions. For CO_2 capture from iron and steel manufacturing, the low end of the cost range corresponds to CO_2 capture from the blast furnace, while the high end corresponds to capture from other small point sources. Costs associated with CCUS in industry are not yet fully understood and can vary by region; ongoing analysis of practical application is needed as development continues. SMR = steam methane reforming.

Source: IEA analysis based on own estimates and GCCSI (Global CCS Institute) (2017), Global Costs of Carbon Capture and Storage, 2017 Update; IEAGHG (2014), CO_2 capture at coal based power and hydrogen plants; NETL (National Energy Technology Laboratory) (2014), Cost of Capturing CO_2 from Industrial Sources.

Beyond cost considerations, there are a number of technical and practical challenges for implementing CCUS in industry that need to be considered during project development. These range from space restrictions at existing sites to production shutdowns during retrofitting. Some CCUS capture methods require changes to core manufacturing processes and the implementation of measures to ensure reliability (Berghout et al., 2013). For example, in the case of carbon capture retrofits, it could be important to have capability to take carbon capture equipment offline while maintaining operations.

New momentum is building for the future

Although CCUS progress in key industry sectors has been slow compared with its use in fuel transformation, there are signs of growing momentum. In 2018, the number of large-scale CCUS projects operating or under development globally increased for the first time since 2010, to 43. This includes the commissioning of China's first large-scale CCUS project, at CNPC's Jilin Oil Field, which is capturing CO_2 from a natural gas processing facility for use in EOR. In Europe, plans for six new CCUS projects were announced in 2018; in Ireland, the Netherlands and the United Kingdom. At least four of these projects involve capturing CO_2 from hydrogen production and three involve the development of industrial CCUS hubs.

The first iron and steel-related CCUS facility began operating in Abu Dhabi in 2016,[10] and there are now 17 CCUS projects outside the power sector that are under construction or in the early planning stage globally. The five large-scale industrial and fuel transformation CCUS projects currently in construction are expected to come online in 2019 and 2020, which would bring the total number of operational industrial facilities to 21 (GCCSI, 2019).

[10] See Chapter 2 for progress and initiatives by industry subsector.

Two of the five projects coming online are in China and relate to chemical production. The Sinopec Qilu Petrochemical Project advanced to the construction phase in 2018 and will capture 0.4 million tonnes per annum (Mtpa) from fertiliser production. The Yanchang integrated demonstration project, which currently captures 0.05 Mtpa from a coal-to-chemical plant, will capture an additional 0.36 Mtpa from a larger chemical production CO_2 source. The captured CO_2 will be transported for use in EOR in central China's Ordos Basin.

The other three projects in construction are the 4 Mtpa Gorgon CO_2 injection project in Australia, which will capture CO_2 from natural gas processing, and the two Alberta Carbon Trunk Line projects in Canada, which will capture CO_2 from fertiliser production (0.5 Mtpa) and oil refining (1.3 Mtpa).

In Norway, feasibility studies are underway for CO_2 capture from a cement facility – potentially the first large-scale cement CCUS plant – and from a waste-to-energy recovery plant. A partnership between Equinor, Shell and Total is developing offshore CO_2 storage in the North Sea to support Norway's plans for a fully integrated industrial project.

Box 2. Industrial CCUS hubs in the United Kingdom, Australia and the Netherlands

Interest in developing CCUS hubs in industrial centres is increasing in a number of locations around the world, driven by decarbonisation objectives and the potential to attract and maintain industry investment. Three projects are highlighted below.

United Kingdom Industrial CCUS Hubs

The UK government's recent Action Plan for CCUS underlines the technology's potential to reduce CO_2 emissions in most of the country's industrial centres as part of its Clean Growth-based Industrial Strategy (UK Government, 2018). The Action Plan argues that, given increasing domestic and international incentives to decarbonise, CCUS can help protect long-term competitiveness. It also describes efforts underway in the country to reduce costs and develop investment-friendly business models, and envisions at-scale deployment of CCUS in the 2030s.

Furthermore, the Action Plan reports opportunities to exploit economies of scale in creating a CO_2 infrastructure network in an industrial cluster to reduce costs for various users, and it offers six promising locations for such a CCUS model. The UK government plans to continue studying opportunities to create industrial CCUS hubs and to further assess the technology's potential. In May 2019, the UK Committee on Climate Change recommended that the first industry CCUS cluster be operational by 2026, with a second coming online by 2030 to bring total capture to at least 10 $MtCO_2$ (UK CCC, 2019).

The Teesside Collective is one potential hub that has received significant attention. The group is composed of five large emissions intensive-companies covering, hydrogen, ammonia, plastic, as well as a chemical cracker and a utility, though the location includes a variety of additional industrial facilities. Considerable engineering work has already taken place, a business case published, and an economic impact assessment undertaken.

Other potential and planned hubs are at St Fergus, Grangemouth, Humberside, Merseyside and South Wales.

The CarbonNet project, Australia

The CarbonNet project is investigating the prospects for developing a CO_2 transportation and storage hub in Victoria's Latrobe Valley. The region includes offshore basins believed to have among the most significant storage potentials in the country, and the project is assessing the potential to initially store 5 $MtCO_2$ per year. The project would serve to commercialize transport and storage, aggregating CO_2 captured in a variety of industrial sites in the region, and could serve to attract further industrial development. Project proponents plan to build an appraisal well in late 2019 or early 2020, ahead of moving to establish a commercial structure aimed at attracting private investment. CarbonNet could provide a future CO_2 transport and storage solution for the Hydrogen Energy Supply Chain (HESC) pilot project, which is demonstrating production of hydrogen gas from brown coal, its liquefaction and transport by ship to Japan (HESC, 2019).

Porthos: Port of Rotterdam CO_2 Transport Hub & Offshore Storage project, the Netherlands

The Porthos project seeks to create a CCUS hub based on storage in depleted gas fields in the North Sea, the construction of a collective 33 km pipeline running through the Port of Rotterdam area, and the CO_2 generated by a variety of companies in the heavily industrialised region (Rotterdam CCUS, 2019). The project aims to use a share of the captured CO_2 to enrich greenhouse farming in the region and to store 2 to 5 $MtCO_2$ annually by 2030. A feasibility study completed in 2018 validated both the technical feasibility, and, in the context of the Netherlands' climate targets, cost-effectiveness of the project. Further, the European Union (EU) has acknowledged Porthos as a Project of Common Interest – cross border infrastructure projects that helps the EU achieve energy policy and climate objectives. Various companies have recently expresses interest in being part of the project (Port of Rotterdam, 2019).

Industrial CCUS hubs are being planned in a variety of locations, including Australia (CarbonNet, initial capture of 1-5 Mtpa), the Netherlands (Port of Rotterdam, 2-Mtpa capture by 2020), and the United Kingdom (Teesside Collective, initial capture of 0.8 Mtpa; Acorn Scalable CCS Development, 3-4 Mtpa) (Box 2). These projects seek to benefit from economies of scale in capturing CO_2 from multiple activities with shared transport and storage infrastructure.

In addition to stronger project development and planning momentum in China and Europe, a significant stimulus for CCUS investment has recently been introduced in the United States. The 45Q tax credit has been expanded to provide USD 50 per tonne of CO_2 stored and USD 35 per tonne of CO_2 used in EOR, and smaller industrial facilities are now eligible for the credit. Although these developments suggest better conditions for CCUS deployment in the industry sector, there are still challenges to overcome.

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Towards a sustainable and competitive industrial transformation

The industry sector will continue to be critical to economic growth and social prosperity, as demand for materials such as cement, steel and chemicals expands to accommodate an increasingly urbanised and significantly larger global population. The United Nations projects that the global population could increase by almost 30% by 2050, to reach 9.8 billion people, with almost all of this growth in developing economies (UN, 2017).

A key challenge is to ensure that these materials can be produced with significantly lower emissions. This section examines potential emissions reductions in industry and how carbon capture, utilisation and storage (CCUS) can support transformation of the cement, iron and steel, and chemical subsectors sustainably and as part of a least-cost portfolio of technologies and measures.

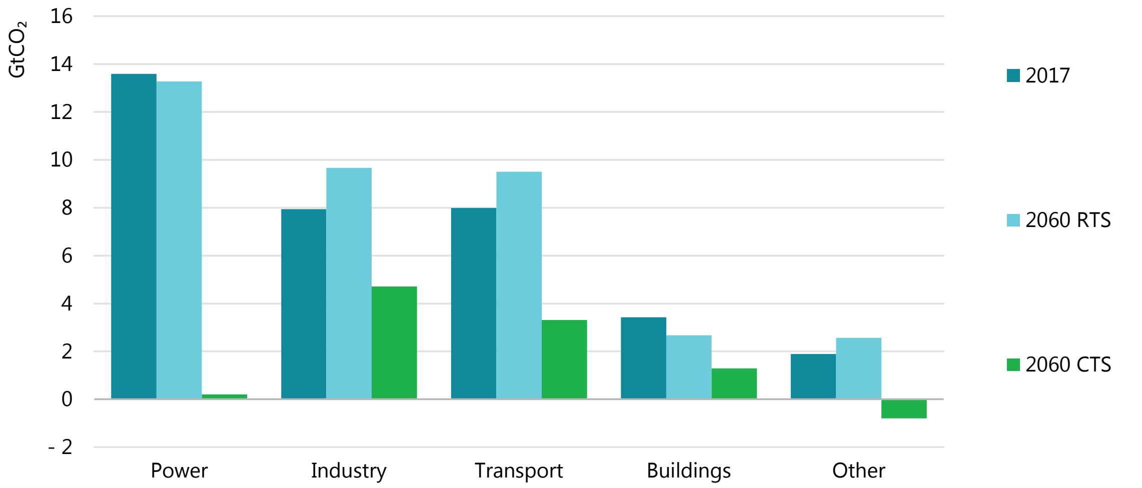
Without action, industrial emissions will exceed total emissions in the CTS

Greater focus on industrial emissions will be necessary to meet globally agreed climate goals. In the International Energy Agency (IEA) Reference Technology Scenario (RTS), which describes a pathway consistent with policy ambitions currently in place around the world (see Box 3 for scenario descriptions), direct industrial emissions grow by around 20% to reach 9.7 gigatonnes of carbon dioxide ($GtCO_2$) by 2060 (Figure 23). This keeps industry firmly in place as the second-largest emitter behind the power sector, neck-and-neck with the transport sector.

In the RTS, existing and announced policies and targets do not provide sufficiently strong signals to reduce industrial CO_2 emissions, as energy consumption in the sector increases to 240 exajoules (EJ) by 2060 – a more than 40% rise from 2017 (Figure 24). While some improvement is projected, reliance on fossil fuels for industrial processes remains pronounced at 66% in 2060 (compared with 73% today) and the share of electricity meeting final energy demand[11] rises from 20% in 2017 to almost 25% in 2060. Industrial emissions therefore peak only in the mid-2040s and remain at 9.7 $GtCO_2$ in 2060 (16% above the current level).

[11] Including energy for blast furnaces and coke ovens, and petrochemical feedstocks.

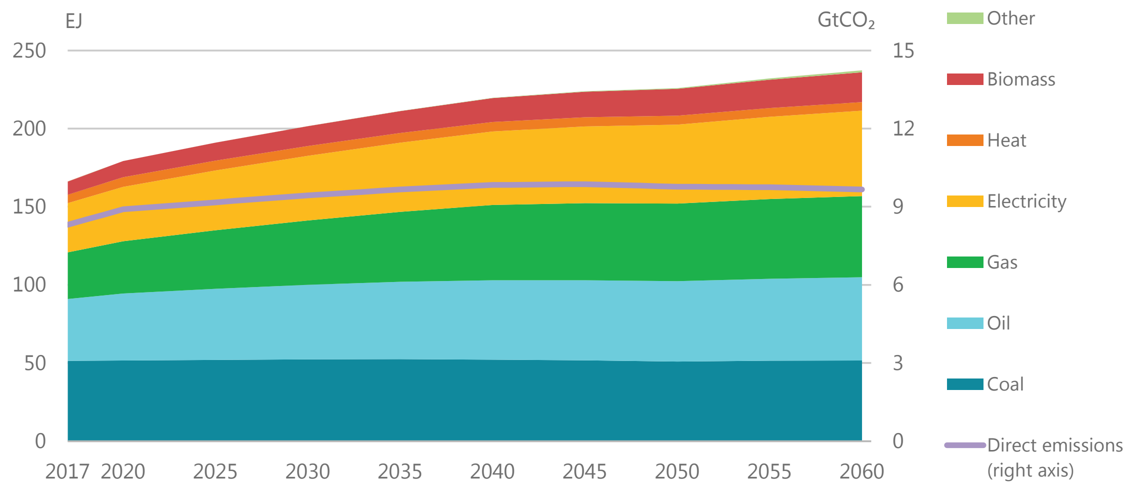
Figure 23. CO_2 emissions in the RTS and CTS by sector



Notes: RTS = Reference Technology Scenario; CTS = Clean Technology Scenario. *Other* refers to emissions from fuel transformation and agriculture.

In a scenario consistent with the Paris Agreement goals, the industry sector becomes the primary source of CO_2 emissions.

Figure 24. Global final energy use and CO_2 emissions in industry in the RTS, 2017-60

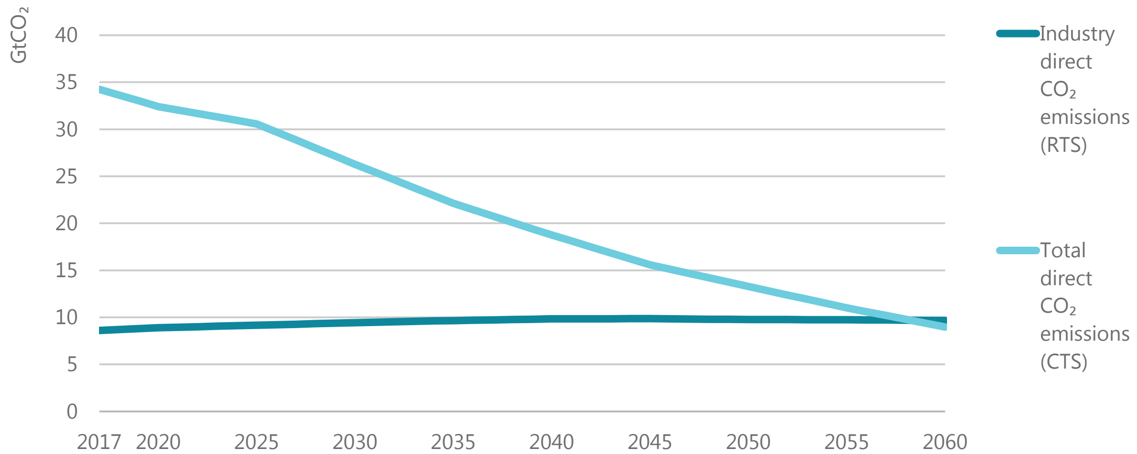


Industrial emissions in the RTS do not peak until the mid-2040s and remain above today's level as energy use continues to grow.

Although the RTS includes some CCUS deployment in industry (mainly in the cement and iron and steel subsectors), it is insufficient considering the scale of emissions reductions required for consistency with the Paris Agreement pathway. Cumulative CO_2 capture to 2060 amounts to 12.5 $GtCO_2$ in the RTS.

With continued reliance on fossil fuels in the industry sector and comparably limited deployment of CCUS, the RTS emissions trajectory falls short of the change needed to address the climate change challenge. Emissions from existing industrial infrastructure alone account for 25% of the carbon emissions compatible with the Paris Agreement by 2040. Looking ahead to 2060 and considering industry capacity changes in the RTS over the projection period, the industry share of emissions rises markedly to emit up to 45% of the cumulative carbon emissions in a pathway consistent with the Paris Agreement (Figure 25). In fact, industry sector emissions under the RTS in 2060 exceed total annual emissions in the CTS from all sectors combined.

Figure 25. Industry emissions pathway in the RTS compared with overall CTS emissions



Source: IEA (2019).

Without large-scale deployment of new technologies such as CCUS, industry emissions in the RTS exceed total emissions in the CTS by 2060.

Box 3. Scenarios discussed in this analysis

The scenarios presented in this report should not be considered predictions, but as analyses to help understand the impact and trade-offs of different technology developments and policy choices on future energy systems. They thereby offer quantitative analyses to inform decision-making in the energy sector.

The **RTS (Reference Technology Scenario)** encapsulates current country commitments to limit emissions and improve energy efficiency, including Nationally Determined Contributions (NDCs) pledged under the Paris Agreement.[12] Although factoring in these commitments and recent trends already results in a major shift from the historical "business-as-usual" approach (i.e. no meaningful climate policy response), global emissions in 2060 are still 8% higher than in 2017, which is insufficient to achieve the objectives of the Paris Agreement.

[12] NDCs reflect policy action to support the aims of the Paris Agreement reached during the 21st Conference of the Parties (COP) to the United Nations Framework Convention on Climate Change (UNFCCC) in 2015.

In contrast, the **CTS (Clean Technology Scenario)** lays out an energy system pathway on which direct CO_2 emissions drop to one-quarter of the current level by 2060. Among the decarbonisation scenarios in the Intergovernmental Panel on Climate Change (IPCC) database that project a median temperature rise of 1.7 degrees Celsius (°C) to 1.8 °C in 2100, the CTS trajectory of energy- and process-related CO_2 emissions is one of the most ambitious in the medium term and remains well within the range of all the scenarios through 2060. The Clean Technology Scenario is the central climate mitigation scenario used in this analysis. It models a highly ambitious and challenging transformation of the global energy sector that relies on a substantially strengthened response compared with today's efforts. It opens the possibility of the pursuit of ambitious global temperature goals, contingent on actions taken outside the energy sector and on the pace of further emissions reductions after 2060.

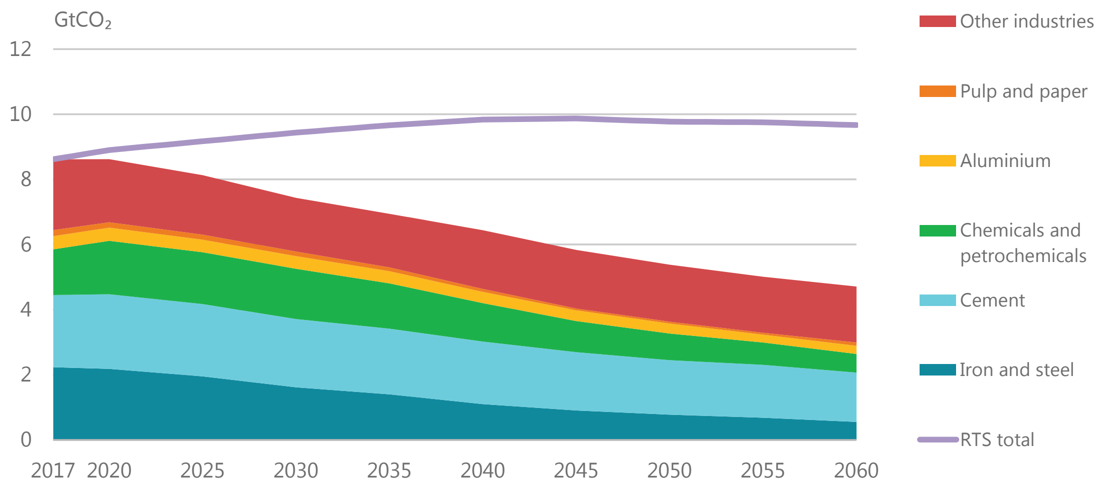
See IEA (2019) Annex I for a more detailed overview of the RTS and CTS, and Annex II for additional details on the Energy Technology and Policy modelling framework.

Targeting industrial emissions in the CTS

The CTS, which describes an energy system pathway consistent with the Paris Agreement climate goals, requires a significantly more ambitious policy response than the RTS. In the CTS, global direct CO_2 emissions from industry fall to 4.7 $GtCO_2$ in 2060, less than half the RTS level.

CTS emissions reductions between 2017 and 2060 are most pronounced in iron and steel (-75%) and chemicals (-60%) (Figure 26). Emissions in the cement subsector prove to be the most difficult to reduce: although they fall 30% by 2060, cement becomes the single highest-emitting industry subsector over the outlook period.

Figure 26. Global direct CO_2 emissions by industry subsector in the CTS, 2017-60



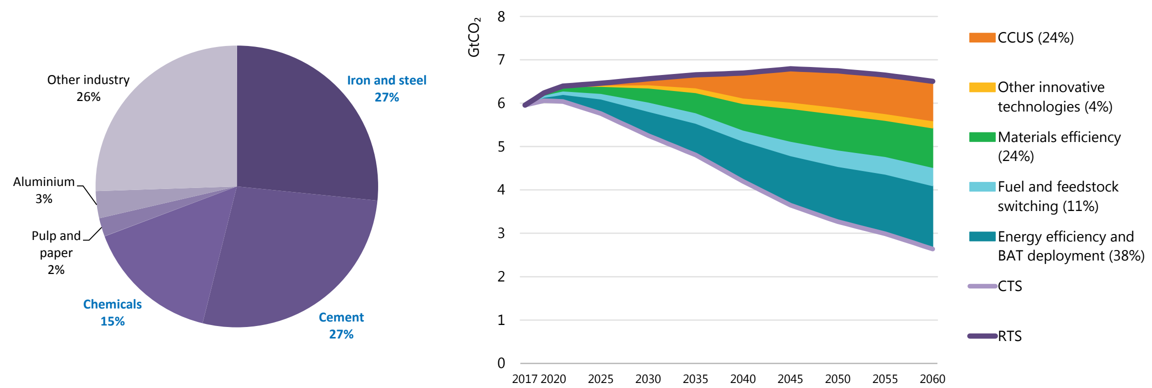
Source: IEA (2019).

Energy-intensive industry subsectors account for over 80% of the difference in cumulative direct emissions reductions between the CTS and the RTS.

Cement, iron and steel, and chemicals are the three industry subsectors with the highest direct CO_2 emissions today, accounting for about 70% of the total (Figure 27). Due to the scale of their emissions, the discussion on decarbonising industry concentrates on these three subsectors. However, even though other emissions-intensive industries such as pulp and paper and aluminium are not the focus of this report, these subsectors, which have their own characteristics and challenges, also require attention and have CCUS potential. Pulp and paper, for example, has the potential for negative emissions as a result of using a substantial share of biomass fuels.

Several key strategies enable CO_2 emissions reductions in the CTS compared to the RTS in the focus subsectors: implementation of material efficiency strategies, energy efficiency and best available technology (BAT) deployment, fuel and feedstock switching, process innovations and CCUS. Improved energy efficiency and material efficiency deliver the greatest direct CO_2 emissions reductions in the CTS relative to the RTS. CCUS is the third most-important contributor, providing 27% (21 $GtCO_2$) of the total emissions reductions obtained under the CTS compared with the RTS from 2017 to 2060. Given the scale of the emissions reduction challenge, all technologies will be needed as part of significantly strengthened and accelerated international efforts to decarbonise.

Figure 27. Share of global direct CO_2 emissions by industry subsector, today (left), and emissions reductions for the three focus subsectors by mitigation strategy, CTS compared with RTS, 2017-60 (right)



Notes: *Other industry* includes less emissions-intensive manufacturing sectors such as textiles and food and beverages; BAT = best available technology.

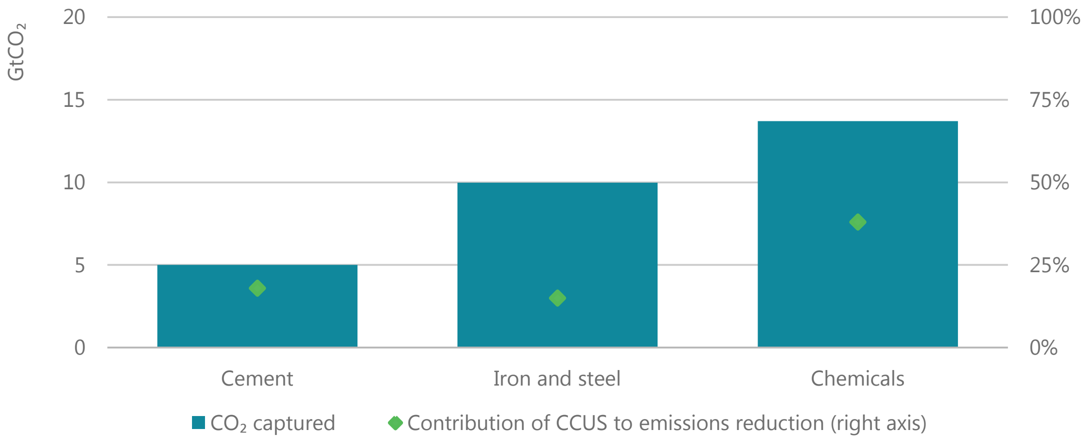
Source: IEA (2019).

CCUS contributes 24% of the cumulative emissions reductions from the RTS to the CTS.

Decarbonising industry: the role of CCUS in the CTS

CCUS plays a crucial role in decarbonising the cement, iron and steel and chemical subsectors. It contributes 18% to direct emissions reductions in the cement industry between 2017 and 2060 with some 5 $GtCO_2$ captured (Figure 28). While the relative contribution of CCUS to emissions reductions is slightly lower in the iron and steel subsector (15%), cumulative capture over the period (10 $GtCO_2$) is around double that for cement. In the chemical subsector, CCUS is the most important contributor to decarbonisation accounting for 38% of the overall emissions reductions. CO_2 capture in chemicals is also the highest (14 $GtCO_2$) owing to several production processes that yield relatively pure streams of CO_2 that are relatively inexpensive to capture.

Figure 28. CCUS contribution to emissions reductions by sector, 2017-60



Source: IEA (2019).

CCUS provides significant emissions reductions in the iron and steel, cement and chemical subsectors in the CTS.

Box 4. Carbon capture technology options

CO_2 capture involves isolating CO_2 from industrial processes and energy-related point sources such as furnaces and power plants. Separating CO_2 requires energy, and often modifications to existing processes from adding extra process steps. After separation, the CO_2 stream can be further purified and compressed to make it ready for transport. There are four main carbon capture approaches, and in certain cases they can be combined to create hybrid capture methods.

- **Post-combustion capture:** CO_2 is separated from a mixture of gases at the end of an industrial or energy process, for example from combustion flue gases using an absorptive or adsorptive substance or a membrane.[13]
- **Oxy-fuel combustion:** Instead of air, nearly pure oxygen is used to combust fuel, producing flue gas composed almost solely of CO_2 and water vapour. Part of the flue gas is recycled to the combustion chamber to control the combustion temperature, while the remainder is dehydrated to obtain a high-purity CO_2 stream. Oxygen is commonly produced by separating it from the air.
- **Pre-combustion capture:** In a reforming/gasification process, fossil fuels or bioenergy can be processed with steam and/or oxygen to produce a gaseous mixture called syngas,

[13] Post-combustion capture, also referred to as *post-process capture*, includes capture of both combustion and process CO_2 emissions.

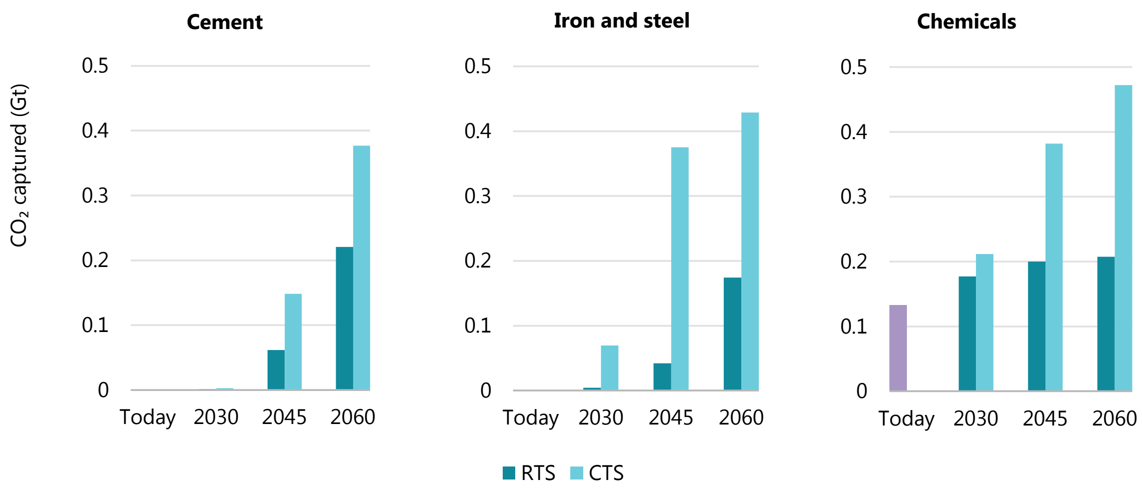
consisting of carbon monoxide and hydrogen. The carbon monoxide is reacted with more steam (in a water-gas shift reaction) to yield additional hydrogen and convert the carbon monoxide to CO_2. The CO_2 can then be separated from the high-pressure gas mixture, yielding raw syngas for combustion or chemical production.

- **Inherent separation:** Certain processes in industry and fuel production generate high-purity CO_2 streams as an intrinsic part of the process (e.g. gas processing and ethanol production). Without CO_2 capture, the CO_2 produced is vented to the atmosphere.

The need for deep emissions reductions in the CTS results in large volumes of CO2 being captured from industrial production and transported for use or storage (Figure 29). The chemicals subsector already has significant CO_2 capture today, with more than 0.1 GtCO2 annually captured from ammonia production for use as a raw material in fertiliser manufacture. In the CTS, CO_2 capture from chemical production would triple to nearly 0.5 $GtCO_2$ by 2060, with most of the additional CO_2 permanently stored. Iron and steel sees significant implementation of CCUS by 2030, with deployment accelerating after 2030 as CCUS becomes an increasingly competitive and important decarbonisation option for the sector.

In the cement sector, implementation of strong material efficiency measures in the CTS leads to a 5% reduction in global cement demand in 2030 compared to RTS levels, which contributes to relatively slow CCUS uptake over the coming decade. However, a rapid increase in CO2 capture levels occurs from 2030, to reach 0.4 $GtCO_2$ by 2060. This future scale-up in the cement sector is dependent on significant investment in CO_2 capture demonstration projects and infrastructure development prior to 2030.

Figure 29. CO_2 capture in cement, iron and steel and chemical subsectors in the RTS and CTS, today through 2060



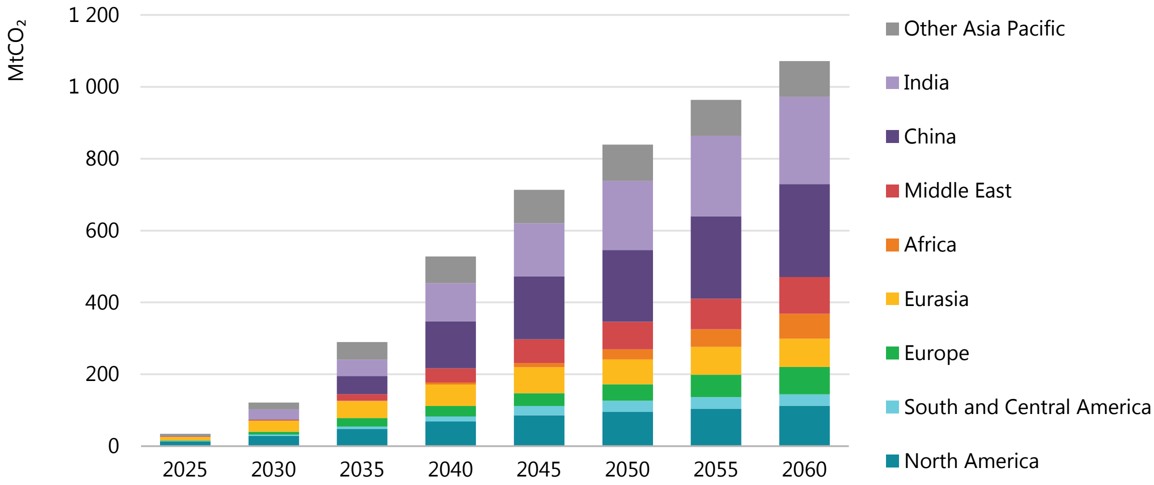
Source: IEA (2019). All rights reserved.

There is a significant ramp up in CO_2 capture in industry by 2060, reaching nearly 1.3 $GtCO_2$ across cement, iron and steel, and chemical production in the CTS.

Effective management of large volumes of CO_2 from industrial production will require planning and development of CO_2 transport and storage infrastructure in the near term. These investments can have lead-times of several years, particularly for pipelines and for greenfield CO_2 storage sites, and could become a limiting factor for CCUS uptake without timely action.

In terms of regional CCUS distribution, Asia[14] accounts for more than half of total industrial CO_2 emissions captured and stored by 2060 in the CTS, with China and India each registering 20% of the global share (Figure 30). These high shares reflect the expectation that most growth in demand for bulk materials will be in Asia as the region's economies continue to enlarge their infrastructure and buildings stock, and as the expanding population demands more consumer goods.

Figure 30. Captured CO_2 in industry by region in the CTS, 2025-60



Note: $MtCO_2$ = million tonnes of carbon dioxide.
Source: IEA (2019).

Asia accounts for more than half of industrial CO_2 emissions captured by 2060 in the CTS.

Cement

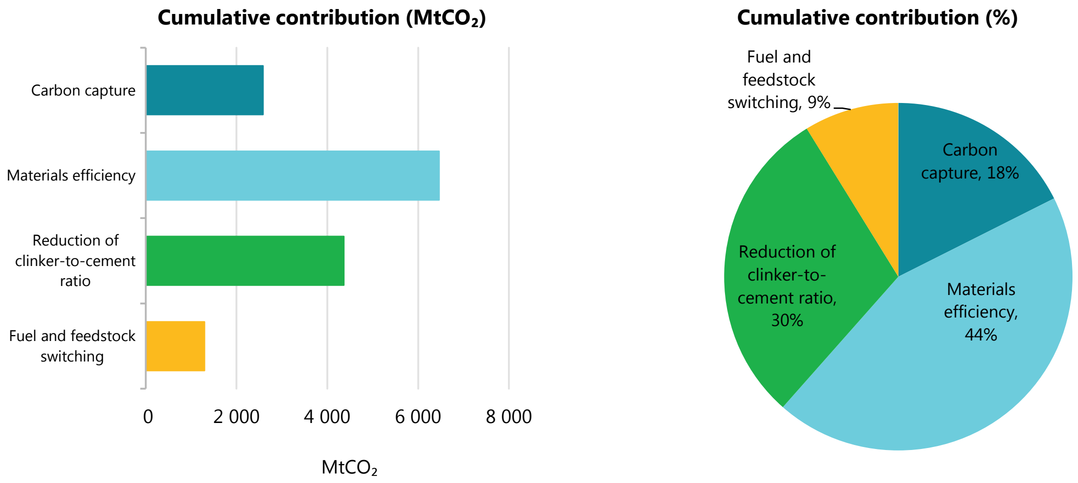
Cement production is highly emissions-intensive, with one tonne of cement typically resulting in about half a tonne of direct CO_2 emissions (IEA, 2018a). Global cement production currently totals around 4 100 t per year, and demand for cement is expected to increase to almost 4 600 t by 2060 in response to population growth and urbanisation. Under the CTS, however, cement production drops to some 3 900 t per year over the same period, reflecting strong material efficiency improvements.

To meet the climate objectives set out in the CTS, aggressive CO_2 emissions reductions are needed as production climbs. Cement subsector emissions are among the hardest to abate in industry, mainly because of the high share of process CO_2 emissions that cannot be reduced through greater energy efficiency or fuel switching. In the CTS, direct emissions in the cement subsector decrease by 30% from today's levels to reach 1.5 $GtCO_2$ in 2060.

[14] Including the People's Republic of China ("China"), India and Other Asia-Pacific.

CCUS delivers 18% of the cumulative emissions reductions in cement under the CTS, making it the third-largest decarbonisation lever in the subsector after material efficiency, which contributes 44%, and reduction of the clinker-to-cement ratio, which contributes 30% of the emissions cuts (Figure 31). Cement demand in the CTS in 2060 is 15% lower than in the RTS – and 5% below the current level – owing to the application of material efficiency measures such as extending building lifetimes and improving building design and construction. However, if these strategies to improve the efficiency of materials are not rolled out to the high extent assumed in the CTS, CCUS will become even more important in cement industry decarbonisation. CCUS is integral to cement decarbonisation because it addresses the otherwise hard-to-abate process emissions.

Figure 31. Global cumulative CO_2 emissions reductions in cement production by abatement option from RTS to CTS, 2017-60



Source: IEA (2019).

CCUS is the third-largest decarbonisation lever in the cement subsector under the CTS, accounting for nearly one-fifth of the emissions reductions needed.

Under the CTS, CCUS is deployed extensively in cement production, capturing 0.4 $GtCO_2$ annually by 2060 and 5 $GtCO_2$ cumulatively over the projection period. CCUS is widely deployed in developing Asia in general, and in the People's Republic of China ("China") and India especially, as they are the two largest cement producers. Deployment is also significant in advanced economies countries by 2060 in the CTS.

In addition to capturing fossil fuel-based emissions and process emissions from cement kilns, CCUS technology in cement manufacturing could also be used to capture emissions from biomass combustion, generating negative emissions. As biomass co-firing in kilns becomes more common, and as necessary CO_2 emission reductions accelerate in a CTS context, CCUS could become significantly more valuable at the system level. The amount of sustainable biomass available, as well as its cost and usefulness for reducing CO_2 emissions in other sectors, will dictate how much of this potential can be used.

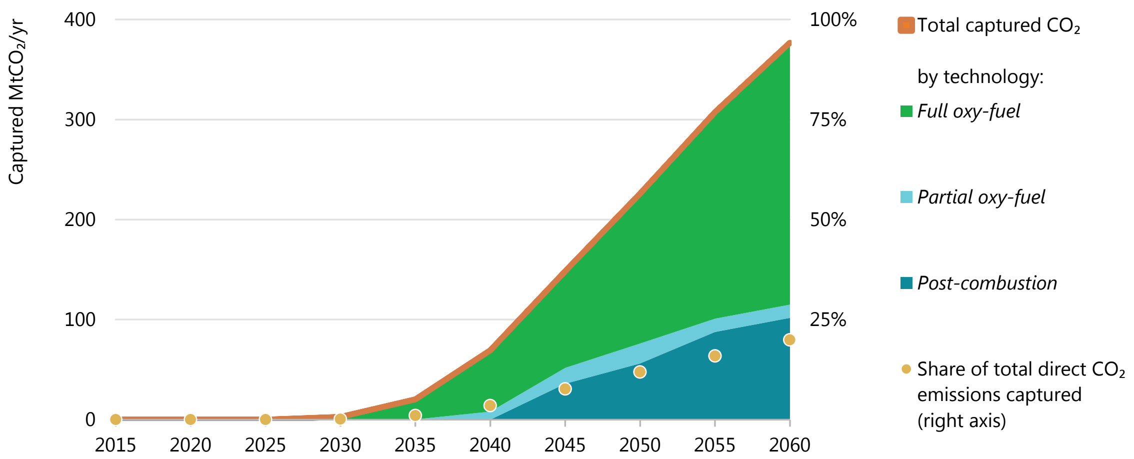
Early action is required in the cement subsector to avoid more costly investments in the long run. Despite the necessity of using CCUS and scaling up its deployment rapidly to meet CTS targets, progress has so far been limited. Ongoing research is at the early stages only, and several technologies are being tested at pilot scale (see Box 5).

Additional long-term opportunities may arise with the development and implementation of low-carbon cement processes based primarily on lower-carbon raw materials, reducing the process emissions that result from the calcination of limestone. For example, using clinkers based on belite-calcium sulphoaluminate could reduce the process CO_2 intensity of clinker production. Accelerated laboratory endurance tests to validate new materials are needed to bring these options to commercial scale. Early deployment is expected to begin in niche applications to build market confidence and to eventually expand the portfolio of applications, but construction and infrastructure codes will also need to be revised to allow these materials onto the market. Such options could go hand in hand with CCUS, reducing the levels of CO_2 capture needed to achieve deep emissions reductions.

The CO_2 abatement costs reported in theoretical techno-economic studies of cement plants with CCUS range from USD 55-70 (United States dollars) per tonne of CO_2 (/tCO_2) avoided for oxy-fuel technologies, and USD 90-150/tCO_2 avoided for post-combustion (subject to plant size and excluding CO_2 transport and storage).[15]

Oxy- fuel techniques account for the largest share of captured CO_2 emissions by 2060 in the CTS, ahead of post-combustion capture (Figure 32). Oxy-fuel technologies, which generally must be more deeply integrated into the cement plant than post-combustion, may however impact the quality of the cement and require additional treatment. Plus, even though oxy-fuel technologies are currently considered the more economical capture option, costs associated with fitting cement plants with CO_2 capture are still uncertain because no real plant data are available. Nevertheless, further experience in integrating CO_2 capture into the cement process as market deployment develops could lead to better-optimised systems, which could reduce investment costs and the energy penalty associated with the additional energy required for carbon capture.

Figure 32. CO_2 capture in cement production under the CTS by technology



Source: IEA (2019).

Oxy-fuel technologies account for the largest share of CO_2 capture in the cement subsector under the CTS.

[15] Transport and storage cost estimates are typically USD 5-25/tCO_2.

Box 5. Cement production and CCUS: An introduction

Rotary dry-process kilns are currently the most widely used process technology for cement production. These kilns heat raw materials, including limestone for calcination, to about 1 450°C, calcining the limestone and creating clinker, which is the main ingredient in cement. Dry kilns have a better (i.e. lower) energy intensity than wet-process kilns, as they operate with raw materials of low moisture content.

Coal and oil are used to fuel cement production in many regions, though co-firing alternative fuels such as biomass and waste is becoming more prevalent. However, most CO_2 emissions from cement-making are process-related. Cement manufacturing requires calcined limestone (i.e. calcium carbonate; $CaCO_3$) as its primary raw material, and the calcination of limestone releases lime (i.e. calcium oxide; CaO) and carbon dioxide (hence: $CaCO_3 \rightarrow CaO + CO_2$). These emissions that stem from the chemical reactions inherent in the process – rather than from fuel combustion – account for around two-thirds of the cement subsector's total CO_2 footprint. Thus, process emissions, combined with fossil fuel reliance, make deep decarbonisation of cement production difficult.

CO_2 generated in the cement kiln can be captured through post-combustion capture techniques or purified from kiln flue gases through oxy- fuel capture technologies when oxy-fuel combustion is used. Pre-combustion capture technologies have limited mitigation potential in cement production, as only energy-related CO_2 emissions, which are the source of around 35% of total emissions, are affected.

Post-combustion capture technologies do not require fundamental modifications of cement kilns and can be applied to existing facilities provided there is enough physical space available onsite:

- Chemical absorption, which yields up to 95% CO_2 capture, is the most mature post-combustion capture technology. Thermal energy is required for regeneration of the sorbent used, however, and electricity is needed to operate the capture unit. This raises the plant's energy imports, as simulations show that no more than 15% of the additional thermal energy required can be recovered from the cement kiln under normal circumstances (IEAGHG TCP, 2013). Trials in 2013-16 using amine-based sorbents at a cement plant with a mobile capture unit in Brevik, Norway, were successful (Bjerge and Brevik, 2014), and preparations are now under way to scale up capture to cover half of the plant's emissions, with plans to eventually reach 100% carbon-free operations (Euractiv, 2018). Also, in 2015 the Capitol SkyMine project began chemically capturing 75 kilotonnes of carbon dioxide ($ktCO_2$) per year from a cement plant and transforming it into sodium bicarbonate, bleach and hydrochloric acid that can be sold (Perilli, 2015).
- Using membranes for CO_2 separation could theoretically yield more than 80%, but membrane technology has so far been proved at only small or laboratory scale, with yields of up to 60-70% recovery achieved (ECRA and CSI, 2017). The low capture rates of membranes can therefore be problematic when higher capture is desired. In addition, although membranes do not have energy requirements for regeneration, they can be sensitive to sulphur compounds and other potential contaminants, and in some cases to high temperatures. Another option being investigated is the combination of a single-membrane separation unit for bulk separation, followed by a CO_2 liquefaction step from

which the waste stream is recycled and mixed with the feed to the membrane system. This combination would enable both systems to operate within their optimal ranges in terms of CO_2 concentration (Bouma et al., 2017).

- Calcium looping separates the CO_2 contained in flue gases from calcium oxide-based sorbents through sequential carbonation/calcination cycles (Romano et al., 2013). A pilot plant using calcium looping to capture 1 tCO_2 per hour was commissioned in 2013 in Chinese Taipei (Chang et al., 2014), and the ZECOMIX (Zero Emissions of CarbOn with MIXed technologies) research infrastructure in Italy is investigating the calcium looping process to capture CO_2 from coal gasification and steam methane reforming processes (Stendardo et al., 2016).

Oxy-fuel capture technologies are differentiated by the extent to which oxy-firing is applied in the cement kiln. Oxy-firing or oxy-fuel combustion refers to burning a fuel with pure oxygen as opposed to air. Removing the nitrogen component of air raises fuel efficiency and yields a stream of CO_2 and steam, allowing for direct CO_2 purification. Partial oxy-combustion applies it at the precalciner stage only, whereas full oxy-combustion also includes oxy-fuel in firing of the cement kiln. While the yields for CO_2 separation in partial oxy-combustion are reportedly in the 55-75% range, full oxy-combustion can theoretically yield 90-99% capture (ECRA and CSI, 2017). However, even if these technologies do not necessarily incur additional fuel consumption, their use requires the re-engineering of plants to optimise the heat recovery system and minimise air ingress. Cement plant CO_2 capture based on oxy-combustion can also impact the quality of the clinker produced, necessitating additional post-treatment of the clinker to improve its quality and thus raise costs (ECRA, 2012). Furthermore, oxygen provision requires that electricity be generated onsite or purchased. There is experience in operating with oxy-enrichment conditions in Europe and the United States, and several simulations and trials have been undertaken in recent years. In fact, specific plans are in place for the first oxy-fuel capture technology demonstration projects in Europe, as Heidelberg-Cement and LafargeHolcim intend to dedicate two facilities in Austria and Italy to test incorporating oxyfuel technology into the cement production process (ZKG International, 2018).

Other carbon capture technologies or configurations that do not strictly fit within the post-combustion or oxy-fuel categories discussed above are also being explored:

- The advantages of replacing part of the "raw meal" (a fine powder made of the raw materials) with the purge from a calcium looping system in a cement kiln are being investigated in Italy. Theoretical optimisation results indicate reductions of up to 75% in fuel consumption and 85% in CO_2 emissions compared with conventional cement plants (Romano et al., 2013).
- A new concept called direct separation, which captures process CO_2 emissions by applying indirect heating in the calciner, is being piloted at a cement plant in Belgium (LEILAC, 2017).

Source: IEA (2018a), *Technology Roadmap: Low-Carbon Transition in the Cement Industry*.

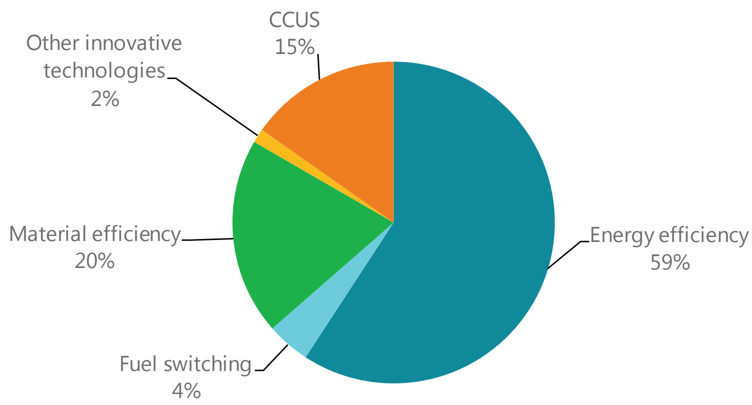
Iron and steel

Iron and steel production is projected to expand modestly in the coming decades and then decline to around today's level by 2060 in the CTS – nearly 25% lower than in the RTS. Emissions reductions in the iron and steel subsector in the CTS are responsible for around

40% of all reductions in the industry sector through 2060 relative to the RTS. Direct CO_2 emissions are dramatically reduced in the CTS, to around 25% of the current level (0.5 $GtCO_2$) by 2060.

CCUS, coupled with upgraded process technologies for hot metal production that incorporate oxygen-rich conditions, becomes important in the iron and steel subsector to meet the CTS emissions reduction targets. CO_2 capture amounts to nearly 11 $GtCO_2$ and contributes 15% of the difference in total CO_2 emissions reductions between the CTS and the RTS. CCUS is hence the third-largest decarbonisation lever in the subsector, behind energy efficiency (59%) and material efficiency (20%) (Figure 33).

Figure 33. Global cumulative direct CO_2 emissions reductions in iron and steel under the CTS, 2017-60



Source: IEA (2019).

CCUS is the third-largest decarbonisation lever in the iron and steel subsector under the CTS, accounting for 15% of emissions reductions.

The blast furnace-basic oxygen furnace (BF-BOF) route is currently used in around 70% of global crude steel production, while scrap-based electric arc furnaces (EAFs) are used for most of the remaining production. Thus, the iron and steel subsector depends heavily on coal for the production of coke, the main reducing agent used to convert iron ore into pig iron in the BF-BOF route (making up almost half of the total final energy mix of the subsector globally). Even in the CTS, 17 EJ of coal are consumed in iron and steel in 2060.

In the short term, CCUS retrofits to existing plants are possible, particularly top-gas recycling (TGR) retrofits of existing blast furnaces, and the suitability of CCUS for alternative iron and steel production processes – such as direct reduced iron (DRI) and oxygen-enhanced reduction technologies – raises CCUS potential in the subsector. Further investment and research and development (R&D) are necessary to explore and fully develop CCUS technology options for iron and steel production (Box 6).

Box 6. Status of CCUS in iron and steel

Several CCUS technologies are being explored in the iron and steel subsector and are currently at the demonstration phase.

- Promising first steps have been taken to integrate carbon capture technologies into hot metal processes. The first commercial project, which came online in 2016 in the United Arab Emirates, is a natural gas-based DRI process in which the 800 ktCO_2 captured per year is used for enhanced oil recovery (EOR).
- As an upgraded smelting reduction (SR)-based process developed by Ultra-Low Carbon Dioxide Steelmaking (ULCOS, a research programme of the European Commission), HIsarna combines a hot cyclone and a bath smelter and does not require the use of coke or sinter. HIsarna is particularly suited for CCUS, as the process operates with pure oxygen and off-gases therefore have a CO_2 concentration almost high enough to be directly stored (Birat, 2010). Commercial-grade steel was first produced through the HIsarna process in 2013 and continued until June 2014, supported by private funding. A longer trial to test process stability and continuous operations began in 2016 (Tata Steel, 2017), and additional public funding has been provided by the LoCO_2Fe programme through Horizon 2020 (European Commission, 2017). The outcome of this trial will determine the design parameters for a commercial-scale plant (ESEC, 2014).
- Coke oven gas (COG) reforming is a process that partially converts the carbon compounds of COG into hydrogen and carbon monoxide. The COURSE 50 programme (CO_2 Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50) in Japan is developing (1) a process that uses this technique to produce enhanced reducing gas for blast furnaces, and (2) complementary technologies to separate and recover CO_2 from blast furnace gas; it aims to reach commercial demonstration by 2030. Korea's POSCO, a steelmaker, and its Research Institute of Industrial Science and Technology (RIST) are also developing a conversion process to produce a hydrogen-rich gas from COG and CO_2 through steam reforming, which could be used for iron ore reduction in a blast furnace or SR process. The design of the COG reforming process was completed in 2012 and construction of a pilot plant began in 2013 (RIST, 2013).
- The top gas recycling blast furnace process (TGR-BF) is a process technology developed by ULCOS and a promising opportunity for carbon capture deployment. Top gas, a by-product of blast furnaces, is collected, treated and reused as a reducing agent to displace coke. The TGR-BF system also operates with pure oxygen, which produces a higher concentration of CO_2 in the top gas and thus easier carbon capture (Birat, 2010). A commercial-scale plant planned for the ArcelorMittal site in Florange, France, was cancelled in 2013 for financial reasons.
- Ulcored, a DRI-based process, was also developed by the ULCOS research programme. DRI is produced by reducing iron ore in a shaft furnace with reducing gas from coal gasification or gas reforming, and off-gases from the shaft are reused in the process following CO_2 capture (Birat, 2010). In 2013, there were plans to build a pilot plant to produce 1 t of DRI per hour to demonstrate this process (LKAB, 2013).

Chemicals

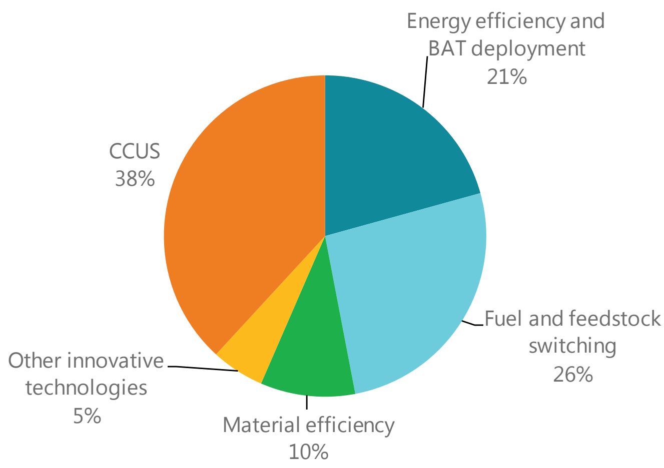
The chemical subsector is the third-largest industrial source of CO_2 emissions. Ammonia production accounts for 30% of total direct CO_2 emissions from the subsector, followed by high-value chemicals[16] (16%) and methanol (13%). Demand for chemicals grows by around 40% between 2017 and 2060 in the CTS – lower than in the RTS due to increased plastic recycling.

In the CTS, the chemical subsector contributes around one-quarter of the cumulative direct emissions reductions from industry over the projection period. By 2060, direct CO_2 emissions from chemicals are 0.6 $GtCO_2$ – 60% below the 2017 level.

CCUS deployment is critical to chemical subsector decarbonisation: it accounts for 38% of the subsector's emissions reductions by 2060 and is the single largest emissions-reduction lever, ahead of fuel switching (Figure 34). A cumulative 15 $GtCO_2$ are captured for use and storage by 2060 in the CTS, the largest cumulative capture volume of all industry subsectors. In 2060, 265 $MtCO_2$ are captured for storage, primarily from the production of ammonia (65%), high-value chemicals (22%) and methanol (13%). Today, two large-scale CCUS facilities are capturing almost 2 $MtCO_2$ from fertiliser production in the United States.

The high CO_2 capture rate in chemicals is partly associated with coal-chemical plants, particularly in China. These facilities produce relatively pure streams of CO_2, so CCUS is a relatively low-cost emissions reduction solution. In the CTS, a large-scale shift from coal- to natural gas-based primary chemical production greatly reduces the rate of CO_2 capture compared with the RTS. Gas-chemical facilities are equipped with CCUS, but they produce less CO_2 per unit of primary chemical production.

Figure 34. Global cumulative direct CO_2 emissions reductions in the chemical subsector in the CTS, 2017-60



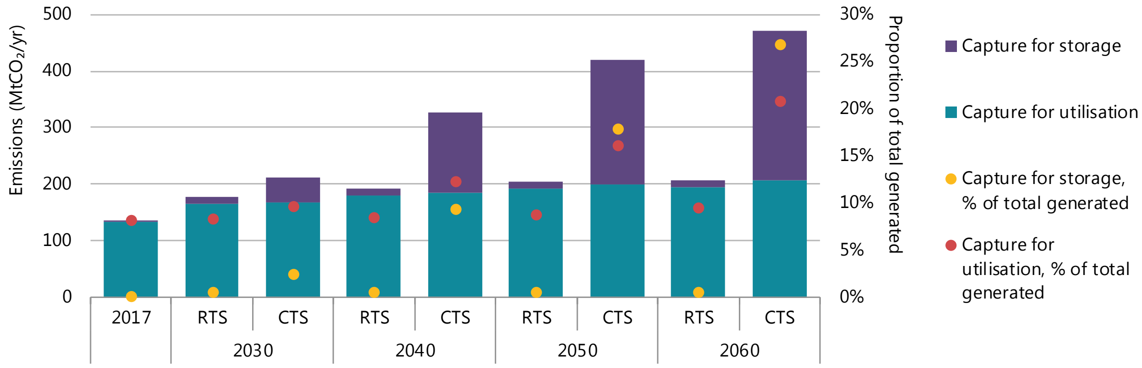
Note: BAT = best available technology.
Source: IEA (2019).

CCUS plays a leading role in decarbonising the chemical subsector, accounting for 38% of the difference in emissions reductions between the RTS and the CTS.

[16] High-value chemicals refers to light olefins (ethylene and propylene) and aromatics (benzene, toluene and mixed xylenes [BTX]).

Today, around 130 $MtCO_2$ is used in the chemical subsector each year, primarily for producing urea and methanol. The role of carbon capture and utilisation (CCU) grows incrementally in both the RTS and CTS but remains well below that of carbon capture and storage (CCS). The demand for urea – the largest utilisation application within the chemical subsector – varies only slightly to 2060 (Figure 35).

Figure 35. CCUS deployment in the chemical subsector in the CTS and RTS, 2017-60



Source: IEA (2019).

Additional CO_2 capture capacity deployed in the CTS relative to the RTS is primarily for storage applications.

Around 45% of the cumulative CCUS capacity in the CTS is deployed to capture concentrated CO_2 emissions streams, and the remaining 55% is applied to dilute streams. Concentrated CO_2 streams are targeted for early CCUS deployment, accounting for around 60% of cumulative chemical emissions captured before 2030. The fact that CO_2 separation is an inherent part of methanol and ammonia production means that these capture options are less costly and therefore more attractive, albeit limited in scope. The only additional capital investment required within the production facility is for CO_2 compression, which is less than one-fifth the capital cost of a capture application for dilute streams. However, the availability of these more attractive streams is limited. After 2030, feedstock shifts from coal to natural gas reduce the availability of concentrated emissions streams for capture and permanent storage.

The implications of limiting CCUS in industry

The important role of CCUS in supporting a least-cost transformation of the industry sector is highlighted in new IEA analysis that limits the availability of CO_2 storage while still meeting the emissions reductions required under the CTS (IEA, forthcoming a). In the Limited CO_2 Storage (LCS) scenario variant, the availability of CO_2 storage is assumed to be limited to 10 $GtCO_2$ in the period to 2060, in contrast with the 107 $GtCO_2$ of CO_2 storage in the CTS.[17] Nonetheless, the LCS case still represents a 15-fold increase in CO_2 storage from today's levels.

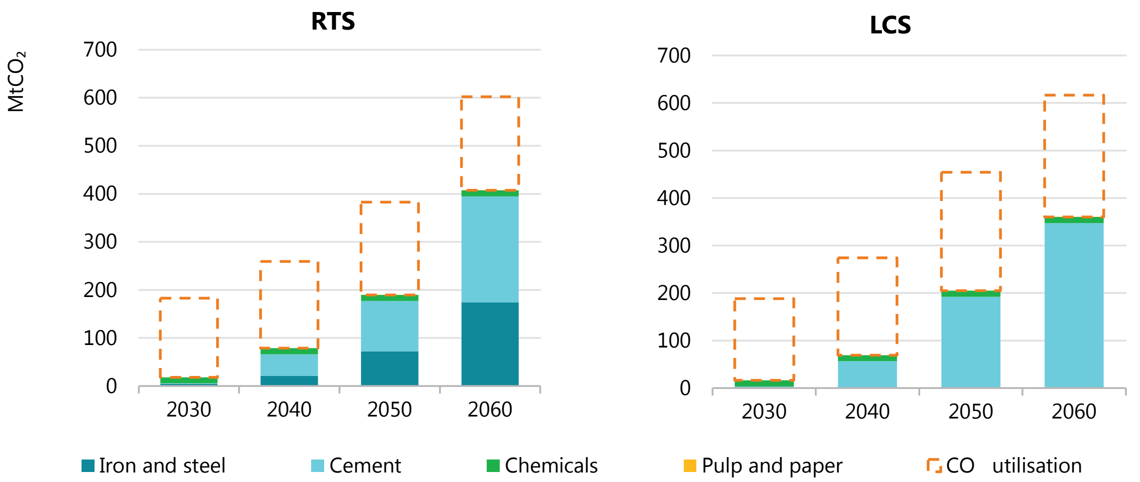
[17] An additional 7.7 $GtCO_2$ are used in the CTS in the period to 2060.

The LCA analysis highlights that restricting the role of CO_2 storage would result in higher costs and significantly higher electricity demand, with widespread use of electrolytic hydrogen in industry and the production of "Power-to-X" fuels. More generally, the LCS would increase reliance on technologies that are at an earlier stage of development, which in practice may delay emissions reductions. Beyond 2060, continued constraints on CO_2 storage are unlikely to be consistent with climate goals given the role of CO_2 storage in carbon removal and negative emissions.

The industry sector would be particularly impacted should CO_2 storage be limited:

- The marginal abatement costs in industry would double in 2060 relative to the CTS. This results in some emissions reduction efforts shifting to other sectors, particularly in buildings and transport.
- Increased reliance on less mature and expensive technology options would see the investment needs and power generation requirements increase in the LCS. The LCS would require an additional generation capacity of more than 3 300 GW in 2060, which is half of the installed global capacity in 2016.
- For cement production, advances to reduce the clinker-to-cement ratio and material efficiency strategies would become more important, but the lack of alternatives to CO_2 storage would mean that reliance on CCUS is reduced by only 15%, with a commensurate increase in the sector's emissions. The cement sector would absorb almost half of the available CO_2 storage capacity in the LCS (Figure 36).

Figure 36. Captured CO_2 for storage by industry sub-sector and for utilisation by scenario



Notes: Final energy demand includes energy consumption in blast furnaces and coke ovens, and feedstocks for chemical production; RTS = Reference Technology Scenario, LCS = Limited CO_2 Storage scenario variant.
Source: IEA (2019).

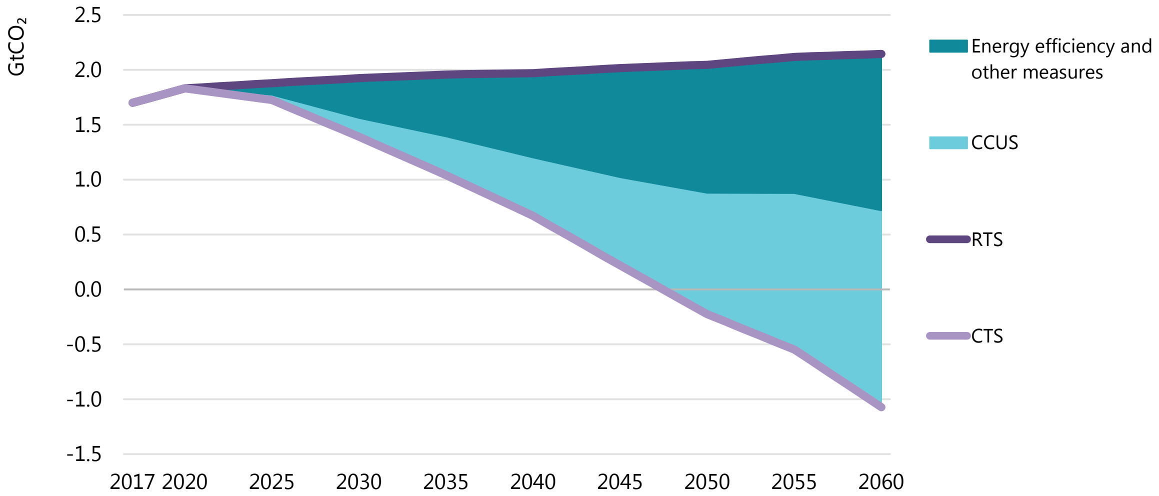
The lack of alternatives to CCUS to decarbonise cement production would mean the subsector would absorb almost half of the limited CO_2 storage resources under the LCS.

Lower-cost opportunities for CCUS: Fuel transformation

CCUS utility is by no means limited to industry. While this analysis focuses on industry sector applications, synergies and learnings from other sectors should not be overlooked. In particular, lower-cost CCUS applications in fuel transformation (such as natural gas processing and ethanol production) have potential to drive early CCUS deployment and support the development of CO_2 transport and storage networks.

In the RTS, around 3 $GtCO_2$ is captured and stored from fuel production and transformation up to 2060, compared with 31 $GtCO_2$ in the CTS. CCUS contributes about half of the emissions reductions in the CTS relative to the RTS (Figure 37). Demand for biofuels, including biodiesel, hydrogen and ethanol, increases significantly in the CTS, as they offer net-neutral emissions. Since the combination of CCUS and bioenergy can create negative emissions, CCUS is applied widely to biofuel production in the CTS.

Figure 37. Direct CO_2 emissions reductions for fuel production and transformation sectors by mitigation strategy, CTS compared with RTS, 2017-60



Source: IEA (2019). All rights reserved.

CCUS contributes half of the cumulative emissions reductions from the RTS to the CTS.

Many early applications of CCUS have been in hydrogen production and natural gas processing, since CO_2 separation is often required or inherent in the process (see Chapter 1). Applying CCUS in some fuel transformation applications can also have less impact on facility competitiveness owing to the distinct market and pricing dynamics. Furthermore, many of the companies involved in the upstream fuel sector have the subsurface capability and expertise necessary to develop CO_2 storage sites.

Prospects for hydrogen in industry

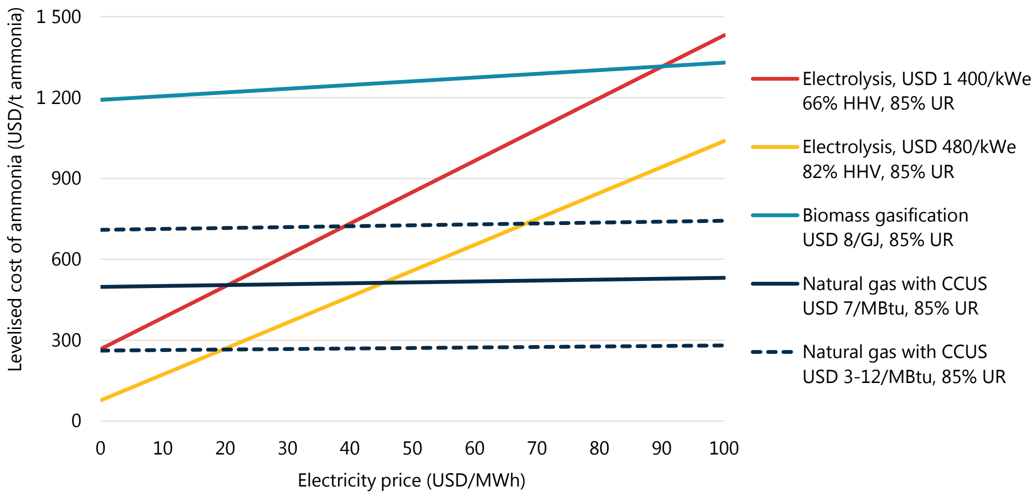
Today, hydrogen is used in industry, primarily for ammonia production and refining, with almost all of this produced from natural gas and, to a lesser extent, coal. The potential for hydrogen to support the decarbonisation of industry and other sectors has recently gained increased attention.[18]

[18] An IEA special report to be released in June 2019 elaborates on the potential for clean hydrogen applications in industry (IEA, forthcoming b).

There are two main routes for clean hydrogen production: hydrogen production from fossil fuels in combination with CCUS or from renewable electricity. The former is expected to be the least-cost low-carbon option in the medium term, especially in regions where inexpensive natural gas is readily available (Figure 38). Coal-based hydrogen production may also remain cost-competitive in countries such as China for some time, whereas electrolytic hydrogen will be most competitive in locations with favourable conditions for renewables and sufficient space. These locational considerations could suggest a need for the construction of significant transport infrastructure for hydrogen or other carriers such as ammonia, or the relocation of industrial production sites.

In the near term, significant quantities of hydrogen could be introduced into the iron and steel subsector through blending with fossil fuel inputs; however, producing steel with electrolytic hydrogen in a DRI process would only be cost-competitive with other decarbonisation methods (including CCUS) where electricity rates are low enough. In the chemical subsector, ammonia and methanol production can in principle be fuelled by non-fossil sources. Producing these chemicals with electrolytic hydrogen would also require low electricity rates to be cost-competitive with methods such as CCUS. Given a natural gas price of USD 7 per million British thermal units (MBtu), electrolysis competes with gas-based production equipped with CCUS at electricity prices between USD 20-45/MWh, depending on electrolyser efficiency and cost (Figure 38).

Figure 38. Simplified levelised cost of ammonia via various pathways



Notes: Energy cost assumptions: USD 3-12 per million British thermal units (MBtu) for natural gas; USD 8-18 per gigajoule (GJ) for biomass; USD 30-90 per megawatt hour (MWh) for electricity. CAPEX assumptions: USD 860 per tonne (t) of ammonia for natural gas steam reforming; USD 50-270/t captured CO_2 for carbon capture, with the range encompassing both concentrated (process CO_2) and dilute (energy-related CO_2) sources and a 90% capture rate applied to each source; USD 6 000/t ammonia for biomass gasification; USD 9/t nitrogen for air separation unit; USD 95/t ammonia for air separation unit; USD 480-1 400 per kilowatt electrical capacity (kWe) for electrolysis. CAPEX assumptions stated per unit of output, apart from electrolysis which is stated per unit of electricity input. Fixed operational expenditure: 2.5-5.0% of CAPEX. Electrolyser efficiency = 66-82% on a higher heating value (HHV) basis. Energy performance of an average ammonia plant. Storage and transportation costs as USD 20/t captured CO_2. Discount rate: 8%. A 25 year design life is assumed for all equipment. UR = utilisation rate.

Source: IEA (2018b), *The Future of Petrochemicals*, https://www.iea.org/petrochemicals/.

Electrolysis competes with gas-based ammonia production equipped with CCUS at electricity prices between USD 20-45/MWh.

Hydrogen is also a potential low-carbon alternative for providing high-temperature heat, but cost comparisons in many situations tend to favour incorporating CCUS or biomass into industry sector processes. While in this context CCUS and hydrogen are competing options for reducing CO_2 emissions from generating heat, the hydrogen supply itself could be derived from a process based on fossil fuel with CCUS.

Carbon capture and utilisation

Industry has become increasingly interested in using CO_2 to manufacture low-carbon products, as it holds the promise of generating economic revenue in addition to mitigating climate change. Further, the economic benefits of using CO_2 in turn support the business case for CCS projects by reducing costs or supplementing revenue sources, for example, by selling some of the captured CO_2 for use in products and services elsewhere, or by selling CO_2-derived products if the CO_2 is used onsite. Especially in the short term, such revenues could be important for CCS projects for which financing and economic incentives are limited.

Already today, more than 220 $MtCO_2$ are used each year. The largest consumer is the fertiliser industry, which consumes 100 $MtCO_2$ per year for urea manufacturing, followed by the oil sector at nearly 80 $MtCO_2$ for EOR. Other commercial applications include food and beverage production, metal fabrication, cooling, and fire suppression; CO_2 is also used in greenhouses to stimulate plant growth. The range of potential CO_2 uses is diverse and includes the production of fuels, chemicals and building materials.[19]

In the buildings sector, using CO_2 in the production of construction materials could prove particularly interesting, as CO_2 can replace water in the manufacture of concrete (in a process called CO_2 curing) or can be a feedstock in its constituents (cement and aggregates). These applications involve reacting CO_2 with calcium or magnesium minerals to form low-energy carbonate molecules, which is the form of carbon that makes up concrete. CO_2-cured concrete is one of the most mature and promising applications of CO_2 use, while integrating CO_2 into the production of cement itself is at an earlier stage of development.

CO_2-cured concrete can have superior performance, a lower manufacturing cost and a smaller CO_2 footprint than conventionally produced concrete. The climate benefits come mainly from the lower consumption of input cement, which is responsible for the bulk of the cost and lifecycle emissions of concrete. Two North American companies, CarbonCure and Solidia Technologies, lead the development and marketing of CO_2 curing technology, but quantifying the emissions reduction potential of CO_2-cured concrete remains challenging. CarbonCure reports that the CO_2 footprint of concrete can be reduced by around 80%, but this has not been independently verified.

[19] Opportunities for future CO_2 use will be examined in detail in upcoming IEA analysis (IEA, forthcoming c).

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Conclusions and policy recommendations

Carbon capture, utilisation and storage (CCUS) is a critically important part of the portfolio of technologies and measures needed for the sustainable transformation of industry. Emission reductions in industry can be achieved by changing fuels, improving energy efficiency and increasing use of renewable energy. However, for deep emissions reductions in key sectors, CCUS is indispensable.

There are signs of renewed momentum for CCUS deployment, as discussed earlier in this analysis. This includes in Europe, where industrial CCUS hubs are being planned; in the United States, where the expansion of the 45Q tax credit is expected to stimulate significant new investment;[20] and in the People's Republic of China ("China") where the first large-scale CCUS project was commissioned in 2018. However, a substantially strengthened policy response will be needed to support widespread uptake of CCUS as part of the shift to low-carbon production processes in industry.

Accelerating technological and business innovations for CCUS

While CCUS has now been demonstrated in a number of industrial applications, challenges remain in order to achieve much-needed scale-up in industry. Industrial CCUS technologies are at different stages of development and the technological and commercial challenges can vary depending on the application, sector and location.

Today, there is one commercial steel plant applying CCUS (in the United Arab Emirates) and one cement plant with CCUS under development (in Norway). This underscores that CCUS is at an earlier stage of development in these sectors and, therefore, also at the higher end of the technology cost curve. Significant cost reductions can be achieved through project deployment and experiential learning: the first-of-a-kind CCUS projects in industry and power applications have identified potential capital and operating cost reductions in the order of 30% or more.

Policies will be crucial to facilitate early deployment of CCUS in industry and, in turn, to support future technology cost reductions and new business models for investment. As the development time frame for CCUS projects is typically between four and eight years, policy and investment decisions need to be taken soon for new facilities to be operational by the mid-2020s.

There is no one-size-fits-all policy approach to support investment in industrial applications of CCUS. Policies will need to consider the specific attributes and challenges faced by industry

[20] The expanded 45Q tax credit will provide up to USD 50 (United States dollars) per tonne of carbon dioxide (/tCO_2) permanently stored and USD 35/tCO_2 when it is used for enhanced oil recovery (EOR) or other industrial applications.

sectors in different regions, including potential competitiveness impacts. However, a number of key priorities and strategies are discussed below.

Create a market for low-carbon products: Public and private procurement

Public and private procurement of lower-carbon products and materials – including steel, cement, chemicals and fuels – can play an important role in establishing early markets and facilitating investment and innovation. This has been demonstrated in the power sector, where the preparedness of both public and private sector customers to pay a premium for low-carbon electricity has spurred new business opportunities and a growth in renewable energy deployment. The interest in renewables-based electricity has not yet fully spilled over into the procurement of low-carbon materials (Box 7), although the emissions embedded in the supply of construction materials and transport fuels can be significant in an organisation's environmental impact.

The power sector experience and other similar ventures could serve as models for heavy industry – the development of which would provide an investment signal for new technology innovations, including in CCUS (IEA, 2016). In the public sector, the Netherlands and Canada have implemented public procurement rules that favour material inputs with low-carbon footprints for construction projects. The size of public contracts for these types of materials can help to establish significant and sustainable markets worldwide.

Box 7. Beyond electricity: Private procurement of low-carbon industrial products

Various companies have voluntarily pledged to source all their power from renewable sources, reflecting shifting customer demands for low-carbon products and services. Companies range from the Lego Group, the IKEA Group and Unilever (which are among the nearly 200 members of the RE100 group of companies that have pledged to move to 100% renewable power) to a variety of technology companies that operate significant data centres. Electricity demand of the world's data centres amounted to nearly 200 terawatt hours (TWh) in 2015 – about 1% of global electricity demand (IEA, 2018). Owing to their size, some of the largest companies have the ability to sign major power purchase agreements and develop sizeable renewable power generation capacities.

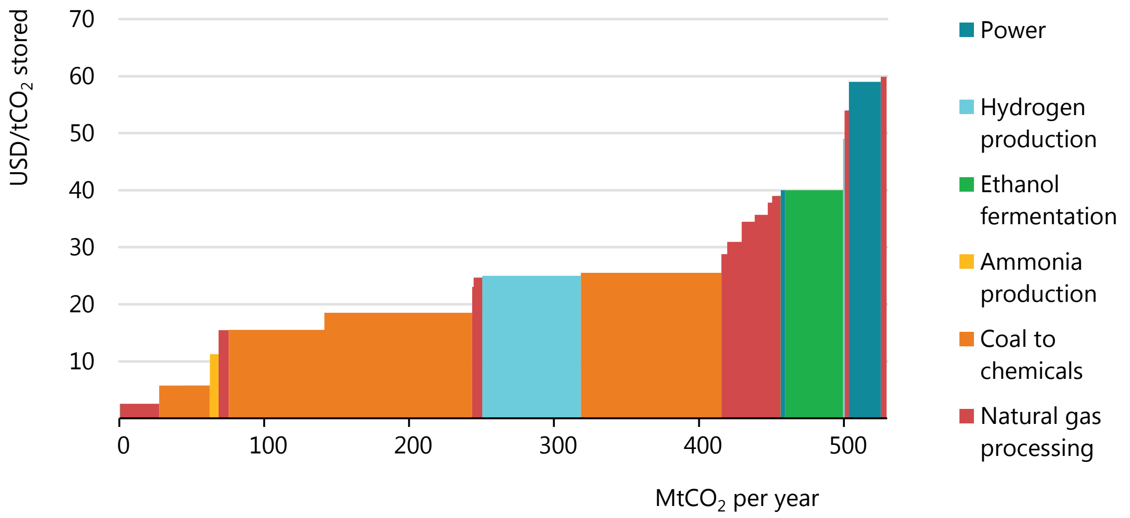
Beyond electricity, many companies are also important consumers of industrial materials such as steel, aluminium, cement and petrochemical products (e.g. plastics and resins), the production of which generates substantial CO_2 emissions. Although the momentum seen in private renewable power procurement has not yet extended to other products, positive developments and partnerships are beginning to emerge.

An example involves Apple Inc., which teamed up with two major global aluminium companies, Alcoa Corporation and Rio Tinto Group (with support from the Government of Canada and the Government of Quebec) to develop a process that removes CO_2 emissions from the aluminium smelting process (RioTinto, 2019). Other aluminium companies such as Rusal have recently made similar efforts to decarbonise aluminium production (Rusal, 2019).

Prioritise competitive investment opportunities in industry

Globally, as much as 450 million tonnes of carbon dioxide ($MtCO_2$) per year could be captured for use or storage with an incentive of less than USD 40 per tonne (Figure 34). This CO_2 would come primarily from industrial and fuel transformation facilities such as those used for ethanol production and hydrogen and natural gas processing, which otherwise vent relatively pure CO_2 into the atmosphere. Early investment in CCUS could therefore reduce emissions substantially at a competitive cost while providing the experience and infrastructure to help to decarbonise other industry subsectors such as iron and steel and cement.

Figure 39. Break-even costs for CO_2 capture and storage by application



Source: IEA (2019).

As much as 450 $MtCO_2$ could be captured with an incentive of less than USD 40/tCO_2.

Develop industrial CCUS hubs

Widespread deployment of CCUS in industry will require new business models and a swift transition from building stand-alone CCUS facilities with dedicated transport and storage infrastructure, to developing multi-user "hub and cluster" facilities in industrial regions. The economies of scale inherent in the hub structure reduce unit costs, while separating the elements of the CCUS value chain can reduce commercial risks and financing costs. The benefits of this approach are increasingly being reflected in investment plans, particularly in Europe where several CCUS hubs are under development (see Box 2).

Regarding transport and storage, CCUS projects that do not have access to existing infrastructure must necessarily build this investment into the project. Sizing transport infrastructure to accommodate future CCUS projects adds to the immediate project costs but provides the potential to significantly reduce the cost of the next projects. For example, the now-abandoned White Rose CCS project in the United Kingdom planned to over-size the infrastructure, which would have reduced the transport and storage unit cost of future projects by an estimated 60-80% (CCSA, 2016).

Public-private partnerships are an effective option to support the development of transport and storage infrastructure. Appropriate risk-sharing arrangements between governments and industries will be important to support the cost-effective deployment of CCUS infrastructure.

Identify and develop "bankable" CO_2 storage

The challenges for applying CCUS to industrial production are not restricted to capture technologies only, but include the necessary ramp-up of a CO_2 transport and storage infrastructure. In particular, confidence in the availability of safe, secure and adequate CO_2 storage is a prerequisite for investment in transport infrastructure and industrial capture facilities. Although global CO_2 storage resources are considered well in excess of likely future requirements, significant further assessment work is required in many regions to convert theoretical storage capacity into "bankable" storage, wherein capacity, injectivity and containment are well understood. Regional and interregional collaborations and partnerships are important to identify and develop CO_2 storage facilities globally, and should continue to be supported.

Policy frameworks for investment certainty

A carbon price or CO_2 tax can provide an important long-term investment signal for CCUS, but boosting early investment will require complementary and targeted policy measures. A range of options including regulatory levers, market-based frameworks, and measures such as tax credits, grant-funding, feed-in tariffs, public procurement, low-carbon product incentives and sector-specific CCUS obligations and certificates, could all play a role depending on national circumstances and preferences.

Policy frameworks need to recognise that industry subsectors operate in competitive international environments (less so for cement), and that carbon leakage is a risk. Achieving emissions reductions while ensuring economic prosperity requires that de-risking and incentive mechanisms be in place to ensure the competitiveness and viability of heavy industry in the transition to a low-carbon world. At the same time, climate policies must also protect business competitiveness, given potential economic impacts to emissions-intensive and trade-exposed sectors such as steel and chemicals.

In the context of carbon pricing, one effective approach that can help protect business competitiveness is using an intensity-based pricing system that includes specific benchmarks for emissions intensity, and emissions credits. Firms that achieve emissions reductions can sell credits to other firms. Such a mechanism can ensure price incentives for all firms to reduce emissions, but prevent negative economic impacts and carbon leakage. In addition, funding to support clean energy transitions in industry, which applies to CCUS projects, can have an important role to play.

Short-term concerns about competitiveness and carbon leakage need to be carefully managed, but in the long-term, facilities that are relatively carbon-intensive could become uncompetitive in the face of increasingly stringent decarbonisation policies throughout the world. Early efforts to include carbon capture in industrial production, and to locate facilities near CO_2 transportation and storage infrastructure, can in fact help ensure the *long-term* competitiveness of hard-to-abate sectors and attract investment.

Develop CO_2 use opportunities

Innovation in CO_2 use – to produce chemicals, building materials, fuels and products such as low-carbon cement – could boost future demand for CO_2 as a valuable commodity (IEA, forthcoming). In addition to creating new markets for low-carbon and carbon-based products, CO_2 use technologies can provide a commercial incentive for CO_2 capture. Two-thirds of CCUS projects operating today were driven by demand for CO_2 for EOR, and there is significant potential for further EOR-enabled CCUS investment in North America, China and the Middle East.

Although opportunities for CO_2 use are expected to complement (rather than substitute) broader CCUS deployment efforts and the need for geological storage, the growing number of CO_2 use applications and projects have potential to support capture technology improvements and cost reductions, while creating new economic opportunities for industry. Research and innovation in both capture and use technologies across a wide variety of industry subsectors should therefore continue in parallel with industrial-scale deployment of available CCUS technologies.

Accelerating the deployment of CCUS in industry is both complex and increasingly vital. It requires government, industry, financial services and key stakeholders to work in partnership and put in place new, investable business models, reaching agreement on the sharing of costs, risks and liabilities. It should include partnerships with developing countries to support CCUS capacity building and action. And it needs to ramp up quickly.

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