THE RESILIENCE OF COAL-BASED INDUSTRIES IN THE TRANSITION TO NET ZERO

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MARCH 2023

INTERNATIONAL CENTRE FOR SUSTAINABLE CARBON

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PREFACE

This report has been produced by the International Centre for Sustainable Carbon (ICSC) for the International Energy Agency's Coal Industry Advisory Board (CIAB). It is based on a survey and analysis of published literature, and on information gathered in discussions with interested organisations and individuals. Their assistance is gratefully acknowledged. It should be understood that the views expressed in this report are our own, and are not necessarily shared by those who supplied the information, nor by our member organisations.

The ICSC was established in 1975 and has contracting parties and sponsors from: Australia, China, Italy, Japan and South Africa.

The overall objective of the International Centre for Sustainable Carbon is to continue to provide our members, the International Energy Agency (IEA) Working Party on Fossil Energy and other interested parties with definitive and policy relevant independent information on how various carbon-based energy sources can continue to be part of a sustainable energy mix worldwide. The energy sources include, but are not limited to coal, biomass and organic waste materials. Our work is aligned with the UN Sustainable Development Goals (SDGs), which includes the need to address the climate targets as set out by the United Nations Framework Convention on Climate Change (UNFCCC). We consider all aspects of solid carbon production, transport, processing and utilisation, within the rationale for balancing security of supply, affordability and environmental issues. These include efficiency improvements, lowering greenhouse and non-greenhouse gas emissions, reducing water stress, financial resourcing, market issues, technology development and deployment, ensuring poverty alleviation through universal access to electricity, sustainability, and social licence to operate. Our operating framework is designed to identify and publicise the best practice in every aspect of the carbon production and utilisation chain, so helping to significantly reduce any unwanted impacts on health, the environment and climate, to ensure the well-being of societies worldwide.

The ICSC is organised under the auspices of the International Energy Agency (IEA) but is functionally and legally autonomous. Views, findings and publications of the ICSC do not necessarily represent the views or policies of the IEA Secretariat or its individual member countries.

The CIAB consists of a group of high-level executives from coal-related enterprises. It was established by the IEA in July 1979 to provide advice to the IEA on a wide range of issues relating to coal. CIAB Members are currently drawn from 12 countries accounting for approximately 70-80% of world coal production and coal consumption. Members are drawn from major coal producers, electricity producers, other coal-consuming industries and coal-related organisations. The CIAB provides a wide range of advice to the IEA, through its workshop proceedings, meetings, work programme and associated publications and papers.

ABSTRACT

Many countries, particularly in Europe, have committed to phase out coal, as part of efforts to achieve net zero emissions (NZE). However, this will be very difficult, if not impossible for heavy industries to achieve in a cost-effective and resilient manner, whilst producing the necessary steel, cement, aluminium and chemicals to provide the future NZE infrastructure.

Consequently, fossil fuels including coal, fitted with carbon capture utilisation and storage (CCUS), will continue to play a role as industry decarbonises and moves towards NZE. Although coal use will inevitably reduce, perhaps by as much as 80% from the current 5 Gt/y, 0.6–1.4 Gt/y it is still forecast to be used in 2050, largely in heavy industry.

Heavy industries can be NZE compliant by 2050. However, the technologies that are likely to be relied upon to mitigate their emissions are largely immature. Fortunately, in the short to medium term, technologies that are already mature or in the early adoption phase can play an important role, including material efficiency gains, switching to bioenergy, and the electrification of low and medium temperature heat as well as the significant low-carbon electricity required for aluminium smelting. In the longer term, fundamental technology shifts are needed, where innovative technologies incorporating CCUS and hydrogen will be key for heavy industry decarbonisation. In order to ensure that these technologies are available for deployment at least cost, development work needs to be caried out.

For heavy industries to decarbonise in a cost effective and resilient way, coal fitted with CCUS will be a key technology for all of the heavy industries assessed, particularly cement.

ACRONYMS AND ABBREVIATIONS

ASU	air separation unit
BECCS	biomass energy carbon capture and storage
BF-BOF	blast furnace to basic oxygen furnace
BEIS	Department for Business, Energy and Industrial Strategy, UK
CCGT	combined cycle gas turbine
CCS	carbon capture and storage
CCUS	carbon capture, utilisation and storage
CHP	combined heat and power
COP	Conference of the Parties
DAC	direct air capture
DOE	Department of Energy, USA
DRI	direct reduced iron
EAF	electric arc furnace
EfW	energy from waste
EOR	enhanced oil recovery
EPC	engineering procurement contract(or)
ETO	Energy Transition Outlook
ETS	emissions trading scheme
EU	European Union
FEED	front end engineering and design
GCCSI	Global Carbon Capture and Storage Institute
GHG	greenhouse gases
HESC	Hydrogen Energy Supply Chain
ICSC	International Centre for Sustainable Carbon
IEA	International Energy Agency
IEAGHG	IEA Greenhouse Gas R&D Programme
IGCC	integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
LHV	lower heating value
LNG	liquefied natural gas
MEG	mono ethylene glycol
MHI	Mitsubishi Heavy Industries
MTO	methanol-to-olefins
MTG	methanol-to-gasoline
NZE	net zero emissions
OECD	Organisation for Economic Co-operation and Development
PCI	pulverised coal injection
PPA	power purchase agreement
PSA	pressure swing adsorption
R&D	research and development

SDGs	Sustainable Development Goals, UN
SNG	synthetic natural gas
TRL	technology readiness level
TSA	temperature swing adsorption
VRE	variable renewable energy
UN	United Nations
USC	ultrasupercritical
WGS	water-gas shift

Note: all monetary values are in United States dollars ($) unless otherwise stated.

UNITS

Bt	billion tonnes (10^9 tonnes)
EJ	exajoule (1×10^{18} joules)
Gt	gigatonnes (10^9 tonnes)
GW	gigawatts (10^9 watts)
gCO_2	grammes of carbon dioxide
GJ	gigajoules
$GtCO_2$	gigatonnes of carbon dioxide
m	metres
Mt	million tonnes (10^6 tonnes)
Mtce	million tonnes of coal equivalent
$MtCO_2$	million tonnes of carbon dioxide
MW	megawatt
MWe	megawatt-electric
MWth	megawatt-thermal
t	tonne
t/d	tonnes per day
t/y	tonnes per year
TW	terawatt
TWh	terawatt-hour

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EXECUTIVE SUMMARY

Around 130 countries have announced net zero emission (NZE) ambitions, representing over 90% of the global economy, by gross domestic product. Growing economies depend on heavy industries, which are a major source of greenhouse gas (GHG) emissions. Industry produces about 8000 $MtCO_2$/y of direct emissions, 70% of which come from the cement, iron and steel, and chemical sectors. Adding indirect emissions means that industry accounts for nearly 40% of global CO_2 emissions from human activity. Almost 2000 $MtCO_2$/y of industry-related emissions are inherent to the production processes so cannot be avoided using current production technologies. Industrial emissions are also 'hard to abate' because the processes require high temperatures, industrial plants have a long life, and most are young. Finally, the products are traded in competitive global markets, adding pressure to maintain cheap production pathways.

COAL WILL STILL BE USED IN IN HEAVY INDUSTRY IN 2050

Coal use will inevitably decline from the current 5 Gt/y, perhaps by as much as 80% by 2050, but 0.6–1.4 Gt/y will still be used, largely in industry. Most of this will be in China, home to 50–60% of global production of cement, steel and aluminium, where coal accounts for 70–83% of Chinese production. Thus, coal is vital to these heavy industries and the commitment to phase out coal by many countries will be incredibly difficult for these industries on which we depend.

HEAVY INDUSTRY CAN BE NZE COMPLIANT BY 2050

Heavy industries can be NZE compliant by 2050 and a technology-agnostic approach is key to achieving NZE in terms of cost, energy and supply-chain security. In the short to medium term, technologies that are already mature or in the early adoption phase will be important. These include material efficiency gains, switching to bioenergy, and the electrification of low and medium temperature heat. Fundamental technology shifts are needed in the longer term to decarbonise heavy industry, where innovative technologies incorporating carbon capture utilisation and storage (CCUS) and hydrogen will be key. Development work needs to be carried out now to ensure that these technologies are available for deployment at least cost.

CCUS IS KEY TO DECARBONISING HEAVY INDUSTRY

CCUS is a proven and understood technology.

- The elements of the CCUS technology chain are in place for commercial deployment and are available at demonstration to commercial scale. Much more investment is needed.
- Next-generation technologies that could provide step-change cost reductions and increase efficiency are in R&D and could come to the market.

CCUS projects are spreading around the globe and increasing in diversity. There are 30 operational large-scale CCUS facilities globally, with the potential to store close to 43 $MtCO_2$/y.

- The number of new projects has risen from 28 in 2019 to 102 in 2021 with facilities in development in power generation, liquefied natural gas (LNG), cement, steel, waste-to-energy, direct air capture and storage and hydrogen in Europe, the Middle East, North America and China.
- Asia, and in particular China, should become a key focus for the roll-out of commercial CCUS.

The cost of CCUS has reduced significantly, to around 65 \$/tCO_2. Further cost reductions are expected, perhaps by 50–75%, through learning by doing. The hub and cluster approach can improve the economics of CCUS due to economies of scale and overall de-risking of storage liability and cross-chain risk. There are already four hubs operating in Brazil, Canada, Norway and the United Arab Emirates.

Carbon capture rates of 90–95% are available and will need to move closer to 100%, or to include other options such as cofiring with biofuels, to allow industrial plants to continue to operate in a NZE future.

The global storage potential for CO_2 is almost 14,000 Gt, (almost 2000 years of CO_2 emissions to meet NZE projections). Suitable CO_2 storage basins are generally located near to emissions-intensive regions. Key regions for heavy industry including China, SE Asia, USA, India and Europe all have access to potential geological storage sites.

STEEL HAS AN IMPORTANT ROLE IN A LOW-CARBON FUTURE – $200 BILLION IS NEEED TO MAKE IT NET ZERO COMPATIBLE

Steel is the third most used bulk material after cement and timber. It has a key role in the energy transition as a component of wind turbines, transmission and distribution infrastructure, hydropower, nuclear power and CCUS systems. China produces 53% of global steel (1033 Mt in 2021) followed by India and Japan. Steel production could increase by 12–60% by 2050. Emissions from the steel industry are currently around 2.6 $GtCO_2$/y, direct (Scope 1) emissions (1/4 of industrial CO_2 emissions) and indirect (Scope 2) emissions are almost 9% of total emissions from energy systems.

About 70% of total steel production is produced in the blast furnace to basic oxygen furnace (BF-BOF) process, which relies on coal. Metallurgical coal will be hard to replace due to its threefold role in the blast furnace – as a source of heat, a reducing agent for the iron ore, and it provides permeability to the blast furnace burden. The remaining 30% of steel is mainly produced from recycled steel in electric arc furnaces (EAF); limiting factors here include the availability of scrap steel and the inability to produce high-carbon steel. Thus, coal's share of the energy used for iron and steel production will reduce but will remain at a significant level, at up to 50% in 2050 (representing 14 EJ or 480 Mtce).

Emissions reduction can be achieved by commercialising emerging and breakthrough technologies, the availability of affordable and reliable renewable energy, the successful adoption of hydrogen in steel making, increasing availability of quality raw materials and appropriate government policies. Efficiency improvements to steel plant include operational efficiency, enhanced process control and predictive maintenance strategies, together with the use of best available technologies. These measures could contribute around 20% of cumulative emissions savings.

Blast furnace steel production assets typically have a 40-year life, and the average plant age is only about 13 years old. Younger plants are more likely to be retrofit with energy-efficient and less carbon-intensive technologies such as CCUS. Some individual BFs will come to the end of their life, requiring realignments before 2030. Emerging 'green steel' technologies are promising, but not yet ready for large-scale implementation by 2030. Individual steelmakers may need to use other emission reduction measures while longer-term breakthrough low-emission technologies are developed.

The ongoing, critical role for coal in the iron and steel sector means that most of the emissions reduction required to achieve NZE targets after 2030 will come from new, innovative technologies. They include hydrogen-based DRI and iron ore electrolysis as well as CCUS.

STEEL PRODUCTION USING CCUS WILL BE THE SINGLE LARGEST TECHNOLOGY, ACCOUNTING FOR 45–53% OF PRIMARY STEEL PRODUCTION IN 2050. THIS WOULD EQUATE TO AROUND 530-670 MTCO_2/Y BY 2050.

The steel sector will need an average of $31 billion/y in investment to meet growing demand to 2050. Transitioning global steel assets to net zero compatible technologies requires an additional $6 billion/y, ($200 billion by 2050) with CCUS as a key technology. Companies should allocate investment funds over the next 5–10 years. Actions should include optimising current operating assets and preparing for emerging and breakthrough technologies including CCUS and establishing related infrastructure.

CONCRETE IS A FUNDAMENTAL NATION-BUILDING MATERIAL – MAJOR INVESTMENT IS NEEDED TO ACHIEVE NZE

Concrete is the most widely used material in the world after water. Concrete is crucial for infrastructure and low-carbon power systems to support clean energy development. It will also play a significant role in improving the energy efficiency of buildings.

About 80% of cement is used as a binder in concrete. Global production of cement is 4.4 Gt/y (2021), an increase of over 20% in the past 10 years. Demand may increase by 12–23% by 2050. Most cement is produced in Asia; 58% of global cement (2.5 Gt, 2021) in China, followed by India and Vietnam. China's kiln fleet is young, with an average age of 13 years. China's demand may reduce, but it will increase in industrialising and urbanising areas including Africa, India, Southeast Asia, Turkey and Latin America.

Coal currently meets over 60% of the energy demand of the sector. This share will reduce but will stay as high as 50% by 2050 representing 3.5 EJ (120 Mtce). This is partly because fossil fuels will remain the main source of high temperature process heat input, particularly coal in Asia.

Cement production results in emissions of around 3 $GtCO_2$/y, (7% of global CO_2 emissions). Direct process emissions (Scope 1), produced during the calcination of limestone to form clinker, comprise the bulk of industry emissions, together with thermal emissions (Scope 1 and 2) from the use of fossil fuels to generate the heat (1400–1500°C) required to form clinker, and electricity.

The cement industry aims to achieve at least a 20% reduction in emissions by 2030, by reducing the use of fossil fuels and increasing the use of alternative fuels, improving efficiency in concrete production, and in the design of concrete projects, better use of concrete during construction, and recycling. Efficiency improvements to cement plant could include operational efficiency, enhanced process control and predictive maintenance strategies, together with the widespread implementation of best available technologies.

Significant investment, collaboration and focused innovation will be required to increase clinker substitution and unleash new technologies to decarbonise, such as clean hydrogen and kiln electrification from 2040.

The main levers to decarbonise the cement sector are reducing demand, fuel switching, decreasing the clinker to cement ratio, replacing clinker with alternative cementitious materials, together with the recognition of the long-term carbonation properties of concrete.

Given the ongoing role for coal, by 2030 the capability and commercial case for CCUS will need to be established and CCUS infrastructure must begin to be rolled out.

DEPLOYMENT OF CCUS AT SCALE WILL BE REQUIRED FROM 2030 TO ENSURE THE CEMENT INDUSTRY CAN ACHIEVE NZE BY 2050. TOGETHER WITH BIOMASS AND CEMENT PRODUCTS INCORPORATING CO_2, THIS COULD RESULT IN THE FUTURE DELIVERY OF CARBON-NEGATIVE CONCRETE.

THE TRANSITION TO A LOW-CARBON PRIMARY ALUMINIUM SECTOR WILL COST $1 TRILLION

Aluminium is the second most-used metal in the world by mass after steel. It is integral to several vital industries, including construction, transport and power transmission. This is due to its unique combination of properties (lightness, strength, durability, formability, recyclability and electrical/thermal conductivity), making it an essential enabler of a low-carbon future.

Primary aluminium production is 68 Mt/y (2021) and total aluminium production, including secondary production based on recycled aluminium, is about 100 Mt/y. Almost 80% of scrap aluminium is reused without losing quality, making it one of the most recycled materials. Recycled aluminium constitutes around 33% of aluminium demand and its production uses around 5% of the energy needed for primary aluminium production.

The aluminium sector emits 1.1 $GtCO_{2\text{-}e}$/y (2% of global GHG emissions), mainly Scope 1 and 2 emissions associated with process heat for alumina refining and Scope 2 emissions from purchased electricity for electrolytic aluminium smelting.

Globally, coal provides 57% of the aluminium smelting power and 52% of alumina refining fuel consumption. China dominates, producing 54% of alumina and 57% of primary aluminium. Coal provides around 75% of China's combined alumina/aluminium energy requirement. In Asia (excluding China) 97% of the electricity used in aluminium production is self-generated, mainly from coal, gas or oil.

The aluminium industry needs to reduce its emissions but many of the technology solutions are currently under development, while others do not yet exist. ***As an industry, moving from a 1.1 $GtCO_{2\text{-}e}$/y base to 250 $MtCO_{2\text{-}e}$/y by 2050, while growing production by up to 80%, will require action from all participants in the value chain.***

Approximately $1 trillion is required to deliver the transition to a low-carbon primary aluminium sector. Most of the investment is required in the electricity sector to supply low-carbon electricity. Increased investment in research, development and deployment of electrified processes, low emission hydrogen, inert anodes and CCUS are needed. Additional funds will be needed to decarbonise the alumina sector and downstream users of aluminium products.

The main levers to achieve the necessary 95% decarbonisation in electricity-related emissions and 50% in direct (process and thermal energy) emissions by 2050 are:

- transitioning to low-carbon power (around 650 $MtCO_2$/y reduction);
- recycling more aluminium to maximise secondary production (possibly 456 $MtCO_2$/y);
- maximising product design efficiency (possibly 321 $MtCO_2$/y reduction); and
- deploying new technology to deliver NZE refineries and smelting facilities (some 232 $MtCO_2$/y), by decarbonising thermal energy in refineries, such as heat recovery and fuel switching, and low-carbon anodes and CCUS in smelters.

These measures would reduce coal usage to 2050, but coal will remain in the energy mix at perhaps 50% of current levels. Here, CCUS retrofit to existing coal plant could be the preferred solution to produce low-carbon electricity.

ENERGY SECURITY CONCERNS DRIVE COAL-TO-CHEMICALS ACTIVITY

Chemicals derived from fossil fuels are used to produce a wide range of end products including plastics, fertilisers, packaging, clothing, digital devices, medical equipment, detergents, tyres and explosives. The chemical industry is the largest consumer of fossil fuels but ranks third in terms of direct CO_2 emissions behind cement and steel. This is because 50% of the fossil hydrocarbons consumed in the industry are used as feedstock. Typically, three primary chemicals are produced which form the precursors of all other chemical products. They are light olefins/alkenes and aromatic compounds, known as 'high value chemicals' (HVCs), ammonia and methanol.

The chemical industry emits 1.1 $GtCO_2$/y of Scope 1 emissions, over 30% of which are process-related, meaning they are difficult to reduce. The remaining direct emissions are due to fuel combustion. A high percentage of the chemical industry's emissions are downstream Scope 3 emissions, so addressing these is vital to achieving NZE.

Chemical production is more evenly spread globally than other industries, particularly HVCs. However, Asia and specifically China are leading producers of ammonia and methanol, responsible for over 30% of the global ammonia market. The largest application of coal-to-chemicals is in China. Coal gasification accounts for around 26% of global ammonia production. In China, around 80% of ammonia and methanol is produced from coal. Chemical production plants have an average age of 10–16 years.

By the end of 2019, China had invested $85 billion in coal chemicals, and this is set to increase, with further investments taking place in Indonesia and India. Demand for primary chemicals is set to grow through to 2050, with methanol forecast to grow the most at around 7% per year, increasing demand from 100 Mt/y in 2020 to possibly 500 Mt/y by 2050. Energy security concerns are driving this coal-to-liquids activity as it reduces the need for imported oil and gas.

Decarbonisation options will vary across applications, but increased recycling, fuel switching to biomass, waste fuels and hydrogen, together with CCUS will form key parts of the portfolio. In addition, dramatically increased plastics recycling, reducing single-use plastics and improved nitrogen-use efficiency will be required to achieve NZE.

Achieving net zero Scope 1–3 emissions will require around $100 billion/y in Capex deployment between 2020-2050.

Coal will remain a significant energy source whilst achieving NZE compliance, accounting for around 2 EJ in 2050 (70 Mtce). This is partly because coal will remain an important, affordable source of ammonia and increasingly methanol in Asia and potentially elsewhere.

Investment in CCUS infrastructure, capture plants and proving storage resources is required. Up to 640 $MtCO_2$/y of CCUS will be needed by 2050, with CCUS providing a retrofit option for existing coal-to-chemicals plant, particularly where the plant is relatively young, such as in China. Investment in low-emission hydrogen (including electrolysis, biomass and fossil fuels with CCUS) is the other main way to decarbonise chemicals production.

FUNDAMENTAL TECHNOLOGY SHIFTS ARE NEEDED

Technologies that are already mature with a technology readiness level of 11 (TRL 11) or in the early adoption phase (TRL 9-10) are important. They deliver savings from technology performance improvements, material efficiency gains, switching to bioenergy, and the electrification of low and medium temperature heat. These savings are particularly important in the short term but will continue to play a role through to 2050. A large contribution is made by the gains from material efficiency by the construction sector (including buildings and infrastructure), which currently accounts for about half of the demand for steel and all the demand for cement. In the longer term, fundamental technology shifts are needed and technologies currently at the demonstration (TRL 7-8) and prototype (TRL 4-6) stage will play an integral role. This is especially true in heavy industry where innovative technologies incorporating CCUS and hydrogen will be key to achieving NZE (*see* Figure 1) (IEA, 2021a; 2022f).

CCUS IS THE MOST SIGNIFICANT INDIVIDUAL TECHNOLOGY FOR NZE

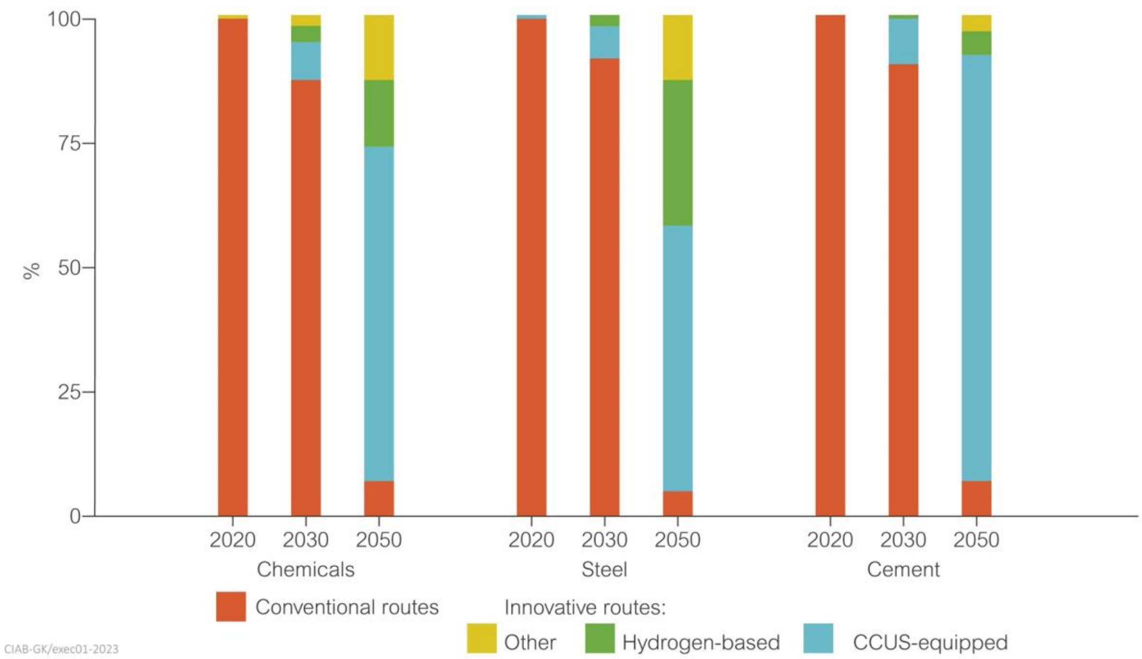


Figure 1 Technology routes to global heavy industrial NZE compliance (IEA, 2021a)

CCUS could contribute more than 2.5 $GtCO_2$/y emissions reduction from the manufacturing industry (*see* Figure 2).

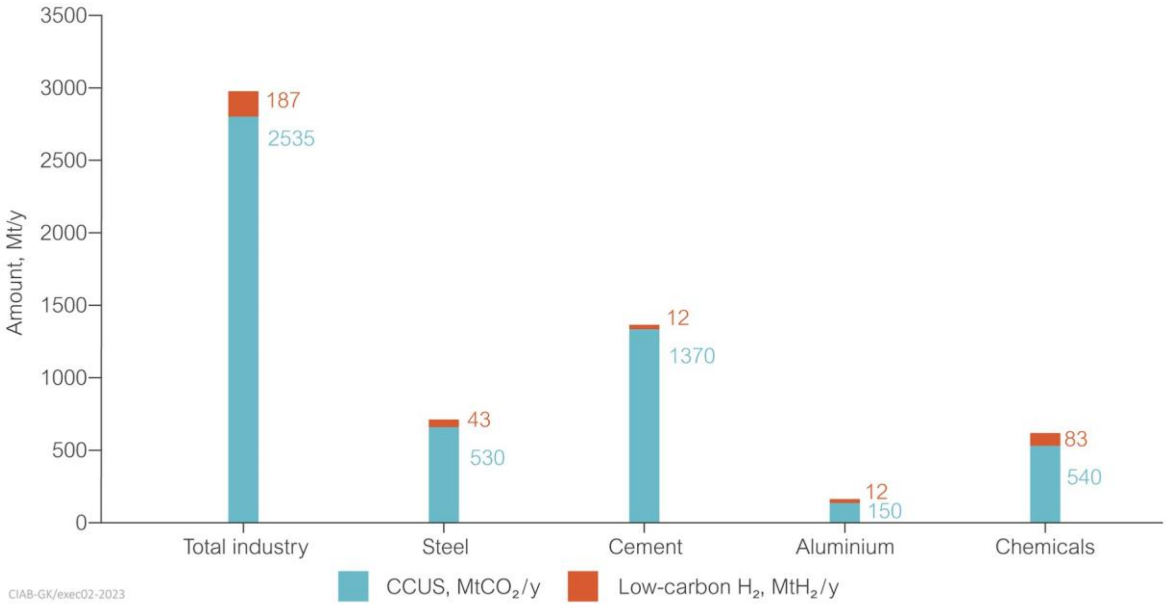


Figure 2 Enabling infrastructure capacity requirements for NZE by 2050 (WEF, 2022; IEA, 2021a)

For heavy industries to decarbonise in a cost-effective and resilient way, coal fitted with CCUS is a key technology for all those assessed, particularly cement. Capture levels of 95% are routinely offered commercially and higher levels approaching 100% capture are technically achievable, particularly for the coal gasification and coal-to-liquid type processes. Industrial CCUS projects feature in the global list of commercial scale projects, but more is needed to showcase coal-based heavy industrial projects, particularly iron and steel, and cement. It is vital that CCUS plays a substantial role in the decarbonisation of heavy industry to reach net zero emissions at least cost. In their industry roadmaps for NZE, the international aluminium, cement, and iron and steel and chemicals industries all see CCUS as required given the ongoing need to use fossil fuels.

The majority of heavy industry is in China, which has massive coal resources, wants to retain fuel independence, and is a leader in coal gasification and efficient power generation. For these reasons, CCUS is fundamental to industrial decarbonisation in China. For global decarbonisation of heavy industry, substantial investment in CCUS and other low-emission technologies is needed worldwide.

1 INTRODUCTION

1.1 THE IMPORTANCE OF HEAVY INDUSTRIES

Industrial manufacturing is integral to our way of life. The key materials produced include cement, steel, aluminium and chemicals such as ammonia and methanol used as building blocks for fertilisers, plastics and fibres. For example, 4.4 billion tonnes (Gt) of cement are produced every year and is forecast to increase to 4.5–5 Gt/y by 2050. This cement is used to make concrete, the second most widely used material on earth after water. Concrete, often reinforced with steel, forms much of global infrastructure including buildings, roads, bridges and dams. Steel at around 2 Gt/y production is also used in infrastructure, in vehicles and to make the tools that fashion many other products. Aluminium demand, as a lighter material than steel, is forecast to grow to around 300 Mt/y by 2050 due to growth of the electric vehicle industry, greater use in packaging of consumer goods to replace single-use plastics and the construction of renewable (solar, wind, energy storage) power equipment. The manufacture of chemicals includes around 185 Mt/y of ammonia, primarily for the production of nitrogen-based fertilisers, needed to grow crops to feed the world's eight billion inhabitants (Smil, 2022). Around 400 Mt/y of plastics are used to make a wide range of products across several sectors including packaging, building and construction, textiles, consumer products, transportation, electrical and electronics and industrial machinery. The material is so ubiquitous that it is difficult to find any man-made product that does not contain plastic components in some form.

The vital importance of these materials seems set to continue and indeed grow, in part because they cannot be easily replaced by other materials, certainly not in the foreseeable future or at scale. Their large-scale manufacture depends significantly on fossil fuels, as a chemical feedstock, as a reducing agent in steel production and as a source of process heat. Thus, heavy industries are a major source of greenhouse gas (GHG) emissions. Industry produces about 8000 $MtCO_2$/y of direct emissions, 70% of which come from the cement, iron and steel, and chemical sectors, as shown in Figure 1. If indirect emissions are added, industry accounts for almost 40% of global anthropogenic CO_2 emissions (IEA, 2020a; GCCSI, 2020).

Almost 2000 $MtCO_2$/y of these industry-related emissions are a by-product of chemical reactions within the production processes. Process-related emissions cannot be avoided using feasible production technologies. For example, 55–65% of CO_2 emissions from cement production are created when calcium carbonate (limestone) is converted to calcium oxide (lime); these emissions are thus an inherent part of the cement manufacture process.

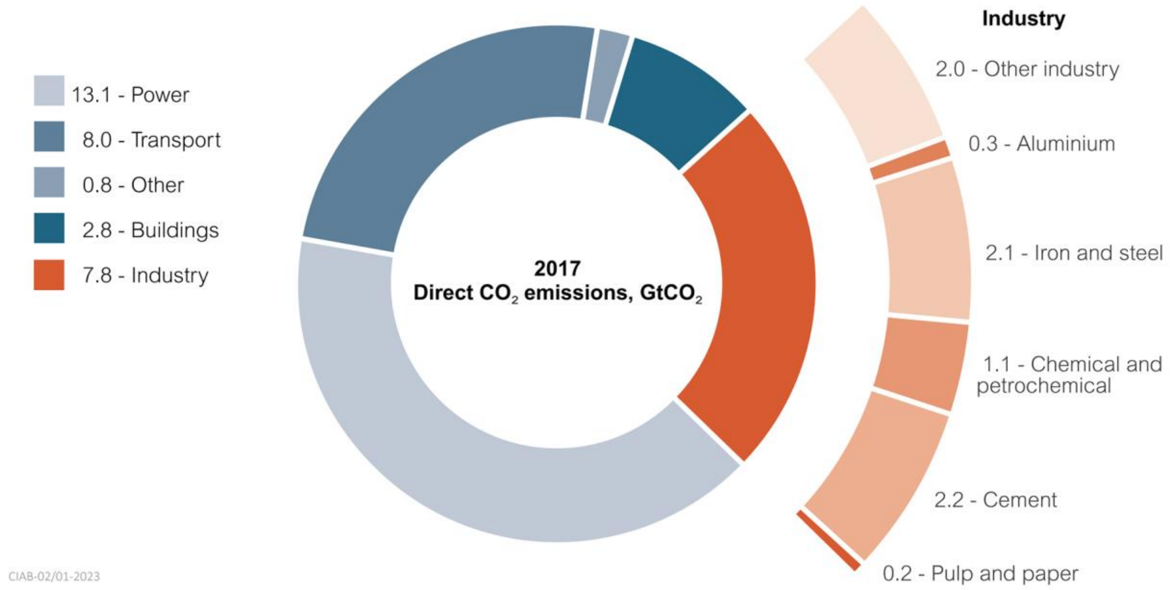


Figure 1 Contribution of industry to global direct emissions of CO_2 (Zapantis, 2022)

A further significant concern for heavy industry is the reliability and price of energy supplies and raw materials. In Europe for example, the move away from coal to a large extent achieved by an increased reliance on natural gas, raises concerns about energy security and resilience, particularly as much of Europe depends on natural gas from Russia. Alternative energy sources such as renewables, hydro and nuclear are available but have their own associated risks and challenges, such as the intermittency of variable renewable energy, or the ageing asset base of nuclear power. Significantly increased energy costs due to rising wholesale electricity and gas prices have an impact on heavy industries' business profitability and overall sustainability, to the point where manufacturing in certain high energy cost regions may no longer be a commercial prospect.

NET ZERO EMISSIONS

The Paris Agreement on climate change was adopted at the 2015 United Nations Climate Change Conference of the Parties (COP21). The central aim of the Agreement is to strengthen the global response to the threat of climate change by keeping global temperature rise by 2100 to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C (IPCC, 2019). Recognition is growing that GHG emissions need to be reduced to net zero by around 2050 to limit the global temperature rise this century to the 1.5°C target and to mitigate the more severe impacts of climate change (IPCC, 2021).

This is reflected in the latest updates to the Nationally Determined Contributions of the Parties to the Agreement and recent government announcements, particularly at COP26 in Glasgow and the more recent COP27 in Sharm El-Sheikh. More countries have committed to achieving NZE by 2050 to 2070, including the key regions of China (Tu, 2020) and India (Reuters, 2021). Currently, around 130 countries have announced NZE ambitions, accounting for 80% of the global population and responsible for over 90% of the global economy as represented by gross domestic product (Net Zero Tracker, 2022).

Achieving NZE will require an increase in the level of renewable energy sources, particularly solar and wind, together with a reduction in the use of fossil fuels. According to one NZE scenario from the IEA, the resulting energy mix could be as shown in Figure 2 (IEA, 2021a). In this pathway, renewables could provide some two-thirds of energy use, comprising bioenergy, wind, solar, hydroelectricity and geothermal, together with a large increase in energy supply from nuclear power, which nearly doubles between 2020 and 2050. The IEA NZE scenario is one pathway to achieve net zero global GHG emissions. Alternative routes have been devised, such as those from the Intergovernmental Panel on Climate Change (IPCC, 2019).

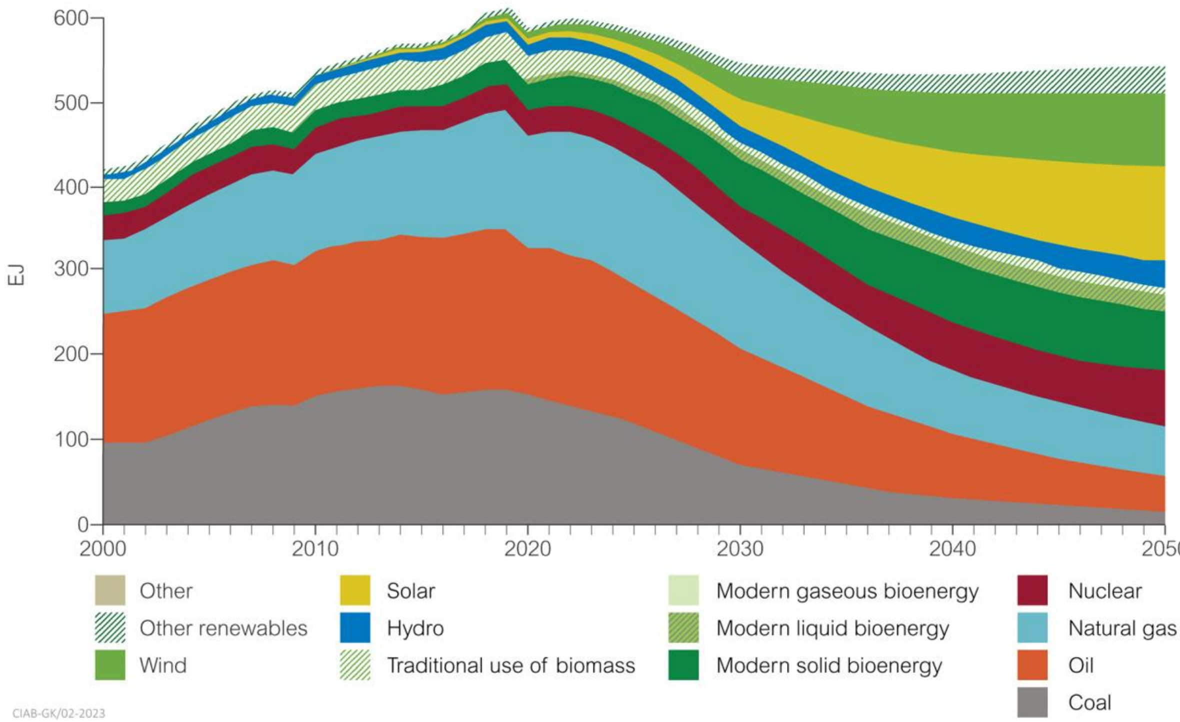


Figure 2 Global energy mix in the IEA net zero emissions pathway (IEA, 2021a)

1.1.1 Impact on coal

In the IEA NZE scenario, fossil fuels' share of total energy supply falls from 80% in 2020 to a little over 20% in 2050. This would mean that coal consumption for energy would reduce from over 5 Gt/y in 2020 to below 0.6 Gt/y in 2050, representing an average annual reduction of 7%. A similar reduction in coal use has been projected by other NZE forecasts, such as the recent Energy Transition Outlook (ETO) (DNV, 2022). Here, coal use is again forecast to reduce significantly, down to around 1.4 Gt/y in 2050.

Despite these reductions, the quantities of coal used in 2050 still point to an important role for the fuel, particularly when combined with carbon capture utilisation and storage (CCUS) and in relation to:

- heavy industries such as steel, cement, aluminium and chemicals manufacture where emissions are difficult to abate; and
- power generation.

1.1.2 Dominance of China

The steel, cement, aluminium and chemical sectors are largely dependent on coal in a number of regions, because it is cost-effective, reliable and widely available. This is particularly true in Asia and more specifically China, which is responsible for 50–60% of the global production of cement, steel and aluminium, and coal is the dominant feedstock and source of process heat for these heavy industries. Thus, coal accounts for 70% of steel, 83% of cement and 75% of aluminium production in China as shown in Figure 3 (Kelsall and Baruya, 2022; Yang, 2020). In China, if the sources of electricity generation are also considered, direct coal consumption and electricity generated from coal account for around 90% of China's iron and steel industry (Zhang and others, 2022; Sheng, 2022). Global consumption of coal in the iron and steel industry was around 900 Mtce, equating to around 15% of global primary demand for coal. This highlights the importance of coal in industrial manufacturing and the scale of the challenge to move to NZE in the industrial sector.

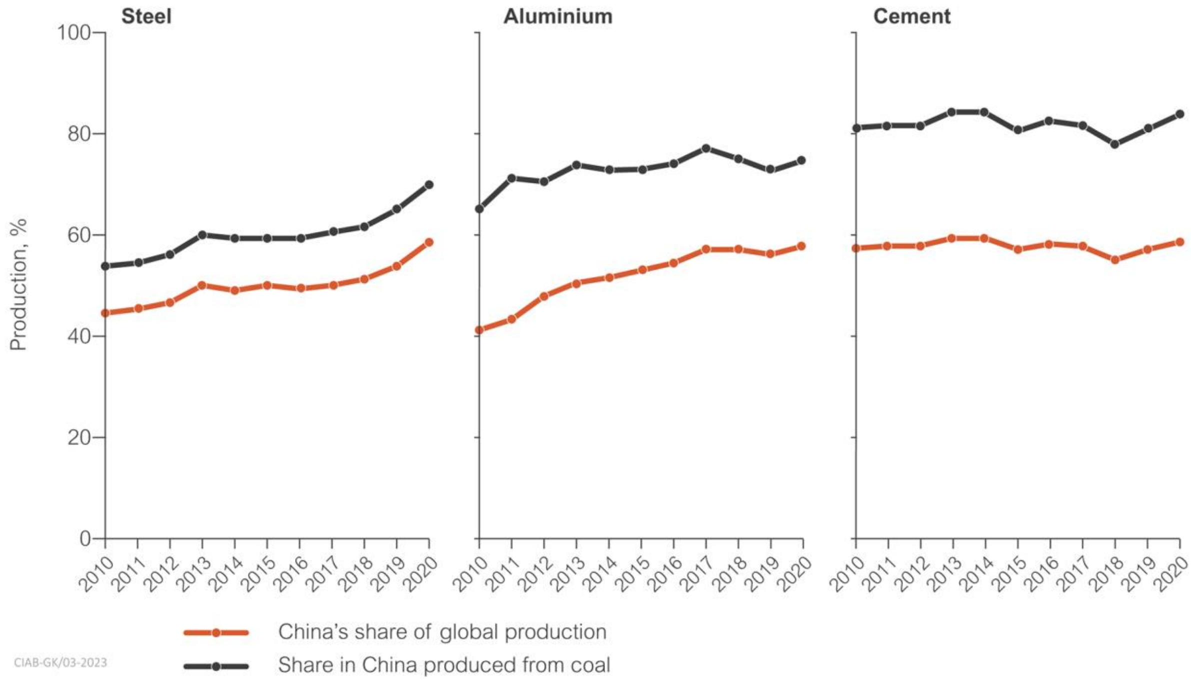


Figure 3 Proportion of steel, aluminium and cement production in China derived using coal (Yang, 2020)

In other locations where there has been a political drive to move away from coal, the recent energy crisis and the resulting need for secure and resilient energy supplies have brought coal back to the fore in the short term. Thus, in some regions, coal use is actually increasing for industrial manufacture and power production, mainly for the reasons listed below (Mills, 2021):

- use of indigenous energy resources;
- ease of availability;
- enhancing national energy security and reducing energy imports;
- diversification of sources of energy;
- growing electricity demand or shortages of supply;
- generates cheaper, more affordable electricity than alternatives;
- drives economic and/or social development; and
- can be instrumental in providing universal access to electricity.

The challenge for heavy industries is how to continue in a cost-effective and secure manner and be compliant with approaching NZE requirements. In the near term, efficiency improvements can reduce emissions. Efficiency improvements made since 2000 have resulted in a 14% reduction in energy-related CO_2 emissions. More than half of these energy savings can be attributed to efficiency measures in the industrial sector (IEA, 2022a). In the medium to longer term, however, more fundamental changes to the manufacturing process will be required to achieve NZE as discussed below.

1.1.3 Industrial emissions challenge

Industrial emissions are often classified as 'hard to abate'. This is largely due to the immaturity of the technologies that are likely to be relied upon to mitigate their emissions. While solar PV and electric cars are in use today in many markets, the same cannot be said for many technologies that will be required to achieve deep reductions in emissions in heavy industry. For industry, the specific factors that make emissions hard to abate include (IEA 2020b; IEA 2022f):

- ***High temperature heat requirements***: Heavy industry requires high temperature heat for many of its processes, which is currently almost exclusively provided by burning fossil fuels. Generating high temperature heat from electricity, especially on a large scale and for electrically non-conductive applications, is impractical and costly with current commercial technologies.
- ***Process emissions***: Several industrial processes result in emissions from chemical reactions that are inherent in production processes. A key example is the CO_2 that results from the calcination reaction that is necessary to produce clinker, the active ingredient in cement.
- ***Long-lived capital assets***: Heavy industry plants tend to have long lifetimes, typically 30-40 years. Retiring them early to switch to alternative technologies would be expensive. As such, emissions from recently built plants can be considered 'locked-in'.
- ***Trade considerations***: Many industrial products such as steel, chemicals and aluminium are traded in highly competitive global markets. This makes it challenging for an individual producer or region to turn to more expensive production pathways in order to reduce emissions, without being undercut on price.

1.2 SCOPE OF REPORT

The International Energy Agency's (IEA) Coal Industry Advisory Board (CIAB) has therefore commissioned the International Centre for Sustainable Carbon (ICSC) to undertake a study into the resilience of coal-based heavy industrial processes in the transition to a NZE future. The study has drawn on the network and expertise of the CIAB members and other organisations.

The study investigates and assesses the impact on energy system resilience as countries seek to move away from coal for heavy industrial manufacturing including steel, cement, aluminium and a range of chemicals. This may lead to an increased reliance on, at times, a more limited and costly energy source pool with the additional risks presented by associated supply/demand economics, security of supply and economic stability.

The report shows how coal can continue to be used, where necessary, in heavy industry and that CCUS will be a key enabling technology, both in terms of direct usage as part of the industrial processes, or indirectly for the production of low-carbon hydrogen and ammonia, as well as for electricity production for certain industrial processes and low/medium temperature heating applications. The report, therefore, covers CCUS technology status as an overarching clean energy process, together with an assessment of CO_2 storage potential globally in locations relevant to the centres of heavy industrial manufacture.

The key heavy industrial processes of steel, cement, aluminium and chemicals manufacture are examined in terms of their global scale and potential opportunities to move towards NZE whilst maintaining resilience and security of supply in a cost-effective manner. The study has a global outlook and is a complement to the IEA's world roadmap to NZE by 2050 (IEA, 2021a).

2 CCUS – A KEY TO INDUSTRIES' TRANSFORMATION TO NET ZERO

2.1 KEY MESSAGES

A technology agnostic approach is key to achieving NZE in terms of cost and energy security.

CCUS as a technology is proven and understood.

- The various elements of the CCUS technology chain are in place for commercial deployment with technologies now available at demonstration to commercial scale that are applicable to the decarbonisation of heavy industries.
- Barriers to widespread large-scale CCUS deployment are not technical.
- Several other next generation technologies that could provide step change cost reductions and increase efficiency are being researched and developed and could, in time, reach the market.

There are 30 operational large-scale CCUS facilities globally, with the potential to store close to 43 $MtCO_2$/y.

CCUS projects are spreading around the globe and increasing in diversity.

- Over the past three years the number of new projects has risen from 28 in 2019 to 102 in 2021 with facilities in development in power generation, liquefied natural gas (LNG), cement, steel, waste-to-energy, direct air capture and storage and hydrogen in Europe, the Middle East, North America and China.
- North America remains an important region, but several countries now have commercial CCUS facilities under development including Belgium, Denmark, Hungary, Indonesia, Italy, Malaysia, Sweden and the UK.
- Asia, and in particular China, should become a key focus for the roll-out of commercial CCUS.

The cost of CCUS has reduced significantly, with a current cost of capture of around 65 $/t$CO_2$. Further cost reductions can be expected through learning by doing where perhaps a 50–75% cut could be achieved as the technology is rolled out commercially.

There are no technical barriers to increasing capture rates beyond 90% in the three capture routes of post-, pre- and oxyfuel combustion.

- CCUS capture levels of 90–95% are typically being offered and will need to move closer to 100%, or to include other options such as cofiring with biofuels, to allow industrial plants to continue to operate in a NZE future. This is because any residual CO_2 emissions from CCUS facilities will not be compliant without being offset by negative CO_2 emissions elsewhere.

The hub and cluster approach is increasingly being adopted to enable the sharing of transport and storage infrastructure. This can improve the economics of CCUS due to economies of scale and overall de-risking of storage liability and cross-chain risk.

- There are already four hubs operating in Brazil, Canada, Norway and the United Arab Emirates.
- CCUS hubs are evolving to become the dominant operating model for CCUS in North America and Europe.

2.2 THE NEED FOR CCUS

Irrespective of the policy scenario, technology and innovation will be the key driver to achieving the goals of the Paris Agreement. In particular, CCUS fitted to power generation, industrial manufacturing plant and low emissions hydrogen production facilities will be needed to help heavy industrial manufacturing achieve a NZE future at the lowest cost. According to the IPCC (2019), between 350 and 1200 GtCO_2 will need to be captured and stored this century to limit the global temperature rise to the 1.5°C target (IPCC, 2019). The majority of climate models indicate that without CCUS it becomes nearly impossible and significantly more costly to keep the temperature increase within the target. Moreover, the risk of overshooting would be increased by limiting the potential for large-scale CO_2 removal or 'negative emissions' using biomass energy with CCS (BECCS) (Stechow and others, 2016; Consoli, 2019).

A technology agnostic approach is key to achieving NZE in terms of cost and energy security. Relying exclusively on renewables and storage is the most expensive strategy. Strategies that rely exclusively on renewable energy also tend to result in unmet or suppressed demand which may hinder economic growth in developing countries. Although other dispatchable technologies, such as nuclear and energy storage can be followed, CCUS is essential for decarbonisation. A recent study by the ICSC shows that without CCUS, costs to achieve NZE increase by between 75% to over 4800% and up to 42% of power demand may not be met (Pratama and Mac Dowell, 2022). In addition to the techno-economic challenges, relying solely on variable renewable energy (VRE) may require significant areas of land.

The latest analysis from the IEA shows that to achieve the NZE pathway, 7.6 GtCO_2/y needs to be captured by 2050, almost 50% of which would be from fossil fuel combustion, 20% from industrial processes and around 30% from BECCS and direct air capture (DAC) (IEA, 2021a). In heavy industrial processes, CCUS is virtually the only technology solution for deep emissions reductions from cement production. It is also the most cost-effective approach in many regions to curb emissions in iron and steel and chemicals manufacturing (IEA, 2020c). The following sections explore the technical status of CCUS globally.

2.3 CCUS TECHNOLOGIES

CCUS prevents CO_2 from being released to the atmosphere. It involves capturing CO_2 produced by large power and industrial plants, compressing it for transportation and then either injecting it into rock formations underground, using it for enhanced oil recovery (EOR) or to form useful products. CCUS as a technology is proven and understood. Carbon capture equipment has been used commercially to purify natural gas and other gases since the 1930s. CO_2 was first injected underground in commercial-scale operations in 1972 and it is transported daily by pipelines and to a lesser extent, trucks, trains and ships in many parts of the world. CCUS is also of strategic value as a climate change abatement option. It is a solution for hard-to-abate industries such as cement, steel, aluminium and chemical production, as well as a platform for the hydrogen economy. It can be applied to fossil fuel power plants (both coal- and natural gas-fired) to provide low emissions generation capacity to complement intermittent renewable power sources. It will also become important in removing carbon from the atmosphere, for example, BECCS and direct air capture (DAC with CCUS) to balance emissions that are challenging to avoid (IEA, 2020e; IChemE, 2018). The ICSC has published many reports on CCUS; see for example (Pratama and Mac Dowell, 2022, Kelsall, 2020; Lockwood, 2016, 2018a,b, 2021; Minchener, 2019).

CO_2 CAPTURE TECHNOLOGIES

There are four principal types of capture process:

Post-combustion capture – CO_2 is removed from the flue gas after the main process conversion step (typically combustion). The remaining flue gas is primarily nitrogen together with other minor components. Most post-process capture technologies used in projects today are amine-based absorption systems of the post-combustion capture type. Additional technologies that fall into the post-process capture category include adsorption onto a solid sorbent, fuel cells including molten carbonate fuel cells (MCFC) and membrane separation.

Oxyfuel combustion – Fuel is burned with oxygen in a stream of recycled CO_2. By excluding the nitrogen from the process, CO_2 separation becomes a relatively easy process of condensing out the water from the flue gas. However, it requires an air separation unit (ASU) to produce the oxygen for the oxyfuel combustion process which adds to the system cost.

Pre-combustion capture – In an integrated gasification combined cycle (IGCC) power plant in which the fuel is gasified/reformed to a $CO/H_2/CO_2$ mixture, typically incorporating a water-gas shift (WGS) reaction step to increase the concentration of hydrogen by reacting the carbon monoxide with steam. The CO_2 is then captured from the pressurised fuel gas stream. The IGCC system combines chemical processing with power generation, with the flexibility of being able to produce hydrogen. The typical separation technologies that fall into this category include solvent separation processes such as Rectisol and Selexol, pressure swing adsorption and water enhanced gas-shift.

Calcium and chemical looping – A further approach with calcium or chemical looping technologies involves the use of metal oxides or other compounds, as regenerable sorbents to transfer either CO_2 or oxygen from one reactor to a second reactor. Circulating fluidised beds, which are available commercially, can be used as one or both reactors. Both calcium and chemical looping technologies are second-generation CO_2 capture technologies utilising high-temperature streams to significantly reduce the energy penalty associated with CO_2 capture.

Post-combustion capture is the most widely deployed approach and most of these projects use chemical absorption through amines. This capture technology has been used commercially in industrial settings in chemical production and to purify natural gas and other gas streams for over 80 years.

2.3.1 CCUS commercial readiness

The technology readiness level (TRL) of a component or system qualitatively assesses the maturity of technology through the different stages of research and development (R&D). Of the different CCUS technologies at varying stages of development, most are at the pilot plant stage (TRL 6) or higher (IChemE, 2018). There are several technologies for capture, transport and storage that are readily deployable at commercial scale (TRL 9). Various other technologies that can reduce costs and increase efficiency are at TRL 7–8 and most should, in time, move to TRL 9.

A compendium of CCUS technologies has been compiled by the GCCSI (Mirza and Kearnes, 2022) describing technologies available at demonstration to commercial scale, including some which are being applied to heavy industrial applications. Additionally, CCUS technologies have been reviewed in a study for the UK's Department for Business, Energy and Industrial Strategy (BEIS) which shows the technologies considered to be commercially available, together with those at the demonstration scale (AECOM, 2022). The technologies available at demonstration scale are summarised in Table 1. An assessment of the application of the demonstration and development technologies to a range of CO_2 concentrations, including 1–5% applicable to typical alumina applications and 15+% applicable to typical cement and steel industrial applications, is shown in Table 2.

Neither of these sources of CCUS technologies are exhaustive. However, they highlight that a range of technology options are available for heavy industry applications at near commercial scale, demonstrating the readiness of CCUS for this key sector.

TABLE 1 CCUS TECHNOLOGIES AT DEMONSTRATION SCALE (AECOM, 2022)

Technology provider	Overview
Mitsubishi Heavy Industries	Mitsubishi Heavy Industries (MHI)'s KS-1 solvent was used at the 1.4 $MtCO_2/y$ Petra Nova project in Texas, USA. MHI's next generation solvent is KS-21. The new solvent, along with process improvements, is anticipated to offer incremental improvements over plants using KS-1.
Shell	Shell's Cansolv technology has been demonstrated at scale at the 2740 t/d Boundary Dam site in Canada. The next generation deployment is likely to include Energy from Waste (EfW) applications
Fluor	A previous iteration of Fluor's Econoamine FG Plus technology was deployed at 320–350 t/d scale at Bellingham Gas Power Plant, Massachusetts, USA. The next generation technology will attempt to employ energy improvement features at large scale.
Carbon Clean Solutions	Carbon Clean Solutions' proprietary amine has been used at the 160 t/d scale in India on a coal plant. The technology uses their proprietary APBS advanced solvent. Additionally, Carbon Clean has offerings of bespoke large-scale carbon capture plants and smaller modular carbon capture units.
Aker Carbon Capture	Aker Carbon Capture designed and delivered the 80,000 t/y (~240 t/d) CO_2 capture amine plant at the TCM facility which has been in continuous operation since opening in 2013. Aker's 'Just Catch' technology uses their proprietary S26 advanced solvent. Aker offers large-scale carbon capture plants termed 'Big Catch' and smaller modular carbon capture units termed 'Just Catch'. Aker has plans for future projects in the EfW and cement sectors.

TABLE 2 CCUS TECHNOLOGIES APPLICATION MATRIX (AECOM, 2022)

Flue gas CO_2 concentration category	Low 1–5%	Medium 5–10%	High 10–15%	Very high 15+%
Typical application	CCGT Aluminium Glass	NG fired boiler Fired heater Oil refining	Coal-fired boiler EfW Biomass-fired boiler	Iron and steel Cement Hydrogen Anaerobic digestion
Demonstration scale technologies				
MHI	🟡	🟡	🟢	🟡
Shell	🟢	🟢	🟢	🟡
Fluor	🟢	🟢	🟢	🟡
Carbon Clean Solutions	🔴	🟢	🟢	🟢
Aker Carbon Capture	🟢	🟢	🟢	🟢
Development scale technologies				
BASF/Linde	🔴	🔴	🟢	🟡
C-Capture	🟢	🟢	🟢	🟡
CO2 Capsol	🔴	🔴	🟢	🟡
CO2 Solutions/SAIPEM	🔴	🟢	🟢	🟡
Baker Hughes CAP	🟢	🟢	🟡	🟡
ION Clean Energy	🟡	🟡	🟢	🟡
RTI International	🔴	🟡	🟢	🟡
Kawasaki CO_2 Capture	🔴	🔴	🟢	🟡
Svante	🔴	🟢	🟡	🟡
TDA Research	🔴	🔴	🟢	🟡
Fuel Cell Energy	🟡	🟢	🟢	🟢
Membrane Technology and Research	🔴	🔴	🟢	
Air Liquide	🔴	🔴	🔴	🟢

🟢 applicable; 🟡 likely to be applicable; 🔴 possibly applicable

Air Liquide

Technology offerings from Air Liquide include amine solutions for precombustion and post-combustion capture, Rectisol and Recticap for pre-combustion capture, together with Cryocap as an industrial solution to compress, liquefy, and purify CO_2 streams resulting from upstream units.

Industrial applications include Cryocap™ Steel, designed to specifically capture CO_2 from steelmaking plants, with CO_2 stream concentrations of 20–50%. The gas is first compressed, dried and sent to a PSA (Pressure Swing Adsorption) system. The PSA pre-concentrates the CO_2 in the off-gas while producing a CO-rich stream. The pre-concentrated CO_2 stream is compressed and sent to a cold process. There, the CO_2 is recovered through a combination of partial condensation and distillation. The pressurised CO-rich stream is either recycled to the blast furnace or used to produce fuels. The technology is available at capacities of 300 to over 5000 tCO_2/d, with a cost of CO_2 captured of 25–60 €/tCO_2 and capture rates of 80–95%. Reference examples include:

- 2005 – Pilot scale CCS for 15 ktCO_2/y in Sweden (MEFOS)
- 2012 – Industrial scale CCS Front End Engineering Design (FEED) for 1.3 MtCO_2/y in France (ULCOS)
- 2019 – CCU for 0.3 MtCO_2/y in Belgium (Steelanol)
- 2020 – CCU LCO_2 Pre-FEED for 0.1 MtCO_2/y in South Korea.

Air Products

Air Products offers an integrated technology for hydrogen and syngas production from input fossil fuel, biomass or waste-derived fuels, with CO_2 capture achieved using vacuum swing adsorption technology. The approach has been successfully demonstrated at large scale at its Port Arthur hydrogen facility in Texas, USA. Operating since 2013, key learnings from this project have helped the company develop the next generation of low-carbon hydrogen projects in its franchise. In Canada, the Net-Zero Hydrogen Energy Complex, targeted for 2024, incorporates 95%+ carbon capture and hydrogen-fired power generation. In the US Gulf Coast, the Louisiana Blue Hydrogen Clean Energy Complex, targeted for 2026, includes the development of one of the world's largest carbon sequestration operations.

Aker Carbon Solutions

Aker Carbon Capture's Advanced Carbon Capture (ACC™) technology has been developed since 2005 and offered commercially since 2009. It is an energy and cost-efficient post-combustion capture process with minimal environmental impact, based on ACC™ proprietary solvents and proprietary process solutions. The system is suitable for industrial applications. An example is the Norcem Cement Plant where Aker Carbon Capture has worked together with Heidelberg Norcem and partners in developing a full-scale CO_2 capture, conditioning, compression, heat integration, intermediate storage and loading facility for the Brevik cement plant. CO_2 is captured from the flue gases of the cement kiln using waste heat recovered from the cement plant and the CO_2 compression plant through a proprietary heat integration technology. The ACC™ capture plant at Norcem will be the world's first unit to capture CO_2 from a cement plant when the capture commences in 2024. It is part of the Norwegian Longship Project, where the CO_2 capture capacity is 0.4 $MtCO_2/y$.

Axens

Axens' DMX™ CO_2 capture process is based on absorption using a demixing solvent. The DMX™ solvent consists of a mixture of two organic compounds in an aqueous solution, which demixes under certain conditions of temperature and CO_2 partial pressure. Axens and IFPEN have been involved in several R&D programmes to develop enhanced CO_2 capture technologies, with the DMX™ process being an outcome of these developments. The technology will next be demonstrated at industrial scale at the Arcelor Mittal steel mill in Dunkirk, France. This project will also study the full-scale CO_2 capture, conditioning, transport and storage of 1 $MtCO_2/y$ from blast furnace gas. The project will contribute to the development of a CO_2 hub located in Dunkirk and connected with the storage facilities like those foreseen with the Northern Lights (or Longship) Project supported by the Norwegian government.

C-Capture

C-Capture's solvent technology is based on novel solvents of salts of simple organic acids. It is claimed to have a 40 % lower energy penalty than state-of-the-art amine-based systems of typically 2.5 GJ/t captured. The technology is suitable for a wide range of industrial applications including cement and lime manufacture, hydrogen production, glass furnaces and iron and steel production (Carbon Capture Journal, 2022). These latter applications are possible because of the high chemical stability of C-Capture's solvents, as well as their high selectivity towards CO_2, which minimises the scope for solvent-degrading side reactions. However, the technology is at the pilot demonstration phase with testing including a side-stream at the Drax biomass power plant in the UK and plans for an intermediate-scale demonstration plant for Ince Bio Power, owned by Bioenergy Infrastructure Group, in the UK.

Carbon Clean

CycloneCC™ is a fully modular carbon capture solution that addresses two major concerns of cost and space. The technology uses a combination of two proven process intensification technologies, namely Carbon Clean's advanced, proprietary amine-promoted buffer salt solvent (APBSCDRMax®) and rotating packed beds. As a result, the physical footprint of CycloneCC™ is up to 50% smaller than conventional carbon capture units and Capex and Opex costs are also reduced by 50%. The technology is particularly suitable for use with small- to medium-sized emission point sources and can be used to capture carbon from several point sources. CycloneCC™ has been pilot-tested successfully at 1 tCO_2/d and is currently being commercialised at 4 $ktCO_2/y$ and 40 $ktCO_2/y$ with partners, including CEMEX, Chevron and Veolia. For example, CEMEX has announced a project at its Rüdersdorf plant in Germany to use CycloneCC™ technology to capture 40 $ktCO_2/y$ before increasing the carbon capture by an additional 110 ktCO_2/d. The plant is expected to be operational by 2026 and a study will also be completed to investigate how to scale up to 0.7 MtCO_2/y.

CO_2 Capsol

Capsol EoP™ uses a hot potassium carbonate absorption solvent for CO_2 which is described as being used by thousands of plants globally in multiple industries. The absorption process operates at 0.5–0.8 MPa pressure, with a low energy penalty of 0.7–1.5 MJ/tCO_2 captured, around 40% lower than an amine-based system. The cost for the capture system (excluding compression) is 25–30 €/tCO_2 captured.

The technology is suitable for large-scale emitters including cement and other industrial facilities, with an optimum CO_2 concentration in the exhaust of 7-25%. It has been tested at 0.16 MtCO_2/y scale at the biomass-fired Stockholm Exergi Combined Heat and Power (CHP) plant in Sweden, with plans to move to 0.8 MtCO_2/y by 2025.

Honeywell

Honeywell offers a portfolio of carbon capture technologies including:

Chemical solvents

- AmineGuard™ and Amine Guard FS Process - largest licensor of high concentration MEA-based systems; formulated solvents have low Opex compared to MEA (operating on more than 600 units); and
- Benfield™ Inorganic solvent for pressurised flue gas and industrial processes (>650 units).

Advanced solvent for carbon capture

- Direct CO_2 capture from flue gas for power, steel, cement, natural gas, refining and petrochemical industries.

Physical solvents

- SeparALL™ Process; and
- H_2S/CO_2 selectivity using Selexol solvent for sources containing sulphur in oxidative conditions (>50 units).

Adsorbents

- Polybed™ PSA system optimised adsorbents and cycles for CO_2 rejection (>1100 units, 3 operating in CO_2 application).

Cryogenics and membranes

- Separex™ Membrane Systems high, partial-pressure CO_2 capture, significant experience in offshore capture and storage (>300 units); and
- Ortloff CO_2 Fractionation captures CO_2 and also provides it as a high-purity liquid product.

IHI

IHI offers both post-combustion chemical absorption and oxyfuel CO_2 capture solutions:

- ***Post-combustion*** – chemical absorption applied to various flue gases including those from steel, cement and other industrial processes. Pilot plant scale testing at 7.3 ktCO_2/y in a coal-fired boiler at IHI's AIOI Works in Japan.
- ***Oxyfuel*** – IHI applied the oxyfuel combustion technology to the Callide A thermal power plant and operated it for more than 10,000 hours. Benefits of the oxyfuel approach include a 98% CO_2 capture rate and energy storage based on stored oxygen from the air separation unit (ASU).

Leilac Group (Calix)

Calix carbon capture technology for the cement and lime industries is based on process modification rather than requiring additional chemicals or processes. It uses externally heated tubes that keep the CO_2 released during the manufacturing process pure, that is, uncontaminated by flue gases or air. The technology can be retrofitted and can use a range of fuel/energy sources including fossil fuel, biomass, hydrogen and electricity. The LEILAC2 project has passed its Final Investment Decision (FID) to build a plant capable of capturing 20% of a cement plant's CO_2 and will be integrated into Heidelberg Cement's plant in Hannover, Germany (Heidelberg Cement, 2020).

Saipem

In 2019, SAIPEM acquired a disruptive and innovative technology from CO_2 Solutions Inc (CSI), now marketed as 'CO_2 Solutions by SAIPEM', which uses an aqueous carbonate solution catalysed by an enzyme. It improves a proven scheme with carbonates to capture CO_2 with a salt and protein water solution. The technology is at TRL 8, with the first commercial start-up in 2019 cleaning flue gas from a lime kiln in a Kraft pulp mill and delivering up to 30 tCO_2/d to an adjacent greenhouse.

Shell

Shell offers amine solvent technology and novel solid sorbents:

Post-combustion chemical absorption

- CANSOLV™ CO_2 Capture System is capable of capturing 99% of CO_2. Units have been designed for CO_2 concentrations from 3.5% to 27% and treating gas flow rates from 11,000 to 4,500,000 m^3/h. The leading reference plant is the coal-fired Boundary Dam power plant in Canada at 1 MtCO_2/y.
- ADIP™ ULTRA ADIP ULTRA™ technology captures CO_2 from high pressure, pre-combustion process streams, for example, from hydrogen manufacturing units, chemical plants and natural gas treating plants. The technology is deployed at more than 500 Shell and non-Shell sites worldwide and has an established record for deep CO_2 removal in the natural

gas sector. ADIP ULTRA™ technology uses two amines, methyl diethanolamine (MDEA) as the main reactant and piperazine as the accelerator, and water. In September 2021, a final investment decision was made to build an 0.82 $MtCO_2$/y biofuels facility, as part of the transformation of the Pernis refinery into the Shell Energy and Chemicals Park Rotterdam, the Netherlands, one of five global energy and chemical parks. Once built, the facility will be among the biggest in Europe to produce sustainable aviation fuel and renewable diesel made from waste. CO_2 emissions from the manufacturing process will be captured using Shell's ADIP ULTRA™ technology and stored in a depleted North Sea gas field as part of the Porthos CCUS project.

Solid sorbents

- The Solid Sorbent Technology (SST) is a novel technology that separates CO_2 from flue gas in a continuous temperature swing adsorption (TSA) fluidised bed process using solid adsorbent. The technology is being developed for medium to small CO_2 capture capacities across a range of sectors, with industrial partners. The technology potentially delivers simultaneously > 90% CO_2 capture efficiency and > 95% CO_2 purity with low to no process-related emissions and with lower capture costs. SST development focuses on medium- to small-scale application at the 0.1–0.5 $MtCO_2$/y scale, including waste to energy, hydrogen manufacturing and specific applications in the steel and cement industries.

Svante

Svante's energy-efficient and low-cost technology, the VeloxoTherm™ carbon capture process, is an intensified rapid-cycle TSA system using advanced Structured Adsorbent Beds. The process is designed to capture CO_2 directly from industrial sources and release pure CO_2 in less than 60 seconds, compared to hours for other technologies, potentially requiring significantly less capital cost. The capture process is implemented via a device similar to that of regenerative air heaters widely used in power plants, in which a proprietary structured adsorbent is arranged on a circular rotating structure, known as a Rotary Adsorption Machine.

Svante's technology is being deployed in the field at pilot plant scale in the energy and cement manufacturing sectors:

- CO2MENT Pilot Plant Project: Partnership between Holcim and Total Energies operating a 1 tCO_2/d plant in Richmond, British Columbia, Canada, that will re-inject captured CO_2 into concrete;
- Cenovus: Construction and commissioning of a 30 tCO_2/d demonstration plant completed in 2019 at an industrial facility in Lloydminster, Saskatchewan, Canada; and
- Chevron USA: A 25 tCO_2/d demonstration plant under construction for deployment near Bakersfield, California, USA.

2.3.2 CCUS R&D priorities

A study in the UK sponsored by the UK Government's BEIS, looked to identify the key innovation needs to help prioritise investment in low-carbon innovation. Part of the study focused on CCUS (EINA, 2019) and defined the following as key R&D priorities:

- **For pre-combustion** – advanced reformer technologies to unlock the potential to combine hydrogen production with CCUS for power, which opens further opportunities across the energy system. Cost reduction is possible by using cheaper and more energy-efficient materials and processes.
- **For post-combustion** – R&D into new solvent and absorption processes aimed at lowering cost and improving capture performance, whilst also having the potential to reduce regeneration costs, corrosion effects, environmental impacts and product degradation.
- **For oxyfuel combustion** – new technologies for lower cost air separation in oxycombustion, including ion transport membranes (ITMs). Ceramic materials that conduct oxygen ions at elevated temperatures are an early-stage technology with significant potential for a step-change cost reduction in air separation.

A selection of next-generation technologies showing how they could progress through the TRL levels is shown in Figure 4. They could offer benefits, either through material innovation, process innovation or equipment innovation, for reduced capital and operating costs and improved capture performance.

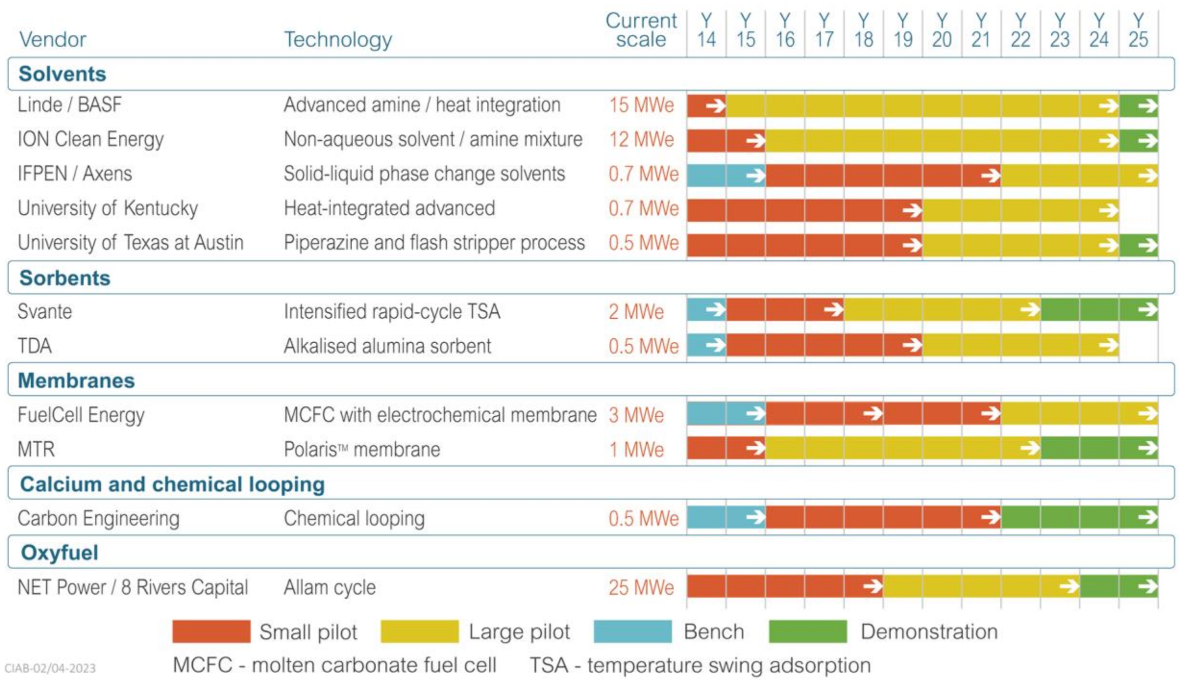


Figure 4 Selection of next-generation CCUS technologies being tested at >0.5 MWe (Kearns and others, 2021)

2.4 CCUS TECHNOLOGY STATUS

There are 30 operational (October 2022) CCUS facilities globally, including one project relating to direct air capture (GCCSI, 2022, 2021b), with further details of European CCUS projects provided by IOGP (2022). The majority of these facilities relate to natural gas processing applications, together with production of chemicals such as ethanol and fertilisers, hydrogen for refinery applications, steel production and power generation. Together, they provide the potential to store almost 43 $MtCO_2/y$. In addition, 12 facilities are in construction and are due to be completed by 2026 providing a further 11 $MtCO_2/y$ of storage capacity (*see* Table 3 for a summary with details of the projects in operation and construction provided in Table 4 and Table 5).

In addition, there are a significant number of projects in advanced development using a predominantly front end engineering design (FEED) approach, or in the early stages of development. The number of projects in the pipeline is over 150, bringing the total number of CCUS projects to 196, with a combined storage capacity of 244 $MtCO_2/y$. This represents an increase of 44% over the past 12 months, as shown in Figure 5. While this is encouraging, it remains significantly below the growth rate required for CO_2 capture and storage levels to meet the targets set for 2030 and 2050 (WEF, 2022). For example, an order of magnitude increase in the number of CCUS projects is required by 2030.

TABLE 3 COMMERCIAL CCUS FACILITIES – INCLUDING DIRECT AIR CAPTURE (GCCSI, 2022)

Classification	Operational	In construction	Advanced development	Early development	Operation suspended	Total
Number of facilities	30	12	77	75	2	196
Capture capacity, $MtCO_2/y$	42.6	11.1	96.1	91.9	2.3	244

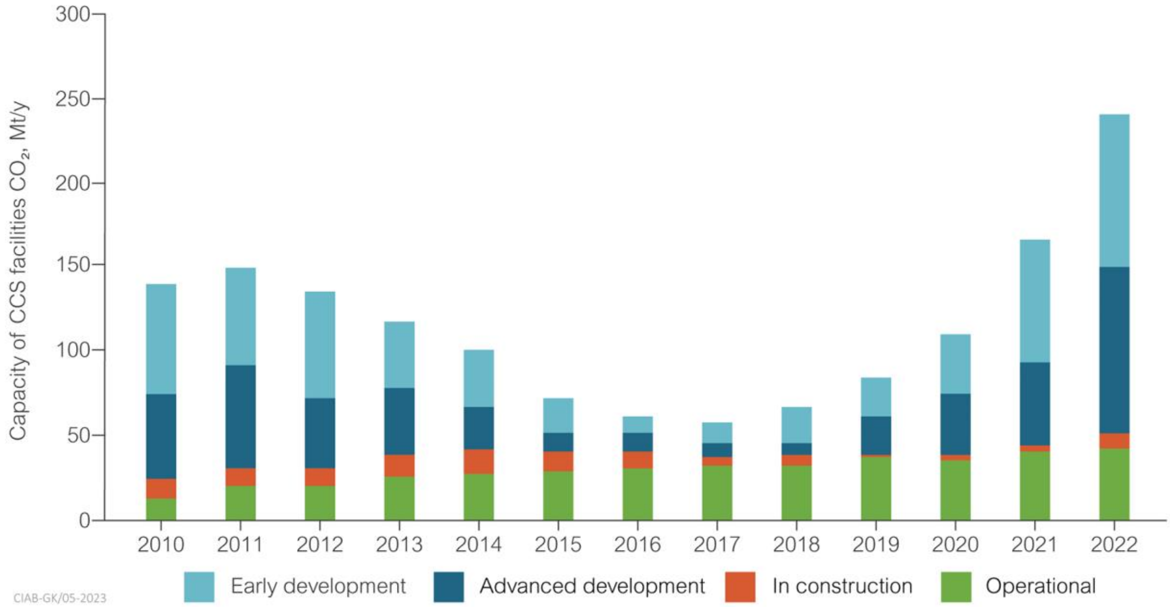


Figure 5 CO_2 storage capacity of global CCUS facilities (GCCSI, 2022)

TABLE 4 GLOBAL CCUS INSTALLATIONS IN COMMERCIAL OPERATION EXCLUDING DIRECT AIR CAPTURE (GCCSI, 2022)

	Title	Status	Country	Date	Industry	Capture capacity, $MtCO_2/y$	Storage type
1	Red Trail Energy CCS	Operating	USA	2022	Ethanol production	0.2	Dedicated geological storage
2	Sinopec Qilu- Shengli CCUS	Operating	China	2022	Chemical production	1.0	EOR
3	Glacier Gas Plant MCCS	Operating	Canada	2022	Natural gas processing	0.2	Dedicated geological storage
4	Alberta Carbon Trunk Line (ACTL) with Sturgeon Refinery CO_2 Stream	Operating	Canada	2020	Hydrogen for oil refining	1.6	EOR
5	Alberta Carbon Trunk Line (ACTL) with Nutrien CO_2 Stream	Operating	Canada	2020	Fertiliser production	0.3	EOR
6	Gorgon Carbon Dioxide Injection	Operating	Australia	2019	Natural gas processing	4.0	Dedicated geological storage
7	Qatar LNG CCS	Operating	Qatar	2019	Natural gas processing	2.2	Dedicated geological storage
8	CNPC Jilin Oil Field CO_2-EOR	Operating	China	2018	Natural gas processing	0.6	EOR
9	Illinois Industrial Carbon Capture and Storage	Operating	USA	2017	Ethanol production	1.0	Dedicated geological storage

10	Abu Dhabi CCUS (Phase 1 was Emirates Steel Industries)	Operating	UAE	2016	Iron and steel	0.8	EOR
11	Karamay Dunhua Oil Technology	Operating	China	2015	Chemical production-methanol	0.1	EOR
12	Quest	Operating	Canada	2015	Hydrogen for oil refining	1.3	Dedicated geological storage
13	Uthmaniyah CO_2-EOR Demonstration	Operating	Saudi Arabia	2015	Natural gas processing	0.8	EOR
14	Boundary Dam CCS	Operating	Canada	2014	Power generation	1.0	Various
15	Coffeyville Gasification Plant	Operating	USA	2013	Fertiliser production	0.9	EOR
16	Air Products Steam Methane Reformer	Operating	USA	2013	Hydrogen for oil refining	1.0	EOR
17	PCS Nitrogen	Operating	USA	2013	Fertiliser production	0.3	EOR
18	Bonanza Bioenergy CCUS EOR	Operating	USA	2012	Ethanol production	0.1	EOR
19	Petrobas Santos Basin Pre-Salt Oil Field CCS	Operating	Brazil	2011	Natural gas processing	7.0	EOR
20	Century Plant	Operating	USA	2010	Natural gas processing	5.0	EOR
21	Arkalon CO_2 Compression Facility	Operating	USA	2009	Ethanol production	0.3	EOR
22	Snøhvit CO_2 Storage	Operating	Norway	2008	Natural gas processing	0.7	Dedicated geological storage
23	Core Energy CO_2-EOR	Operating	USA	2003	Natural gas processing	0.4	EOR
24	Great Plains Synfuels Plant and Weyburn-Midale	Operating	USA	2000	Synthetic natural gas	3.0	EOR
25	Sleipner CO_2 Storage	Operating	Norway	1996	Natural gas processing	1.0	Dedicated geological storage
26	MOL Szank field CO_2	Operating	Hungary	1992	Natural gas processing	0.2	EOR
27	Shute Creek Gas Processing Plant	Operating	USA	1986	Natural gas processing	7.0	EOR
28	Enid Fertilizer	Operating	USA	1982	Fertiliser production	0.2	EOR
29	Terrell Natural Gas Processing Plant (formerly Val Verde)	Operating	USA	1972	Natural gas processing	0.5	EOR

TABLE 5 GLOBAL CCUS INSTALLATIONS IN CONSTRUCTION EXCLUDING DIRECT AIR CAPTURE (GCCSI, 2022)

No	Title	Status	Country	Date	Industry	Capture capacity, Mt/y	Storage type
30	CNOOC South China Sea Offshore CCS	Construction	China	2023	Natural gas processing	0.3	EOR
31	Guodian Taizhou Power Station Carbon Capture	Construction	China	2023	Power generation	0.3	EOR
32	Santos Cooper Basin CCS	Construction	Australia	2023	Natural gas processing	1.7	Dedicated geological storage
33	Huaneng Longdong Energy Base CCUS	Construction	China	2023	Power generation	1.5	Dedicated geological storage
34	Norcem Brevik-Cement Plant	Construction	Norway	2024	Cement	0.4	n/a
35	Norcem Brevik-Shipping Route	Construction	Norway	2024	Cement		n/a
36	Northern Lights-Storage	Construction	Norway	2024	Various		Dedicated geological storage
37	Hafslund Oslo Celsio-Klemetstrud Waste-to-Energy Plant	Construction	Norway	2025	Waste incineration	0.4	n/a
38	North Field East (NFE) Project CCS	Construction	Qatar	2025	Natural gas processing	1.0	Under evaluation
39	Louisiana Clean energy complex	Construction	USA	2026	Hydrogen/ Various	5.0	Dedicated geological storage

n/a = not available

2.4.1 CCUS projects becoming widespread and more diverse

Eighteen of the 29 commercial scale CCUS operating facilities (excluding direct air capture) are in North America. Thirteen of them are in the USA, due in large part to supportive national policy frameworks, a focus on low-emission technology innovation, a history of oil and gas exploration/operation and accessible CO_2 storage sites. However, the use of the captured CO_2 for EOR has been a strong driver, and there is also stakeholder support including from the private sector. The recent passing of the Inflation Reduction Act (2022) in the USA seems set to result in a wave of new projects, suggesting the North American pipeline will increase significantly over the next few years (McKinsey, 2022). Asian capacity is also being added, which is expected to rise substantially from 2030 onwards.

Looking to 2030, CCUS projects are becoming increasingly diverse, with development projects in a broad range of sectors including power generation, liquefied natural gas (LNG), cement, steel, waste from energy, direct air capture and storage and hydrogen production. North America continues to lead in CCUS deployment. However, several new countries now have commercial CCUS facilities under development, including Belgium, Denmark, Hungary, Indonesia, Italy, Malaysia and Sweden.

2.4.2 Coal-related CCUS projects for heavy industry

The number of projects involving coal and petroleum coke as the fuel remains limited, particularly in the pipeline of development projects. There are however projects in the existing operational category which provide a track-record of successful deployment in the chemicals and cement industries, with examples including:

Great Plains Synfuels project

The Great Plains Synfuel plant in North Dakota, USA, produces 1300 t/d of syngas from the gasification of lignite. This facility has been producing syngas since 1988 and capturing CO_2 for storage since 2000, with around 3 MtCO_2/y transported to Saskatchewan, Canada for EOR. The plant produces synthetic natural gas (SNG) and anhydrous ammonia for fertiliser production using fourteen 14 Lurgi Mark IV gasifiers (NETL, nd).

Capital Cement

The Capital Cement Aggregates plant in San Antonio, Texas is a predominantly coal-fired process which has been capturing CO_2 using the SkyMine® process at commercial scale since 2015 (Skyonic, 2016). The project captures 50–75 ktCO_2/y, based on 90% capture of the CO_2 from a slipstream of the cement plant, which represented approximately 15% of its total CO_2. A mineralisation process is utilised to make sodium bicarbonate, bleach and hydrochloric acid. In the process, conditioned flue gas is fed to a multicolumn chemical absorption system, where a concentrated sodium hydroxide (NaOH) solution reacts counter-currently with the CO_2 from the flue gas in two packed absorbers working in parallel to form sodium carbonate (Na_2CO_3). The SkyMine® capture process was constructed, installed and maintained by CarbonFree Chemicals, with the process described as requiring 30% less energy than amine-based technologies. CarbonFree Chemicals is working on a second-generation carbon mineralisation process called SkyCycle™ which uses calcium and magnesium salts as a key part of the conversion chemistry to produce high purity precipitated calcium carbonate and synthetic limestone (CarbonFree, 2021).

Sinopec Qilu-Shengli

Sinopec Qilu petrochemical plant has retrofitted a 1 MtCO_2/y CCUS system to an existing coal/coke water slurry gasification unit at a fertiliser plant in Zibo City, Shangdong Province, China. The captured CO_2 is transported by pipeline to the Shengli oilfield for EOR. EOR is seen as a potential way of utilising the significant quantities of CO_2 from China's power and chemical manufacture industries to enhance oil production from indigenous oil fields (Hill and others, 2020). The opportunity for revenue from EOR to support the roll-out of CCUS has been discussed previously by the ICSC (Kelsall, 2020).

Sinopec Qilu was licensed initially in 2006 and uses three GE gasifiers, allowing two to run while one is on standby for planned maintenance. Operation of the plant with CCUS began in September 2022 producing 100 t/d of hydrogen for fertiliser production.

2.5 LESSONS LEARNED FROM CCUS PROJECTS

Several studies have been carried out to identify the potential to reduce the costs of CCUS (*see* Irlam, 2017; Bruce and others, 2019; IEA 2020a; Kearn and others, 2021). Generally, they point to cost reduction through increased deployment at demonstration and subsequently commercial scale – so-called 'learning by doing'. There is growing knowledge, based on Boundary Dam, Petra Nova and the more recent pipeline of FEED studies, that provides the initial practical understanding to drive cost reduction and improve performance of next-generation CCUS facilities. In addition, pilot and early TRL research projects are underway to develop the potential for innovating existing technologies and developing new technologies which could bring step-change cost reduction.

2.5.1 Cost reduction

Technology costs fall in real terms due to innovation and learning by doing. Environmental technology examples include the costs of manufacturing solar cells and offshore wind, which have fallen significantly and are projected to fall further. Another example is the development of wet desulphurisation scrubbers for coal-fired power plants in the USA where capital costs fell by about half as the deployment of the technology increased.

Capture forms the bulk of total CCUS costs. The cost of CO_2 capture is much lower for concentrated sources (such as hydrogen production, coal-to-chemicals, steel and cement production) than for power generation and alumina processing, where it is even lower. Over the past 15 years, the costs of capture from coal-fired power flue gas have fallen by about 50% following R&D, demonstrations and learning by doing. Diverse technologies, platforms and innovations developed outside the energy sector are now being transferred into this sector to reduce costs, risks and timescales for CCUS projects.

Current carbon capture costs for coal-fired power plant with post-combustion CO_2 capture using amine-based solvents are in the range of 105 $/t$CO_2$ captured at Boundary Dam, to 65 $/t$CO_2$ captured at Petra Nova (GCCSI, 2020). The US Department of Energy (USDOE) has noted that carbon capture costs need to come down to around 30 $/t$CO_2$ for CCUS to be commercially viable (GHGT, 2018). These costs will naturally decline in the future as CCUS technology becomes more commercialised through economies of scale. Based on a typical learning rate of 8–13% for coal-related technologies (Zapantis and others, 2019) and assuming a target capacity of 220 GWe of coal-fired power plant fitted with CCUS to achieve the IEA's NZE scenario (IEA, 2021a), a cost reduction in the range of 50–75% could be achieved by 2050 for amine-based post-combustion CO_2 removal. Taking the current price of CCUS as the more recent Petra Nova price of 65 $/t$CO_2$ captured, the price for future CCUS plant could therefore fall to 18–30 \$/tCO_2, depending on final capacity and the actual learning rate. With the additional learning from industrial applications of CCUS, this price could be even lower.

It is interesting to compare the cost projected for the proposed Shand Power plant FEED study (Bruce and others, 2019; Int CCS KC, 2018) with the existing Boundary Dam project. The cost reduction projected for the single 300 MWe Shand coal power plant with an assumed 90% CO_2 capture is 57% relative to Boundary Dam, resulting in a capture cost of 45 \$/t CO_2, with capital cost and variable operating and maintenance costs being the key areas for achieving this cost reduction. This level of cost reduction is higher than that predicted by the learning rate-based cost reduction, indicating that the learning rate is steeper at this relatively early stage of commercialising demonstration technologies (Kelsall, 2020).

The Shand FEED study fits into a cluster of more recent project studies at around the 43–45 \$/t CO_2 cost level, within a proposed timescale for the commencement of plant operations by 2024-28, (*see* Figure 6). This figure also indicates the potential for a further cost reduction by moving to advanced capture systems within a similar timescale, where costs below 35 \$/tCO_2 could be expected based on pilot plant tests.

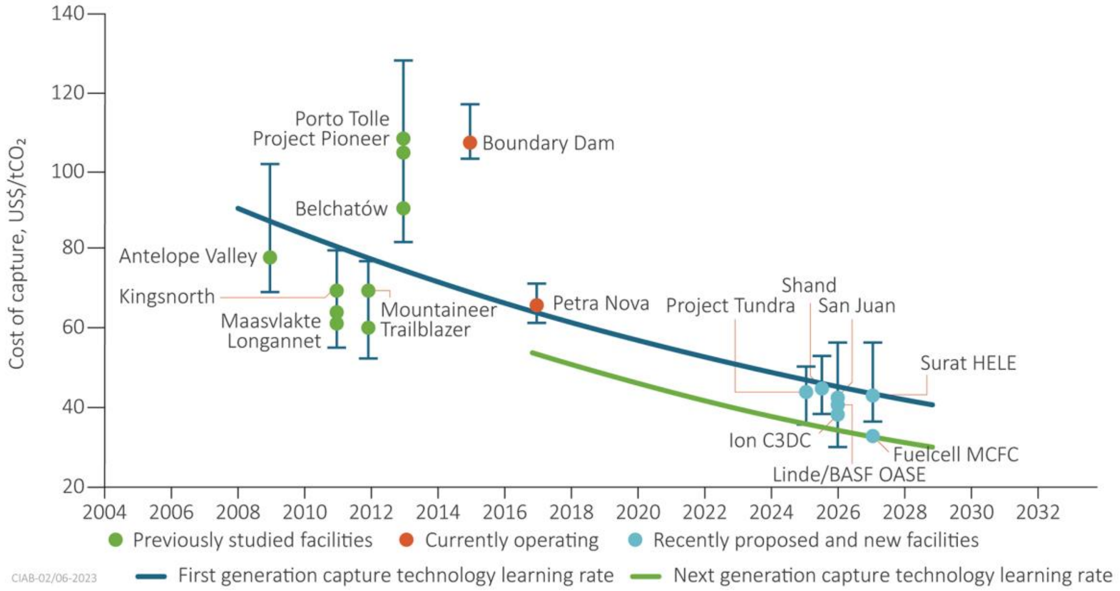


Figure 6 Levelised cost of electricity for large-scale coal power generation plant with post-combustion carbon capture (Zapantis and others, 2019)

GCCSI analysis based on an 8% discount rate, 30 years project life, 2.5 years construction time, capacity factor of 85%. Fuel prices were based on the reported data in the project feasibility and FEED reports. Cost data normalised to 2017 values.

In terms of industrial CCUS, a study by the National Energy Technology Laboratory (NETL) shows that CO_2 purity, as expected, plays a large role in the cost of capture (Hughes and Zoelle, 2022). However, the amount of CO_2 and therefore the varying economies of scale from one industrial process to another also has a strong effect on the cost of capturing CO_2. The analysis evaluated potential decarbonisation opportunities in representative industrial plant applications, and the results show that capturing CO_2 can be cost-effective in the industrial sector, especially when a facility has two specific emissions stream characteristics:

- high CO_2 purity so that further purification is not required, such as coal-to-liquids (CTL); and
- large amounts of CO_2 available, for example, cement manufacture.

2.5.2 Capture level

In its NZE modelling [for 'Net Zero by 2050 A Roadmap for the Global Energy Sector' May 2021 and 'World Energy Outlook 2021'] the IEA assumes that capture rates from fossil fuel power plants are capped at 90%. However, this is an artificial limit which has, in fact, been exceeded at Petra Nova. Today CCUS based on post-combustion CO_2 capture typically aims for a 90–95% capture level and the more recent studies form the IEA have assumed a CO_2 capture rate to 97% (IEA, 2022g).

In the longer term, as near zero emissions power plants will be needed, higher capture efficiencies will be required. Feron and others (2019) have shown that from a technical perspective, there is no limiting factor to increasing capture rates. A fossil fuel power or heavy industrial plant could be made effectively CO_2 neutral by capturing 99.7% of the $CO_{2,}$ utilising intercooling in the CO_2 absorption tower for example. (At this capture rate the power station is CO_2 neutral as the only emitted CO_2 is that in the incoming combustion air.)

However, this increases the capital cost of the CCUS facility due to the requirement for larger equipment (absorber/desorber columns, heat exchangers and CO_2 compressor), as well as increased energy consumption. For an ultrasupercritical (USC) coal-fired power plant the efficiency, based on lower heating value (LHV) is reduced from 44.4% to 34.5% for 90% capture, and to 33.0% for 99.7% CO_2 capture, representing an additional drop of 1.5 percentage points in efficiency. The cost per tonne of CO_2 avoided increases from 55.0 €/tCO_2 ($62) at a 90% capture level to 56.9 €/tCO_2 ($64.5) at a 99.7% capture level, which is an increase of 3.5%.

It should be noted there are other possibilities to achieve NZE in a coal-fired power plant. These include cofiring coal with biofuels or potentially ammonia. For example, the cocombustion of 10% biomass in a coal-fired power plant with 90% CO_2 capture can be more economic than 99% and 99.7% capture, with a 2% increase in electricity generation cost over the usual 90% capture rate and only 1.5% increase in CO_2 avoided cost (IEAGHG, 2019). This study showed that the CO_2 avoided cost of 99% capture was 58.3 €/tCO_2 for a standard plant, compared with 55.8 €/tCO_2 for 90% capture and 10% biomass cofiring in a PCC. Similar costs have been shown by Feron and others (2019).

A 90–95% capture level should not be seen as an obstacle to an industrial or power plant continuing to operate in the transition to net zero as it can take alternative approaches and/or buy reputable offsets.

2.5.3 Hub and cluster approach

CCUS hubs, in which multiple emission sources share transport and storage infrastructure, are evolving to become the dominant operating model for CCUS in North America and Europe. The technologies to develop CO_2 hubs exist and are mature but experience and learning from their operation are still limited (CSLF, 2021). To address this, the Global CCS Institute (GCCSI) has developed a database of major hubs, including four in operation and thirty under development. A significant number of these hubs have heavy industries embedded within them, which are included in Table 6 below.

TABLE 6 MAJOR GLOBAL HUBS AND CLUSTERS (GCCSI, 2021)

No	Name	Country	Facility industry	Transport type	Storage type
1	Abu Dhabi Cluster	United Arab Emirates **Operating**	Natural gas processing, hydrogen production, iron and steel production	Pipeline	EOR
4	Alberta Carbon Trunk Line (ACTL)	Canada **Operating**	Fertiliser, hydrogen, chemical	Pipeline	EOR
5	Antwerp@C	Belgium	Hydrogen, chemical, oil refining	Pipeline	Dedicated geological (saline formations)
6	ARAMIS	Netherlands	Oil refining, hydrogen, waste incineration, chemical, steelmaking	Pipeline, ship	Dedicated geological storage (saline formations)
7	ATHOS (Amsterdam CO_2 Transport Hub & Offshore Storage)	Netherlands	Hydrogen, iron and steel, chemical production	Pipeline	Various options
8	Barents Blue	Norway	Chemical, hydrogen, waste incineration	Ship	Dedicated geological storage (saline formations)
10	Carbon Connect Delta (Port of Ghent)	Belgium & Netherlands	Steelmaking, chemical production	Pipeline, ship	Under Evaluation
11	CarbonNet	Australia	Natural gas processing, coal-fired power, hydrogen, ammonia, fertilisers, waste to energy, DAC	Pipeline	Dedicated geological (saline formations)
12	CarbonSAFE	USA	Coal-fired power, ethanol	Pipeline	Various options
13	Dartagnan	France	Aluminium production, steelmaking	Pipeline, ship	n/a
14	Carbon Transport and Storage Company	Australia	Coal-fired power initially, cement, chemical production	Pipeline	Dedicated geological storage (saline formations)
15	Edmonton Hub	Canada	Natural gas power, hydrogen, oil refining, chemical production, cement	Pipeline	Dedicated geological (saline formations)
16	Greensand	Denmark	Waste incineration, cement	Pipeline, ship	Depleted oil and gas reservoirs

17	Houston Ship Channel CCS Innovation Zone	USA	Various	Pipeline	TBD
18	Humber Zero	UK	Natural gas power, oil refining	Pipeline	Dedicated geological storage (saline formations)
19	HyNet North West	UK	Hydrogen, cement	Pipeline	Dedicated geological (saline formations)
20	Illinois Storage Corridor	USA	Coal power, bioethanol	Pipeline	Dedicated geological storage (saline formations)
21	Integrated Mid-Continent Stacked Carbon Storage Hub	USA	Coal-fired power, cement, ethanol production, chemical production	Pipeline	Various options
22	Langskip	Norway	Waste incineration, cement	Pipeline	Dedicated geological storage (saline formations)
23	Louisiana Hub	USA	Hydrogen, iron and steel, oil refining, chemical, ethanol	Pipeline	Dedicated geological (saline formations)
24	East Coast Cluster – previously Net Zero Teesside (NZT, 2020) and Zero Carbon Humber (H2H, 2022)	UK	Hydrogen, natural gas power, fertiliser, iron and steel, chemical production	Pipeline	Dedicated geological (saline formations)
25	North Dakota CarbonSAFE	USA	Iron and steel	Pipeline	Various options
27	PORTHOS (Port of Rotterdam CO_2 Transport Hub and Offshore Storage)	Netherlands	Hydrogen, chemical	Pipeline	Depleted oil & gas reservoirs
28	Ravenna Hub	Italy	Hydrogen, natural gas power	Pipeline	Depleted oil and gas reservoirs
29	South Wales Industrial Cluster	UK	Natural gas power, hydrogen, oil refining, chemical	Pipeline, ship	Dedicated geological storage (saline formations)
30	Summit Carbon Solutions	USA	Bioethanol	Pipeline	Dedicated geological storage (saline formations)
31	Valero Blackrock	USA	Bioethanol	Pipeline	TBD
32	Wabash CarbonSafe	USA	Coal-fired power, natural gas power, hydrogen, chemical, cement, biomass power	Direct injection	Various options
33	Xinjiang Junggar Basin CCS Hub	China	Coal-fired power, hydrogen, chemical	Pipeline, tank, truck	EOR
n/a = not available; TBD = to be determined					

Shared transport and storage networks can improve the economics of CCUS due to economies of scale and overall de-risking of storage liability and cross-chain risk (IEA, 2020c; Zapantis and others, 2019; CCUS Cost Challenge Task Force, 2018). Heavy industries often exist in clusters close to local resources, power generation supply and port or rail infrastructure. These industrial clusters can be supported by providing CO_2 transport and storage network infrastructure which multiple CO_2 sources can access. This reduces the unit cost of CCUS as the CO_2 network capital cost is spread out across an increased quantity of CO_2. It also reduces cross-chain risk by creating multiple customers for the operators of the CO_2 transport and injection business and multiple CO_2 storage service providers for industrial CO_2 sources. This provides greater levels of operational flexibility than single source and sink facilities and reduces operational risk.

The hub and cluster approach is driving the way CCUS projects are being carried out in several locations, particularly those associated with industrial carbon capture. Capturing CO_2 from clusters of industrial installations and using shared infrastructure for the subsequent CO_2 transport and storage network, is the preferred approach to drive down unit costs across the CCUS value chain. Examples include the Port of Rotterdam, the Netherlands (Porthos, 2019), the Northern Lights project, Norway (Northern Lights, 2019) and the HyNet (HyNet, 2021) and East Coast Cluster projects in the UK (NZT, 2020; East Coast Cluster, 2021; H2H, 2020, 2022). The hub and cluster approach was also used in the Shand FEED study (Int CCS KC, 2018) where the CO_2 is used for EOR. EOR operators require reliable sources of CO_2 to avoid interruptions in oil production, so connecting two or more CO_2 sources to an EOR operation reduces the potential operating risk. A further example of this CO_2 hub concept is the Alberta Carbon Trunk Line (ACTL) in Canada which is large enough to transport 14.6 $MtCO_2/y$ in its 240 km pipeline with the transported CO_2 utilised for EOR and geological storage.

Socially desirable levels of investment in the hub and cluster model are likely to be less than optimal in the absence of government assistance and other mechanisms such as guarantees provided for revenue during the early stages of development. In the UK for example, the Regulated Asset Base (RAB) model has been used to enable private investment in infrastructure (CCUS Cost Challenge Task Force, 2018). RABs use a legally binding license with a periodical regulatory review of long-term tariffs.

Where the balance of risk and return is still insufficient for initial private sector investment in the CO_2 transport and storage network, the relevant government should consider taking this role. In this way, governments can kickstart a hub and cluster development with the option of privatising the business after it has gained sufficient CO_2 source and sink 'customers'. Alternatively, the relevant government could invest in establishing a regulatory framework that provides the private sector with the right incentives to invest in transport and storage networks, which may be preferable in regions where this is already common practice for infrastructure projects (Zapantis and others, 2019).

3 CO_2 STORAGE

3.1 KEY MESSAGES

The potential for CO_2 storage globally is almost 14,000 Gt, sufficient to store approaching 2000 years of CO_2 emissions to meet net zero emissions projections.

- Suitable CO_2 storage basins are generally located near to emissions intensive regions. Key regions for heavy industrial manufacture including China, SE Asia, USA, India and Europe all have access to potential geological storage sites.
- This tie-up should facilitate CCUS development, particularly where infrastructure is being established through hubs and clusters.
- 97% of the storage sites identified are in saline aquifers, with the remaining sites primarily in depleted or partially depleted oil and gas fields.
- Most CO_2 storage basins are commonly classified as 'undiscovered' meaning that they are currently commercially inaccessible because of inadequate data to confer discovered status and the lack of a regulatory framework for CO_2 storage in most countries.

3.2 CO_2 STORAGE POTENTIAL

Another key aspect of CCUS is the availability of suitable sites for the storage of CO_2. One such review has been undertaken by the GCCSI (2022), which ranked storage locations as unlikely, possible, suitable or highly suitable (*see* Figure 7). The suitability ranking combined spatial analysis of existing geological, energy and infrastructure data. Two key findings were:

- Nations with suitable storage locations are generally near emissions-intensive regions. This tie-up should facilitate CCUS development, particularly where infrastructure is being established through hubs and clusters. The USA, the Middle East, parts of Europe, China and parts of SE Asia are leading regions where this tie-up exists; and
- The distribution of suitable storage sites correlates with countries where sites have been formally assessed for geological storage.

It is important to note that a detailed assessment does not however imply a high suitability ranking. For example, some European storage sites have been analysed in detail, but achieved a low ranking due to their geological characteristics. Understanding the global distribution of suitable and accessible storage sites will be required for the commercial deployment of CCUS.

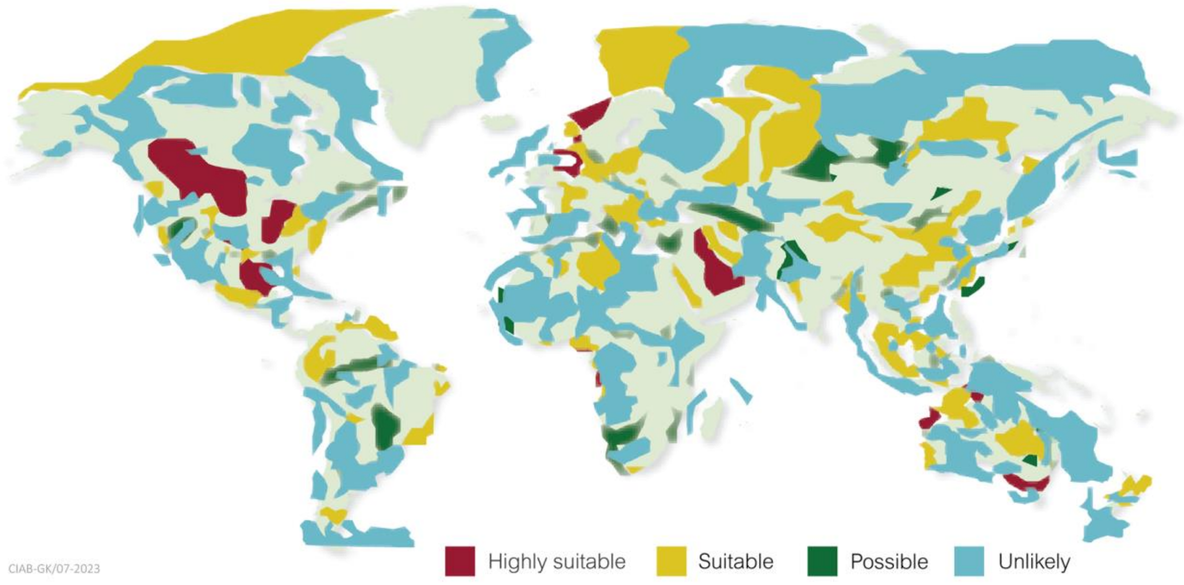


Figure 7 Potential CO_2 storage sites worldwide (GCCSI, 2022; Baines and others, 2022)

3.3 THE CO_2 STORAGE RESOURCE CATALOGUE

The above assessment of CO_2 geological storage sites was based on the CO_2 Storage Resource Catalogue (CSRC) which is an on-going programme aimed at building a global view of the commercial readiness of CO_2 storage resources in key markets (Baines and others, 2022). The Catalogue was created by classifying the resource maturity of published storage resource evaluations using the Society of Petroleum Engineers' CO_2 Storage Resources Management System (CSRMS, 2017). CSRMS is a project-based classification system, with progression based on commercial triggers including national/federal regulatory systems and project development milestones. Rigorous use of the CSRMS in the CSRC reduced the subjective nature of resource assessment and allowed comparison of resource potential and maturity. The issue of CO_2 store classification, the availability of data and compatibility between databases was discussed in a recent workshop led by the IEA Greenhouse Gas R&D Programme (IEAGHG, 2022).

The CSRC, together with the CSRMS, include CO_2 storage in saline aquifers and depleted or partially depleted oil and gas fields but excludes CO_2 used for EOR and other storage options such as un-mineable coal, mineralisation and organic-rich shales. The CSRC is being built up in stages over six annual cycles, with the current revision including updates to the end of the third cycle. It includes 852 CO_2 storage resource sites across 30 countries, with both oil and gas fields and saline aquifers being assessed.

A summary of the global resource base in the CO_2 Storage Resource Catalogue is presented in Table 7 and Figure 8. This shows a total potential global resource estimate of close to 14,000 Gt. When compared with an estimated storage requirement for CO_2 of around 7.6 $GtCO_2$/y by 2050, as noted earlier in Section 2.2, this would give an estimated global storage of approaching 2000 years.

It should be noted that there is uncertainty associated with the storage estimates based on the methodology used in the CSRC, where it is advised that evaluations should ideally include a range of resource estimates from either deterministic or probabilistic methodologies. At present, CSRC includes uncertainty ranges for 20% of the sites assessed, with the other 80% providing mid-case estimates only. It should also be noted that as the CO_2 Storage Resource Catalogue is compiled exclusively from public domain sources, it is likely that significant additional storage resource exists. It is possible for a country to have few published evaluations and consequently low/no storage resources in the CSRC despite having significant storage potential. As noted above, the catalogue is halfway through its six-year total cycle of compilation, so more storage resource will be added. Overall, the CSRC analysis provides encouraging evidence for storage potential on a scale that will enable carbon capture and storage to play an important role in maintaining global net zero emissions for many centuries to come.

Looking at the results in more detail, saline aquifers make up the vast majority, some 97%, of the total CO_2 storage resource identified. These are commonly classified as 'undiscovered' meaning that they are currently inaccessible commercially because of inadequate data to confer discovered status and the lack of a regulatory framework for CO_2 storage in most countries.

Of the thirty countries assessed, the commercial readiness of the global storage resource remains low due to barriers to resource progression, such as the lack of CCUS-specific regulation and policy support in many countries, (*see* Figure 8). This is illustrated by the fact that only Australia, Canada, Norway and the USA have CO_2 storage resource which is being utilised commercially.

Some publicly announced projects do not appear in the CSRC database because no technical evaluations of storage resources have been published. Additional information about CCUS projects in development is available in the CO2RE Database maintained by GCCSI (CO2RE, 2022).

TABLE 7 GLOBAL CO_2 STORAGE POTENTIAL BASED ON 2022 CO_2 STORAGE RESOURCE CATALOGUE (BAINES AND OTHERS, 2022)

Classification	CO_2 storage resource (Gt) Project and no project	CO_2 storage resource (Gt) Project specified
Stored	0.04	0.04
Capacity	0.21	0.21
Sub-commercial	577	66
Undiscovered	13,377	30
Total	**13,954**	**97**

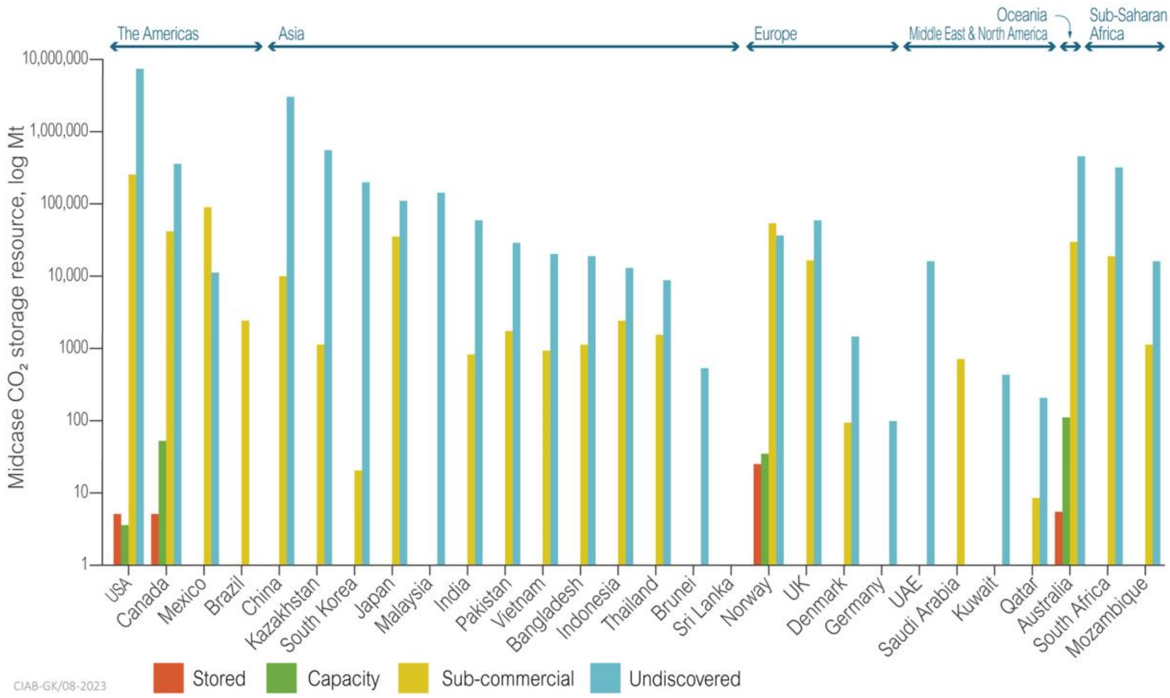


Figure 8 CSRC global storage resource (Baines and others, 2022)

3.4 PROXIMITY TO SOURCES

The analysis also shows that there is good availability of CO_2 storage basins relatively close to the main sources of global industrial emissions. Significant potential resources are identified across the major industrial emissions regions of Asia, North America and Europe. A brief overview of some of the key regions/countries is provided below.

3.4.1 China

China has a large potential geological CO_2 storage capacity of a little over 3000 Gt. There is a total of 72 sites in the CSRC, largely at a regional scale or at a high-level evaluation. The storage resource is located across a minimum of 21 geological basins, both onshore and offshore (Baines and others, 2022). Most of the onshore sedimentary formations are in the northern, western, and central-eastern parts of the country, while offshore basins are available along most of the coastal area (IEA, 2020c). In its 2019 CCUS roadmap, the Chinese government expressed interest in exploiting early opportunities associated with CO_2-EOR. Most of these opportunities are in Xinjiang in the north-western region; Gansu, Ningxia, and Shaanxi in the central region; and Heilongjiang and Jilin in the north-east. A considerable share of the stationary sources of CO_2 in China are relatively close to at least one geological CO_2 storage reservoir. In China, 45% of existing power and industrial facilities have at least one storage formation within 50 km, and 65% of the sources are located within 100 km of a potential storage site. Further assessments would be required to determine the suitability of potential reservoirs, their exact technical capacity and their economic feasibility.

The south-central and eastern provinces, which have high CO_2 emissions, are the furthest from potential onshore CO_2 storage reservoirs. In these areas, offshore storage may be cheaper than the development of long-distance CO_2 pipeline infrastructure to inland onshore reservoirs. Offshore storage may also be the preferred option for populous areas along the coast where high land prices and public opposition could hamper the development of onshore storage resources (IEA, 2020c).

3.4.2 USA

The USA has the largest potential CO_2 storage capacity with over 8000 Gt identified. Potential storage resource has been identified in 36 US states with 12 projects and 14 regional studies included in the CSRC assessment. While the US storage resource is distributed across mainland USA, the regional saline aquifer studies are dominated by the northern states within the Williston, Michigan, Illinois, Powder River, and Denver basins. Future assessments of the country's storage potential should focus on updating the vast potential in other parts of the country, including California, the southern states, the Gulf of Mexico region and the Federal Offshore.

The majority of CO_2 sources in the USA are located close to potential CO_2 storage sites. Around 80% of industrial facilities and power plants, accounting for 85% of emissions, are located within 100 km of a potential storage site and 75% of plants are within 50 km (IEA, 2020c). To put these distances into context, the average distance over which CO_2 is transported by pipeline between existing CCUS facilities is around 180 km, with the maximum around 375 km from the Lost Cabin Gas Plant. The USA has the world's largest CO_2 pipeline network of over 8000 km, which can provide a basis for developing new capacity to link emissions point sources to dedicated CO_2 storage and EOR sites in the future.

3.4.3 Europe

Much of the European storage capacity is onshore, where storage projects are likely to face public opposition (IEA, 2020c). The CRSC assessment has therefore focused on offshore storage where around 173 Gt of storage capacity has been identified. These are expected to be more feasible to exploit commercially in the near term.

The bulk of Europe's energy sector emissions are from sources located relatively near potential storage sites. Around 68% of all the emissions from power plants and factories in Europe are within 100 km of potential storage. This includes 54% of emissions from iron and steel plants, 56% of emissions from refineries, 52% from cement, 72% from power and 79% from chemical plants. An estimated 19% of industrial plants in Europe are located within 100 km of a suitable offshore storage site, with oil refineries accounting for 25% of these emissions, followed by chemical plants at 20%, iron and steel plants at 17% and cement plants at 10%.

Most of Europe's potential offshore CO_2 storage capacity is in the North Sea, where there are several depleted oil and gas fields and saline aquifers that could provide suitable storage. These sites are close to industrial clusters in Belgium, Denmark, Netherlands, Norway, Sweden and the UK. Norway has a potential storage capacity of 94 Gt with a total of 42 sites at both local and regional scales, located across five geological basins in the Norwegian North Sea. The Utsira offshore saline formation, considered the largest potential sink for CO_2 in Europe, is in this region with a storage capacity of up to 16 $GtCO_2$. Norway is the global leader in terms of actual CO_2 stored with more than 25 $MtCO_2$ injected to deep geological storage in the North Sea, at the Sleipner and Snøhvit CO_2 stores.

As in Norway, CO_2 storage capacity in the UK at around 78 Gt is mostly located offshore, including in deep saline formations and depleted oil and gas fields. There were a total of 87 sites at both local and regional scales, across five geological basins in the UK offshore sector (Baines and other, 2022).

The Baltic region including Germany and Denmark accounts for the remaining 1.6 Gt of European off-shore storage in the CRSC, including a series of closures in the western Baltic region. Whilst this does not portray a complete picture of the resource profile for the Baltic region, which includes countries surrounding the Danish North Sea and the Baltic Sea, it points to the availability of significant resource in that region.

4 IRON AND STEEL

4.1 KEY MESSAGES

Steel has an important role to play in a low-carbon future:

- It is the third most used bulk material after cement and timber; and
- It will play a key role in the energy transition, serving as a critical material for wind turbines, transmission and distribution infrastructure, hydropower, nuclear power and CCUS systems.

China, India and Japan are the top three steel producing countries, with China producing 1033 Mt steel in 2021, representing 53% of global production. Steel production could increase by a further 12–60% by 2050.

The blast furnace to basic oxygen furnace (BF-BOF) process accounts for about 70% of total steel production. The remaining 30% is principally produced from recycled steel in electric arc furnaces (EAF), where limiting factors include the availability of scrap steel and the inability to produce high-carbon steels.

The future role of coal is intrinsically linked to the blast furnace. Over the past decade coal has met around 75% of the energy demand of the sector. Its share in the energy use for iron and steel production will inevitably reduce but will remain at a significant level, as high as 50% by 2050 representing 14 EJ, equivalent to around 480 Mtce. From a technical perspective, it is difficult to see a suitable replacement for metallurgical coal, due to its threefold role in the blast furnace, acting as a source of heat, as a reducing agent for the iron ore and providing permeability to the blast furnace burden.

The industry needs to drive towards net zero emissions by 2050 by reducing its direct (Scope 1) emissions, currently around 2.6 GtCO_2/y, representing around a quarter of industrial CO_2 emissions, and its Indirect (Scope 2) emissions of almost 9% of total emissions from energy systems. This will be highly dependent on several enablers, including the commercialisation of emerging and breakthrough technologies, availability of affordable and reliable renewable energy, addressing the challenge in adopting hydrogen in steel making, availability of quality raw materials, adequacy of recycled materials and appropriate government policies.

Achieving 2030 mid-term targets while ensuring industry resilience – The average lifetime of blast furnace steel production assets is typically around 40 years, with major investment decisions after each 20 to 25-years. The weighted global average plant age is only about 13 years (and around 12 years in China where over 50% of global assets are located).

In countries with younger assets greater emphasis is likely to be placed on retrofitting with more energy-efficient and less carbon-intensive technologies such as CCUS. In other countries some individual BFs will come to the end of their current operating campaign life requiring realignments before 2030. Emerging 'green steel' technologies, whilst promising, are not yet ready for large scale implementation in this timeframe. If it is assessed that a reline is the most feasible option for an individual steelmaker, other emission reduction measures will need to be employed while longer-term breakthrough low-emission technologies are developed.

Efficiency improvements to steel plant could include operational efficiency, enhanced process control and predictive maintenance strategies, together with the implementation of best available technologies. Such measures could improve energy efficiency and contribute around 20% of cumulative emissions savings.

Industry investment requirements to ensure resilience – Given the ongoing, critical role for coal, the majority of the emissions reduction required in the iron and steel sector to achieve NZE targets after 2030 will come from new, innovative technologies. This includes hydrogen based DRI and iron ore electrolysis as well as CCUS. Steel production using CCUS will be the single largest technology, accounting for 45–53% of primary steel production in 2050. This would equate to around 530–670 MtCO_2/y by 2050.

The steel sector will need an average $31 billion in investment annually to meet growing steel demand over the next 30 years. Transitioning global steel assets to net zero compatible technologies requires an additional $6 billion annually, equivalent to $200 billion in total by 2050 with CCUS a key technology. Companies will need to allocate investment funds over the next 5–10 years for their climate-related technology plan. This will include optimising current operating assets and preparing for emerging and breakthrough technologies including CCUS and establishing related infrastructure. There is significant flexibility and optionality to adopt new technologies and iron making configurations in the medium to longer term.

4.2 THE ROLE OF IRON AND STEEL

Steel is the third most abundant man-made bulk material after cement and timber. It is used as a key component in many sectors and applications including buildings, infrastructure, transport, machinery and consumer goods. Steel will also play a key role in the energy transition, serving as a critical material for many low emissions technologies including wind turbines, transmission and distribution infrastructure, hydropower, nuclear power, CCUS systems and advanced manufacturing processes. Indeed, the generation and use of electricity depends in part on the ferromagnetic properties of iron and steel alloys.

The steel industry is an integral part of many global economies and is one of the most widely traded commodities in the world, with producers competing in an international market. While other materials provide alternatives to steel in some applications, its high strength, recyclability, durability, ease of use and its relatively low cost make its large-scale substitution unlikely for the foreseeable future.

Iron and steel production is a highly energy-intensive industrial activity, ranking as the largest carbon emitter of all the heavy industries. While being an enabler of the energy transition, iron and steel is therefore also a large contributor to the emissions reduction challenge with direct CO_2 emissions from the sector accounting for around 2.6 $GtCO_2$/y, representing around a quarter of industrial CO_2 emissions and almost 9% of total emissions from energy systems (MPP, 2021a). This is due to its large dependence on coal and coke in the production process as a source of heat, as a reducing agent and to provide permeability to the blast furnace burden. Coal currently meets around 75% of the energy demand of the sector, a figure that has remained relatively constant over the past decade (IEA, 2022c).

IRON AND STEEL DEFINITIONS

Iron – In the context used here, iron denotes not only the chemical element in its pure form, but also the carbon-saturated intermediate of 'pig iron' and the final 'cast iron' products in the iron and steel sector.

Steel – denotes the various alloys of iron and carbon, of which 'carbon steel' is the simplest and most common type. Several other elements can be added to form more complex steel alloys, tailoring the physical properties of the alloy to suit a given application. For example, chromium or nickel are added to form stainless steel, known for its ability to withstand corrosion. Molybdenum, vanadium, manganese, tungsten and titanium are further examples of alloying elements used. There are around 3500 different grades of steel in use, many of which have been developed in the past 20 years (IEA, 2020d).

A further 1.1 $GtCO_2$ of emissions can be attributed to the use of its off-gases in combination with other fuels, to generate the electricity and imported heat required by the production processes (IEA, 2020d).

4.3 GLOBAL SCALE OF IRON AND STEEL PRODUCTION

Global crude steel production totalled 1950 Mt in 2021, an output which has grown by 25% over the last 10 years, as shown in Figure 9 (Statista, 2022a).

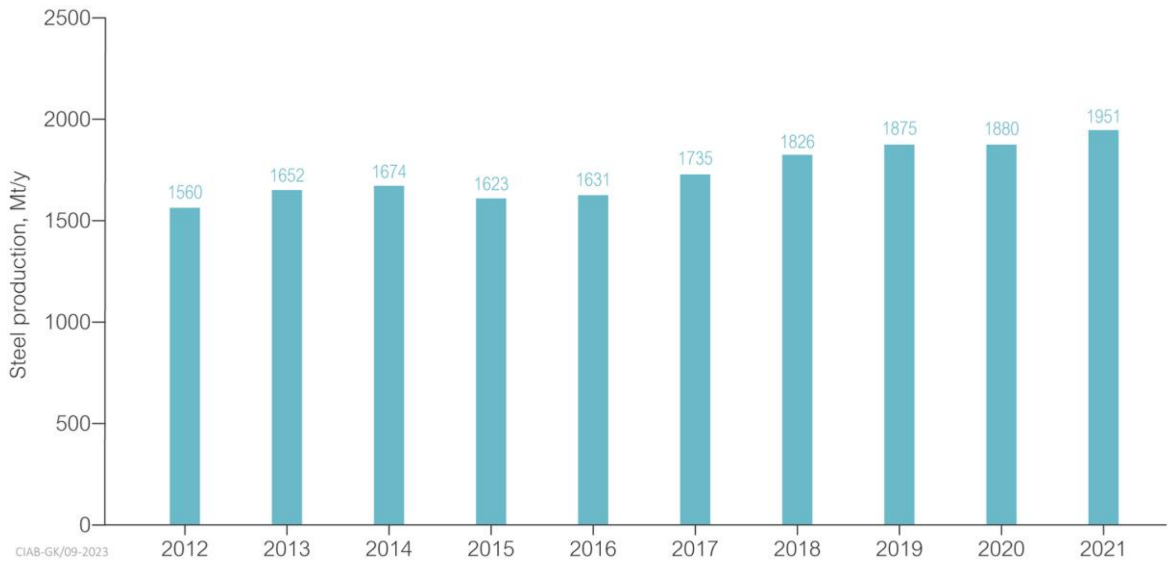


Figure 9 World crude steel production from 2012 to 2021 (Statista, 2022a)

Various projections see steel production increasing by around 30-60% by 2050 from current levels, driven by growing urbanisation in developing countries in Asia and Africa in particular. As discussed in Section 4.5.1, this increase in demand will need to be limited to achieve NZE targets (IEA, 2021a).

In developed countries with stable population growth, including those in Europe and North America, steel demand is already starting to plateau or steadily reduce as demand shifts from construction to maintenance, with demand per capita converging in the region to 0.15–0.25 t/y per person (IEA, 2021a).

However, during early development and for manufacturing-intense nations in particular, the need to build infrastructure can see annual demand increase to 1 t/y per person. China, South Korea and Japan, for instance, all had a demand of over 0.5 t/y per person in 2020. In the medium term, these will be joined by other developing nations such as Bangladesh, India, Indonesia, Nigeria, Pakistan, Philippines, Tanzania, and Vietnam. Such countries are yet to experience peak steel demand per capita and will drive an increase in global steel use.

4.3.1 Regional breakdown

Iron ore production

The total quantity of ire ore produced in 2020 was 2338 Mt as shown in Table 8 (World Steel Association, 2022). Australia was the largest producer with 923 Mt produced in 2021, almost 94% of which was exported, leaving around 50 Mt to be processed in Australia itself. Other countries with high production levels are Brazil at 391 Mt, China at 271 Mt, India at 204 Mt and Russia Commonwealth of Independent States (CIS) together with the Ukraine at 203 Mt. As is the case with Australia, Brazil exports most of its iron ore, almost 88%, for other countries to process further.

In terms of iron imports, China is by far the largest importer with 1170 Mt/y. Together with its indigenous iron ore production, this gives China an apparent iron usage of 1425 Mt/y, representing 62% of global iron ore use. Other large importing countries are Japan at 99 Mt/y and Korea at 70 Mt/y, both of which have zero or negligible iron ore production.

TABLE 8 GLOBAL IRON ORE PRODUCTION AND USAGE BY COUNTRY/REGION IN 2020 (WORLD STEEL ASSOCIATION, 2022)

Country	Production, Mt/y	Exports, Mt/y	Imports, Mt/y	Apparent consumption, Mt/y
Austria	3	0	3.2	6.2
Belgium-Luxembourg	–	–	–	0
Czechia	–	0	4.9	4.9
France	–	0.1	11.2	11.1
Germany	1.2	0.9	33.4	33.8
Italy	–	0	5.4	5.3
Netherlands	–	16.9	24.4	7.5
Poland	–	–	5.2	5.2
Romania	–	–	2.2	2.2
Slovakia	–	0.1	4.4	4.3
Spain	–	0.1	3.6	3.5
Sweden	29.2	27.1	0	2.2
Other EU	–	0.5	4	3.5
Bosnia-Herzegovina	1.4	0	0	1.4
Norway	1.6	1.8	0	-0.2
Turkey	7.9	2.2	9.9	15.6
UK	–	0	7.1	7.1
Other Europe	–	0	1.4	1.4
Europe (Total)	**44.2**	**49.7**	**120.3**	**114.9**
CIS Russia + Ukraine	**203.1**	**86.1**	**8.2**	**125.2**
Canada	58.8	55.1	7.1	10.7
Mexico	11.4	1.9	1.5	11
USA	38.6	10.4	5.2	33.3

North America + Mexico (Total)	**108.7**	**67.5**	**13.7**	**55**
Brazil	391	342.6	0.2	48.6
Chile	15	17	0.2	-1.8
Peru	8.9	11.6	0	-2.8
Venezuela	1.5	0.8	–	0.7
Other Central & South America	0.3	0.6	5.1	4.8
Central & South America (Total)	**416.6**	**372.6**	**5.5**	**49.5**
Liberia	5.1	5.1	–	0
Mauritania	13.5	14.1	–	-0.6
South Africa	69	65.5	0	3.5
Other Africa	5.7	0.5	23.2	28.4
Africa (Total)	**93.3**	**85.1**	**23.2**	**31.4**
Middle East	**53.6**	**10.4**	**25.1**	**68.3**
China	270.5	15.6	1170.4	1425.2
India	203.8	52	0.7	152.5
Japan	–	0	99.4	99.4
South Korea	0.3	0.3	70.4	70.5
Other Asia	17.9	40.9	78.9	55.9
Asia (Total)	**492.6**	**108.8**	**1419.8**	**1803.6**
Australia	922.5	873	0.9	50.4
New Zealand and other Oceania	3.8	2.9	0	0.9
World	**2338.4**	**1656.1**	**1616.8**	**2299.1**

Crude steel production

Global crude steel production, the main use of iron ore, totalled 1950 Mt in 2021 (World Steel Association, 2022). Asia dominated production (*see* Table 9), as China, India and Japan are the top three steel-producing countries. China alone produced 1033 Mt steel in 2021 representing almost 53% of global production. The USA and Germany are the only other G7 countries appearing in the top 10 list of primary steel-producing countries.

TABLE 9 TOP 20 CRUDE STEEL PRODUCING COUNTRIES (WORLD STEEL ASSOCIATION, 2022)

Country	Global rank, 2021	Steel, Mt/y (2021)	Global share, %
China	1	1032.8	52.9
India	2	118.2	6.1
Japan	3	96.3	4.9
USA	4	85.8	4.4
Russia	5	75.6	3.9
South Korea	6	70.4	3.6
Turkey	7	40.4	2.1
Germany	8	40.1	2.1
Brazil	9	36.2	1.9
Iran	10	28.5	1.5
Italy	11	24.4	1.3
Taiwan	12	23.2	1.2
Vietnam	13	23.0	1.2
Ukraine	14	21.4	1.1
Mexico	15	18.5	0.9
Indonesia	16	14.3	0.7
Spain	17	14.2	0.7
France	18	13.9	0.7
Canada	19	13.0	0.7
Egypt	20	10.3	0.5
Others		150.7	6.9
Global (Total)		**1951.2**	

4.4 STEEL PRODUCTION PROCESSES

4.4.1 Current processes

There are two main ways in which steel is produced. The first is from mined iron ore, involving a series of highly energy-intensive processes centred around the blast furnace to basic oxygen furnace (BF-BOF). The second is from recycled steel scrap, directly melted into steel in an electric arc furnace (EAF). Direct reduction iron (DRI), usually applied in conjunction with EAF, is also increasing as a production process. These are fundamentally different manufacturing routes, with different raw material and energy inputs as shown in Figure 10 and as described in full by the ICSC (Baruya, 2020).

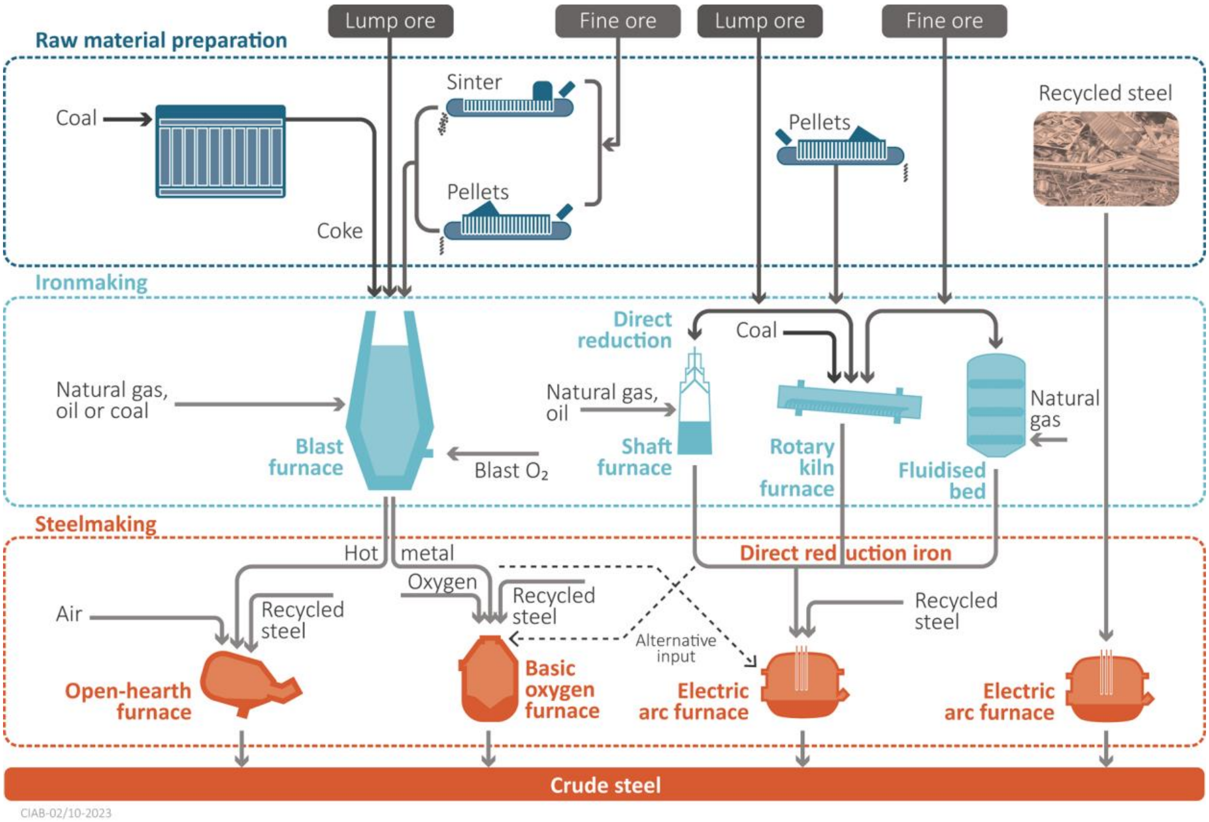


Figure 10 Primary steel production methods (Baruya, 2020)

Blast furnace to basic oxygen furnace

The BF-BOF process accounts for about 95% of the world's primary steel production and some 70% of total steel production, with the remaining 30% produced from recycled steel.

In this process, iron ore is first pre-processed into sinter or pellets in dedicated plants, an agglomeration process that requires temperatures of about 1000°C using coal or natural gas as process heat. This step typically requires 1–2 GJ/t of pellets or sinter, noting that sintering usually occurs at the integrated steelmaking site, while pelletising tends to take place upstream at the iron ore mining stage.

In the blast furnace, the reducing gases that bind and remove the oxygen from iron ore are generated from coke and injection coal. Coke is a refined coal derivative, made from heating metallurgical coal in a coke oven in the absence of air at around 1000°C. This energy-intensive process requires around 6.5 GJ/t coke.

The sinter or pellets and coke are charged into the blast furnace, while hot air and pulverised coal are blown in from the bottom, forming reducing gases from coke which react with iron ore to produce pig iron. This reaction requires high temperatures of up to 1400°C and consumes around 12 GJ/t hot metal. Additionally, limestone is added to the blast furnace as a fluxing agent, facilitating the removal of impurities.

To make steel, the molten hot pig iron is poured into the basic oxygen furnace (BOF), where oxygen is blown into the metal to reduce its carbon content from around 4% to around 1% as required for steel. This is an exothermic process that does not require additional fuel inputs. At this stage, steel scrap can also be fed into the basic oxygen furnace, acting as a coolant and as a source of iron, typically providing around 15–25% of the total steel output (World Steel Association, 2021).

The crude steel from the BOF is then cast into different intermediary steel products through various hot-and cold-rolling downstream processes.

The primary steelmaking BF-BOF route is highly integrated, with all its processes usually located at the same site, except for the pelletising plant which is typically found at the iron ore production site. The waste gases emitted by the coke oven, blast furnace and basic oxygen furnace form an important part of the energy balance since they are recovered and reused as fuel to provide process heat or to fire onsite power plants that generate electricity. In total, the primary steel production route requires around 21 GJ/t crude steel (Somers, 2022; World Steel Association, 2022).

Electric arc furnace (EAF)

In the secondary steelmaking route, recycled steel scrap is smelted in an electric arc furnace (EAF) at 1600°C to produce liquid steel. Electricity is the main energy input to this process, but natural gas from dedicated burners to melt the scrap can also be used as an additional energy input (Somers, 2022). A small amount of solid carbon, such as coal or coke, at around 12 kg/t steel is also used to increase the energy efficiency of the process, through slag foaming and as a carburising agent (Echterhof, 2021). In terms of direct energy input, the secondary steelmaking route requires around 2.5–3 GJ/t of crude steel.

Direct reduced iron (DRI)

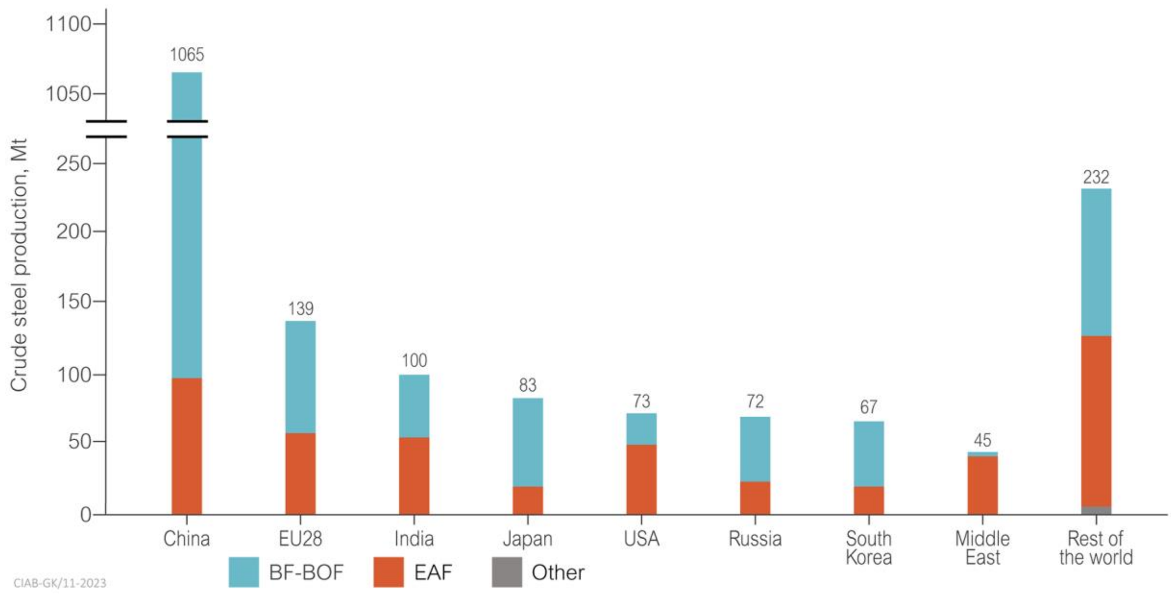
DRI is another commercially deployed method of primary steel production, whereby iron ore is directly reduced in its solid state to produce direct reduced iron or sponge iron. DRI does not need a blast furnace and coke oven, since the main reduction gases in the process, hydrogen and carbon monoxide syngas, are generated from natural gas or coal. The sponge iron is then melted and refined into steel, often with additional scrap steel, in an EAF. This production route accounts for the remaining 5% share of global primary steel production (Baruya, 2020), although the proportion is increasing. Between 2015 and 2019, the production of DRI increased by 46% (Somers, 2022).

There are several types of DRI processes currently in use globally, which can use different sources of reducing gases (natural gas or coal) and types of iron ore feeds (pellets or fine ores). The most common DRI processes are based on a shaft furnace, where the reduction of iron ore to sponge iron takes place in the presence of gaseous reductants. Steel made with the DRI-EAF route using natural gas as the reductant requires around 13 GJ of energy per tonne of steel, made up of 10 GJ of natural gas in the DRI and 3 GJ of electricity in the EAF (Somers, 2022).

Having described the main steel production routes, it should however be recognised that the distinction between primary and secondary steel is not clear cut. As noted, BOF in the integrated steelmaking route can use scrap steel as a coolant in the exothermic BOF process, where up to 30% of the charge can be steel scrap. The steel scrap fed into EAFs in the secondary route can also be 'sweetened' with a charge of pig iron from the BF-BOF route to improve the quality of the resulting steel.

Global mix of crude steel production technologies

The breakdown of these main production methods on a regional basis is shown in Figure 11, where the mix varies significantly by region. The decarbonisation pathway for steel producers in North America, where high volumes of scrap have driven growth in EAF capacity, will look different from the pathway in markets such as Europe and China, where primary steel production through the BF-BOF route represents a larger share of production. In other locations with readily available and low-cost natural gas, such as the Middle East, DRI-EAF technology typically plays a larger role.



Note: DRI-produced iron is used in both BF and EAF routes and was equal to 106 Mt in 2020.

Figure 11 Global steel production by country/region in 2020 (MPP, 2021a)

4.4.2 Steel plant age

BF and DRI furnaces are the primary sources of CO_2 emissions from iron and steel industry assets and are also amongst the longest-lived and most capital-intensive assets. They also tend to be the installations around which investment decisions for the plant as a whole are based. The average lifetime of these assets is typically around 40 years, although there are examples where BF installations have operated for several decades longer than this, with several rounds of refurbishments (IEA, 2020b).

After each 20 to 25-year period of operation, a BF will need to have its internal refractory lining replaced. During operation, this lining is subjected to temperatures in excess of 1400–1500°C, where corrosive compounds present in the slag and molten iron eventually cause degradation. The initial installation cost of a blast furnace is around $200–300 million per Mt capacity, with the relining cost typically around half this figure. This significant level of additional investment to renew the life of the furnace must be considered in the context of several competing outlets for capital expenditure, including greenfield investments in a new location.

For example, some individual BFs will come to the end of their current operating campaign life of some 20–25 years requiring realignments before 2030. In Australia, emerging 'green steel' technologies, whilst promising, are not considered ready for large-scale implementation in this timeframe (BlueScope, 2021). If it is assessed that a reline is likely to be the most technically feasible and economically attractive option for an individual steelmaker, other emission reduction measures will need to be employed while longer-term breakthrough low-emission technologies are developed.

Assuming a typical lifetime of 40 years, alongside an interim investment cycle of 25 years, it is possible to assemble the regional average age profile of the existing fleet of blast furnaces and DRI furnaces (*see* Figure 12). The weighted global average age of these regional assets is about 13 years for blast furnaces and 14 years for DRI furnaces. Coal injection blast furnaces tend to be a little younger at 13 years, whereas gas injection installations average around 16 years old. For coal and gas-based DRI furnaces, the figures are 13 years and 14 years respectively. Underlying these global figures is considerable regional differentiation. China accounts for over 50% of all ironmaking capacity and its relatively young blast furnace fleet age of around 12 years is the main factor explaining the youth of the global fleet overall. Its coal-based DRI furnaces are younger still, at typically eight years.

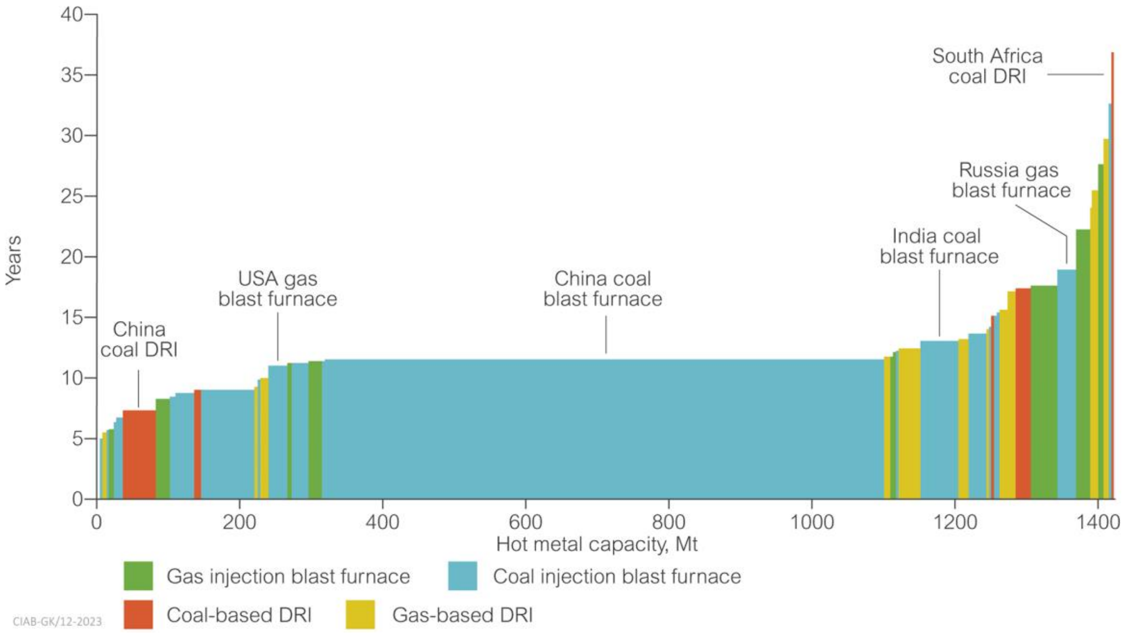


Figure 12 Average age of iron and steel sector assets by main production route (IEA, 2020b)

There is significant variation in average age across the other regions. At the younger end are refurbished European blast furnaces at less than 10 years and on the older side are coal-based DRI furnaces in South Africa at around 35 years. The other major producing regions at the younger end of the spectrum are the US gas injection blast furnaces at around 12 years and the Middle East gas-based DRI furnaces at around 10 years. In India and Japan, coal blast furnaces are similar in average age to those in China at 15 years and 14 years respectively.

In the regions where industrial capacity is generally older, there is potential for early retirement, as the economic losses involved would be significantly lower. However, in those countries with younger assets, significantly China, greater emphasis is likely to be placed on retrofitting with more energy-efficient and less carbon-intensive technologies such as CCUS.

4.4.3 Process improvements

The energy intensity of state-of-the-art blast furnaces is already approaching the practical minimum energy requirement. As a long-established industrial process, the BF-BOF production system has optimised over the last 100 years with a 67% reduction in GHG emissions intensity already achieved over that timescale (Wang and others, 2021).

As noted earlier, steel production is an energy-intensive process and the drive to reduce costs further is significant given the recent increases in global energy prices. There is therefore pressure for the more inefficient of the global steel production fleet to be retired or updated. Improvements to steel plant could include operational efficiency, enhanced process control and predictive maintenance strategies, together with the implementation of best available technologies. Such measures could improve energy efficiency and contribute around 20% of cumulative emissions savings (IEA, 2020d).

One example is Hirsana, a process developed by Tata steel in the Netherlands under the ULCOS initiative (TATA Steel, 2020) as an alternative to the blast furnace process. In this process, the raw materials of iron and metallurgical coal can be used in powder form and directly converted into liquid pig iron. The process eliminates the stages of iron ore processing and coke production and could improve energy efficiency and reduce CO_2 emissions by more than 20%. The high concentration of CO_2 is also suited to CCUS, which means that efficiency and process improvement projects are likely to be used in combination with CCUS to achieve emissions that are close to NZE compliant (*see* Section 4.5.3 for further details). The pilot-scale Hisarna plant has a capacity of 60,000 t/y, and TATA Steel has announced plans for a larger-scale Hisarna pilot facility to be built at the Tata Steel site in Jamshedpur, India.

4.5 OPPORTUNITIES TO DECARBONISE STEEL

The main levers for the steel sector to decarbonise are discussed below. These include reducing demand, increasing the proportion of steel produced from recycled scrap materials and innovative technologies including CCUS and hydrogen fuel switch (DNV, 2022; Chen J and others, 2021; World Steel Association 2021; Bataille, 2019; IEA, 2022f).

The potential impact of this is shown in Figure 13, where emissions could reduce by over 90% relative to 2021 levels. In terms of the impact on fossil fuels, coal would still be a significant energy source accounting for around 14 EJ in 2050, equivalent to approximately 480 Mtce, as shown in Figure 14.

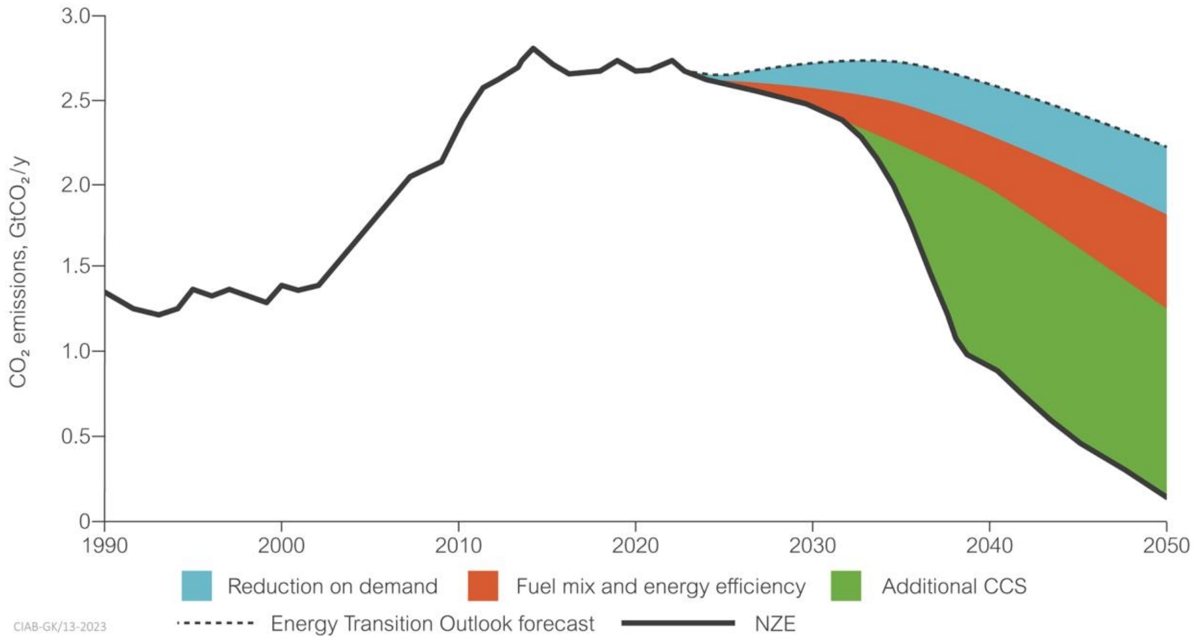


Figure 13 Iron and steel sector CO_2 emissions reduction for NZE by 2050 (DNV, 2022)

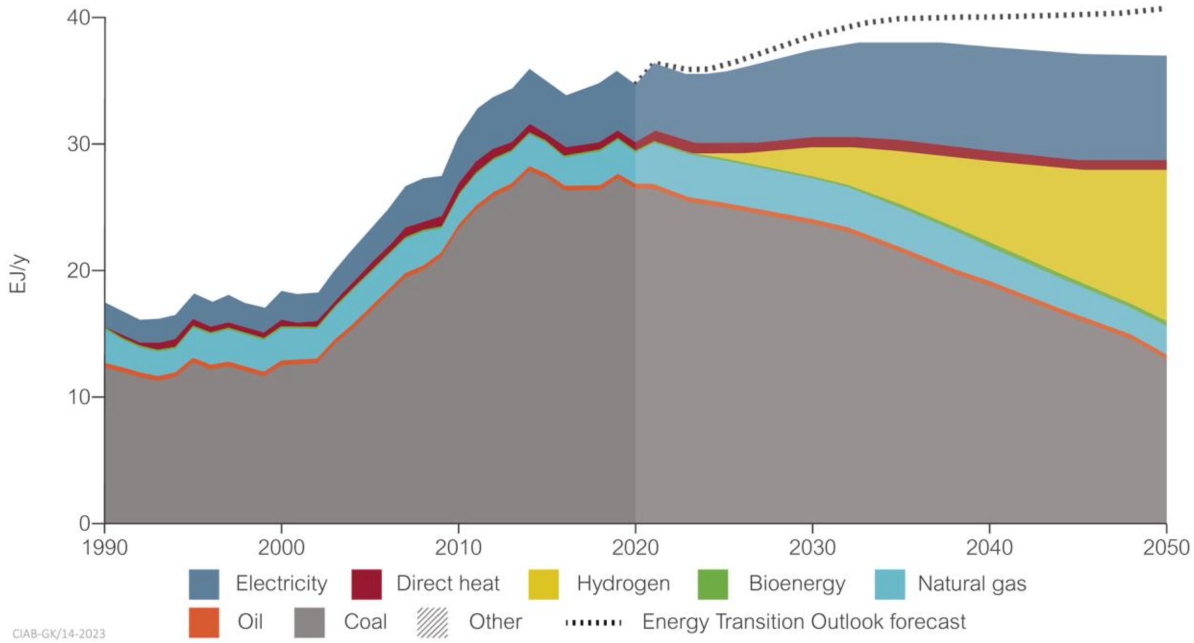


Figure 14 Iron and steel sector energy demand for NZE by 2050 (DNV, 2022)

4.5.1 Reduce demand

It is essential to assess how total demand for steel could be reduced and whether a greater proportion of demand could be met through secondary steel production from scrap steel, which is less carbon-intensive than primary production.

Under a business-as-usual scenario, where steel consumption patterns and product life cycles stay relatively consistent, crude steel demand will likely be 30–60% higher in 2050 than the current levels. Much of this growth will be in low-income and emerging economies. In India for example, demand is expected to reach 440 Mt/y by 2050 from around 120 Mt/y in 2021, more than offsetting declining demand in China, Europe, Japan, and South Korea. Certain segments of steel demand will increase rapidly to support the required expansion of energy-related infrastructure in the NZE, notably renewable electricity generation and transport infrastructure. The additional infrastructure required for these two segments by 2050 relative to today alone contributes roughly 10% of steel demand in 2050. Coordinated cross-sector strategies, including changes in transport and building renovation, as well as other changes in design, manufacturing methods, construction practices and consumer behaviour, more than offset this increase. Such changes could reduce global demand for steel in 2050 to around 12% higher than current levels (IEA, 2021a).

Material efficiency strategies could lead to greater emissions savings by reducing demand in the first place. It is less emissions-intensive to avoid producing a tonne of steel altogether than to produce it and later have it available as scrap for secondary production. Some of this change can be driven by the steelmakers themselves, such as through improved metallurgy, but many of the strategies to reduce demand require collaboration with downstream industries or significant behavioural change in society. Demand side reduction could be based on the following approaches:

Productivity of use strategies to increase the utilisation and lifetime of steel in use:

- a shared, service-oriented, and increasingly electric, mobility system;
- shared buildings, especially as virtual work and commerce models persist post the Covid-19 pandemic; and
- more durable product design to extend product lifetimes.

Material efficiency strategies to decrease the amount of crude steel needed per product by decreasing steel losses in fabrication and using less steel in each end use:

- lightweight vehicles;
- substitution of steel for other materials and increased efficiency in building construction;
- 3D printing and powder metallurgy; and
- designing products and processes to minimise fabrication scrap.

4.5.2 Increase scrap recycling – secondary steel production

Recycling scrap steel as an input material for steel production reduces **emissions** as it eliminates the need to undertake emission-intensive mining practices for iron ore. Also, when processed through EAF, both emissions and energy consumption fall by around 75% compared with the BF-BOF route. Emissions are set to fall further as the electricity used to power an EAF continues to shift towards low-carbon and renewable sources.

SCRAP STEEL

Scrap is a term used to describe steel that has reached the end of its useful life, known as 'post-consumer scrap' or it has been generated during the manufacture of steel products, known as 'pre-consumer scrap'.

Due to its inherent magnetism, steel is very easy to separate and recycle, making steel the most recycled material in the world.

Making greater use of recycled steel and replacing older BF-BOF plants with EAF plants reduces emissions as EAF production emits 0.4 tCO_2/t of crude steel, compared with the BF-BOF process which emits 1.7–1.8 tCO_2/t of crude steel, and DRI which emits 2.5 tCO_2/t.

Total recycled steel usage (both pre- and post-consumer scrap) is around 650 Mt/y, compared to a total crude steel production volume of 1950 Mt/y, with comparable amounts of scrap used in both the primary and secondary route steel production routes. In 2020, the global end-of-life or post-consumer scrap steel usage reached close to 463 Mt and is forecast to increase to as high as 900 Mt/y by 2050 (World Steel Association, 2021), as shown in Figure 15 .

There is considerable global variation in the amount of scrap steel used in steel production, primarily due to the age of steel stock including buildings currently erected and cars on the road. Steel in the average building has a lifecycle of 43 years, vehicles typically last around 19 years, while machinery and consumer goods have lifetimes of 22 years and 10 years respectively. In countries such as China, the installed steel stock is much younger than in countries that experienced earlier economic growth. Scrap steel, as a result, only accounts for 25% of the country's crude steel production. In India, which is in an earlier stage of economic growth, the proportion is below 20%. Whilst in China and India the available scrap steel will start to increase as more consumer goods, vehicles and buildings reach their end of life, the same issue will be faced by other countries in earlier stages of economic growth.

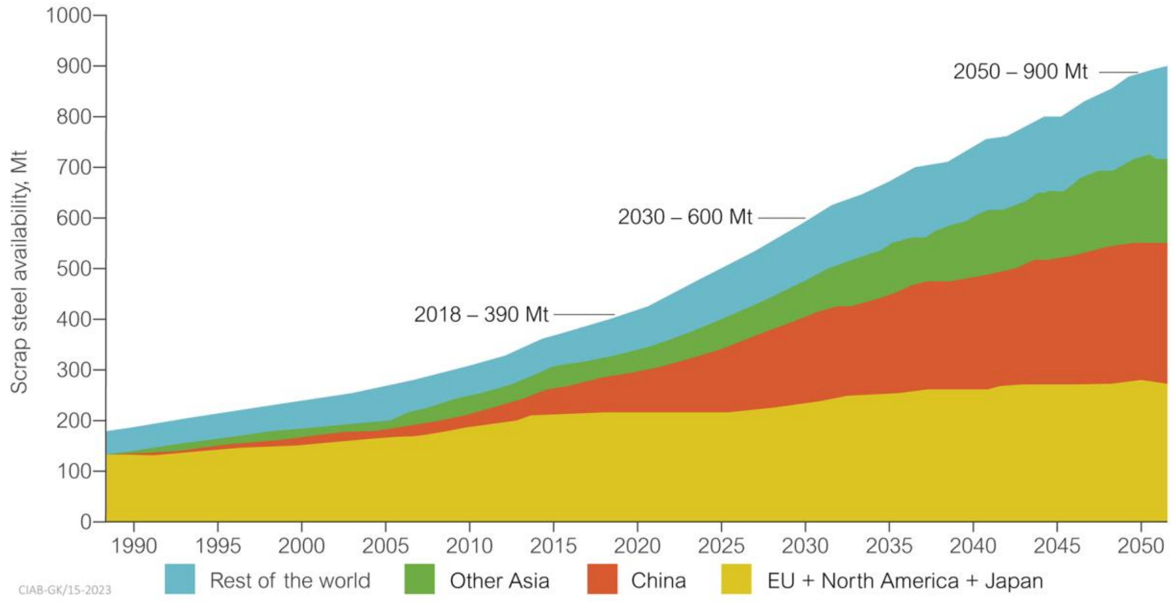


Figure 15 End of scrap life availability (World Steel Association, 2021)

An increase in the proportion of recycled steel will require the following:

Material recirculation strategies to increase the collection of end-of-life steel and improve recycling

- design for end-of-life and reuse;
- better systems for collecting and separating end-of-life steel through logistics and metallurgy; and
- better differentiating of scrap streams by composition, especially copper content, to reduce contamination and downgrading of steel.

Based on a projection of maximised levels of both reduced demand and increased recycling of scrap, this could lead to global steel demand reducing by up to 40% in 2050 compared with a business-as-usual projection. The scrap steel share of steel production would increase up to 70%, as lower steel demand and greater scrap recirculation combine to reduce iron ore consumption by 75% (MPP, 2021a). Scope 3 emissions associated with iron ore and coal mining would also decline, with further associated environmental benefits to air quality and resource use.

However, limits to the quantity and quality of available scrap mean that decarbonising primary steel production remains critical to a net zero future. A key approach, certainly in China in the medium term, will be to introduce low emissions technologies into the BF-BOF process. This is because EAF can only fully decarbonise steel production where the electricity used is from low carbon sources. Due to the volume of steel produced, grid electricity would need to be used which in the near to medium term will be coal-dominated in this region. In addition, DRI which is often used to supplement scrap steel to increase the quality of the steel produced uses predominantly natural gas as the fuel source, which is not cost-competitive in China.

4.5.3 Innovative technologies

According to analysis by the IEA (2021a), the majority of the emissions reduction required in the iron and steel sector to achieve NZE targets after 2030 will come from innovative technologies. This includes hydrogen-based DRI and iron ore electrolysis as well as CCUS-based technologies. For the CCUS-based technologies, examples include smelting reduction, natural gas-based DRI technologies and innovative blast furnace retrofit arrangements in regions with a young fleet plant age and with access to low cost fossil fuels and accessible CO_2 storage. The share of coal in the energy use for iron and steel production will inevitably reduce, perhaps to as low as 22% by 2050, but it will be used to a large extent with CCUS to be consistent with NZE requirements (IEA, 2021a).

A portfolio of these technologies is shown in Table 10, where around 17 potential technology families are foreseen consisting of technologies which are considered transitional to NZE, as well as those considered consistent with NZE (MPP, 2021a). This analysis is based on the assumption of 90% carbon capture, which is a low value, as shown in Section 2.5.2. CCUS based on post-combustion CO_2 capture typically aims for a 90–95% capture level and a fossil fuel power or heavy industrial plant could be made effectively CO_2 neutral by capturing 99.7% of the CO_2 (Feron and others, 2019). Specific examples of technologies include HIrsana, Oxyfuel top gas recycled blast furnace with CCUS, Finex, COURSE50 (2021), Hybrit (Åhman and others, 2018) and Salcos, which have all been described previously by the ICSC (Baruya, 2020; Kelsall and Baruya, 2022).

A further input source on technology development is the Green Steel Tracker which gathers public announcements on low-carbon investments in the steel industry. This database is a collaboration between research and non-governmental organisations and is hosted by the Leadership Group for Industry Transition (Vogl and others, 2021). The database includes at least 25 publicly announced projects developing various breakthrough iron and steelmaking technologies, with the majority concentrated in Europe.

TABLE 10 STEEL PRODUCTION TECHNOLOGY DESCRIPTION (MPP, 2021A)

Technology	NZE technology consistent	Year of commercial availability (TRL8 or higher)	Technology overview
Average blast furnace-basic oxygen furnace (BF-BOF)	No	2020	Feed consisting of iron ore and coke is prepared via pelletising and sintering, integrated with coke ovens. Feed is fed into a blast furnace, which undergoes a set of reactions ending in stripping iron ore of oxygen, thus producing molten iron (hot metal). Hot metal (HM) is purified in a BOF using pure oxygen, which reacts with carbon and ore impurities, generating heat. Scrap steel is used as a coolant in the process and could also improve the economics of the process. Business case assumes a ~16.5% scrap ratio and 195 kg pulverised coal injection (PCI)/t HM.

Best available technology blast furnace-basic oxygen furnace (BAT BF-BOF)	No	2020	Business case represents BF-BOF route with several improvements to its operations, including increased PCI ratio (230 kg/t HM), scrap ratio (30%), general heating efficiency gain (10%), and top gas recycling (TGR), allowing a reduction of solid carbon input to the blast furnace by ~15%.
Best available technology blast furnace-basic oxygen furnace (BAT BF-BOF) with CCUS	Yes	2027	BAT BF-BOF route in which CO and H_2 from the blast furnace is used for production of methanol/ ethanol instead of being reutilised in the BF-BOF. The CO_2 sink is assumed to be sufficiently long-term to provide carbon credits due to either circulation of carbon in the economy or use in products with a long lifetime. PCI is assumed to be fully replaced with carbon-dense plastic waste (polyolefins). Remaining CO_2 emissions from all major parts of the process are captured using post-combustion amine-based CCS solution. Heating (3.6 GJ/tCO_2) required for regeneration of sorbent is assumed to be supplied with electricity. Capture efficiency is assumed to be 90%, constant across the analysed period.
Best available technology blast furnace-basic oxygen furnace (BAT BF-BOF) with CCS	Yes	2027	BAT BF-BOF route in which CO_2 from all major parts of the process is captured using post-combustion amine-based CCS solution. Heating (3.6 GJ/tCO_2) required for regeneration of sorbent is assumed to be supplied with electricity. Capture efficiency is assumed to be 90%, constant across the analysed period.
Best available technology blast furnace-basic oxygen furnace (BAT BF-BOF) with biomass PCI	No	2020	BAT BF-BOF route in which pre-treated biomass replaces coal injection into the blast furnace. Wood charcoal is assumed as the reference (Brooks and others, 2022; Rio Tinto, 2021).
Best available technology blast furnace-basic oxygen furnace (BAT BF-BOF) with H_2 injection	No	2025	BAT BF-BOF route in which part of the injected coal is replaced with low carbon hydrogen. It is assumed that hydrogen replaces 120 kg coal/t HM (out of total 230 kg coal/t HM) due to endothermic nature of iron reduction with hydrogen, which may disturb the blast furnace temperature profile and render it inoperable.
Electric arc furnace (EAF)	Yes	2020	Dominant steel recycling technology in which scrap steel is melted in an arc furnace using electric current. Preheating is assumed not to require natural gas, but finishing and casting assumed to require natural gas for temperature control. Power consumption in EAF is assumed to be ~1.9 GJ electricity/t liquid steel.
DRI-EAF	No	2020	Steelmaking process replacing coal as carbon source with natural gas in shaft furnace rather than blast furnace. Assumed ~10 GJ/t DRI (shaft furnace consumption) and 16.5% scrap ratio.
DRI-EAF with CCUS	Yes	2020	DRI-EAF route in which CO_2 emissions from shaft furnace and natural gas combustion are captured using post-combustion amine-based CCS solution. Heating (3.6 GJ/tCO_2) required for regeneration of sorbent is assumed to be supplied with electricity. Capture efficiency assumed to be 90%, constant across the analysed period.

DRI-EAF with 100% low carbon H_2	Yes	2028	DRI-EAF route in which natural gas is replaced with low carbon hydrogen as reductant. Since the reaction of hydrogen with iron ore is endothermic, additional heating of the shaft furnace is required, along with preheating of hydrogen feed. All additional heating requirements are assumed to be met with electric heating. Hydrogen consumption is assumed to be 63 kg/t iron, which is ~17% higher than theoretical requirement for reduction of hematite (54 kgH_2/tFe) due to presence of impurities in ore, eg silica. Scrap ratio assumption is the same as in reference DRI-EAF business case (16.5%).
DRI-EAF with 50% biomethane	No	2020	DRI-EAF route in which natural gas used across the plant is blended in equal proportions with biomethane.
DRI-melt-BOF	No	2026	Combination of DRI shaft furnace with Basic Oxygen Furnace. DRI is made using natural gas, similar to the DRI-EAF route, then hot sponge iron is fed into the melter where it is melted using natural gas combustion. Liquid sponge iron is fed into BOF where it undergoes oxygen treatment similar to BF-BOF route. Given presence of melter and carbon content in sponge iron, it is assumed that scrap ratio can be as high as in case of BAT BF-BOF route (30%).
DRI-melt-BOF with 100% low carbon H_2	Yes	2028	DRI-BOF route in which natural gas in shaft furnace is replaced with hydrogen. Since the reaction of hydrogen with iron ore is endothermic, additional heating of the shaft furnace is required, along with preheating of hydrogen feed. All additional heating requirements are assumed to be met with electric heating. Hydrogen consumption is assumed to be 63 kg/t iron, which is ~17% higher than theoretical requirement for reduction of hematite (54 kgH_2/tFe) due to presence of impurities in ore, ie, silica. Since there is no carbon in the sponge iron coming from Hydrogen DRI process, there is less heat generated during oxygen treatment in BOF. Hence scrap ratio is assumed to be the same as in DRI-EAF route (16.5%). In addition, heating in melter is assumed to come from electricity.
DRI-melt-BOF with CCS	Yes	2028	DRI-BOF route in which CO_2 emissions resulting from all major processes are assumed to be captured using post-combustion amine-based CCS solution. Heating (3.6 GJ/tCO_2) required for regeneration of sorbent is assumed to be supplied with electricity. Capture efficiency assumed to be 90%, constant across the analysed period. Heating in the melter is assumed to come from electricity.
Electrolyser-EAF	Yes	2035	Molten Ore Electrolysis process in which iron is made via direct electrolysis of molten iron ore or a high-temperature (>1550°C) solution of it, similar to aluminium smelting (*see* Section 6). Molten iron is fed into EAF and a small amount of metallurgical coal (or pre-treated biomass) is added to supply carbon required to turn iron into steel. Power consumption in electrolyser is assumed to be ~13 GJ/t iron.

Electrolyser-winning EAF	Yes	2035	Direct iron ore electrolysis process in which iron ore particles are suspended in aqueous alkaline solution in ~110°C. Current passing through the solution breaks down ore into oxygen and iron, which crystallises on cathode. Iron is fed into EAF where small amount of metallurgical coal (or pre-treated biomass) is added to supply carbon required to turn iron into steel. Power consumption in electrolyser is assumed to be ~12 GJ/t iron.
Smelting reduction	No	2028	Type of process in which liquid hot metal is produced from iron ore without coke. Business case is based on HIsarna, a type of smelting reduction in which iron ore fines are injected at the top of Cyclone Converter Furnace along with pure oxygen, while coal powder is supplied at the bottom. The process reduces iron ore into liquid pig iron without coke production and iron ore agglomeration steps. Pig iron is fed into BOF where it undergoes oxygen treatment similar to BF-BOF route. Coal consumption is assumed to be 12.7 GJ/t pig iron, scrap ratio is assumed to be similar to BAT BF-BOF (30%). BOF gases are assumed to be utilised on-site to generate a small amount of electricity (majority is supplied from grid).
Smelting reduction with CCS	Yes	2028	Smelting reduction process that takes advantage of the fact that CO_2 emissions from Cyclone Converter Furnace exit as concentrated stream (85–95% CO_2) which facilitates carbon capture. CCS technique used in the modelling is cryogenic distillation in which the CO_2-rich stream is liquefied and split into main constituents via distillation – it is assumed to consume ~2.2 GJ electricity/t captured CO_2.

A potential share of these technology families to achieve NZE is shown in Figure 16, which was based on a Technology Moratorium (Tech Moratorium) scenario as one of two scenarios modelled (MPP, 2021a).

TECH MORATORIUM (MPP, 2021A)

The Tech Moratorium scenario confines investments to NZE consistent technologies from 2030 onwards to reach net zero. Steel assets switch to whichever technology offers the lowest total cost of ownership at each major investment decision. In the absence of measures to incentivise their adoption in the 2020s, lower-emissions technologies are initially only built where they can compete on cost with the conventional steelmaking process. From 2030 onwards, however, it is assumed that steel manufacturers will not be able to reinvest in high emission technologies. With industry average relining cycles of 20 years for steel assets, this 2030 cut-off date ensures that no assets must be prematurely shut down for the industry to achieve NZE by 2050. This scenario could be realised in various forms, including government regulation on environmental standards for new plants, privately driven finance conditions, or industry initiatives that encourage the phaseout of high-carbon investments.

In this analysis, after 2030, existing iron and steel infrastructure is maintained where possible while transitioning to NZE compatible technologies, as these upgrades minimise capital and operating expenditure. For example, existing BOF infrastructure can be coupled with less emissions-intensive ironmaking technologies, such as smelting reduction or DRI, as an alternative to the conventional blast furnace ironmaking process.

Steel production technologies utilising CCUS account for 45% of primary steel production in 2050. This would equate to around 650 MtCO_2/y by 2050 (MPP, 2021a). Slightly higher levels are foreseen in the IEA's NZE analysis where CCUS would account for 53% of primary steel production requiring 670 MtCO_2/y capture by 2050 (IEA, 2021a). As noted earlier in this sub-section, higher capture levels could allow CCUS-based technologies to play an even larger potential role in moving to NZE. A range of technologies based on CCUS, including HIsarna, Top Gas, COURSE50 (2021) and Finex, will become commercially available and could be deployed in certain geographic regions such as Asia to significantly decarbonise steel production whilst continuing to use coal (Kelsall and Baruya, 2022).

In addition, natural gas is gradually replaced with hydrogen in DRI-EAF and DRI-Melt-BOF technologies as low-carbon hydrogen prices become competitive in favourable locations, accounting for around 40% of primary steel production in 2050 (IIMA, 2018). This low emissions hydrogen can be produced by water electrolysis, natural gas reforming with CCUS or coal gasification with CCUS (Kelsall, 2021).

In regions with access to low-cost, low-emissions electricity, electrolyser-based technologies coupled with EAFs may become a cost-competitive route for steel production once the technology matures, ultimately scaling to provide the remaining 15% of the 2050 primary steel technology mix. Finally, the role of scrap-based production via EAF grows as large volumes of end-of-life scrap, particularly from China, become available.

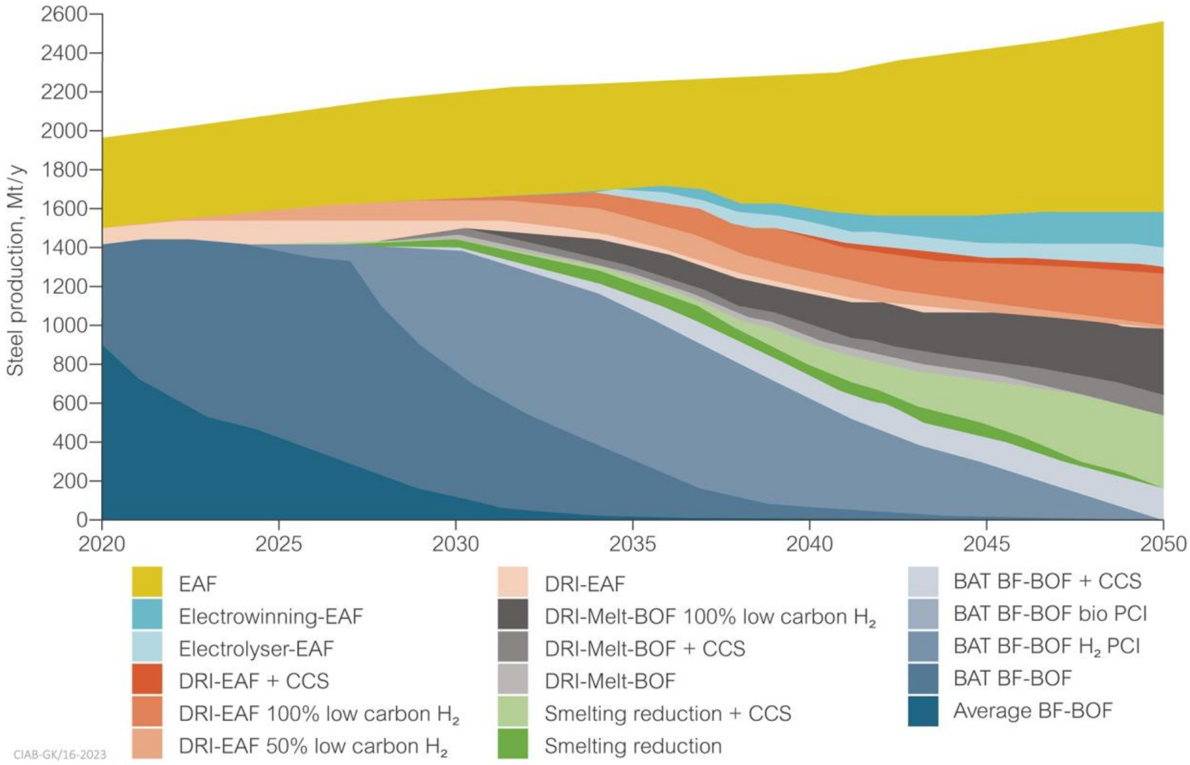


Figure 16 Technology routes to achieve net zero emissions (MPP, 2021a)

4.5.4 Cost

Steel production is cost intensive with a new BF-BOF integrated steel plant using best available technology costing around $1.4 billion in Capex per million tonnes of steel capacity. While retrofits to existing assets require about a quarter of the capital expenditure of building new plants, the steel sector will need an average $31 billion in investment annually to meet growing steel demand over the next 30 years and maintain the existing sites, even in the absence of a major transformation. Transitioning global steel assets to net zero compatible technologies requires an additional $6 billion annually, equivalent to $200 billion in total by 2050.

However, the investment in enabling infrastructure such as CO_2 pipelines, hydrogen infrastructure, and zero-carbon electricity production is likely to be significantly higher than the additional cost of the steel assets themselves. For example, delivering sufficient zero-carbon electricity to meet the needs of the steel sector, including the generation of the necessary volumes of low-carbon hydrogen, is estimated to require around $2000 billion in cumulative investment up to 2050.

In terms of the cost of steel, this would increase the average cost of steelmaking to approaching 500 $/t steel by 2050, representing an increase of less than 15% (*see* Figure 17a and Figure 17b) (MPP, 2021a).

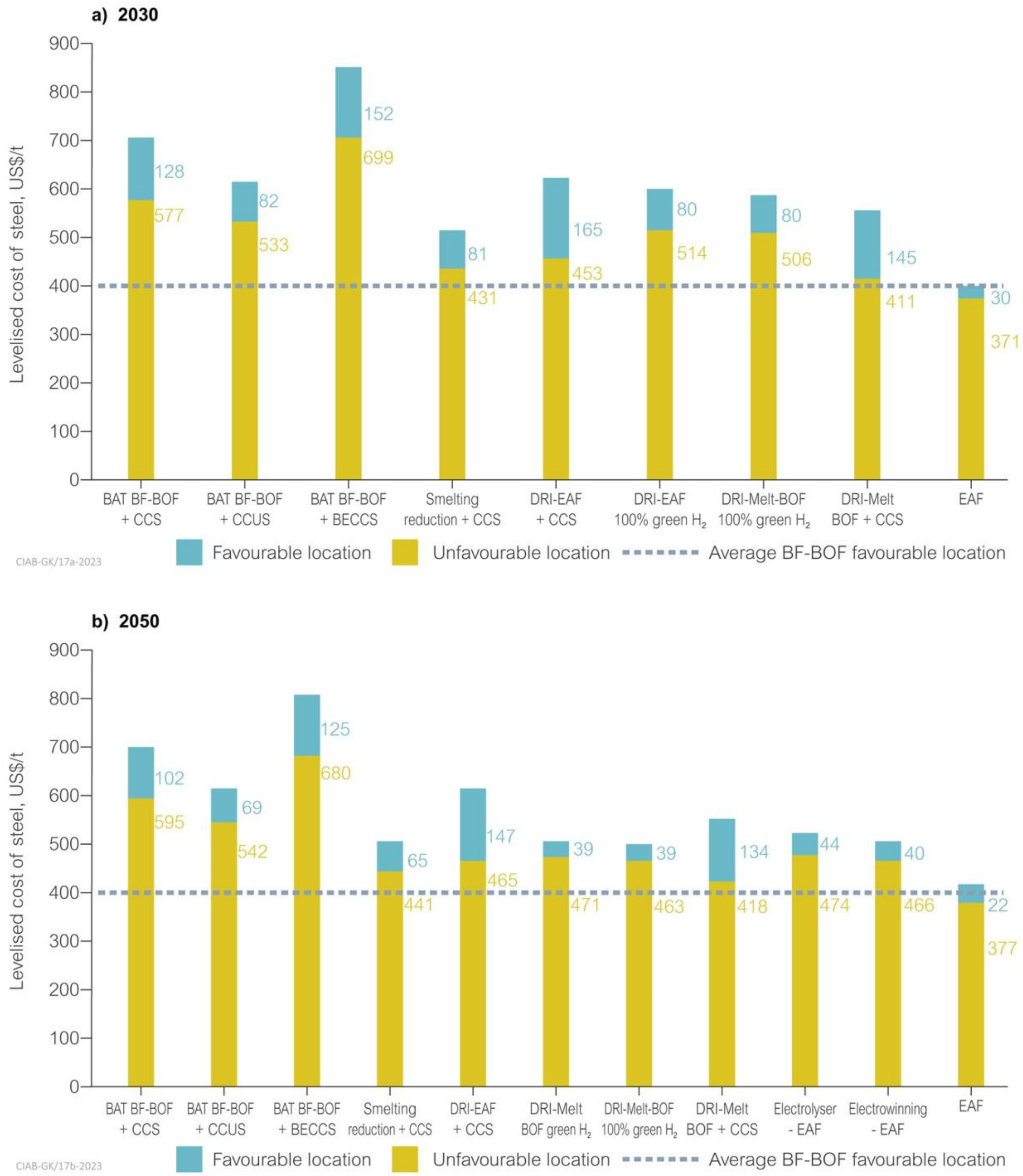


Figure 17 Levelised cost of near zero emissions technologies (MPPa, 2021)

5 CEMENT

5.1 KEY MESSAGES

Concrete is the most widely used material in the world after water. Like steel it is a nation-building material fundamental in shaping the world:

- Global production of cement was 4.4 Gt in 2021, an increase of over 20% in the past 10 years.
- About 80% of cement is used as a binder in concrete. Concrete is crucial for infrastructure and low-carbon power systems to support clean energy development. It will also play a significant role in improving the energy efficiency of buildings.
- Various projections have cement demand increasing by 12–23% by 2050.

Asia dominates global cement production with China, India and Vietnam being the top three cement producing countries. China alone produced 2.5 Gt of cement, representing almost 58% of global production in 2021. China accounts for over 50% of all kiln capacity and its relatively young fleet age of around 13 years is the main factor explaining why the global cement kiln fleet is less than 15 years old. After decades of significant investment in infrastructure, China's demand is forecast to plateau or reduce. However, demand will increase in industrialising/urbanising areas including Africa, India, SE Asia, Turkey and Latin America.

Coal currently meets over 60% of the energy demand of the sector. This share will inevitably reduce but will remain at a significant level, as high as 50% by 2050 representing 3.5 EJ, equivalent to around 120 Mtce. This is partly because fossil fuels will remain the main source of high temperature process heat input, particularly coal in the Asian context.

The large volume of cement produced means that emissions are high at around 3 $GtCO_2$/y, representing 7% of global CO_2 emissions. The industry needs to drive towards net zero emissions by 2050 by reducing its direct process emissions (Scope 1), produced during the calcination of limestone to form clinker and representing the bulk of industry emissions, together with its thermal emissions (Scope 1 and 2) associated with the use of fuels such as coal and gas to generate the heat (1400–1500°C) required to form clinker, and with electricity.

Achieving 2030 mid-term targets while ensuring industry resilience – The international cement industry aims to achieve at least a 20% reduction in emissions by 2030, the same level of reduction achieved over the past three decades. It will do this by fossil fuel reductions and increased use of alternative fuels, improved efficiency in concrete production, improved efficiency in the design of concrete projects, better use of concrete during construction, and recycling.

Efficiency improvements to cement plant could include operational efficiency, enhanced process control and predictive maintenance strategies, together with the implementation of best available technologies to bring the cement plant fleet to the standards of the most modern plant.

Given the ongoing role for coal, by 2030 the capability and commercial case for CCUS will need to be established and CCUS infrastructure must begin to be rolled out.

Industry investment requirements to ensure resilience – A zero growth rate is targeted by the IEA to achieve NZE by 2050. The main levers to decarbonise the cement sector are reducing demand, fuel switching opportunities, decreasing the clinker to cement ratio, replacement of clinker with alternative cementitious materials, together with the recognition of the long-term carbonation properties of concrete.

Ultimately, the industry's remaining process emissions will need to be captured, re-used where possible or stored. Deployment of CCUS at scale will therefore be required from 2030 to ensure the industry can achieve net zero by 2050. This, in conjunction with biomass and cement products incorporating CO_2, could result in the future delivery of carbon negative concrete.

Significant investment, collaboration and focused innovation will be required to increase clinker substitution and unleash new technologies to decarbonise, such as clean hydrogen and kiln electrification from 2040.

5.2 THE ROLE OF CEMENT

About 80% of cement is used as a binder in concrete, which is a mixture of sand and gravel, cement and water. Cement is typically composed of several materials, dominated by around 65% cement clinker together with around 30% supplementary cementitious materials (Fennell and others, 2021; GCCSI, 2020). Concrete is the most utilised man-made substance globally and second only in use to water. For example, it is used to build much infrastructure including buildings, roads, railways, ports and dams. It is also a vital material to build low-carbon power systems such as wind turbines and CCUS systems. These are important for quality of life and social and economic well-being. Raw materials for concrete are abundant and available in most parts of the world.

The leading role for concrete is due to its affordability, strength, durability and resilience to fire, floods and pests, together with its flexibility to be able to produce complex and large structures. There is no other material available currently, or for the foreseeable future, that is available in the quantities necessary to meet the demand for buildings and infrastructure.

Cement production involves the decomposition of carbonated minerals, typically limestone (calcium carbonate), as a raw material releasing CO_2 as part of the production process. This inherent CO_2 represents about 60-65% of the direct CO_2 emissions generated in the process, or around 55% of the total CO_2 emissions, with the remainder of CO_2 emissions being due primarily to combustion of fuels for process heat (*see* Table 11).

TABLE 11 SOURCES OF CO_2 EMISSIONS FROM THE CEMENT MANUFACTURE PROCESS (TYRER, 2021)

Process step	CO_2 emissions, %	Comment
Calcination	55	Determined from the composition of the clinker
Fuel for process heat	38	Coal, petcoke, waste-derived fuels
Primary electricity	7	All site electricity including grinding, blending and conveyors

The cement sector is the third-largest industrial energy consumer, comprising 7% of global industrial energy use. Globally, CO_2 emissions from the cement industry have increased from 0.86 Gt in 1990 to 2.46 Gt in 2019, an increase of approaching 200%, due largely to the developing countries in Asia, the Middle East and Africa. As an illustration, the Middle East and Africa, including mostly developing or underdeveloped countries, represented 0.07 Gt CO_2 in 1990 (8.4% of the total), compared with 0.26 Gt (10.4% of the total) CO_2 in 2019, a 4.5% average annual growth rate during 1990–2019 (Chen C and others, 2022).

The cement manufacture process is relatively efficient in terms of CO_2 emissions. A typical cement plant uses around 3.3–3.5 GJ/t of clinker (a mixture of calcium silicates) produced, compared with a thermodynamic minimum energy of 2.8 GJ/t (IEA/CSI, 2018). This compares favourably with the energy demand of manufacturing steel, aluminium and chemicals. However, due to the large volumes of cement produced, emissions are high, with total emissions at around 3 GtCO_2/y, representing 7% of global CO_2 emissions.

5.3 GLOBAL SCALE OF CEMENT PRODUCTION

Global production of cement reached 4.4 Gt in 2021 (Statista, 2022b), which has grown by over 20% in the last 10 years (*see* Figure 18).

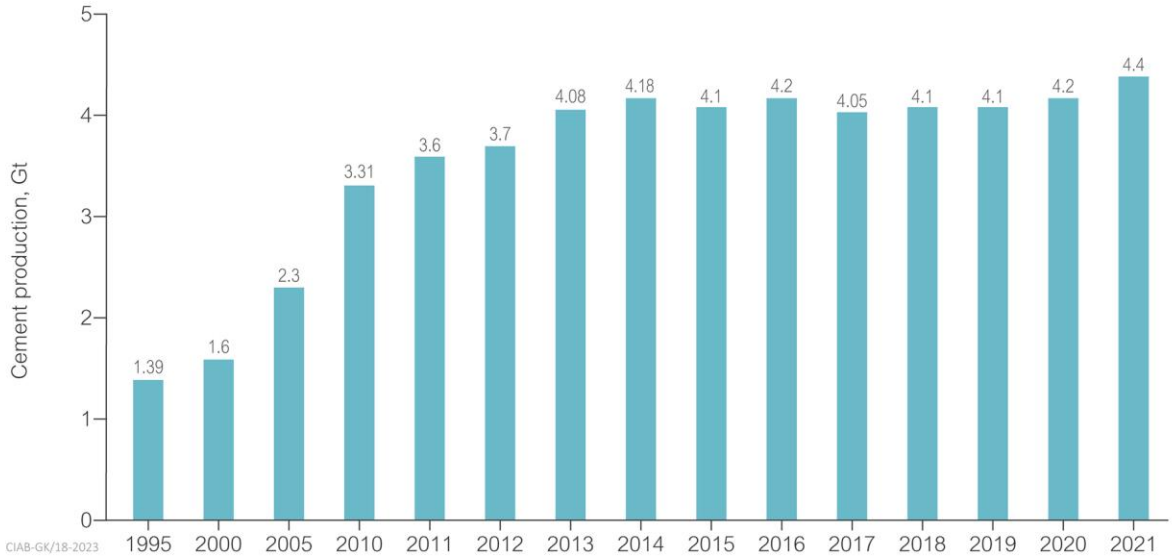


Figure 18 Global cement production from 1995-2021, Gt (Statista, 2022b)

Societal needs and urbanisation are expected to increase cement demand by 12-23% by 2050 (IEA/CSI, 2018) and perhaps as high as 45% to 6 Gt based on a business-as-usual growth forecast (WEF, 2022). This increase in demand will need to be limited to achieve NZE targets; the IEA targets a near zero growth rate to achieve NZE by 2050 (IEA, 2021a). As a bulky, relatively low value commodity, cement is typically uneconomic to transport more than around 250 km from the site of production to the point of use. As such, it is typically produced and consumed in the same region, although there are opportunities for international trade (Hodgson, 2022).

5.3.1 Regional breakdown

China is the largest cement producer by far, with a global share of 57%, followed by India at 8% (*see* Table 12). In 2021, China had 875 cement plants, the highest overall number of plants worldwide, comprising 818 integrated plants and 57 grinding plants. India was next with 159 integrated plants and 95 grinding plants giving 254 plants in total (Statista, 2022c; WCA, 2021).

TABLE 12 TOP 15 CEMENT PRODUCING COUNTRIES (STATISTA, 2022C)

Country	Global rank (2021)	Cement, Mt/y (2021)	Global share, %
China	1	2500	56.8
India	2	330	7.5
Vietnam	3	100	2.3
USA	4	92	2.1
Turkey	5	76	1.7
Indonesia	6	66	1.5
Brazil	7	65	1.5
Iran	8	62	1.4
Russia	9	56	1.3
Saudi Arabia	10	55	1.3
Japan	11	52	1.3
Mexico	12	50	1.1%
South Korea	13	48	1.1
Egypt	14	40	0.9
Other countries		810	18.4
Global total		**4400**	

There is significant regional variation in the forecast demand to 2050. Following recent decades of significant investment in infrastructure in China, where the majority of global concrete is consumed, demand is forecast to plateau or reduce, with demand increasing in countries and regions including Africa, India, Indonesia, Thailand, Turkey and Latin America (Hodgson, 2022). Here, the increase in population coupled with increasing levels of urbanisation increases the need for infrastructure and hence the quantities of concrete and cement required.

5.4 CEMENT PRODUCTION PROCESSES

5.4.1 Current processes

Cement manufacture is a three-stage process including raw materials preparation, clinker production and clinker grinding with other components to produce cement. Figure 19 represents a typical state-of-the-art cement manufacturing process. Limestone, or other calcium carbonate source feedstock is first ground with clay and other minor components and fed to the preheater, where the raw feed contacts the hot kiln exhaust gases counter-currently, in a series of vertical cyclones, being heated up to approximately 900°C. At the bottom of the preheater, in the calciner, limestone decomposes to form calcium oxide, releasing CO_2. This is referred to as process emissions because they are inherent to the clinker manufacturing process. Most of the CO_2 is normally released from the limestone raw material in the preheater and the calciner. The pre-calcined stream is then heated up to around 1450°C in the rotary kiln, where the calcination is completed and the calcium oxide reacts with silica, alumina, and iron oxides, to form the calcium silicates, aluminates, and ferrites that constitute the clinker. At the kiln outlet, the clinker is rapidly cooled in the grate cooler using incoming combustion air. Finally, the cooled clinker is mixed with gypsum and ground into a powder, to produce Portland cement, or with additional components such as slag, fly ash, or limestone that can substitute part of the clinker, to produce blended cement (*see* Section 5.5.4). Each cement product has its own unique composition of raw materials, which depends strongly on the location of the cement plant and the availability of the raw materials (Plaza and others, 2020).

There are two basic types of clinker production, depending on the moisture content of raw materials, referred to as 'wet' and 'dry' and there are also different kiln designs. The wet process consumes more energy than the dry process, as the moisture needs to be evaporated. Overall, the cement-making process is complex, requiring control of the chemical formulation and involving multiple steps that require specialised equipment (IEA/CSI, 2018).

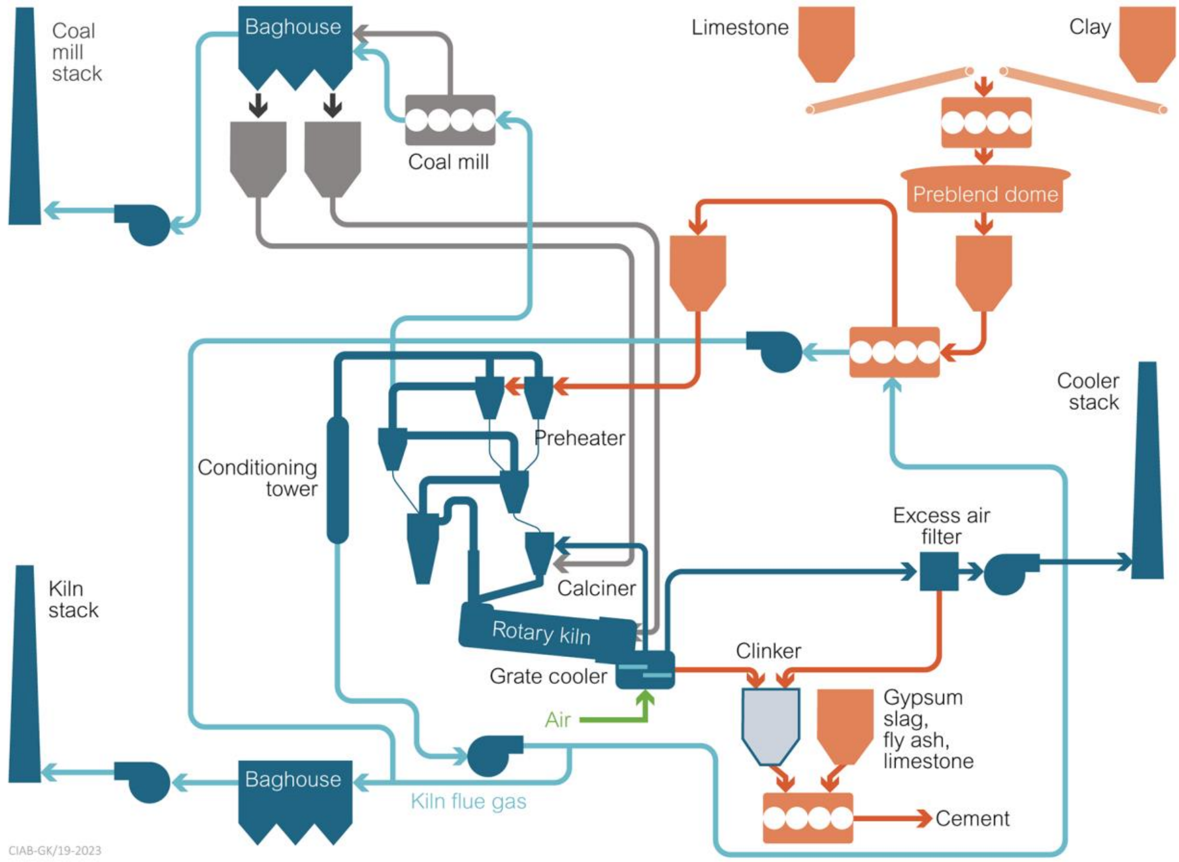


Figure 19 State-of-the-art cement manufacturing process (Plaza and others, 2020)

5.4.2 Cement plant life

Cement kilns are the primary sources of CO_2 emissions from cement industry assets and are also among the longest-lived and most capital-intensive assets. Assuming a typical lifetime of 40 years (IEA, 2020b), it is possible to assemble the regional average age profile of the existing fleet of cement kilns (*see* Figure 20). Around 85% of the global cement kiln fleet is less than 15 years old. China accounts for over 50% of all cement kiln capacity and its relatively young fleet age of around 13 years is the main factor explaining the youth of the global fleet overall. Kilns in India, the Middle East and Africa are also relatively young.

In general, this reflects the increasing population growth and urbanisation in recent years where new cement kilns have been built to support this development.

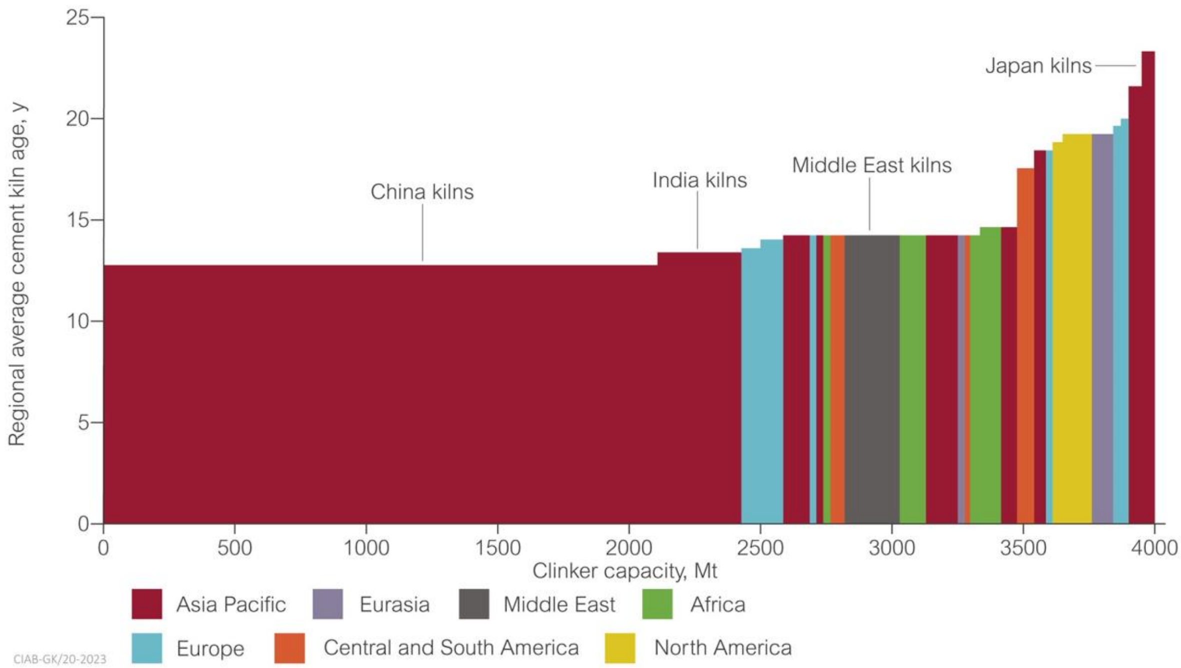


Figure 20 Average age of cement sector kilns (IEA, 2020b)

The options for moving these plants towards achieving NZE targets are broadly as discussed earlier for steel plant assets (*see* Section 4.4.2). However, because of the higher process-related CO_2 emissions from cement plant, the options to achieve significant emissions reductions rely more heavily on CCUS. As a result, a high proportion of cement production in 2050 is projected to be performed in plants that already exist today and where retrofitting cement plant with more energy-efficient and less carbon-intensive technologies will be the favourable abatement option (DNV, 2022). This is particularly the case in those countries with youngest cement plant assets, notably China.

5.4.3 Process improvements

The thermal energy and electricity intensities of cement production have gradually declined over the past decades as dry-process kilns, including staged preheaters and pre-calciners have replaced wet-process kilns and as more efficient grinding equipment is deployed. In recent years, however, the global thermal energy intensity of clinker is estimated to have remained relatively flat at around 3.4-3.5 GJ/t, indicating that efforts to decarbonise cement manufacture through process improvements have plateaued (IEA, 2022d). This compares with the theoretical minimum energy required of 2.8 GJ/t of clinker, which is close to being achieved in the most modern cement plant at around 3 GJ/t (Tyrer, 2021). There are therefore opportunities for incremental improvement in cement production efficiency, as some basic operating and maintenance best practices and objectives have been identified to bring the cement plant fleet to the standards of the most modern plant (IFC, 2017):

- ***Reduce kiln exit gas losses*** by installing devices to provide better conductive heat transfer from the gases to the materials, particularly in the kiln; operating at optimal oxygen levels (control combustion air input); optimising burner flame shape and temperature; and improving or adding additional preheater capacity;
- ***Reduce moisture absorption*** opportunities for raw materials and fuels, avoiding the need to evaporate adsorbed water;
- ***Reduce dust in exhaust gases*** by minimising gas turbulence. Dust carries energy away from the kiln where it is captured in dust collectors, with the dust recycled into the raw material and fed into the kiln where it is reheated;
- ***Lower clinker discharge temperature***, retaining more heat within the pyro-processing system;
- ***Lower clinker cooler stack temperature*** by recycling excess cooler air and reclaiming cooler air by using it for drying raw materials and fuels or for preheating fuels or air;
- ***Reduce kiln radiation losses*** by using the correct mix and more energy-efficient refractories to control kiln temperature zones;
- ***Reduce cold air leakage*** by closing unnecessary openings, providing more energy-efficient seals and operating with as high a primary air temperature as possible; and
- ***Optimise kiln operations*** to avoid upsets.

A further opportunity is to consider solutions for thermal energy utilisation to integrate waste heat recovery systems in cement plants. These can contribute to enhancing the overall energy efficiency of cement manufacturing while also helping to lower emissions deriving from electrical energy consumption. As noted earlier, the cement manufacturing process uses a high amount of thermal energy in the kiln and raw material preheating and burning processes. A huge part of this heat energy, up to 45%, is lost primarily as waste gases. This waste heat can become the resource used to feed a waste heat recovery system and generate electricity, where the commonly employed technologies in a cement plant are a conventional steam Rankine cycle or an organic Rankine cycle, capable of utilising lower-grade waste heat (World Cement, 2022).

5.5 OPPORTUNITIES TO DECARBONISE CEMENT

The main levers to decarbonise the cement sector are discussed below and CCUS is the most significant. Additional levers include reducing demand, fuel switching opportunities, decreasing the clinker-to-cement ratio, replacing clinker with alternative cementitious materials, together with recognition of the long-term carbonation properties of concrete (DNV, 2022; Beläid, 2022; Bataille, 2019; IEA, 2022f).

The international cement industry aims to reduce its emissions by at least 20% by 2030, the same level as achieved over the three decades to 2020 (GCCA, 2021).

The potential impact of this is shown in Figure 21, where emissions could reduce by over 85% relative to 2021 levels, from 2.6 $GtCO_2$ to around 0.4 $GtCO_2$. In terms of the impact on fossil fuels, coal would still be a significant energy source accounting for around 3.5 EJ in 2050, equivalent to approximately 120 Mtce, as shown in Figure 22. This is in part because fossil fuels will remain the main source of high temperature process heat input, particularly coal in the Asian context. No alternative production technologies exist that combine technological maturity and economic cost-competitiveness, whilst ensuring similar output quality as the conventional cement manufacture process, described in Section 5.4.1 (Nilsson and others, 2020), which utilises coal.

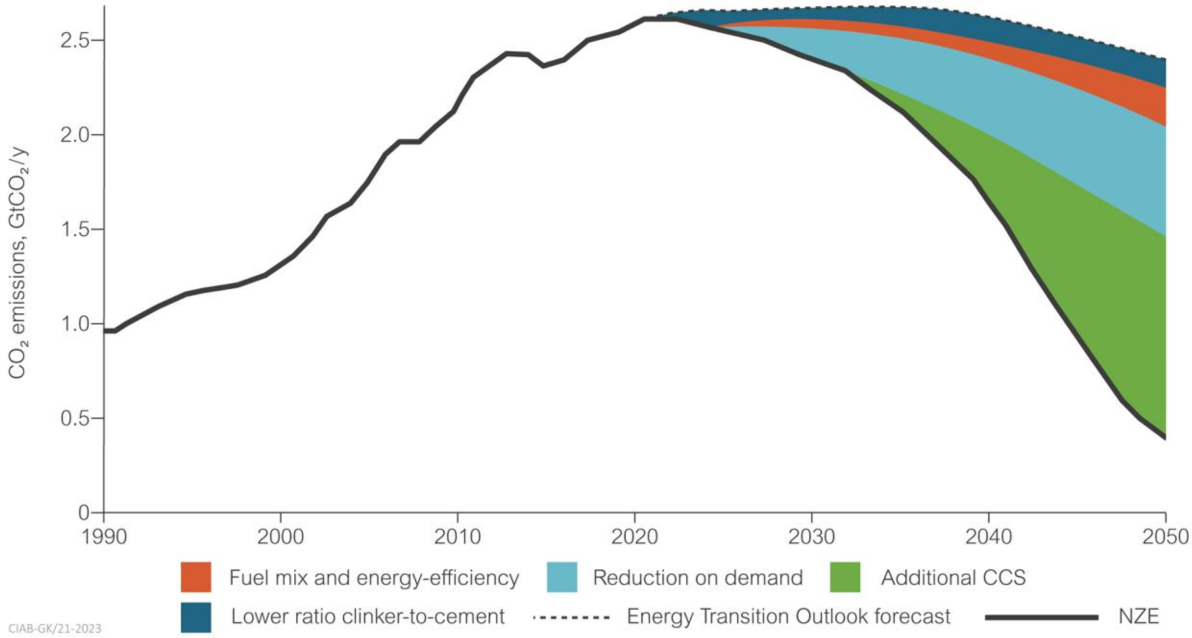


Figure 21 Cement sector CO_2 emissions reduction for NZE by 2050 (DNV, 2022)

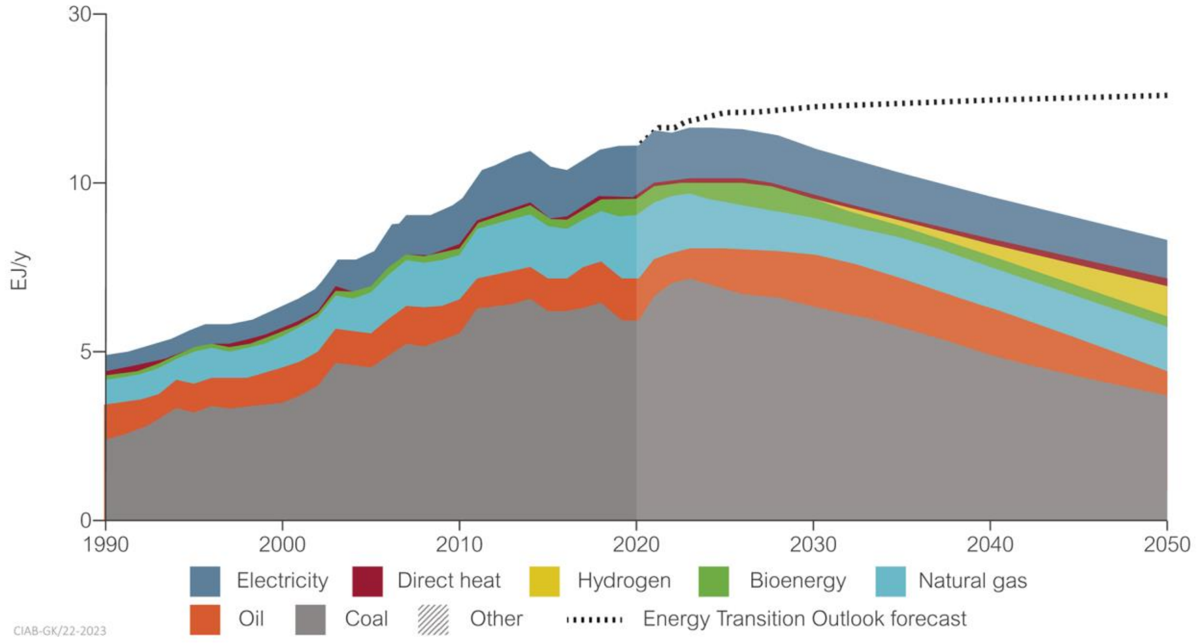


Figure 22 Cement sector energy demand for NZE by 2050 (DNV, 2022)

Deeper levels of decarbonisation to fully achieve NZE targets within the cement sector by 2050 are also predicted to be possible (GCCA, 2021), as shown in Figure 23. This shows the importance of a portfolio approach, with CCUS again making the most significant contribution.

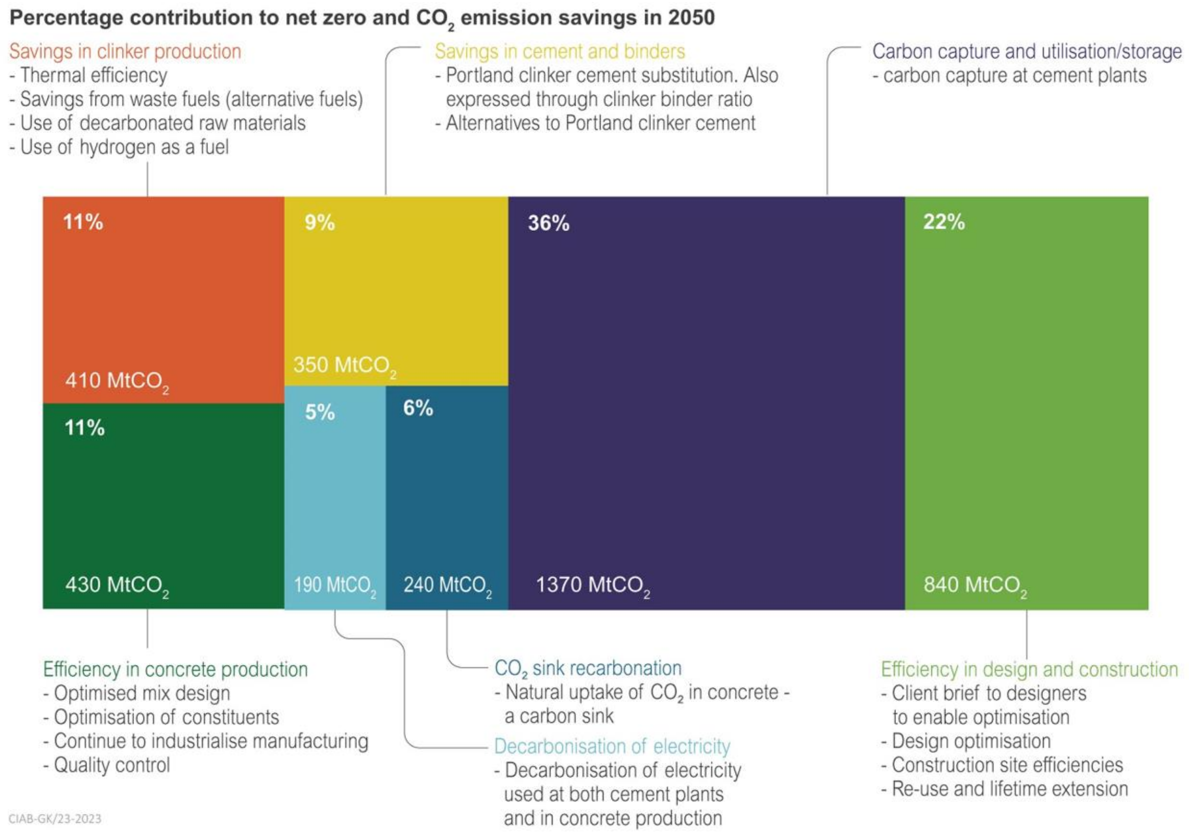


Figure 23 Actions to achieve net zero emissions in the cement sector by 2050 (GCCA, 2021)

5.5.1 CCUS

Significant deployment of CCUS is required to achieve NZE compliant emissions by 2050; this is the main and most effective abatement solution, due to the unavoidable process CO_2 emissions. It could provide around 1370 MtCO_2/y reduction by 2050, capturing 76% of the cement industry's direct emissions (DNV, 2022; IEA 2021a).

In the cement industry, CO_2 capture can be accomplished using post-combustion, oxyfuel combustion and chemical looping technologies (Rolfe and others, 2018). Pre-combustion capture technologies tend to have limited mitigation potential in the cement sector, as they address the energy-related CO_2 emissions only, rather than the process-related emissions. Such technologies may however find application in new cement plants integrated with gasification technologies to produce syngas or hydrogen fuel. A third type of CO_2 capture technology with great promise for the cement sector is direct capture. An excellent review of the state of the art of these groups of carbon capture technologies in the cement sector is provided by Plaza and others (2020).

The status of CCUS technology has been discussed earlier in this report (*see* Chapter 2), where cement-related projects remain in the early phases of deployment, with limited projects relating to coal in the pipeline. As noted by the IEA (2021a), a failure to develop CCUS for fossil fuels could delay or prevent the development of CCUS for process emissions from cement production and carbon removal technologies, making it much harder to achieve NZE by 2050. Examples of CCUS projects on a global basis relating to cement production are shown in Figure 24. Projects are concentrated in Europe, North America and, to a more limited extent, in Asia. The predominantly coal-fired Capital Cement project in Texas, USA was described in Section 2.4.2, selected other key projects are highlighted below. Whilst these projects in general do not relate directly to coal-fired applications, they develop and prove the technology families that could subsequently be utilised for coal-related cement plant.

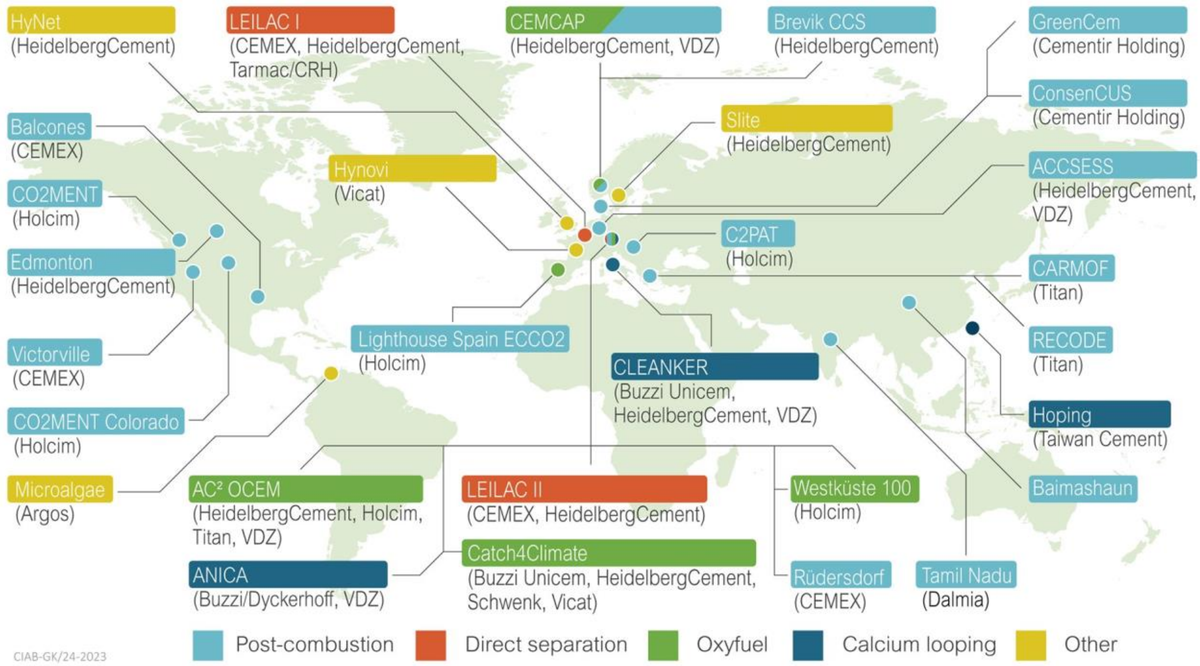


Figure 24 Selected CCUS-related projects in the cement sector (GCCA, 2021)

Lehigh Cement with CCUS study

Lehigh Cement, International CCS Knowledge Centre and Mitsubishi Heavy Industries America, part of the MHI group, have carried out a CCUS feasibility study for Lehigh Cement's plant in Edmonton, Alberta, Canada. The study assessed the viability of 90–95% CO_2 capture, equating to around 0.6 $MtCO_2$/y from the cement plant's flue gas (MHI, 2021). It used the amine-based post-combustion capture knowledge gained through the design, construction, operation, and subsequent enhancements/modifications of SaskPower Boundary Dam 3 CCUS Facility, together with the Shand CCS Feasibility Study (Int CCS KC, 2021).

Due to the similarities in flue gas composition, the expertise acquired at the Boundary Dam facility was adapted to the cement sector in the study. The Lehigh CCS Feasibility Study considered an engineering design that tailored the KM CDR Process owned by MHI, for integration with Lehigh's plant and output specifications, such as a flue gas pretreatment system and the carbon capture and compression process.

Norcem CCUS project

Norcem, a subsidiary of Heidelberg Cement, has assessed solutions to capture 0.4 $MtCO_2$/y from its cement plant in Brevik (Petroleum and Energy, 2016). Norcem aspires to achieve zero CO_2 emissions from its concrete products from a lifecycle perspective by 2030 through a combination of CCUS and fuel switching to biofuels. Norcem has identified amine-based post-combustion capture as the most suitable technology and has chosen Aker Solutions as its technology provider. Aker Solutions has conducted more than 8000 hours of testing on Norcem's flue gas with its mobile test unit. A key part of the development has been the optimal use of residual heat from the cement production process for use in the CCUS plant. This available heat was a main factor in sizing the facility at 0.4 $MtCO_2$/y, corresponding to around 50% of the cement plant's total CO_2 emissions. The CCUS facility is targeted to be operational by 2024, with the technology potentially applicable to cement plant globally.

Heidelberg Cement has also been developing an oxyfuel-based cement kiln. Oxyfuel-based systems could increase the CO_2 concentration in the flue gas to over 70%, making downstream CO_2 capture more energy efficient, significantly reducing the flue gas volume to be treated and hence reducing capital costs (GCCSI, 2020).

Project LEILAC – (Low emissions intensity lime and cement)

Calix, a company based in Australia, is trialling its calcination reactor technology in the LEILAC project. This will achieve a fourfold scale-up of its earlier pilot plant testing. In conventional rotary kilns for cement and lime manufacture, combustion air is used to burn fuels at very high temperatures. The nitrogen left over from this process mixes with the CO_2 produced through calcination. Nitrogen lowers the purity of CO_2, increasing the energy and cost involved in carbon capture. Calix's technology separates the CO_2 produced through calcination from the heat source by using a separate fired heater or electrical heating source. CO_2 produced from the calcination process is therefore kept separate from any air or nitrogen from the combustion used to provide process heat. As a result, the inherent process-related CO_2 from the Calix calciner is dry, capture-ready and close to 100% concentration.

To achieve full decarbonisation, this approach would require the Calix reactor to be heated using low-emission electricity, fired with biofuels or low emissions hydrogen to provide low emissions heat. An advantage of the system is that the Calix calciner could be retrofitted into conventional cement plant making it a potential technology to contribute to the decarbonisation of Asia's existing cement plant fleet (GCCSI, 2020).

5.5.2 Demand side reduction

Around 840 $GtCO_2$ emissions reduction could be achieved through measures aimed at reducing the demand for cement (GCCA, 2021; DNV, 2022).

These measures include would include:

- Designing buildings to have a longer service life.
- Increasing the proportion of old building stock that is refurbished rather than replaced. Modern concrete buildings typically come to the end of their useful life because no further use can be found for them, rather than because the concrete failed due to age. Due to the flexibility and adaptability of concrete, seemingly redundant structures can often be stripped back to their core and then rebuilt to new, contemporary specifications.
- Optimising building design to use less cement in concrete to better match the required strength. Building and infrastructure design should ensure that the reduction of CO_2 emissions becomes a design parameter in addition to the current parameters of quality, cost,

speed and specific project client requirements. Building designers and architects, with the support of clients, can achieve CO_2 emission reductions through the choice of concrete floor slab geometry and system, the choice of concrete column spacing and the optimisation of concrete strength/element size/reinforcement percentage. This could be achieved while still obtaining the performance benefits of concrete construction. Infrastructure projects offer analogous opportunities.

- If a building does have to be demolished, it can provide a source of recycled aggregate and recycled concrete aggregate, used in granular subbases, soil-cement, and in new concrete.

5.5.3 Fuel switching

Fuel switching, to replace some or all of the input coal with alternative sources of fuel is one option to reduce CO_2 emissions in cement production. When combined with cement process efficiency improvements and the use of decarbonated raw materials, this could account for around 410 $MtCO_2$/y reduction by 2050 (GCCA, 2021). Here, the use of sustainable raw materials can replace some of the limestone in the kiln to reduce the total process emissions from the conversion of limestone to lime. By definition, the decarbonated materials, such as the fine material from recycled concrete, do not emit CO_2 when heated because they have already had the CO_2 removed. Globally this is forecast to provide a 2% reduction in total emissions from the sector.

In terms of alternative fuels to generate high temperature process heat, this would include fuels derived from non-primary materials, that is, waste or by-products and can be biomass, fossil fuel or mixed fossil and biomass. There are current examples of cement kilns operating with 100% alternative fuels which demonstrates the potential of this lever (GCCA, 2021).

The cement industry is already a well-established consumer of non-recyclable waste-derived alternative fuels from a range of sources, for example, municipal, agricultural, chemical and food production. The extremely high temperatures and residence times reached in cement kilns ensure they are managed in a safe and environmentally sound way. Supply chain logistics and infrastructure, permitting and waste policy to reduce or eliminate waste to landfill are required to support the industry in increasing its use of alternative fuels. On average globally, alternative fuel use is forecast to increase from the current 6% to around 43% by 2050. However, as noted by DNV, fuel switching can be a challenge given potential issues of compatibility with dry kiln designs (DNV, 2022). This will tend to mean that coal remains the main heat source for clinker production, although hydrogen will have an important role in certain regions. Hydrogen could provide around 10–12% of energy demand to achieve NZE by 2050, being used mainly in Europe, the Middle East and Northern Africa.

5.5.4 Clinker-to-cement ratio and supplementary cementitious materials (SCMs)

A further technique to reduce CO_2 emissions is to replace clinker with other materials such as slag, limestone powder, fly ash, silica dust and natural pozzolans. The type of replacement material depends on availability (quantity, price and transport possibilities), and therefore is influenced by the geographic location of the cement plant.

Certain materials, especially fly ash and ground granulated blast furnace slag, develop good hydraulic cementitious properties by reacting with lime, such as that released by the hydration of Portland cement. Where readily available, these supplementary cementitious materials (SCMs) are increasingly used as partial substitutes for Portland cement in many concrete applications and are components of finished blended cements (USGS, 2022).

At the cement or concrete plant, fly ash, ground granulated blast-furnace slag (GGBS), ground limestone and other materials can be added to deliver concretes with reduced CO_2 emissions but still the required performance. In some applications the concrete performance is enhanced. As an example, using one tonne of GGBS manufactured from a by-product of the iron-making industry can reduce the embodied CO_2 of concrete by around 900 kg, compared to using one tonne of Portland cement, and also increases its durability. It can replace 70% or more of Portland cement (Hanson, nd; GCCA, 2021).

In the coming decades, there will be increased use of ground limestone and the introduction of calcined clays to both compensate for the reduced supply of fly ash and GGBS, and further reduce the clinker binder ratio. Calcined clays rely on clay deposits that are geographically spread and sufficiently abundant to meet projected demand. To assist with this, modelling has been employed to calculate the CO_2 emissions of several low-carbon binders and SCMs for alternative materials that are not currently used in cement production and therefore have no data available (Nie and others, 2022).

While the availability of materials can be a limitation on the clinker/binder ratio, client acceptance is a current barrier to fully exploiting this lever in some developed and emerging economies.

On average globally, the clinker/binder factor is currently 0.63. It is projected to reduce to 0.52–0.60 by 2050 (IEA, 2018, 2021a; GCCA, 2021). As shown in Figure 23, reducing the clinker content of cement and using SCMs could contribute to around 350 $MtCO_2$/y reduction in the cement sector by 2050.

5.5.5 Carbonation

Finally, carbonation is a natural process of CO_2 uptake by concrete. Carbonation of concrete is the chemical reaction between CO_2 in the air and calcium hydroxide and hydrated calcium silicate in the concrete to give mainly carbonates. The formation of carbonates in these chemical reactions leads to a permanent sequestration of this CO_2.

This process has been well understood by engineers and has been incorporated into engineering standards for many years. It is now starting to be considered in carbon accounting, most recently the IPCC Sixth Assessment Report published in August 2021 (GCCA, 2021).

Calculations of CO_2 uptake in concrete are complex and include both chemical and physical processes. A simplified calculation method for estimating the annual uptake of CO_2 in existing concrete structures on a national basis is described by IVL (2021). This 'tier 1' calculation methodology permits a 20% value for carbonation to be adopted. This 20% value is applied to the theoretical maximum of 525 kgCO_2/t of clinker, giving a carbonation value of 105 kgCO_2/t of clinker. This is considered to be a lower-bound conservative value within the IVL methodology. Global carbonation is therefore forecast to provide a reduction of around 242 MtCO_2/y by 2050 (GCCA, 2021).

Additionally, capturing CO_2 in concrete that is produced from cement represents an innovative method of carbon capture and utilisation. In this process, the CO_2 gas from clinker production is captured in concrete while the concrete is setting. As an example, a joint venture between Korea Advanced Institute of Technology and Aramco CCU is developing a process to lock CO_2 into concrete using calcium metasilicate (Seo and others, 2018).

6 ALUMINIUM

6.1 KEY MESSAGES

Aluminium is the second most-used metal in the world by mass after steel. It is integral to several vital industries, including construction, transport and power transmission. This is due to its unique combination of properties (lightness, strength, durability, formability, recyclability and electrical/thermal conductivity). This means it will be an essential enabler of a low carbon future in these key industries.

Primary aluminium production in 2021 was 68 Mt/y and total aluminium production, including secondary production based on recycled aluminium, was about 100 Mt/y. Almost 80% of scrap aluminium is reused without losing quality, making it one of the most recycled materials. Recycled aluminium currently constitutes around 33% of aluminium demand and its production uses around 5% of the energy needed for primary aluminium production.

The aluminium sector emits approximately 2% of global greenhouse gas emissions, equivalent to around 1.1 $GtCO_2$/y. These are mainly Scope 1 and 2 emissions associated with process heat for alumina refining and Scope 2 emissions from purchased electricity for electrolytic aluminium smelting.

Globally, coal provides 57% of the aluminium smelting power and 52% of alumina refining fuel consumption. China dominates, producing 54% of alumina and 57% of primary aluminium. Coal provides around 75% of China's combined alumina/aluminium energy requirement. In Asia (excluding China) 97% of electricity used in aluminium production is self-generated, mainly from coal, gas or oil.

Achieving 2030 mid-term targets while ensuring industry resilience – The aluminium industry accepts it must reduce its Scope 1 and 2 emissions. However, many of the necessary technology solutions are currently under development while others do not yet exist.

As an industry, moving from a 1.1 $GtCO_{2-e}$ base to 250 Mt CO_{2-e} by 2050, while growing production by up to 80%, will require action from all participants in the value chain. There are three main routes to achieve this goal: electricity decarbonisation; direct emissions reduction and recycling; and improved resource efficiency (including by users). Secure access to competitively priced renewable electricity and increased investment in research, development and deployment of electrified processes, low emission hydrogen, inert anodes and CCUS are needed.

Industry investment requirements to ensure resilience – A significant investment of approximately $1 trillion is required to deliver the transition to a low-carbon primary aluminium sector. The majority of the investment is required in the electricity sector to supply low-carbon electricity. Additional funds will be needed to decarbonise the alumina sector and downstream users of aluminium products.

The main levers to achieve the necessary 95% decarbonisation in electricity related emissions and 50% in direct (process and thermal energy) emissions by 2050 are:

- transitioning to low-carbon power (which could deliver around 650 $MtCO_2$/y reduction);
- recycling more aluminium to maximise secondary production (perhaps a further 456 $MtCO_2$/y);
- maximising product design efficiency (a further 321 $MtCO_2$/y reduction) for example by extending building and automotive lifetimes; and
- deploying new technology to deliver NZE refineries and smelting facilities (some 232 $MtCO_2$/y). Here, new technology is required to decarbonise thermal energy in refineries, such as heat recovery and fuel switching, and low-carbon anodes and CCUS in smelters.

These measures would reduce coal usage through to 2050. However, due to the high dependence on coal in China and some other regions for electricity generation to power aluminium smelters and provide process heat for refineries, coal will remain in the energy mix at perhaps 50% of current levels. Here, CCUS retrofit to existing coal plant could be the preferred solution to produce low-carbon electricity.

6.2 THE ROLE OF ALUMINIUM

Aluminium is sometimes referred to as the 'green metal', due to its high specific strength, corrosion resistance and recyclability. As the second most-used metal in the world by mass behind steel, it is integral to several vital industries including construction, transport and power transmission. Roughly half of semi-finished aluminium products distributed worldwide were consumed by the transport and construction industries in 2020; construction corresponded to a quarter of the total demand for that year (Statista, 2022d).

Aluminium is the most abundant metal in the earth's crust comprising around 8% content. Due to its high reactivity, it is found as stable compounds, typically potassium aluminium sulphate, and aluminium oxide. Of these, bauxite is the most common raw material used to produce aluminium.

Almost 80% of scrap aluminium is reused without loss of quality, making it one of the most recycled materials. Recycled aluminium constitutes around 33% of aluminium demand currently and its production uses around 5% of the energy needed for primary aluminium production. Replacing primary aluminium with recycled aluminium is therefore key to reducing overall emissions from the aluminium industry.

Based on a 'business-as-usual' forecast within the International Aluminium Institute's 'global aluminium cycle' model, the demand for aluminium is anticipated to grow by around 80% by 2050 to 179 Mt/y, (MPP, 2022; IAI, 2021a), driven by:

- global population growth;
- increased urbanisation requiring new construction and expanded transportation;
- growth of the electric vehicle industry where aluminium is a lightweight material;
- expansion of the electrical grid, especially in developing countries;
- greater use in packaging of consumer goods to replace single-use plastics; and
- sustainable economy where aluminium is necessary for the construction of both conventional (coal, natural gas, nuclear) and renewable (solar, wind, energy storage) technologies. This is particularly true for solar photovoltaics where aluminium accounts for more than 85% of most solar PV components.

This increase will in part be achieved by using recycled scrap aluminium. However, it would require 88 Mt/y of primary aluminium production by 2050, assuming an increased recycling rate of perhaps 50% recycled aluminium content in final aluminium products by 2050. (WEF, 2020).

In terms of total emissions, the aluminium sector is currently responsible for approximately 2% of global emissions, equivalent to around 1.1 $GtCO_2/y$. This emission represents a 92% increase from 2005 and comprises Scope 1 (direct process emissions) of 29%, Scope 2 (electricity-related emissions) of 64% and Scope 3 (other) emissions of 7%. Around 90% of the aluminium industry's emissions relate to primary aluminium production, despite primary aluminium comprising around two-thirds of total aluminium production. Without efforts to curtail them, annual emissions could grow by as much as 90% by 2050 due to population growth and economic development (MPP, 2022).

6.3 GLOBAL SCALE OF ALUMINIUM PRODUCTION

In 2021, primary aluminium production was 68 Mt/y (Statista, 2022b), with total aluminium production, including secondary production based on recycled aluminium at almost 100 Mt/y.

There was a 160% increase in global demand for aluminium ingots between 2000 and 2020, illustrating the material's growing role. As noted above, this trend is set to continue, although for the industry to achieve NZE compliance by 2050, the increase in demand will need to be reduced (*see* Section 6.4.2 for further details).

6.3.1 Regional breakdown

The top five bauxite-producing nations in 2021 were Australia, China, Guinea, Brazil and India, with the top three countries responsible for over 72% of global bauxite production (*see* Table 13). The countries with the largest reserves are Guinea, Australia and Vietnam (USGS, 2021; Statista, 2022d). Vietnam does not feature significantly in the list of top alumina or aluminium-producing countries, but it does have significant bauxite reserves, estimated to be around 3.7 Gt (USGS 2021). This suggests that Vietnam could become a major alumina producer in the medium term as the country develops economically.

TABLE 13 BAUXITE MINING PRODUCTION BY COUNTRY (STATISTA, 2022D)

	Bauxite, Mt (2021)	Global share, %
Australia	110.0	28.2
China	86.0	22.1
Guinea	85.0	21.8
Brazil	32.0	8.2
India	22.0	5.6
Indonesia	18.0	4.6
Russia	6.2	1.6
Jamaica	5.8	1.5
Kazakhstan	5.2	1.3
Saudia Arabia	4.3	1.1
Vietnam	3.5	0.9
Others	12.0	3.1
Total	**390.0**	

In terms of the next stages of alumina extraction from bauxite and then primary aluminium production, China is the largest producer by far of both, as shown in Table 14 and Table 15. It accounted for 74 Mt of alumina and 39 Mt of primary aluminium in 2021, representing 54.3% and 57.4% of global production respectively (Statista, 2022d,e). India is the second largest producer of primary aluminium, together with Russia, producing 3.6 Mt in 2020, representing 5.5% of global production.

TABLE 14 TOP ALUMINA PRODUCING COUNTRIES (STATISTA, 2022E)

	Alumina, Mt (2021)	Global share, %
China	74.0	54.3
Australia	21.0	15.4
Brazil	11.0	8.1
India	6.8	5.0
Russia	3.1	2.3
Germany	1.9	1.4
Ireland	1.9	1.4
Saudi Arabia	1.8	1.3
Ukraine	1.7	1.2
Spain	1.6	1.2
Canada	1.5	1.1
Indonesia	1.5	1.1
Kazakhstan	1.5	1.1
Vietnam	1.4	1.0
Jamaica	1.2	0.9
USA	1.0	0.7
Guinea	0.4	0.3
Others	3.0	2.2
Total	**136.3**	

Coal as a source of electricity for the electrolytic aluminium smelting process and as process heat for the alumina refining process dominates in China, providing around 75% of the combined energy input. On a global basis, coal provides 57% (59 Mtce) of the aluminium smelting power and 52% (22 Mtce) of alumina refining fuel consumption (IAI, 2022). This is likely to continue in the short-medium term, certainly in China, requiring CCUS or cofiring with low-carbon fuels to move towards NZE. There will however be opportunities to switch to renewable energy sources. As an example, China Hongqiao Group, the largest global private aluminium manufacturing company, is relocating around 2 Mt/y of aluminium manufacturing capacity from Shandong in eastern China to Yunnan's Wenshan prefecture in the southwest to allow easier access to hydropower electricity (Daly, 2021).

TABLE 15 TOP 10 PRIMARY ALUMINIUM PRODUCTION BY COUNTRY (STATISTA, 2022F)

	Primary aluminium, Mt (2021)	Global share, %
China	39.0	57.4
India	3.9	5.7
Russia	3.7	5.4
Canada	3.1	4.6
UAE	2.6	3.8
Australia	1.6	2.4
Bahrain	1.5	2.2
Norway	1.4	2.1
USA	0.9	1.3
Iceland	0.9	1.3
Others	9.4	13.8
Total	**68.0**	

6.4 ALUMINA/ ALUMINIUM PRODUCTION PROCESS

6.4.1 Current refining process to produce alumina

Approximately 70% of global bauxite production is refined to alumina (Al_2O_3) through the Bayer chemical process, which is a wet chemical caustic leach method operated at 140–280°C and a pressure of approximately 3.5 MPa. The Bayer process is the most economic means of obtaining alumina from bauxite and comprises the following key steps (IAI, 2018a):

Milling

The bauxite is first washed and crushed, reducing the particle size and increasing the available surface area for the digestion stage. Lime together with caustic soda returned from the precipitation stage, often called 'spent liquor', are added at the mills to make a pumpable slurry.

Desilication

Bauxites that have high levels of silica go through a process to remove this impurity since silica can cause problems with scale formation and quality of the final product.

Digestion

A hot caustic soda (NaOH) solution is used to dissolve the aluminium-bearing minerals in the bauxite (gibbsite, böhmite and diaspore) to form a sodium aluminate supersaturated solution or 'pregnant liquor'.

$$\text{Gibbsite: } Al(OH)_3 + Na^+ + OH^- \rightarrow Al(OH)_4^- + Na^+$$

$$\text{Böhmite and Diaspore: } AlO(OH) + Na^+ + OH^- + H_2O \rightarrow Al(OH)_4^- + Na^+$$

Key operating conditions within the digester, including caustic concentration, temperature and pressure, are set according to the properties of the bauxite ore. Ores with a high gibbsite content can be processed at 140°C, while böhmitic bauxites require temperatures of between 200–280°C. The pressure is not important for the process as such but is defined by the steam saturation pressure of the process. At 240°C the pressure is approximately 3.5 MPa.

The slurry is then cooled in a series of flash tanks to around 106°C at atmospheric pressure and by flashing off steam. This steam is used to preheat the spent liquor. In some high-temperature digestion refineries, higher-quality bauxite (trihydrate) is injected into the flash train to boost production. This 'sweetening' process also reduces the energy usage per tonne of production.

Although higher temperatures are often theoretically advantageous, there are several potential disadvantages, including the possibility of oxides other than alumina dissolving into the caustic liquor.

Clarification/settling

The first stage of clarification is to separate the bauxite residue from the pregnant liquor via sedimentation, noting that the sodium aluminate remains in solution. Flocculants are added to assist the sedimentation process. The bauxite residue sinks to the bottom of the settling tanks, before being transferred to the washing tanks, where it undergoes a series of washing stages to recover the caustic soda, which can then be reused in the digestion process.

Further separation of the pregnant liquor from the bauxite residue is performed using a series of security filters. The security filters ensure that the final product is not contaminated with impurities present in the residue. Depending on the requirements of the residue storage facility, further thickening, filtration and/or neutralisation stages are employed prior to it being pumped to the bauxite residue disposal area.

Precipitation

In this stage, the alumina is recovered by crystallisation from the pregnant liquor, which is supersaturated in sodium aluminate. The crystallisation process is driven by progressive cooling of the pregnant liquor, resulting in the formation of small crystals of aluminium trihydroxite ($Al(OH)_3$), commonly known as 'hydrate', which then grow and agglomerate to form larger crystals. The precipitation reaction is the reverse of the gibbsite dissolution reaction in the digestion stage:

$$Al(OH)_4^- + Na+ \rightarrow Al(OH)_3 + Na^+ + OH^-$$

Evaporation

The spent liquor is heated through a series of heat exchangers and subsequently cooled in a series of flash tanks. The condensate formed in the heaters is re-used in the process, for instance as boiler feed water or for washing bauxite residue. The remaining caustic soda is washed and recycled back into the digestion process.

Classification

The gibbsite crystals formed in precipitation are classified into size ranges. This is normally done using cyclones or gravity classification tanks (a series of thickeners utilising the same principles as settlers/washers on the clarification stage). The coarse size crystals are destined for calcination after being separated from spent liquor using vacuum filtration, where the solids are washed with hot water.

The fine crystals, after being washed to remove organic impurities, are returned to the precipitation stage as fine seed to be agglomerated.

Calcination

The filter cake is fed into calciners and roasted at temperatures of up to 1100°C to drive off free moisture and chemically connected water, producing alumina solids. There are different calcination technologies in use, including gas suspension calciners, fluidised bed calciners and rotary kilns.

The following equation describes the calcination reaction:

$$2Al(OH)_3 \rightarrow Al_2O_3 + 3H_2O$$

6.4.2 Current primary aluminium production

Most of the resulting alumina produced from this refining process described above is then used as the feedstock for the Hall-Héroult electrolytic smelting process. The Hall-Héroult process was developed in 1886 and is the primary industrial method for smelting primary aluminium. A large direct electric current at typically 600 kA is passed through a molten mixture of cryolite (Na_3AlF_6), alumina and aluminium fluoride operated at 960-980°C. The current is fed into a line of electrolytic cells connected in series. Each cell, called a 'pot' is a large carbon-lined metal container, which is used as the negative electrode (cathode) in the cell. Typically, a cathode lasts between 1000 and 2500 days before needing replacement.

The smelting of aluminium takes the form of a reduction-oxidation reaction between the raw material, alumina, and carbon anodes, in which three electrons are provided to each aluminium ion to reduce it to its metal form, while the carbon atoms of the anodes are oxidised to form CO_2, as follows:

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2$$

Details of the electrochemical process are provided by Mandin and others (2009).

As a result, CO_2 emissions from this process are proportional to the production of aluminium. This electro-chemical process (electrolysis) requires electricity, carbon anodes and ancillary products, such as cryolite (sodium aluminium fluoride), and thermal energy to cast liquid metal into solid products. The molten aluminium sinks to the bottom of the cell, while the gaseous by-products evaporate to the top. The aluminium is then siphoned from the pot in a process called tapping and transported to dedicated alloying and/or casting operations.

6.4.3 Process improvements

The energy required by the Bayer Process is dependent on the quality of the raw material, with böhemitic or diasporic bauxites requiring higher temperature digestion, often associated with a higher fuel input (IAI, 2018b). Investments in cost-effective technology upgrades at existing facilities can improve the energy efficiency with no change in input material, as can 'sweetening' the feedstock with small quantities of higher quality bauxite. Such improvements, along with the addition of best available technology have driven an almost 10% improvement in global refining energy efficiency in the past five years. The average specific energy consumption is around 14.5 GJ/t of alumina, including electrical energy of around 150 kWh/t of alumina.

Cogeneration or CHP is increasingly employed in alumina refineries. While a significant capital investment is required to build a CHP plant, there can be benefits, both in terms of energy efficiency and as a valuable resource for local communities. The waste heat from the generator is captured and used to produce steam for the refining process. The CHP plant is sometimes designed to produce surplus electricity for export to local communities, a local customer or to the grid. In some instances, excess or lower quality steam can also be exported.

In terms of aluminium smelting, cell resistance is high due to ohmic electrolyte and gas bubble resistances, plus ohmic resistances in the anodes and cathodes. The anode-cathode-distance must be kept above a certain minimum distance to avoid the back reaction of aluminium with CO_2. Additionally, some heat loss is necessary to protect the side walls. Despite these technical challenges, the process can be fine-tuned to optimum levels by reducing the cell-specific energy consumption, together with eliminating the occurrence of anode effects. A natural step to save energy in the present electrolysis process would be to recover energy from the main heat loss sources of the cells, the cathode sidewalls and the anode gas exhaust systems (Banerjee and Ray, 2017). The growth in smelting capacity worldwide, with new facilities tending to be the most energy efficient, has seen a reduction in energy consumption of 10% per tonne of aluminium over the last 20 years.

Additional improvements in efficiency can be made at the aluminium fabrication stage, where reducing material losses in manufacturing, which are significant in the aluminium sector (approximately 15% of the global production output is scrap/wastage from the manufacturing process), can further increase the efficiency of production (MPP, 2022).

6.4.4 CO_2 emissions profile

The main CO_2 emitting process steps are shown in Figure 25. The aluminium smelting process is responsible for around 77% of the overall CO_2 emissions from the aluminium production chain, of which 64% on a sector-wide emissions basis are due to electricity usage. Around one-third of the aluminium industry is reliant on grid power for electricity, while two-thirds use dedicated power sources. It is the dedicated plants, most notably coal-fired power plants in China, that are driving emissions across the sector (WEF, 2020). The primary aluminium smelting process has a high energy intensity of 14.3 MWh/t aluminium as a global average. In total, Global Energy Monitor has identified 84 GW of coal power plants that generated electricity for aluminium plants in 2019, 82 GW of which were in China and India (Jones, 2020).

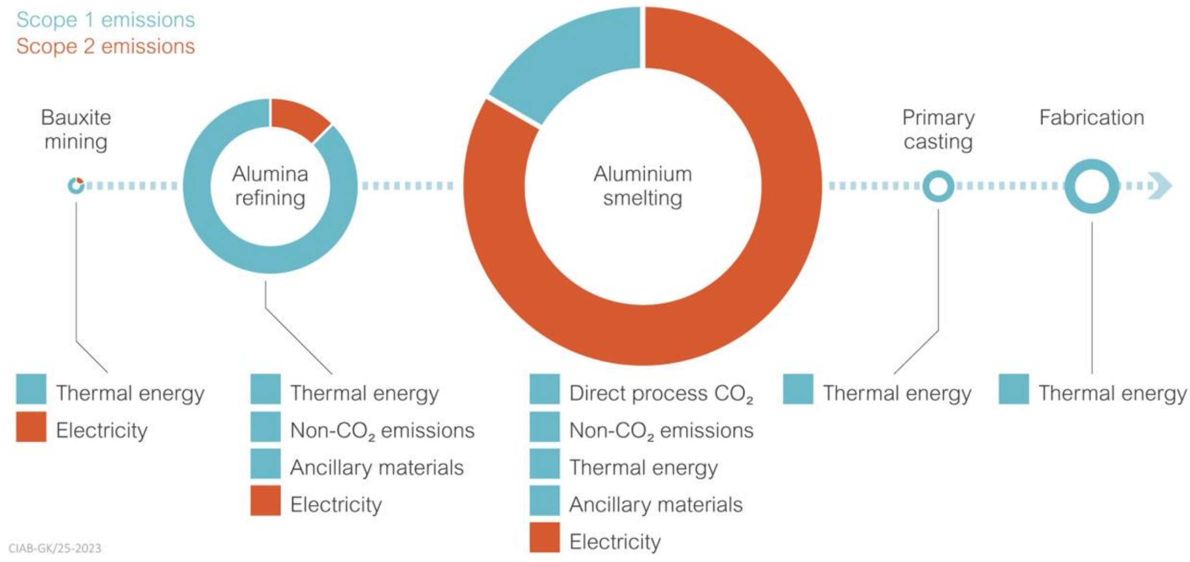


Figure 25 CO_2 emissions in primary aluminium production (WEF, 2020)

The second largest source of CO_2 emissions is the direct emissions from aluminium processing which account for a combined 25–30% of sectoral emissions. They are principally caused by the electrolysis of alumina using a carbon anode during smelting, as well as fuel combustion during refining in the Bayer process to produce heat and steam. For the alumina refining step, energy usage, which is mainly process heat, is 10.5 GJ/t alumina as a global average (IAI, 2021a).

There are relatively few additional emissions generated during the post-smelting steps of casting and fabrication and even lower emissions in the initial bauxite mining step.

6.5 OPPORTUNITIES TO DECARBONISE ALUMINIUM

The aluminium sector can achieve a technically and economically feasible path to net zero by 2050, with 95% decarbonisation shown to be possible by this time based on various studies and assessments (MPP, 2022; IAI, 2021b; WEF, 2020). Achieving NZE will require a mix of levers within the primary aluminium sector, in the wider aluminium value chain, and in partnership with the power sector, as shown in Figure 26.

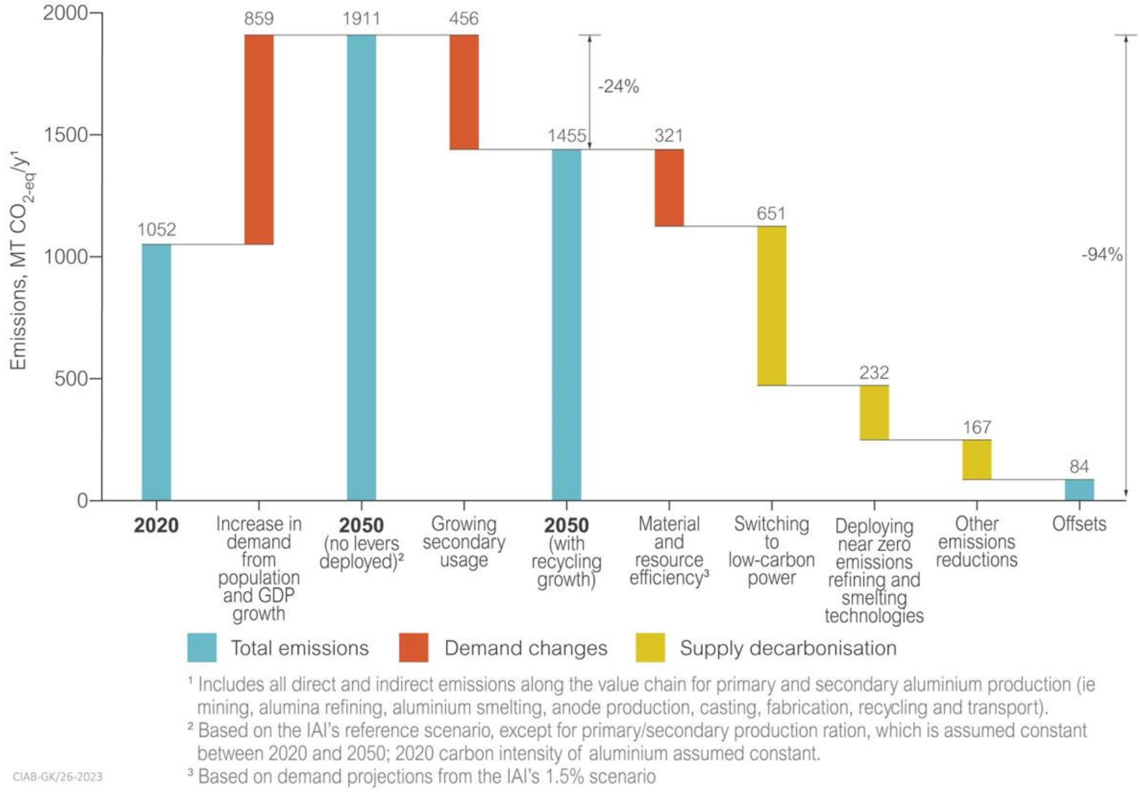


Figure 26 Emissions reduction potential by main decarbonisation lever (MPP, 2022)

The four main contributors to decarbonising aluminium are highlighted below and discussed in more detail in the subsequent sub-sections (MPP, 2022):

- Transitioning to low-carbon power is the single largest contributor, delivering around 650 $MtCO_2$/y reduction by 2050;
- Maximising secondary aluminium production delivers a further 456 $MtCO_2$/y, noting that recycling aluminium has a significantly lower carbon footprint of 0.5 tCO_2/t aluminium compared with 16 tCO_2/t aluminium for primary aluminium production;
- Maximising resource efficiency, where product design uses aluminium more efficiently, could deliver 321 $MtCO_2$/y reduction by 2050. Examples include extending the life of

buildings, extending automotive lifetimes and using mobility as a service to reduce the number of vehicles needed; and

- Deploying new technology to deliver near zero emissions refineries and smelting facilities could achieve 232 $MtCO_2$/y reduction by 2050. Here, new technology is required to decarbonise thermal energy in refineries, such as heat recovery and fuel switching, low-carbon anodes in smelters and CCUS fitted to smelters.

The impact of these measures is set to reduce coal usage through to 2050. However, due to the high dependence on coal in China and some other regions for electricity generation to power the aluminium smelters, coal will remain in the energy mix at perhaps 50% of current levels. This is particularly the case for geographic regions with limited access to renewable electricity at low cost. Here, CCUS retrofit to existing coal plant could be the preferred solution (*see* Section 6.5.1 for further details).

To deliver these steps, the whole value chain will have to address key problems such as access to low cost and low carbon power, lack of availability of aluminium to recycle, and lack of a business case for low-carbon aluminium production.

6.5.1 Low-carbon electricity

Low emissions electricity generation offers the largest opportunity to reduce emissions in the sector to near zero by 2050. Assuming the additional three main carbon reduction measures, as defined below in Sections 6.5.2–6.5.4 can be achieved, the total electricity demand for aluminium production stays relatively constant at 900–1000 TWh through to 2050.

As aluminium is a traded commodity with relatively narrow profit margins, this low emissions electricity will need to be from low-cost sources which will depend on local factors. It could be from solar, wind, hydro or nuclear power sources, or in the case of Asian countries, from coal fitted with CCUS, or from coal cofired with low emissions fuels such as ammonia or hydrogen, or carbon neutral fuels including biomass and wastes.

Given the level of power-related emissions in primary aluminium's carbon footprint, the main avenue for decarbonisation is switching aluminium smelter power supply from unabated fossil fuels towards low-carbon power supply. Several viable options exist to do this, including:

- Retrofitting CCUS to aluminium smelter fossil fuel–based captive power plants can reduce power emissions by typically 90-95%, depending on the availability of CO_2 transport and storage infrastructure (*see* Chapter 2).
- Switching to grid supplied electricity. Smelters based in locations with possible connections to the grid may find it favourable to switch to it if it's decarbonised or if renewable power purchase agreements (PPAs) are available. Under this option, grid connection costs would need to be incurred at the outset.

- Nuclear small modular reactors (SMRs) have the potential to offer smelters consistent high-load, low-carbon power. While still needing significant R&D (current TRL is just 4–5), the technology could become commercially available in the aluminium industry from around 2035 and become cost competitive around 2040 (MPP, 2022).

The suitability of these options varies greatly depending on local availability, electricity systems and prices. CCUS is preferable in locations without access to a grid or where grid emissions intensity is high without a clear path to decarbonisation. Switching to the grid is only a good option when low-carbon power sources already make up, or are expected to make up, a significant share of the electricity mix, or where a mature power market exists for renewable PPAs. Currently, around 34% of the power mix provided to smelters consists of low-carbon electricity, with the majority of this generated by hydropower plants. Although adding new hydropower capacity is possible, there is limited appetite to do this due to the lack of suitable locations and social and environmental concerns.

Interactions with the electricity system

Aluminium smelters typically require a reliable and stable electricity supply, serving as a major consumer of baseload power, accounting for 4% of global power consumption in 2019. However, this is expected to decrease to 1% by 2050 in a net zero future as other industries increase power demand because of electrification.

Given that aluminium is such a major consumer of dependable power, it has a significant role to play in defining future low-carbon power systems. This is important from an economic perspective because grid supply is often the most cost-effective of all the power options. It is also important from a swift decarbonisation perspective, as smelters will need to start exploring low-carbon power supplies by 2025, to achieve decarbonisation of power supply.

It is expected that about 70% of aluminium smelters will be able to source PPAs or low-carbon grid power to reduce their average emissions intensity while still benefitting from the dependability of a grid connection. A significant exception is China, where around half of smelters are unlikely to access local PPAs because they are not located in areas with sufficiently high wind or solar generation capacity factors (*see* Figure 27). Here, the preferred solution may be to retrofit the coal-fired direct power generation facilities with CCUS. Due to the dominance of China in aluminium production, this presents a significant opportunity for coal to play a continuing role in the decarbonisation of the aluminium sector, enabling around 30 Mtce continued usage to produce low-carbon electricity.

Even where higher proportions of low-carbon electricity from renewable, non-dispatchable sources are more feasible, coal with CCUS can play a vital role in providing fully dispatchable low-carbon electricity to achieve stable and resilient low-carbon electricity systems. An excellent example of this is the 10 GW Huaneng multi-energy power plant in Qingyang, Gansu Province, China, comprising 2 GW of low emissions coal-based power generation using two 1 GW ultrasupercritical (USC) power generation units equipped with CCUS. The remaining 8 GW of power will be derived from the renewable sources of wind and solar, with around 10% of energy storage provided using battery-based technology (Liu, 2021; Kelsall and Baruya, 2022).

Over the longer term, aluminium smelters could play a key role in being more flexible users of power to help alleviate the stress of balancing a decarbonised variable generation grid system. To date, there have been some successful demand-side response trials in Australia, such as the Tomago aluminium smelter, which is able to ramp potlines down by 50 MW (about 17% of power consumption) or shut down up to two potlines if it has more than one hour's notice. Ramping up this flexibility capability will be more critical as the world moves towards a decarbonised grid system that has a large share of variable renewable generation (MPP, 2022).

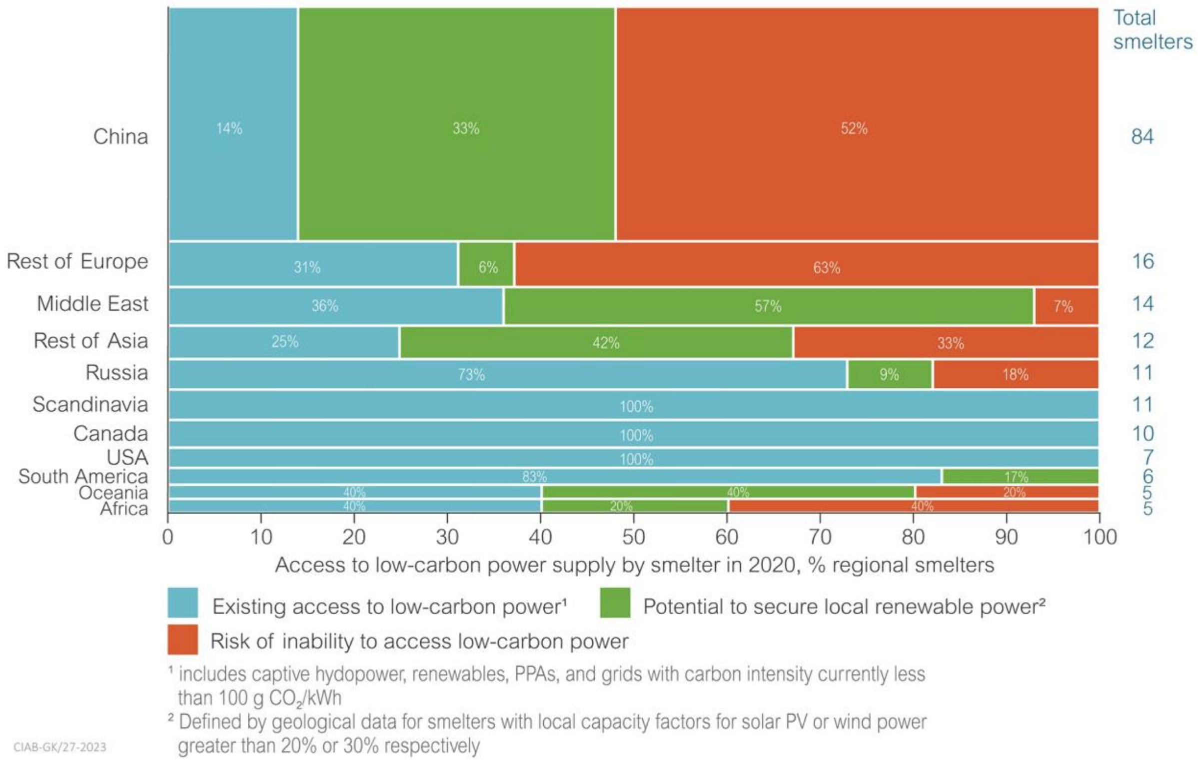


Figure 27 Aluminium smelter access to low-carbon power by region (MPP, 2022)

6.5.2 Maximising secondary production

Aluminium can be remelted and cast infinitely without compromising quality and with minimal loss. This applies to both pre- and post-consumer scrap, though the latter requires treatment to remove impurities and alloy-specific methods to safeguard quality. Substituting secondary for primary aluminium is a highly cost-efficient solution to reduce CO_2 emissions. Producing 1 tonne of secondary aluminium typically generates about 3% of the emissions associated with 1 tonne of primary aluminium while costing significantly less, due to the approximately 95% lower energy consumption compared with primary aluminium.

Maximising secondary production will require an increase in volumes of both pre- and post-consumer scrap available for recycling. This can be achieved only if industry leaders, policymakers and the waste management sector take collective action on product design and end-of-life collection and dismantling. Indeed, it is unlikely that the aluminium industry can meet a NZE target by 2050 without maximising the collection of aluminium scrap. Efforts to increase scrap recovery should focus on:

- advancing methods to divert aluminium from landfills;
- improving separation techniques to decrease the mixing of alloys;
- working with downstream partners for circular business models and closed-loop recycling;
- supporting more complex collection and separation processes with digitisation to track scrap throughout its lifetime and direct it to the correct channel to retain its value; and
- designing and creating products that are easily separated, collected and recycled.

By increasing recycle rates from the current over 95% for manufacturing (pre-consumer) scrap and just over 70% for end-of-life (post-consumer) scrap, to closer to 100%, secondary aluminium could account for around 80 Mt/y of final demand by 2050, minimising any increase in primary aluminium production (MPP, 2022; IAI, 2021a).

The scale-up of secondary production is likely to face two barriers:

- around 25%–30% of aluminium is lost in each use cycle because of post-consumer scrap collection leakage and pre-consumer scrap processing loss; and
- producers of secondary aluminium currently tend to avoid combining alloy-specific scrap batches, which results in a downcycling of scrap that undermines the establishment of closed-loop systems. Both barriers will need to be addressed for secondary aluminium to fully take up its role in the sector's decarbonisation.

Growth of secondary production also faces important regional dynamics that may become even more significant over the coming years. For instance, regional scrap export bans may lead to a dearth of scrap on the global market. This could end up limiting the potential of some regions to significantly scale up secondary production.

6.5.3 Material and resource efficiency

In a future circular economy aligned on a NZE by 2050 pathway, most sectors and the broader society will need to make a fundamental change in consumption patterns. Throughout the value chain, new and best-practice measures are likely to lead to reduced demand for common metals such as aluminium. This could be achieved by implementing material efficiency strategies at every stage of aluminium's life cycle, such as:

- at the design stage, 'lightweighting' can reduce the amount of aluminium needed to supply a given service, robust designs incorporating ease of repair can increase product lifetimes, and designs that facilitate end-of-life recycling can help maximise secondary production;
- at the fabrication stage, reducing material losses in manufacturing, can increase the efficiency of production;
- at the use stage, increasing the lifetime of goods and assets containing aluminium, for example through repair and refurbishments, can reduce the need for new aluminium; and
- at the end-of-life stage, repurposing and reuse can help alleviate the demand for new aluminium in other applications of the material.

6.5.4 Deploying new technologies

A successful NZE ambition for the aluminium sector requires direct emissions from refining and smelting in particular, which currently make up 26% of primary aluminium life-cycle emissions, to be abated. This fourth lever can be used only if NZE technologies are deployed widely at the three energy-intensive steps of the primary aluminium value chain, namely bauxite digestion, aluminium hydroxide calcination and aluminium smelting. A range of solutions in decarbonising digestion will likely become commercially available in the late 2020s, whereas newer technology options are expected from 2030 onwards for calcination and smelting.

Digestion

Heat and steam, needed to convert the raw material bauxite into alumina in the Bayer process, are primarily generated using fossil fuels. Near-zero emissions alternatives include:

- **Fuel switching –** electric and hydrogen boilers both have the potential to abate close to 100% of direct emissions. They benefit from high levels of technological maturity and existing applications in other sectors. To maximise their emissions reduction potential, their deployment in alumina refineries needs to be coupled with the use of low-carbon electricity and hydrogen.
- **Mechanical vapour recompression (MVR)** – An MVR system captures process waste heat, which it recompresses using electricity to increase the temperature to the level needed at process entry. By turning waste vapour into new process steam, the technology can replace fossil fuel boilers. Due to a coefficient of performance of 3, MVR systems require less electricity than the fossil fuel energy they eliminate. By replacing a significant majority of the steam produced from conventional fossil fuel boilers for digestion, MVR technology could enable up to a 95% reduction in fossil fuel consumption and emissions compared with using conventional boilers. Although it is already used in other sectors, MVR requires further R&D efforts to be adapted to refining before it can be deployed at scale, which is expected to be possible from 2027 onwards.

- **Concentrated solar thermal (CST)** – has the potential to meet around 75% of a refinery's digestion energy requirement, with the rest provided by backup boilers. The technology requires high levels of consistent solar irradiation, which is why it is suitable in specific locations. CST applications already exist in power generation, but the technology has yet to be deployed in an alumina context and is not expected before 2027.

In summary, fuel switching, MVR, and CST all have the potential to cut thermal energy emissions from alumina refining, although their suitability depends on local conditions.

Calcination

Calcination is a direct-firing process with temperature requirements of 1000–1300°C that are currently met by fossil fuel combustion. Fuel switching, either to electricity or to hydrogen, is the only option currently researched by the industry to decarbonise calcination. Like electric and hydrogen boilers, electric and hydrogen calciners have the potential to reduce emissions from refining, provided they are coupled with low-carbon electricity and hydrogen, making the effectiveness of their rollout dependent on the parallel deployment of renewable energy. These calciners are at initial stages of development and will require an increase in R&D efforts to achieve commercial readiness by 2030.

Smelting

Process emissions consisting of both CO_2 and perfluorocarbons (PFCs) are generated during the smelting of aluminium. The most promising avenues to reduce these emissions are:

Substituting carbon anodes for inert anodes: these anodes have the potential to eliminate direct CO_2 emissions. The promising emissions reduction profile of the technology has generated interest in the industry, and several companies are leading R&D efforts (WEF, 2020). Despite a current TRL level of 7, however, inert anodes are not expected to achieve commercial deployment before 2030. In addition, retrofitting the technology to existing pot rooms would imply a significant redesign resulting in large upfront capital expenditures. However, the estimated longer lifetime for inert anodes of around one year compared with one month for conventional carbon anodes, together with capital costs of inert anodes projected to be 10–30% less than carbon-based equivalents, has the potential to achieve operating expenditure savings of about 10%.

Retrofitting smelters with CCUS: CUCS technology is expected to be capable of reducing CO_2 emissions in smelter flue gases by over 90%. Its emissions reduction potential can be increased if the emissions from fuel combustion in the CCUS plant are recycled into the absorber, and if the CCUS system is designed to include emissions from the carbon anode production facilities for smelters with on-site production. From a cost perspective, deploying CCUS in aluminium is likely to be more expensive than in other sectors because of the low CO_2 concentration in aluminium smelter flue gases of approximately 1%. Cell redesign to increase CO_2 concentration is technically possible but would require a substantial upfront investment.

The overall potential contribution of these new technologies on CO_2 emissions reduction across the aluminium sector value chain are shown in Figure 28. The exact contributions of each will depend on the R&D efforts and ultimately on their impact on CO_2 emissions reduction cost. The World Economic Forum for example show CCUS potentially contributing 150 $MtCO_2/y$ reductions by 2050 (WEF, 2022), a higher value than that implied in Figure 28.

Frontier technology	Value chain imapct					Conditions where technology works best	Maximum potential to decarbonise sector emissions
	Mine	Refinery	Smelter	Casting	Recycling		
Inert anodes			✓			- Greenfield assets – Existing sites where electrolytic cells are ready for replacement	12%
CCUS		✓	✓	✓	✓	- Areas with access to cheap fossil fuels and limited recourse for renewable alternatives - Proximity to CO_2 geological storage capacity - Proximity to other industrial sites to form a hub	6%[1]
Hydrogen	✓	✓		✓	✓	- Areas with access to affordable renewable electricity - Proximity to other industrial sites to form a hub	17%
Mechanical vapour recompression		✓				- Greenfield assets - Areas with access to affordable renewable electricity	8%

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[1] Process emissions - does not include any CCUS potential for low carbon electricity

Figure 28 Technology options to reduce direct process emissions (MPP, 2021b) (modified by author)

6.6 COST

A significant investment of approximately $1 trillion, is required to deliver the transition to a low-carbon primary aluminium sector. The majority of the investment will not be in deploying new technologies at smelters or refineries. Instead, the investment is required mainly in the electricity sector to supply low-carbon electricity. Looking at this investment in more detail, achieving NZE by 2050 will require:

- investments in low-carbon electricity, both within and external to the aluminium industry, including renewable PPAs, grid decarbonisation, CCUS retrofits to existing thermal captive power, requiring approximately $500 billion by 2050;
- investments by aluminium producers in smelters, primarily in low-carbon anode retrofits of approximately $200 billion by 2050;
- investments by aluminium producers in refineries covering the transition to low-carbon fuels at refineries, estimated to be $36 billion by 2050; and
- investments in CO_2 transport and storage infrastructure as well as hydrogen production, estimated to be $26 billion by 2050.

Delivering these significant investments in diverse and new types of projects will require partnerships across the value chain, particularly in coordinating power investments with the aluminium sector needs (MPP, 2022).

7 CHEMICALS

7.1 KEY MESSAGES

Chemicals derived from oil, natural gas and coal are used to produce a wide range of end products including plastics, fertilisers, packaging, clothing, digital devices, medical equipment, detergents, tyres and explosives.

Of all industrial sectors the chemical industry is the largest consumer of fossil fuels, but it ranks third in terms of direct CO_2 emissions behind cement and steel. This is because 50% of the fossil hydrocarbons consumed in the industry are used as feedstock.

Typically, three primary chemicals are produced which form the precursors of all other chemical products. They are light olefins/alkenes and aromatic compounds, often referred to as 'high value chemicals' (HVCs), ammonia and methanol.

The chemical industry emits 1.1 $GtCO_2$/y of Scope 1 emissions, over 30% of which are process-related, meaning they are difficult to reduce. The remaining direct emissions are due to fuel combustion. A high percentage of the chemical industry's emissions are downstream Scope 3 emissions, so addressing these is vital to achieving NZE.

Compared to other hard to abate sectors, chemical production is more evenly spread globally, particularly HVCs. However, Asia and specifically China are leading producers of ammonia and methanol, responsible for over 30% of the global ammonia market. Existing methanol and HVC plants are on average around ten years old. Ammonia plants are on average 15 years old, and around 16 years old in China.

The largest application of coal-to-chemicals is in China, primarily for ammonia and methanol production. Coal gasification accounts for around 26% of global ammonia production. In China around 80% of ammonia and methanol is produced from coal. HVCs however, are primarily made using natural gas and oil.

At the end of 2019, China had invested $85 billion in coal chemicals and this is set to increase, with further investments taking place in Indonesia and India. In Indonesia for example, coal gasification to produce dimethyl ether (DME) and methanol is planned with production potentially reaching 14 Mt and 6 Mt respectively by 2045. Energy security concerns are driving this coal-to-liquids activity as it reduces the need for imported oil and gas.

Achieving 2030 mid-term targets while ensuring industry resilience – Demand for primary chemicals is set to grow through to 2050, with methanol forecast to grow the most at around 7% per year, increasing demand from 100Mt/y in 2020 to perhaps as high as 500 Mt/y by 2050.

Due to the wide range of chemicals produced, with differing process and heat requirements, the mix of decarbonisation options is likely to vary across applications. However, a generic view is that increased recycling, fuel switching to biomass, waste fuels and hydrogen, together with CCUS will form key parts of the portfolio. In addition, radically increased plastics recycling (currently running at around 10% of production), reducing single-use plastics and improved nitrogen-use efficiency will be required to achieve NZE.

Industry investment requirements to ensure resilience – Achieving net zero Scope 1–3 emissions will require around $100 billion per year in Capex deployment between 2020-2050.

Coal will remain a significant energy source whilst achieving NZE compliance, accounting for around 2 EJ in 2050, equivalent to approximately 70 Mtce. This is in part because coal will remain an important, affordable source of ammonia and increasingly methanol in Asia and potentially elsewhere.

- This underlines the importance of investing in CCUS infrastructure, capture plants and proving up storage resources. Up to 640 $MtCO_2$/y of CCUS will be needed by 2050, with CCUS providing a retrofit option for existing coal-to-chemicals plant, particularly where the plant is relatively young, as is the case with many of the coal-to-methanol and some coal-to-ammonia plants in China.
- Investment in low-emission hydrogen (including electrolysis, biomass and fossil fuels with CCUS) is the other main way to decarbonise chemical production.

7.2 ROLE OF CHEMICALS

Chemicals derived from oil, natural gas and coal provide a wide range of end products including plastics, fertilisers, packaging, clothing, digital devices, medical equipment, detergents and tyres amongst many others (IEA, 2018). Chemicals are also found in many parts of the modern energy system, including solar panels, wind turbine blades, batteries, thermal insulation for buildings and electric vehicle parts. Demand for plastics has outpaced the growth in steel, aluminium and cement, nearly doubling over the last 20 years or so. Europe, the USA and other advanced economies currently use up to 20 times as much plastic and up to 10 times as much fertiliser as India, Indonesia, and other developing economies on a per capita basis. This highlights the significant potential for growth in global demand in the chemicals sector.

The chemical industry is the largest consumer of fossil fuels of all industrial sectors, although it ranks third in terms of direct CO_2 emissions, behind cement and steel. This difference results from the fact that around 50% of the fossil hydrocarbons consumed in the chemical industry are used as feedstock providing a source of carbon and hydrogen, rather than being burned as fuel. The feedstock contains the precursors of the building blocks of a limited number of primary chemicals, often referred to as petrochemicals, from which all other chemical products are derived. These primary chemicals are (Planet Positive Chemicals 2022):

- light olefins/alkenes – typically ethene/ethylene and propene/propylene, together with the aromatic compounds of benzene, toluene and xylenes, collectively called BTX. This group of chemicals is often referred to as high-value chemicals (HVCs);
- ammonia – mainly used in the production of nitrogenous fertilisers, of which urea and ammonium nitrate are the most important (IEA, 2021b). Ammonia production requires hydrogen, which can be obtained from fossil fuel hydrocarbons or could be generated from renewable energy. The ammonia market could evolve drastically with the use of low-carbon ammonia as a hydrogen fuel carrier for multiple sectors such as shipping or the power sector; and
- methanol – used in the production of formaldehyde, which is employed for the production of special plastics and coatings, liquid-fuel component either directly or indirectly through conversion to ethers such as methyl tert-butyl ether (MTBE), and intermediaries to produce high-value chemicals replacing oil as feedstock. Similar to ammonia, the methanol market could evolve significantly as the chemical becomes used as an energy carrier.

The production of these basic chemical intermediates has direct emissions of 0.9 $GtCO_2$/y, with ammonia being the largest contributor at 417 $MtCO_2$/y, with HVCs at 258 $MtCO_2$/y and methanol at 250 $MtCO_2$/y (WEF, 2022). This represents the majority of the overall chemical industry direct emissions of 1.1 $GtCO_2$/y. The Asia-Pacific region, dominated by China, accounts for around two-thirds of these emissions. Over 30% of the direct CO_2 emissions are process related, so are difficult to reduce by techniques other than CCUS.

When Scope 2 and 3 emissions are included, the total increases to 2.4 Gt CO_2/y, representing just under 4% of annual global emissions. Within the 2.4 GtCO_2/y total emissions, Scope 3 emissions represent the majority at 64% equating to 1.5 GtCO_2. The magnitude of Scope 3 in the chemical system is driven by its dependence on fossil fuels, leading to upstream Scope 3 emissions from oil and gas extraction of 0.5 GtCO_2/y, but more significantly from carbon-dense products such as plastics and urea resulting in high associated downstream Scope 3 emissions of 1 Gt CO_2/y. Examples include end-of-life incineration and nitrous oxide emissions from fertiliser. It is for this reason that control of Scope 3 emissions from the chemical sector is essential for the transition to net zero (Planet Positive Chemicals, 2022; WEF, 2021).

7.3 GLOBAL SCALE OF CHEMICALS PRODUCTION

The growth rate on an indexed basis for HVCs, ammonia and methanol is shown in Figure 29 (IEA, 2022e).

HVC – Demand for high-value chemicals, the key precursors of plastics, is driven by an increase in demand in sectors such as packaging, construction and automobiles. Demand has grown at an annual rate of 3.5 % from 2000 to 2020, with growth expected to continue at a similar rate from 2020 to 2030, due to increasing consumption in developing countries. In many developing countries, annual consumption of plastics can be as low as 4 kg/y per person, but growth rates in those countries are high with strong growth potential. In developed countries, plastics consumption can range from 55 to 80 kg/y per person, although in some mature economies consumption has become stable at around 60 kg/y per person.

Oil is the main feedstock for HVCs typically produced in refineries, with 40% of propene and 80% of BTX globally being produced in refineries, or through cracking of petroleum products, such as ethane and naphtha in steam cracking plants. HVC production accounts for as much as 14% of the global oil demand and also a substantial proportion of demand for natural gas (IEA, 2018).

Ammonia – Ammonia demand has been stable over the last few years, at a level of about 185 Mt/y, due to increased efficiency in fertiliser use in developed countries. Demand is nevertheless expected to increase evenly across the world at an annual rate in the range of around 2% and could reach as high as 253 Mt/y by 2050 under a business-as-usual growth scenario. However, achieving NZE compliance for the chemical sector would mean limiting this growth to around 228 Mt (Zhu, 2022; IEA 2021a; WEF, 2022).

Methanol – Methanol has one of the highest growth rates of demand. With an average annual rate of about 7% from 2000 to 2020, demand growth is expected to continue at that rate over the near term.

This is because, despite an expected decrease in its use for gasoline blending, methanol can also be used as an intermediate for olefin production as a replacement for oil products. Global methanol demand was 100 Mt in 2020, with demand potentially reaching 500 Mt by 2050 (Wiatros-Motyka and Lai, 2022).

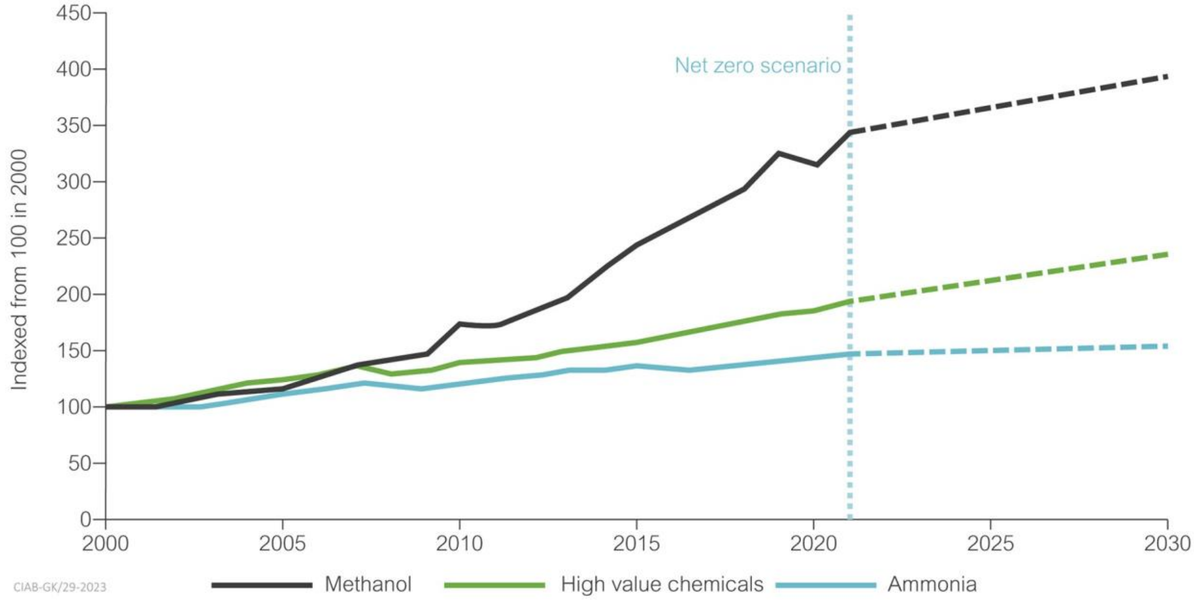

Figure 29 Forecast growth of key primary chemicals (IEA, 2022e)

7.3.1 Regional breakdown

Ammonia – 47% of ammonia production is in the Asia-Pacific with China alone accounting for 30%. To achieve NZE by 2050, this share is forecast to decline slightly to 42%, with China reducing to 16%, India growing to 15%, and South-East Asia reaching 8% of total production. Coal is the primary feedstock for the chemicals industry in China using gasification-related technology. This versatile technology is also important to produce liquid fuel products using coal-to-liquid processes and SNG.

The hydrogen required for most ammonia production is generated by the reforming of natural gas and by the gasification of coal, primarily in China. A recent report from the IEA (2022h) shows the continuing importance of coal to hydrogen in China, with CCUS used to make this a low-carbon hydrogen source, for the production of low-carbon ammonia.

Methanol – There has been a change in regional demand for methanol, the development of new end uses, and the emergence of new feedstocks and production centres. Currently, there are around 340 methanol plants in operation with a total capacity of nearly 140 Mt/y. In the next 10 years, methanol derived from fossil fuels will remain dominant. Coal as the feedstock will be used in China, India and Indonesia, while alternative feedstocks are considered more attractive in Europe (Wiatros-Motyka and Lai, 2022).

HVCs – For HVCs, the USA, China and the Middle East are the largest producers, together accounting for 54% of global production.

In terms of coal usage, the largest application of coal-to-chemicals is in China, primarily for ammonia and methanol production. Coal gasification accounts for around 26% of global ammonia production, primarily in China where it accounts for around 80% (Zhao and others, 2022; Zhu, 2022). In China, 70–80% of methanol is produced from coal (Wiatros-Motyka and Lai, 2022; Wang and others, 2022). Coal is seen as a strategic feedstock for various chemicals and products, as it helps the country avoid dependence on imported feedstocks and fuels. The remainder of this section therefore focuses on coal-to-chemicals applications in Asia, primarily in China.

New coal chemicals facilities – gasification and liquefaction

Table 16 summarises Chinese facilities under construction in terms of key products produced. There are 150 plants in the first phase with an additional 220 projects announced and expected to begin construction before the end of 2023.

TABLE 16 CHINA COAL CHEMICAL AND FUEL PLANTS ANNOUNCED IN 2019: PLANNED, UNDER DEVELOPMENT AND UNDER CONSTRUCTION AND COMMISSIONING (REID, 2021, AIZHU, 2020)

Product	2019-21 Under construction or commissioning, Mt/y	2020-24 Planned and under development, Mt/y
Methanol	19.2	32.2
Mono ethylene glycol (MEG)	8.3	17.3
Polyester		9
Methanol/coal-to-olefins (MTO/CTO)	7.7	13
Polyethylene	1.8	2
Polypropylene	2.9	2.5
Ethanol	0.5	2.1
Formaldehyde	0.4	
Dimethyl ether (DME)	0.9	
Methanol-to-gasoline (MTG)	0.9	4.8
Acetic acid	1.6	1.2
Coal-to-liquids (CTL) or gasification by Fischer-Tropsch (FT)	1.2	33
Tar deep processing, coal tar hydrogenation and lignite upgrading	15.8	86.8
Synthetic natural gas (SNG)	6.5	95.2
Ammonia	10.2	6.9
Urea	11.7	7.4

Methanol derived from syngas forms the basis of MTO (methanol-to-olefins) processes for polymer production. There are plans for 52 Mt capacity requiring gasification of over 125 Mt of coal by 2024, largely sourced from indigenous mines in the region. In effect, 10 Mt of methanol capacity will be added each year with the products directed primarily to olefins and the production of mono-ethylene glycol (MEG) for polyester fibres. Of the olefins produced, a significant proportion will be converted to polyethylene and polypropylene, adding a total of 10 Mt/y of new capacity by 2023 which would double current production (Reid, 2021).

The scale of coal-to-fuel conversion is also gathering pace with 1 Mt/y of methanol-to-gasoline (MTG) scheduled for 2021 with a further 5 Mt/y to be added in subsequent years. In total, Fischer Tropsch and coal liquefaction-related products are set to increase by 33 Mt/y.

For heavier components, coal hydrogenation and tar processing are scheduled to increase capacity by an additional 100 Mt by 2023. There is growing interest in the use of coal tar for new materials and the addition of these new plants indicates that tar from coking coal plants will be insufficient to meet demand for coal tar pitch.

China's coal chemicals strategy also includes facilities to manufacture polyvinyl chloride (PVC), purified terephthalic acid (PTA), polyethylene terephthalate (PET), styrene, aromatics, nitric acid, melamine and propionic acid, among others (Reid, 2021).

At the end of 2019, China had invested $85 billion in coal chemicals and this is set to increase. For example, Hengli has recently announced a $20 billion investment in an operation to convert 20 Mt of coal to 9 Mt of polyester via an ethylene glycol intermediary. It includes mining operations and chemical facilities and aims to be operational by 2025 (Reid, 2021). Other leading companies in the coal-to-chemicals sector include the Shenhua Group and Sinopec, with a list of reference plant for Sinopec shown in Table 17 as an example.

TABLE 17 SINOPEC REFERENCE COAL AND NATURAL GAS TO CHEMICALS PLANT (KELSALL, 2021)

No	Project	Year
1	1.2 Mt/y coal-to-methanol project, Sinopec Great Wall Energy & Chemical (Ningxia) Co Ltd	2019
2	Syngas debottleneck and acetic acid revamp and upgrade project, Sinopec Great Wall Energy & Chemical (Ningxia) Co Ltd. This is China's first big coal chemical upgrade and revamp project, with a capacity expansion of 40%. The coal slurry concentration is increased to 64.1%, and the effective gas volume is up to 216,854 m^3/h. SNEI delivered this EPC project based on a revamp solution developed in-house	2017
3	1.7 Mt/y coal-based MTO project (purification, methanol synthesis, steam recovery unit, ASU, air compressor station, etc), Zhong'an United Coal Chemical Co Ltd. The project is a joint venture between Sinopec and Anhui's Wanbei Coal-Electricity Group. Sinopec Nanjing Engineering & Construction Incorporation (SNEI) delivered as EPC contractor the syngas plant with a capacity of 505,563 m^3/h (as $CO+H_2$), and the methanol plant with a capacity of 1.8 Mt/y (as 100% methanol)	2015
4	100,000 m^3/h coal-based hydrogen production unit, Sinopec Jiujiang Company. SNEI delivered this EPC project based on Sinopec's low-temperature methanol wash semi-lean solution circulation technology and coal slurry gasification at 4.0 MPa. SNEI earned the National Quality Project Award, Sinopec Quality Project Award, and the second prize of the National Excellent Project Engineering Award	2014
5	1.8 Mt/y MTO, Henan Hebi Integrated Coal Project	2013
6	1.8 Mt/y methanol project, Sinopec Great Wall Energy & Chemical Co Ltd	2012
7	2 billion m^3/y coal to natural gas project, Sinopec Great Wall Energy & Chemical Co Ltd	2011
8	90 kt/y coal-based hydrogen production unit and associated air separation unit (ASU), Sinopec Nanjing Chemical Industrial Corporation. This project is based on a licensed coal slurry gasification technology, with a hydrogen production capacity of 126,000 m^3/h, 3 gasifiers (2 running and 1 standby), coal feed of 1000 t/d per gasifier; with an associated ASU of 56,000 m^3/h	2011
9	100 kt/y acetic anhydride project, Yankuang Lunan Fertiliser Factory (earned 'Sun Cup' award and 'Quality Project Award' in 2011)	2010
10	1 billion m^3/y natural gas purification plant of Songnan gas field, Sinopec Northeast Oil and Gas Company	2009
11	CO plant for 500 kt/y acetic acid plant, Sinopec Yangzi Petrochemical Co Ltd	2008
12	Coal slurry gasification unit for 300 kt/y ammonia plant, Sinopec Nanjing Chemical Industrial Corporation	2005
13	Syngas project, BASF-YPC Company Limited	2004
14	300 kt/y ammonia, 520 kt/y urea project, Sinopec Nanjing Chemical Industrial Corporation	2002

Synthetic natural gas and hydrogen

The demand for natural gas in China is rising with the modernisation of domestic heating and cooking methods and the new Russian 'Power of Siberia' pipeline to China supplying imported gas for domestic use. Coal-to-SNG production capacity reached 6.5 Mt/y in 2021 but is set to ramp up to perhaps 100 Mt/y before 2024, with a list of some of the earlier coal-to-liquid and SNG projects in China shown in Table 18.

TABLE 18 A SUMMARY OF MAJOR CTL/SNG RESEARCH AND DEVELOPMENT PROJECTS IN CHINA (XU AND OTHERS, 2015)

CTL/SNG project	Capacity	Commission date	Location	Gasifier licensor	Synthesis technology licensor
ICC slurry bed reactor pilot test	750–1000 t/y	2000-02	Taiyuan		ICC MFT
Yankuang industrial test plant	4500 t/y	2003-04	Lunan	ECUST-OMB	Yankuang Fe-LTFT
Yitai ICTL Demonstration	160 kt/y	2009-11	Dalu	Texaco	Synfuels China MTFT
Luan ICTL Demonstration	160 kt/y	2009	Tunliu	Lurgi	Synfuels China MTFT
Shenhua ICTL Demonstration	180 kt/y	2009-10	Majiata	Shell	Synfuels China MTFT
Shenhua-Ningmei	4 Mt/y	2016	Yinchuan, Ningxia	Siemens-GSP	Synfuels China MTFT
Shanxi Luan High Sulphur Coal Co-production	1 Mt/y	2015	Changzhi	Lurgi	Synfuels China MTFT
Yankuang Shaanxi Yulin ICTL	1Mt/y	2015	Yulin	ECUST	Yankuang ICTL
Yitai Xinjiang ICTL	2 Mt/y		Xinjiang		Synfuels China MTFT
Yitai Yili ICTL	1 Mt/y		Yili		Synfuels China MTFT
Datang International Power Keqi SNG	4 billion m^3/y	2012	Hexigten	Lurgi	Lurgi
Datang International Power Fuxin SNG	4 billion m^3/y		Fuxin, Liaoning Province		Lurgi
Huineng Coal Power Erdos SNG	1.6 billion m^3/y		Erdos, Inner Mongolia		
Qinghua Yili SNG	1.4 billion m^3/y		Ili, Xinjiang		Haldor Topsoe TREMP™
Sinopec Zhundong SNG Demonstration	30 billion m^3/y		Zhundong, Xinjiang		

The conversion of coal to hydrogen and subsequently to ammonia required an additional 10.2 Mt of capacity by 2021 but then a more gradual increase to give a total of perhaps 20 Mt by 2024. Urea is formed from ammonia and CO_2 to be used as fertiliser, and as such offers an outlet for CO_2 captured from the gasification plant as a potential circular economy solution.

A new project aims to recover CO_2 from Shaanxi industrial facilities and manufacture 3.5 Mt/y methane applying Hitachi Zosen methanation technology that uses hydrogen obtained from renewable generation. As CO_2 may be more easily recovered from coal gasification plants relative to power plants, this could offer an alternative to storage for a portion of the CO_2 (Ng, 2020).

Coal-to-chemicals in India and Indonesia

Some coal-to-chemicals projects outside China are partly associated with China's Belt and Road Initiative promoting coal technologies to developing nations, as shown in Table 19. More generally the logic of using domestic feedstock rather than importing oil and gas is the driving force for developing these plants.

TABLE 19 COAL CHEMICAL AND FUEL PLANT DEVELOPMENTS OUTSIDE CHINA (ARGUS 2020A,B; NS ENERGY, 2020; JASI, 2020; HARSONO, 2020; RIVERVIEW ENERGY, 2020)

Location	Product	Scale
India	Fuel	100 Mt/y coal to be gasified with an investment of $55 billion over 10 years (Argus, 2020a,b)
Dankuni, Bengal, India	Methanol (hybrid blend with petrol)	0.6 Mt/y (NS Energy, 2020)
East Kalimantan, Indonesia	Methanol	2 Mt/y requiring gasification of 6 Mt/y coal (Jasi, 2020)
Sumatra, Indonesia	DME	$2 billion coal-to-methanol and DME (Harsono, 2020)

As the largest economy in Southeast Asia, Indonesia's national strategy aims to increase the use of renewables, together with phasing-out of coal power plants by 2030. As a country with huge coal reserves, alternative uses for its indigenous coal are being assessed. The Indonesian government has prepared at least eight roadmaps for the utilisation of coal, which aim to use its coal resources and reserves optimally. Among these roadmaps, coal gasification to produce dimethyl ether (DME) and methanol is planned with DME and methanol production, potentially reaching 14 Mt and 6 Mt respectively by 2045 (Haryanto, 2022).

Air Products plans to invest $2 billion in a 2 Mt/y coal-to-methanol plant (6 Mt/y feedstock) located in East Kalimantan, Indonesia, reducing oil imports and countering an anticipated decline in coal exports from Indonesia. The facility will sell methanol to produce thermosetting polymers derived from formaldehyde (Jasi, 2020), although it should be noted that these projects are still under review (PwC, 2021). The production cost of DME is currently still around 490 $/t. This amount does not include the cost of carbon capture which is predicted to reach around 20–40 $/t$CO_2$ (Reid, 2021).

Coal India is planning to install a 0.6 Mt/y coal-to-methanol plant at Dankuni, Bengal. The methanol will form a hybrid blend with petrol (15:85 ratio) as a mixed fuel, which avoids the safety issues associated with 100% methanol. In all, India has earmarked 100 Mt/y of coal specifically for coal gasification to provide fuels, fertiliser, and chemical feedstocks, with a total investment of $55 billion envisaged over the next 10 years to establish a new coal-to-chemicals sector (Argus, 2020b).

7.4 COAL GASIFICATION PROCESS

Rather than describe the wide range of chemical processes to produce HVCs, ammonia and methanol, this section focuses on gasification as the first step in the conversion of coal-to-chemicals. A full description of coal-to-ammonia and coal-to-methanol is provided in ICSC reports (Zhu, 2022; Wiatros-Motyka and Lai, 2022).

There are three main coal gasification routes to produce chemicals and fuels (Reid, 2021):

- using a methanol intermediate and applying the MTO technology to make polymers;
- using syngas-based Fischer-Tropsch technology; and
- direct coal liquefaction to produce fuels.

The technology underpinning coal gasification is mature although there are developments to improve the efficiency and operation of syngas generation with a gradual shift away from established designs. Figure 30 shows two designs in use currently, namely the General Electric/Texaco single burner slurry gasifier used in over 70 installations, particularly in early plants, and the Shell dry feed pressurised entrained flow reactor, both deployed by Air Products. The latter technology is intended for a recently announced Indonesian project (Jasi, 2020). Other reactor designs include Siemens dry entrained flow reactor, the Sasol Lurgi reactor deployed in South Africa, U-gasifier from Synthesis Energy, and more significantly the HT-L single burner, entrained flow reactor, designed in China, which now competes in China's pulverised coal gasification sector (Reid, 2021; Minchener, 2019).

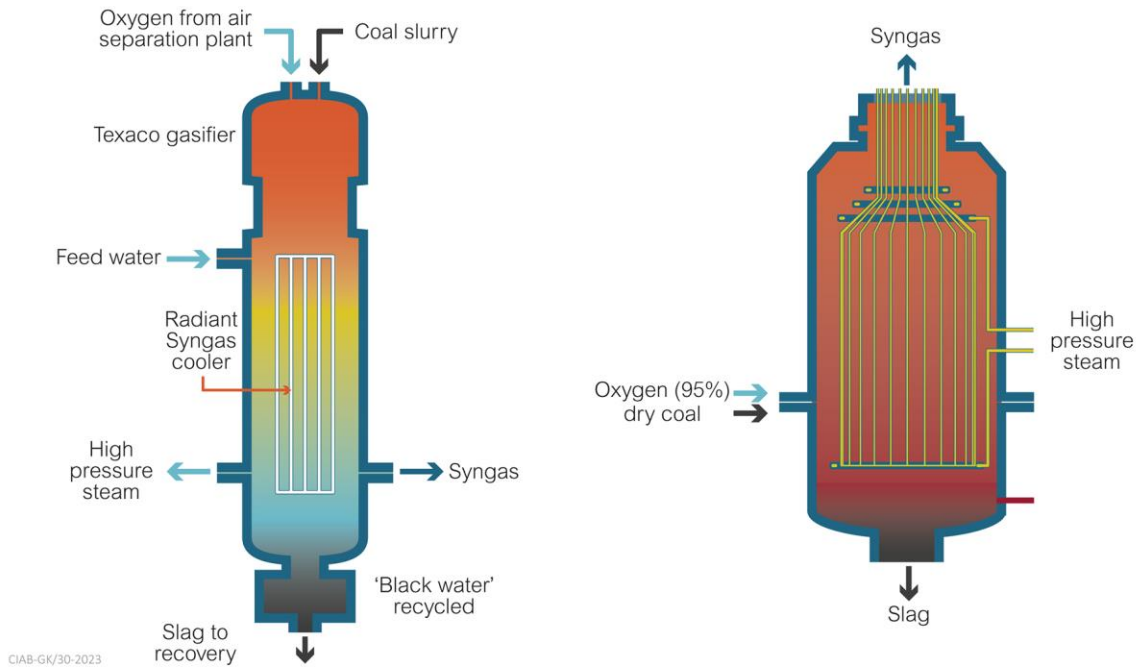

Figure 30 Air Products Syngas Solutions: formerly GE Energy's coal slurry gasifier (left) and Shell's dry pressurised entrained flow reactor (right) (Air Products, 2019)

Since 2018, a substantial construction programme has been underway to expand and build new coal chemical facilities that will maintain or even increase the share of chemicals production from coal. Although much carbon is locked into chemical products, carbon intensity is a prime concern of the coal gasification industry. It will attract more international scrutiny given the large number of coal chemical plants under construction and in development. Typically, it takes 2.5 t of coal to make 1 t of methanol, as much of the carbon is effectively rejected as CO_2, noting also that a modern methanol plant produces around 1 Mt/y of methanol (Chatterjee, 2020). Similarly, for synthesised methane, over half the carbon in the coal is rejected as CO_2, with the production of 1 tonne of SNG requiring about 2.5 tonnes of coal, equivalent to CO_2 emissions approaching 8 tonnes, allowing for ash (Reid, 2021).

New plants for coal-based chemicals and fuels production have also been constructed in Africa and Asia, partly associated with the Belt and Road Initiative (Metzger, 2021). Most recently there are plans for a $10 billion investment in coal gasification facilities in India to make chemicals, particularly urea and fuels using Air Products technology (Chatterjee, 2020). The coal-to-chemicals and fuels sector is expanding at an unprecedented rate, influenced in part by the transition away from coal in many geographic locations in the power sector.

7.4.1 Chemical plant life

The sector is capital intensive with substantial long-term physical assets and infrastructures, and is present in all regions of the world, with particularly strong development in the last 20 years in Asia, mainly China (WEF, 2022).

Compared with steel and cement, the chemical sub-sector has a more even distribution of capacity, both regionally and in terms of age, as shown in Figure 31. Several chemical facilities have been built in recent years in advanced economies such as the USA as well as in the Middle East. Most of the investment in methanol and HVC capacity has taken place in regions with access to low-cost petrochemical feedstocks, particularly North America, the Middle East and China. The shale gas revolution has made US ethane comparable in price to ethane in the Middle East, leading to a re-balancing in the geographical spread of chemical production capacity. Methanol and HVC plants are on average around ten years old. Ammonia output growth has been slower than that of HVCs and methanol, with emerging economies generally adding these facilities early in their development, in step with agricultural development. Ammonia plants are on average 15 years old, and around 16 years old in China (IEA, 2020b).

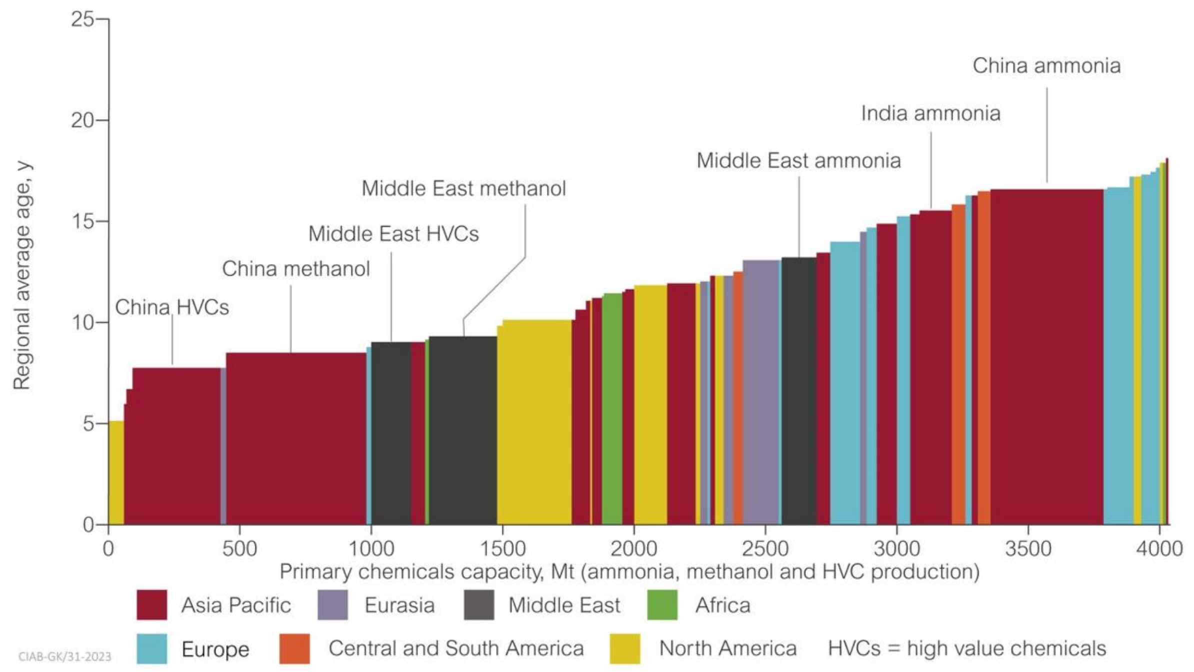

Figure 31 Average age of chemical sector plant life (IEA, 2020b)

7.5 OPTIONS TO DECARBONISE CHEMICALS PRODUCTION

In the IEA NZE scenario, emissions from the chemicals sub-sector fall from 1.3 Gt in 2020 to 1.2 Gt in 2030 and around 65 Mt in 2050 (IEA, 2021a). The share of fossil fuels in total energy use falls from 83% in 2020 (mostly oil and natural gas), to 76% in 2030 and 61% in 2050. Oil remains the largest fuel used in primary chemicals production by 2050 in the NZE scenario, with smaller quantities of gas and coal.

Due to the wide range of chemicals produced, with differing process and heat requirements, the mix of decarbonisation options is likely to vary across applications. However, a generic view of options is provided in Table 20, where increased recycling, fuel switching to hydrogen and CCUS form key parts of the portfolio (IEA, 2021a).

TABLE 20 KEY MILESTONES IN TRANSFORMING GLOBAL CHEMICALS INDUSTRY (IEA, 2021A)

Source	2020	2030	2050
Share of recycling - reuse in plastics collection - reuse in secondary production	17% 8%	27% 14%	54% 35%
Hydrogen demand (MtH_2/y)	46	63	83
Share of production via innovative routes	1%	13%	93%
CO_2 captured ($MtCO_2/y$)	2	70	540

Technologies that are currently available on the market account for almost 80% of the emissions savings achieved globally in the chemical industry by 2030 in the IEA NZE scenario. They include recycling and re-use of plastics and more efficient use of nitrogen fertilisers, which reduce the demand for primary chemicals, and measures to increase energy efficiency. Beyond 2030, the bulk of emissions reductions result from the use of technologies whose integration in chemical processes is under development. This includes CCUS applications and electrolytic hydrogen generated directly from variable renewable electricity. CCUS-equipped conventional routes and pyrolysis technologies are most competitive in regions with access to low cost natural gas or coal, while electrolysis may be the favoured option in regions where the deployment of CCUS is impeded by a lack of infrastructure or public acceptance (IEA 2021a).

A further assessment is provided by DNV, where emissions could reduce by over 85% relative to 2021 levels, from almost 2.5 $GtCO_2$/y to around 0.35 $GtCO_2$/y as shown in Figure 32. In terms of the impact on fossil fuels, coal would still be a significant energy source accounting for around 2 EJ in 2050, equivalent to approximately 70 Mtce, as shown in Figure 33. This is in part because coal will remain an important source of ammonia and increasingly methanol in Asia (DNV, 2022).

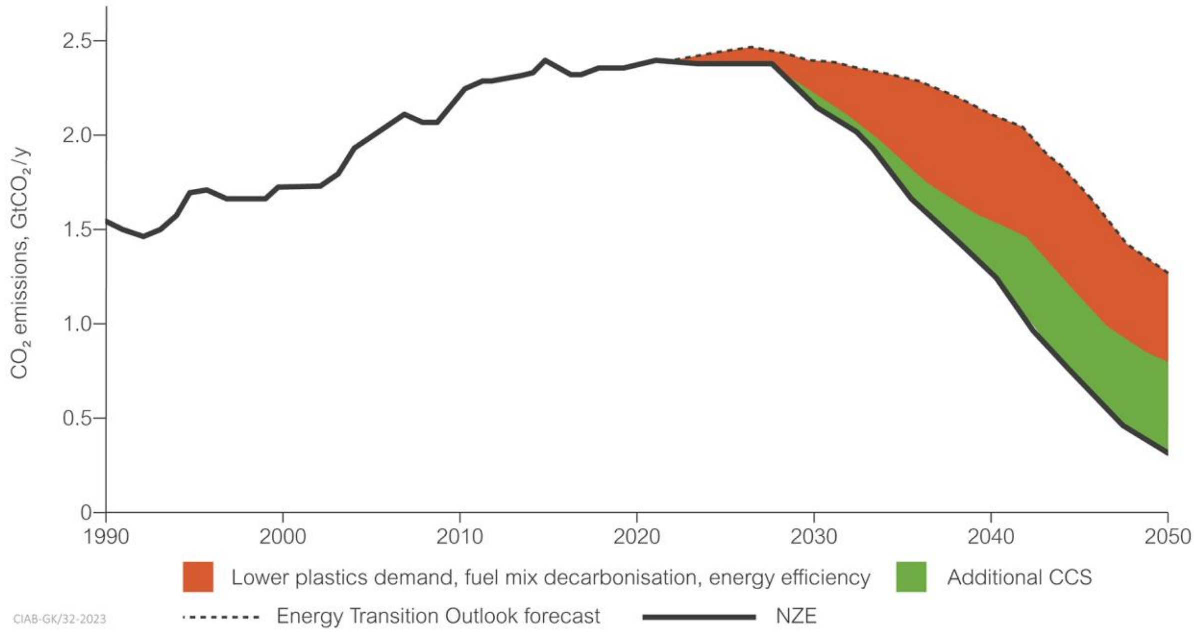

Figure 32 Chemical sector CO_2 emissions reduction for NZE by 2050 (DNV, 2022)

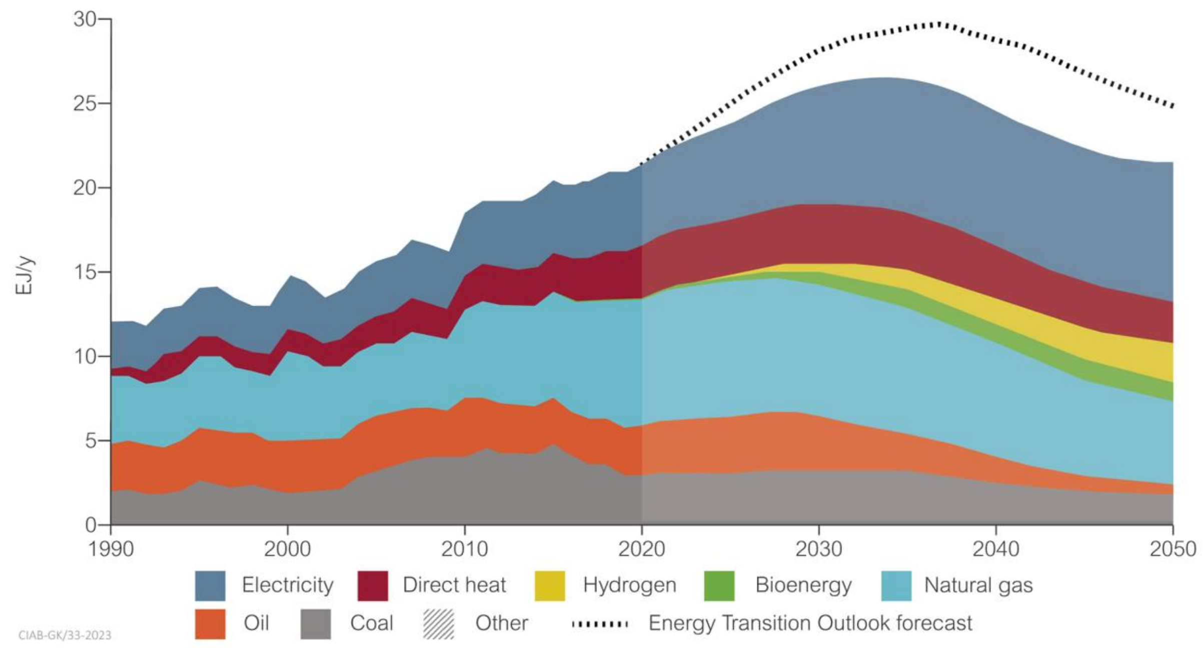

Figure 33 Chemical sector energy demand for NZE by 2050 (DNV, 2022)

7.5.1 Demand reduction

Demand-side circular economy approaches of reduction, reuse, substitution and recycling, can reduce the absolute amount of future chemicals production.

This requires coordinated and ambitious action from the chemical system and the downstream value chains using chemicals in materials, fertilisers and products. Currently, the global chemical industry has low reuse and recycling rates with significant waste generation. For example, up to 70% of nitrogen input in fertilisers is not taken up by crops and only 9-14% of all the plastic ever created has been recycled.

Applying circular economy approaches to the chemical sector value chain can reduce total demand in the system by 23–31% (372–526 Mt/y). This is particularly relevant for non-ammonia demand resulting in a 33–51% reduction. Of total system reduction, elimination represents 41% of total circularity impact, reuse 19%, substitution 14%, and recycling 26% (Plant Positive Chemicals, 2022).

7.5.2 CCUS

Around 30% of chemical industry emissions are process related, which together with the need for high process heat in some applications means that CCUS will be part of the portfolio of technologies to achieve NZE compliance. Up to 640 $MtCO_2$/y of CCUS will be needed by 2050 for abatement of the system (Plant Positive Chemicals, 2022), with a slightly lower value of 540 $MtCO_2$/y identified by the IEA NZE scenario (IEA, 2021a).

CCUS provides a retrofit option to add to existing coal-to-chemicals plant, particularly where the plant is relatively young, as is the case with many of the coal-to-methanol and some coal-to-ammonia plants in China.

Due to the higher concentration and partial pressure of CO_2 in the syngas stream from coal gasifiers used in coal-to-chemicals processes, pre-capture systems using Selexol and Rectisol type technologies are likely to be preferred over post-capture amine-based technologies. Further details of CCUS are provided in Chapter 2 where examples of CCUS added to chemical plant are highlighted, including the Great Plains Synfuels project in the USA and the Sinopec Qilu petrochemical plant retrofit of a 1 $MtCO_2$/y CCUS system to an existing coal/coke water slurry gasification unit at a fertiliser plant in China. A further example of coal gasification plant is Sinopec's flagship project in China, the 1.7 Mt/y coal-based MTO project of Zhong'An United Coal Chemical Company. The project is a joint venture between Sinopec and Anhui's Wanbei Coal-Electricity Group. As the EPC contractor, Sinopec delivered the syngas plant with a capacity of 505,500 m^3/h (as $CO+H_2$) and the methanol plant with a capacity of 1.8 Mt/y, as 100% methanol (Kelsall, 2021).

7.5.3 Fuel switching

'Fuel' switching to low emissions fuels of hydrogen and ammonia, biomass and electricity via electrification is a further decarbonisation option.

Electrification is applicable to low and medium temperature heat applications but can be limited in terms of providing high-grade heat. Hydrogen fuel switching away from coal can be an option, with 83 MtH_2/y demand forecast by the IEA to achieve NZE (*see* Table 20). An in-depth review of hydrogen as a decarbonisation option for industry and more widely as an energy vector is covered elsewhere by the ICSC (Zhu, 2023; Kelsall, 2021).

7.5.4 Scope 3 downstream emissions

Due to the high percentage of the chemical industry's downstream Scope 3 emissions, addressing these is vital to achieving NZE. This in part requires changing the end-of-life 'carbon destination' from GHG emissions to recycling and carbon capture.

One example is in fertiliser production where ammonium nitrate production is expected to increase as it has less intensive Scope 3 emissions than the conventional urea-based production method. Further, it is the only intermediate where a low emissions process allows direct synthesis, bypassing ammonia production. Ammonium nitrate is one of the largest nitrogen-based fertilisers, after urea, with 48 Mt of production in 2020. Filtration of wastewater can yield ammonium nitrate. Given its affordable cost and feedstock availability, wastewater is overwhelmingly available and an externality in most countries; therefore, it needs to be valorised. Wastewater is likely to be recovered instead of synthesised via ammonia, but it often requires a significant scale to justify the initial capital investment.

Additionally, ammonium nitrate is 28–41% less Scope 3 emissions-intensive than urea, making the substitution an attractive option for limiting nitrous oxide emissions. As a result, ammonium nitrate production is expected to benefit from a shift away from urea and to reach 157–236 Mt/y by 2050 for fertiliser application only (Planet Positive Chemicals, 2022).

Fuel switching to waste fuels, biomass and low-carbon hydrogen (combined with CCU) feedstocks can also reduce Scope 3 emissions, by preventing fossil fuel-related carbon from entering the chemical manufacture production chain.

Recycling of plastic materials as feedstock to replace a portion of the input of fossil fuels is a further potential technique to reduce Scope 3 downstream emissions. Both recycling and fuel switching were highlighted earlier in Sections 7.5.1 and 7.5.3.

7.6 COST

Achieving net zero Scope 1–3 emissions will require around $100 billion per year in Capex deployment between 2020-2050. First, adequate large-scale capital must be allocated for deployment into the transition of the system. Second, a network of financial intermediaries, infrastructure, products and expertise to deploy the capital must be developed. Third, a pipeline of high-quality joint venture transformation projects is needed to create a clear track record for mainstreaming circular and low-emissions technologies. Achieving this will require government policy support as well as shifting perceptions of value, business models, technology risk, rates of return, and Capex profiles across the chemical value chain (Plant Positive Chemicals, 2022).

8 CONCLUSIONS

Many countries, particularly in Europe, have committed to phase out coal, as it is widely seen as part of the measures required to achieve net zero emissions (NZE). However, for industrial manufacturing this will be very difficult, if not impossible, to achieve in a cost-effective manner. The key heavy industries are iron and steel, cement, aluminium and chemicals production such as ammonia and methanol used as building blocks for fertilisers, plastics and fibres. The vital importance of these heavy industries seems set to continue and indeed grow, in part because they cannot easily be replaced by other materials, certainly not in the foreseeable future or at a global scale.

Industrial emissions are ‘hard to abate’ because:

- Heavy industry requires high temperature heat for many of its processes, which is provided almost exclusively by burning fossil fuels. Generating high temperature heat from electricity, is impractical and costly with current commercial technologies. Constraints on the availability of sustainable biomass limit its use for fuel substitution.
- Several industrial processes result in emissions from chemical reactions that are inherent in production processes.
- Industrial plants tend to have long lifetimes, typically 30–40 years. Retiring them early to switch to alternative technologies would be extremely costly.

For these reasons, fossil fuels including coal, fitted with CCUS, will continue to play a key role as industry decarbonises and moves towards NZE. Coal use will inevitably reduce, perhaps by as much as 80% from the current 5 Gt/y, but 0.6–1.4 Gt/y is still forecast to be used in 2050, to a large extent in heavy industry.

COAL WILL CONTINUE TO BE REQUIRED IN AN NZE FUTURE, WITH AROUND 0.6–1.4 GT/Y USED IN 2050 IN CONJUNCTION WITH CCUS AND LOW-CARBON FUELS, PRIMARILY IN HEAVY INDUSTRIES.

Iron and steel

Global crude steel production totalled 1950 Mt in 2021. Coal met around 75% of the energy demand of the sector, a figure comparable to its share over the past decade. Asia dominated global production with China, India and Japan being the top three steel-producing countries. China alone produced 1033 Mt of steel in 2021 representing almost 53% of global production.

Steel production may increase by a further 12–60% by 2050. The share of coal in energy use for iron and steel production will reduce, but will remain at a significant level, as high as 50% of the current value by 2050 representing 14 EJ, or 480 Mtce.

The average lifetime of blast furnace steel production assets is typically around 40 years. The weighted global average age is about 13 years and only around 12 years in China where over 50% of global assets are located. Where the assets are younger, greater emphasis is likely to be placed on retrofitting with technologies such as CCUS and hydrogen.

The iron and steel industry can achieve NZE by 2050. The main levers to decarbonise are:

- Reduced steel demand, where coordinated cross-sector strategies, including changes in transport and building renovation, as well as other changes in design, manufacturing methods, construction practices and consumer behaviour changes could reduce global demand for steel in 2050 to around 12% higher than current levels.
- Increased recycling of scrap to achieve a global scrap steel share of steel production of up to 70%. Lower steel demand and greater scrap recirculation could combine to reduce iron ore consumption by 75%.
- The majority of the emissions reduction required in the iron and steel sector to achieve NZE targets after 2030 will come from innovative technologies. This includes hydrogen-based DRI and iron ore electrolysis as well as CCUS. Steel production technologies using CCUS will be the single largest technology, accounting for 45–53% of primary steel production in 2050. This would equate to around 530–670 $MtCO_2/y$ by 2050.

Cement

Global production of cement reached 4.4 Gt in 2021, an increase of over 20% in the last 10 years. Cement demand may increase by 12–23% by 2050. Asia dominates global production with China, India and Vietnam being the top three cement-producing countries. China alone produced 2.5 Gt of cement in 2021 representing almost 58% of global production.

The share of coal in energy use for cement production will reduce, but remain at a significant level, as high as 50% by 2050 representing 3.5 EJ, equivalent to around 120 Mtce. This is in part because fossil fuels will remain the main source of high temperature process heat input, particularly coal in the Asian context.

Around 85% of the global cement kiln fleet is less than 15 years old. China accounts for over 50% of all cement kiln capacity and its relatively young fleet age of around 13 years places emphasis on retrofitting with technologies such as CCUS and hydrogen to decarbonise.

The cement industry can be NZE compliant by 2050. The main levers to achieve this are CCUS, reducing demand, fuel switching opportunities, decreasing the clinker-to-cement ratio, replacement of clinker with alternative cementitious materials, together with the recognition of the long-term carbonation properties of concrete.

Significant deployment of CCUS is required to achieve emissions that can be compliant with a NZE ambition by 2050. This is because CCUS is the main and most effective abatement solution, due to the cement industry producing close to 65% of unavoidable process CO_2 emissions. It could provide around 1370 $MtCO_2/y$ reduction by 2050, capturing 76% of the cement industry's direct emissions.

Alumina and aluminium

The level of primary aluminium production in 2021 was 68 Mt/y, with total aluminium production, including secondary production based on recycled aluminium, at almost 100 Mt/y. China is responsible for 54% of global alumina and 57% of global primary aluminium production. Coal as a source of electricity for the electrolytic aluminium smelting process and as process heat for the alumina refining process dominates in China, providing around 75% of the combined energy requirement. On a global basis, coal provides 57% of the aluminium smelting power, corresponding to 59 Mtce and 52% of alumina refining fuel consumption, corresponding to 22 Mtce.

The aluminium sector can achieve a technically and economically feasible path to NZE by 2050, with the main levers being:

- transitioning to low-carbon power could deliver around 650 $MtCO_2/y$ reduction by 2050, making it the single largest contributor;
- maximising secondary aluminium production delivers a further 456 $MtCO_2/y$, noting that recycling aluminium has a significantly lower carbon footprint of 0.5 tCO_2/t aluminium compared with 16 tCO_2/t aluminium for primary aluminium production;
- maximising resource efficiency, where product design uses aluminium more efficiently, could deliver 321 $MtCO_2/y$ reduction by 2050; and
- deploying new technology to deliver near zero emissions refineries and smelting facilities could deliver 232 $MtCO_2/y$ by 2050. Here, new technology is required to decarbonise thermal energy in refineries, such as heat recovery and fuel switching, low-carbon anodes and CCUS in smelters.

These measures would reduce coal usage through to 2050. However, due to the high dependence on coal in China for electricity generation to power the aluminium smelters, coal will remain in the energy mix at perhaps 50% of current levels, enabling around 30 Mtce continued usage to produce low-carbon electricity.

Chemicals

Three main primary chemicals are produced which form the precursors of all other chemical products. They are light olefins/alkenes and aromatic compounds, known as 'high value chemicals', ammonia and methanol.

The demand for primary chemicals will grow through to 2050, with methanol forecast to grow the most at around 7% per year, increasing demand from 100 Mt/y in 2020 to perhaps as high as 500 Mt/y by 2050.

The chemical industry is the largest consumer of fossil fuels of all industrial sectors, although it ranks third in terms of direct CO_2 emissions, behind cement and steel. This is due to 50% of the fossil hydrocarbons consumed in the chemical industry being used as feedstock.

The largest application of coal-to-chemicals is in China, primarily for ammonia and methanol production. Coal gasification accounts for around 26% of global ammonia production, and in China around 80% of ammonia and methanol is produced from coal. At the end of 2019, China had invested $85 billion in coal chemicals, with further investments taking place in Indonesia and India. The logic of using domestic feedstock rather than importing oil and gas is the driving force for developing coal-to-chemicals capacity.

The chemicals sector can be NZE compliant by 2050. This will be based on increased recycling, fuel switching to biomass, waste fuels and hydrogen, together with CCUS. Up to 640 $MtCO_2$/y of CCUS will be needed by 2050 to abate the system.

Coal will still be a significant energy source whilst achieving NZE compliance, accounting for around 2 EJ in 2050, equivalent to approximately 70 Mtce. This is in part because coal will remain an important source of ammonia and increasingly methanol in Asia.

Measures needed

A variety of measures will be required to achieve deep emissions reductions in industry. Technologies that are already mature with a technology readiness level of 11 (TRL 11) or in the early adoption phase (TRL 9-10) play an important role. They deliver savings from technology performance improvements, material efficiency gains, switching to bioenergy, and the electrification of low and medium temperature heat. These savings are particularly important in the short term but continue to play a role through to 2050. A large contribution is made by the gains from material efficiency by the construction sector (including buildings and infrastructure), which currently accounts for about half of all demand for steel and all of the demand for cement. In the longer term, fundamental technology shifts are needed and technologies currently at the demonstration (TRL 7-8) and prototype (TRL 4-6) stages play an integral role in these shifts. This is especially the case in heavy industry where innovative technologies incorporating CCUS and hydrogen will be key to achieving NZE (IEA, 2021a; 2022b; 2022f). CCUS is the most significant individual technology (*see* Figure 34).

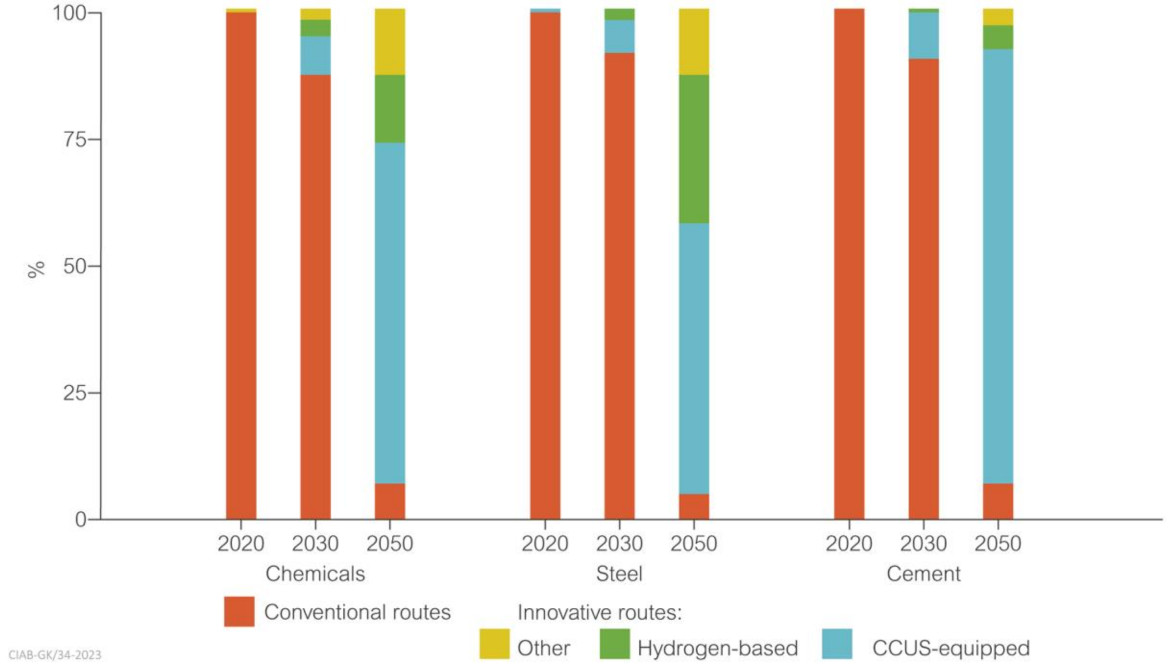

Figure 34 Technology routes to global heavy industrial NZE compliance (IEA, 2021a)

In terms of emissions, CCUS could contribute more than 2.5 $GtCO_2$/y to the reduction of emissions from manufacturing industry, as shown in Figure 35. It will make a significant contribution to the decarbonisation of cement in particular, due to the inherent process emissions of cement production. Fuel switching to hydrogen will also be a contributing solution to the decarbonisation of industry, with a value potentially approaching 190 MtH_2/y being required by 2050 (IEA, 2021a; IEA, 2022b). Hydrogen production issues are addressed specifically in a separate report by the ICSC (Zhu, 2023).

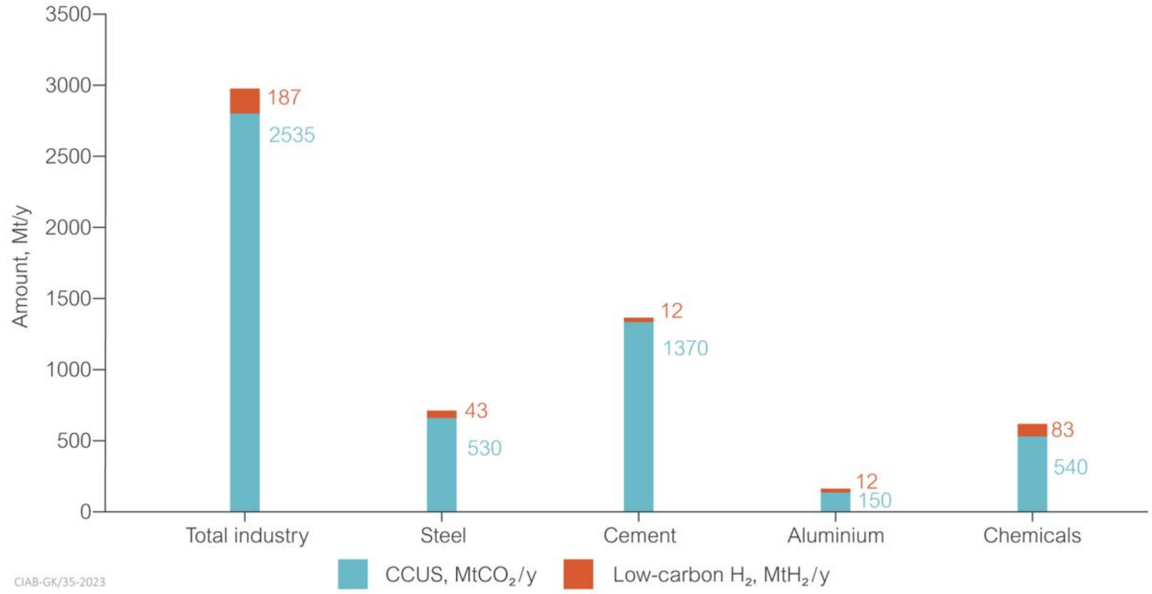

Figure 35 Enabling infrastructure capacity requirements for NZE by 2050 (WEF, 2022; IEA, 2021a)

CCUS is an over-arching decarbonisation technology for heavy industry. It is clear that for heavy industries to decarbonise in a cost-effective and resilient way, coal fitted with CCUS will be a key technology for all of the heavy industries assessed, particularly cement. CCUS as a technology is proven and understood and the various elements of the technology chain are in place for commercial deployment with several technologies now available at demonstration to commercial scale and applicable to the decarbonisation of heavy industries. Capture levels of 95% are routinely offered commercially and higher levels approaching 100% capture are technically achievable, particularly for the coal gasification and coal-to-liquid type processes. Industrial CCUS projects feature in the global list of commercial-scale projects, but more is needed to showcase coal-based heavy industrial projects, particularly iron and steel, and cement.

The majority of heavy industry is located in China, which has massive coal resources, wants to retain fuel independence, and is a leader in coal gasification and efficient power generation. For these reasons, CCUS is vital for industrial decarbonisation in China and hence the achievement of global NZE.

Finally, the potential for CO_2 storage globally is almost 14,000 Gt, sufficient to store approaching 2000 years of CO_2 emissions to meet net zero emissions projections. The location of CO_2 storage basins is generally near to emissions-intensive regions. Key regions for heavy industrial manufacture including China, Southeast Asia, the USA, India and Europe all have access to potential geological storage basins.

In order to reach net zero emissions at least cost, it will be vital that CCUS plays a substantial role in the decarbonisation of heavy industry. Notably, in their industry roadmaps for NZE, the international aluminium, cement, iron and steel and chemicals industries all see CCUS as required given the ongoing need to use fossil fuels.

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