China's impressive strides towards carbon capture, utilisation and storage (CCUS)

Illustrated through two case studies

Report prepared by Nathan Bongers,
Low Emission Technology Australia

LETA | CIAB

Low Emission Technology Australia

China's impressive strides towards carbon capture, utilisation and storage (CCUS): Illustrated through two case studies

Report prepared by Nathan Bongers

Report edited by Damian Dwyer and Clare Dahlstrom,
With special thanks to Siyuan Liu, Hanming Liu, Steve Malss, Peter Morris and Geoff Bongers

Coal Industry Advisory Board Working Group

Mick Buffier Glencore (Chair)

Paul Baruya FutureCoal

Michael Caravaggio Electrical Power Research Institute

Kate du Preez Anglo American

Damian Dwyer Low Emission Technology Australia

Nikki Fisher Thungela

Devinson Gil Anglo American

Peter Morris Minerals Council of Australia

Larry Sheng China Energy

Veronica Shime National Mining Association

Akira Yabumoto J-Power

Karl Bindemann Coal Industry Advisory Board

Preface

This report has been produced by Low Emission Technology Australia (LETA) for the International Energy Agency's (IEA) Coal Industry Advisory Board (CIAB). It is based on analysis of information provided by China Energy Investment Corporation (China Energy) and China Huaneng Group (China Huaneng), discussions with organisations and individual experts that have been integral to the development of the next generation of CCUS projects in China, and other relevant published literature. The assistance of those providing information and commentary is gratefully acknowledged. The views expressed in this report are those of the author's and not necessarily shared by those who supplied information, or our member organisations.

Introduction to LETA

LETA is a not-for-profit investment fund that accelerates the development and large-scale deployment of technology solutions to reduce and remove greenhouse gas emissions from critical industries like steel, cement and power generation.

LETA's investment in technology unlocks a faster, cheaper pathway to net zero for hard-to-abate industries that are critical to our economy, provide thousands of Australian jobs and support our households every day.

Since 2006, LETA members have contributed more than A$400 million to low emission projects and unlocked a total investment of A$1.1 billion. LETA members recognise the crucial role of low emission technology in enabling a net zero future for their industries, their customers, their workforces and Australian communities.

LETA works with our members, industry, governments, international trading partners and research organisations to unlock new technologies that will help meet Australia's climate targets and contribute to global emissions reduction.

LETA has invested in leading edge projects that explore opportunities for global decarbonisation across the energy and manufacturing lifecycle, with an investment portfolio focus on:

- Reducing emissions from resource extraction and mining operations.
- New advanced near-zero emission on-demand power generation and clean fuel technologies like hydrogen, using coal, natural gas or biomass.
- Decreasing the costs and improving the efficiency of carbon capture in many industries like steel, cement and fertiliser production.
- Facilitating partnerships between Australian industries and trading partners on large-scale carbon capture hubs.
- Developing large scale and cost-effective transport solutions for captured CO_2.
- Commercial utilisation of captured CO_2, including in food and beverage manufacturing and construction.
- Decreasing the costs, improving the efficiency and developing new areas for permanent and safe CO_2 storage.

Introduction to CIAB

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 drawn from 12 countries accounting for approximately 70–80 per cent 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.

Tables

Figures

Definitions

Equivalents

Chinese Yuan to US$: Exchange rate of 1 : 0.14

Case study organisations

China Energy: China Energy Investment Corporation

China Huaneng: China Huaneng Group

Units

GJ	gigajoule, one billion joules
GJ/tCO_2	gigajoule per tonne of carbon dioxide
Gt	gigatonne, 1000 million tonnes
GW	gigawatt, 1000 million watts
kg/tCO_2	kilogram per tonne of carbon dioxide
km/tCO_2	kilometre per tonne of carbon dioxide
kWh	kilowatt-hour, 1000 watt-hours
KWh/tCO_2	kilowatt hour per tonne of carbon dioxide
Mt	million tonnes
Mtpa	million tonnes per annum
MW	megawatt, million watts
Nm^3	normal cubic metre
Nm^3/h	normal cubic metres per hour
Tpa,t/a	tonnes per annum
TWh	terawatt-hour, one million megawatt-hours
RMB	Renminbi / Chinese Yuan
RMB/tCO_2	Renminbi per tonne of carbon dioxide
US$	United States dollar
US$/t$CO_2$	United States dollar per tonne of carbon dioxide

Acronyms and abbreviations

BECCS	biomass energy carbon capture and storage
CCUS	carbon capture, utilisation and storage
CERI	Clean Energy Research Institute
CO_2	carbon dioxide
DAC	direct air capture
DACCS	direct air carbon capture and storage
EOR	enhanced oil recovery
FOAK	first of a kind (NOAK—Nth of a kind)
H_2O	water
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
MVR	mechanical vapor recompression
N_2	nitrogen
NDC	nationally determined contributions
NDRC	China's National Development and Reform Commission
NO_x	nitrogen oxides
NZE	net zero emissions
PCC	post-combustion capture
R&D	research and development
RD&D	research, development and demonstration
SNCR	selective non-catalytic reduction
SCR	selective catalytic reduction
SO_2	sulfur dioxide
TRL	technology readiness level

Executive summary

Reaching net zero without CCUS will be 'all but impossible' ...

Following the ratification of the Paris Agreement in 2016, most Parties to the Agreement have committed to achieving net zero greenhouse gas emissions by 2050 (or earlier). Other major economies to commit to net zero include China and Indonesia by 2060 and India by 2070.

Parties to the Paris Agreement outline and communicate their proposed climate actions every five years through their Nationally Determined Contributions (NDCs). To date, 27 Parties include or reference carbon capture, utilisation and storage (CCUS) amongst these measures in their NDCs.

CCUS includes a suite of technologies that are used to capture and transport carbon dioxide (CO_2) to be injected into geological formations where it is trapped and permanently stored or to be utilised in a range of industrial applications and products.

The International Energy Agency has found that reaching net zero without CCUS will be 'all but impossible'. Similarly, the Intergovernmental Panel on Climate Change has pointed to the role for CCUS technologies in limiting the impacts of climate change.

CCUS is deployed in a wide range of industrial projects, including coal-fired power generation …

Carbon capture technology is deployed or is capable of being deployed across the globe in industries including but not limited to cement, steel, fertiliser, power generation and natural gas processing. For over 80 years, CO_2 has been captured, transported, and used by business and industry.

Coal-based CCUS technologies have been in operation since 2007 when the first capture of CO_2 from a coal-fired power station was undertaken at China Huaneng's Gaobeidian plant in Beijing. Subsequent demonstrations have seen the technology maturing to support wider technological deployment and improve capital and operating costs.

Over the past decade or so two significant, large-scale projects, both located in North America, have led the way for coal-based CCUS. The SaskPower, Boundary Dam 3 capture unit came online in 2014, with a design capture capacity of 1 Mtpa. The WA Parish power plant's Petra Nova CCUS project began in 2017 with a capture capacity of 1.4 Mtpa.

In Asia, where industrialisation and urbanisation continue, unabated coal remains the dominant source of energy. With the average age of the coal-fired power generation fleet in Asia being relatively low, the retrofit of CCUS to existing power plants is not only technically feasible, but key to enabling the region to reach net zero and still maintain energy security and accessibility.

The pipeline of CCUS projects continues to grow, but accelerating the pace of project development remains vital …

As of July 2024, there were 50 CCUS projects operating around the world, with capture capacity of around 51 Mtpa. An additional 44 projects, with capture capacity of 51 Mtpa, are under construction. The total pipeline of CCUS projects totals 628 projects, with capture capacity of 416 Mtpa.

A key goal for many nations as they seek to reduce emissions is to do so at the lowest possible cost. Many of these nations, particularly developing nations, have rapidly growing economies that rely on coal and natural gas and have established power generation fleets, and steel, alumina and cement plants.

This means there is an important role for low emission technologies, including CCUS, in reducing emissions in these 'hard-to-abate' sectors. The rapid scaling up of CCUS that is essential to meeting global emissions reductions targets can drive down costs through economies of scale and scope, and process and technology improvements.

China has a significant focus on CCUS due to its substantial domestic resources of coal and its emissions reduction ambitions …

As a Party to the Paris Agreement, China has outlined 'Dual Carbon Goals', to see emissions peak by 2030 and achieve carbon neutrality by 2060. China is a nation where CCUS will play a vital role in reducing emissions while ensuring energy security and economic growth are maintained.

China is the world's largest consumer, producer and importer of coal and operates the world's largest and one of the youngest fleets of coal-fired power stations. China also utilises coal in the world's largest chemicals industry and extensively in steel production along with a broad range of industrial applications.

China has been developing its domestic carbon capture technology expertise for over 20 years, with multiple industrial-scale pilot plants built to progress the development of capture technology. China has also been developing both stand-alone carbon capture technologies and various CCUS opportunities through to fully integrated capture-to-storage projects.

Post-combustion capture (PCC) is widely deployed across the globe and has been used commercially for more than 80 years. PCC equipment can be retrofitted to existing facilities, which has the potential to reduce both the cost and speed to operation. Given these advantages, China is focussing on PCC technology to decarbonise its fleet — the world's largest — of coal-fired power plants.

The importance of those low emission coal technologies is recognised within policy documents across multiple levels of the Chinese government. For example, the Global CCS Institute has identified more than 55 individual Chinese policies that exist in support of CCUS.

The multiple inclusions of CCUS in the 14th Five Year Plan, supporting the growing CCUS industry, highlights China's goal to 'Foster low-carbon development and the circular economy'. To scale-up low-carbon development, more investments in strategic clean and low-carbon technologies will be required.

In addition, China has a long history of international collaboration on CCUS and other low emission coal technologies. For example, the US–China 2023 Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis includes that '… the two countries aim to advance at least five large-scale cooperative CCUS projects each by 2030, including from industrial and energy sources.'

China's advancement of CCUS projects was initially supported by the demand for industrial use CO_2, including for food and industrial purposes, but now is heavily influenced by environmental drivers, particularly the 2030/2060 targets.

China has more than 100 CCUS demonstration projects either in operation, completed or in the development pipeline. The aim is to transition these through learning-by-doing from small- and medium-scale to large-scale operations. Among these projects, coal-based CCUS projects have a high priority.

CCUS in action: CCUS coal-fired power generation projects …

This report illustrates CCUS in action by outlining the development of new full-scale, operational and globally significant carbon capture projects deployed by China Energy and China Huaneng. These projects focus on reducing greenhouse gas emissions from coal-fired power generation in China.

China Energy

China Energy Investment Corporation (China Energy) is a key central state-owned energy enterprise that integrates 'coal, power, railway, port, and shipping', 'production, transportation, sales, storage and utilisation' and 'coal, power, oil, gas, and chemicals'.

China Energy started in the CCUS industry in 2015, and by 2021 had deployed the first 150,000 tpa PCC unit on coal-fired power generation in China, which remains a key testing facility for China Energy's capture technologies. To support China Energy's continued research and development, the coal-based National CCUS Technology and Research Development Centre was established in April 2023.

Launched in 2015, China Energy's Jinjie 150,000 tpa CCUS Demonstration Project, known as the Jinjie CCUS Project, located at the Jinjie Power Plant, has been recognised as a major 'sci-tech innovation project' of China Energy since 2016 and is listed in China's key research and development (R&D) projects.

As the first large scale deployment of CCUS on a coal-fired power generation project in China, China Energy collaborated with more than ten entities, bringing together industry and universities to move from research to large-scale applications.

As the project moved into construction, multiple challenges were addressed. These included new chemical project management standards and procedures, gaps in equipment safety technology, and the developing nature of core materials such as absorbents. The project continued to collaborate through multiple CCUS project implementation promotion and technical exchange meetings with universities, research institutes, and the design units to tackle these challenges.

Significant work was undertaken to develop a new blended amine absorbent, with high performance and low energy consumption, contributing to reducing the plant's regeneration energy consumption. In addition, China Energy developed process intensification equipment to reduce cost and explored efficient energy-saving processes across the plant.

Alongside the Jinjie project, China Energy developed the Taizhou 500,000 tpa Carbon Capture Demonstration Project, known as the Taizhou CCS Project, located at the Taizhou Power Plant in Jiangsu Province. This project was launched in 2023.

The Taizhou CCS Project also faced and overcame challenges along its development pathway. A key issue has been the long-term ability to find uses for the CO_2. To mitigate this risk and provide for the continuous operation of the project, China Energy is exploring opportunities to expand the CO_2 utilisation market, and invest into technical research into carbon storage, EOR and other chemical utilisation such as methanol or sustainable aviation fuel.

China Energy is now undertaking a feasibility study to deploy a full unit scale capture plant at the Jinjie Power Plant. This capture plant will be fed by the entire flue stream from one unit of the 600 MW coal-fired units, with an estimated capture rate greater than 90 per cent resulting in around 4 Mtpa of CO_2 being captured.

China Energy is also exploring the ability to store captured CO_2 in multiple saline aquifers. With this access to storage and maturing PCC technology, China Energy can now examine opportunities to deploy this technology at cement plants, iron and steel plants, and other thermal power plants across China.

China Huaneng

China Huaneng Group (China Huaneng) is a state-owned company with total assets of over 1.2 trillion RMB, an installed electricity capacity of over 2,059 GW and over 130,000 employees. China Huaneng also produces approximately 86 Mtpa of coal.

China Huaneng undertook the first capture of CO_2 from a coal power station in 2007. In 2006, it established the Clean Energy Research Institute (CERI) as an innovation research and development centre. CERI is dedicated to developing and commercialising advanced carbon capture technology and other clean energy technologies such as renewable energy, integrated gasification combined cycle and coal technology for China and the world. This includes construction of multiple demonstration projects, such as the 3,000 tpa CO_2 capture system in Beijing in 2008 (the first in China) and the 1,000 tpa two phases CO_2 capture industrial plant in Changchun in 2014, both at coal-fired power generators.

China Huaneng is constructing the largest coal-fired power generation capture plant in the world, a 1.5 Mtpa CCUS plant, capturing 27 per cent of the CO_2 from Unit 1 at the Longdong Energy Base in Gansu Province. The Longdong Project will demonstrate that coal with CCUS can be a flexible solution, co-existing alongside the increasing penetration of variable renewable energy in power generation.

China Huaneng continues to promote the integration of CCUS technology with traditional industries and emerging industries to support the development of low-carbon industry. This will also be demonstrated as part of the Longdong project with the integration of the capture and compression component (upstream) and CO_2 utilisation and storage (downstream).

A key challenge in integrating a PCC unit in a coal-fired steam power plant is that it traditionally leads to a reduction in net power generated. To reduce this efficiency loss, the Longdong Projects deploys an innovative new generation capture technology — a two-phase absorption solution. This has effectively reduced the heat consumption required for the capture plant.

In addition to this important innovation, a range of challenges have been addressed during the development and construction of the Longdong Project. These have included:

- The need for careful systems integration to ensure that the CCUS system can work flexibly along with the power plant unit.
- A policy regime that appropriately recognises the role of low emission technologies.
- The need for collaboration and research, development and demonstration (RD&D) to overcome storage cost hurdles, as the need for large scale dedicated geological storage grows.
- Effective ongoing communication to ensure all stakeholders remain fully informed on the important emission reduction opportunity demonstrated by projects such as Longdong, and that they can be undertaken in a safe and reliable manner.

Governments and industry have drawn valuable lessons from the operation of the projects …

Valuable lessons can be drawn from the development and construction of China Energy's Jinjie CCUS Project and Taizhou CCS Project and China Huaneng's Longdong Project.

These lessons include improved operating methods, novel optimisations, significant cost reductions for the next generation of coal-power with CCUS, reduced energy consumption per tonne of CO_2 captured, and strategies for optimising CO_2 capture. Six key lessons have emerged:

1 **China's success is driven by significant government support.** This includes the significant investment in research and development by both China Energy and China Huaneng. China's support for CCUS has also been explicitly led by government, which recognises the technology as a key enabler to reaching its carbon emission reduction pledges. China incorporates CCUS in policy and actively advocates for it in global decarbonisation.

2 **China's technical success will provide for a global scale-up of CCUS on coal power.** The technology developed can be deployed in coal-fired power stations across the globe, increasing the opportunities for other countries to follow in China's footsteps. The projects have demonstrated significant technical advancements for PCC units, with costs savings and efficiency improvements through 'learning-by-doing' as new units are developed. China Energy and China Huaneng have been able to reduce the cost of capture for these projects to under US$35/t$CO_2$, compared with current capture costs of greater than US$60/t$CO_2$. This results in a cost reduction of more than 40 per cent.

3 **Scale-up success**. Both China Energy and China Huaneng have been successful in significantly scaling-up their technology, with both the scale of the projects and technical readiness level improving with each new project. The projects are now significant assets to China's CCUS industry, providing opportunities for continual testing development and proving up CCUS technology.

4 **The CCUS business case continues to evolve.** CCUS technology is commercially available and has so far been successfully deployed in over 50 large-scale facilities and demonstration projects around the world. For the business case to improve, there are various factors to be considered, including but not limited to: capital expenditure cost, the cost of CO_2 storage or a market for CO_2 utilisation/sale.

5 **Speed at which projects move from concept to operation**. China has been investing in RD&D in the key areas of the CCUS value chain. These activities involve increasing levels of scale, system integration and operational learning-by-doing. This has been achieved in a relatively short timeframe partly informed by collaborative research and applying the public domain learning from other CCUS projects around the world.

6 **Application of the next generation's technological advancements to the harder-to-abate sector.** Capture technologies like PCC can also be applied to enable the harder-to-abate sector to decarbonise. This includes steel and cement facilities, responsible for around 14 per cent of global greenhouse gas emissions.

These projects send a clear signal to governments and policymakers that CCUS technology is available now and ready for deployment to help countries meet their Paris Agreement targets.

1 Introduction

Key points

Following the ratification of the Paris Agreement in 2016, most Parties to the Agreement have committed to reaching net-zero greenhouse gas emissions by 2050 (or earlier). Other major economies that have committed to net zero include China and Indonesia by 2060, and India by 2070.

Parties to the Paris Agreement outline and communicate their proposed climate actions every five years through their Nationally Determined Contributions (NDCs). To date, 27 Parties have included or referenced carbon capture, utilisation, and storage (CCUS) among these measures in their NDCs.

CCUS includes a suite of technologies used to capture and transport carbon dioxide (CO_2), which is then injected into geological formations where it is trapped and permanently stored, or utilised in a range of industrial applications and products.

The International Energy Agency has found that reaching net zero without CCUS will be 'all but impossible.' Similarly, the Intergovernmental Panel on Climate Change has highlighted the role of CCUS technologies in limiting the impacts of climate change.

The Global CCS Institute reports that as of July 2024, there were 50 CCUS projects operating worldwide, with capture capacity of around 51 Mtpa. An additional 44 projects, with capture capacity of 51 Mtpa, are under construction. The total CCUS pipeline totals 628 projects, with capture capacity of 416 Mtpa.

A key goal for many nations as they seek to reduce emissions is to do so at lowest possible cost. Many of these nations, particularly developing nations, have rapidly growing economies that rely on coal and natural gas and have established power generation fleets, and steel, alumina and cement plants. This means there is an important role for low emission technologies, including CCUS, in reducing emissions in these 'hard-to-abate' sectors. The rapid scaling up of CCUS, which is essential to meeting global emissions reductions targets can drive down costs through economies of scale and scope, and process and technology improvements.

As a Party to the Paris Agreement, China has outlined its 'dual carbon goals' to peak emissions by 2030 and achieve carbon neutrality by 2060. As a nation, China will rely on CCUS to play a vital role in reducing emissions while maintaining energy security and economic growth.

China is the world's largest consumer, producer, and importer of coal and operates the world's largest—and one of the youngest—fleets of coal-fired power stations. China also utilises coal in the world's largest chemicals industry and extensively in steel production and a broad range of industrial applications.

This report outlines the development of new, full-scale, operational, and globally significant carbon capture projects by China Energy Investment Corporation (China Energy) and China Huaneng Group (China Huaneng). These projects aim to reduce greenhouse gas emissions from coal-fired power generation in China. The report also examines the lessons that industry and governments can learn from China's approach.

Following the ratification of the Paris Agreement in 2016 [1],[1] most Parties to the Agreement have committed to achieving net zero greenhouse gas emissions by 2050 (or earlier). Other major economies to commit to net zero include China and Indonesia by 2060 and India by 2070. Parties to the Agreement have agreed to a range of commitments, including:

> Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change.

Parties to the Paris Agreement are also requested to outline and communicate their proposed climate actions every five years. This is achieved through their respective NDCs, whereby Parties commit to greenhouse gas emission reductions and outline the domestic mitigation measures they will implement to meet those commitments.[2]

To date, 27 Parties include or reference CCUS amongst these measures in their NDCs to 2030.[3] As technology continues to develop and costs decrease it can be expected that more countries will utilise CCUS because for many sectors it represents the only viable option to achieve near-zero emissions. This anticipated growing need for CCUS is also borne out by an examination of the '... long-term low greenhouse gas emission development strategies' also requested to be lodged by Parties to the Agreement.[4]

1 The Paris Agreement was negotiated at 21st yearly session of the Conference of the Parties (COP21) to the 1992 United Nations Framework Convention on Climate Change (UNFCCC) and the 11th session of the Meeting of the Parties (CMP11) to the 1997 Kyoto Protocol, held in Paris from 30 November–12 December 2015. The Agreement entered into force once joined by at least 55 countries which together represented at least 55 per cent of global greenhouse gas emissions. This occurred on 4 November 2016. The text of the Paris Agreement can be found at https://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf.

2 The UNFCCC notes 'Nationally determined contributions (NDCs) are at the heart of the Paris Agreement and the achievement of its long-term goals. NDCs embody efforts by each country to reduce national emissions and adapt to the impacts of climate change. The Paris Agreement (Article 4, paragraph 2) requires each Party to prepare, communicate and maintain successive nationally determined contributions (NDCs) that it intends to achieve. Parties shall pursue domestic mitigation measures, with the aim of achieving the objectives of such contributions.' The UNFCCC maintains a register of NDCs at https://unfccc.int/NDCREG.

3 Details of the commitments made by these 27 Parties are outlined in Global Carbon Capture and Storage Institute (2024). *Carbon Management in NDCs: Collation, Assessment and a Path Forward*. https://www.globalccsinstitute.com/wp-content/uploads/2024/12/Carbon-management-in-NDCs-Report.pdf.

4 As of 12 November 2024, 48 of 75 countries that have submitted these include CCUS as a mitigation activity. To this list can be added a further 10 countries that are yet to lodge their long-term strategies but have included CCUS in their NDCs: Armenia, Australia, Austria, Bahrain, Belgium, Cambodia, Canada, China, Cyprus, Czech Republic, Denmark, El Salvador, Germany, the European Union, Ethiopia, Finland, France, Hungry, Iceland, India, Indonesia, Ireland, Japan, Kazakhstan, Kuwait, Latvia, Lithuania, Malawi, Malta, Mexico, Mongolia, Morocco, Netherlands, New Zealand, Nigeria, Norway, Oman, Pakistan, Portugal, Qatar, Russia, Saudi Arabia, Singapore, Slovak Republic, Slovenia, South Africa, South Korea, Spain, Sweden, Switzerland, Thailand, Tunisia, Türkiye, Turkmenistan, Ukraine, United Arab Emirates, the United Kingdom, the United States, and Vietnam.

CCUS includes a suite of technologies that are used to capture, compress and transport CO_2 to be injected into geological formations (usually depleted oil and gas reservoirs or deep saline aquifers) where it is trapped and permanently stored or to be utilised in a range of applications and industrial products:

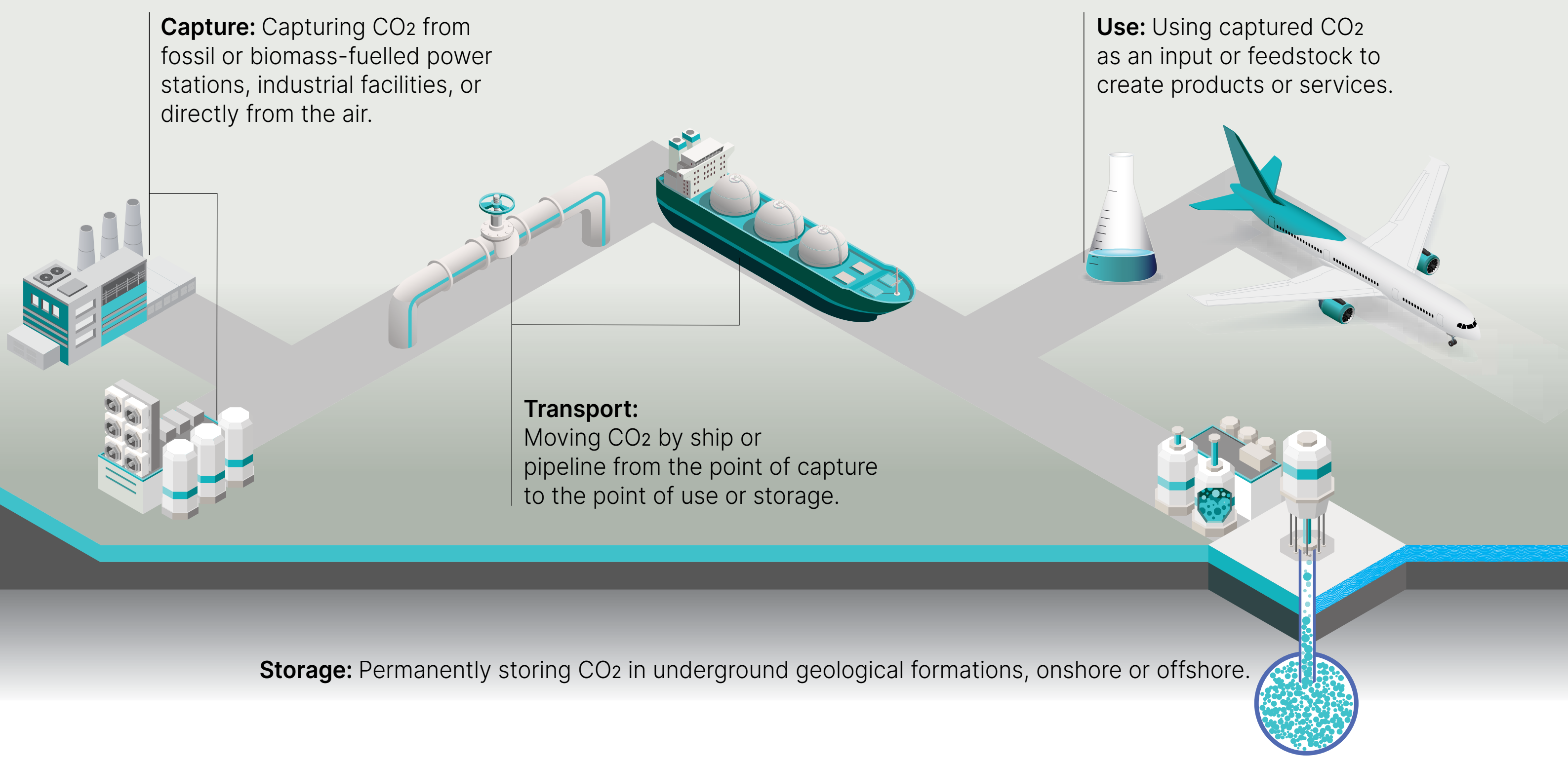
CO_2 has been safely transported and used in industry for over 80 years.

CCUS—whilst often viewed as a new technology—was first proposed in 1938 and was commercialised in the 1970s in the US to separate and capture CO_2 from oil processing operations and inject it back into oil reservoirs to enhance oil recovery.

A quarter of a century later, Norway launched the world's first integrated CCUS project, known as Sleipner, in the North Sea. Through these and other projects, CO_2 has been captured, compressed, and injected into underground geological formations, safely and permanently preventing this CO_2 from entering the atmosphere.

CCUS has a major role in reducing the emissions from a wide range hard-to-abate industrial sectors, including the production of steel, cement, fertiliser, chemicals and ethanol, natural gas processing, power generation and clean (low-emission) hydrogen production.

Figure 1: Overview of CCUS technology



1.1 Why CCUS is vital to realising Paris Agreement goals at least cost

The International Energy Agency (IEA), in its *2020 Special Report on Carbon Capture Utilisation and Storage: CCUS in clean energy transitions* [2], found that reaching net zero without CCUS will be 'all but impossible'. The IEA explained this finding on page 151 of the report, where it stated:

> The next decade will be critical to the prospects for CCUS and for putting the global energy system on a path to net-zero emissions. A significant scale-up of deployment is needed to provide the momentum for further technological progress, cost reductions and more widespread application in the longer term. Without a sharp acceleration in CCUS innovation and deployment over the next few years, **meeting net-zero emissions targets will be all but impossible**. [Emphasis added].

The IEA's 2024 update of its announced policy scenario and net zero emissions (NZE) scenario [3] found CCUS could account for around 8 per cent of the cumulative emissions reductions required under the NZE scenario (that would see the global energy sector achieve net zero emissions by 2050). This would require growth in CCUS projects and associated storage capacity to reach over 2.5 gigatonnes (Gt) by 2035 and almost 6 Gt by 2050. The IEA found that:

> For the next decade, the list of announced projects falls short of what is needed to capture 1.3 Gt CO_2 globally by 2035 in line with the APS, and still further below the 2.5 Gt CO_2 required in the NZE. To get closer to NDCs and net zero emissions targets, new projects are needed to reduce emissions from fossil fuel-fired power plants and in hard-to-abate industrial processes. [Page 163].

The IEA also finds that, while relatively modest, coal with CCUS plays a role reducing emissions in power generation and industry in 2050 as part of the IEA's NZE scenario.

Similarly, the Intergovernmental Panel on Climate Change (IPCC) has pointed to the role for CCUS technologies in limiting the impacts of climate change. The IPCC's *Climate Change 2023, Synthesis Report, Summary for Policymakers* [4] found:

> Implementation of CCUS currently faces technological, economic, institutional, ecological-environmental and socio-cultural barriers. Currently, global rates of CCUS deployment are far below those in modelled pathways limiting global warming to 1.5°C to 2°C. Enabling conditions such as policy instruments, greater public support and technological innovation could reduce these barriers.

The Global CCS Institute's *Global Status of CCS 2024* reports that as of July 2024, there were 50 CCUS projects operating around the world, with capture capacity of around 51 Mtpa. The report found an additional 44 projects, with capture capacity of 51 Mtpa, are under construction. The total CCUS pipeline (in operation, under construction, in advanced development or in early development) totals 628 projects, with capture capacity of 416 Mtpa [5].

Whilst CCUS has played a relatively small role in emissions reduction to date, the rapid scaling up of CCUS that is essential to meeting global emissions reductions targets can drive down costs through economies of scale and scope, and process and technology improvements.

There are four crucial ways in which CCUS technology can contribute to a cleaner energy future:

- It can be retrofitted to power and industrial plants and included as part of the construction of new power and industrial plants.
- It can reduce greenhouse gas emissions in sectors with limited other options, such as cement, steel and chemicals manufacturing, and in the production of synthetic fuels for long-distance transport.
- It enables the production of low-emissions hydrogen from coal and natural gas, a relatively low-cost option in several regions around the world.
- It can remove CO_2 from the atmosphere by combining it with bioenergy or direct air capture (DAC) to balance emissions that are unavoidable or technically difficult to avoid — a critical part of achieving 'net' zero goals.

1.2 The competitiveness of CCUS

A key goal for many nations as they seek to meet their emissions reduction targets is to do so at the lowest possible cost.

Many of these nations, particularly developing nations, have rapidly growing economies that rely on coal and natural gas and have relatively 'young' power generation, steel, alumina and cement plants. This means there is an important role for low emission technologies in reducing emissions in these 'hard-to-abate' sectors.

Learning by doing and technology development can play key roles in reducing costs and improving the competitiveness of CCUS. Government policies that encourage the development of common-user CCUS transport and storage hubs can also play an important role in industry development. Private investors and government officials are also exploring other areas to reduce costs including utilisation of the captured CO_2 for beneficial purposes and international strategic partnerships that utilise CCUS to cost effectively reduce emissions.

- The first area recognises that many CCUS projects to date have been for enhanced oil recovery (EOR) because EOR provides for improved resource utilisation can help offset the costs of capture. CCUS-EOR is an established process that is overseen by existing regulations and standards. It is also an important greenhouse gas mitigation technology.
- Many other uses of CO_2 are emerging as a commercial opportunity to help defray the cost of capture at power plants and industrial facilities. These include utilising CO_2 in the manufacture of food and beverages, in the production of urea and as a feedstock for fertiliser production. This focus on competitiveness is also on driving innovation and entrepreneurial leadership in developing new ways to use captured CO_2, such as producing CO_2-based synthetic fuels, chemicals and building aggregates.
- The second area recognises that international customers for coal, oil and natural gas are also Parties to the Paris Agreement and so have their own emissions reduction obligations. This means there are opportunities for energy exporters to work with their customers to see emissions reduced in both countries.

In other words, to achieve a country's net-zero goal at the lowest cost while maintaining economic growth, a range of solutions—both local and regional—will be required, with CCUS being an integral part of that mix.

- Local—harnessing cost-effective storage, if available, while considering CO_2 point sources, transport options, and geological storage capacity.
- Regional—some countries have limited storage options but could still utilise feedstocks from coal and natural gas to produce, for example, clean (low-emission) hydrogen, with storage occurring near the locations of these reserves and resources.

...to achieve a country's net-zero goal at the lowest cost while maintaining economic growth, a range of solutions will be required, with CCUS being an integral part of that mix.

1.3 Why focus on China?

China is an example of a nation where CCUS will play a vital role in reducing emissions while ensuring energy security and economic growth are maintained. China is the world's largest consumer, producer and importer of coal, with its consumption and production each accounting for around half of the global totals. China operates the world's largest and one of the youngest fleets of coal-fired power stations, reflecting its significant coal resources and the energy needs of its large, growing economy. It also utilises coal in the world's largest chemicals industry and extensively in steel production and in a broad range of industrial applications.

At the same time, as a Party to the Paris Agreement, China has outlined 'Dual Carbon Goals', to see emissions peak by 2030 and achieve carbon neutrality by 2060 [6,7].

1.4 Report structure

This report outlines the development of new full-scale, operational and globally significant carbon capture projects by China Energy and China Huaneng. These projects focus on reducing greenhouse gas emissions from coal-fired power generation in China. The report discusses the progress of these operating projects and their substantial contribution to China's emissions reduction commitments within a broader global context. It also provides examples of how coal with CCUS and renewables can complement each other—coal with CCUS serving as a clean backup power option to support large industries and ensure grid stability.

The report examines the lessons for industry and governments that can be drawn from China's approach to developing these projects. It also considers the implications of these projects both in terms of CCUS developments in China and globally, and how they can lead to real CO_2 reductions in a timely, cost-effective, and focused manner.

Following this introduction:

Chapter 2 of the report considers the global status of CCUS and provides an overview of post-combustion capture (PCC) technology and the application of PCC technology to coal-fired power generation.

Chapter 3 considers CCUS in China, its role in meeting Chinese greenhouse gas emission reduction commitments under the Paris Agreement, policies and regulatory arrangements to support CCUS and China's growing role in international collaboration, before providing an overview of Chinese CCUS projects and introducing the projects of focus for this report and their developers, China Energy and China Huaneng.

Chapter 4 provides an overview of China Energy's CCUS projects, with a particular focus on the Jinjie and Taizhou projects, as well as China Energy's plans for the future.

Chapter 5 follows a similar approach for the China Huaneng CCUS projects, with a particular focus on the world leading Huaneng Longdong CCUS project that recently commenced operation as part of the China Huaneng Longdong Energy Base in northwest China.

Chapter 6 highlights the lessons that both governments and industry can take from China's CCUS progress, particularly highlighting that China's technical success can benefit all, and that many of the lessons learned apply beyond the power sector, to include many parts of the hard-to-abate sector.

Chapter 7 presents the report's conclusions.

2

CCUS around the world

Key points

Carbon capture technology is already being deployed or is suitable for deployment globally across industries including cement, steel, fertiliser, power generation, and natural gas processing. For over 80 years, CO_2 has been captured, transported, and used by businesses and industries.

Coal-based CCUS technologies have been in operation since 2007, when the first capture of CO_2 from a coal-fired power station was undertaken at China Huaneng's Gaobeidian plant in Beijing. Subsequent demonstrations have seen the technology mature, supporting wider technological deployment and improving capital and operating costs. More recently, these CCUS technologies have been deployed at a large-scale at two coal-fired power stations in North America, as well as plants in China.

In Asia, where industrialisation and urbanisation continue, unabated coal remains the dominant source of energy. With the average age of the coal-fired power generation fleet in Asia being relatively low, retrofitting CCUS to existing power plants is not only technically feasible, but also key to enabling the region to reach net zero while maintaining energy security and accessibility.

CCUS networks, also referred to as hubs and/or clusters, continue to be developed globally, with shared infrastructure offering economies of scale and opportunities to decarbonise industrial hubs.

CCUS technologies related to coal include capturing CO_2 from coal-fired power stations, coal-to-chemicals and/or liquid plants, as well as steel and cement plants (where coal is used as an input).

PCC is the most widely deployed method of CO_2 capture globally and has been used commercially for more than 80 years. PCC equipment can be retrofitted to existing facilities, reducing both costs and speed to operation. Given these advantages, China is focussing on PCC technology to decarbonise its coal-fired power plants.

Coal-based PCC projects have been in operation for many years, allowing the technology to progress from lab scale to full-size commercial applications. Notable demonstration projects include China Huaneng's Shindongku 120,000 tpa capture plant and the 150,000 tpa capture plant at Alabama Power's Plant Barry.

Over the past decade or so two significant, large-scale projects, both located in North America, have led the way for coal-based CCUS. The SaskPower, Boundary Dam 3 capture unit came online in 2014, with a design capture capacity of 1 Mtpa. The WA Parish power plant's Petra Nova CCUS project began in 2017 with a capture capacity of 1.4 Mtpa.

The industry has gained valuable insights from the operation of these plants, including improved operating methods, novel optimisations, significant cost reductions for the next generation of coal power with CCUS, reduced energy consumption per tonne of CO_2 captured, and strategies for optimising CO_2 capture.

Leading climate agencies, including the IEA have identified the critical role that CCUS technology must play to achieve Paris Agreement targets. The IEA have declared 'achieving net-zero goals will be virtually impossible without CCUS' [2]. Technologies that have been identified as crucial include CCUS, bioenergy with carbon capture and storage (BECCS) and direct air carbon capture and storage (DACCS). CCUS is also a key component in the production of clean hydrogen and ammonia [8].

Carbon capture technology is deployed or is capable of being deployed across the globe in industries including cement, steel, fertiliser, power generation and natural gas processing.

For over 80 years, CO_2 has been captured, transported, and used by business and industry. Additionally, CO_2 separation technology has been deployed in natural gas processing and other industries for decades. Although this by-product CO_2 can be of very high purity, it was initially vented because there were no large scale uses for it. The first instance of CO_2 being captured and not emitted into the atmosphere as part of gas processing occurred in the 1970s, with the CO_2 being utilised through EOR [8].

The Sleipner CCS project has been successfully and safely storing CO_2 underground in a saline aquifer since 1996, in a location 800 metres–1,000 metres under the Norwegian North Sea [9–11]. In 2018, after 20 years of operation, it was reported that the project had stored over 16 million tonnes of CO_2 [12].

Coal-based CCUS technologies have been in operation since 2007 when the first capture of CO_2 from a coal power station was successfully undertaken at China Huaneng's Gaobeidian plant in Beijing. The plant had a capture capacity of 3,000 tpa [13]. Subsequent demonstrations have proven that CCUS technology is maturing to support wider technological deployment and improve capital and operating costs. More recently, CCUS technology has been deployed at a large scale at two power stations in North America (Boundary Dam in Canada and Petra Nova in the United States), as well as multiple plants in China [8,14].

While many regions across the world are moving away from coal-fired electricity, other countries will continue to rely on it for decades. In Asia, where industrialisation and urbanisation are still underway, unabated coal remains the dominant source of energy [15]. With the average age of the coal-fired power generation fleet in Asia being relatively low, and without a pathway to replace the capacity with renewable alternatives at the speed required by the Paris Agreement [1], the retrofit of CCUS to existing power plants is not only technically feasible, but key to enabling the region to reach net zero and still maintain energy security and accessibility [16].

CCUS networks, also referred to as hubs and/or clusters, continue to be developed across the globe, with common infrastructure having the ability to provide economies of scale advantages and provide opportunities to decarbonise industrial hubs [8]. A relevant example of clusters is seen in the UK, where the UK Government has committed '£21.7 billion of funding for carbon capture projects located in the East Coast Cluster and the HyNet cluster, marking a crucial step forward in the development of these large scale CCUS clusters' [17]. This funding support has enabled Equinor to reach Final Investment Decision and financial close on the Northern Endurance Partnership, which includes the onshore facilities required to collect CO_2 from multiple locations, before bringing the CO_2 to a central compression facility where it is compressed and then transported via pipeline to a subsea injection site, 145 kilometres offshore. [18]

2.1 What is CCUS?

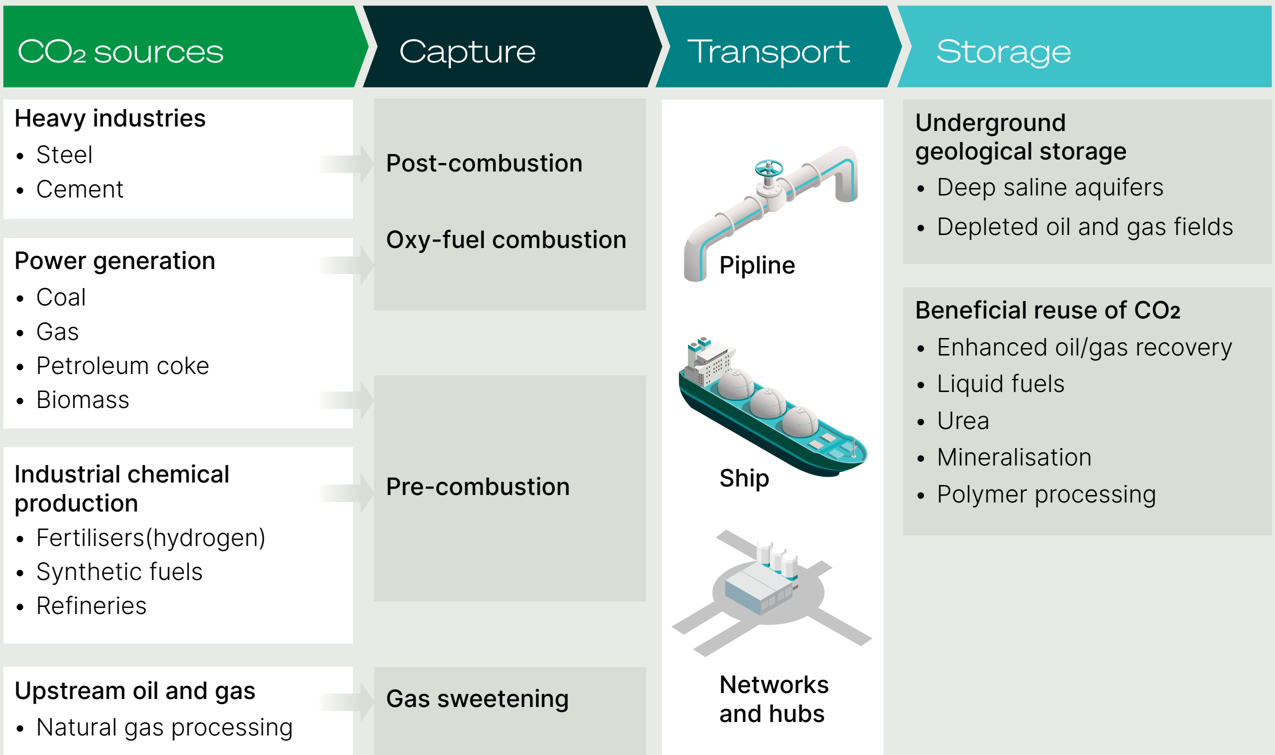
CCUS is an umbrella term for a range of technologies that have been developed to prevent CO_2 from entering the atmosphere by capturing it and either using or permanently storing it. During the capture process, CO_2 is separated out from other gases and particles in the exhaust stream. The remaining pure CO_2 is then compressed into a liquid-like state called supercritical carbon.

After capture, the liquid carbon can then be transported by road tanker, ship or pipeline. Transporting carbon is similar to other fluids such as liquefied natural gas and oil, and has been transported safely this way for more than three decades. The CO_2 is then compressed and transferred by pipelines and/or ships to a suitable storage site for injection deep underground. This could either involve storage in depleted oil and gas fields or in deep saline aquifers. Alternatively, the CO_2 can be utilised in a beneficial way, including being used in concrete, fuels, and other industrial processes [19]. This process is outlined in Figure 2.

Technologies along the CCUS value chain are at various stages of commercial availability. Capture technology is available for deployment across a range of industries, including cement, steel, fertilisers, power generation and natural gas processing, and can be used in the production of clean hydrogen and ammonia [8].

CCUS technologies related to coal include capturing CO_2 from coal-fired power stations, capture from coal to chemicals and or liquid plants, as well as steel and cement plants (where coal is an input). Following the capture and purification of CO_2, the rest of the CCUS value chain follows a consistent process, regardless of the original emissions source.

Figure 2: CCUS value chain



2.2 What is PCC?

PCC is the most widely deployed method of CO_2 capture globally and has been used commercially for more than 80 years. PCC equipment can be retrofitted to existing facilities which reduces both the cost and speed to operation, providing a pathway for near-term CO_2 capture. Given these advantages, China is focussing on PCC technology as a way to decarbonise its coal-fired power plants.

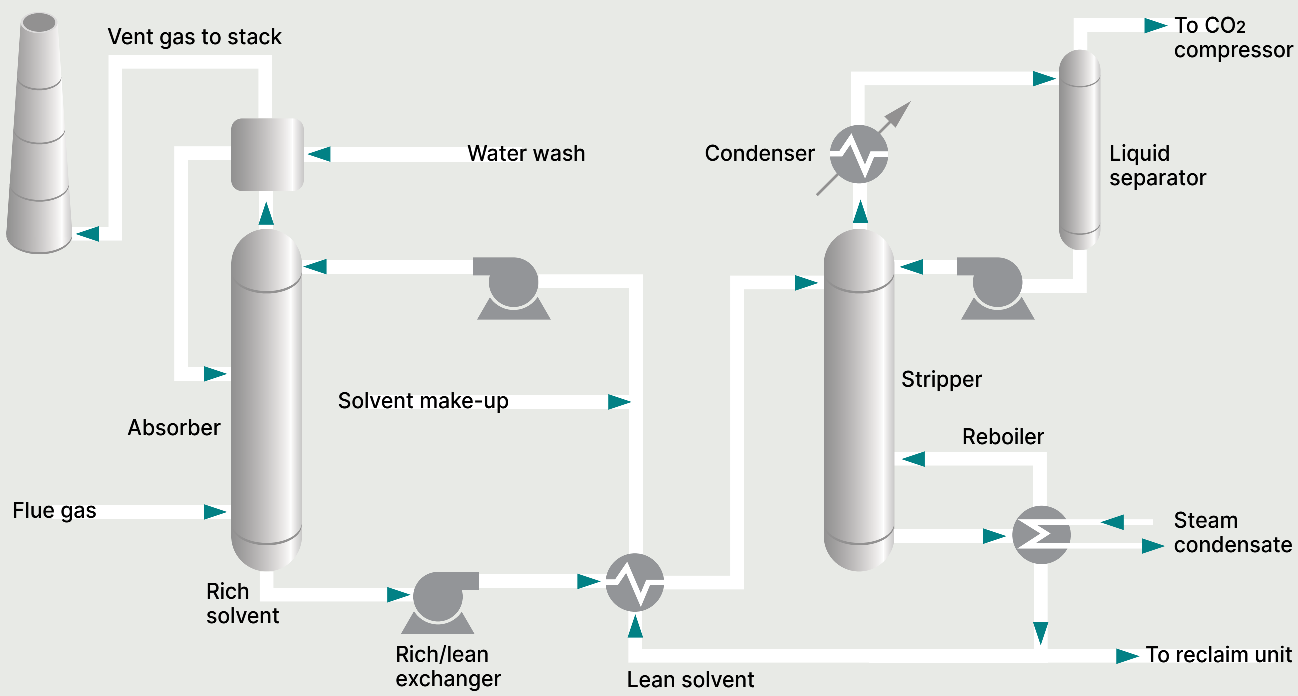
PCC is the capture of CO_2 from flue gas derived from the combustion of fuels such as coal [20] and natural gas [21] as well as processes occurring in cement kilns, steel mills and other sites that are fed by coal, natural gas or bio-mass (a carbon source). Some industrial processes also include chemical reactions that create additional CO_2 emissions.

At a traditional coal-fired power station, coal is combusted in air, and the liberated heat is converted to steam that in turn drives a steam turbine to produce electricity. The combustion of coal results in a flue gas mixture that primarily consists of nitrogen (≥70%), CO_2 (10–15%), oxygen (2–5%) and water.

When a PCC unit is retrofitted to a flue stream, instead of being vented, the flue stream will enter the PCC plant, which will separate the CO_2 from the rest of the flue stream prior to venting the remaining flue gases and particulates. The CO_2 is then purified in readiness for permanent storage or utilisation.

While multiple PCC technologies exist, the most commonly deployed technology is an advanced sorbent system that utilises a chemical liquid 'amine' to which the CO_2 molecule becomes attached. The sorbent is then passed through a stripper or desorption column, which traditionally utilises steam to heat the sorbent, releasing the CO_2 from the sorbent. This results in a pure stream of CO_2 and regenerated sorbent. Figure 3 provides a flow chart of the typical solvent process, illustrating how the flue gas enters the absorber where the CO_2 bonds with the solvents, before passing through to the stripper where the solvent is heated, releasing the CO_2 from the solvent.

Figure 3: Typical solvent PCC process [22]



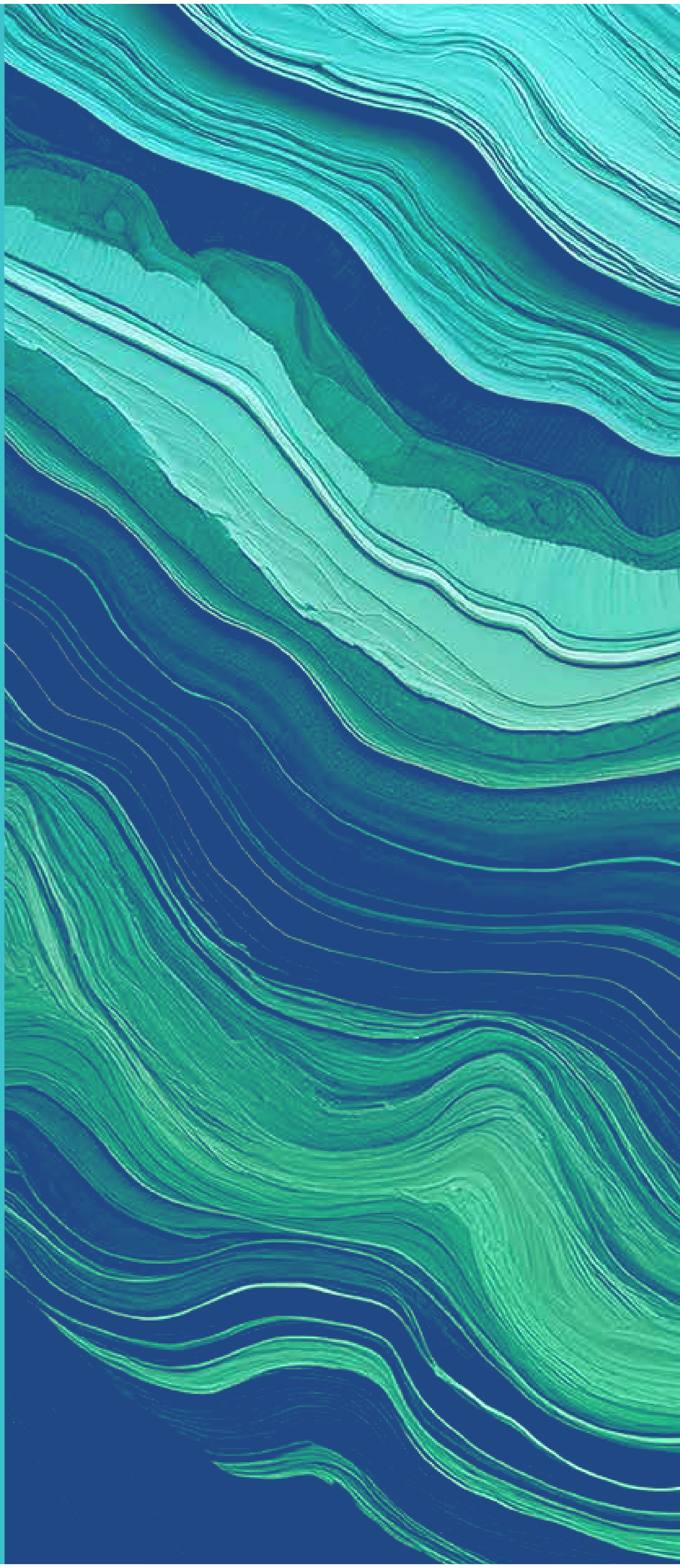
2.3

Snapshot of PCC projects on coal

Coal-based PCC projects have been in operation for many years, with many demonstration projects deployed across the world. This experience has enabled the technology to progress from lab scale to full-size commercial applications. Some of the demonstration projects of note include China Huaneng's Shindongku 120,000 tpa capture plant (operations began in 2009) [23] and the 150,000 tpa capture plant at Alabama Power's Plant Barry (operations began in 2011) [24].

Over the past decade two significant, large-scale projects, both located in North America, have led the way for coal-based CCUS. The SaskPower, Boundary Dam 3 capture unit came online in 2014, with a design capture capacity of 1 Mtpa. The WA Parish power plant's Petra Nova CCUS project began in 2017 with a capture capacity of 1.4 Mtpa.

The industry has drawn valuable lessons from the operation of these plants, including improved operating methods, novel optimisations, significant cost reductions for the next generation of coal-power with CCUS, reduced energy consumption per tonne of CO_2 captured, and strategies for optimising CO_2 capture.



3 CCUS in China

Key points

China places significant focus on CCUS due to its substantial domestic coal resources, the prominence of coal as an energy source for both power generation and industrial development, and its emissions reduction ambitions.

China has been developing its domestic carbon capture technology expertise for over 20 years, with multiple industrial-scale pilot plants built to advance the development of capture technology. Additionally, China has been developing both standalone carbon capture technologies and various CCUS opportunities through fully integrated capture-to-storage projects.

The importance of low-emission coal technologies is recognised in policy documents across multiple levels of the Chinese Government. Reflecting this, the Global CCS Institute has identified more than 55 individual policies that support CCUS.

The multiple inclusions of CCUS in the 14th Five-Year Plan, which support the growing CCUS industry, highlight China's goal to 'Foster low-carbon development and the circular economy'. To scale up low-carbon development, more investments in strategic clean and low-carbon technologies will be required.

In addition, China has a long history of international collaboration on CCUS and other low-emission coal technologies. For example, the US-China 2023 Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis includes a commitment that '… the two countries aim to advance at least five large-scale cooperative CCUS projects each by 2030, including from industrial and energy sources.'

China's advancement of CCUS projects was initially driven by the demand for industrial CO_2, including for food and industrial purposes, but is now heavily influenced by environmental factors, particularly the 2030/2060 targets.

China has more than 100 CCUS demonstration projects either in operation or in the development pipeline. The goal is to transition these projects through learning-by-doing, from small- and medium-scale to large-scale operations. Among them, coal-based CCUS is a high priority.

This report focusses on CCUS coal-fired power projects by China Energy and China Huaneng.

China Energy started in the CCUS industry in 2015 and by 2021, had deployed the first 150,000 tpa PCC unit on coal-fired power generation in China, which remains a key testing facility for China Energy's capture technologies. To support China Energy's continued research and development, the coal-based National CCUS Technology and Research Development Centre was established in April 2023.

China Huaneng conducted the first capture of CO_2 from a coal-fired power station in 2007. In 2006, it established the Clean Energy Research Institute (CERI) as an innovation and research development centre. CERI is dedicated to developing and commercialising advanced carbon capture technology, along with other clean energy technologies, such as renewable energy, integrated gasification combined cycle, and coal technologies for both China and the world.

China places significant focus on CCUS due to its substantial domestic coal resources, the prominence of coal as an energy source for both power generation and industrial development, and its emissions reduction ambitions.

China utilises coal extensively for thermal electricity production, with around a quarter of all coal used to produce electricity, burnt in China's relatively young and highly efficient coal-fired power generation fleet. China also uses coal as an input for steelmaking, cement production, as well as for chemicals used to make plastics and fertilisers.

According to the IEA, in 2024 [25]:

- China was the world's largest coal consumer, accounting for 4,939 Mt of coal consumption, over 56 per cent of global demand.
- The majority (85%) of this consumption was thermal coal, amounting to 4,146 Mt, primarily used for power generation. The remaining 737 Mt was metallurgical coal, which is essential for steelmaking.
- Coal-fired power generation accounted for 60 per cent of China's electricity supply.
- China was responsible for 52 per cent of global coal production, with the IEA estimating total production in China of 4,653 Mt out of global coal production of 9,068 Mt.
- Electricity generation is responsible for about 74 per cent of China's thermal coal demand and about 63 per cent of its total coal demand.
- Chinese coal-fired power generation accounted for around 52 per cent of global coal-fired power generation.
- China's thermal coal consumption for non-power uses was 1,094 Mt, representing 22 per cent of the country's total coal consumption.
- Consuming over 200 Mt annually, cement production is the largest industrial consumer of thermal coal. China also uses coal across various industries, including food, textiles and paper.
- China used 40 Mt of coal to produce approximately 11 Mt of oil products.
- Ammonia for fertilisers is mainly produced using synthesis gas from coal gasification. It is estimated that China produced 48 Mt of ammonia from coal.
- Coal-to-chemicals involves the gasification of coal to synthesis gas, which is then processed into products like methanol or ethylene glycol. The IEA estimates that 80 Mt of methanol was produced. It is often converted into olefins for plastics production, while ethylene glycol is used for polyester and other materials.

China's utilisation of coal as a primary energy/fuel source is also a factor of its relatively small domestic reserves of both oil and natural gas, and significant domestic coal reserves and resources. For example, in 2020, China's proved coal reserves were estimated at 143 billion tonnes — 35 years of production at current rates. China has the world's fourth-largest coal reserves — after the United States, Russia and Australia — with roughly 13 per cent of the global total.

China's reliance on coal features in its primary policy and national directive documents, but the government also views CCUS as playing an essential role in reaching carbon neutrality. This support features in both policy and regulatory frameworks, as well as individual support from key government officials.

At the United Nations General Assembly in September 2020, President Xi outlined China's 'Dual Carbon Goals' (2030/2060 targets), that China would 'peak' its CO_2 emissions before 2030 and become carbon neutral before 2060 [6].

China subsequently released various climate and environmental policy documents ahead of the 2021 Conference of the Parties meeting (COP26), including its 1+N policy framework. This consists of overarching guidance (the '1') and action plans and policy measures for key sectors and industries (the 'N'). As the Global CCS Institute highlights [8]:

> Since 2020, most of the released policy documents within China's '1+N' climate framework at the national and sectoral level have incorporated CCS. The '1+N' climate framework refers to a series of directives guiding China's efforts to peak emissions before 2030 and achieve carbon neutrality by 2060. There is also a growing interest from the sub-national authorities — around 10 provincial governments have included CCS development in their decarbonisation efforts. The national consensus is clear that CCS will play an essential role in China's carbon neutrality journey.

China has been developing its domestic carbon capture technology expertise for over 20 years, with multiple industrial-scale pilot plants built to progress the development of capture technology. China has also been developing both stand-alone carbon capture technologies and various CCUS opportunities through fully integrated capture-to-storage projects. Though China is developing multiple permanent storage locations, many of the capture projects to date have focussed on utilising the CO_2 through EOR and other food, industry, and beverages applications.

In late 2019, a report by the Centre for Climate Change and Environmental Policy, Chinese Academy of Environmental Planning indicated that as of August 2019, China had nine capture demonstration plants and 12 geological utilisation and storage projects. Ten of the geological utilisation and storage projects are full-process demonstration projects [26].

In addition to those nine capture demonstration plants, a further nine CO_2 capture projects were also operating in China, with a total capture rate of 1.7 Mtpa and a focus on coal-based technology. Following the announcement of China's 2030/2060 targets, this already established momentum has accelerated [27].

In 2022, Sinopec commissioned the country's first integrated, large scale CCUS project and since then China has made major CCUS advances every year. For example, in mid-2019 China was the location of only one of 19 operating, large scale CCUS project on the Global CCS Institute's CO2RE database [28]. By October 2024, 14 of the 52 listed projects were in China with a further six having reached Final Investment Decision or under construction.

3.1 Policies

The importance to China of coal as an energy source and driver of industrial development underscores the need to reduce the associated CO_2 emissions utilising technologies such as CCUS. The importance of those low emission coal technologies is recognised within policy documents across multiple levels of the Chinese government. As outlined in the Global CCS Institute's 2022 *Repositioning CCUS for China's Net-Zero Future* progress review [29], more than 55 individual policies exist that support CCUS.

In the 14th Five-Year Plan documentation, CCUS is highlighted and supported in many different sectors/areas. Table 1 provides a snapshot of the various references to CCUS in the 14th Five-Year Plan documentation.

The multiple inclusions of CCUS in the 14th Five-Year Plan, supporting the growing CCUS industry, highlight China's goal to 'Foster low-carbon development and the circular economy'. To scale up low-carbon development, increased investments in strategic clean and low-carbon technologies (that is, CCUS and green hydrogen technologies) are required [30].

In February 2024, China's National Development and Reform Commission (NDRC) released its 2024 catalogue of green-transition-related industries [31]; the catalogue included CCUS as a greenhouse gas emission control technology. This development will provide an additional impetus to CCUS uptake and deployment across China [32]. That is because the catalogue serves as guidance for local governments and financial institutes as to the sectors and technologies for which support should be provided.

In July 2024, an action plan was released by both the NDRC and the National Energy Administration to promote the low-carbon transformation of coal-fired power generation. As outlined in the action plan, China will work towards expanding low-carbon, coal-fired power generation with the goal of significantly reducing both the construction and operating costs, while ensuring that greenhouse gas emissions will decline by around 50 per cent from the level in 2023 [33].

Table 1: China's 14th Five-Year Plan documentation [29]

Date	Name	Contents
3 December 2021	14th Five-Year Plan on Industrial Green Development	CCUS is included in exploration of industrial carbon abatement pathway, focusing on technology, demonstration, and financing policy support.
6 December 2021	14th Five-Year Plan for High-Quality Development Standardization Mechanism Establishment	CCUS standards were included.
22 March 2022	14th Five-Year Plan on Modern Energy System	The document mentioned CCUS in terms of major national demonstration projects in provinces like Shanxi, Shaanxi, Inner Mongolia and Xinjiang, exploring commercial pathway, providing financial support and enhancing international collaboration.
2 April 2022	14th Five-Year Plan for Science and Technology Innovation in Energy Sector	The document highlights CCUS technology application and development in depleted oilfield and green use of coal where mega tonne all-chain demonstration projects and relevant technology research are planned.
1 May 2022	14th Five-Year Plan for Renewable Energy	Encourage demonstration on BECCS.

3.2 International collaboration

China has a long history of international collaboration on CCUS and other low emission coal technologies. Some of the programs that have existed include:

- US-China Clean Energy Research Center (CERC). [34]
- Australia China Joint Coordination Group on Clean Coal Technology (JCG). [35]
- Cooperation Action within CCS China-EU (COACH). [36]
- Near-Zero Emissions Coal plant China-UK (NZEC). [37]
- China-France Carbon Neutrality Center. [38]
- Sino-Italy Cooperation on Application of CCS to Coal Fired Power Plants. [39]

China and the US have also been cooperating on energy issues through programs initiated by the private sector. For example, the US–China Energy Cooperation Program, or government-to-government, with the most recent being the US–China 2023 Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis. This statement reaffirms the commitment of both China and the United States to work jointly and together with other countries to address the climate crisis. The statement includes that 'The two countries aim to advance at least five large-scale cooperative CCUS projects each by 2030, including from industrial and energy sources.' [40]

As part of this climate cooperation, representatives from both China and the United States have held a number of exchanges to promote practical results [41]. The Sunnylands Statement reiterates that the world's two largest economies see CCUS as a critical element on the journey to net zero emissions.

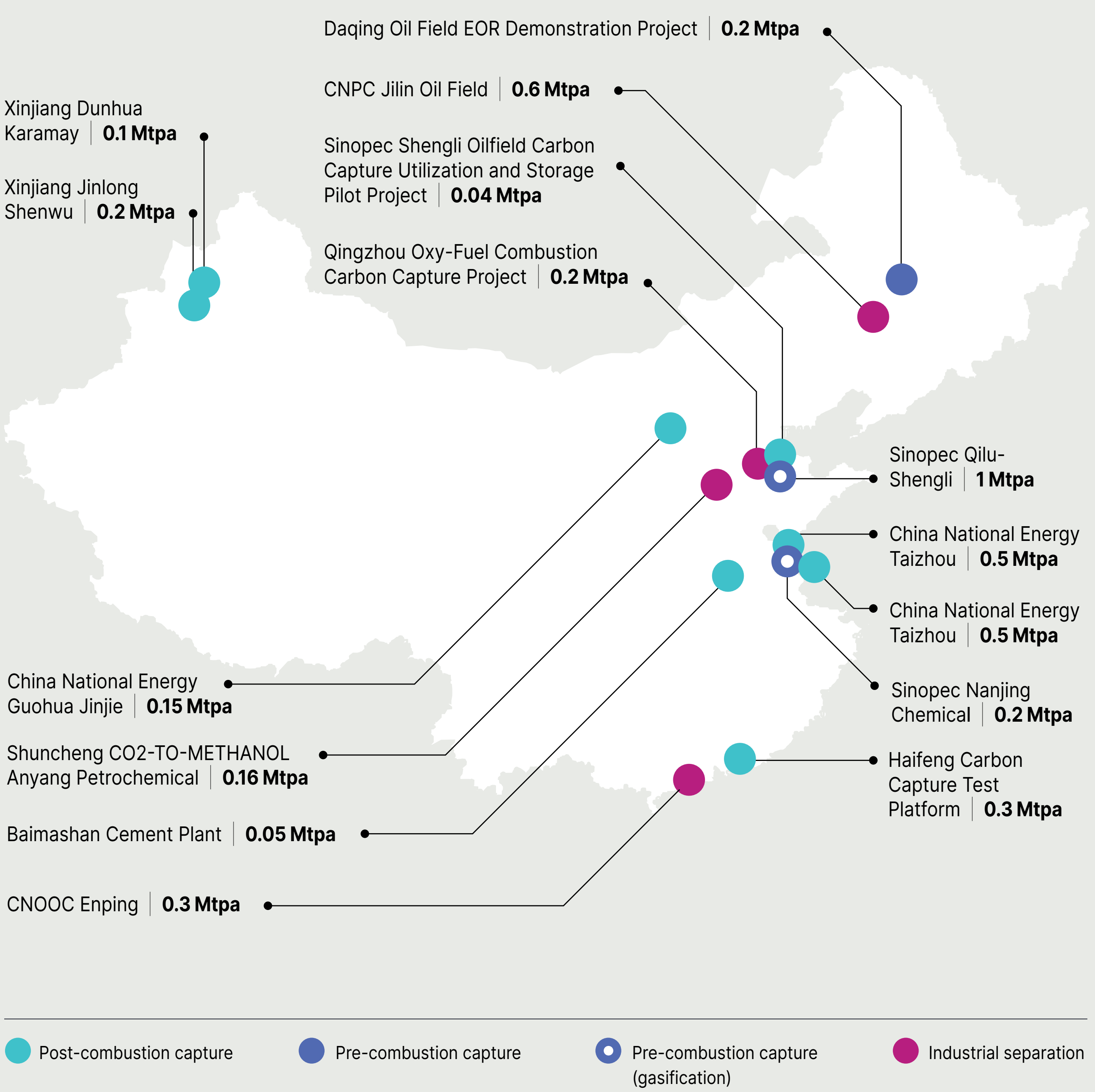
3.3 Projects to date

China currently has more than 100 CCUS demonstration projects either in operation or in the development pipeline. The aim is to transition these through learning-by-doing from small- and medium-scale to large-scale operations. In addition, they are expected to evolve from dispersed operations to a hub and cluster approach where feasible. Among these projects coal-based CCUS has a high priority.

In 2021, the 150,000 tpa capture unit at China Energy's Jinjie Power Plant was commissioned, followed by the 500,000 tpa plant at their Taizhou Power Plant in 2023. In 2023, a 1 Mtpa plant as part of the Sinopec Qilu Petrochemical Oilfield (coal-gasification) project also commenced. Other coal related CCUS projects operating in China include the Sinopec Nanjing Chemical plant (coal-to-chemicals, 200 tpa), the Yangchang Yulin CO_2-EOR chemical project (300 tpa), the Guanghui Energy Methanol Plant (100 tpa) and Sinopec Jinling Petrochemical's Nanjing Refinery, which involves hydrogen production from coal (300 tpa).

Currently, a 200,000 tpa capture plant is being built by Shenwu Energy, a 1.5 Mtpa Longdong plant by China Huaneng, a 3 Mtpa coal-to-liquids project by China National Energy Ningxia and a 500,000 tpa capture unit by Baotou Steel Group, more than doubling the 2019 capture capacity in China. Figure 4 shows the distribution across China of some of the operating CCUS project. A more detailed overview of the many CCUS projects, demonstrations and research and development work being undertaken in China can be found in Table 9 located in the Appendix.

Figure 4: Some of the operational CCUS projects in China



China's advancement of CCUS projects was initially supported by the demand for industrial use CO_2, including for food and industrial purposes, but now is heavily influenced by environmental drivers, particularly the 2030/2060 targets.

3.4 Introducing China Energy and China Huaneng

This report focusses on CCUS coal-fired power projects by China Energy and China Huaneng.

China Energy

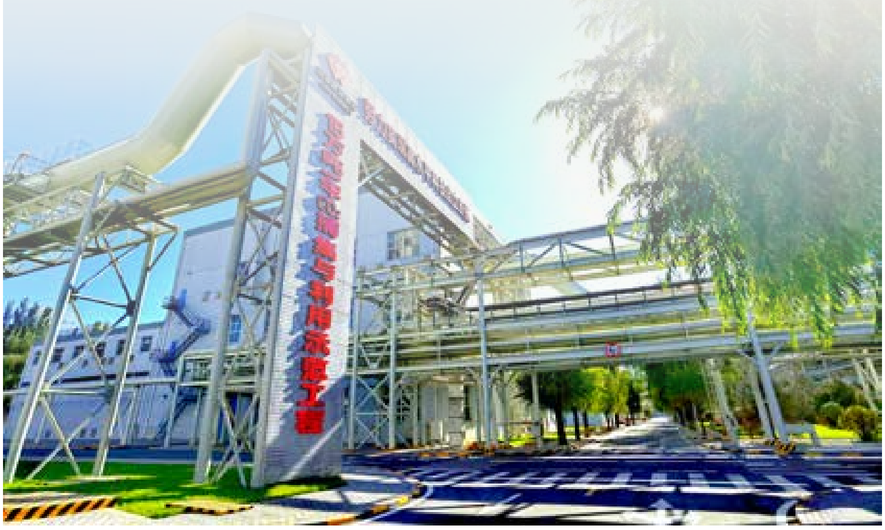
China Energy started in the CCUS industry in 2015 and, after attending an event with the IEA in 2016, it agreed that CCUS deployed on coal-fired power was an essential 'tool in the toolbox'. By 2021, China Energy had deployed the first 150,000 tpa PCC unit on coal power in China, which remains a key testing facility for the further development of China Energy's capture technologies. To support China Energy's continued research and development, the coal-based National CCUS Technology and Research Development Centre was established in April 2023.

The National CCUS Research and Development Centre has focused on four key areas of research and development:

1. Efficient and low-energy CO_2 capture.
2. Multi-channel CO_2 resource utilisation.
3. Large scale CO_2 geological storage.
4. CCUS Development strategies and policies.

Since China's 12th Five-Year Plan, the National CCUS Research and Development Centre has been actively engaged in coal-based energy CCUS innovations, exploring various CO_2 capture methods such as absorption, adsorption, membrane separation, and oxygen-enriched combustion. The Centre is also exploring opportunities to develop and improve CO_2 utilisation and storage approaches including geological storage, mineralisation utilisation, EOR, and chemical utilisation. This research is supporting multiple CCUS demonstration projects underway in China.

Chapter 4 highlights the path that China Energy has taken as they develop their CCUS activities.



China Huaneng

In 2006, it established CERI as an innovation research and development centre with support from the Ministry of Science and Technology of China and the National Energy Administration of China. CERI is dedicated to developing and commercialising advanced carbon capture technology and other clean energy technologies such as renewable energy, integrated gasification combined cycle (IGCC) and coal technology for China and the world [42]. China Huaneng undertook the first capture of CO_2 from a coal power station in 2007.

China Huaneng has also cooperated with multiple domestic and foreign universities, along with domestic and foreign research institutions, on CCUS research and development utilising the opportunity to learn from international advanced technology and management experience. Through China Huaneng's wide integration across research and upstream and downstream industry, China Huaneng promotes the use of CCUS technologies for traditional industries as well as emerging industries, thereby helping to build a low-carbon industry chain.

CERI utilise multiple research laboratories as part of their CCUS work, including their coal-based Clean Energy State Key Lab and their Beijing Key Lab of CO_2 Capture and Process. These two facilities, as well as their CCUS pilot facility in Shanghai, have enabled CERI to take significant steps forward to becoming a leading CCUS player.

Chapter 5 focusses on China Huaneng's Longdong CCUS project.

4 China Energy CCUS plants

Key points

China Energy was established on 28 November 2017. It is a key central state-owned energy enterprise that integrates 'coal, power, railways, ports, and shipping,' as well as 'production, transportation, sales, storage, and utilisation,' covering sectors such as 'coal, power, oil, gas, and chemicals.'

Launched in 2015, China Energy's Jinjie 150,000 tpa CCUS Demonstration Project—known as the Jinjie CCUS Project and located at the Jinjie Power Plant—has been recognised as a major 'sci-tech innovation project' by China Energy since 2016 and is listed among China's key R&D projects.

As the first large-scale deployment of CCUS on a coal-fired power plant in China, China Energy collaborated with more than ten entities, bringing together industry and academia to move from research to large-scale applications.

As the project moved into construction, several challenges were addressed. These included new chemical project management standards and procedures, gaps in equipment safety technology, and the evolving nature of core materials, such as absorbents. The project continued to collaborate through multiple CCUS project implementation promotion and technical exchange meetings with universities, research institutes, and the design units to tackle these challenges.

Significant work was also undertaken to develop a new blended amine absorbent, with high performance and low energy consumption, helping to reduce the plant's regeneration energy use. In addition, China Energy developed process intensification equipment to cut costs and explored energy-saving processes across the plant to improve efficiency.

Alongside the Jinjie CCUS Project, China Energy developed the Taizhou 500,000 tpa Carbon Capture Demonstration Project, known as the Taizhou CCS Project, located at the Taizhou Power Plant in Jiangsu Province. This project was launched in 2023.

The Taizhou CCS Project also faced challenges throughout its development. A key issue has been the long-term ability to find uses for the CO_2. To mitigate this risk and ensure the continuous operation of the project, China Energy is exploring opportunities to expand the CO_2 utilisation market and invest in technical research on carbon storage, EOR, and other chemical uses, such as methanol or sustainable aviation fuel.

China Energy is currently conducting a feasibility study to deploy a full-scale capture plant at the Jinjie Power Plant. This capture plant will be fed by the entire flue stream from one unit of the 600 MW coal-fired units, with an estimated capture rate greater than 90 per cent resulting in approximately 4 Mtpa of CO_2 being captured.

China Energy is also exploring the ability to store captured CO_2 in multiple saline aquifers. With this access to storage and maturing PCC technology, China Energy can now assess opportunities to deploy this technology at cement plants, iron and steel plants, and other thermal power plants across China.

4.1 China Energy

With the approval of the Communist Party of China Central Committee and the State Council, China Energy was formally established on 28 November 2017, following the merger of China Guodian Corporation and Shenhua Group. China Energy is a key central state-owned energy enterprise that integrates 'coal, power, railway, port, and shipping', 'production, transportation, sales, storage and utilisation' and 'coal, power, oil, gas, and chemicals'. It is a pilot enterprise that integrates state-owned capital investment company reform, world-class model enterprise, and state-owned corporate governance model enterprise. In 2024, China Energy ranked 84th in the Fortune Global 500 [43].

China Energy operates across the whole industry value chain, including coal, power, transportation and chemicals. They achieve globally leading performance in safe and advanced coal production, clean, efficient and stable coal-fired power generation, transportation and logistics integration, diversified and low-carbon modern coal-to-chemicals, and diversified, innovative and large-scale development of new energy. At the end of 2023, China Energy had 310,000 employees with total assets of RMB2.1 trillion. China Energy has a 665 Mtpa coal production capacity alongside 320 GW of installed power generation capacity, an exclusive railway network of 2,708 kilometres, seaborne ports with 290 Mtpa handling capacity, and 5.31 Mtpa coal-to liquids annual total production capacity.

In 2023, China Energy produced and sold 620 Mt and 830 Mt of coal respectively, generated 1,200 TWh of electricity, delivered 570 Mt of freight through its railways and produced 29.23 Mt of chemicals. To put this into global perspective, if China Energy was a country, it would rank fourth in total electricity generation, behind only China at 9,459 TWh, the US at 4,249 TWh, and India at 1,967 TWh [44].

4.2 Introduction to Jinjie and Taizhou

Launched in 2015, the Jinjie 150,000 tpa CCUS Demonstration Project, known as the Jinjie CCUS Project, (located at the Jinjie Power Plant), has been recognised as a major sci-tech innovation project of China Energy since 2016 and is listed in China's key research and development projects. This project began with a three-year research and development period, progressing to a two-year construction period and then a year-long optimisation and operation period. This resulted in China's first 150,000 tpa post-combustion CO_2 capture with EOR, and geological storage, whole value chain, demonstration being completed in 2021.

Alongside the Jinjie project, China Energy also developed a scaled-up project, the Taizhou 500,000 tpa Carbon Capture Demonstration Project, known as the Taizhou CCS Project, located at the Taizhou Power Plant in Jiangsu Province. Operations commenced at the 500,000 tpa Taizhou CCS project on 2 June 2023 and by 31 October 2023 had successfully captured 300,000 tonnes of liquid CO_2.

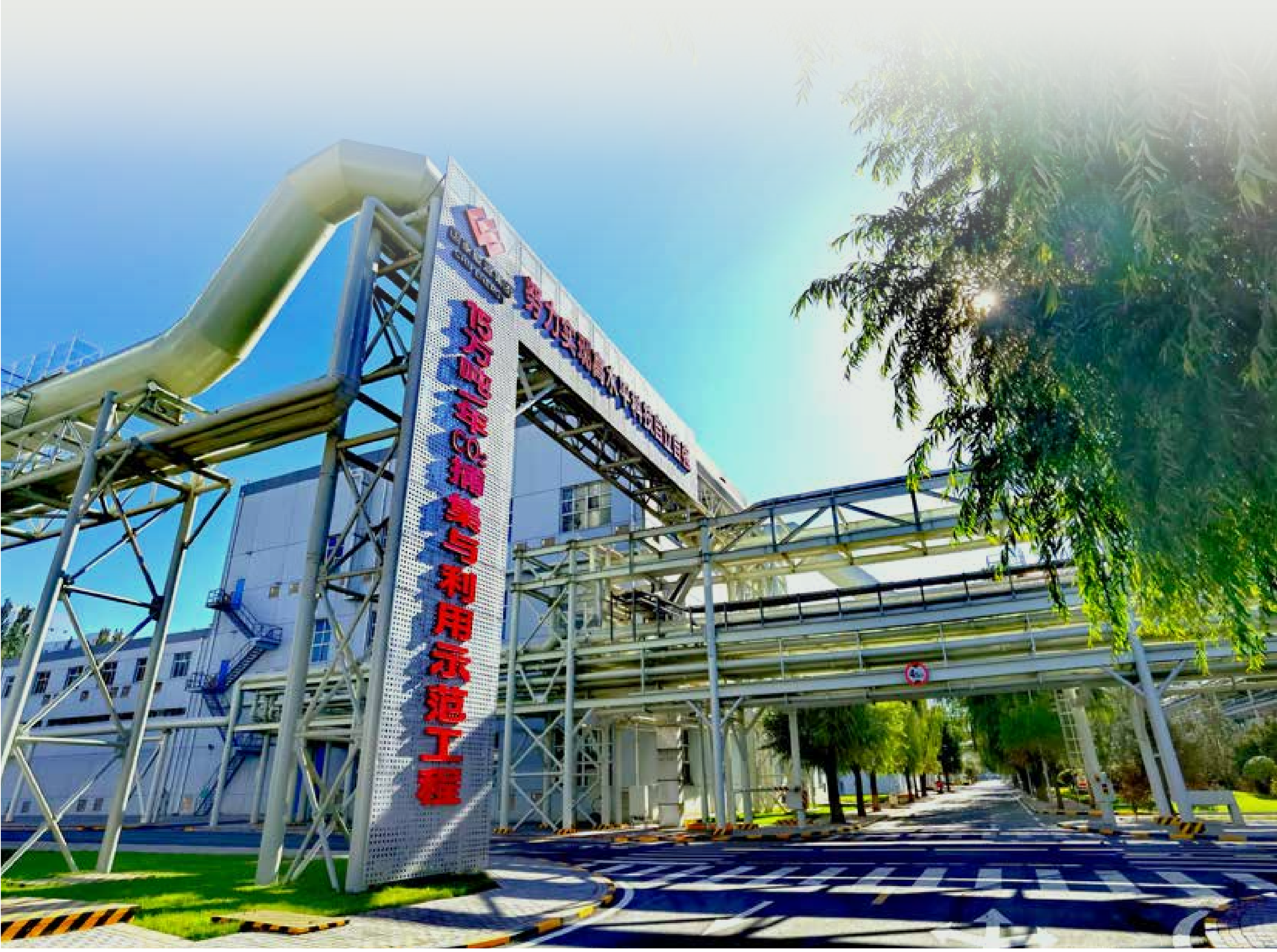
As China Energy continues to align with China's goal for carbon peaking by 2030 and 'Carbon Neutrality' by 2060, China Energy continues to progress the deployment and scaleup of CCUS. China Energy has announced a 4 Mtpa project, aiming to capture 100 per cent of the flue gas of one unit of the 600 MW coal-fired units, at a coal power station, achieving a greater than 90 per cent carbon reduction. Though in the early stages of development, this project demonstrates the significant investment that China is making into a low-carbon future.

4.3 Jinjie CCUS project

Initiated in 2015, China Energy's Jinjie 150,000 tpa CCUS demonstration project is located at the 3.7 GW Jinjie power plant. China Energy took three years to progress this project from early research and development stages to construction. In 2016 it was China Energy's major scientific and technological innovation project, included as one of the National Key Research and Development Program Projects, and highlighted as one of Shaanxi Province's key construction projects.

As this was a demonstration project, after the two years of construction, a year of operational optimisation occurred, prior to official 'commercial' operations. The project successfully completed a 168-hour operational trial on 25 June 2021. The project has now completed over 950 days of safe and stable operations.

Figure 5: Jinjie 150,000 tpa CCUS demonstration project



Process walk through

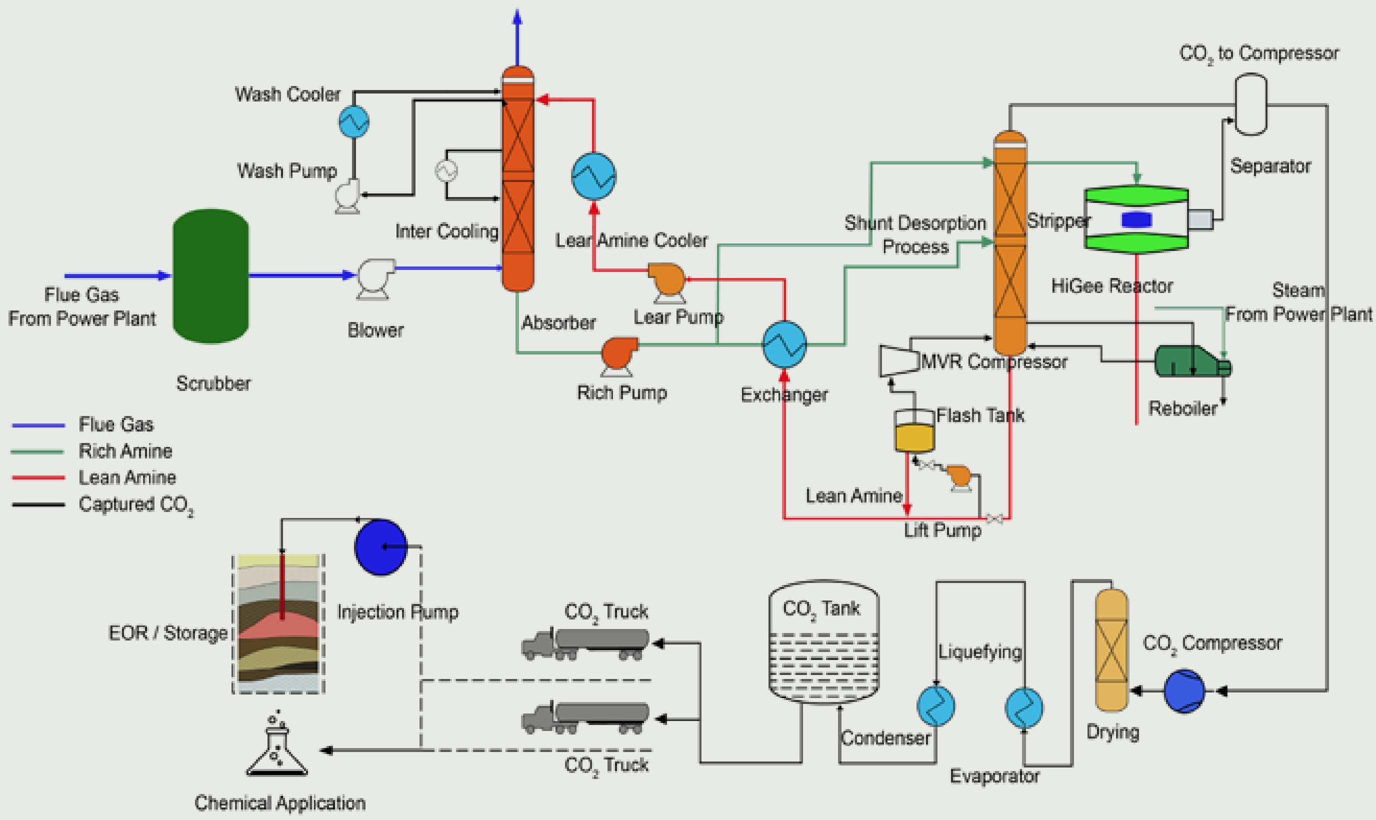
The capture plant at Jinjie is fed through a 4–5 per cent offtake from Unit 1's flue stream. Prior to the offtake, the flue gas exiting the power plant boiler passes through denitrification, dedusting and desulfurisation treatment. The gas entering the capture facility's primary components are N_2 (70.7%), H_2O (12.1%), CO_2 (11.1%), O_2 (6.1%).

Most of China Energy's 600 MW and greater coal-fired units have applied denitrification and desulfurisation facilities. Multiple different types of these facilities are applied across China Energy's fleet; desulfurisation facilities include limestone gypsum flue gas desulfurisation, sea water flue gas desulfurisation and others, with the denitrification facilities primarily being based on selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) technologies.

Unit 1 of the Jinjie power plant deploys SCR technology for denitrification and limestone gypsum flue gas desulfurisation for desulfurisation. SCR uses a reducing agent to selectively react with the nitrogen oxides (NOx) in the flue gas with a catalyst, to convert the NOx into nitrogen (N2) and water (H_2O). SCR technology is relatively mature and very effective in reducing NOx in boiler flue gas. It has become one of the most widely used and effective flue gas de-nitrification technologies in the world. This technology ensures that Jinjie Power Plant meets its environmental requirements/standards, which includes NOx concentrations below 50 mg/normal cubic metre (Nm^3) and a sulfur dioxide (SO_2) concentration of less than 35 mg/Nm^3.

Figure 6 provides an overview of the various components of the capture plant, including the input and outputs of the process.

Figure 6: Jinjie CCUS Project capture plant process diagram

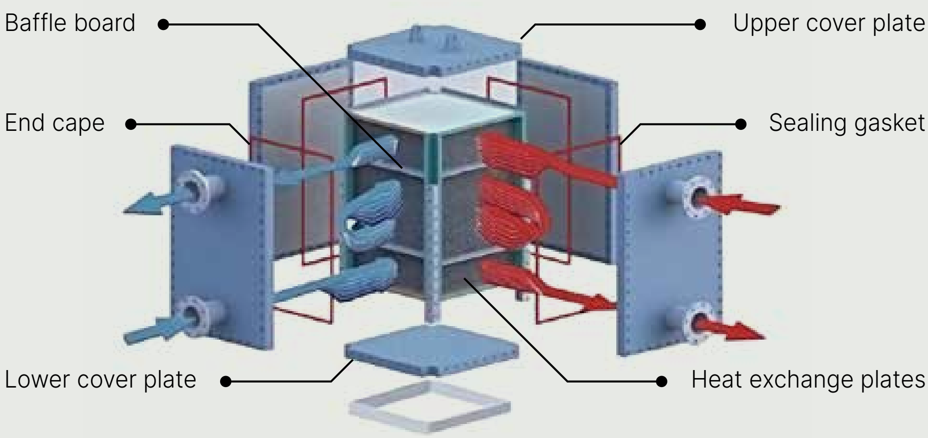


China Energy developed a new blended amine absorbent which enabled the project to achieve low energy consumption without hindering capture performance. It has also developed a new heat exchanger capable of handling the low temperature difference between the lean and rich amine. These developments, as well as modified plastic fillers, staged intercooling in the absorber, splitting the CO_2-rich solvent feed into the stripper, and utilising mechanical vapor recompression (MVR) flash technology have enabled China Energy to reduce energy consumption and reduce costs.

A new blended amine absorbent enabled the project to achieve low energy consumption without hindering capture performance and a new heat exchanger capable of handling the low temperature difference between lean and rich amine.

Figure 7: Some of the new process equipment designed for Jinjie CCUS project

Lean/rich amine heat exchanger with low temperature difference



Modified plastic filler

Four layers of stainless steel filler + a single layer of modified PP filler

Auxiliary load

A key constraint in the retrofitting of PCC technology is the auxiliary load placed on the plant through the demand for steam and electricity. This demand placed on the existing plant either significantly affects the plant's total net available electricity production or requires a plant to build a gas turbine and a heat recovery steam generator plant to supply the required steam and electricity.

Petra Nova is an example of the latter, building a 78 MW co-generation plant to meet the required load. This plant was sized for the steam requirement with the capture plant only requiring approximately 35 MW with the remainder of the power sold into the local energy market [45]. This demand for auxiliary services has led to capture developers placing a significant focus on reducing the required gigajoule of energy per tonne of CO_2 (GJ/tCO_2) captured with multiple reports outlining the importance of reducing this load below what is considered a baseline of 2.5 GJ/tCO_2 steam requirements [46].

Solvent regeneration is one of the largest uses of energy in a traditional solvent-based, PCC CO_2 capture island. Regeneration heat consumption refers to the total amount of heat required to release the CO_2 from the CO_2-rich solvent in the regeneration column (alternatively a desorption and separation device) of a capture system. As a result, it is often used as an efficiency metric for CCUS projects as it focuses on the energy performance of the absorbent during the absorption and desorption of CO_2.

The electrical consumption refers to the total electricity required for all the electrical equipment or device units in the capture system. The electrical power consumption of the CO_2 capture island can be used as a comparison of the design features of a capture system. The factors affecting electrical power consumption are related to the design of the capture system's devices, such as height, diameter, and packing surface area of the stripper, the scrubber, and other equipment, with less correlation to the overall performance of the absorbent.

To support the deployment of PCC technology, it is important to minimise the total energy consumed by a capture plant, which is the combination of the electrical consumption and regeneration heat consumption. After the optimisation of the plant was complete, China Energy was able to operate their capture plant with a regeneration heat consumption of under 2.35 GJ/tCO_2. Under optimal operating conditions, the plant has been able to reach a regeneration heat consumption of 2.16 GJ/tCO_2. The plant has been able to achieve a total electrical consumption of approximately 80 kWh/tCO_2 for the capture island (excluding the compression and liquefication requirements).

Table 2: Jinjie CCUS project energy consumption breakdown

Energy consumption	kWh	Unit
Regeneration heat consumption	2.16	GJ/tCO_2
Electrical consumption	80	kWh/tCO_2

Cost

The full-scale capture cost for this project, is under 185 RMB/tCO_2 (US$25.45) (including labour costs and depreciation). While the primary focus of the project is research and development, it also includes a commercial element as the captured CO_2 is sold externally. The CO_2 is predominantly transported by truck, with the transport cost being under 1 RMB/km/tCO_2 (US$0.14). The CO_2, which is stored through EOR, has a storage cost of below 50 RMB/tCO_2 (US$6.88).

Table 3: Jinjie CCUS project cost breakdown

Item	RMB	US$	Unit
Capture cost	185	25.45	/tCO_2
Storage cost	<50	<6.88	/tCO_2
Transport cost	1	0.14	/km/tCO_2

Hurdles overcome to enable the project to succeed

As the first large scale deployment of CCUS on a coal-fired power plant in China, China Energy collaborated with more than ten entities, bringing together industry and universities to move from research to large-scale applications.

Significant work was undertaken to develop a new blended amine absorbent, with high performance and low energy consumption, contributing to reducing the plant's regeneration energy consumption. In addition, China Energy developed process intensification equipment to reduce cost and explored efficient energy-saving processes across the plant.

As the project moved into construction, multiple challenges needed to be overcome. These included entirely different chemical project management standards and procedures compared with China Energy's previous thermal power plant projects, gaps in equipment safety technology, and the further development of core materials such as absorbents. The project continued to collaborate through multiple CCUS implementation promotion and technical exchange meetings with universities, research institutes, and design units to address these challenges. This collaborative approach is not new to China Energy, which has extensive experience and successful research and development achievements in ultra-low emission coal-fired power technology and environmental processes.

4.4 Taizhou CCS project

At the 4 GW Guodian Taizhou power plant in Jiangsu Province is China Energy's 500,000 tpa PCC CO_2 capture plant. Construction was initiated on 22 March 2022, with liquid CO_2 first produced on 27 May 2023 before officially commencing commercial operation on 2 June 2023. This project represents a significant scaling up of China Energy's post-combustion process successfully deployed at the Jinjie plant. Now operating stably, as of January 2025 the plant had successfully captured over 300,000 tonnes of CO_2.

The captured CO_2 from this plant is utilised in multiple industrial processes, including but not limited to, welding shielding gas, dry ice, and high-tech machinery cleaning. This CO_2 utilisation benefits from the very high purity rate the capture plant produces, with CO_2 purity of greater than 99 per cent.

Figure 8: Taizhou 500,000 tpa carbon capture demonstration project

Scale up

Both the Jinjie plant and the Taizhou plant are scale-up projects to China Energy's 1,000 ton and 10,000 ton CO_2 capture test platforms. China Energy had to undertake numerous steps to scale-up the technology. The core designs, key technologies, and equipment processes were successfully adapted and applied to the 500,000 tpa carbon capture project at the Taizhou Power Plant. This achievement marks the successful transfer and implementation of the carbon capture technology and process package to a larger scale, providing a blueprint for further scale-up.

As part of the significant scale-up undertaken, China Energy developed the amine recovery device, utilising a new drying method, which reduced the amine loss by over 50 per cent. China Energy also developed a high-efficiency, small addendum angle filler, which reduced the pressure drop of absorber by 30 per cent and improved the mass transfer by 15 per cent. These improvements, along with a ternary compound amine absorbent (which enhances the absorption capacity and its resistance to degradation), illustrates some of the lessons that China Energy learned and applied at the Tazhiou CCS Project.

An amine recovery device, utilising a new drying method, reduced the amine loss by over 50 per cent.

Process walk through

The flue gas being fed to the capture plant is typical of most of China Energy's facilities across China. The flue gas composition consists of approximately 65–75 per cent N_2, 10–15 per cent CO_2, 6–12 per cent water vapour and other minor components.

The Taizhou coal-fired power plant applies SCR technology for denitrification and limestone gypsum flue gas desulfurisation for desulfurisation to process the flue gas stream. Through this, the NO_x concentration in the flue gas can be reduced to less than 50mg/Nm^3 and SO_2 concentration to less than 35mg/Nm^3.

The flue gas enters the carbon capture device from the dedusting system of the thermal power unit, and firstly undergoes the water washing process, and then enters the absorber for the low-temperature absorption of CO_2. After high-temperature desorption of the gaseous CO_2 in the stripper, it is compressed, gas-liquid separated and condensed to make liquid CO_2. In the Taizhou CCS Project, the HiGee Reactor and MVR Compressor are removed from the capture, compression and liquefaction stages of the process. The captured CO_2 will be fully applied to physical utilisation (for example, dry ice products, welding shielding gas), which is different from the Jinjie CCUS project.

With China Energy's high concentration absorbent, the Taizhou CCS Project achieves CO_2 capture rates exceeding 90 per cent, with the CO_2 concentration surpassing 99 per cent. Taizhou CCS Project is the largest coal-fired power CCUS demonstration project in Asia and has been selected as one of the '2023 Top 10 Scientific and Technological Innovation Achievements in the Energy Industry' by National Energy Administration.

Auxiliary load

China Energy has been able to optimally reduce their regeneration heat consumption to 2.35 GJ/tCO_2, with an electricity demand of 55 kwh/tCO_2 for the Taizhou capture unit. With both the Taizhou and Jinjie projects demonstrating operational regenerative heat consumption of 2.35 and 2.16 GJ/tCO_2 respectively, China Energy have demonstrated a significant reduction in energy consumption compared with what is considered the baseline (2.5 GJ/tCO_2).

Table 4: Taizhou CCS project energy consumption breakdown

Energy consumption		
Regeneration heat consumption	2.35	GJ/tCO_2
Electrical consumption	55	kWh/tCO_2

Cost

Though the Taizhou CCUS project is still considered partial capture due to capturing approximately one-eighth of the plant's total CO_2 profile, the project has achieved a CO_2 capture cost in the range of 208–250 RMB/tCO_2 (US$28.62 – US$34.40).

This range is the cost of the CO_2 being captured — this project is not a storage project, but a utilisation project, with a CO_2 temporarily stored cost of 1 RMD/tCO_2 at the China Energy boundary before this CO_2 is sold/transported to third parties for utilisation.

The CO_2 capture cost has only a minor influence on the total cost of electricity production at the site.

Due to the plant's location, the coal price, electricity price and steam price are higher in Taizhou City, Jiangsu Province compared to Jinjie City, Shaanxi Province. This results in a higher cost of CO_2 capture for the Taizhou CCUS project compared to the Jinjie CCUS project.

Table 5: Taizhou CCS project cost breakdown

Item	RMB	US$	Unit
Capture cost	208–250	28.62–34.40	/tCO_2
Transport cost	1	0.14	/km/tCO_2

Hurdles overcome to enable the project to succeed

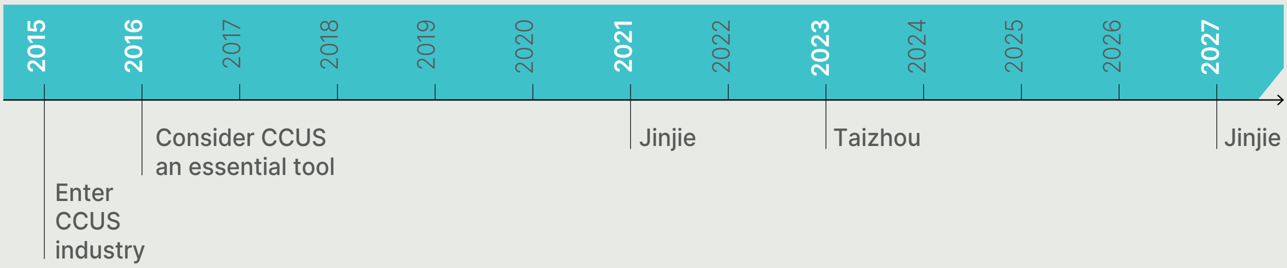
As with all projects developing up the technology readiness level (TRL) scale, this project faced challenges along its development pathway. As China Energy was developing the Taizhou project, one key issue that they continue to face is the long-term ability to find uses for the CO_2. The utilisation of CO_2 across China is significant, but as this project operates, China Energy is aware that the market will begin to be more fully supplied, given that some of the utilisation cases are not necessarily fully utilising the CO_2 and the possibility of other CO_2 sources coming online at lower cost.

There are still limitations on the demand for captured CO_2 for utilisation in China. Long-term operation of the Taizhou CCUS project therefore requires further development of the CO_2 market and technical research on carbon storage.

To mitigate this risk and provide for the continuous operation of the Taizhou CCUS project, China Energy is exploring opportunities to expand the CO_2 utilisation market, and invest into technical research into carbon storage, EOR and other chemical utilisation such as methanol or sustainable aviation fuel.

4.5 China Energy — moving forward (4 Mtpa)

Figure 9: China Energy CCUS journey



The successful scale-up of China Energy's PCC developments through the Jinjie and Taizhou projects has enabled China Energy to continue the development of their technology, pushing towards a CCUS demonstration project of an entire power generation unit.

China Energy is now undertaking a feasibility study to deploy a full unit scale capture plant at Jinjie Power Plant. This capture plant will be fed by the entire flue stream from one of the 600 MW coal-fired units, with an estimated capture rate greater than 90 per cent resulting in a total 4 Mtpa of CO_2 being captured. Though still in the feasibility stage, both permanent storage in saline aquifers along with various utilisation methods are being investigated as viable end solutions for the captured CO_2. The project is targeting some significant goals, including ≥99.5 per cent CO_2 purity (dry basis), ≤0.4kg/tCO_2 absorbent loss, ≤2.0 GJ/tCO_2 regeneration heat consumption, and a capture unit electrical consumption of ≤55 kWh/tCO_2 (total energy consumption ≤2.2 GJ/tCO_2).

China Energy is also exploring, through related projects, the ability to store captured CO_2 in multiple saline aquifers including but not limited to those found in the Ordos Basin, the Tarim Basin and the Junggar Basin. Through the success of the capture technology, China Energy now has valuable data points which enables the modification of the capture units to be deployed on a range of flue gas compositions. With this access to storage and maturing PCC technology, China Energy could explore the opportunities to deploy this technology at cement plants, iron and steel plants, and other thermal power plants across China.

5 China Huaneng CCUS project

Key points

China Huaneng is a state-owned company with total assets exceeding 1.2 trillion RMB, an installed electricity capacity of over 2,059 GW, and more than 130,000 employees. China Huaneng also produces approximately 86 Mtpa of coal.

In 2006, CERI was established to focus on clean energy research and development for China Huaneng. This includes construction of multiple demonstration projects, such as the 3,000 tpa CO_2 capture system in Beijing in 2008 (the first in China) and the 1,000 tpa two phases CO_2 capture industrial plant in Changchun in 2014, both at coal-fired power plants.

China Huaneng is constructing the largest coal power capture plant in the world, a 1.5 Mtpa CCUS plant, capturing 27 per cent of the CO_2 from Unit 1 at the Longdong Energy Base in Gansu Province. The Longdong project will demonstrate that coal with CCUS can be a flexible solution, co-existing alongside the increasing penetration of variable renewable energy in power generation.

China Huaneng continues to promote the integration of CCUS technology with traditional and emerging industries to support the development of low-carbon industry. This will also be demonstrated as part of the Longdong project, with the integration of the capture and compression component (upstream) and CO_2 utilisation and storage (downstream).

A key challenge in integrating a PCC unit into a coal-fired steam power plant is that it traditionally leads to a reduction in net power generated. The main contributors to the power loss are the heat required for the regeneration of the chemical solvent in the desorber of the CO_2 capture unit (approximately 67 per cent) and the auxiliary power demand of the CO_2 compressor (approximately 25 per cent). To reduce this efficiency loss, an innovative new-generation capture technology — a two-phase absorption solution — was deployed. This has effectively reduced the heat consumption required for the capture plant.

In addition to this important innovation, a range of challenges have been addressed during the development and construction of the Longdong Project. These include the need for careful systems integration to ensure the CCUS system can operate flexibly with the power plant unit, a policy regime that appropriately recognises the role of low emissions technologies, the need for collaboration and R&D to overcome storage cost hurdles as the demand for large-scale dedicated geological storage increases, and effective ongoing communication to keep all stakeholders informed about the important emissions reduction opportunity demonstrated by projects such as Longdong, ensuring they are carried out safely and reliably.

5.1 China Huaneng

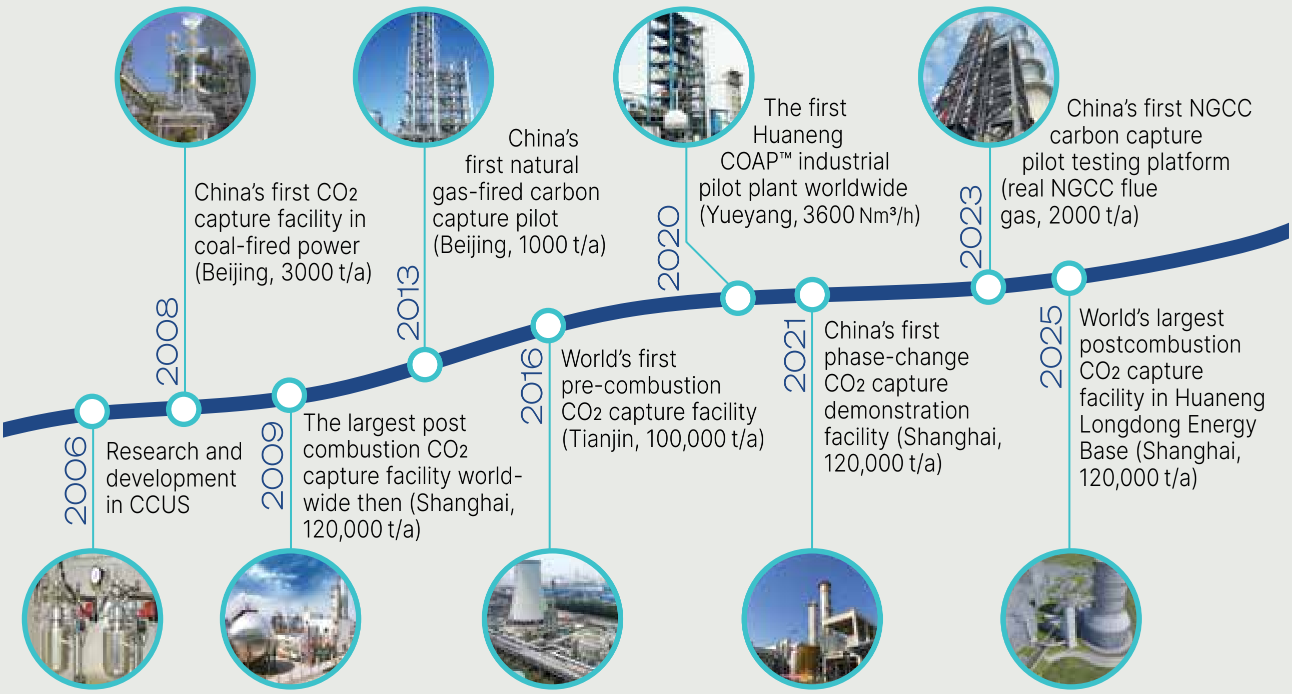
China Huaneng is a state-owned company with total assets of over 1.2 trillion RMB, an installed electricity capacity of over 2,059 GW and employees numbering over 130,000. The group, through its many secondary and tertiary enterprises, also produces approximately 86 Mtpa of coal. China Huaneng was the first Chinese power generation enterprise to join the ranks of the Fortune Global 500 and was ranked 238th in 2024 [43].

The group owns 51 secondary units, more than 460 tertiary enterprises and five listed enterprises. They are mainly engaged in the:

- Development, investment, construction, operation and management of power sources.
- Production and sale of power and heat.
- Development, investment, construction, production and sale of businesses and products related to finance, coal, transportation, renewable energy and environmental protection.
- Industrial investment, operation and management.

In 2006, CERI was established to focus on clean energy research and development for China Huaneng. CERI has since accumulated significant intellectual property including as a patent designer, as a leader in developing international carbon capture standards and, most significantly, from over 17 years of RD&D. The latter includes construction of multiple demonstration projects (illustrated in Figure 10), including the 3,000 tpa CO_2 capture system in Beijing in 2008 (the first in China) and the 1,000 tpa two-phase CO_2 capture industrial plant in Changchun in 2014, both at coal-fired generators. In 2013, CERI built China's first gas-fired carbon capture pilot plant and in 2016 it started operation of the first pre-combustion CO_2 capture unit in China.

Figure 10: History of CERI CCUS deployment



Evolution of CERI's cutting-edge CO_2 capture technologies

Since 2006, CERI has undertaken research and development and engineering demonstrations of various CO_2 capture technologies. This has led to the development of a broad spectrum of technologies and systems for coal- and gas-fired power, waste-to-energy, steel and oil refinery application.

With the support from China Huaneng and the Chinese Government, CERI developed China's first PCC demonstration facility in Beijing (3,000 tpa) in 2008 and scaled-up its engineering expertise to build a second in Shanghai (120,000 tpa) in 2009. Through these and other pilot and larger-scale demonstrations with different CCUS technology, CERI further developed its technology, conducting research and performing 'testing and optimisations'. This involved demonstrations in coal and gas power plants in more than 16 international and domestic applications.

CERI's commercial CO_2 capture technologies include:

- advanced amine absorbents.
- next generation HNC-6 solvent technology.
- slurry-based CO_2 absorbents.
- a phase-change CO_2 absorbent.

5.2 Longdong project

China Huaneng is in the process of constructing the largest coal power capture plant in the world, a 1.5 Mtpa CCUS plant, capturing 27 per cent of the CO_2 from Unit 1 at the Longdong Energy Base in Gansu Province. This project will demonstrate that coal with CCUS can be a flexible solution, co-existing alongside the increasing penetration of variable renewable energy in power generation. This will be demonstrated at the Longdong Energy Base, which consists of 8 GW renewables-based power generation and 2 GW of ultra-supercritical coal-based power generation [47].

The captured CO_2 from this plant will be transported via pipeline to both dedicated geological storage and for EOR.

Figure 11: Artist's impression of Longdong Energy Base

Next generation phase change technology

The integration of a post-combustion CO_2 capture unit in a coal-fired steam power plant leads to a reduction in net power generated ('power sent out'). The main contributors to the power loss are the heat required for the regeneration of the chemical solvent in the desorber of the CO_2 capture unit (approximately 67%) and the auxiliary power demand of the CO_2 compressor (approximately 25%).

To increase the energy efficiency, in 2021 CERI deployed a new generation capture technology, a two-phase absorption system. This efficency was gained by the reduced heat consumption required for the capture plant.

The two-phase absorption solution system includes the traditional CO_2 absorption process, where the flue stream is passed through the absorption tower. Most of the absorbed CO_2 will be transferred into the rich liquid phase (more than 95%). Then biphasic CO_2 absorbent will separate into two liquid 'rich' and liquid 'lean' phases (the rich will have absorbed the CO_2, while the lean will only consist of a small amount of CO_2.) Only the rich phase is transferred to the energy intensive regeneration system for CO_2 desorption, while the lean is redirected back into the adsorption process. The results show a regeneration energy reduction of up to 40 per cent when compared with the conventional amine MEA process [47].

This new process will significantly reduce regenerative heat consumption and thereby reduce operating costs. This technical improvement will also enhance the business case for scaling-up from small- to large-scale projects.

CERI's experience in investing in RD&D, including this two-phase absorbent innovation, has culminated in the construction of the Longdong facility, which is the world's largest PCC capture facility at a coal power station.

China Huaneng continues to promote the integration of CCUS technology with traditional industries and emerging industries to support the development of low-carbon industry. This will also be demonstrated as part of the Longdong project with the integration of the capture and compression component (upstream) and CO_2 utilisation and storage (downstream).

Project schedule

The PCC Project was approved in early 2022 with the engineering preliminary design and feasibility completed by August 2023. China Huaneng commenced construction in 2023, with civil foundations completed in February 2024. In parallel, China Huaneng has been enhancing its new PCC capture technology. Through this parallel work, China Huaneng have been able to ensure the deployment of current best practice technology.

Figure 12: Project schedule for CO_2 capture plant

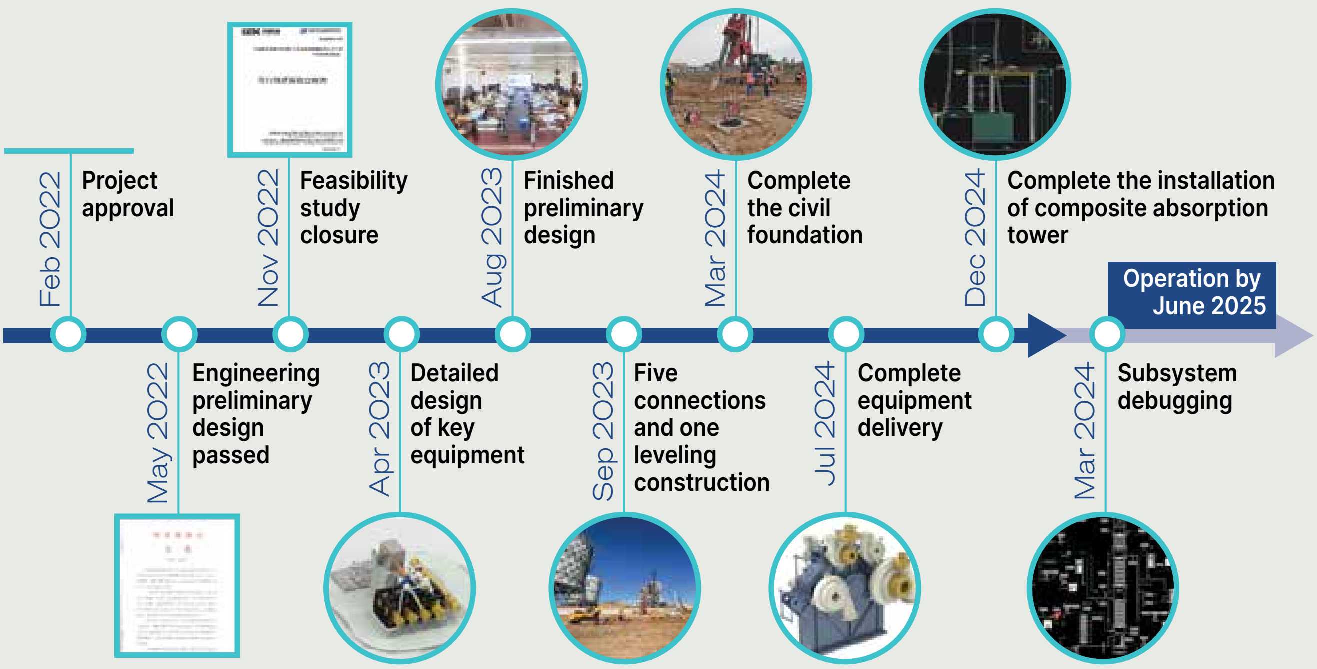


Figure 13: 3D model of the capture facility

Construction

As illustrated in Figure 12, the PCC facility has been constructed over a period of 19 months. The 3D model of the PCC facility, seen in Figure 13, highlights the unique approach taken by China Huaneng to locate the desorption column in the PCC's cooling tower.

China Huaneng have provided multiple images, found in Figure 14, showing the progress made over this timeframe and the speed at which this plant has been constructed.

Key milestones completed as part of the construction phase include the installation of the desorber, the installation of the composite absorber, the construction of the heat exchangers and solution purification device as well as the CO_2 compressor. By delivering all these milestones, China Huaneng are moving towards mechanical completion and the commencement of the commissioning stage.

Figure 14: Construction timeline pictures

December 2023

June 2024

July 2024

September 2024

October 2024

China Huaneng are moving towards mechanical completion and the commencement of the commissioning stage.

Process walk through

The Longdong project was designed with the option to deploy China Huaneng's next generation carbon capture technology with innovative processes, which ensures that PCC can be a low-energy consuming and flexible decarbonisation option.

Simulation and data-driven advancements have enabled the technology being deployed at Longdong to involve a reduction in auxiliary load compared to previous generations, without compromising CO_2 capture rate or CO_2 purity.

Key innovative features of the facility are:

- Heat consumption of less than 2.28 GJ/tonne CO_2.
- A power consumption less than 58.2 KWh/tonne CO_2.
- A two-phase absorption solution which reduces the heat consumption of the capture system compared with traditional baselines.
- Reduction in the circulation flow of the absorbing solvent.
- CO_2 capture rate of greater than 90 per cent, and CO_2 purity of greater than 99 per cent.

As noted above, the project is deploying a two-phase absorption solution. Almost all of the absorbed CO_2 transfers into the rich phase, meaning that only the rich phase needs to be transferred to the regeneration system for CO_2 desorption. This will reduce the heat consumption of the carbon capture unit. China Huaneng's next generation technology involves significant innovation on the absorption unit and regeneration unit as well as process optimisation on the upstream and downstream process units.

The flue gas stream captured at the Longdong CCUS project comes from the outlet of the desulfurisation absorption tower of the generating unit. The flue gas composition entering the capture unit is detailed in Table 6, and is at 47°C.

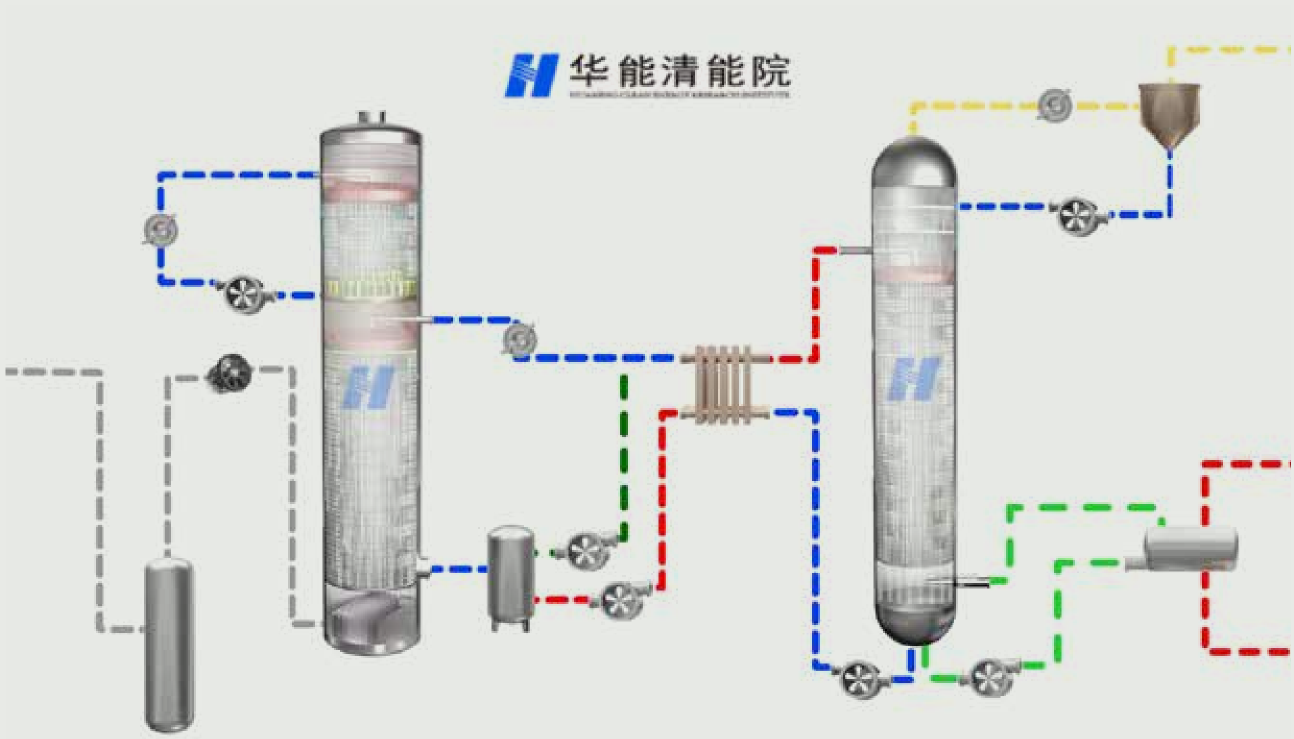
Table 6: Longdong flue gas composition

Flue gas composition (wet)	%
CO_2	11.13
N_2	71.68
O_2	6.53
H_2O	10.65
SO_2	<15mg/Nm³
NO_x	<50mg/m³

The capture process involves two stages: capture and compression. It begins with the low-temperature absorption of CO_2 onto the solvent, followed by the desorption of CO_2 in the desorber. The CO_2 stream discharged from the desorber is then compressed into supercritical CO2 for supply to the storage site. Supercritical CO_2 is denser than gaseous CO_2, allowing the storage of a greater volume.

Temperature naturally increases with depth in the Earth's crust, as does the pressure of any fluids (for example, brine, oil or gas) in the formations. At depths below about 800 metres (about 2,600 feet), the natural temperature and fluid pressures exceed the critical point of CO_2 for most places on Earth. This means that CO_2 injected at this depth or deeper will remain in the supercritical condition given the temperatures and pressures present.

Figure 15: Longdong capture plant process diagram



The capture process involves two stages: capture and compression. It begins with the low-temperature absorption of CO_2 onto the solvent, followed by the desorption of CO_2 in the desorber. The CO_2 stream discharged from the desorber is then compressed into supercritical CO_2 for supply to the storage site. Supercritical CO_2 is denser than gaseous CO_2, allowing the storage of a greater volume.

Figure 16: 3D model of adsorption tower

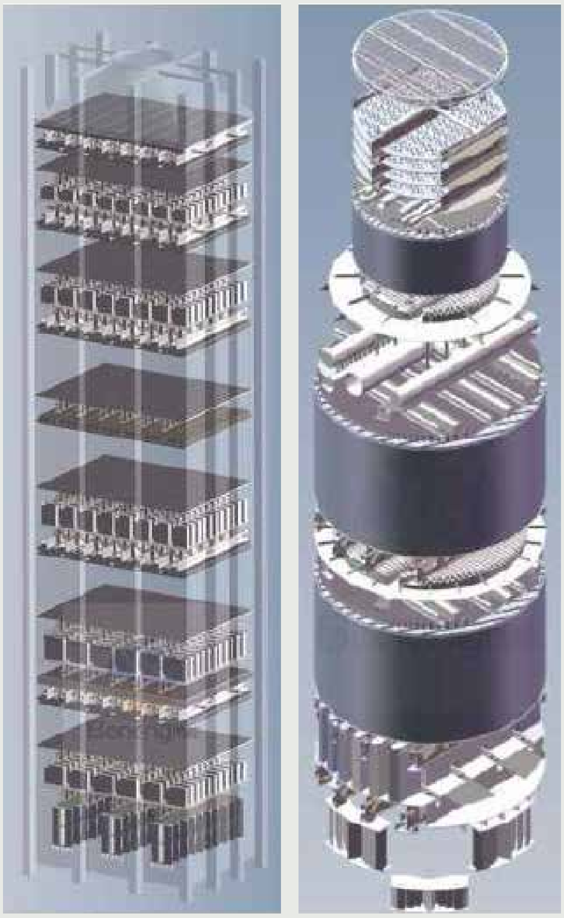
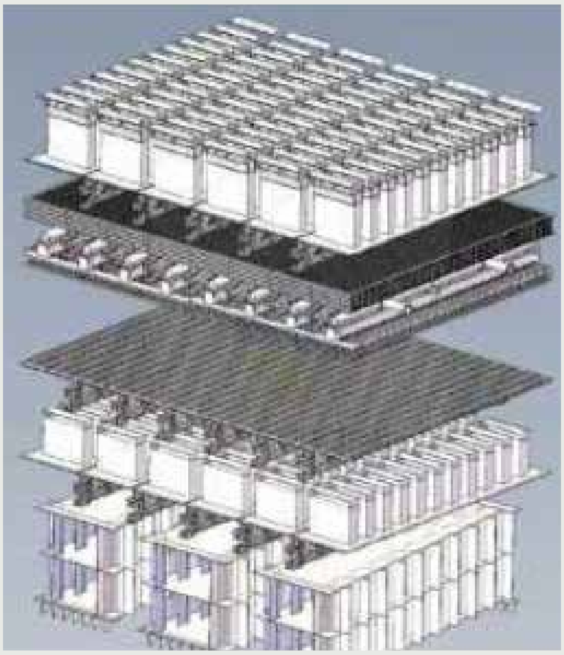


Figure 17: Innovative packing design



Absorber design

The next generation carbon capture technology includes an innovative design of the composite absorption tower, which includes combining the pre-washing tower and the absorption tower in the same structure. This will not only reduce the footprint and capital cost, it will also reduce the flue gas resistance and eliminate the influence of fan temperature rise on the absorption section.

The next generation capture technology also features a new packing structure, as seen in Figure 17. This new packing design has significantly reduced the pressure drop through the structure, resulting in a 30 per cent lower pressure drop than that seen in the conventional industrial packing.

Thermal optimisation

The cooling process of the absorption tower has also been optimised, working to reduce the temperature of the absorber, which will improve the CO_2 capture process. By deploying a condensing waste heat recovery process, the condensed water is heat exchanged with the CO_2-rich liquid, taking advantage of the low-grade waste heat in the condensed water, which reduces the demand for high-grade steam otherwise required in this process, improving the integrated system's overall energy efficiency.

A lean liquid flash MVR process is also adopted for energy efficiency improvements. After flash evaporation of lean liquid and MVR compression, the gas is returned to the regenerator for stripping, with the latent heat of steam phase change being used to reduce the regenerator heat consumption.

Auxiliary load

The capture unit is designed to consume 2.28 GJ/tCO_2 of steam and 125.6 kWh/tCO_2 of electricity including the required compression of CO_2 for end use. The capture components electrical consumption is equal to or less than 58.2 kWh/tonne CO_2. The capture units consumption of only 2.28 GJ/tCO_2 of steam is a significant step forward in the push to reduce steam requirements below what is considered a baseline of 2.5 GJ/tCO_2 [46].

Table 7: Longdong energy consumption breakdown

Energy consumption	kWh	Unit
Regeneration heat consumption	2.28	GJ/tCO_2
Electrical consumption	58.2	kWh/tCO_2

Transport and storage

As part of the Longdong capture project, China Huaneng are developing a dedicated CO_2 geological storage site located 300 metres from the capture plant. It is important that the storage site is carefully integrated with the capture plant to minimise impacts on neighbouring communities and commercial activities. The project will utilise the first eight-stage integral gear multi-axis centrifugal CO_2 compressor in China to meet the needs of supercritical pipeline transportation. The captured CO_2 will be compressed and transported by pipeline rather than by truck. The geological storage site will begin with a storage capacity of 200,000 tpa (roughly 13% of Longdong's capture rate) with the remaining CO_2 used for EOR.

A dedicated team at China Huaneng has been developing the storage site, to bring it online as the capture plant comes online. Figure 18 outlines the project schedule for the CO_2 storage component of the project.

Figure 18: Project schedule of Longdong storage project

Figure 19: Online monitoring website

Through seismic survey work, China Huaneng has undertaken detailed evaluations of the various reservoirs located near Longdong, established strong understanding of the caprock, and developed a detailed storage monitoring and verification plan. As part of this monitoring and verification work, significant background data has been retrieved over a two-year period.

This is complemented with an online monitoring website, Figure 19, fed by multiple atmosphere, soil and subsurface water sensors seen in Figure 20.

This work is further supported by high-accuracy ground and surface deformation monitoring. These practices are designed to contribute to China Huaneng's social licence to operate, given the proximity to neighbours. It also ensures that the CO_2 storage is undertaken in a safe manner and in line with international best-practices including rigorous monitoring.

These practices are designed to contribute to China Huaneng's social licence to operate, given the proximity to neighbours. It also ensures that the CO_2 storage is undertaken in a safe manner and in line with international best-practices including rigorous monitoring.

Figure 20: Atmosphere, soil and subsurface water monitoring systems

Cost

The Longdong Energy Base is a large project, consisting of 8 GW renewables-based power generation and 2 GW of ultra-supercritical coal-based power generation along with the world's largest post combustion capture facility deployed onto a coal power plant.

The total capital expenditure for the Longdong CCUS project is RMB 810 million or US$111 million. This results in a CO_2 capture cost of less than RMB 220/tCO_2 (less than US$30.33/t$CO_2$).

Hurdles overcome to enable Longdong to succeed

As with the other CCUS projects highlighted in this report, a range of challenges have been addressed during the development and construction of the Longdong Project. These have included:

Integration with ultra-supercritical coal unit

Integrating a CO_2 capture plant with an ultra-supercritical coal-fired unit, which has been designed to operate at high efficiency (higher temperature and pressure), requires careful systems integration to ensure that the CCUS system can work flexibly along with the power plant unit. Following the thorough study and consideration of key hurdles including safety, ramp-up speed, CO_2 capture efficiency, extraction of steam and power generation performance, the project was able to successfully construct an integrated CCUS system on an ultra-supercritical coal unit.

Economics

CCUS systems, particularly on such a large scale, involve substantial capital investment and ongoing operational expenditure. A policy regime that recognises the role of low emissions technologies and other sources of cleaner firmed power generation (such as natural gas with CCUS) will be important, as will a regime that is similar to the one providing support for renewables and energy storage. Long-term government support, in the form of financial incentives or carbon credits, will support low emissions technologies, including CCUS. This will be important in underpinning the competitiveness of CCUS and to encourage future CCUS deployment.

CO_2 use and geological storage

With the carbon price in China relatively low and the level of commercial demand, it can be attractive for smaller sized carbon capture projects to utilise CO_2 as a key input to other CO_2 utilisation technologies, such as EOR, CO_2 mineralisation and CO_2 to chemicals. However, as large capture facilities (such as at Longdong) increasingly come online capturing a million tonnes or more, large scale dedicated geological storage will be required as the most economic pathway for large-scale emissions reduction.

Longdong has progressed and overcome the storage cost hurdle by collaborating with state owned oil enterprises in this project. This has been complemented by CERI's RD&D activities aimed at reducing costs and derisking investment. However, given the importance of coal for generating power and in other industrial applications in China, growing rollout of geological storage and the development of appropriate standards for safe and permanent storage will be required to support more large-scale projects. With this in mind, China Huaneng's CERI has been using its expertise to help develop international CCUS standards.

Public awareness and acceptance

Public trust and support is crucial for the project's ongoing success, not just through the construction stage, but also as the project operates. Therefore, effective ongoing communication will be required to keep the general public, industry, and government informed about the important emissions reduction opportunity demonstrated by first-of-a-kind (FOAK) projects like Longdong, along with reassurance that they can be undertaken in a safe and reliable manner [48].

5.3 China Huaneng—moving forward

In 2025, China Huaneng will continue to progress the commissioning and then operation of the Longdong CCUS project, demonstrating both large scale capture of CO_2 from a coal facility as well as the safe injection of CO_2 into the sequestration site.

In parallel to the Longdong CCUS Project, China Huaneng is also working to enable flexible carbon capture for natural gas combined cycle power plants, demonstrating the efficient and effective capture of CO_2 from the low concentration flue steam.

China Huaneng understands the important role that both coal- and natural gas-fired power plants will play in the future energy system, complementing renewables, therefore they recognise that the decarbonisation of these plants is critical.

6 Lessons from China's development of the next generation of CCUS projects

Key points

Valuable lessons can be drawn from the development and construction of China Energy's Jinjie CCUS Project and Taizhou CCS Project as well as China Huaneng Longdong Project.

China's success is driven by significant government support. This includes the significant investment in research and development by both China Energy and China Huaneng. The government has also explicitly led support for CCUS, recognising it as a key enabler in helping China meet its carbon emission reduction pledges. Additionally, China incorporates CCUS into its policy and advocates for its use in global decarbonisation efforts. These projects illustrate the role of government policies and approval processes as central to the deployment of CCUS. Favourable policies can enable faster development of CCUS projects, including in the coal-fired power sector, and assist in addressing business case limitations for early movers.

China's technical success will provide for a global scale-up of CCUS on coal-fired power generation. The technology developed can be deployed in coal-fired power stations worldwide, increasing opportunities for other countries to follow China's lead. The projects have demonstrated significant technical advancements for PCC units, with cost savings and efficiency improvements through learning-by-doing as new units are developed.

Scale-up success. Both China Energy and China Huaneng have successfully scaled up their technology, with both the size of the projects and their technical readiness improving with each new initiative. These projects are significant assets to China's CCUS industry, providing opportunities for continuous testing, development, and further validation of CCUS technology.

Storage is safe and effective. For more than a decade, China has been monitoring the impacts of CO_2 permanently stored deep underground. Monitoring has shown no evidence of leakage or of adverse impacts on groundwater.

The CCUS business case continues to evolve. CCUS technology is commercially available and has been successfully deployed in over 50 large-scale facilities and demonstration projects world-wide. To strengthen the business case, various factors must be considered, including, but not limited to, capital expenditure costs, the cost of CO_2 storage, and the further development of a market for CO_2 utilisation or sale. With every large-scale PCC unit deployed, reductions to costs and improvements on efficiencies will provide significant benefits to the wider CCUS industry.

Speed at which projects move from concept to operation. China has been investing in RD&D in the key areas of the CCUS value chain. These activities involve increasing levels of scale, system integration and operational learning-by-doing. This has been achieved in a relatively short timeframe, partly informed by collaborative research and the application of public domain knowledge from other CCUS projects worldwide. The lessons from these projects will continue to inform future projects and support an increasingly accelerated path to operation.

Application of the next generation's technological advancements to the harder-to-abate sector. Capture technologies like PCC can also be applied to enable the harder-to-abate sector to decarbonise. This includes steel and cement facilities, responsible for around 14 per cent of global greenhouse gas emissions.

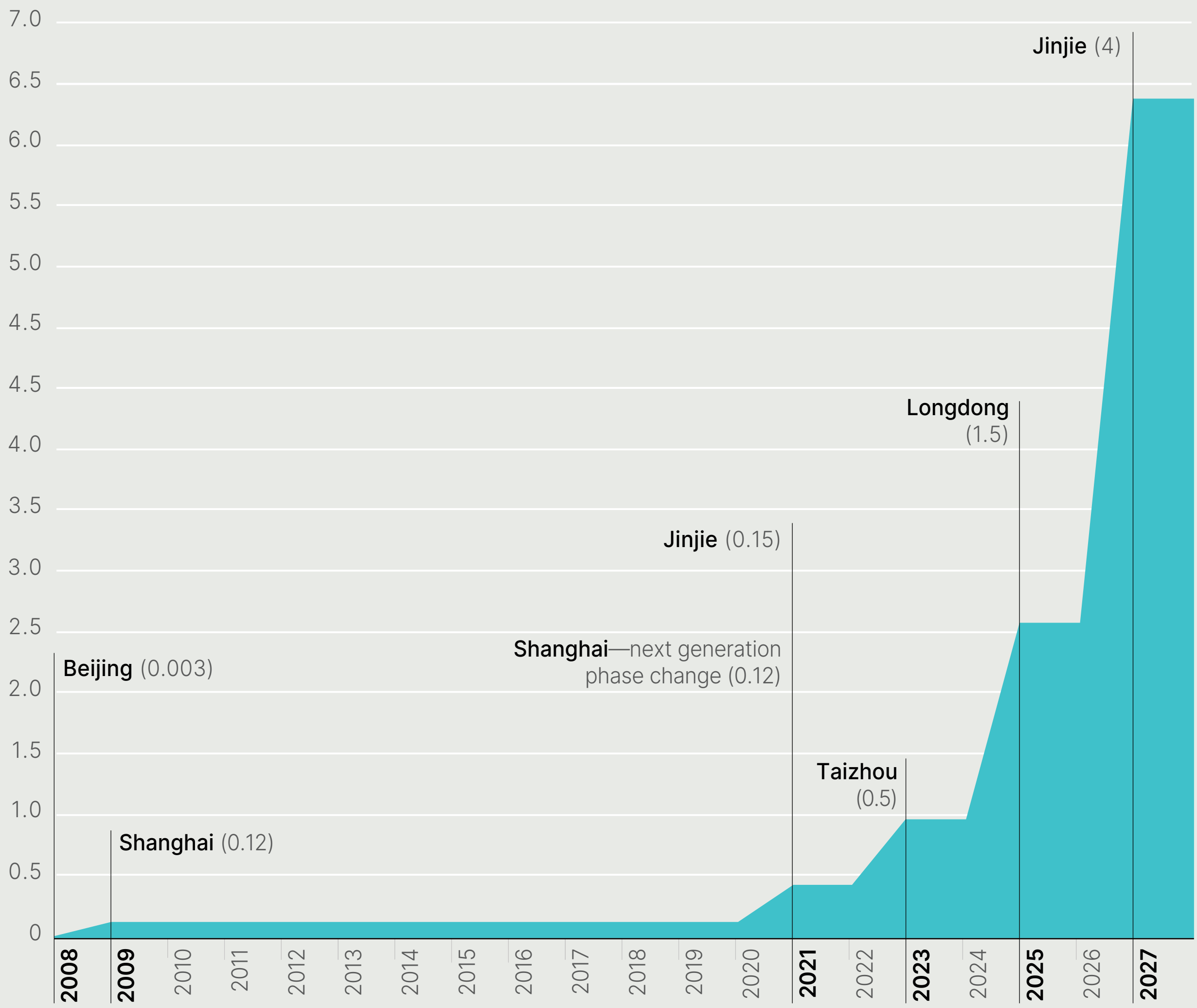
With the lessons learned from these projects, governments and policymakers can see that CCUS technology is available now and ready for deployment to help countries meet their Paris Agreement targets.

China has made significant progress in the development and deployment of the next generation of CCUS technology.

This progress is globally important given the critical role that CCUS will play in the decarbonisation of many hard to abate industries and the ongoing role for coal in many economies around the world.

This chapter summarises lessons that can be drawn from China Energy's Jinjie CCUS Project and Taizhou CCS Project as well as China Huaneng's Longdong Project.

Figure 21: China coal-based CCUS growth (Mtpa)



6.1 China's success is driven by significant government support

China's success in CCUS technology can be attributed to a number of factors, including the significant investment in research and development by both China Energy and China Huaneng. As the world prioritises the reduction of CO_2 emissions, ongoing research and development will be required to enable industry to abate emissions at least cost to remain viable.

Since the early 2000s, research institutions, universities and industry in China have collaborated to develop CCUS technologies that are now deployed at large scale.

Since the mid-2010s, China's support for CCUS has also been explicitly led by government, which recognises the technology as a key enabler to China reaching its carbon emission reduction pledges of peaking its CO_2 emissions before 2030 and achieving carbon neutrality before 2060. China incorporates CCUS in policy and advocates for its inclusion in global decarbonisation. Examples of China's outward advocacy for CCUS include many international research collaborations and the 2023 Sunnylands Statement, which includes a commitment for both the US and China to develop five large-scale CCUS projects by 2030.

In China, particularly since 2020, various large-scale CCUS plants, including at coal-fired power, chemical and oil plants, have been constructed or are under construction (including at a steel plant). This push has been led by strong support across various levels of government and into the commercial sector. With this political backing, the CCUS industry has been given the opportunity to expand so that it can play a role in enabling China to achieve its carbon reduction goals.

6.2 China's technical success allows a global scale-up of CCUS on coal-fired power generation

China's successful deployment of PCC on coal power plants brings the total capture capacity of large-scale PCC on coal-fired power from 2.4 Mtpa in 2017, to 4.55 Mtpa in 2025 with another 4 Mtpa anticipated to come online in 2026. The technology China Energy and China Huaneng have developed can be deployed in coal-fired power stations across the globe, increasing the opportunities for other countries to follow in China's footsteps.

China Energy and China Huaneng are not the only technology providers of PCC technology. Various technology providers in Japan, North America and Europe also offer commercial PCC technology, which can be retrofitted to existing coal-fired power stations.

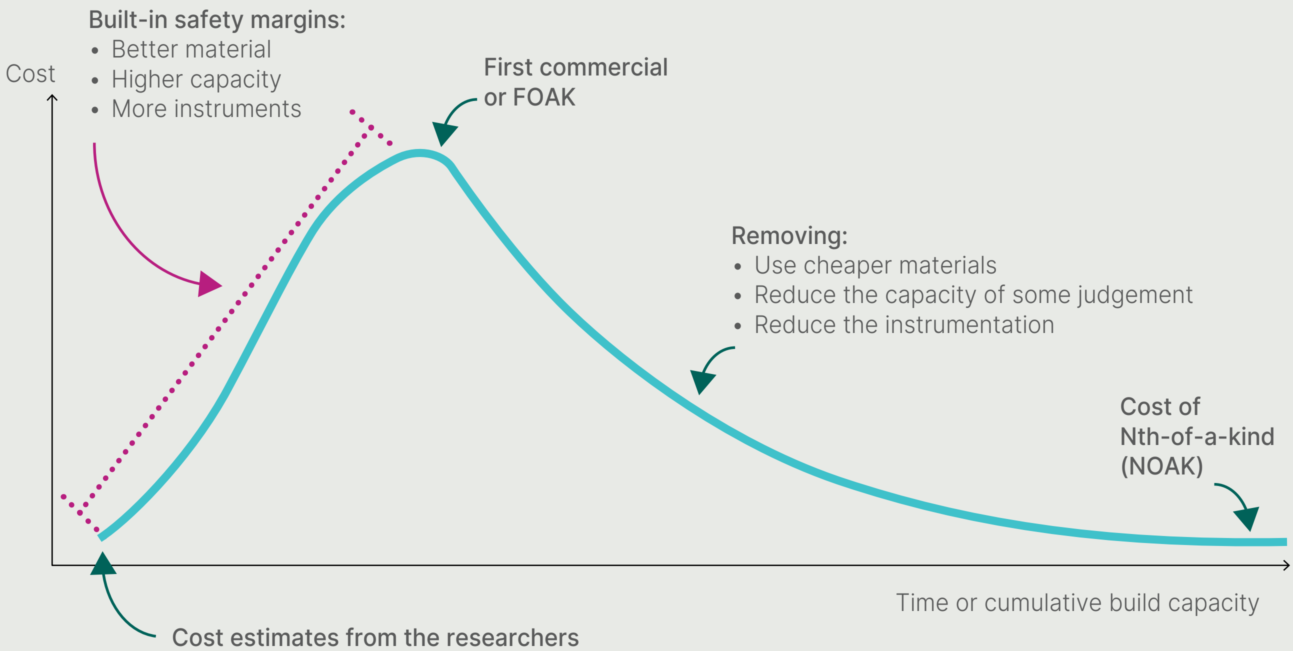
As these units continue to come down in cost and improve their energy consumption, there is an increasing opportunity for the large-scale roll out of cost competitive CCUS plants on a broader range of power stations across the world. Importantly, every very large-scale PCC unit deployed that reduces costs and improves on efficiencies provides benefits to the wider CCUS industry.

Technical advancements for PCC

A term commonly used when considering the cost reduction potential of technologies such as CCUS is 'learning-by-doing'. The cost reductions from learning-by-doing were seen in the progression of PCC in North America, starting with Boundary Dam, then Petra Nova, and most recently the feasibility study for Shand [49]. In a 2019 study [50], the International CCS Knowledge Centre outlined how 'First-generation projects often have anticipated savings of around 20–30 per cent should they be repeated using the expertise and educated hindsight gained from early operation'. The Shand CCS Feasibility Study [49] estimated that the cost for a new CCUS plant could reduce by as much as 67 per cent on the FOAK Boundary Dam facility by applying lessons learned.

As a technology moves from a FOAK plant to second and third, the reduction in cost will be more significant than the cost reduction from plant five and six, However, the learning-by-doing curve seen in Figure 22, shows that cost reductions continue as more plants are deployed.

Figure 22: Learning-by-doing cost curve [51]



The technical advancements made in China through the three plants studied in this report will not only reduce the cost of future plants in China but also worldwide. This is due to four key technological improvements made by these projects, which will have a lasting impact on the CCUS industry.

Technological improvements

China Energy have made multiple improvements to both the amine absorbent and its resistance to degradation and losses. By deploying an amine recovery device, they have significantly reduced the amine loss observed at the absorber tower. As the loss of amines through the process is a general concern as CCUS projects progress through various environmental approvals, this development is important to the continued growth of CCUS.

China Energy have also developed a new high-efficiency, small addendum angle filler that can increase the contact area between the flue gas stream and the absorbent solution. This results in accelerating the capture reaction and has the potential to be applied through commercial arrangements at other projects with existing capture units.

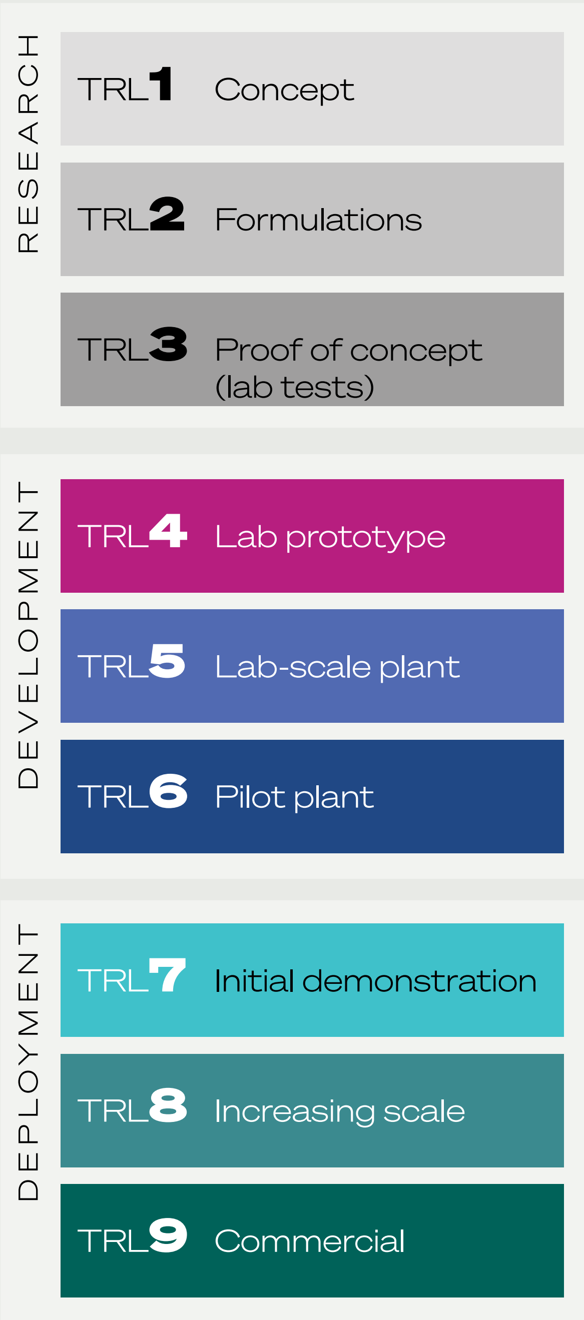
Reducing the energy requirement

As is well established, the energy required to capture CO_2 represents a significant operating cost of a PCC plant as the more electricity the plant consumes the less it can sell to the market. The primary consumer of energy in a capture island is the regenerative process, which often requires a significant level of heat input. Any successful reduction in this heat demand can have significant benefit to the overall feasibility of deploying a PCC at a facility.

All three of the plants examined as part of this report have made reductions to the 'baseline' regenerative heat demand. Both of China Energy's plants have achieved a regenerative rate of 2.35 GJ/tCO_2 (Taizhou) and 2.16 GJ/tCO_2 (Jinjie), with the Longdong Project aiming to achieve a regenerative rate of 2.28 GJ/tCO_2. These are significant improvements compared to Boundary Dam at 3.8 GJ/tCO_2, and Petra Nova at between 2.4 and 2.6 GJ/tCO_2. Such improvements, in what can be said to be China's next generation capture technology, are very significant in the wider context of deploying PCC technology.

China Energy developed a new blended amine absorbent; this absorbent enabled the project to achieve low energy consumption without hindering capture performance. China Energy also developed a new heat exchanger capable of handling the low temperature difference between the lean and rich amine. These developments, as well as modified plastic fillers, staged intercooling in the absorber, splitting the rich CO_2 feed into the stripper, and utilising MVR flash evaporation, enabled China Energy to reduce energy consumption and reduce costs.

Figure 23: TRL progress scalability



Scale up success

In May 2011, China Energy successfully completed a three-year, 100,000 tpa CCUS demonstration project in Erdos. With CO_2 capture being captured from a coal-to-oil facility and then stored in a low-porosity, low-permeability terrestrial saline aquifer, with ongoing monitoring of the plume showed that the CO_2 remained safely stored.

As outlined in the case studies, in 2021, China Energy then completed the 150,000 tpa coal-fired power CCUS demonstration project at the Jinjie Power Plant and in June 2023, the 500,000 tpa coal-fired power CCS demonstration project was completed at the Taizhou Power Plant. These two large-scale projects, as well as the construction of China Energy's new 10 tpa, 50 tpa, 1,000 tpa and 10,000 tpa test platforms, constructed in 2024 and used for carbon capture absorbent testing, CO_2 utilisation and other scientific research tests, showcase the continual advancements and work being undertaken to scale up this CCUS technology. This significant progress also benefited from the important collaboration between industry and universities through the National CCUS Research and Development Centre.

China Huaneng have also significantly scaled up their technology, progressing from the Beijing Project (3,000 tpa) to the Shanghai Project (120,000 tpa) and the Longdong Project (1.5 Mtpa).

The TRL range from the concept stage of technology development, all the way through to a commercial configuration that can be used at several locations.

As seen in Figure 23, both China Energy and Huaneng moved their projects along the TRL scale, and did so at what can be considered a larger scale (in terms of the capture capacity of the projects) than other technology developers have deployed. This shows that China's technology development has undertaken a conservative approach as they proceed towards reaching a commercial scale offering.

China Energy have opportunities to conduct further research and testing to stimulate additional technology development

China Energy's Jinjie Plant could be called a large-scale science facility, that is, China Energy continue to conduct optimisation work to further enhance the plant's performance.

This is a significant asset to China's overall CCUS industry, providing opportunities for continual testing development and proving up their CCUS technology.

6.3 Business case continues to evolve

As noted above, CCUS technology is commercially available and has been successfully deployed in over 50 large-scale facilities and many demonstration projects around the world. However, one of the limiting factors has been the business case, particularly if there is an absence of commercial EOR opportunities.

For the business case to improve, there are various factors to be considered, including but not limited to: capital expenditure cost, the cost of CO_2 storage or a market for CO_2 sale, as well as the operational costs of the capture island including the auxiliary load.

China Energy and China Huaneng have been able to reduce the cost of capture for these projects to under US$35/t$CO_2$, compared with current capture costs of greater than US$60/t$CO_2$ [52]. This results in a cost reduction of more than 40 per cent. Every very large-scale PCC unit deployed that reduces costs and improves on efficiencies provides benefits to the wider CCUS industry.

Dedicated geological storage will become essential

China Energy and China Huaneng have been able to sell most of their captured CO_2 for EOR and other uses by industry. This has helped defray some project costs. However, as more projects are developed in China there will likely be fewer opportunities for large scale utilisation of the captured CO_2.

As noted earlier in this report, China has the largest coal-fired power generation fleet in the world, with an average age of just 14 years in 2023 but a campaign life for a well-maintained plant is around 50 years. Though CO_2 utilisation can strengthen a business case (selling CO_2 instead of paying to 'offload' it), the volume of captured CO_2 will often be so significant a utilisation case may not be available.

This suggests that, going forward, large scale, integrated CCUS projects will need to find and appraise storage resources in saline aquifers to a sufficient level of confidence (in sustained injectivity and storage security) to justify the large capital investment in capture plant.

China's storage exploration and appraisal data acquisition and research programs therefore have a particular focus on reducing large geotechnical uncertainties. This work continues produce important data, firming up the theoretical storage capacity in China, which could be around 1.21–4.13 trillion tonnes [53].

6.4 Application of the next generation's technological advancements to the harder-to-abate sector

Capture technologies like PCC can also be applied to enable the harder-to-abate sector to decarbonise.

Steel and cement facilities contribute to 14 per cent of the world's total greenhouse gas emissions. For the world to decarbonise, these industries not only need to continue producing steel and cement but also must significantly reduce their emissions, without increasing the cost of the products. Although other technologies, such as clean fuels (hydrogen, ammonia, etc.) and electrification with renewable energy input exist and will be utilised, the steel and cement industries have made it clear that CCUS will be doing the heavy lifting.

The cement industry has identified CCUS as a key lever to enable it to decarbonise. As outlined in the Global Cement and Concrete Association roadmap, this could account for 36 per cent of the industry's emissions reduction by 2050 [54,55]. The steel industry has made similar commitments, with the IEA's Net Zero Roadmap 2023 showing CCUS contributes ~37 per cent of the industry's emissions reduction by 2050 [3].

In addition to China Energy and China Huaneng, PetroChina and various chemical companies and one steel manufacturer are also progressing large scale CCUS project in China, including a 1 Mtpa project in Karamay, Xinjiang [56].

In 2023, the International Centre for Sustainable Carbon authored a report for the CIAB titled *The Resilience of Coal-Based Industries in the Transition to Net Zero*, which focuses on the role that coal will play in heavy industry in a net zero world, with the significant heavy lifting in emissions reduction done by CCUS [57].

6.5 Speed at which projects move from concept to operation

The case studies presented here show how China has been investing in RD&D in the key areas of the CCUS value chain—encompassing the capture of CO_2 at power stations, transportation of high-pressure CO_2 to designated storage sites for permanent underground storage or for utilisation in industrial applications. These activities involve increasing levels of scale, system integration and operational learning-by-doing. This has been achieved in a relatively short timeframe partly informed by collaborative research and applying the public domain learning from other CCUS projects around the world.

Historically, pilot capture projects have been undertaken in a controlled operational environment followed by larger projects and finally large-scale demonstration in a commercial, operational environment. Prudent investment of limited RD&D funds required that costs were minimised by designing projects where research objectives are achieved at the least expensive scale and operational environment. This has meant the scale of a pilot or demonstration project is typically less than that required to capture CO_2 from all power plant emission sources.

As an example, initially only a slipstream or a portion of the flue gas would be utilised for testing. For highly modular capture technologies, a slipstream may be sufficient for full-scale demonstration projects otherwise further demonstration at scale will be required.

By taking the carefully ordered approach outlined above, China has been able build the necessary commercial-scale CCUS projects required to perform significant 'reality checks' regarding scheduling, cost (both capital and operating) and performance. It is also only at scale that locally relevant deployment challenges emerge and can be understood and addressed. As a result, the two companies featured in this report have been able to risk-optimise large scale CCUS investment decisions in plant and capture after ensuring confidence that geological storage is available, will perform as required and is monitored, reported and verified.

Most importantly, the projects highlighted in this report signal a significant shift in typical concept to operational timeframes observed with some 'first-movers' in CCUS project and development. It also highlights the importance of applying this integrated and ordered approach with urgency to fast-track global CCUS deployment.

Though different regulatory processes exist in every country and region across the world, and locational and other differences exist in each jurisdiction, these Chinese projects have demonstrated that this technology is ready and can be deployed today.

Throughout the early 2020s, the Longdong project progressed from an open, greenfield site to a 2 GW power station with the world's largest PCC unit of 1.5 Mtpa capture capacity, taking approximately two years from the 'first shovel' to the first tonne of CO_2 being captured and compressed.

Table 8: Construction duration

Name	Jinjie	Taizhou	Londgong
Capacity (tpa)	150,000	500,000	1,500,000
Duration	20 months	16 months	19 months

7 Conclusion

CCUS is a necessary bridge between the reality of today's energy system and the increasingly urgent need to reduce emissions. Not only can it avoid locking in emissions from existing power and industrial facilities, it also provides a critical foundation for carbon removal or negative emissions.

Dr Fatih Birol, Executive Director,
The International Energy Agency

The message from the experts is clear — rapid scaling up of CCUS is essential to meeting global emissions reductions targets. China Energy's Jinjie CCUS Project and Taizhou CCS Project and China Huaneng's Longdong Project have responded to that message and valuable lessons can be drawn from both projects.

Key amongst these is that carbon capture technology is available now and can be deployed to help countries meet their Paris Agreement targets.

The projects have demonstrated:

- The technologies developed and applied by China Energy and China Huaneng can be deployed in coal-fired power stations across the globe. This can increase the opportunities for other countries, particularly countries with fleets of coal-fired power stations, to follow in China's footsteps, maintaining energy costs competitiveness and security while significantly lowering emissions.
- The technologies can also be applied to enable the harder-to-abate sector, including steel and cement facilities, to decarbonise. These industries underpin economic development and face a significant emissions reduction task with a relatively narrow range of technical solutions. CCUS can play a key role in securing the future of these industries and contributing to their emissions reduction opportunities.
- Success in significantly scaling-up CCUS technology, with both the scale of the projects and technical readiness level improving with each new project.
- Significant technological improvements, including in multiple improvements to amine absorbent and its resistance to degradation and losses, reductions to the 'baseline' regenerative heat demand. These and the other technological improvements highlighted in this report are very significant in the wider context of deploying PCC technology.
- CCUS projects can move from concept to operation in a relatively short timeframe. Improvements in project development timeframes are vital to underpinning the rapid scaling up of CCUS.
- China Energy and China Huaneng have reduced the capture cost for these projects to under US$35/t$CO_2$, compared to the current capture costs of over US$60/t$CO_2$. This results in a cost reduction of more than 40 per cent. Every large-scale PCC unit deployed that reduces costs and improves efficiency benefits the wider CCUS industry.

References

1. United Nations Framework Convention on Climate Change (2015). Paris Agreement, United Nations.
2. International Energy Agency (IEA) (2020). *CCUS in Clean Energy Transitions*. https://www.iea.org/reports/ccus-in-clean-energy-transitions.
3. International Energy Agency (IEA) (2023). *Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach*, International Energy Agency (IEA). https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach.
4. Intergovernmental Panel on Climate Change (IPCC) (2023). *Synthesis Report of the IPCC Sixth Assessment Report (AR6)—Summary for Policymakers*. https://www.ipcc.ch/report/ar6/syr/downloads/report/IPCC_AR6_SYR_SPM.pdf
5. Global CCS Institute (GCCSI) (2024). *The Global Status of CCS: 2024*. https://www.globalccsinstitute.com/resources/global-status-report.
6. UN Affairs (2021). *China Headed Towards Carbon Neutrality by 2060*. United Nations. https://news.un.org/en/story/2021/09/1100642.
7. Xinhua News Agency (2021). Opinions of the CPC Central Committee and the State Council on fully and accurately implementing the new development concept and doing a good job in carbon peak and carbon neutrality. https://www.gov.cn/zhengce/2021-10/24/content_5644613.htm.
8. Global CCS Institute (GCCSI) (2023). *Scaling up Through 2023* (Global Status of CCS), Global CCS Institute (GCCSI). https://status23.globalccsinstitute.com.
9. Chadwick, RA, Noy, D, Arts, R, & Eiken, O (2009). Latest Time-Lapse Seismic Data from Sleipner Yield New Insights into CO_2 Plume Development. *Energy Procedia 1*(1), 2103–2110. https://doi.org/10.1016/j.egypro.2009.01.274.
10. Haszeldine, RS, et al. (2014). *Sleipner CO_2 Securely Stored Deep Beneath Seabed, in Spite of Unexpected Hugin Fracture Discovery*. https://www.sccs.org.uk/sites/default/files/2023-05/wp-2014-01.pdf
11. Global CCS Institute (GCCSI) (2015). *The Global Status of CCS: 2015 Summary Report*, Global Carbon Capture and Storage Institute Ltd. https://www.globalccsinstitute.com/wp-content/uploads/2018/12/Global-Status-Report_2015_Summary.pdf.
12. Furre, A-K, Eiken, O, Alnes, H, Vevatne, JN, & Kiær, AF (2017). 20 Years of Monitoring CO_2-injection at Sleipner, *Energy Procedia 114*, 3916–3926. https://doi.org/10.1016/j.egypro.2017.03.1523
13. Global CCS Institute (GCCSI) (2013). *The Global Status of CCS: 2013*, 2013 Global CCS Institute.
14. Global CCS Institute (GCCSI) (2024). *State of the Art: CCS Technologies 2024*. https://www.globalccsinstitute.com/resources/publications-reports-research/technologycompendium2024.
15. Kelsall, G, & Baruya, P (2022). *Role of Low Emission Coal Technologies in a Net Zero Asian Future* (Technology Collaboration Programme), International Centre for Sustainable Carbon (ICSC). https://www.sustainable-carbon.org/report/the-role-of-low-emission-coal-technologies-in-a-net-zero-asian-future.
16. International Energy Agency (IEA) (2021). *World Energy Outlook 2021*, International Energy Agency (IEA). https://www.iea.org/reports/world-energy-outlook-2021.
17. Global CCS Institute (GCCSI) (2024). *UK Commits to £21.7 Billion to Advance Carbon Capture Projects, Aiming to Become a Global Leader in CCUS and Hydrogen*. https://www.globalccsinstitute.com/news-media/latest-news/uk-commits-to-21-7-billion-to-advance-carbon-capture-projects-aiming-to-become-a-global-leader-in-ccus-and-hydrogen.
18. Equinor (2024). *Equinor and Partners Approve Execution of UK's First Carbon Capture and Storage Projects*. https://www.equinor.com/news/20241210-approve-execution-of-uks-first-ccs-projects
19. International Energy Agency (IEA) (2019). *Putting CO_2 to Use*, International Energy Agency (IEA). https://www.iea.org/reports/putting-co2-to-use
20. Bongers, G, Byrom, S, & Constable, T (2017). *Retrofitting CCS to Coal: Enhancing Australia's Energy Security*, CO2CRC Limited. https://www.powerfactbook.com/downloads/energy-reports.
21. Bongers, G, Byrom, S, & Constable, T (2017). *Retrofitting Australian Gas Power Plants with Post Combustion Capture*, CO2CRC Limited. https://www.powerfactbook.com/downloads/energy-reports.
22. Lockwood, T (2016). *Next-generation Carbon Capture Technologies For Coal*. https://www.sustainable-carbon.org/library/reports.

23. Wang, J, & Xu, S (2014). CO_2 Capture RD&D Proceedings in China Huaneng Group, *International Journal of Coal Science & Technology, 1*(1), 129–134. https://doi.org/10.1007/s40789-014-0013-6.

24. li, MAI, et al. (2013). Project Status and Research Plans of 500 TPD CO_2 Capture and Sequestration Demonstration at Alabama Power's Plant Barry, *Energy Procedia 37*, 6335–6347. https://doi.org/10.1016/j.egypro.2013.06.563.

25. International Energy Agency (IEA) (2024). *Coal 2024—Analysis and Forecast to 2027*, International Energy Agency (IEA). https://www.iea.org/reports/coal-2024

26. Cai, B, & Li, Q (2020). *China Status of CO_2 Capture, Utilization and Storage*. https://www.researchgate.net/publication/342354904_China_Status_of_CO2_Capture_Utilization_and_Storage_CCUS_2019.

27. Yang, X, & Li, X (2024). *A Gap Analysis of China's Regulatory Framework for CO_2 Geological Storage*, Global CCS Institute (GCCSI). https://www.globalccsinstitute.com/resources/publications-reports-research/a-gap-analysis-of-chinas-regulatory-framework-for-co2-geological-storage.

28. Global CCS Institute (GCCSI) (2024). *CO2RE* https://co2re.co.

29. Wu, Y (2022). *Repositioning CCUS for China's Net-Zero Future*, Global CCS Institute (GCCSI). https://www.globalccsinstitute.com/resources/publications-reports-research/repositioning-ccus-for-chinas-net-zero-future.

30. Asian Development Bank (ADB) (2021). *The 14th Five-Year Plan of the People's Republic of China —Fostering High-Quality Development* (Observations and Suggestions). https://www.adb.org/publications/14th-five-year-plan-high-quality-development-prc.

31. National Development and Reform Commission of the People's Republic of China (2024). *Notice on Issuing the 'Green and Low-Carbon Transformation Industry Guidance Catalogue (2024 Edition)' (Fagaihuanzi [2024] No. 165)*. https://www.ndrc.gov.cn/xxgk/zcfb/tz/202402/t20240229_1364291_ext.html

32. Global CCS Institute (GCCSI) (2024). *Recent Chinese Policy Announcements Will Help Facilitate Deployment of Low Carbon Technologies, Including CCUS*. https://www.globalccsinstitute.com/news-media/latest-news/three-recent-policies-announced-by-the-chinese-government-will-help-facilitate-deployment-of-low-carbon-technologies-including-ccus.

33. Mingyang, T (2024). *China Issues Plan to Support Low-Carbon Transformation of Coal-Fired Power*. http://en.people.cn/n3/2024/0716/c90000-20194165.html.

34. Zhou, N (2017). *Introduction to CERC-BEE*. https://www.energy.gov/eere/buildings/articles/us-china-clean-energy-research-center-cerc.

35. Ferguson, M (2010). *Australia-China Joint Study For Commercial Scale CCS Project*. https://china.embassy.gov.au/bjng/mrccs.html.

36. Espie, T, & Zhang, J (2011). Integration and Findings from the EU-China COACH Project. *Energy Procedia 4*, 5948–5955. https://doi.org/10.1016/j.egypro.2011.02.597.

37. Senior, B, et al. (2011). Carbon Capture and Storage in China — Main Findings from China-UK Near Zero Emissions Coal (NZEC) Initiative, *Energy Procedia 4,* 5956–5965. https://doi.org/10.1016/j.egypro.2011.02.598.

38. Ministry of Foreign Affairs, The People's Republic of China (2023). *The China-France Carbon Neutrality Center is Officially Inaugurated*. https://www.mfa.gov.cn/eng/wjbzhd/202311/t20231130_11190194.html.

39. Ping, Z, et al. (2014). The Application of CCS Technology in China: Lesson from the Sino-Italy Collaboration on Coal Fired Power Plants, *Energy Procedia, 63,* 8116-8133. https://doi.org/10.1016/j.egypro.2014.11.847.

40. Office of the Spokesperson (2023). *Sunnylands Statement on Enhancing Cooperation to Address the Climate Crisis*, US Department of State. https://2021-2025.state.gov/sunnylands-statement-on-enhancing-cooperation-to-address-the-climate-crisis.

41. Xinhua News Agency (2024). China's Special Envoy for Climate Change to visit US. https://english.news.cn/20240507/d4ee039a60d642e6ab49a0fd6eaaee49/c.html.

42. Huaneng Clean Energy Research Institute (CERI). *Huaneng Clean Energy Research Institute (CERI)*. https://itcn-global.org/downloads/factsheets/FS+CERI+161009.pdf.

43. Fortune (2024). *Fortune Global 500 — The largest companies in the world by revenue*. https://fortune.com/ranking/global500.

44. Our World in Data (2023). *Total Electricity Generation*. https://ourworldindata.org/grapher/electricity-generation?tab=table.

45. PETRA NOVA PARISH HOLDINGS LLC (2020). *Final Scientific/Technical Report,* (DOE-PNPH-03311). (WA Parish Post-Combustion CO_2 Capture and Sequestration Demonstration Project, National Energy Technology Laboratory (NETL). https://www.osti.gov/biblio/1608572.

46. Schmitt, T, et al. (2022). *Cost and Performance Baseline For Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas To Electricity,* (DOE/NETL—2023/4320). National Energy Technology Laboratory (NETL). https://www.osti.gov/biblio/1893822.

47. Global CCS Institute (GCCSI) (2023). *State of the Art: CCS Technologies 2023*. https://www.globalccsinstitute.com/resources/publications-reports-research/state-of-the-art-ccs-technologies-2023.

48. Liu, B, Xu, Y, Yang, Y, & Shijian Lu (2021). How Public Cognition influences Public Acceptance of CCUS in China: Based on the ABC (affect, behavior, and cognition) model of attitudes. *Energy Policy 156.* https://doi.org/https://doi.org/10.1016/j.enpol.2021.112390.

49. International CCS Knowledge Centre (2018). *The Shand CCS Feasibility Study,* International CCS Knowledge Centre. https://ccsknowledge.com/our-services/expertise/2nd-generation-ccs---shand-study.

50. International CCS Knowledge Centre, & Coal Industry Advisory Board (2019). *The Cost Reduction Potential for CCUS at Coal-Fired Power Plants* (Learn-by-Doing). https://www.iea.org/reports/opportunities-for-hydrogen-production-with-ccus-in-china.

51. Skagestad, R, Lach, A, Røkke, N, & Eldrup, NH (2014). Critical Factors Influencing CO_2 Capture Cost, a Case Study, *Energy Procedia 63,* 7298–7306. https://doi.org/10.1016/j.egypro.2014.11.766.

52. Baylin-Stern, A, & Berghout, N (2021). *Is Carbon Capture too Expensive?* International Energy Agency. https://www.iea.org/commentaries/is-carbon-capture-too-expensive.

53. The Administrative Center for China's Agenda 21 (2023). *CCUS Progress in China,* Global CCS Institute. https://www.globalccsinstitute.com/resources/publications-reports-research/ccs-progress-in-china.

54. Global Cement and Concrete Association (GCCA) (2021). *Concrete Future.* https://gccassociation.org/concretefuture.

55. Global Cement and Concrete Association (GCCA) (2024). *CCUS Progress.* https://gccassociation.org/cement-industry-net-zero-progress/ccus-progress.

56. Xinjiang Daily (2024). China Petroleum's Largest Integrated Project of 'New Energy + Coal Power + CCUS' Launched in Xinjiang. https://www.cpnn.com.cn/news/nyqy/202405/t20240523_1703505.html.

57. Kelsall, G (2023). *The Resilience of Coal-Based Industries in the Transition to Net Zero*, International Centre for Sustainable Carbon (ICSC). https://www.sustainable-carbon.org/report/the-resilience-of-coal-based-industries-in-the-transition-to-net-zero-icsc-ciab.

58. International Energy Agency (IEA) (2022). *Opportunities for Hydrogen Production with CCUS in China*. https://www.iea.org/reports/opportunities-for-hydrogen-production-with-ccus-in-china.

Appendix

Table 9: Snapshot of some of the demonstration and commercial CCUS facilities in operation in China [29,58]

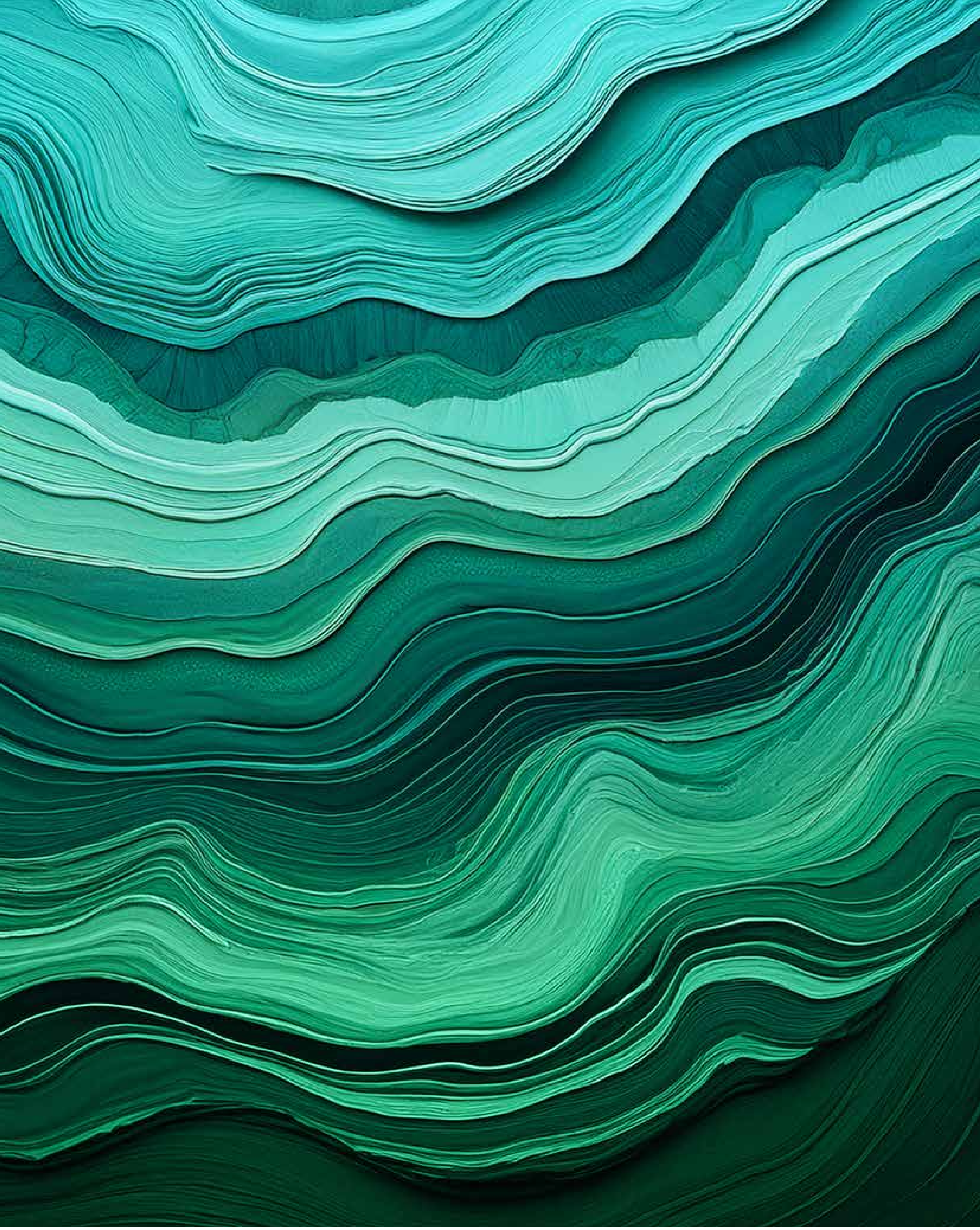
Title	Category	Operational		Industry	Capture rate (Mtpa)	Capture type	Transport code	Storage code
		status	date					
Australia–China PCC Feasibility Study Project	Pilot and demonstration CCS facility	Completed	2010	Coal power generation and heat		PCC	N/A	N/A
Baimashan Cement Plant	Utilisation facilities	Operational	2018	Cement and concrete	0.05			N/A
Baotou Steel	Commercial CCS facility	In construction	2024	Iron and steel	0.5	PCC	Under eval.	Under eval.
China National Energy Guohua Jinjie	Commercial CCS facility	Operational	2021	Coal power generation and heat	0.15	PCC	Road	Deep saline formation
China National Energy Ningxia	Commercial CCS facility	In construction	2024	Chemical	3	Under eval.	Under eval.	EOR
China National Energy Taizhou	Commercial CCS facility	Operational	2023	Coal power generation and heat	0.5	PCC	Under eval.	EOR
Chinese-European Emission-Reducing Solutions (CHEERS)	Pilot and demonstration CCS facility	Advanced development	2022	Oil refining		N/A	N/A	N/A
CNOOC Enping	Commercial CCS facility	Operational	2023	Natural gas/ LNG	0.3	Industrial separation	Minimal (direct injection)	Deep saline formation
CNPC Jilin Oil Field	Commercial CCS facility	Operational	2018	Natural gas/ LNG	0.6	Industrial separation	Pipeline	EOR
CNPC Jilin Oil Field EOR Demonstration Project	Pilot and demonstration CCS facility	Completed	2008	CO2 transport/ storage	0.35	Pre-combustion capture (natural gas processing)	Pipeline	EOR
CNPC Junggar Basin Hub	Commercial ccs facility	Early development	Under eval.	CO2 transport/ storage	3	N/A	Combination	EOR
CNPC Songliao Basin Hub	Commercial ccs facility	Early development	2025	Power generation and heat	3	Industrial separation		Under eval.

Title	Category	Operational		Industry	Capture rate (Mtpa)	Capture type	Transport code	Storage code
		status	date					
CNPC Xinjiang Karamay Coal-Fired Power Plant Integrated Project	Commercial CCS facility	Advanced development	2026	CO2 transport/ storage		N/A	Under eval.	EOR
Daqing Oil Field EOR Demonstration Project	Pilot and demonstration CCS facility	Operational	2003	CO2 transport/ storage	0.2	Pre-combustion capture (natural gas processing)	Combination	EOR
Daya Bay Hub	Commercial CCS facility	Early development	Under evel.	CO2 transport/ storage	10	N/A	Under eval.	Under eval.
Guanghui Energy Methanol Plant	Commercial CCS facility	Operational	2023	Chemical	0.1	Industrial separation	Pipeline	EOR
Haifeng Carbon Capture Test Platform	Pilot and demonstration ccs facility	Operational	2018	Power generation and heat	0.03	PCC	N/A	N/A
Hengli Dalian Changxing Island CCUS	Utilisation facilities	Announced	Under evel.	Chemical	3			Dedicated geological storage
Huaneng GreenGen IGCC Demonstration-scale System (Phase 2)	Pilot and demonstration CCS facility	In construction	2025	Power generation and heat	0.1	Pre-combustion capture (gasification)	Truck	EOR
Huaneng Longdong Energy Base	Commercial CCS facility	In construction	2025	Coal power generation and heat	1.5	PCC	Pipeline	Under eval.
Huaneng Yangpu Gas-fired Carbon Capture Demo Project	Commercial CCS facility	Operational	2023	Natural gas power generation and heat	0	Industrial separation		EOR
ITRI Calcium Looping Pilot	Pilot and demonstration CCS facility	Operational	2013	Cement and concrete	0.008	Industrial separation	N/A	N/A

Title	Category	Operational status	Operational date	Industry	Capture rate (Mtpa)	Capture type	Transport code	Storage code
PetroChina Changqing Oil Field EOR CCUS	Pilot and demonstration CCS facility	Operational	2017	CO2 transport/ storage	0.1	Pre-combustion capture (natural gas processing)	Road	EOR
Qingzhou Oxy-Fuel Combustion Carbon Capture Project	Commercial CCS facility	Operational	2024	Cement and concrete	0.2	Industrial separation		EOR
Shanghai Shidonkou	Pilot and demonstration CCS facility	Operational	2010	Power generation and heat	0.12	PCC	N/A	N/A
Shenhua Group Ordos Carbon Capture and Storage (CCS) Demonstration Project	Pilot and demonstration CCS facility	Completed	2011	CO2 transport/ storage	0.1	Industrial separation	Road	Dedicated geological storage
Shuncheng CO2-TO-METHANOL Anyang Petrochemical	Utilisation facilities	Operational	2022	Chemical	0.16	Industrial separation	N/A	N/A
Sinopec Jinling Petrochemical (Nanjing Refinery)	Commercial CCS facility	Operational	2023	Oil refining	0.3	Pre-combustion capture (gasification)	Road	EOR
Sinopec Nanjing Chemical	Commercial CCS facility	Operational	2021	Chemical	0.2	Pre-combustion capture (gasification)	Road	EOR
Sinopec Qilu-Shengli	Commercial CCS facility	Operational	2022	Chemical	1	Pre-combustion capture (gasification)	Combination	EOR
Sinopec Shengli Oilfield Carbon Capture Utilization and Storage Pilot Project	Pilot and demonstration CCS facility	Operational	2010	CO2 transport/ storage	0.04	PCC	Road	EOR
Sinopec Shengli Power Plant	Commercial CCS facility	Advanced development	Under eval.	Coal power generation and heat	1	PCC	Pipeline	EOR

Title	Category	Operational		Industry	Capture rate (Mtpa)	Capture type	Transport code	Storage code
		status	date					
Sinopec Zhongyuan Carbon Capture Utilization and Storage	Pilot and demonstration CCS facility	Completed	2006	Chemical	0.12	Industrial separation	Road	EOR
Tong PetroTech Xinjiang CCUS Integrated	Commercial CCS facility	Announced	Under eval.	Chemical	0.5	Under eval.		EOR
Xinjiang Dunhua Karamay	Commercial CCS facility	Operational	2015	Chemical	0.1	PCC	Road	EOR
Xinjiang Jinlong Shenwu	Commercial CCS facility	In construction	2024	Coal power generation and heat	0.2	Under eval.	Under eval.	EOR
Yanchang Integrated Demonstration	Commercial CCS facility	Operational	2012	Chemical	0.05			EOR
Yanchang Yan'an CO2-EOR	Commercial CCS facility	Operational	2021	Chemical	0.1	Under eval.	Road	EOR
Yanchang Yulin CO2-EOR	Commercial CCS facility	Operational	2022	Chemical	0.3	Under eval.	Road	EOR
Yangtze River Delta Hub	Commercial CCS facility	Announced	Under eval.	Chemical	10	Under evaluation	Under eval.	Under evaluation
Yulin Integrated Coal Liquefication	Commercial CCS facility	In construction	Under eval.	Chemical	4	Under eval.	Under eval.	EOR
Zhejiang Lanxi CO2 Capture and Mineralisation Project	Commercial CCS facility	Operational	2024	Power generation and heat	0.015			Mineral carbonation
China Energy Erdos Saline Storage	Pilot and demonstration CCS facility	Completed	2011	Chemical	0.1	Pre-combustion capture (gasification)	Road	Deep saline formation
Yanchang Coal-to-Chemical	Commercial CCS facility	Operational	2013	Chemical	0.3	Pre-combustion capture (gasification)	Road	EOR

Title	Category	Operational		Industry	Capture rate (Mtpa)	Capture type	Transport code	Storage code
		status	date					
Guodian Tianjin Beltane Coal-Fired Power Plant	Commercial CCS facility	Operational	2012	Coal power generation and heat	0.02	PCC	Road	Industrial utilisation and food
Huaneng Shidongkou Power Plant	Pilot and demonstration CCS facility	Operational	2009	Coal power generation and heat	0.12	PCC	Unknown	Industrial utilisation and food
China Power Investment Chongqing Shuanghuai Power Plant	Pilot and demonstration CCS facility	Operational	2010	Coal power generation and heat	0.01	PCC	Road	Industrial utilisation
HUST 35 MW Oxy Combustion	Pilot and demonstration CCS facility	Operational	2004	Coal power generation and heat	0.1	Oxy-combustion	Road	Industrial utilisation
Karamay Dunham Oil Technology CCUS EOR	Pilot and demonstration CCS facility	Operational	2015	Chemical	0.1	Pre-combustion capture	Road	EOR
Changqing Oilfield CO2-EOR	Pilot and demonstration CCS facility	Operational	2017	Chemical	0.05	Pre-combustion capture	Road	EOR
Conch Baimashan Cement Plant CO2 Capture and Purifization	Pilot and demonstration CCS facility	Operational	2018	Cement and concrete	0.05	Pre-combustion capture	Road	Sold in market
SINOPEC East China Oilfield CCUS Full Chain Demonstration	Pilot and demonstration ccs facility	Operational	2005	Chemical	0.1	Pre-combustion capture	Road and ship	EOR
Beijing Liulihe Cement Capture	Pilot and demonstration CCS facility	Operational	2017	Cement and concrete	0.001	Pre-combustion capture		Industrial utilisation



LETA

Low Emission Technology Australia

CIAB