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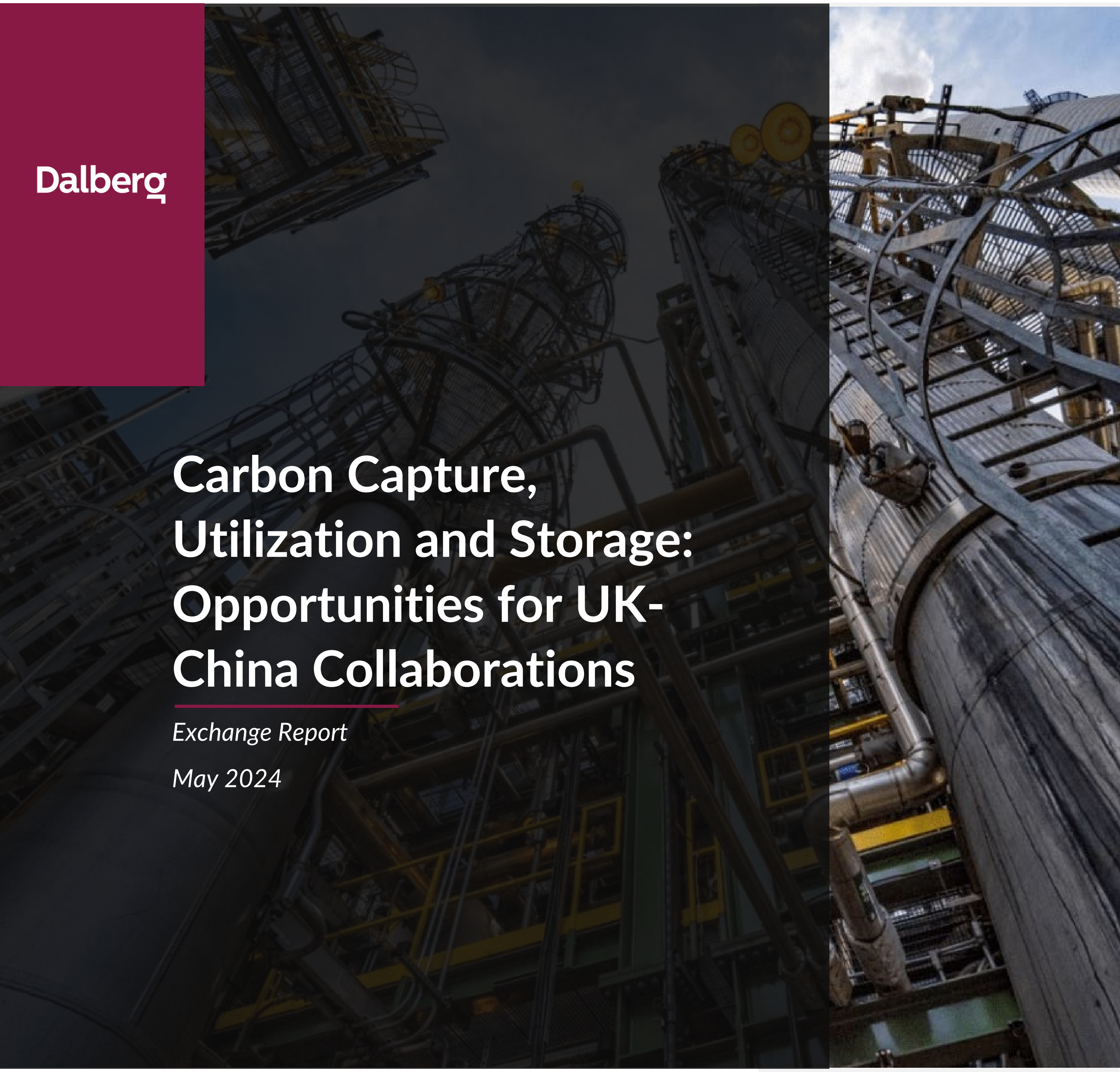

Carbon Capture, Utilization and Storage: Opportunities for UK-China Collaborations

Exchange Report

May 2024

Royal Academy of Engineering

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1. EXECUTIVE SUMMARY

Carbon capture, storage, and utilisation (CCUS) has emerged as a key technology to facilitate the transition to net zero in the United Kingdom (UK) and the People's Republic of China (PRC or China). Both countries have set ambitious goals to develop CCUS. The UK aims to deploy CCUS in 4 industrial clusters by 2030, capturing 20-30 Mt of CO2 each year. China, which already has ~50 operational CCUS projects, also aims for extensive deployment by 2050 supported by multiple industrial hubs.

To explore how to deepen UK-China collaboration on CCUS, a UK delegation led by the Royal Academy of Engineering (RAEng) attended a bilateral exchange from the 20th to the 24th of May 2024 in multiple cities across China. Eleven UK CCUS experts engaged in technical exchanges with China's CCUS community including through seminars, closed door meetings and visits to a CO2 capture and storage site and a CCUS R&D lab.

Several opportunities for greater collaboration across the CCUS value chain between academia, policymakers, and industry in the UK and China have emerged from the convening. Broad pathways for collaboration include conducting joint research and sharing knowledge to fill critical gaps in R&D, aligning policy frameworks and developing common standards to serve as enablers for further collaboration, and identifying supply chain synergies across the two countries. A summary of opportunities has been provided below:

#1 Deploying a CCUS demonstration project: Jointly develop a CCUS demonstration project in China, potentially using the plant of a UK company with a presence in China.

#2 Sharing lessons on deploying CCUS in clusters and diverse industries: Share lessons and best practices from the United Kingdom's experience in developing industrial CCUS clusters and China's experience in deploying first-of-a-kind CCUS projects such as those in the glassmaking industry.

#3 Testing CCUS innovations from the UK in China: Use existing testing facilities and projects in China to test and scale promising, early-stage CCUS technologies from the UK.

#4 Align carbon accounting standards and develop emissions trading systems: Consider opportunities to align carbon accounting standards, further enabling standardised definitions of key green products, and identify opportunities to jointly advance thinking on effectively incorporating CCUS within the ETS.

#5 Share policy learnings on CCUS regulation and incentivisation: Share best practices and learnings on developing relevant regulatory frameworks, policy incentives, and business models (particularly Contract for Difference models) for CCUS with Central and local governments in China.

#6 Enabling student and faculty exchanges between universities: Conduct student exchanges, summer schools, faculty visits and secondments to offer a more holistic education on CCUS and green technologies.

#7 Reducing the cost of capture via research, standardisation, and supply-chain collaboration: Conduct joint research, standardise project design, and identify opportunities to competitively supply components to bring down the cost of capturing CO2.

#8 Advancing research and supply-chain collaboration to develop pipelines for CO2 transportation: Conduct research and share learnings on safe and effective development of pipelines. Also enable UK companies to offer expertise in pipeline design, corrosion resistance and detection to projects in China.

#9 Advancing research, policy solutions and supply-chain collaboration for CO2 storage: Conduct joint research on the effective storage of CO2 in basalts, saline aquifers etc., jointly progress policy thinking on licensing and liability management and, enable UK companies to offer their expertise in site description, injection, risk analysis, leakage monitoring and management.

#10 Advancing research and advocacy for negative emissions technologies: Jointly advocate for greater focus on direct air capture (DAC) and bioenergy with carbon capture and storage (BECCS) technology, as removing CO2 and greenhouse gasses from the atmosphere will be crucial to meeting net-zero targets. Joint research can help identify feasible projects, advance technology readiness and, reduce costs.

#11 Advancing research, advocacy, and standardisation for biochar: Conduct joint research to advance carbon storage and sequestration via biochar, benchmark and potentially align domestic standards on its production and use, and advocate for its inclusion under each country's ETS.

#12 Addressing technical challenges in CO2 shipping: Enable collaboration among researchers and companies to design and manufacture ships that are fit for transporting CO2.

#13 Exchanging learnings on advancements in CO2 utilisation: Exchange learnings from each country's progress on utilisation of captured CO2. For example, to produce sustainable fuels in the UK and chemical utilisation in China.

To drive progress on these opportunities, we call on stakeholders from the UK and China to come together and explore where mutual interest and value is the greatest. Additionally, there is a need to sustain momentum, drive alignment among actors and establish effective governance mechanisms:

- **Sustaining momentum** entails organising additional exchanges to bring together a diverse range of stakeholders including industry representatives, regulators, policy makers etc. In the immediate term the Royal Academy of Engineering could organise a reciprocal exchange for Chinese delegates to witness and learn from the UK's progress on CCUS. This could be followed-up by a letter of intent which identifies high-potential opportunities and pathways for collaboration. Sustained outreach with stakeholders via active follow-ups, reports, seminars etc. is also required to better communicate the benefits of UK-China collaboration.
- **Driving alignment** among relevant actors is essential to develop a common foundation for further collaboration. For the Royal Academy of Engineering this could entail convening challenge prioritisation workshops to shortlist the top 5-10 research questions or collaboration opportunities that present quick wins. Streamlining frameworks, standards, and definitions can also create a 'common language' for collaboration by ensuring consistency in trading, technological and operating norms.
- **Establishing governance** is crucial to ensure the longevity of collaboration efforts. A joint statement at the ministerial level can indicate 'open doors' for collaboration and having in place relevant policy measures can streamline the partnership process. Identifying a dedicated governing body to provide collaborators with potential discovery and funding support can also make collaboration sustainable.

The China CCUS market, while still nascent, is rapidly expanding and is expected to continue to do so, as outlined in the country's ambitious Roadmap for Development of CCUS Technology. The Chinese Central Government's substantial commitment to its carbon peaking and carbon neutrality goals and the UK's legal commitment to meet its net zero target provides a stable foundation for innovation and growth. The time is right to further CCUS momentum in both countries by forging enduring partnerships focused on knowledge sharing, research, standardisation, and supply-chain linkages.

**Note: Findings on collaboration opportunities in the report are derived largely from the UK delegation's experience and interpretation of the CCUS landscape in China.*

2. UK-China Carbon Capture, Utilization & Storage Landscape

2.1. The UK & Chinese government's CCUS objectives

The UK and China have set ambitious net-zero targets and CCUS is expected to play a key role in achieving these.

The UK's Climate Change Committee declared CCUS a "necessity not an option" to achieve net zero emissions by 2050, with carbon capture offsetting up to 10% of current emissions. In this regard, the country will establish CCUS in two industrial clusters by the mid-2020s and aim for a total of four sites by 2030, with an ambition to capture and store 20-30 megatonnes (Mt) of carbon dioxide (CO2) each year. This is equivalent to ~7-10% of annual net CO2 emissions in 2023 or taking 4-6 million cars off the road.[1] CCUS can also offset carbon emissions from the processing of blue hydrogen[2] production, for which the UK aims to develop 10 gigawatts (GW) of production capacity by 2030.[3]

China has also positioned CCUS as one of the most important means of achieving its target of carbon peak by 2030 and carbon neutrality by 2060. In 2019, the government issued an updated Roadmap for Development of CCUS Technology in China which defined its overall vision and several phase-wise goals in five-year increments to 2050. By 2030, China aims for CCUS to be ready for industrial application, and long-distance onshore pipelines with capacities of 2 Mt of CO2 to be available. China also aims to reduce the cost and energy consumption of CO2 capture by 10-15% by 2030 and 40-50% by 2040. By 2050, CCUS technology is targeted to be deployed extensively, supported by multiple industrial CCUS hubs across the country.[4]

The CCUS ambitions of both countries can reap significant economic and employment benefits. Analysis commissioned by the UK's Department for Business, Energy and Industrial Strategy suggests that the global market for CCUS could generate around £260 billion per annum in turnover by 2050, of which, the UK has the potential to capture up to £200 billion, or over three-fourths.[5] The UK's CCUS Vision is expected to boost its economy by £5 billion a year by 2050 and support 50,000 jobs by 2030.[6] The International Energy Agency (IEA) and the Asian Development Bank (ADB) estimate that CCUS could create additional value of between 0.2-0.6% of China's 2019 GDP by 2030, amounting to ~£80 billion.[7,8] This is also expected to create between 90,000 and 200,000 direct jobs by 2030.[9]

2.2. The UK & Chinese government CCUS funding & policy support

The UK is at the forefront of providing policy and funding support for CCUS. China's long-held focus on CCUS has also been reiterated by recent policy developments.

The UK government, in the first phase of its approach, has focused on outlining the framework for CCUS regulation and laying the foundations for a self-sustaining private market. The UK government has a three-phased approach to CCUS development – (i) market creation by 2030, (ii) market transition, and finally (iii) a self-sustaining market by 2050. In the first phase, the government has created a robust legislative framework for the regulation of CCUS via the *Energy Act 2023*.[10] This framework has been designed to address cross-chain risks[11] and encourage the development of CCUS business models that attract private investment.[12] To

[1] UK Infrastructure Bank, Strategy Update: Carbon capture, usage, and storage, 2023
[2] According to the World Economic Forum, hydrogen is labelled blue whenever the carbon generated from steam reforming is captured and stored underground through industrial carbon capture and storage (CSS).
[3] UK Government's Department for Business and Trade, Carbon capture, usage and storage, Accessed May 2024
[4] IEA, Energy Technology Perspectives: Special Report on Carbon Capture Utilisation and Storage, 2020
[5] UK Government's Department of Business, Energy and Industrial Strategy, CCUS Supply Chains: a roadmap to maximize the UK's potential, 2021
[6] UK's Department from Energy Security and Net Zero, Press Release: New vision to create competitive carbon capture market follows unprecedented £20 billion investment, 2023
[7] McKinsey & Company, Unlocking Asia-Pacific's vast carbon capture potential, 2023
[8] This value is converted from US$100 billion as per the exchange rate prevailing on 7th May 2024.
[9] Oil and Gas Climate Initiative, CCUS in China: The value and opportunities for deployment, 2021
[10] The Energy Act 2023 sets out the powers and duties given to the Office of Gas and Electricity Markets (Ofgem) as the economic regulator for CO2 transport and storage (T&S), makes provisions for government fiscal support, allows for new types of T&S economic licenses and allocation processes to be established and gives the Secretary of State the power to designate a CCUS Strategy and Policy statement which will articulate the government's priorities and desired policy outcomes for CCUS.
[11] Cross chain risks arise when the actions or omissions of one part of the value chain have the potential to negative impact other parts.
[12] UK's Department for Energy Security & Net Zero, Carbon Capture, Usage and Storage: A Vision to Establish a Competitive Market, 2023

further improve investor confidence in this highly nascent sector, a "build it and they will come" approach has been adopted, offering financial assistance and guaranteed returns to first movers in industrial CCUS and transportation and storage sectors.[13]

The UK government has significantly stepped-up funding for CCUS, committing £20 billion to directly support transport and storage networks and industrial carbon capture projects. Many other net-zero transition funding mechanisms are also available for CCUS. In 2020, the UK government confirmed a £1 billion investment for the deployment of CCUS in four industrial clusters by 2030. In 2023, this was subsumed by a longer-term funding package of £20 billion, to be rolled out over 20 years.[14] CCUS-enabled hydrogen projects can also access capital support through the £240 million Net Zero Hydrogen Fund.[15,16] Between 2004-21, the UK government funnelled over £346 million towards CCUS research and innovation and has planned for an additional £115 million to support CCUS and Greenhouse Gas Removal technologies under the Net Zero Innovation Portfolio.[17,18] Furthermore, to encourage private investments in sectors like CCUS, the government set up the UK Infrastructure Bank with an initial capital infusion of £12 billion.[19]

In subsequent phases, policymakers in the UK will focus on measures to improve private sector confidence in CCUS. A few examples of developments already underway or being explored include evolving the UK's Emissions Trading Scheme to better align with the net zero trajectory, designing policies that address carbon leakage, a potential Carbon Take Back Obligation or Carbon Storage Obligation for companies that extract fossil fuels, among others.[20]

CCUS has long been a policy focus in China. CCUS had been included in China's national carbon mitigation strategies as far back as the 12th Five-Year Plan (2011-2015). These early-stage policies focused on demonstrations and pilots.[21] With the announcement of China's 30/60 goals and the establishment of the country's "1+N" policy system[22] for emission peaking and carbon neutrality, the Chinese government has increased policy cover for CCUS. As of October 2022, China had issued 70 CCUS-related policies at the national level, including plans, standards, roadmaps, and technology catalogues. These documents lay out proactive plans for future CCUS research and development, investment, and technology cooperation.[23]

The Chinese government has also been expanding the scope of CCUS-related policies, including through an increased number of policies related to technical standards, investment, and financing. For example, CCUS projects were included in the updated *Green Bond Endorsed Projects Catalogue (2021 Edition).* This has the potential to attract further green investments in the country. CCUS has also been mentioned in more sectoral policies including those in hard-to-abate sectors, whereas it was previously only mentioned in power and oil & gas industries. Local governments have also increased their support for CCUS development. As of late 2022, ten subnational governments had deployed CCUS R&D and promotion programs according to local conditions.[24] For e.g., the Guangdong Province has offered incentives for CCUS demonstration projects in the power plant industry.[25]

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[13] NITI Aayog, Carbon Capture, Utilization and Storage (CCUS): Policy Framework and its Deployment Mechanism in India, 2022
[14] This amount includes the £1 billion in funding committed earlier.
[15] The Net Zero Hydrogen Fund is a grant fund by the UK government that provides development and capital expenditure to support the commercial deployment of new low carbon hydrogen production projects.
[16] UK Infrastructure Bank, Strategy Update: Carbon capture, usage, and storage, 2023
[17] The Net Zero Innovation Portfolio is a £1 billion packet of competitive funding schemes by the UK government to accelerate the commercialisation of low carbon technologies, systems, and business models in power, buildings and industry.
[18] UK's HM Government, Hydrogen Net Zero Investment Roadmap, 2024
[19] UK's HM Treasury, UK Infrastructure Bank Policy Design, 2021
[20] UK's Department for Energy Security & Net Zero, Carbon Capture, Usage and Storage: A Vision to Establish a Competitive Market, 2023
[21] Global CCS Institute, Repositioning CCUS for China's Net-Zero Future, 2022
[22] China's "1+N" policy framework consists of overarching guidance: the "1", and action plans and policy measures for key sectors and industries: the "N". These policies prioritize the decarbonization of the industrial sector, primarily focusing on building materials, metallurgy, and chemical industries.
[23] The Administrative Center for China's Agenda 21, Global CCS Institute, Tsinghua University, CCUS Progress in China – A Status Report, 2023
[24] The Administrative Center for China's Agenda 21, Global CCS Institute, Tsinghua University, CCUS Progress in China – A Status Report, 2023
[25] Jiutian, Z., Zhiyong, W., Jia-Ning, K. *et al.*, Several key issues for CCUS development in China targeting carbon neutrality, 2022

State-owned enterprises in China have provided most of the funding for CCUS to date.[26,27] One such example is China's first 1 Mt per annum-scale CCUS project developed by Sinopec for ~£40.5 million.[28,29] The Chinese national and provincial governments have contributed roughly £110 million[30] towards CCUS development to date, largely focused on research and innovation.[31] The People's Bank of China, the country's central bank, has also made ~£32.5 billion[32] in concessional finance available to Chinese financial institutions to incentivize re-lending for green projects. This Carbon Emission Reduction Facility had led to ~£65 billion[33] in re-lending to such projects by the end of 2022 and helped reduce carbon emissions by 100 Mt in that year.[34] The proportion of this allocable to CCUS projects is unclear.

2.3. Current CCUS projects in the UK and China

Similar to the state of CCUS globally, most existing projects are at the pilot or demonstration stage however, both the UK and China have a strong pipeline of large-scale projects.

The UK government has aimed to support the development of CCUS projects in 4 industrial clusters by 2030. Currently there is only one operational commercial CCUS project in the UK, capturing 40,000 tons of CO2 per year.[35] In 2021, the government launched the CCUS cluster sequencing process, structured in two tracks. In 2023, negotiations commenced with eight capture projects in two Track 1 clusters (HyNet and the East Coast Cluster) set to enter operations by mid-2020s. In the same year two additional clusters (Acorn and Viking) were selected for Track-2 development due to launch by 2030.[36] The response from business has also been positive. The number of planned projects in the wider UK pipeline have grown, with enough schemes to capture 94 Mt of CO2.[37] Government-supported cluster projects continue to edge closer to operation despite delays due to slow decision making on outlining business-model blueprints, long permitting processes, and rising costs[38,39,40].

China has several CCUS projects in operation already and the scale of projects has been increasing. As of late 2022, there were around 100 CCUS demonstration projects either in operation or planning in China. Almost half of these had been put into operation with a capture capacity of more than 6 Mt per year.[41,42] At present, these are largely point-to-point projects[43] in the pilot or demonstration phase, are implemented by state-owned enterprises and use trucks for transportation.[44] In recent years, the scale of projects in operation or under construction has been increasing. The number of projects with a capacity of 100 kilotonnes (kt) has reached more than 40 and among these more than 10 have a capacity of 500 kt CO2. Between 2022 and 2023, China's first Mt per annum-scale CCUS project and first commercial-scale CO2 transport pipeline with a length of 109 km were put into operation.[45]

China also has a strong pipeline of larger projects, and projects under development are covering an increasing range of sectors. Several large-scale demonstration projects are under development in China including one

[26] Insights from UK-China Bilateral Exchange on CCUS
[27] Total amount spent by Chinese State-owned Enterprises on CCUS projects is unknown.
[28] Converted from RMB 374 million using exchange rate prevailing on 28th May 2024
[29] Insights from UK-China Bilateral Exchange on CCUS
[30] Converted from RMB 1 billion using exchange rate prevailing on 28th May 2024
[31] Insights from UK-China Bilateral Exchange on CCUS
[32] Converted from RMB 300 billion as per exchange rate prevailing on 28th May 2024
[33] Converted from RMB 600 billion as per exchange rate prevailing on 28th May 2024
[34] Central Banking, PBoC has lent banks $44 billion for 'green projects', 2023
[35] UK Research and Innovation, India's Department of Science and Technology, Carbon Capture Utilisation and Storage (CCUS) in India and the UK, 2022
[36] UK's Department for Energy Security & Net Zero, Carbon Capture, Usage and Storage: A Vision to Establish a Competitive Market, 2023
[37] The Carbon Capture and Storage Association, CCUS Delivery Plan Update, 2023
[38] Upstream, Final investment decisions in doubt: UK government go-slow hurting CCS dreams, 2023
[39] Upstream, Industry warms UK to strengthen carbon capture commitments or see lead fade away, 2023
[40] Energy Voice, UK considers delaying some carbon capture projects as costs soar, 2024
[41] The Administrative Center for China's Agenda 21, Global CCS Institute, Tsinghua University, CCUS Progress in China – A Status Report, 2023
[42] UK-China (Guangdong) CCUS Centre, UKCCS, The Administrative Center for China's Agenda 21, Carbon Capture, Usage & Storage (CCUS) Supply Chain Cooperation: Unlocking the full potential of CCUS for the UK and China, 2024
[43] Point-to-point projects typically focused on the emissions of a single emitter where CCUS hub and cluster networks brings together multiple carbon dioxide (CO2) emitters and/or multiple storage locations using shared transportation infrastructure.
[44] The Administrative Center for China's Agenda 21, Global CCS Institute, Tsinghua University, CCUS Progress in China – A Status Report, 2023
[45] Global CCS Institute, China Continues to Advance CCUS in 2023, 2023

cluster in Xinjiang which is expected to reach an annual capacity of 10 Mt CO_2 by 2030 and another 10 Mt-scale cluster in the Daya Bay area which is being studied. Moreover, projects are being demonstrated in a vast variety of sectors with those in hard-to-abate sectors increasing significantly from 2021 to 2022.[46]

2.4. Primary assets of the UK and China for CCUS

Both countries have distinct strengths in the CCUS domain, and they stand to benefit significantly from collaborating with each other.

The UK is well positioned to develop CCUS due to its early policy efforts, strong R&D and select supply chain capabilities, and robust capital markets. The UK is an early mover in the development of complex and interconnected regional decarbonization hubs and at the forefront of developing policy frameworks and business models for CCUS.[47,48] The country is a source of several cutting-edge CCUS innovations.[49] Industry in the UK also holds key capabilities in engineering consultancy, project development, financing expertise and manufacturing of key components such as heat exchangers, column internals and filters.[50] Moreover, London is home to Europe's largest capital market with a deep pool of liquidity and international investors (including from China), laying a strong foundation to capitalize on financing opportunities for planned CCUS clusters.[51,52]

China's market scale, cost advantages, and robust domestic supply chains create a favourable environment to scale CCUS rapidly. The technology can leverage unmatched economies of scale in China due to the immense volume of industrial cluster developments across the country. This can lead to significant cost reductions.[53] In fact, China already has certain cost advantages. Given the sizable number of CCUS projects already underway in China, costs have been falling year on year as the local industry climbs the learning curve. Overall, CCUS costs in China have the potential to be 10-30% lower than in advanced economies like the UK.[54] This is due to reduced labour costs, efficient equipment manufacturing, transportation, and access to cost-effective materials.[55] This large canvas in China presents an opportunity to embrace early lessons from major projects around the world.[56] China's comparative advantage in manufacturing, availability of required capabilities within the country, and a strong logistics sector have also enabled rapid development of CCUS projects.[57,58]

2.5. Key roadblocks to scaling CCUS in the UK and China

Despite their strengths, the growth of CCUS is hindered in both countries by several common roadblocks.

High capex and opex costs in the face of low carbon prices and unproven business models: In the UK, CCUS deployment costs have more than doubled since 2020 due to inflation and are expected to increase further.[59] Even in China, the cost of CO_2 capture is high in sectors like cement and coal-fired power[60] due to low concentration of CO_2 in the flue gas and presence of impurities which demands the use of more cost-intensive technologies.[61] Cement plants in China are small and geographically dispersed, also increasing cost.[62] In both countries, a lack of design standardization adds to upfront cost and the high risk associated with projects drives

[46] The Administrative Center for China's Agenda 21, Global CCS Institute, Tsinghua University, CCUS Progress in China – A Status Report, 2023
[47] Insights from the UK-China Bilateral Exchange on CCUS
[48] Department for Energy Security and Net Zero, A Remarkable New Infrastructure System: Opportunities for economic growth in the UK's Carbon Capture & Storage Industry, 2023
[49] Insights from UK-China Bilateral Exchange on CCUS
[50] UK-China (Guangdong) CCUS Centre, UKCCS, The Administrative Center for China's Agenda 21, Carbon Capture, Usage & Storage (CCUS) Supply Chain Cooperation: Unlocking the full potential of CCUS for the UK and China, 2024
[51] China-Britain Business Council, KPMG, Targeting Net Zero: The Role of UK-China Business, 2021
[52] Insights from the UK-China Bilateral Exchange on CCUS
[53] China-Britain Business Council, KPMG, Targeting Net Zero: The Role of UK-China Business, 2021
[54] UK-China (Guangdong) CCUS Centre, UKCCS, The Administrative Center for China's Agenda 21, Carbon Capture, Usage & Storage (CCUS) Supply Chain Cooperation: Unlocking the full potential of CCUS for the UK and China, 2024
[55] Ibid.
[56] China-Britain Business Council, KPMG, Targeting Net Zero: The Role of UK-China Business, 2021
[57] London School of Economics, Seizing sustainable growth opportunities from carbon capture, usage and storage in the UK, 2021
[58] Insights from UK-China Bilateral Exchange on CCUS
[59] Carbon Tracker, Curb your Enthusiasm: Bridging the gap between the UK's CCUS targets and reality, 2024
[60] The Administrative Center for China's Agenda 21, Global CCS Institute, Tsinghua University, CCUS Progress in China – A Status Report, 2023
[61] Insights from the UK-China Bilateral Exchange on CCUS
[62] Ibid.

up the cost of capital.[63] At the same time China's ETS is yet to cover emission reductions from CCUS[64] and the price of carbon on UK's ETS had slumped to an all-time low towards the end of January 2024.[65] Most other business cases for CCUS today rely on specific policy enablement (e.g., subsidies, revenue support packages etc.). Non-subsidy revenues which are critical to scaling the sector are still immature potentially leading to hesitation in committing commercial capital.[66]

Need for significant multi-sectoral collaboration and managing of risks across stakeholders: Developing integrated CCUS projects requires collaboration across multiple stakeholders (emitters, transport operators, storage sites etc.) along a complex value chain. The need for complicated commercial agreements has reduced the appeal of such projects in China in the past.[67] Moreover, members of the value chain are exposed to significant cross-chain risks[68] which have been cited as a major reason for the failure of historical attempts to develop large-scale CCUS projects in the UK.[69,70]

Technologies required for scale-up are still in early stages: Around three quarters of capture capacity envisioned by 2050 in the International Energy Agency's Net Zero Roadmap relies on technologies and applications that are still in the demonstration or prototype stage.[71] These include carbon removal, new ways of utilising captured CO2 (particularly to make fuels and chemicals), carbon capture in cement and iron & steel production, among others.[72] The UK has a comparative advantage in CCUS innovation but the business case for investing may depend on the pace of developing commensurate skills and supply chains, which are essential to retain economic value.[73]

Lower realistic storage potential and relatively slow progress on storage-related policy and infrastructure: Realistic CO2 storage potential in the UK and China is expected to be much lower than theoretically predicted.[74] For example, 1 in 10 boreholes in the UK cannot be sealed properly and hence are not fit for storing CO2.[75] Moreover, major emission sources in the Eastern region of China and the South Wales or Southampton clusters in the UK lack available sites for CO2 storage.[76,77] Challenges such as limited policy mechanisms to transition from public to market funding of storage projects in the UK and lack of geological survey technology in China has led to slower development of CO2 storage capacity than required.[78,79]

Both countries are also facing unique challenges owing to their specific characteristics:

The CCUS sector in the UK is facing a shortage of skilled individuals especially in design and engineering construction, potentially impeding the timely completion of projects. This stems partly from competition among CCUS projects and against other large infrastructure projects which might need to be implemented over similar timeframes. Further, the engineering construction industry will need to replace or re-train an aging and non-diverse workforce, implying the need to attract a large number of new and re-skilled personnel into extensive training programs in a sector that suffers from low public awareness. In engineering construction alone, ~40% of the UK's workforce is over the age of 50, and only 5% under the age of 25. Similar challenges are expected to persist with trainers.[80] In one survey of UK energy professionals expecting a switch to the CCUS field, 50% cited barriers to their professional development including a lack of appropriate training.[81]

63 Ibid.
64 Ibid.
65 Carbon Tracker, Curb your Enthusiasm: Bridging the gap between the UK's CCUS targets and reality, 2024
66 McKinsey and Company, Scaling the CCUS industry to achieve net-zero emissions, 2022
67 Global CCS Institute, Repositioning CCUS for China's Net-Zero Future, 2022
68 Cross chain risks arise when the actions or omissions of one part of the value chain have the potential to negative impact other parts.
69 Clean Air Taskforce, Risk Allocation and Regulation for CO2 Infrastructure, 2024
70 Cross chain risks arise when the actions or omissions of one part of the value chain have the potential to negative impact other parts.
71 IEA, New policy and business approaches are needed to support scaling up of CCUS to reach net zero goals, 2023
72 IEA, Energy Technology Perspectives: Special Report on Carbon Capture Utilisation and Storage, 2020
73 London School of Economics, Seizing sustainable growth opportunities from carbon capture, usage and storage in the UK, 2021
74 Insights from the UK-China Bilateral Exchange on CCUS
75 Ibid.
76 Wang, P., Shi, B., Li, N. et al., CCUS development in China and forecast its contribution to emission reduction, 2023
77 Insights from the UK-China Bilateral Exchange on CCUS
78 Ibid.
79 Sun Y, Li Y, Zhang F, Liu C., Obstacle Identification and Analysis to the Commercialization of CCUS Technology in China under the Carbon Neutrality Target, 2022
80 The Carbon Capture and Storage Association, CCSA Workforce & Skills Position Paper, 2023
81 London School of Economics, Seizing sustainable growth opportunities from carbon capture, usage and storage in the UK, 2021

Lack of incentive policies and regulatory frameworks for CCUS in China lead to uncertainties around long-term sustainability of projects. At present, costs for CCUS projects are absorbed by companies (largely state-owned) due to a lack of subsidy and incentive policies.[82] High operating and maintenance costs also increase financial strain on enterprises.[83] The lack of an overarching regulatory framework also leads to limited legal protection and increased risk for companies carrying out such projects.[84] This might hinder the long-term commercialisation potential of CCUS in China.[85]

2.6. Existing CCUS collaborations between the UK and China

Greater coordination at the political level has led to longstanding, fruitful collaborations between businesses and researchers in the UK and China towards net-zero transitions.

The UK and China have been collaborating with each other on climate action more broadly since over a decade. The UK-China joint statement on climate change released in 2014 is among the most ambitious bilateral documents in the area. In 2015, both governments signed an agreement for a Clean Energy Partnership to support each other during their transitions to low carbon economies. The UK-China Green Financing Taskforce, established by the City of London Corporation and the China Green Finance Committee has served as a key platform for green finance collaboration since 2016. More recent government level meetings between the two countries have reiterated a commitment to enhance cooperation on key green technologies.[86]

Notably, the China-UK Near Zero Emissions Coal (NZEC) Initiative, the UK-China (Guangdong) CCUS Centre and the Sino-British Engineering Technology Cooperation represent key milestones in bilateral collaboration. The China-UK NZEC Initiative was developed in 2005 to support the broader EU-China NZEC Agreement and examined the merits of various options for carbon capture, transport, and geological storage in China.[87,88] Under the initiative collaborative research activities were undertaken by Chinese and UK experts from ~30 organizations.[89] Further collaboration is championed by the UK-China (Guangdong) CCUS Centre, established in 2013. The centre is a hub for research and engineering activities, including development of CCUS demonstration projects in South China. It is supported by a variety of players across government, industry and academia from both the UK and China.[90] This spirit of collaboration has sustained over the years. In 2022, the Royal Academy of Engineering and the Chinese Academy of Engineering launched the Sino-British Engineering Technology Cooperation to promote partnership among the engineering communities of both countries on the topic of decarbonisation, with a focus on offshore wind technology and CCUS in the near term.[91,92]

China's green light for foreign investments in CCUS and close ties of UK companies in China's CCUS sector also highlight strong industrial collaboration. In 2022, China issued the Catalogue of Industries for Encouraging Private Investment, which calls for foreign investment in a number of CCUS-related fields. Prominent UK companies like Shell, bp, Howden, and Wood play significant roles in China's CCUS sector. These companies directly collaborate with Chinese enterprises to develop projects, supply key inputs, provide research and strategic expertise etc. Shell, in particular, is a major player with several collaborations across regions for example, through a partnership with Sinopec, Baowu Steel, and BASF to explore an open-source CCUS cluster in Shanghai and Jiangsu. Several other UK companies are also linked to China's CCUS sector or have expressed an interest in exploring such opportunities.[93]

[82] Insights from the UK-China Bilateral Exchange on CCUS
[83] Sun Y, Li Y, Zhang F, Liu C., Obstacle Identification and Analysis to the Commercialization of CCUS Technology in China under the Carbon Neutrality Target, 2022
[84] Ibid.
[85] Ibid
[86] China-Britain Business Council, KPMG, Targeting Net Zero: The Role of UK-China Business, 2021
[87] This was supported by up to £3.5 million from the UK's Department on Energy and Climate Change in partnership with the Chinese Ministry of Science and Technology (MOST).
[88] NZEC, China-UK Near Zero Emissions Coal (NZEC) Initiative Summary Report, 2009
[89] Ibid.
[90] SCCS, Renewed Memorandum of Understanding to mark 10th anniversary of the UK-China (Guangdong) CCUS Centre, 2024
[91] Chinese Academy of Engineering, Steering Committee on Sino-British Engineering Technology Cooperation inaugurated, 2022
[92] Chinese Academy of Engineering, Steering Committee on Sino-British Engineering Technology Cooperation holds annual meeting, 2023
[93] UK-China (Guangdong) CCUS Centre, UKCCS, The Administrative Center for China's Agenda 21, Carbon Capture, Usage & Storage (CCUS) Supply Chain Cooperation: Unlocking the full potential of CCUS for the UK and China, 2024

3. Key Findings from the Exchange

3.1. Conference objectives

The UK-China Bilateral Exchange on Carbon Capture, Utilization and Storage was convened to deepen UK-China partnership on CCUS by facilitating knowledge exchange and promoting mutual learning to catalyse progress towards net-zero goals.

The Royal Academy of Engineering (RAEng) along with the Chinese Academy of Engineering (CAE) and the Guangdong Electric Power Design Institute (GEDI) in Guangzhou convened a UK-China bilateral exchange on CCUS between the 20th and 24th of May 2024 to aid cross-national learnings on CCUS development. The exchange, held in China, provided a platform for delegates from academia, industry, and government from both countries to highlight cutting-edge innovations, discuss shared challenges, and identify potential collaboration opportunities to advance CCUS.

In the span of a week, UK delegates engaged with Chinese experts via technical seminars, site visits, and discussions. This fostered dialogue around emerging CCUS technologies, critical infrastructure and innovation needed across the value chain, the need to bring down costs, safety concerns, the application of CCUS in hard-to-abate sectors, and major opportunities for collaboration across the value chain.

3.2. Major opportunities for collaboration to be explored

Several collaboration opportunities across the CCUS value chain emerged from 1-on-1 conversations and a workshop conducted with delegates from the UK.

Collaborating with China on CCUS could benefit the UK substantially in the form of learnings from a vast portfolio of operational CCUS projects, the ability to pilot and scale cutting edge UK technologies in a large and growing CCUS market, potential for cost and time efficiencies via supply chain collaboration, commercial opportunities for UK companies in China's CCUS market, and joint efforts to advance research and technology readiness.

To provide a comprehensive overview of the opportunities across the CCUS value chain, the following illustration presents a summary of the major collaborative avenues identified during the exchange. In a workshop, UK delegates were asked to identify the highest potential opportunities for collaboration which are highlighted in the illustration. Each opportunity box also contains colour markers depicting the relevant pathways for collaboration.

Figure 1: Illustrated collaboration opportunities across the CCUS value chain

Separation and capture → **Transportation and temporary storage** → **Storage or utilization**

Opportunities

● ● **#1. Jointly deploy and co-fund a CCUS demonstration project:** Collaborate at the ministerial level to establish and co-fund a joint-full scale CCUS project in China, potentially using a UK company's plant. This can generate learnings on cost and risk reduction for both countries and on rapid implementation for the UK. It can also demonstrate UK technologies' viability in the Chinese context. ★

● **#2. Share knowledge on lessons learnt in deploying CCUS in clusters and diverse industries:** The UK and China have complementary expertise from learning-by-doing. China could benefit from the UK's learnings on cluster development while the UK could benefit from China's experience capturing CO2 from dilute sources via first-of-a-kind projects such as those in the glass-making industry. ★

● ● **#3. Pilot UK technologies in China at scale:** The UK is a source of several cutting edge CCUS innovations which are in early stages of development. China has several operational projects in various industries including Asia' first testing platform for CCUS. Piloting UK technologies in China can help identify and address pain points for scalability and leverage opportunities to further commercialize these in the Chinese market. ★

● **#4. Align carbon accounting standards and jointly develop emissions trading systems (ETS):** Wherever possible, both countries could align on common standards for carbon accounting and jointly progress thinking on effectively incorporating CCUS within the ETS. This could enable standardized definitions of 'green' products such as decarbonized steel and the development of trade agreements thereby increasing bilateral trade. ★

● ● **#5. Enable student and faculty exchanges between universities:** Universities in the UK and China can collaborate with each other to provide holistic CCUS and green technologies education via student exchanges, scholarships, faculty visits, secondments, summer schools etc. This could particularly benefit the UK as it attempts to address a significant skill-shortage in CCUS-relevant sectors.

Separation and capture

● ● ● **#6. Reduce cost of capture via research, standardisation and supply-chain collaboration:** Joint research can improve the energy efficiency of capture technology, standardising and modularising design can reduce upfront capex. and both countries can competitively supply components to the other. ★

● ● **#9. Improve focus and research on direct air capture and bioenergy with carbon capture and storage:** Joint advocacy and research can increase focus on negative emission technologies, identify feasible projects, lower costs etc.

● ● ● **#10. Undertake advancement of biochar:** Joint research, benchmarking domestic standards and advocacy to recognize it under the ETS can advance biochar technology.

Transportation and temporary storage

● ● **#7. Conduct joint research and skills exchange on pipeline development:** The UK (and China) could benefit from jointly researching and sharing learnings on the safe design of pipelines, preventing corrosion, repurposing existing pipelines etc. Ongoing collaborations such as the pipeline rupture test facility in China can be leveraged. UK firms can offer expertise in design, corrosion resistance, and detection. ★

● ● **#11. Address technical challenges in CO2 shipping:** Multi-modal transportation for CO2 is increasing in importance in both the UK and China. Joint research and supply-chain collaboration can solve technical challenges associated with shipping CO2, for e.g., design of CO2 terminals.

Storage or utilization

● ● **#8. Conduct joint research and skills exchange on geological CO2 storage:** The UK (and China) could benefit from joint research on storage of CO2 in basalts, saline aquifers etc. UK companies could lend expertise in site description, injection, risk analysis, leakage management and monitoring. Policy thinking on storage licensing and liability management could also be furthered together. ★

● **#12. Learn from advances in chemical utilisation of CO2:** Research on chemical utilisation of CO2 in China is strong, providing opportunities for knowledge exchange to the UK. China could also learn from the UK's advancements in the use of CO2 to produce sustainable aviation fuels.

Pathway: ● *Conducting research and sharing knowledge* ● *Aligning policies and standards* ● *Contributing to and linking supply chains* | ★ *Identified as 'top' priority by UK delegates*

3.3. Next steps to drive progress

The exchange emphasized the need to sustain momentum, drive alignment and establish governance to further UK-China collaboration on CCUS. Some initiatives can be led by the UK's Royal Academy of Engineering.

In charting the course forward for collaborative efforts in the CCUS space, the following illustration outlines the key next steps identified during deliberations with delegates from the UK at the exchange – namely sustaining momentum, driving alignment and establishing governance. Under each step, the immediate, near term and long-term actions needed for partnerships are highlighted along with those that are particularly relevant for the Royal Academy of Engineering to lead.

Figure 2: Next steps identified during the exchange to drive progress

Sustain momentum

***Create excitement among stakeholders** around UK-China collaboration on CCUS*

- **Organize more exchanges and share a letter of intent:** Continue to bring together diverse stakeholders including via a reciprocal exchange followed by a letter of intent identifying key areas for collaboration
- **Communicate the benefits of greater collaboration:** Continue sustained outreach with relevant stakeholders to communicate aligned priorities and key synergies of the UK and China on carbon capture, storage & utilisation

Drive alignment

***Bring stakeholders on the same page** to create a foundation for further collaboration*

- **Convene a challenge prioritization workshop:** Organise a workshop to shortlist the top 5-10 high priority research problems and areas for collaboration with potential for quick wins and scalability
- **Develop a 'common language' for collaboration:** Streamline frameworks, standards, definitions, certifications etc. to ensure consistency in trading, technological and operating norms.

Establish governance

***Equip stakeholders with support** required to take collaborations forward*

- **Release joint government statement:** Facilitate dialogue among government stakeholders to identify policy levers needed to enhance cross-border collaboration and release a joint statement to indicate 'open doors'
- **Identify an administrative center to support collaborations:** Identify a governing body to advance UK-China collaborations on CCUS, potentially providing opportunity discovery and funding support.

PENDING RAEng INPUT

Legend:

Time horizon: Immediate | Near term | Long term

Relevant for RAEng to lead:

3.4. Potential pitfalls to manage to ensure seamless collaboration

Cross-border partnerships to advance CCUS between the UK and China must adequately manage early questions around intellectual property sharing, regulatory uncertainties, public pushback, and effective governance.

#1 Difficulties in IP and data sharing: Sharing intellectual property (IP) and potentially sensitive data presents a significant challenge for cross-border partnerships on CCUS initiatives between China and the UK. Issues may arise regarding the protection, licensing, and transfer of proprietary technologies, particularly if there are discrepancies in IP laws and regulations between the two countries. Failure to address these challenges could impede the exchange of critical knowledge and hinder the development and implementation of innovative CCUS solutions.

#2 Regulatory uncertainties: Environmental regulations are evolving in China which may make navigating permitting and compliance for CCUS projects complicated however, the Chinese Government's commitment to its 30/60 targets ensures sustained and stable policy focus. Similarly, potential government changes in the UK could create uncertainties surrounding CCUS and collaboration with China however, a legal commitment to meet net-zero targets also ensures stability.

#3 Public pushback: Concerns over the environmental impact and safety of carbon capture, as well as the impact of the technology on climate change, may result in a negative perception of the technology. Greater awareness-raising, transparency, and focus on safe deployment are required.

#4 Effective governance: Without effective mechanisms for coordination, communication, and decision-making that are adequately resourced, partnerships may struggle to maintain long-term collaboration and effectiveness. Establishing clear roles, responsibilities, and accountability mechanisms for participating stakeholders is essential to foster trust, transparency, and mutual respect.

#5 Security risks: Collaborating with China could lead to potential security risks for the UK.

Commented [SR1]: Exact wording to be finalized with the RAEng team.

Measures to address such pitfalls exist and could be further discussed in future dialogues. Mitigation strategies could include careful planning, robust contractual agreements, engaging with relevant authorities to address regulatory concerns, undertaking public awareness campaigns, identifying clear roles and responsibilities for relevant stakeholders coupled with mechanisms for monitoring and accountability, dispute resolution pathways for cross-border partnerships etc. By acknowledging these potential risks, stakeholders can proactively address challenges and work towards fostering successful and resilient partnerships on CCUS between the UK and China.

4. ANNEX

4.1. Details of the exchange

Agenda: UK-China Bilaterial Exchange on CCUS, 20 May – 24 May 2024, China

Day 1: Monday 20th May 2024 | *One-day seminar event*

- **Bilateral Exchange on CCUS:** This one-day seminar was hosted by the Royal Academy of Engineering in collaboration with the Chinese Academy of Engineering at the Beijing University of Chemical Technology. The event hosted several sessions and speakers:
  - Introduction to the overall situation of net-zero emissions in China and the UK by Professor Jianfeng Chen and Professor Martin Blunt
  - Large-scale and low-cost carbon capture and utilisation by Professor Jianfeng Chen
  - Overview of the extent and growth of CCS physical processes in storage and use in enhanced oil recovery by Professor Martin Blunt
  - Development of CCUS in China by Professor Yang Li
  - R&D in CCUS, industry landscape and barriers to innovation by Dr. Charalampos Michalakakis
  - CCUS technologies and industrial decarbonisation, role of clusters anchoring CCUS projects by Professor Mercedes Maroto-Valer
  - Chemical-biological coupled catalysis for carbon fixation synthesis of fuels and chemicals by Professor Tianwei Tan
  - Various delays, revised targets, competition from EU, effective transport and storage, and designing clusters to integrate with GHG removals by Professor Stuart Haszeldine
  - Prospect of biochar-based net-zero emission technology by Professor Wenfu Chen
  - Tasks and challenges of building energy transformation by Professor Yi. Jiang
  - Advanced carbon capture for steel industries integrated in CCUS clusters by Professor Haroun Mahgerefteh
  - The green transformation path of architecture under the drive of materials innovation by Professor Shou Peng
  - Decarbonising the cement and steel industries: CCUS in China's cement and steel sectors by Professor Xi Liang

Day 2: Tuesday 21 May 2024 | *Site visits*

- **Site visit to the Qilu Petrochemical-Shengli Oilfield CCUS project:** The UK delegates visited China's first 1 Mt per annum-scale CCUS project in Zibo. Here, CO2 is captured from tail gas produced in the process of coal-gasification and transported via a 109 km pipeline to Zhenglizhuang oilfield for flooding and storage. The visit was preceded by a technical seminar where representatives introduced the project to the UK delegates and addressed their questions regarding the technologies deployed.

Day 3: Wednesday 22 May 2024 | *Site visits*

- **Site visit to Shengli Oilfield's CO2 Oil Displacement and Storage Demonstration Area:** The UK delegates visited the Shengli Oilfield in Dongying, an important oil industrial base mainly engaged in the exploration and development of oil and gas, the technical service of petroleum engineering, the construction of ground engineering, oil and gas deep processing, and mining service and coordination. Captured CO2 from the Qilu Petrochemical CCUS project is transported is the Shengli Oilfield for enhanced oil recovery.
- **Site visit to the CCUS Laboratory of the Exploration and Development Research Institute.** The UK delegates visited a CCUS lab which is responsible for long-term oil and gas exploration and development, basic research, theoretical and technical research and application, well deployment reserve evaluation, production capacity construction program etc. It is the sole comprehensive geological research institution integrating exploration and development in the Shengli Oilfield and is also the key research institute of the Sinopec Group.

Day 4: Tuesday 23 May 2024 | *Transit*

Day 5: Friday 24 May 2024 | *One-day workshop*

- **UK-China workshop on Carbon Capture Utilisation and Storage R&D Collaboration Opportunities:** This one-day workshop hosted by the UK-China (Guangdong) CCUS Centre, China Energy Engineering Group Guangdong Electric Power Design Institute and the British Consulate-General in Guangzhou presented the UK delegates with an opportunity to further hear from experts on CCUS in China. Sessions included:
    - Welcome speeches by Mr Xia Qifeng, Ms Sarah Mann, Mr Peng Xueping, and Dr Karl McAlinden
    - An introduction to CCUS activities in Guangdong and the UK-China (Guangdong) CCUS Centre by Professor Liang Xi
    - Cutting-edge technological innovation and engineering applications in CCUS by Professor Martin Blunt, Professor Peng Pingan, Professor Stuart Haszeldine, Professor Gu Sai, Professor Haroun Mahgerefteh, and Professor Mercedes Maroto-Valer
    - CCUS technological innovation and engineering applications by Dr Charalampos Michalakakis, Dr Xia Changyou, Mr Sun Zhangwei, Fang Xiaoyu, Dr Li Pengchun, and Dr Li Yixi,
    - Closing speech by Mr Zhu Guangtao

4.2. List of attendees

Delegates from the UK:

Professor Martin Blunt, Professor, Imperial College London

Ms Carys Blunt, Finance and Centre Manager, UK Carbon Capture and Storage Research Centre

Dr Kyra Sedransk Campbell, Research Fellow, University of Sheffield

Professor Sai Gu, Deputy Pro-Vice Chancellor, University of Warwick

Professor Stuart Haszeldine, Professor, University of Edinburgh

Professor Xi Liang, Professor, University College London

Professor Haroun Mahgerefteh, Professor, University College London

Professor Mercedes Maroto-Valer, Deputy Principal, Heriot-Watt University; Director, Research Centre for Carbon Solutions

Dr Charalampos Michalakakis, Lead Energy Technical Advisor, Department for Energy Security and Net Zero

Ms Claudia Hernandez Narciso, Chemical Engineer, C-Capture

Ms Esin Serin, Policy Fellow, London School of Economics

Other attendees from the UK

Ms Sarah Mann, HM Consul General Guangzhou

Dr Karl McAlinden, Consul Commercial of BCG, Head of Energy in China

Mr Reef Erdogan, Head of Innovation, British Consulate Guangzhou

Delegates from China:

Professor Jianfeng Chen, Member and Secretary-General of the Chinese Academy, Chinese Academy of Engineering

Professor Tianwei Tan, Member, Chinese Academy of Engineering; President, Beijing University of Chemical Technology

Professor Yang Li, Member, Chinese Academy of Engineering; Chairman, China Petrochemical Science and Technology Association

Professor Wenfu Chen, Member, Chinese Academy of Engineering; Professor, Shenyang Agricultural University

Professor Jun Meng, Professor, Shenyang Agricultural University; Director, National Biochar Research Institute at Shenyang Agricultural University

Professor Yi Jiang, Member, Chinese Academy of Engineering; Professor, Tsinghua University

Professor Xuwen Xiao, Member, Chinese Academy of Engineering; Chief Expert, China State Construction Engineering Corporation

Mr Xia Qifeng, Deputy Director-General, Guangdong Provincial Department of Science and Technology

Mr Peng Xueping, General Manager, GEDI

Professor Pend Pingan, Academician, Chinese Academy of Sciences; Researcher, Guangzhou Institute of Geochemistry

Dr Xia Changyou, Project Director, GDCCUS

Mr Sun Zhangwei, Director, CCUS Technology Center; Deputy Director, Mechanical and Environmental Protection Department at GEDI

Fang Xiaoyu, Director, Marine green Energy Research Centre

Dr Li Pengchun, Researcher, South China Sea Institute of Oceanology, CAS

Dr Li Yixi, Doctoral Researcher

Mr Zhu Guangtao, Deputy Chief Engineer, GEDI