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CHINA – UK

NEAR ZERO EMISSIONS COAL (NZEC) INITIATIVE

Summary report

September 2009

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Executive Summary

The China-UK Near Zero Emissions Coal (NZEC) Initiative has examined the merits of various options for carbon (CO_2) capture, transport and geological storage (CCS) in China, including the potential for the development of CCS technology and its deployment in the future. It was developed under the wider 2005 EU-China NZEC Agreement which aims to demonstrate CCS in China and the EU.

Reconciling the potential for economic growth in China with the global need to reduce CO_2 emissions, as well as making best use of national resources of coal, is a complicated issue. A range of measures is being put in place in China to tackle greenhouse gas emissions, including energy efficiency improvements as well as the introduction of significant amounts of energy from nuclear, wind, solar and other renewable sources. For the power generation and energy intensive industrial sectors, such as iron / steel and cement, all of which remain heavily dependent on coal, CCS is the only option that can ensure a significant reduction in CO_2 emissions.

A range of CO_2 capture technologies have been examined. The more promising, near term options are post-combustion capture in a state of the art Pulverised Coal power plant and pre-combustion capture in an Integrated Gasification Combined Cycle unit. The cost of electricity generation (which takes into account capital and operating costs and assumes a storage site 200km from the power plant) would be 470 RMB per MWh for both types of plant (within the uncertainties of such estimates). On this basis, either of these capture options together with the transport and storage of the CO_2 would increase the cost of electricity generation by around 200 RMB per MWh compared with a Pulverised Coal power plant without CCS. This is equivalent to a cost of avoided emissions of about 280 RMB per tonne of CO_2. Some of the newer and as yet unproven capture options, such as oxyfuel and chilled ammonia scrubbing, offer some prospect of being constructed and operated at lower overall cost but the difference lies within the uncertainties at present. In principle, the increased cost of electricity generation might be recovered through either higher prices, subsidy, a carbon price or international financing mechanisms.

The assessment of basins in North East China has shown that the capacities of individual oil fields are generally small compared with the annual CO_2 emissions of power stations currently being built in China. However, some have potential to make use of CO_2 for Enhanced Oil Recovery (EOR) although these reservoirs are typically geologically complex, and so they would require a large number of wells to access the available storage capacity, which will increase the costs. While these would provide the opportunity for gaining initial experience with CO_2 injection and storage, the capacity available for Enhanced Oil Recovery would soon be used up. It would then also be necessary to assess, and ultimately use, saline aquifers for storage. Significant further investigations, including detailed site appraisals, of both oil fields and aquifers, would be necessary before they could be confirmed as technically and economically suitable for CO_2 storage.

Regulations will be needed to support the demonstration and deployment of CCS in China, particularly for the storage of CO_2 underground but also to address the safety of pipelines carrying CO_2 and the environmental impact of CCS plants. In other countries, existing regulations are being extended to cover near-term projects (i.e. up to ten years), such as for demonstrations of CCS. For large-scale, longer-term deployment of CCS, additional regulations are being formulated, for example in the EU and Australia, covering issues such as long-term liability and financial responsibility post-closure. China has an opportunity to observe and draw lessons from the experiences of other countries in deciding how it wants to proceed in developing regulations.

The China-UK NZEC Initiative has shown that CCS could provide a key, low carbon option for coal-based industry in China, particularly for power generation, which would enable the continued use of coal with very much reduced greenhouse gas emissions. At the same time, there are several challenges that need to be addressed through further R&D, particularly to reduce the extra costs and energy penalty of CCS technologies, and to establish in sufficient detail the national capacity for CO_2 storage.

The recent formation of a China-EU Co-operation Leading Group by the Ministry of Science and Technology will provide a strong framework to take forward the outcomes of the China-UK NZEC Initiative into the next phases of the China-EU NZEC Agreement, which will assist China in gaining practical experience with CCS technology. Phase II will comprise a feasibility and design study while Phase III will include the construction and operation of a Chinese demonstration plant. China has also established other CCS-related co-operative activities, such as with Japan, Australia and the USA. Accordingly, it is important to ensure that the different activities complement each other to maximise use of resources and the potential for learning.

Contents

Acknowledgements

The China-UK NZEC Initiative is a joint initiative by the Ministry of Science and Technology of the People's Republic of China and the United Kingdom Department of Energy and Climate Change (DECC). The contracted partners and associated organisations who have participated either in the R&D programme or as hosts for Chinese students to undertake CCS related studies in the UK are The Administrative Centre for China's Agenda 21; AEA Technology; Alstom Power; 3E Research Institute of Tsinghua University; BP Clean Energy Research & Education Centre of Tsinghua University; British Geological Survey; British Petroleum; Cambridge University; China United Coalbed Methane Corporation; China University of Petroleum of Beijing; China University of Petroleum of Huadong; Chinese Academy of Sciences; Cranfield University; Department of Environmental Sciences & Engineering of Tsinghua University; Department of Chemical Engineering of Tsinghua University; Department of Thermal Engineering of Tsinghua University; Doosan Babcock; Edinburgh University; Energy Research Institute; Greengen Corporation; Heriot Watt University; Imperial College; Institute of Engineering Thermophysics of the CAS; Institute of Policy & Management of the CAS; North China Electric Power University; Schlumberger; Shell; Thermal Power Research Institute; Wuhan University and Zhejiang University. There has also been a significant contribution by two independent advisers, from Andalin Consulting and Paul Freund.

The contributions of all concerned are gratefully acknowledged.

1. Introduction

China is a rapidly industrialising nation, with a growing economy mainly supported by the use of coal. In this context, especially under the 11th Five Year Plan, China is making considerable progress to reduce the carbon dioxide (CO_2) intensity of its power generation system. This has included the successful introduction of a significant amount of low- and zero- carbon power generation systems, including wind, nuclear, solar and some natural gas. At the same time, recognising that coal-fired power generation will continue to dominate the power sector for decades to come, China has undertaken an unparalleled programme of improvements, through the extensive introduction of modern coal-fired plant with increasingly higher energy efficiency and environmental performance that equals or betters that of most other countries. In addition, there is considerable interest in China in additional steps that might be taken to further tackle emissions, including use of carbon capture and storage (CCS).

In February 2006, China's State Council issued the 'Outline of the National Programme for Medium- and Long-term Science and Technology Development', which provided guidelines, objectives and the general layout for China's science and technology development for the next 15 years[1]. Within this framework, in June 2007, the Ministry of Science and Technology (MOST) published the 'Scientific and Technological Actions on Climate Change', including the intended progress on CO_2 capture, utilisation and storage technologies, with the aim of:

- Developing key technologies and measures for CCS;
- Designing a CCS technology roadmap;
- Carrying out capacity building and establishing an engineering and technical demonstration project [2].

MOST is currently developing technology guidelines for CCS, which will define the objectives in relation to CCS technology in the period up to 2030 and identify key tasks for implementation during the forthcoming 12th Five Year Plan (2011-2015).

MOST also leads a domestic R&D programme on CCS, largely undertaken by Chinese R&D institutes and universities. Chinese stakeholders, including industry, are also participating in a number of cooperation activities with international partners. These include the China-UK Near Zero Emissions Coal (NZEC) Initiative; this resulted from the China-EU NZEC Agreement, announced as part of the EU-China Partnership on Climate Change at the EU-China Summit in September 2005. In this, the parties agreed "to develop and demonstrate in China and the EU advanced, near-zero emissions coal technology through carbon capture and storage" by 2020. More recently, at the China-

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1 Outline of the National Programme for Medium- and Long-term Science and Technology Development, State Council (2006)

2 China's scientific and technological actions on climate change: introductory information, Ministry of Science and Technology (14 June 2007)

UK Summit 2009, both countries announced their support for the acceleration of the China-EU NZEC demonstration to 2015. The Memorandum of Understanding (MOU) for the NZEC Initiative was signed by MOST and the UK Government in December 2005, leading to the launch of the Initiative in November 2007. This Initiative has brought together 19 Chinese and nine UK partners, including universities, institutes and industry, to discover answers to a number of questions, in particular:

- What are the trends of energy use in China and what are the implications for use of CCS?
- What are the options for CCS in China?
- How could CO_2 be captured from power plants?
- Where could CO_2 be stored?
- What are the costs of CCS?
- What are the policy and regulatory issues that would affect the use of CCS?

The China-UK NZEC Initiative is complemented by the China-European Commission COACH project[3]. This resulted from a separate MOU under the China-EU agreement, signed in February 2006. The project focused on CCS and poly-generation in China. The European Commission has also funded the GEOCAPACITY project, working on CO_2 storage assessment[4], and STRACO$_2$, to consider CCS regulatory requirements in the EU and China[5].

This report summarises the outcomes of the China-UK NZEC Initiative and considers further opportunities for cooperation. Details of the various project activities, including the technical reports, can be downloaded from the website: www.nzec.info.

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[3] COACH Cooperative action within CCS China-EU. Available from: http://www.co2-coach.com/. (2009)

[4] GeoCapacity Assessing European capacity for geological storage of carbon dioxide. Available from: http://www.geology.cz/geocapacity. (2009)

[5] STRACO$_2$ Support to Regulatory Activities for Carbon Capture and Storage Available from: http://www.euchina-ccs.org/. (2009)

2. Rationale for CCS

2.1 Reducing CO_2 emissions

Worldwide, there is growing demand for secure supplies of energy to support the needs of economic development. The International Energy Agency (IEA) estimates that global primary energy demand will increase by 45% between 2006 and 2030 under a business as usual scenario[6].Coal is expected to remain a significant part of the energy mix, providing around 44% of global power generation in 2030. However, coal is also the most carbon-intensive fuel and its use could have major global impacts through the emission of greenhouse gases. Consequently, whilst fossil fuels are critical to meeting the economic and energy security needs of today, the global challenge is to reconcile this with a sustainable future. This will require the introduction and implementation of technologies that can achieve deep reductions in CO_2 emissions from energy-intensive industrial processes. Since electricity generation from fossil fuels is the largest source of industrial CO_2 emissions, there will need to be an emphasis on reduction in emissions from this sector.

2.2 The role for CCS

There are various ways of limiting the amount of CO_2 that is emitted due to the use of energy:

- Reduce energy consumption;
- Increase the efficiency of energy conversion;
- Substitute high carbon sources with others of low or zero-CO_2 impact.

All of these approaches will achieve emission reductions but there are limits as to what can be achieved in the near to medium term because of the existing capital stock and the availability of low cost fuels such as coal. It is forecast that coal will continue to be used for the foreseeable future so technologies need to be developed that significantly reduce CO_2 emissions from its use, such as CCS.

2.3 Overview of CCS

CCS is a process in which CO_2 is captured from a large point source (e.g. a power station), transported by pipeline, and then injected into an underground geological reservoir where it can be stored safely for thousands of years. The technology for capturing CO_2 in new or existing power plants (or other industrial processes) is largely known although not yet applied on a large scale. The storage of CO_2 can be achieved using techniques developed by the oil and gas industry, to inject it at depths

Figure 2.1 Schematic diagram of CCS system (Image courtesy of Shell; text modified by AEA)

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[6] World Energy Outlook 2008, International Energy Agency, OECD-IEA, Paris (2008)

of more than 800 metres into saline formations or depleted oil or gas fields. In addition, injection of CO_2 into producing oil fields can be used to enhance the recovery of oil. It may also be possible to store CO_2 and enhance the recovery of coal-bed methane by injecting it into unmineable coal seams although this has not yet been proven at significant scale.

2.4 CO_2 capture options

The purpose is to remove CO_2 from the gas stream of a fossil fuel fired industrial process in order to produce a concentrated stream of CO_2 at high pressure that can readily be transported to a storage site. Depending on the type of plant, there is a choice of three main approaches to capturing the CO_2 as described below. The cost of capturing CO_2 will be lowest if this is done in large plants, in gas streams having a high concentration of CO_2 and which are at elevated pressure.

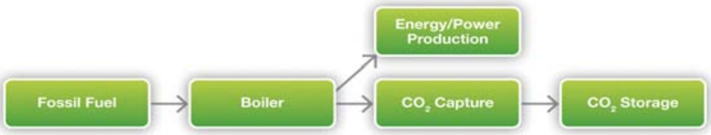

Figure 2.2 Post-combustion capture of CO_2

Post-combustion capture systems separate CO_2 from the flue gases produced by the combustion of the fuel in air; the proportion of CO_2 is low (typically 3–15% by volume) with the main constituent of the flue gas stream being nitrogen (Figure 2.2). Separation is typically by use of a liquid solvent such as monoethanolamine (MEA); such processes have been used with coal- and gas-fired power plants although, to date, there have been no full-size applications of CO_2 capture at large (e.g. 500 MWe) power plants.

Pre-combustion capture systems process the primary fuel in a reactor with steam and air or oxygen to produce a synthesis gas, consisting mainly of carbon monoxide and hydrogen. The carbon monoxide is converted into CO_2 by reacting it with steam in a second reactor (a “shift reactor”). The resulting mixture of hydrogen and CO_2 can then be split into separate streams with the hydrogen being used as fuel by the plant (Figure 2.3). High concentrations of CO_2 (typically 15 to 60% by volume on a dry basis) are produced by the shift reactor; high pressure can be produced in such plant, which is more favourable for CO_2 separation. Pre-combustion capture would be used at coal-power plants based on integrated gasification combined cycle (IGCC) technology. The techniques that would be used for pre-combustion capture are already in use for the large-scale production of hydrogen for ammonia and fertilizer manufacture, in petroleum refineries and coal-to-liquids plants.

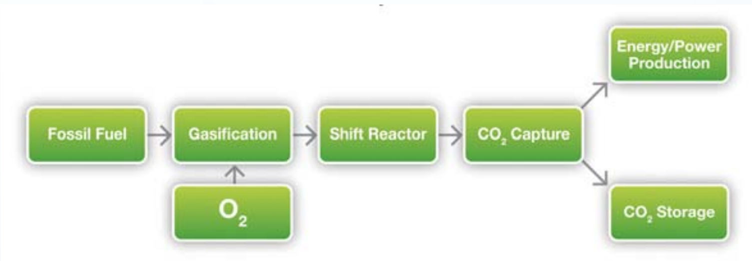

Figure 2.3 Pre-combustion capture of CO_2

Oxyfuel combustion systems would use oxygen instead of air for combustion of the primary fuel to produce a flue gas that is mainly CO_2 and water vapour (Figure 2.4). The latter would then be removed by cooling and compressing the gas stream. Further treatment of the flue gas would be needed to remove pollutants and non-condensable gases (such as nitrogen) before the CO_2 is sent to storage. This need for additional gas treatment to remove pollutants limits the fraction of CO_2 captured. This technology is currently in pilot scale development.

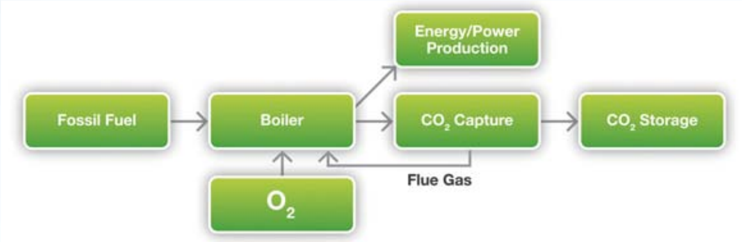

Figure 2.4 Oxyfuel combustion with capture of CO_2

Transport of CO_2 is routinely done today using road, rail and ship tankers as well as pipelines. Road tankers are most suitable for small quantities (i.e. tens to hundreds of tonnes per day), whilst rail and ship tankers and pipelines can handle progressively larger amounts. For the scale of operation envisaged with capture of CO_2 from large coal fired power plants in an onshore location, pipelines are the appropriate method of transport with the CO_2 compressed to a pressure of 10 to 15 MPa (Mega Pascal).

2.5 CO_2 storage options

A number of geological formations may be used for storing CO_2. Storage of CO_2 would be at depths below about 800 metres where the pressure would be high enough for the CO_2 to be almost as dense as liquid water. The reservoir rocks need to be porous, so as to store large volumes of CO_2, and permeable enough to allow the easy flow of fluids but be capped by impermeable rock above to prevent escape of CO_2. The main options are:

- **Enhanced Oil Recovery.** There is considerable potential to inject CO_2 into mature oil fields to improve the recovery of oil through Enhanced Oil Recovery (EOR), although the economics of this process can be quite variable as they depend on the price of oil, the cost of CO_2, and the location of the reservoir in relation to the CO_2 source. There is much experience with large-scale EOR, mainly in the USA.
- **Depleted Oil and Gas Reservoirs.** There is reasonable confidence that reservoirs that have previously held hydrocarbons for millions of years have potential for storage of CO_2. However, this will depend on the exact nature of the reservoirs, and how the hydrocarbons were extracted as the existence of a large number of wells, for example, might involve extensive remedial work to ensure the long-term containment of CO_2.
- **Saline aquifers.** These are likely to have the greatest potential for storage of CO_2 globally. Such aquifers are filled with salt water and typically have no commercial use at present. However, as yet, there is limited information available on their characteristics although this is being gained via

large scale projects in several countries.

The collective experience of the oil and gas industry, with the operation and monitoring of CO_2 EOR projects and from research on natural CO_2 reservoirs, suggests that CO_2 can be contained for very long periods underground. When selecting appropriate CO_2 storage sites, it is essential to address health and safety issues. This will require a rigorous approach to site selection and assessment together with robust monitoring and verification, for which several techniques are being established.

2.6 The price of using CCS

All CCS options incur costs and reduce the efficiency of the plant. Fitting CCS to a power plant requires additional capital investment for the CO_2 capture and compression equipment, the transport infrastructure as well as the equipment associated with the storage activities. In all cases, CO_2 capture will use additional energy for the capture and subsequent compression of the CO_2 that will reduce the overall process efficiency and also increase the amount of fossil fuel used to achieve a given power generation output.

Capital costs are expected to reduce once this technology is demonstrated and then deployed on a significant scale. Improvements in the efficiency of the capture technologies and effective integration with the other process components will lead to reductions in the energy penalty. At the same time, other aspects such as the reliability of the plant, scalability of the equipment, maintainability, as well as consumption of water will need to be considered. The cost of CCS will also be affected by the length of pipeline between the power plant and the storage site, as well as the type and depth of storage. Offshore storage would be more expensive than onshore storage.

2.7 What contribution might CCS make to global efforts to reduce CO_2 emissions?

CCS is one of a number of measures that could help to significantly reduce CO_2 emissions. The IEA has suggested that, in order to meet climate goals, the world may need significant deployment of CCS by 2030, and very widespread deployment by 2050[7] (Figure 2.5). CCS could account for 19% of global CO_2 reductions by 2050 as part of a portfolio approach to halving global emissions (relative to today's levels). The IEA envisages an ambitious growth plan in order to achieve this mitigation level, with 100 projects (from the power sector, industry and upstream sources) globally by 2020 and over 3000 by 2050[8]. Efficiency improvements (36% of the reductions in this scenario) and renewable energy (21%) would also be needed. The deployment of CCS by 2050 in this scenario would involve the capture of 10,400 million tonnes of CO_2 annually which would require over 800 GWe of power plants to be equipped with CCS. In addition, this scenario assumes large-scale introduction of CCS in coal conversion and other fuel transformation sectors, as well as application in other industries such as cement production, and iron and steel manufacture.

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[7] Based on Energy Technology: Scenarios & Strategies to 2050 © OECD/IEA, 2008, figure 2.2, p. 64

[8] IEA (2009) Technology Roadmap: Carbon Capture and Storage, IEA, Paris (2009)

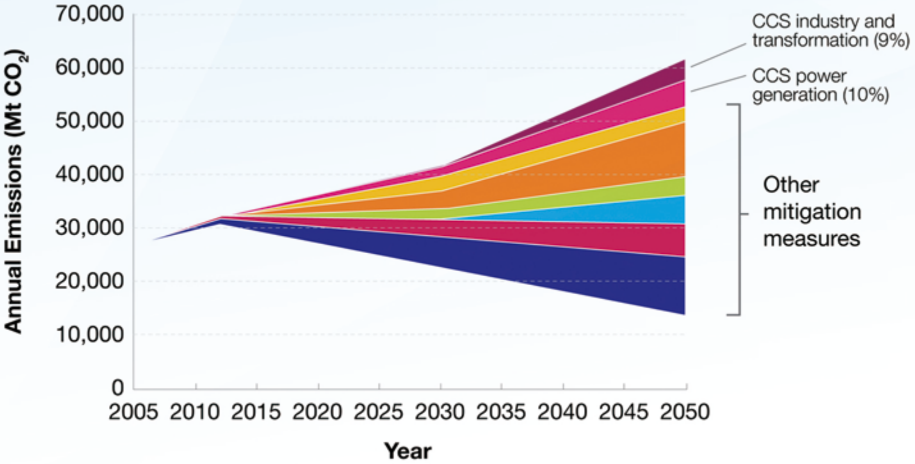

Figure 2.5 A scenario of global emissions showing CCS contribution to the portfolio of mitigation measures (Courtesy of the IEA)

2.8 What is the status of CCS world-wide?

CCS is not yet a commercially available technology but there is considerable research, development and demonstration underway, particularly in Europe, North America, Australia, Japan and now China. The research and development is focused on reducing the costs and improving the efficiency of capture technologies as well as addressing key issues such as mapping the CO_2 storage capacities in numerous countries and developing monitoring and verification techniques for safe overall operation. Demonstration projects are considered as one of the most important next steps in order to scale up the components, test integrated schemes, understand the costs and establish operational familiarity, in order that suppliers and end-users can develop the experience necessary to ensure successful operation at commercial scale. In 2008 the G8 announced the goal of launching 20 CCS demonstration projects world-wide by 2010 to enable commercial CCS deployment from 2020.

Alongside the technical activities, several countries are addressing the legal, financial and policy issues such that large-scale projects can be established and regulations can be put in place to ensure the long-term safety of CO_2 storage. The EU, UK and Australia, for example, have all developed CCS legislation that sets out regimes for safe storage of CO_2. An international forum for advancement of CCS is provided by the Carbon Sequestration Leadership Forum (CSLF) while more recently the Global Carbon Capture and Storage Institute has been established as a facilitator to drive global co-operation on CCS. Further information on international CCS developments can be found in a recent report by the United Kingdom Advisory Committee on Carbon Abatement Technologies[9].

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[9] Accelerating the deployment of carbon abatement technologies, ACCAT report, UK Department of Energy and Climate Change (2009)

3. Achievements of the NZEC Initiative

Chinese and British scientists, engineers and policy experts have worked together to address key issues about CCS for China. The results and achievements of the China-UK NZEC Initiative are summarised below. More information can be found in a series of detailed reports, which are referenced in the appropriate sections of this document and are on the NZEC website[10].

3.1 What are the implications for CCS of the trends in energy use in China?

3.1.1 Introduction

In order to understand how the supply of energy in China, and CO_2 emissions, may change in future, a number of energy scenarios have been modelled by several groups of Chinese researchers and economists, using projections of demand for energy services and assessment of potential energy supply technologies.

Coal provides about 70% of the primary energy used in China[11] (Figure 3.1). As an inexpensive and abundant energy resource with an established infrastructure, coal is very likely to continue to be the dominant source of energy in China for the foreseeable future. However, the large-scale use of coal has put significant pressure on

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[10] www.nzec.info

[11] NZEC Technology Assessment: Coal Technologies, Tsinghua University, Ma L. (2009)

China's ambitions for environmental protection, worker safety and abatement of greenhouse gas emissions.

Principal uses of coal are in industry, in power generation and for heating. Over 70% of China's power generation capacity is based on use of coal. Although there is increasing deployment of renewable energy technologies and nuclear power plant, coal-fired power plant will continue to be built in large numbers for many years to come. Improvements in the efficiency of such plant are taking place, through development and use of larger and more efficient plants, deployment of Supercritical (SC) and Ultra Supercritical (USC) technologies and closure of small, inefficient stations. China is a world leader in the use of cleaner coal power generation technologies.

Coal gasification and coal liquefaction technologies are being developed and deployed for large-scale application. Various types of coal gasifier are under development in China and others are being licensed-in. Existing gasifiers used in the chemical industry are being overtaken by newer types which can also be applied in IGCC power plants, as well as in the manufacture of products by coal liquefaction - methanol and dimethyl ether (DME) are already manufactured from coal in commercial quantities; direct conversion of coal into liquid fuel is now being demonstrated in one plant and an indirect conversion process is also under development. However, all such plants will have substantial CO_2 emissions - typically three to ten tonnes of CO_2 for each tonne of oil produced.

Due to China's rapid industrialisation, energy demand has increased dramatically in recent years[12]. About 40% of total final energy consumption occurs in these sectors of the economy:

- Iron and steel manufacture;
- Cement manufacture;
- Ammonia production;
- Aluminium production;
- Transportation.

Several of these involve large stationary sources of emissions which may be suitable sites for capturing CO_2. The future demands of various energy-intensive industrial sectors have been projected in the NZEC work using assumptions about future social and economic growth.

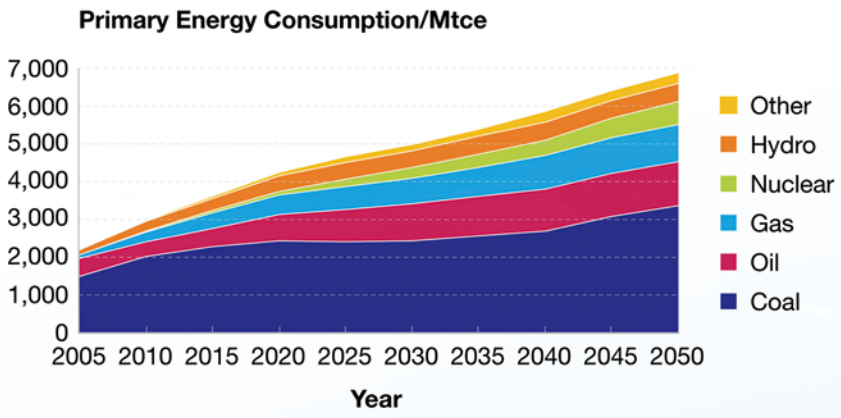

Figure 3.1 Trends in primary energy use in China

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[12] NZEC Technology Assessment: Energy Intensive Sectors report, Energy Research Institute, Kejun J. (2009)

3.1.2 Energy Technology Perspectives

In order to provide some insight into the energy technologies that may be deployed in China between now and 2050, the Chinese energy system has been analysed using the "China MARKAL" model[13]. This is an energy-system optimisation model which can be used to examine the future development of energy supply under certain assumptions about future growth in GDP and population, changes in industrial structure and rate of urbanisation. The MARKAL model minimises the cost of the energy system assuming a particular level and mix of final energy demand, primary energy supply, and power generation capacity. The model is then asked to meet the same energy service demands under specific constraints on CO_2 emissions.

China's CO_2 emissions in 2006 are estimated to be 5,650 million tonnes[14], of which coal-fired power generation accounted for 2,760 million tonnes. With continuing economic development and improvement in living standards, the baseline projection used in the NZEC analysis estimates growth in CO_2 emissions of 2% per year in future, which is lower than the recent rate of growth. This change reflects improvement in energy efficiency and development of new and renewable energy systems. As a result emissions are expected to reach 9,500 million tonnes of CO_2 per year by 2030 and 12,600 million tonnes of CO_2 per year by 2050 (Figure 3.2).

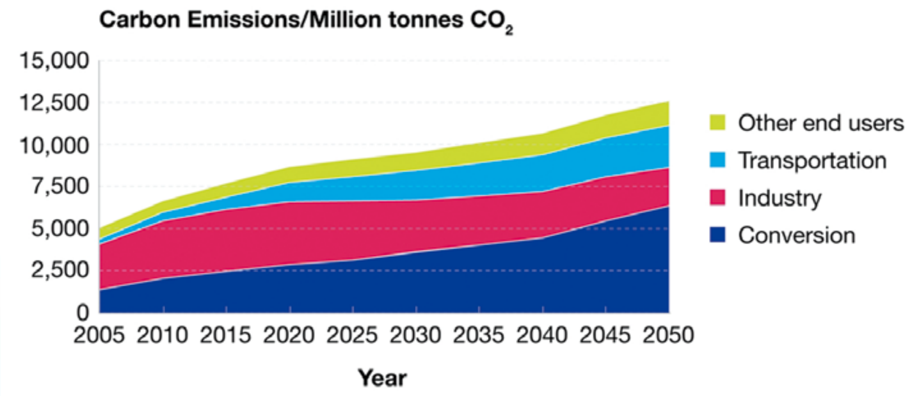

Figure 3.2 Projected trends in CO_2 emissions to 2050 from the main end-use sectors in China

Another more detailed review[15] estimated that there were over 1,600 point sources of CO_2 in China with emissions of over 100,000 tonnes per year from each site, making them potentially suitable for CO_2 capture. Larger point sources are mostly in the eastern half of the country, with very few such sources in western and northern China.

The total amount of emissions between 2005 and 2050 is projected to be 458,000 million tonnes of CO_2[16]. Four carbon-constrained scenarios were examined in the NZEC analysis as indicated in Table 3.1. Due to improvement in energy efficiency and development of new and renewable energy systems, there will be a lower rate of growth of CO_2 emissions in future even in the base case. The carbon constrained scenarios in the model showed that for China's coal-dominated economy, with limited availability of renewable energy and no CCS, achievements of emission reductions would depend on deployment of nuclear power. For the deeper reduction scenarios, the model

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[13] NZEC Future Energy Technology Perspectives: Scenarios Analysis Report, Tsinghua University, Chen W. (2009)

[14] World Energy Outlook 2008, International Energy Agency, OECD-IEA, Paris (2008)

[15] CO_2 point emissions and geological storage capacity in China. Li X. and others, presented at: 9th International conference on greenhouse gas control technologies, Washington DC, USA (16-20 November 2008)

[16] NZEC Future Energy Technology Perspectives: Scenarios Analysis Report, Tsinghua University, Chen W. (2009)

constructs up to 1000GWe of nuclear power. Such large scale deployment of nuclear power may be constrained by other factors such as site selection, public acceptance, investment, safety, and waste disposal which are not represented in the model. CCS technologies have also been examined using MARKAL as part of an alternative approach to meeting the more stringent emission targets; this showed that more than 400GWe of coal-fired power plants with CCS would be needed by 2050 as part of a portfolio of measures to achieve the lowest of the emission scenarios shown in Table 3.1. Achieving even deeper reductions in CO_2 emissions would need more CCS. This modelling indicates there is substantial potential for capturing CO_2 in power generation.

Scenario	Total Emissions Million tonnes CO_2	Reduction compared with base-case
Base-case	458,000	-
Carbon-constrained scenarios:	403,000	12%
	367,000	20%
	330,000	28%
	293,000	36%

Table 3.1 Total emissions in the period 2005 to 2050 under the four scenarios studied[17]

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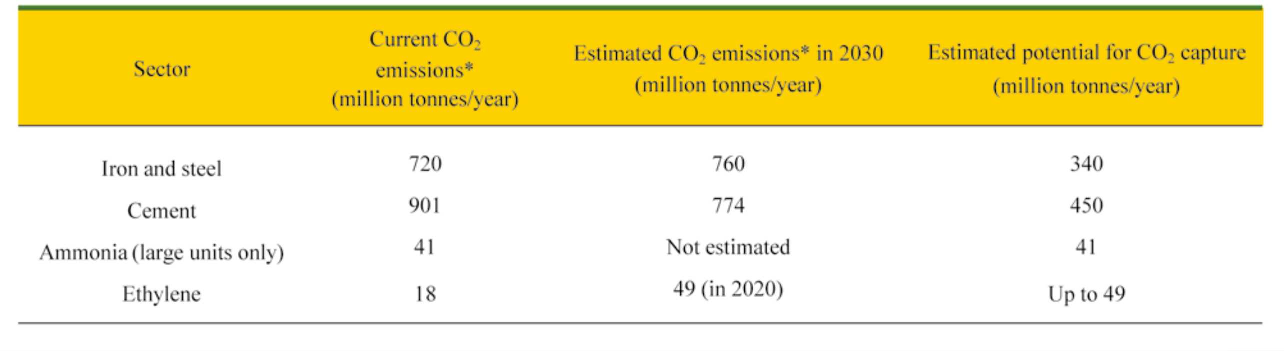
[17] It should be noted that in the full report on this work, the Scenarios Analysis Report, the scenarios are labelled by their equivalents in thousand million tonnes of carbon, thus: C110, C100, C90, C80.

3.1.3 Potential for capturing CO_2 in energy-intensive industry

In addition to the potential for using CCS in power generation, there are also significant opportunities for using CO_2 capture to tackle emissions from some of the energy-intensive industries whose emissions are significant because of China's position as the world's largest producer of steel, aluminium and cement. Several energy-intensive sectors with potential for use of CO_2 capture have been examined as part of the NZEC Initiative[18]. In each case the current technological status of the sector has been examined and sources of CO_2 emissions in China have been identified; a range of opportunities for reducing CO_2 emissions have been considered and, where information is available, the potential for application of CO_2 capture has been assessed.

This assessment shows that there is substantial potential for CO_2 capture in iron and steel production and in the cement industry (Table 3.2). There is also some potential in the ammonia industry especially at the larger production plants, and in the ethylene industry, where CO_2 is emitted as concentrated streams from large plants.

Emissions from oil refining (21 million tonnes per year) have not been included in Table 3.2 because the potential for capture is not judged to be large. However, this survey did not include emissions from the hydrogen plants in the refineries which may produce gas streams concentrated in CO_2, which would be relatively attractive locations for capture. With rapid growth expected in the transport sector, the refining industry may have larger potential in future to apply CO_2 capture.



Sector	Current CO_2 emissions* (million tonnes/year)	Estimated CO_2 emissions* in 2030 (million tonnes/year)	Estimated potential for CO_2 capture (million tonnes/year)
Iron and steel	720	760	340
Cement	901	774	450
Ammonia (large units only)	41	Not estimated	41
Ethylene	18	49 (in 2020)	Up to 49

Table 3.2 Estimated potential for CO_2 capture in energy-intensive industry

* These are emissions directly from the process and, in some cases, are limited to those available for capture

3.1.4 Case-study: Jilin Province

In order to support the analysis of the potential for CCS in China, a case-study was undertaken for Jilin province[19] which included detailed modelling of energy and emission scenarios up to 2030 using the IPAC-AIM model to identify the least-cost mix of technologies to meet the required demand,. The study confirmed that coal-fired power plants will continue to play an important role, with up to 28,000 MWe of coal-fired power plants in use by 2030, accounting for at least 51% of the total installed capacity in Jilin. The model suggested that a total of up to 480 million tonnes of CO_2 could be captured by 2030 but the extent to which this would be done in practice depends on the availability of adequate CO_2 storage. It was assumed that, initially, CO_2 would be injected into oil fields for

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[18] NZEC Technology Assessment: Energy Intensive Sectors report, Energy Research Institute, Kejun J. (2009)

[19] NZEC Energy and emissions scenarios in Jilin Province. Energy Research Institute, Kejun J. (2009)

EOR, and subsequently for storage. The possibility of IGCC being built as well as pulverised-coal power plants was also considered, assuming that IGCC plants with capture would be developed to a state where the technology is competitive with pulverised-coal plants with capture. The results suggest that Jilin might be a pilot for use of CCS, involving as much as 8,700 MWe of supercritical and ultra-supercritical power plants and 7,000 MWe of IGCC power plants by 2030. However, this may be an optimistic scenario in view of the current state of development of IGCC technology.

3.1.5 Implications for use of CCS

Reconciling the potential for growth in China with the global need to reduce CO_2 emissions as well as making best use of national resources of coal is a complicated problem. Possible solutions can be identified, using the various modelling tools deployed in the NZEC Initiative, which shows that CCS could play a significant part in reducing greenhouse gas emissions from power generation and from energy intensive industry over the next 20 to 40 years in China, as part of a portfolio of measures. Further development of the energy system models would provide better understanding of the interactions between the many variables that define this problem.

3.2 How could CO_2 be captured from power plants?

3.2.1 Introduction

A team of Chinese and British scientists and engineers have conducted eight case studies to investigate options for capturing CO_2 in coal-based power plants. The main focus of these studies has been on incorporating capture as part of the design of new plants but some cases have also considered retrofitting existing plant and one case examines the option of generating electricity and methanol in the same unit (otherwise referred to as poly-generation). The case studies have included detailed design of the plant, identification and costing of the components and estimation of the cost of electricity that would be produced. The main features of each of the case studies are described below[20].

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[20] For purposes of assessment a number of important factors have to be standardised, in order to define the operating conditions and emission standards applicable at the location of the plant. For example, it is assumed that each power plant is built in Tianjin City; two types of coal are considered in the designs (Shenhua and Datong coals); once CO2 has been captured, it is dried and compressed to 11 MPa for transport to the storage site. The cost of building and operating these plants is described in section 3.4, based on prices for equipment supply in China.

3.2.2 Post-combustion capture in new construction

The basis for these studies is a pulverised coal (PC) power plant with 800MWe gross output using an ultra-supercritical steam cycle. Flue gas desulphurisation (FGD) and equipment for removal of oxides of nitrogen is included in its design. Several options for post-combustion capture have been examined, all using some form of chemical solvent scrubbing of the flue gas stream:

- Monoethanolamine (MEA)[21], a solvent widely used for industrial CO_2 capture;
- Methyl diethanolamine (MDEA)[22], another established solvent,
- Aqueous ammonia[23], a new solvent;
- A hollow-fibre membrane contactor[24], (in place of the conventional absorber) used with MEA solvent.

	Plant without capture	with MEA capture	with Ammonia capture
Net output, MWe	824	622	670
Net Plant Efficiency (% LHV)	43.9	33.1	35.7
Efficiency penalty (%-points)	-	10.8	8.2
CO_2 recovery ratio,%	-	90	90
CO_2 emissions (g/kWh)	797	106	98
CO_2 emissions avoided (g/kWh)	-	691	699

Table 3.3 Effect of post-combustion capture on performance of a PC plant

The effect on output of the power plant from use of chemical solvent scrubbing is illustrated in Table 3.3. This shows that the capture (and compression) system uses a substantial amount of energy, so the output of the station is reduced substantially compared with a similar plant without capture. The effect on the efficiency of the plant is considerable, although the newer solvent (ammonia) offers some prospect of reducing this penalty. In these examples, 90% of the CO_2 is captured so the level of emissions is substantially less than that of the base-case plant. The effect of using a hollow-fibre membrane contactor would be to improve the operation of the scrubbing system but not the efficiency or the cost.

Figure 3.3 Post-combustion capture pilot plant, Beijing (courtesy of Huaneng Group)

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[21] NZEC Cost estimation for CO2 Capture with a MEA absorption process, ,Tsinghua University,Zheng, Q. and Chen, J. (2009)
[22] NZEC Carbon Dioxide Capture Using MDEA and Ammonia Solutions, Tsinghua University, Wang S. (2009).
[23] ibid
[24] NZEC Carbon Dioxide Capture from a New-built Ultra Supercritical PC Power Plant Using Hollow Fiber Membrane Contactors, Zhejiang University, , Fang M., Yan S., Luo Z. (2009)

3.2.3 Post-combustion capture in existing power plant

Similar capture systems could also be retrofitted to existing power stations. Because of the large amount of existing stock and the rapid rate at which new plant is being constructed at present, retrofit could be highly relevant for wide-spread application of CO_2 capture in the future. Two types of plant were considered[25] – one was a sub-critical power plant typical of the smaller units now in use, and the other a larger supercritical power plant, likely to be representative of units in the power plant fleet for years to come. The results show that the efficiency is reduced even more by the retrofit than by using capture in new construction (an extra 1 to 2 %-points reduction in efficiency); this is mainly because of the difficulty of adapting existing plant to supply the necessary steam to the post-combustion capture unit.

3.2.4 Oxyfuel capture

The oxyfuel concept has also been investigated for two different applications[26] with similar levels of CO_2 capture. In the first case, a new build 800MWe pulverised coal plant with an advanced supercritical boiler is subsequently retrofitted with oxyfuel combustion for CO_2 capture. This shows that a plant could be constructed as a conventional pulverised-coal plant using air-firing and later converted to oxyfuel operation. The second case is the retrofit of an existing 350MWe power plant, typical of units currently in use, combined with the replacement of the boiler and turbine by an advanced supercritical system.

	Without capture	With oxyfuel
Net output, MW_e	824	672
Net Plant Efficiency (% LHV)	43.9	35.6
Efficiency penalty (%-points)	-	8.3

Table 3.4 Effect of oxyfuel capture on performance of $800MW_e$ plant

The results (Table 3.4) show that the efficiency of the larger plant using oxyfuel capture is similar to that of using the new ammonia solvent in a post-combustion capture system. Retrofit of oxyfuel capture to the smaller plant, even with boiler and turbine upgrades, reduces efficiency by a larger amount, about 10% points.

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[25] NZEC Carbon Dioxide Capture from Existing Coal-Fired Power Plant in China. North China Electric Power University, Yang Y, Xu G, Duan L, (2009)

[26] NZEC Oxyfuel Options, Doosan Babcock Energy Limited, Gibson, J.R. and Schallehn, D. (2009)

3.2.5 Pre-combustion capture

This method of capture is based on an adaptation of the IGCC type of power plant[27]. A study of pre-combustion capture has been carried out for a new IGCC plant , of sizes 400MWe and 800MWe, based on the design of the 250 MWe Greengen demonstration plant at Tianjin. In this study, CO_2 is captured using Selexol solvent after a sour-shift reactor. Table 3.5 shows the efficiency penalty due to capture and compression is 7.2%-points compared to a similar plant without capture.

	Without capture	With capture
Net output, MW_e	790	660
Net Plant Efficiency (% LHV)	43.9	36.7
Efficiency penalty (%-points)	-	7.2

Table 3.5 Effect of pre-combustion capture on performance of an 800 MW_e IGCC plant

Figure 3.4 Illustration of Greengen 250MW IGCC power plant at Tianjin (courtesy Greengen)

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[27] The first demonstration in China of a full-size IGCC (without capture) is now being constructed at Tianjin City (Greengen).

[28] NZEC Case Study for IGCC Power Plant In China (with CCS), Greengen Co., Ltd, Cao J. (2009)

3.2.6 Poly-generation

In this system, two products - methanol and electricity - are generated one after the other in the same process[29]. In principle, other chemicals could also be produced in a similar way. The system is based on the IGCC with capture described in section 3.2.5 but, in this case, only part of the cleaned syngas is sent to the shift reactor. Capture is done using Rectisol, a methanol based solvent, which removes H_2S and CO_2. The rest of the syngas is used to produce methanol. The plant is designed to produce 400 MWe plus 890 tonnes per day of methanol. CO_2 emissions are similar to those in the IGCC case in section 3.2.5. No simple measure of efficiency is possible in this case because of the production of both methanol and electricity.

3.2.7 Conclusion on options for capturing CO_2

The solvent processes needed for post-combustion capture are already established in other applications and have been demonstrated at smaller scale in power generation so should be readily applicable to commercial power plants, especially the pulverised-coal fired plant widely used today. Pre-combustion capture technology has been demonstrated at the scale required for use in power plants but the type of power plant that would host it, the IGCC, is not yet widely deployed. If and when IGCC plants are built in quantity, this could provide an attractive way of capturing CO_2. Oxyfuel combustion is still in development but may well have potential in efficient coal-fired power plant if future development is successful. Other methods of capturing CO_2 post-combustion are also under development. In all cases, a key driver will be to improve the efficiency of the capture processes, as is discussed in Section 4.2.

3.2.8 Transport of CO_2

The NZEC Initiative has also examined the transport of CO_2 by pipeline from power plant to storage site, for a range of possible situations[30]. Key parameters considered include the CO_2 quality necessary for transport; the design of pipeline systems including the need for booster compression; the safety and risks of pipeline transport and relevant codes, and the cost of pipeline transport. The dependence of cost on a range of parameters has been estimated for a range of situations, including different quantities of CO_2 and various transport distances. These results are used in Section 3.4, which considers the overall cost of CCS.

Figure 3.5 More than 2500km of CO_2 pipelines are already in use in the USA for EOR (Courtesy of BP)

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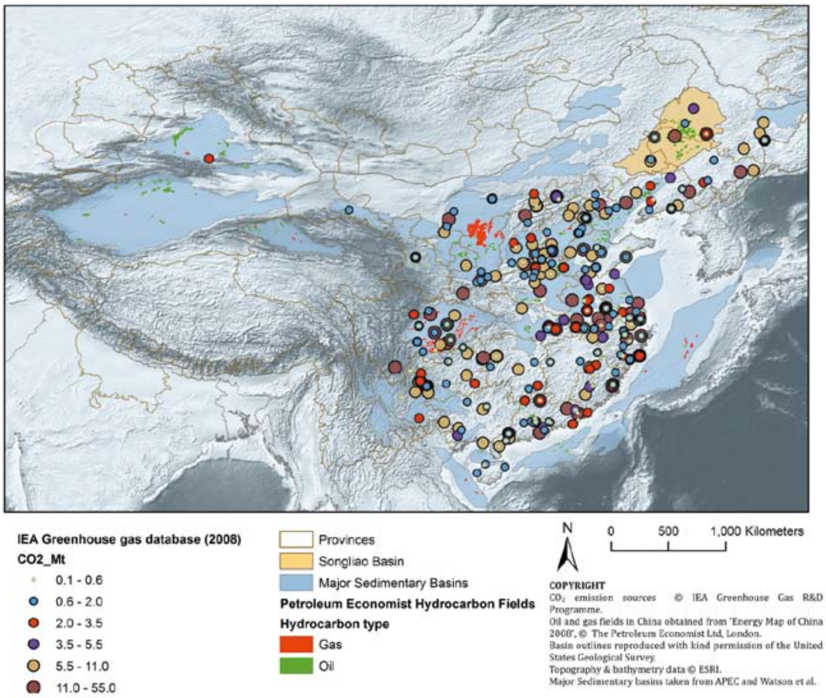
[29] NZEC Polygeneration using two-stage slurry gasifier with CCS, Tsinghua University, Xu Z. (2009)

[30] NZEC Report on CO_2 Transport, Wuhan University, Hu J and Li J. (2009)

3.3 Where could CO_2 be stored?

3.3.1 Introduction

Geological storage involves injecting CO_2 into rock formations, to trap it underground. Suitable rock types are found in oil and gas fields, salt-water bearing formations (i.e. saline aquifers) and possibly coals, all of which are found in certain sedimentary basins. Opportunities for CO_2 storage will typically be at depths below 800m, where the CO_2 will be in the dense (liquid) phase. Various mechanisms will trap the CO_2 - these are similar to those which have kept oil and gas underground for millions of years. The techniques and equipment needed for geological storage of CO_2 are based on the expertise that already exists in the oil industry, such as characterisation of geological formations, modelling, capacity assessment, surveying and monitoring, and drilling of wells.



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Topography & bathymetry data © ESRI.
Major Sedimentary basins taken from APEC and Watson et al.

Figure 3.6 Sedimentary basins potentially suitable for Geological Storage of CO_2 in China showing their co-location with many large sources of CO_2 emissions

Injecting CO_2 into some oilfields can be used to enhance oil recovery (EOR). During this process, some of the injected CO_2 would be stored underground, even though the primary purpose is to produce more oil. The greatest amount of storage would be achieved at the end of the field's productive life when it can be used as a dedicated storage facility. One attraction of storage in oil and gas fields is that the geological structures are known to have trapped buoyant oil and gas. Provided the reservoir's ability to retain these fluids (especially the seal on the formation) has not been impaired by the production of oil or gas, it should then be capable of holding CO_2 for a long time. Saline aquifers do not necessarily have such seals and, as significantly less is known about them, they would need more investigation before they could be used to hold CO_2; nevertheless this type of storage is already in use in Europe.

The NZEC Initiative has evaluated the potential to store CO_2 in two areas of North-East China – the Songliao and the Subei geological basins[31]. These assessments have been performed firstly at a regional scale, to provide a broad overview of the potential of each basin, and then on a site-specific basis, to provide more

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[31] NZEC CO_2 storage potential in selected regions of north-eastern China: regional estimates and site specific studies. British Geological Survey. Pearce J. and others (2009)

detailed assessments. The assessments have covered the capacity for storage, the likelihood of there being a suitable seal which could retain the CO_2, and various aspects of the geological formation's ability to accept CO_2.

This work has covered just a few of the areas of China where there may be potential to store CO_2. There are more than 30 large sedimentary basins across China, on- and off-shore (Figure 3.6), some of which may provide further opportunities for CO_2 storage. These basins include the oil and gas producing regions of western China and the offshore basins close to southern and eastern China, places where there are many sources of CO_2 that could be captured.

3.3.2 Assessment of storage potential

In order to assess basins for possible storage of CO_2, three main characteristics of a geological formation are normally considered: its capacity to hold CO_2; whether it can retain the CO_2 safely and securely; and how easy it would be to inject CO_2 into the formation. Some impression of the amount of capacity needed can be gained by considering that a 1000MWe power plant would need storage for more than 200 million tonnes of CO_2 over its 40-year operating life. Several locations in each of the target basins have been examined and several approaches to estimating storage capacities have been used, based on published methods[32].

Estimating the potential capacity for CO_2 storage as part of an EOR operation is aided by the availability of geological information in the public domain. In contrast, the assessment of storage in saline aquifers is constrained by the limited amount of detailed information available about them (as, until now, there has been little use for them, so they have mostly not been surveyed). For this reason, estimates of storage capacity of aquifers must often be based on gross assumptions extrapolated across large areas rather than more detailed, site-specific assessments.

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[32] In order to ensure that the calculated storage capacities can be compared with those from other regions of China, and more widely, an international calculation method has also been applied based on that published by the Carbon Sequestration Leadership Forum (CSLF).

3.3.3 Capacities for EOR and Storage

The two basins whose storage capacities have been assessed in the NZEC Initiative are complementary to those studied in the COACH and Geocapacity projects (which examined onshore fields in the Bohai Basin). The Songliao Basin contains two large hydrocarbon fields, the Daqing and Jilin oil fields, in an area where there are substantial emissions of CO_2 from power plants and industrial sources. The smaller Subei Basin also contains mature oil and gas fields, as well as natural accumulations of CO_2 ; only the onshore part of this basin has been examined.

3.3.4 Songliao Basin

The Daqing complex comprises numerous individual oilfields, seven of which were selected for this study. The storage capacity of these seven fields was estimated to be about 593 million tonnes of CO_2 of which two fields, the Lamadian and the Sa'ertu, contribute 84%. Between 270 and 1300 million barrels of oil could be recovered by using CO_2 for EOR in these fields; the precise level of recovery would have to be confirmed by site-specific tests. In the Jilin complex, five large oilfields were selected for initial assessment; their combined storage capacity was estimated at about 102 million tonnes of CO_2. The additional oil which could be recovered through EOR from these five fields was estimated to be between 46 and 230 million barrels. A pilot EOR project is underway in this complex.

A large saline aquifer extends over much of this basin; its effective storage capacity has been estimated as 692 million tonnes of CO_2 but could be greater, depending on the properties of the formation which will only be discovered by practical tests. A more detailed simulation and assessment around one site indicated a storage capacity of 288 million tonnes of CO_2. Further work would be necessary to refine these estimates which have been constrained by the limited amount of data available.

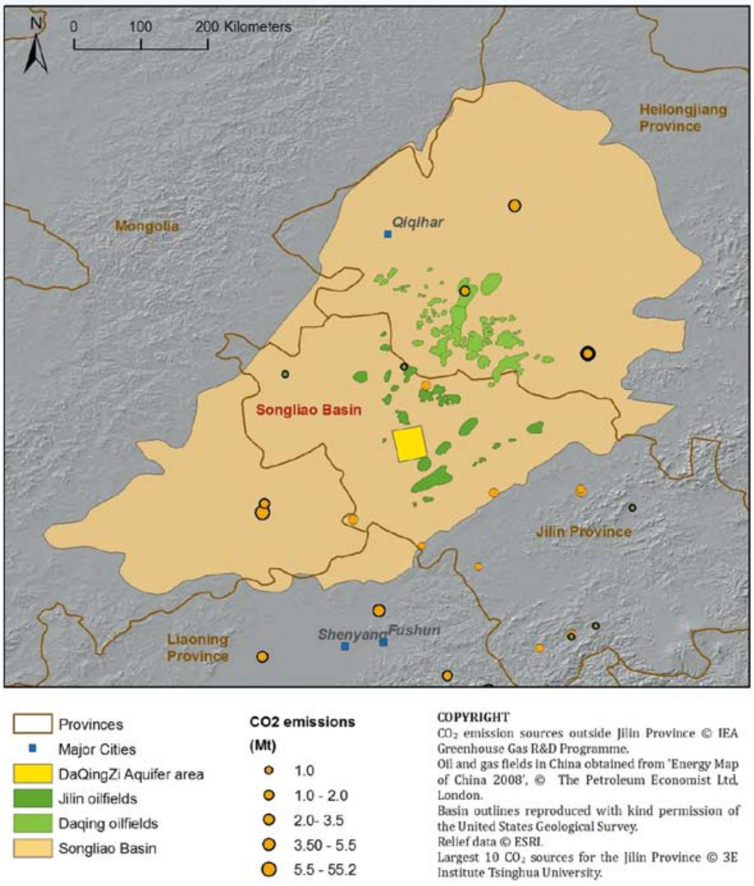
3.3.5 Subei Basin

The Subei Basin is in a heavily developed region of North-East China. There are many medium to large cities in the area with many major industrial sources of CO_2. This basin contains a number of oilfields in the Jiangsu Oilfield complex, with total storage capacity of about 20 million tonnes of CO_2. A site-specific study of one of the fields, the Caoshe Oilfield, was also conducted because a pilot injection of CO_2 for EOR was carried out there in 2006. The oilfields in the Jiangsu complex are small so each one could store relatively little CO_2 ; the 75 oil reservoirs considered suitable for EOR could store a total of 16 million tonnes of CO_2. About 5 million tonnes could be stored in the other 33 reservoirs which are unsuitable for EOR. Use of EOR in the Jiangsu complex is expected to increase the total amount of oil produced by about 35 million barrels of oil.

There are many aquifers in similar geological structures to the oil reservoirs but not much is currently known about them. Further work to characterise these formations would be needed to confirm their potential.

3.3.6 Matching sources with storage

Assessment of possible CCS projects needs to consider the geographic relationship between the sources of emissions and the possible storage sites. The scale of potential capture opportunities also needs to be tested against available storage capacity. This will affect the transportation distances, infrastructure requirements and costs. Preliminary studies[33] have suggested that about 90% of all major industrial sources of emissions in China are situated within 160km of sedimentary basins likely to contain potential CO_2 storage reservoirs. However, while this gives an indication of the transport distances that may be involved, much more detailed assessments would be required to determine whether there is adequate capacity for storage of CO_2 from industrial sources.



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Largest 10 CO_2 sources for the Jilin Province © 3E Institute Tsinghua University.

Figure 3.7 Sources of CO2 emissions and potential storage opportunities in Jilin Province, North East China (map produced by British Geological Survey).

As an example of how source-to-storage matching can be used to test the viability of CCS and to identify specific opportunities, an exercise has been undertaken for Jilin Province in north-east China, using a GIS-based Decision Support System[34]. This was used to match emissions sources and storage sites, and to compute least cost pipeline routes, taking into account geographical features such as ground slope and proximity to urban areas. As an example, two of the power generation units at the Changshan power plant, with annual CO_2 emissions of about 2.4 million tonnes, were selected as a source for a possible CCS project. The pipeline route to a potential storage site at the Qian'an oilfield was calculated to be 75 km long and its likely cost was also estimated (Figure 3.7). This particular storage site could potentially hold ten years' worth of emissions from this source (if all emissions were captured), so further storage capacity would be needed during the life of these generating units.

For the future, it is expected that, as well as significant development in the populated areas of China where existing sources are concentrated, there may also be an increase in the exploitation of coal resources in the west. Especially, if this involved mine-mouth power stations, coal to liquids or coal to chemicals conversion plants, all of which would be large point sources of CO_2, use of CCS would depend on identifying suitable matching storage sites in the vicinity.

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[33] CO_2 point emission and geological storage capacity in China, Li, X, Wei, N., Li, Y., Fanga, Z., Dahowski, R.T., Davidson, C.L., Proceedings of the 9th International Conference on Greenhouse Gas Control Technologies, Elsevier (2009)

[34] WP4 Report: Carbon dioxide emission sources and mapping of sources and sinks in the Jilin Province, Chen, W. and others (2009)

3.3.7 Integrity of storage

If CO_2 were to escape from a storage formation, this would most likely to be either as a result of failure of a well or through geological faults or fractures. Some initial work on the risks of leakage and the containment of CO_2 has been carried out as part of the NZEC Initiative[35]. Studies have been done on the risk of escape from formations with good sealing characteristics in the Songliao Basin. Extensive faults were identified in some parts of the basin although the degree of faulting varies across the area. The presence of oil and gas trapped in some of these formations indicates that some of these faults are not leaking, which is a positive indicator for their possible use for CO_2 storage. However, the high number of wells in the older oilfields, and their age, suggests there might be a greater risk of leakage (via wells) in those areas where there is a long history of oil production.

3.3.8 Conclusions about where CO2 could be stored

In general, the storage capacities of individual oilfields in this region are small when compared with the annual emissions of power stations currently being built in China[36]. The exceptions to this are the Lamadian and Sa'ertu oil fields. In addition, the reservoirs are typically geologically complex, so they would require a large number of wells to access the available storage capacity; this suggests the cost might be relatively high. For storage of substantial amounts of CO_2, the capacity available for EOR would soon be used up so it would be necessary in addition to use saline aquifers. In Jilin Province, a case study has shown that major sources of CO_2 are located within reasonable distances of possible storage sites.

Active oil producing fields, where EOR is technically possible, provide credible opportunities for initial demonstrations of CO_2 storage. However, significant further investigations, including detailed site appraisals, would be necessary before these fields or any other formations could be confirmed as technically and economically suitable for CO_2 storage.

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[35] NZEC CO_2 storage potential in selected regions of north-eastern China: regional estimates and site specific studies. British Geological Survey, Pearce, J. and others (2009)

[36] A 1000MWe power plant may be expected to emit around 6 million tonnes of CO_2/year, so storage of more than 200 million tonnes of CO_2 would be needed to handle the emissions from such a plant over its 40-year operating life.

3.4 What are the costs of CCS?

3.4.1 Introduction

The cost of owning and operating a CCS plant will be dictated by the costs of the underlying power plant plus the costs of the capture unit; in comparison the cost of transporting and storing the CO_2 will be relatively small for significant quantities of CO_2 (e.g. upwards of 3 million tonnes per year), providing the transport distance is not too great (e.g. up to several hundred km), although costs would be higher for an offshore project. For this reason, the discussion on costs here is dominated by the cost of the power plant with capture[37] but estimates of the cost of transport and storage are also included.

The costs derived in the NZEC Initiative are appropriate for construction of several power plants with capture all made to the same design, thereby benefiting from experience and from economies of scale. Such costs will not be representative of the first CCS plant to be built, nor will they reflect the cost of a demonstration plant (especially if it were smaller than a commercial-scale plant). As far as possible the costs presented here are related to Chinese conditions and have been mainly developed by Chinese engineers. As in all such work, these costs are estimates developed from available databases. This means that, for established equipment, uncertainties might be +/-30%. For new equipment, which has not yet been constructed, the uncertainties are likely to be much greater. This should be borne in mind when considering these results.

3.4.2 Cost of CO_2 capture

The base-case for these studies is a pulverised-coal (PC) plant without capture; its net output is around 800MWe[38] ; it uses an advanced supercritical steam cycle and has state-of-the-art efficiency, with a capital cost of 5000 RMB/kWe. This is in line with current construction practice in China although such costs are considerably less than for similar plant being considered in Europe. The most well developed capture system that could be incorporated in such a plant would be a post-combustion system using MEA solvent so this is one of the capture options that has been examined[39]. The other well established capture technology is the pre-combustion capture system using Selexol solvent, which would be used in an IGCC[40].The costs of installing and operating such systems are shown in Table 3.6.

It should be noted that the PC plant with capture would have slightly lower specific cost (i.e. RMB/MWe) than implied by Table 3.6 if it were designed to produce the same output as the base-case plant, because of economies of scale. No allowance has been made for future improvements in efficiency or reduction in cost of either the pulverised coal or the IGCC plants without capture.

[37] NZEC Carbon dioxide capture from coal fired power plants in China, Imperial College, Gibbins, J. and others (2009)

[38] Power plant currently being constructed in China is larger (1000MWe) but the 800MWe unit size was used here because UK partners had experience of designing the advanced supercritical steam cycles at this scale.

[39] NZEC Cost estimation for CO2 Capture with a MEA absorption process, Tsinghua University, Zheng Q. and Chen J. (2009)

[40] NZEC Case Study for IGCC Power Plant In China (with CCS), Greengen Co., Ltd, Cao J. (2009)

	Base-case PC plant without capture	PC plant with MEA capture	IGCC plant with capture
Net output, MW_e	824	622	662
Net Plant Efficiency (%LHV)	43.9	33.1	36.8
Efficiency penalty (%-points) relative to base case	-	10.8	7.1
CO_2 emissions (g/kWh)	796	106	95
CO_2 captured (g/kWh)	0	951	859
Capital cost (M RMB))†	4822	6672	6649
Fuel cost (M RMB/y)*	947	947	908
Levelized cost of electricity (RMB/MWh)	271	463	413

Table 3.6 Cost of power plants with and without CO_2 capture

† Total installed cost plus 10% contingency and 7% owner's costs

* Fuel cost = 16 RMB/GJ; 85% load factor, 10% discount rate, financing costs and taxes not included. Other cases have been assessed at higher fuel cost [41] .

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[41] NZEC Carbon dioxide capture from coal fired power plants in China, Imperial College, Gibbins, J. and others (2009)

A range of other capture technologies have also been considered in the NZEC Initiative. Several of these were for use in post-combustion capture systems. Some offered no significant improvement over the established technologies but one, use of aqueous ammonia solvent, did offer the prospect of better performance but, as this is only now entering field trials, the cost and performance have yet to be confirmed. Another promising method of capture, namely oxyfuel, is still in development so only illustrative costs have been obtained, as shown in Table 3.7. The values for both options should be treated with caution because, as with any new technology before it is applied in practice, the initial estimates of cost and performance may well be over optimistic. For these reasons the oxyfuel and aqueous ammonia solvent cases are presented here as indicative of possible future developments, not as cost projections relevant to policy development at this time.

	Base-case PC plant without capture	PC plant with ammonia solvent capture	PC plant with oxyfuel combustion
Net output, MW_e	824	670	673
Net Plant LHV Efficiency (%)	43.9	35.7	35.6
Efficiency penalty (%-points) relative to base case	-	8.2	8.3
CO_2 emissions (g/kWh)	796	98	98
CO_2 captured (g/kWh)	0	882	884
Capital cost (M RMB)) †	4822	6033	5815
Fuel cost (M RMB/y)*	947	947	953
Levelized cost of electricity (RMB/MWh)	271	398	369

Table 3.7 Cost of power plants with novel CO_2 capture systems

† Total installed cost plus 10% contingency and 7% owner's costs

* Fuel cost = 16 RMB/GJ, 85% load factor, 10% discount rate, financing costs and taxes not included. Other cases have also been assessed at higher fuel cost.

3.4.3 Cost of CO_2 transport

It is assumed the captured CO_2 would be transported by pipeline to the storage site. The size of the pipelines is selected on the basis of the peak flow rate. The annual quantity of CO_2 delivered to store has been calculated to be 4.4 million tonnes per year for the pulverised-coal plant with MEA capture and 4.2 million tonnes per year for the IGCC with capture. The levelised cost of transport is calculated to be 12RMB per tonne of CO_2 for a distance of 100km or 26RMB per tonne of CO_2 for a distance of 200km[42].

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[42] NZEC Report on CO2 Transport, Wuhan University, Hu J. and Li J. (2009)

3.4.4 Cost of CO_2 injection for storage

The precise location of a storage facility has not been identified in this project so only generalised assumptions about the storage installation can be used as the basis for a costing. No estimate has been made of the cost of monitoring the stored CO_2 but international studies suggest this should be small for commercial-scale projects. Based on the costs developed for an EOR project in the Caoshe onshore oil field, the injection facility would cost 228 million RMB. This would result in a levelised cost of about 6 RMB per tonne of CO_2 stored.

3.4.5 Conclusions about the cost of CO2 capture, transport and storage

The levelised costs of electricity generation calculated for the pulverised-coal plant with MEA capture and the IGCC with capture are 493 RMB per MWh and 440 RMB per MWh respectively; these include capital and operating costs and assume a storage site 200km from the power plant. Within the uncertainties recognised above, there is no significant difference between the costs of these options. Some of the newer capture options may offer the prospect of being constructed and operated at lower cost but the difference lies within the uncertainties at present.

On this basis, the post-combustion capture and the pre-combustion capture options (together with transport and storage of the CO_2) would each increase the levelised cost of electricity generation by around 200 RMB per MWh, equivalent to a cost of avoided emissions of about 280 RMB per tonne of CO_2-avoided compared with the PC base-case.

3.5 Developing an enabling environment for CCS in China

3.5.1 Introduction

Acceptance of a new technology depends on achieving satisfactory outcomes in more respects than just cost and capacity. In the NZEC Initiative the enabling environment needed for the development of CCS has also been considered. This includes the scope of regulation, the sustainability of CCS, its acceptability amongst stakeholders and its safety. The outcomes of these investigations are outlined below.

3.5.2 Regulation

Power plants and pipelines are well established industrial features, overseen by existing regulatory authorities and practices, so those parts of a CCS system should not present unusual issues for regulation. Instead the current work has focused on the novel feature of a CCS system, namely the storage facility.

A review of literature[43] on the regulation of CO_2 storage has been conducted to identify the main issues; this was followed by a review of recent developments in regulation in several countries; the scope of existing regulations in China was also considered.

In some countries, existing practices provide a framework within which CO_2 storage is being incorporated. For example, in Canada, acid gas[44] injection has been practiced for some years so existing regulations can be adapted relatively easily to cover CCS. However, the existing regulations do not consider the long-term liability and associated financial issues, so the regulations have to be extended in these respects. In other countries, such as the Netherlands, the current operators of oil or gas fields may still have licenses for some of the candidate storage sites, so amendments would be needed to the relevant laws to allow for the situation where CO_2 is to be injected by a different company.

In the USA, regulation is developing at both the Federal and State level - whilst the Federal Environmental Protection Agency is regulating CO_2 injection within its existing Underground Water Injection Control Program, other Federal proposals are also being considered, which recognise CCS as one of the portfolio of methods for reducing emissions; several States have also amended existing laws to allow for CO_2 storage. Australia also has a system of dual responsibilities - the Offshore Petroleum Amendment Act was introduced in 2008 by the Federal government whilst several States have developed or are developing legislation on greenhouse gas storage. Other countries, that do not have established legislation, are developing new statutes for CCS.

The EU has established a wide-ranging regulatory regime for projects intending to store more than

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[43] NZEC An Update on International Carbon Capture and Storage (CCS) Policies and Regulations and their Relevance to China, AEA, Haydock, H. and Odeh, N. (2009)

[44] Acid gas, in this context, is a mixture of H_2S and CO_2 arising from oil and gas production which is analogous to CO_2 storage

100,000 tonnes of CO_2. This is being implemented through a Directive[45] which, although it covers capture and transport of CO_2, is focussed mainly on CO_2 storage including site selection and exploration, storage permits, site operation, closure, post-closure and the transfer of liability. In the UK, a regulatory framework for offshore storage of CO_2 has been introduced under the 2008 Energy Act. The UK Government is also proposing that electricity companies must capture CO_2 emissions from a significant proportion of any new coal fired capacity as soon as it starts operation, with compulsory retrofit of all coal fired power plants within five years of CCS being technically and economically proven.

Despite the differences between countries, most regulations are being based on similar principles about selection and permitting of sites, construction, operation and closure but with differences in detail, such as the duration of the exploration permit. The new feature of all of these rules concerns the post-closure phase, especially the period after which responsibility for stored CO_2 may be transferred from operator to government.

The experience of these countries can be of value to China in deciding on its own regulation. This survey suggests that China could adapt its existing systems of regulating oil and gas exploration, radioactive waste disposal, EOR and hydropower to develop appropriate regulation for CO_2 storage. China has a well-established system of regulating EOR projects, which might well be used as the basis for regulating CCS deployment in the near-term, if that were to involve EOR. However, amendments would be required in areas such as long-term liabilities, injection site locations, and injection criteria. As other countries have found, adapting existing regulations can be a faster method of enabling demonstration of CCS while more comprehensive legislation is developed for longer-term use.

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[45] EU Directive 2009/31/EC on the geological storage of carbon dioxide

3.5.3 Sustainability

One of the most widely quoted definitions of sustainable development is that of the Brundtland Commission[46] namely "a development that meets the needs of the present without compromising the ability of future generations to meet their own needs". Making a judgement about the sustainability of CCS on the basis of this definition involves reconciling aspects of development with protection of the planet and the lives of future generations. Some of these trade-offs can be treated in a more or less analytical way; others are susceptible only to qualitative examination. The major areas to be considered are environmental, economic and social impacts.

The size of any impact depends on what would happen in the absence of the proposed action – for example, a power plant with CCS could have a larger impact on the landscape than, say, a nuclear power station but less than a wind farm producing the same amount of electricity. Much of the sustainability assessment in this study has been done by comparison with the type of coal-fired power plant that would be constructed today but it is also necessary to consider other measures that might be used to mitigate climate change if CCS were not deployed.

Environment - Impacts on climate change, air quality, landscape, land and water use, and waste production are all considered. Experience with earlier types of pollution control processes, such as selective catalytic reduction or flue gas desulphurisation, has shown that reducing the impact in the target area may increase the impact in another area (e.g. reduction in sulphur emissions is achieved at the cost of increased fuel consumption). An environmental impact assessment would be needed to provide precise information on this but such assessments tend to be specific to a particular project, so have not been carried out here.

Use of CCS will achieve major reductions in CO_2 emissions but the increased use of fossil fuels would lead to more greenhouse gas emissions from coal mining and transport activities, slightly reducing the overall reduction in emissions from use of CCS. However, there would still be a substantial net reduction, which could be maximised by minimising the reduction in efficiency due to CCS. There is also likely to be a small increase in emissions of solvents and some increase in water use from such plant (the impact of this will depend on the availability of water at the location of the plant). The main negative environmental impact is likely to be in production of solid waste (e.g. slag) due to increased fuel consumption, and in spent solvent from use of MEA and certain other solvents. Power companies in China are experienced at putting the

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[46] The report of the World Commission on Environment and Development (1987)

conventional wastes to good use, such as using the slag as aggregate.

Economic – building new power plants with CCS is more expensive than building plants without it but achieving large reductions in greenhouse gas emissions by other means may cost even more; these effects have been examined in a study[47]. According to an IEA report[48], to achieve a scenario which halves global CO_2 emissions by 2050 (relative to today's levels) without using CCS would cost 70% more than one that did use CCS; half of the use of CCS would be in power generation and half in industrial processes and the fuel transformation sector. If suitable carbon price signals are available in future, it should become cost-effective to capture and store, rather than emit, CO_2 .

The liability for storage of CO_2 will also need to be met. Discussions in many countries are still taking place on this, and it is too early to say where such liability would lie in China.

Social - CCS technology will not greatly affect society at large. The deployment of CCS on a large scale will lead to increasing use of coal with associated social impacts, such as a greater amount of mining. Coal power plants with CCS may need additional land space but CCS also has the potential to make a positive contribution by providing opportunities for China to become a worldwide leader in this technology.

3.5.4 Acceptability

For any new technology, the attitudes of key stakeholders can provide important guidance on issues that may need to be addressed in considering its future development and deployment. A survey of 131 Chinese stakeholders[49] has provided insight into a wide range of subjects relevant to CCS development and deployment.

Most respondents viewed climate change as a serious problem, including 20% who perceived it as presenting a challenge in the near future. CCS was widely seen as an important technology in reducing greenhouse gas emissions. The most attractive storage technologies for initial CCS demonstration projects were judged to be EOR and enhanced coal bed methane recovery. Post-combustion capture was perceived as slightly more attractive than pre-combustion capture technologies because most existing power plants are pulverised coal-fired stations, although respondents from the electricity industry and from the oil industry tended to favour pre-combustion capture.

Most stakeholders believed that developing a CCS demonstration project could benefit the image of the Chinese Government, and that such a project could also create advantages for Chinese companies. Views were canvassed on means of financing the deployment of CCS – the preferred method varied depending whether the respondent was in industry or finance. It was expected that the extra operating costs of CCS would be met by foreign governments or by the national government; the Clean Development Mechanism (CDM), if applicable, was expected to play a relatively minor role.

A small number of respondents expressed concerns over the reliability of CCS technologies, the availability of storage sites, and about issues concerning coal supply. A large number of the respondents were concerned about the extra energy use associated with CCS and its impact on the long-term sustainability of coal supply in China.

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[47] NZEC Socio-economic assessment of CCS, CEEP (2009)
[48] CO_2 Capture and Storage - A Key Carbon Abatement Option, IEA, Paris (2008)
[49] NZEC Stakeholder Perceptions of Demonstrating CCS in China, Cambridge University, Reiner, D. and Xi L. (2009).

3.5.5 Safety

Power plants and pipelines are well established industrial features, overseen by existing regulatory authorities and practices and, as such, are regulated to ensure safe operation. The capture and compression of CO_2 are not expected to introduce any new safety issues. For transport of CO_2, the consequences of leakage will need to be examined and taken into account in the routing of pipelines, especially near inhabited areas. Although the same degree of experience has not yet been established with storage, large-scale demonstrations in Europe and the USA, supported by extensive monitoring and verification, are providing confidence that long-term storage of CO_2 in geological reservoirs will be safe. Consequently, safety has not been a major issue for investigation within Phase 1 of the NZEC Initiative. Further development of national capabilities in monitoring and verification will enable Chinese scientists and regulators to satisfy themselves of the safety of CO_2 storage.

3.6 Other CCS activities in China

China has implemented a number of domestic CCS initiatives focussed on longer term technology development, as well as participating in various international activities[50]. The 'National Key Technologies' R&D programme for CCS, funded by MOST, includes strategic studies focussed on the applicability of CCS to China, and the associated impact on energy systems and greenhouse gas emission reduction[51]. Alongside these studies, practical research activities include:

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[50] NZEC CCS Activities in China, ACCA21, Zhang, J.(2009)

[51] Key technologies R&D programme, Ministry of Science and Technology (2007)

- The National Basic Research (973) Programme - a major programme of fundamental research on CO_2 for EOR, on syngas production from coal gasification and pyrolysis, and on high efficiency conversion of natural gas and syngas for either chemical products or for carbon-free use in gas turbines.

- The National High-Tech Research and Development (863) Programme - several projects to develop advanced CO_2 capture technologies such as adsorption and absorption, and to explore CO_2 storage technology.

Several universities and institutes contribute to these projects plus key industrial enterprises such as PetroChina, various oilfield operators, and the major utility companies. For all of this work, the aim is "to establish Chinese-based techniques which can secure independent intellectual property rights"[52].

International collaborative R&D projects outside those covered by the NZEC Initiative include:

- Chinese participation in CCS-related projects under the EU Framework Programme;
- UK Government support to examine capture-ready options for China and explore the potential for CCS in the Guangdong region;
- Australian collaboration with the Huaneng Group to establish a small post-combustion scrubber on a power plant in Beijing (Figure 3.3);
- Collaboration between Geoscience Australia and a number of Chinese partners on an assessment of CO_2 storage capacity in various regions of China to complement the NZEC Initiative and COACH;
- Input from the World Resources Institute to assist Tsinghua University in the preparation of a draft set of 'Guidelines for Safe and Effective CCS in China', which forms part of the activities of the Asia Pacific Partnership[53];
- Support from the US Department of Energy for a study to examine 'Regional Opportunities for Carbon Dioxide Capture and Storage in China', which involves numerous partners from Chinese and USA institutes;
- A Memorandum of Understanding with Italy on CCS in the power sector.

[52] ibid

[53] Asia Pacific Partnership on clean development and climate (2009)

In addition, industrial activities include:

- CO_2 capture initiatives led by the Huaneng Group that include development of pre-combustion CO_2 capture options complementary to the construction of the Greengen IGCC; also a post-combustion capture plant with capacity of 100,000 tonnes CO_2 per year is being developed at the Shi-Dong-Kou power plant in North Shanghai. Other major power generation companies are also interested in post-combustion capture.
- PetroChina started China's first pilot CO_2 injection for EOR in the Jilin Oilfield in 2006.
- Japan and China announced in May 2008 an initiative to develop a CCS and EOR activity with 3 to 4 million tonnes of CO_2 per year captured at two coal-fired power plants in China. Chinese participants include PetroChina and the Huadian power company.
- The Shenhua Corporation is looking at options to capture CO_2 from its direct coal liquefaction demonstration plant in Inner Mongolia, which may be used for EOR or stored in a saline aquifer.
- Several other CCS initiatives have been announced including an EOR project involving EESTech and Tianjin Dagang Huashi Power; a cooperation agreement between Huaneng Group and Duke Energy to explore clean-energy technologies including CCS; and the Clean Energy Commercialization Centre, a joint venture between BP and the Chinese Academy of Sciences.

4. Challenges and opportunities in CCS

4.1 Introduction

As a result of the major effort expended by the partners in this Initiative, the potential for CCS to address CO2 emissions in China is now becoming clearer. There are several challenges that need to be addressed, some of which also provide opportunities that may be of interest to stakeholders in China. The challenges include:

- The extra cost of CCS - adding such equipment to power plants would increase the energy used and cost of electricity generation;
- The novelty of the technology – not only are power plant operators unfamiliar with it, the regulatory authorities and the public have not yet heard about it either; nor are there any regulations governing the storage of CO2 underground;
- The availability of the necessary equipment for deployment of CCS in China is uncertain.

These challenges are discussed below.

4.2 Addressing the extra cost and energy use

Adding the equipment necessary for capturing, transporting and storing CO_2 to power plants or other industrial facilities will increase their energy use, and their capital and operating costs. In principle, the increased cost of electricity generation might be recovered in one of the following ways: through higher prices, or subsidy, a carbon price signal or international financing mechanisms. Use of CCS with other sources of CO_2 (such as from cement production, iron and steel making, or manufacture of liquid fuels from coal) would present similar issues to the operators of those plants.

The IEA[54] has shown that, as part of a portfolio of mitigation options, CCS has the potential to achieve emission reduction goals at lower overall cost than many other technologies. This, coupled with the opportunity that CCS provides to reduce emissions from China's use of its major coal resource, indicates the importance of considering CCS alongside the other mitigation options available.

Decisions on pricing of electricity and subsidy of electricity prices are properly matters for the Chinese government and the supervisory bodies of the electricity industry so are not discussed here. External funding could help offset the additional cost of using CCS, such as by using the flexible mechanisms of the Kyoto Treaty. The Clean Development Mechanism (CDM) has the potential to assist in introducing this technology in China but, at present, CCS is not yet accepted for projects under the CDM.

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[54] CO_2 Capture and Storage - A Key Carbon Abatement Option, IEA, Paris (2008)

When CCS is deployed on a wider scale and in greater numbers, it is very likely that the cost of the technology will come down, as has happened with related technologies in China, such as pulverised coal-fired power plants and flue gas desulphurisation. Further development of CCS technology will also bring improvements in the level of energy use, in system improvements by better integration and in plant specification – all of these will help reduce (but not eliminate) the additional cost of CCS. Appropriately targeted R&D will assist these developments; the increasing number of well qualified Chinese researchers and institutions now working in this area is likely to accelerate this process.

4.3 Responding to operational uncertainties

One of the major hurdles facing any new technology is the simple fact that it is new. So power plant operators are not familiar with it and may be reluctant to use it. The regulatory authorities will not have decided what rules should apply to novel aspects of the system, such as storage, which adds to the operators' difficulties in planning a new project. The general public may come into contact with it, perhaps because they encounter pipelines or storage facilities, and ask whether CCS is safe – without clear answers from someone they trust, this can raise concerns.

The key is for power plant operators, oil and gas companies and other industries to gain experience with CCS in various ways. For example, laboratory work provides information for design of plant and for comparing claims for different solvents; pilot-scale plant can be used to demonstrate how capture systems work with real flue gas streams and provide hands-on experience for operators; construction of a large-scale unit to demonstrate the technology would also enable potential users to gain experience with all aspects of the process including construction, commissioning and operation. If EOR should also be demonstrated, this would provide experience for potential storage operators. The NZEC Initiative has shown the relative attractions of the different capture technologies and has identified locations where CO_2 might be stored. On this basis, the more attractive options for demonstration at the different sizes can be identified – this is discussed further in the following section.

Further experience will be gained through the increasing number of CCS projects being undertaken in collaboration with other countries. In this way experience is being gained with CCS technology and the expertise of the scientists and engineers is being enhanced.

4.4 Adapting regulations to CCS

Issues associated with regulations, particularly concerning the storage of CO_2 underground but also the safety of pipelines carrying CO_2 and the environmental impact of CCS plants, may need to be resolved in order to facilitate deployment of CCS in China.

The survey carried out by the NZEC Initiative has demonstrated how gaps in regulations are being dealt with in other countries. Regulation of shortterm projects (i.e. five to ten years), especially demonstrations, is being handled by extending regulations already in place to cover CCS. For large-scale (hence longer-term) deployment, additional regulations specific to CCS-related issues, such as long-term liability and post-closure financial responsibility, are being formulated. China has an opportunity to observe and draw lessons from the experiences of other countries in deciding how it wants to proceed with developing regulations.

4.5 Equipment availability

Depending on the type of CCS technology implemented, much of the equipment may be constructed in China but other components may need to be imported. A full analysis of this important issue has not been carried out in the NZEC Initiative but, given that CCS is based on application of known technologies, it seems likely that locally-supplied equipment would be able to meet many of the requirements of a CCS project, such as boilers, steam turbines, pipelines and equipment for injection CO_2 underground. Certain process equipment might be licensed from manufacturers in other countries, such as CO_2 separation technology or some types of air separation unit but even gas turbines are now constructed by local joint venture companies who might be able to provide the necessary equipment for a demonstration project, thereby minimising the extent to which imports are needed.

Further down the road, if CCS is demonstrated in China with locally-sourced equipment, the capabilities of Chinese manufacturers to exploit the experience they have built up in such projects should enable them to compete to supply key components to CCS projects in other countries.

4.6 Potential benefits of CCS

Recognising the global need for reduction in greenhouse gas emissions from use of coal, and the major role that coal will continue to play in energy supply to China, use of CCS has the great advantage that it would provide China with the opportunity to take action on climate change without greatly affecting the use of coal as its predominant fuel. The scale of any single plant means that CCS would involve major investment but this would be the case with any substantial project in power generation or in any energy-intensive industry. When considered in relation to other measures for making deep reductions in CO_2 emissions, not only has CCS the potential to be relatively inexpensive (per tonne of CO_2 avoided) but it also offers the opportunity to generate income, e.g. through EOR. EOR also provides the opportunity for learning about the relevant technologies and demonstrating the use of domestically-sourced equipment. In the longer term, establishing a presence in the CCS field would provide business opportunities for equipment suppliers both at home and abroad.

5. Moving forward

5.1 Scope for further cooperation

The ultimate aim of the EU-China NZEC agreement is to establish the foundation for a sustainable CCS solution for China and the EU, with the objective of demonstrating the full chain of the technology, to complement the demonstrations being established in Europe. In that context, the programme of work of the China-UK NZEC Initiative, which was developed jointly by the Chinese and British partners, has helped to establish capabilities in CCS technology in China. Both the Chinese and British partners have improved their understanding of CCS issues in relation to China. This work has strengthened existing links between Chinese and British institutes and has also established new ones. There is now better understanding of a range of options for capturing, transporting and storing CO_2 which provides a good basis for developing future plans for gaining practical experience with CCS technology.

China, the European Commission and the UK have agreed that there should be two further phases under the China-EU NZEC agreement leading to a collaborative demonstration project in China. Phase II should comprise a feasibility study and design of the demonstration project, while Phase III should be the construction and operation of a CCS demonstration plant in China. Both the UK and China support the objective of an operational CCS plant by 2015. Within the overall framework of this joint initiative, it is also important to ensure that the research initiatives are taken further to build on the NZEC results, enhancing scientific and technical capacity, such that any demonstration would form an integral part of the development of a CCS strategy for China. These points are considered below.

5.2 Demonstration issues

The goals of any CCS demonstration activities would be to:

- Establish the technology, including process integration and optimisation, at a scale that is large enough to allow subsequent plants to be built with confidence at commercial scale
- Prove that CCS works and is safe, thereby building public confidence
- Accelerate technology development in order to gain experience that will lead to subsequent cost reduction on larger scale plant

The rationale and choices for demonstration projects in China are strategic considerations. The national context, technology status and other factors, such as feasibility, stakeholder interest, timing and cost, will be taken into account by the Chinese authorities in determining what is required. Several major large-scale demonstration projects are already being considered in China. These include proposals for IGCC with capture (Greengen Phase 2), post-combustion capture (Huaneng large scale side-stream on a pulverised coal power plant), capture at a Coal-to-Liquids demonstration plant with either EOR or aquifer storage (Shenhua). Eventually a portfolio of demonstration activities may be needed in China to cover different CCS applications, storage options and regions.

If the NZEC demonstration is to take place by 2015, with a focus on coal-fired power generation, issues of system integration and energy penalty will need to be addressed. The choice of capture technology would lie between a pulverised coal plant with post-combustion capture and an IGCC with pre-combustion capture. This is because other technology options, such as oxyfuel, lack the maturity to provide confidence in a successful large-scale demonstration in this timescale. The techno-economic assessment undertaken in the NZEC Initiative suggests the costs of electricity would be very similar for both the post- and pre-combustion capture plants. As China is a world leader in the application of advanced pulverised coal plants, there is considerable interest in post-combustion options. For example, Huaneng Group is preparing to establish a large-scale industrial trial on a slip-stream for such a plant which could provide valuable information for demonstration of a subsequent commercial-scale prototype. At the same time, the pre-combustion based approach is also well regarded, and again Huaneng Group is leading the way with the Greengen project.

The choice of location of any demonstration CCS plant will be of critical importance as it should be close to a CO_2 storage site in order to limit CO_2 transport costs. Indeed, the availability of storage sites is likely to be a major determinant of the location of a system to demonstrate CCS. The NZEC storage capacity assessment has shown that, at least in North-East China, the oil fields where CO_2 might be used for EOR are mostly of small capacity relative to the CO_2 emissions of a large coal-fired power plant. One way forward might be through, firstly, EOR and, subsequently, saline aquifer storage (following a more detailed assessment to prove that storage capacity was available commensurate with the plant's lifetime emissions).

Regulations would be needed to support the storage aspects of a demonstration although it may be possible to adapt existing regulations and then subsequently develop a more comprehensive approach to cover establishment of a significant number of commercial-scale CCS plants.

5.3 R&D requirements

In terms of the key R&D needs, the high costs and large energy penalty for current CO_2 capture and compression technologies are seen as important barriers to CCS, according to the NZEC stakeholder survey. The resulting increases in energy costs and coal usage are major concerns. Reducing the costs and energy penalty is the major objective for technology development, either through improvements to the current CO_2 capture options or through the longer term development of alternatives. Potential future activity in China is likely to include:

- Advanced post-combustion capture techniques either based on solvents or alternatives;
- Pre-combustion capture, gas separation and gasification technologies, including membranes;
- Development of oxyfuel applications, including technology for low cost oxygen production;
- Systems engineering and optimisation for IGCC, coal conversion and poly-generation with capture;
- CO_2 capture options for iron and steel, cement and other industry sectors;
- CO_2 separation from natural gas and other applications in oil and gas exploration, production and refining;
- Consideration of the capture-ready approach whereby new plants are designed and constructed such that they can be readily adapted to CCS at a later date.

R&D for CO_2 transportation is generally considered a low priority although there would be benefits from further work on national standards and regulatory requirements, routing and system modelling.

The potential to use captured CO_2 to enhance oil production is of great interest in China. However this option appears to have insufficient capacity for large-scale CO_2 storage in the regions studied to date. In view of the limitations of the storage opportunities identified for EOR in North-East China, there is a pressing need to continue this regional survey and to assess oil and gas reservoirs in other regions of China, as well as initiate a rigorous assessment of saline aquifer storage capacities. Adequate storage capacity will be the limiting step to CCS deployment in China. Future work is likely to include:

- National and regional storage mapping, e.g. a CO_2 storage atlas for China, including defining

site selection criteria and site characterisation methodologies
- Detailed scientific, technological and engineering assessments of CO_2 EOR opportunities
- Depleted oil- and gas-field storage assessment, which could cover capacity, availability and risk, as well as facilities, integrity and re-use
- Aquifer storage mapping, assessment of capacity and integrity, site characterisation and risk assessment.

A related issue is the need to ensure that storage of CO_2 will be safe on a long-term basis, because of the potential risks to people and the environment associated with release of CO_2. While the expectation from activities outside China is that storage is safe and that CCS is a viable option, China needs to gain experience with monitoring and verification as part of an overall risk assessment process.

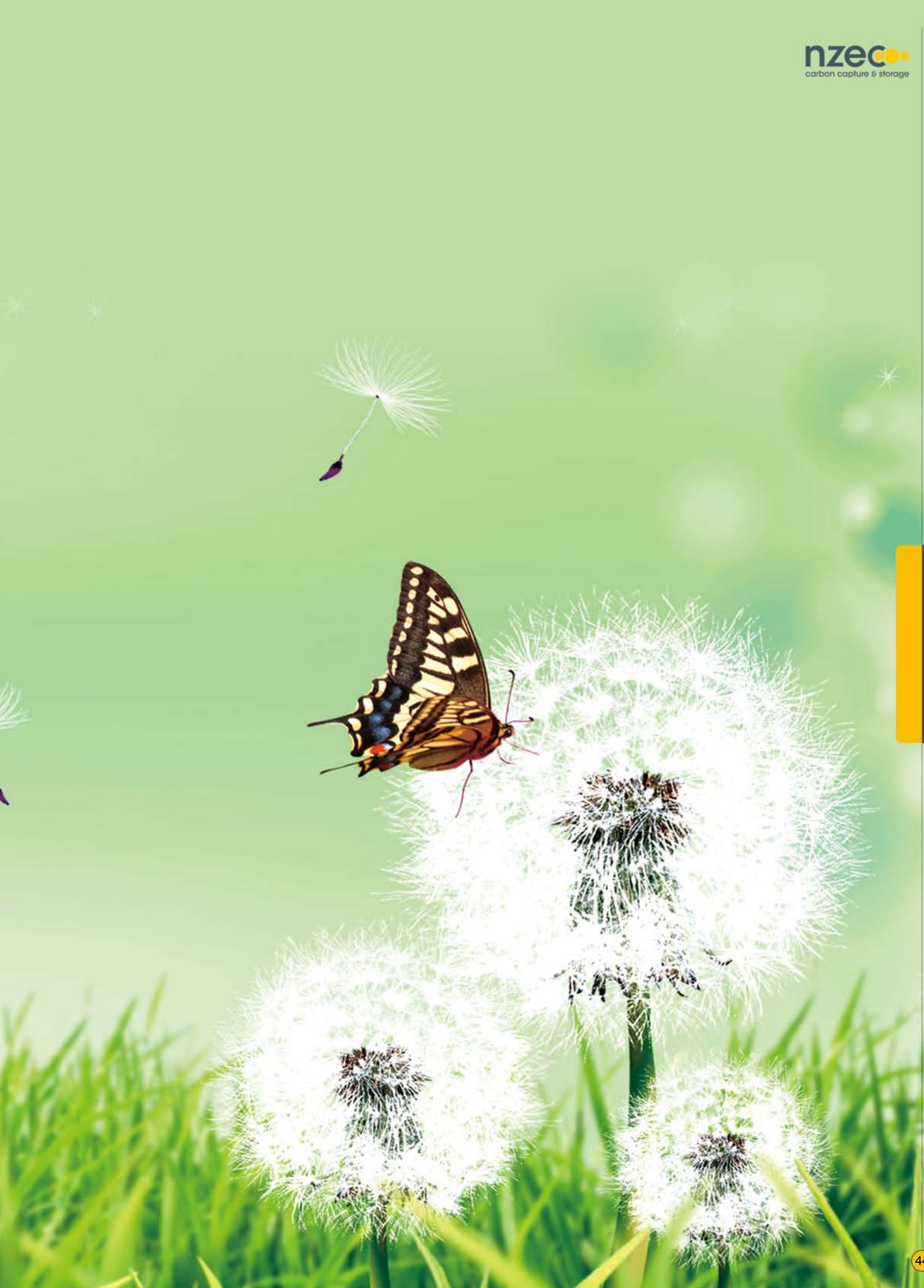
In addition to the technical activities, there is a need to examine in greater detail the possible energy growth scenarios for China, including the impact of various policy measures, in order to build up a more comprehensive picture. This will allow industry and Government to make more informed decisions on the timing of possible large-scale deployment of mitigation measures such as CCS and consider the costs of CCS in relation to alternative approaches to low carbon energy provision and the wider societal costs of addressing climate change and its impacts.

6. Conclusions

The China-UK NZEC Initiative has shown that CCS could provide a key low carbon option for coal-based industry in China, particularly for power generation applications. This would enable the continued use of coal with very much reduced greenhouse gas emissions.

The various development and deployment approaches that have been considered within the China-UK NZEC Initiative have provided valuable experience while also establishing the basis for further UK-China cooperation.

In order to reach the position where Chinese CCS stakeholders can be fully informed of the challenges and opportunities, further R&D and associated capacity-building activities and outreach are required. This needs to involve a wider range of stakeholders, in particular a greater involvement of industry. The continuation of the China-EU NZEC agreement in two further phases is an important part of that process, since its objective is the successful demonstration of an integrated CCS system, ideally by 2015. The recent formation of a China-EU Cooperation Leading Group will provide strong support to take forward this joint CCS initiative. At the same time, it is recognised that, since the start of the NZEC Initiative, China has also established other CCS-related cooperative activities with Japan, Australia and the USA. Accordingly, it is important to ensure that these projects are complementary, to maximise use of resources and the potential for learning.



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