Potential for permanent geological storage of CO_2 in China: the COACH project

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The challenge of climate change demands reduction in global CO_2 mission. Carbon dioxide capture and storage (CCS) technology can be used to trap and store carbon dioxide gas emitted by coal-burning plants and this can reduce the world's total CO_2 emission by about one quarter by 2050 (IEA 2008, 2009; IPCC 2005). Experience from the storage sites of Sleipner in the Norwegian North Sea, Salah in Algeria, Nagaoka in Japan, Frio in USA and other sites shows that geological structures can safely accommodate CO_2 produced and captured from large CO_2 point sources. CCS is regarded as a technology that will make power generation from coal sustainable, based on cost-effective CO_2 capture, transport and safe geological storage of the released CO_2.

China has large coal reserves (DeLaquil *et al.* 2003), and is not about to give up on this reliable source of fossil fuel. Hence a large production of CO_2 can be expected to continue for many years. China also has a large theoretical geological carbon dioxide storage capacity in onshore areas with deep saline formations (Dahowski *et al.* 2009). In an extensive collaborative research effort between Chinese and European scientists, the COACH project (Cooperation Action within CCS China-EU) was successful in building the expertise, developing the capture technologies and mapping transportation routes for CO_2, and it produced two scenarios for geological storage of CO_2 in China.

The aim of the COACH project was to initiate a durable cooperation between Europe and China in response to China's rapidly growing energy demand. The project ran from November 2006 to October 2009 and was set up and funded by the European Commission under the memorandum of understanding on Near Zero Emissions Coal, to build demonstration plants in China. Twenty partners consisting of eight Chinese and twelve European partners evaluated the feasibility of establishing CCS in China (COACH 2009). COACH had four work packages dealing with (1) knowledge sharing and capacity building, (2) capture technologies, (3) permanent geological storage of CO_2 and (4) recommendations and guidelines for implementation. Three tasks were carried out under the

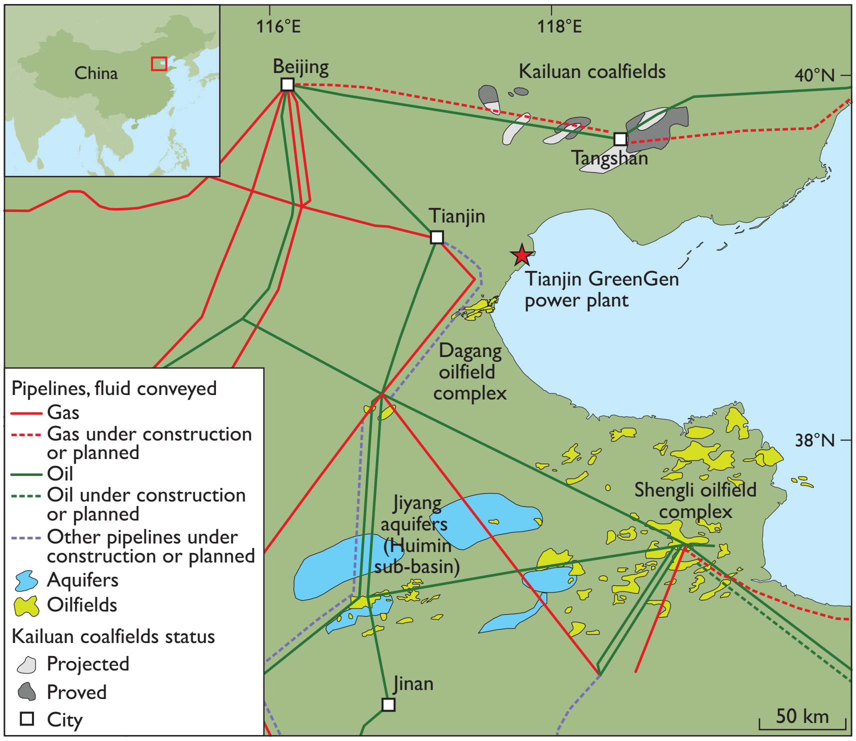

Fig. 1. Map of the study area in eastern China showing CO_2 sources, proposed pipeline network and potential storage sites. Based on data from the Energy, Environment and Economy Research Institute, Tsinghua University; Institute of Geology and Geophysics, Chinese Academy of Sciences; China University of Mining and Technology; Research Institute of Petroleum Exploration and Development, PetroChina and the China University of Petroleum (CUP). The outline of the Shengli oilfield complex and the pipeline data are from 'Energy Map of China 2008', © The Petroleum Economist Ltd, London. © British Geological Survey. British Geological Survey produced the GIS map.

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third work package: (a) capacity estimates at regional level, (b) mapping of the geology and emission point sources and (c) improving methods for storage capacity assessment and site selection criteria. The Geological Survey of Denmark and Greenland and Tsinghua University in Beijing shared the leadership of the third work package. This short article presents the results of the work conducted on the potential for geological storage of CO_2 in China.

Background and methods

Aims of the Carbon Sequestration Leadership Forum

The aim of CO_2 storage is the permanent removal of CO_2 from the atmosphere. The European Union has supported current research on CO_2 capture and storage methods for more than a decade, with emphasis on capture techniques, transport and geological storage. The results of the research on geological storage are summarised in a comprehensive manual by Chadwick *et al.* (2008). Internationally recognised standards for capacity assessments were established by the Carbon Sequestration Leadership Forum (CSLF) in 2004–2005 and a task force on capacity estimation standards has been active since presenting comprehensive definitions, concepts and methods (Bachu *et al.* (2007a, b). These capacity standards were reviewed for the COACH project by Poulsen *et al.* (2009) and were used for the work on permanent CO_2 storage estimates in China (Zeng *et al.* 2009).

Fig. 2. An example of a Shengli oilfield production site.

Comparison of methods

Various methods are available for calculation of CO_2 storage capacity in a geological environment (Koide *et al.* 1992, 1995; Tanaka *et al.* 1995; Shafeen *et al.* 2004) . The methods used in the COACH project (Poulsen *et al.* 2009) were based on Bachu *et al.* (2007a, b) and used in the COACH database to estimate the storage capacity of hydrocarbon fields. Estimates made by the China University of Petroleum applied Tanaka *et al.*'s (1995) method for computing the storage capacity in the Shengli oilfield complex (Zeng *et al.* 2009).

The two methods proposed by the CSLF task force and Tanaka *et al.* (1995) are basically identical in their approach. Both methods are based on a volumetric approach and are applicable to site, regional and basin-scale CO_2 storage capacity estimates. Both can be considered as 'simple' equation models, which try to calculate an 'approximation' of a possible storage capacity. The methods gave almost identical results when applied to the Shengli oilfield complex (Table 1). There are, however, some differences in the approach to CO_2 behaviour in the storage site. The CSLF method works with replacement of oil, gas or formation water but does not incorporate dissolution of CO_2 in formation water. The method of Tanaka *et al.* (1995), on the other hand, operates with a free phase of CO_2 and takes into account dissolution of CO_2 in the formation water, but it does not considerer the time period needed for the dissolution (Poulsen *et al.* 2009).

Long term behaviour of CO_2 in a storage site

The long term behaviour of CO_2 in a storage site depends on (1) a number of reservoir parameters (temperature, pressure, capillary pressure, porosity, permeability, and the cap rock permeability and capillary entry pressure), (2) the CO_2 composition, (3) the formation water and (4) time (Chadwick *et al.* 2008). The solubility of CO_2 in formation water varies with salinity, temperature and pressure of the formation water (the brine). The dissolution of CO_2 in pure water increases with increasing pressure (and thus increasing depth) up to approximately 7 Mpa. On the other hand, the CO_2 solubility in a brine decreases with increasing temperature and salinity and thus in most cases decreases with depth (Bachu & Adams 2003). The

Table 1. Summary of geological sites assessed for geological storage of CO_2 after Zeng *et al.* (2009)

Storage site	Capacity	Injectivity	Seal
Dagang oilfield complex	Selected 7 fields 22 Mt Largest Gangdong field 10 Mt	1000 mD Some compartmentalisation by faulting and stratigraphy	Mudstones
Shengli oilfield complex	472 Mt using CSLF methodology and 463 Mt using CUP method	1000–2500 mD Some compartmentalisation by faulting and stratigraphy	Lower Jurassic mudstones
Huimin Sag aquifers (Jiyang)	For Huimin sub-basin 50 Gt For selected troughs in sub-basin 0.7 Gt	Permeability around 1600 mD in neighbouring oilfields	Mudstones of Minghuanzhen Fm
Kailuan coalfield	504 Gt adsorbed onto coal and 38 100 Mt void capacity	Permeability generally low 3.7 mD in Taiyuan Formation and 0.1 mD in Shanxi and Xiashihezi Fm	Mudstones

result is that in general, the solubility of CO_2 in the brine decreases with increasing salinity (Shafeen *et al.* 2004).

The buoyancy of injected supercritical CO_2 leads to an upward gravity-driven flow of CO_2 towards the top of the formation where it forms a plume below the cap rock. CO_2 (liquid or supercritical) and water are immiscible, but CO_2 can dissolve to a certain extent in water. Due to the slow solubility of CO_2 in brine, a large volume of brine is necessary to dissolve a given amount of CO_2. The density of the brine increases with increasing CO_2 dissolution and a downward gravity-driven flow will be induced by the increased density of the CO_2-saturated brine. On the initiation of storage, before the plume of saturated brine has reached the bottom, the overall dissolution rate is essentially constant due to rapid convective overturn (Ennis-King & Paterson 2007). At a later stage during storage the saturated brine forms a gravity current propagating outwards from the CO_2 source.

Activities and results

The main purpose of the COACH project was to prepare the way for CO_2 capture and storage in China. In order to achieve this, the COACH partners developed an integrated gasification combined cycle capture technique. This is a coal-based energy system with hydrogen production using coal gasification, electricity generation from a combined cycle hydrogen turbine and fuel cell system, and capture of the CO_2.

The partners have mapped emission sources and investigated potential CO_2 storage sites in eastern China (Fig. 1, Table 1). The storage potential of the selected sites was evaluated using published data or data provided by the Research Institute of Petroleum (PETROCHINA). Particular oilfields, saline aquifers and un-exploitable coal beds were investigated. Several test sites are available in some of the oilfields. The storage potential in oilfields is 10–500 Mt, (pilot scale level; Fig. 1, Table 1). Following this, a CO_2 transport infrastructure based on connecting CO_2 sources and storage sites by pipeline or ship has been suggested (Fig. 1; Table 1).

The saline Jiyang aquifers in the Huimin sub-basin show storage capture at an industrial scale (around 50 Gt; Fig. 1, Table 1), but further geological investigations are required. The security of energy supply is a key consideration in China, and enhanced oil recovery (EOR) could be an option. Some of the oilfields in the Dagang and Shengli oilfield complexes may be suitable for an enhanced oil recovery pilot project. Injecting CO_2 into oilfields approaching depletion will not only store CO_2, but may also enhance or prolong oil recovery (COACH 2009).

The coals of the Kailuan coalfield have low permeability and probably low injectivity, but a high theoretical ability to adsorb CO_2 (Fig. 1, Table 1). In general, however, the storage capacity in coal seams is uncertain. On the other hand, it has been demonstrated that injection of CO_2 into coal beds can lead to methane production (enhanced coal bed methane recovery; Yu *et al.* 2007). At the same time it is a very attractive option for geological CO_2 storage as CO_2 is strongly absorbed onto the coal.

Two scenarios for possible CO_2 capture and storage demonstration projects have been proposed by work package 4, based on the mapping of emission point sources, geology, and capacity estimates by work package 3 together with economic analyses. The first scenario is for a pilot scale site with 0.1–1 Mt CO_2/year stored in the Dagang or Shengli oilfield complexes. The second scenario is intended for industrial-scale storage at 2–3 Mt CO_2/year, which could be accommodated in the Shengli oilfield complex or potentially in the saline formations in the Huimin sub-basin. The pilot scale scenarios focus initially on enhanced oil recovery for storage where this is feasible. The large-scale option could begin with enhanced oil recovery but would need to switch to saline aquifer storage once the potential reservoir and sealing formations have been adequately investigated. Both scenarios are based on capture of CO_2 from the Tianjin GreenGen power plant (COACH 2009).

Final remarks

In 2005 construction began of the coal-based Tianjin GreenGen power plant (Fig. 1) and electricity production started in 2009. It will be the first near-zero emission power plant in China. Research over the next decade is expected to develop and demonstrate the efficiency of coal-based power generation, mostly by recycling energy lost in the process. The goal is to achieve sustainability of coal-based power generation.

The project concludes that there is significant potential to develop carbon dioxide capture and storage technologies in China and to make major reductions in CO_2 emissions over the next century.

Experience from the storage sites Sleipner in the Norwegian North Sea, In Salah in Algeria, Nagaoka in Japan, Frio in USA and other sites shows that geological structures can safely accommodate CO_2 produced and captured from large point sources. Thus, geological storage of CO_2 can contribute considerably to the reduction of CO_2 emission in China and other countries.

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References

Bachu, S., & Adams, J. J. 2003: Sequestration of CO_2 in geological media in response to climate change: capacity of deep saline aquifers to sequester CO_2 in solution. Energy Conversion and Management **44**, 3151–3175.

Bachu, S., Bonijoly, D., Bradshaw, J., Burruss, R., Christensen, N.P. Holloway, S., & Mathiassen, O.M. 2007a: Estimation of CO_2 storage capacity in Geological Media – Phase 2. Work under the auspices of the Carbon Sequestration Leadership Forum (www.cslforum.org). Final report from the task force for review and identification of standards for CO_2 storage capacity estimation, 43 pp. Washington: Carbon Sequestration Leadership Forum.

Bachu, S., Bonijoly, D., Bradshaw, J., Burruss, R., Holloway, S., Christensen, N.P. & Mathiassen, O.M. 2007b: CO_2 storage capacity estimation: methodology and gaps. International Journal of Greenhouse Gas Control **1**, 430–443.

Chadwick, A., Arts, R., Bernstone, C., May, F., Thibeau, S. & Zweigel, P. (eds) 2008: Best practice for the storage of CO_2 in saline aquifers – observations and guidelines from the SACS and CO2STORE projects. British Geological Survey Occasional Publication **14**, 267 pp.

COACH 2009: Project N° 038966: COACH, Cooperation Action within CCS China-EU, Executive Report, 38 pp.

Dahowski, R.T., Li, X., Davidson, C.L., Wei, N., Dooley, J.J. & Gentile, R.H. 2009: A preliminary cost curve assessment of carbon dioxide capture and storage potential in China. Energy Procedia **1**, 2849–2856.

DeLaquil, O., Wenying, C., & Larson, E.D. 2003: Modeling China's energy future. Energy for Sustainable Development **7**, 40–56.

Ennis-King, J. & Paterson, L. 2007: Coupling of geochemical reactions and convective mixing in the long-term geological storage of carbon dioxide. International Journal of Greenhouse Gas Control **1**, 86–93.

IEA (International Energy Agency) 2008: Energy technology perspectives: scenarios and strategies to 2050, 650 pp. Paris, France.

IEA (International Energy Agency) 2009: Technology roadmap. Wind energy, 52 pp. Paris: International Energy Agency.

Koide, H., Tazaki, Y., Noguchi, Y., Nakayama, S., Iijima, M., Ito, K., & Shindo, Y. 1992: Subterranean containment and long term storage of carbon dioxide in unused aquifers and in depleted natural gas reservoirs. Energy Conversion Management **33**, 619–626.

Koide, H., Takahashi, M., Tsukamoto. H. & Shindo, Y. 1995: Self-trapping mechanism of carbon dioxide in aquifer disposal. Energy Conversion Management **36**, 505–508.

Metz, B. *et al.* (eds) 2005: Carbon dioxide capture and storage. IPCC 2005, 431 pp. Cambridge University Press.

Poulsen, N.E., Chen, W., Dai, S., Ding, G., Kirk, K., Li, M., Zeng, R., Vangkilde-Pedersen, T., Vincent, C.J. & Vosgerau, H.J. 2009: D3.3. Improving methodologies for storage capacity assessment and site selection criteria. EU project no. 038966. COACH work package 3 report. EU deliverable D3.3, 45 pp. EU COACH project, Brussels.

Shafeen, A., Croiset, E., Douglas, P.L. & Chatzis, I. 2004: CO_2 sequestration in Ontario, Canada. Part I: storage evaluation of potential reservoirs. Energy Conversion and Management **45**, 2645–2659.

Tanaka, S., Koide, H. & Sasagawa, A. 1994: Possibility of underground CO_2 sequestration in Japan. Energy Conversion and Management **36**, 527–530.

Yu, H., Zhou, G., Fan, W. & Ye, J. 2007: Predicted CO_2 enhanced coalbed methane recovery and CO_2 sequestration in China. International Journal of Coal Geology **71**, 345–357.

Zeng, R., Li M., Dai, S., Zhang, B., Ding, G. & Vincent, C. 2009: Assessment of CO_2 storage potential in the Dagang oilfield, Shengli oilfield and Kailuan coalfield. COACH work package 3 report. EU deliverable D3.1, 45 pp. EU COACH project, Brussels.

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