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Originally published in:

Energy Policy, 89 (2016), pp. 64-73

DOI: 10.1016/j.enpol.2015.10.043

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Abstract

China is very active in the research and development of CO₂ capture and storage technologies (CCS). However, existing estimates for CO₂ storage capacity are very uncertain. This uncertainty is due to limited geological knowledge, a lack of large-scale research on CO₂ injection, and different assessment approaches and parameter settings. Hence storage scenarios represent a method that can be used by policy makers to demonstrate the range of possible storage capacity developments, to help interpret uncertain results and to identify the limitations of existing assessments. In this paper, three storage scenarios are developed for China by evaluating China-wide studies supplemented with more detailed site- and basin-specific assessments. It is estimated that the greatest storage potential can be found in deep saline aquifers. Oil and gas fields may also be used. Coal seams are only included in the highest storage scenario. In total, the scenarios presented demonstrate that China has an effective storage capacity of between 65 and 1,551 Gt of CO₂. Furthermore, the authors emphasise a need for action to harmonise storage capacity assessment approaches due to the uncertainties involved in the capacity assessments analysed in this study.

Highlights:

- China's CO₂ storage capacity varies considerably in existing estimates.
- Assumptions must be transparent to enable all stakeholders to evaluate the results.
- The storage scenarios yield a range between the maximum and minimum storage capacity.
- Storage scenarios S1–S3 for China yield a capacity of 1,551, 402 and 65 Gt of CO₂.

Keywords: CCS, CO₂ storage capacity, China, scenarios, uncertainty

1 Introduction

China is the largest emerging economy in the world with a population of 1.37 billion (National Bureau of Statistics, 2011). It became the world's largest emitter of CO₂ in 2007 (The Netherlands Environmental Assessment Agency, 2007), and this growing trend is set to continue in the years ahead. The major reason for China's considerable CO₂ emissions is the country's strong dependence on coal as its fundamental energy source to fuel economic growth. Carbon dioxide capture and sequestration (CCS), which first appeared in China's 11th Five Year Plan (FYP), is regarded as one of the promising options of clean coal technology (Chen and Xu, 2010; Yuan and Zuo, 2011). It is assumed that China will enhance its endeavour to develop CCS (Liang et al., 2011; Li et al., 2015; Zhang et al., 2013). Several projects related to CCS are being conducted under the National High-Tech Research and Development Program (also called "863 Program") and the National Basic Research Program (also called "973 Program"), mainly controlled by the Ministry of Science and Technology (Lai et al., 2012).

CCS technology consists of different steps, beginning with the capture of carbon dioxide (CO₂) emitted from power plants or industrial sources, using a variety of techniques. The gas is then liquefied and transported to storage formations, where it is finally injected. Storage sites have to be selected carefully to ensure that no CO₂ can leak. Since capture and transportation are the most mature technical steps, the essential link in the chain is to ensure the existence of safe storage sites. In other words, sufficient storage space (amongst other things) must be available to prove the economic feasibility of CCS technology. This crucial point is marred by considerable uncertainties, resulting in a very broad range of storage capacity estimates (Bradshaw et al., 2007). Bachu, 2015; Goodman et al., 2013, 2011; IEA, 2013 and Prelicz et al., 2012 provide a complete overview of recent work on the methodology for estimating CO₂ storage capacity.

The informative value of the estimates yielded depends also on the storage concept underlying the calculations. Bachu et al. (2007) classified storage capacity using the techno-

economic resource-reserve pyramid. The *theoretical* capacity is the upper limit of potential storage space, illustrated by the basement of the pyramid. It is reduced to the usually much lower *effective* capacity by applying efficiency factors resulting in the total pore volume that is effectively usable. The final step is the *practical* capacity, the head of the pyramid, yielded by taking into account the distance and connections between sources and sinks, economic conditions, possible acceptance problems in the regions concerned and technical feasibility problems. It can only be estimated based on real-life projects and demonstration sites (for example, Chen et al., 2009).

The purpose of this paper is the calculation of the effective capacity as this capacity is the basis for further estimation of matched or practical capacity. It is beyond the scope of this paper to address the other aspects. Only a few estimates of China's country-wide storage capacity have been published so far, as analysed below. However, neither a systematic overview of the different assumptions underlying these studies nor variations between these studies have yet been published. Our overall aim is therefore to provide a systematic overview of the potential for the geological sequestration of CO₂ assessed to date for China. Although we do not undertake basic geological research, we provide an overview of existing results by reviewing published studies, and apply the scenario methodology to storage capacities in order to identify the different sources of uncertainty in a transparent manner. Furthermore, in order to ensure that the variation of storage capacity figures is understood, we will provide a systematic overview of the different assumptions and the choice of parameters applied in the capacity estimations. This aims to emphasise the need for a transparent and clear basis in assessing CCS capacity.

2 Methodologies

2.1 Methodologies used to calculate CO₂ storage capacity

An overview of internationally applied methods for calculating CO₂ storage capacity is given by (Goodman et al., 2013, 2011). The methods basically differ depending on whether deep saline aquifers, depleted oil and gas fields or coal seams are considered. In China, storage

capacity in *oil, gas and coal fields* is mainly calculated based on the enhanced recovery potential of fossil resources with CO₂ rather than by available volume. Enhanced oil recovery (EOR), enhanced natural gas recovery (EGR) and enhanced coal bed methane production are considered. Xie et al. (2013) provide an overview of the current status of these technologies in China and the relevant methodologies applied.

Concerning *deep saline aquifers*, no reference to fossil resources can usually be made. Storage capacity assessments should therefore be conducted at a site-specific level to achieve the highest spatial resolution. However, due to a lack of geological data for saline aquifers in many parts of the world, simplifications are applied such as making rough estimates for horizontal and vertical extension or taking the average porosity of aquifers. Rock in deep layers is known to have been modified by diagenesis, meaning that porosity, permeability and pore radius are reduced. However, at depths from 800 to 2,500 m, where the gas is compressed to its supercritical state and where both porosity and permeability values are adequate, the injection of CO₂ is suitable (Vangkilde-Pedersen et al., 2009). Several layers of sealing cap rock must be situated above such a storage formation to provide multiple barriers (Maul et al., 2007).

In the case of aquifer formations, two different trapping mechanisms exist, namely physical and geochemical gas trapping (IPCC 2005). Physical gas trapping, also called *volumetric trapping*, is considered for CO₂ storage in the short term. Once CO₂ has been injected into the reservoir, it accumulates beneath the cap rock in a mobile phase. The geochemical process is based on *solubility trapping*, where CO₂ dissolves in the formation water after the injection pressure is reduced. It occurs considerably later over a matter of centuries (Zhang et al., 2009). It is assumed that injection only stops once the storage site has been completely filled with CO₂. Hence, solubility trapping does not influence the short-term capacity, but is important – alongside chemical reactions between CO₂ and rock minerals – when long-term storage and security are involved.

Existing capacity estimates for China's saline aquifers rely either on volumetric or solubility based trapping (Table 3). We consider *volumetric trapping capacity* as the preferred

methodology since the possible capacity for the decades ahead is the figure required to decide whether CCS may contribute considerably to China's low carbon targets. Nonetheless, from analysed studies on China, it is not proven which trapping mechanism provides higher or lower capacity results (compare section 4.1.1).

Since the *effectively* usable storage potential is of greatest interest for this purpose, we will estimate this figure by applying efficiency factors on the appropriate theoretical volumetric storage potential. The equation used to calculate effective CO₂ storage capacity in saline reservoirs for *volumetric trapping* is based on the total pore volume (Equation 1).

$$m_{CO_2} = V_b * n/g * \phi * \rho_{CO_2} * E \quad (1)$$

where

- m_{CO_2} , effective storage capacity, [m_{CO_2}] = kg;
- V_b , bulk volume of the reservoir, [V_b] = m³;
- n/g = net : gross usable space of a rock, i.e. the proportion of porous and permeable rock to the total bulk volume of the aquifer, [n/g] = 1;
- ϕ , average porosity of the formation, [ϕ] = 1;
- ρ_{CO_2} , density of CO₂, [ρ_{CO_2}] = kg/m³; and
- E , efficiency factor, [E] = per cent.

The estimate of storage *efficiencies* is crucial for the potential calculation, especially for deep saline aquifers. The efficiency parameter E is derived differently for open and closed systems, a classification usually used for boundary conditions of the subsurface (Goodman et al., 2011). By injecting CO₂ in an *open* system reservoir, saline fluids are displaced to other parts of the same or neighbouring formations (Thibeau and Mucha, 2011). Impermeable barriers impede the fluid flow in *closed* systems after the injection of CO₂. Both formation water and CO₂ are kept in the formation by increasing the pressure (Zhou et al., 2008). The cumulative storage capacity of adjacent structures is reduced due to the increase in pressure beyond these structures caused by CO₂ injection (Schäfer et al., 2011).

Goodman et al. (2011) provide an overview of efficiency values published in the past. For open systems, which are considered to be the upper limit for storage estimates, they range between 0.8 and 6 per cent, which is about one order of magnitude higher than the values presented for closed formations (0.35 to 1 per cent). Scott et al. (2013) conclude that most formations are semi-closed, i.e. somewhere between open and closed cases.

2.2 Methodologies developed to provide storage scenarios for China

Due to the considerable uncertainty with regard to potential storage capacity for CCS, it makes sense to develop storage scenarios providing a range of possibilities. Our scenarios are based on three different approaches regarding the storage formations considered.

- *Oil and gas fields:* First, we review country-wide storage capacity estimates. Second, we analyse and discuss site- and basin-specific studies for the five most researched sedimentary basins in order to validate the country-wide studies. This is done by taking the average capacity of each oilfield or depression (where available) and their estimated areal extension to upscale the results to the basin level. Apparent implausible assumptions are not considered. To this end, we compare the upscaled and cumulated site-specific results for each basin to the appropriate regional part in country-wide studies. This validation leads to a “best guess” for each basin which is either the average of the country-wide studies for this specific basin or the upscaled results from site-specific values. Finally, we choose the country-wide study that best fits the “best guess” figures and assume that this assessment is also valid for other parts of China, yielding an estimate of the total storage capacity.
- *Deep saline aquifers:* We had to modify the approach described above for saline aquifers because only one detailed study exists on storage capacity in the chosen formations (Dahowski et al., 2009). We analyse the existing site- and basin-specific studies on aquifers within the five selected basins in order to obtain an overview of the choice of crucial parameters, namely CO₂ density and the efficiency factor. From this overview, we calculate the weighted mean for storage efficiency and CO₂ density by taking the frequency of the results across the studies into account (i.e. if E=2 per cent is used 7 times in different

studies, it effects the derived efficiency 7 times more than a value that it is only used once, compare section 4.1.2). Additionally, we computed the median density and used it in our scenarios as it is more robust against outliers than the mean. The results are then applied to the country-wide study by comparing the CO₂ density derived with the densities applied in this study and using the efficiency factor to calculate an effective capacity based on the theoretical capacity determined.

- *Coal seams:* Little information is available on coal seams for the five selected basins, and the feasibility of this storage formation remains uncertain. Li and Fang (2014) describe the existing technical challenges: reduction of permeability and injectivity after injection, definition of unmineability, security, long-term stability, economic aspects and environmental risks. Furthermore, they describe research on alternatives to CO₂ as injection gas which would not lead to any or only minor mitigation effects but seems more promising than using pure CO₂. In contrary, Fang and Li (2013) recently provided an estimate for Chinese coal seams based on the basin-specific analysis of unmineable coal beds as part of ongoing countrywide CO₂ storage capacity evaluations. For this reason, we select this assessment as the “best guess” to be considered for use in the optimistic storage scenario while we exclude coal seams in the more cautious scenarios.

Based on the wide range of parameter assumptions available, we develop three storage scenarios for effective capacity that vary as follows:

- Oil and gas fields: “best guess” for CO₂ storage in proven oil and gas fields or the inclusion of unproven resources.
- Deep saline aquifers: application of different storage efficiencies for saline aquifers.
- Coal seams: considered only for the most optimistic scenario due to high levels of uncertainty.

3 Overview of existing studies on China’s CO₂ storage potential

3.1 Overview of country-wide studies

Following an intensive literature review, we found three detailed studies that deal with total storage capacity and that provide information about all of the sedimentary basins in China where CO₂ could be stored (Table 1). Another study provides a rough estimate, but does not specify any details.

Table 1 Overview of existing theoretical storage capacity calculations for the whole of China

		Study A Dahowski et al. (2009)	Study B CO2CRC & APEC (2005)	Study C Zhang et al. (2005a, 2005b)		Study D Dooley et al. (2005)
Oil fields		4.8	6.2	3.6 ^{a)}	7.8 ^{b)}	1
Gas fields		5.2	3.5			2
Saline aquifers	Onshore	2,288 ^{e)}	Qualitatively only	16.2	1,435	90 ^{d)}
	Offshore	779	Qualitatively only			9
Coal seams ^{c)}		12	-	12	4	12
Total		3,090	?	32	1,455	106
Methodology		Solubility	Unknown	Volumetric	Solubility	Unknown

All quantities are given in Gt CO₂.

^{a)} Includes oil and gas fields from proven fields

^{b)} Includes oil and gas fields from proven and unproven fields

^{c)} Current estimate provides a capacity of 9.9 Gt CO₂ in coal seams (Fang and Li, 2013)

^{d)} Estimates for onshore saline aquifers are updated to 250–300 Gt CO₂ by Dooley (2013)

^{e)} The same research group updated the result for onshore aquifers by using the *volumetric* capacity evaluation methodology (Wei et al., 2013) and came to a similar capacity as in the case of the solubility approach. 1,077 Gt of CO₂ of the total capacity is thought to be “highly suitable” or “very highly suitable”.

Study A

Dahowski et al. (2009) provide quantitative theoretical values for storage capacities in *aquifers* based on *solubility trapping* (but incorporate also volumetric parameters like CO₂ density, basin-wide porosity and net sand thickness values). The authors assume that the entire saline aquifer water can be used to dissolve CO₂. As a simplification, equilibrium of dissolved CO₂ with 100 per cent residual water saturation is expected to be achieved after the end of the injection period, meaning that no free-phase CO₂ will remain in the formation. A specific storage density of 28 kg CO₂/m³ of pore volume is calculated, leading to a total theoretical storage capacity of 3,067 Gt of CO₂ spread over 25 formations, roughly three quarters of which are onshore (2,288 Gt of CO₂).

The same research group updated these results for onshore aquifers by using the *volumetric capacity evaluation* methodology (Wei et al., 2013). The resulting theoretical capacity is similar to that gained by the solubility approach, although slightly different geological data was used. Additionally, a site suitability evaluation for *onshore aquifers* is provided based on injection strategy, risks and security, environmental restrictions and economic considerations. 1,077 Gt of CO₂ of the theoretical onshore storage capacity is thought to be “highly” or “very highly” suitable.

The calculation of capacity in *gas fields* is based on the original “gas in place” resource and a sweep efficiency of 75 per cent. Only fields that can hold more than 2 Mt of CO₂ are included in the calculation. In total, 17 gas fields offer a capacity of 5.2 Gt of CO₂, one fifth of which is offshore. The authors also provide estimates for capacity in *oil fields*, coupled with CO₂ flooding for EOR. A total of 7,020 million barrels of additional oil recovered using CO₂ is estimated for China, yielding a storage potential of 4.8 Gt of CO₂ in oil fields with a CO₂ capacity of more than 2 Mt. Most of this capacity is available onshore. A similar approach is used for *coalbeds*, where the potential to enhance coalbed methane production is estimated first. By assuming 10 per cent coalbed methane extraction per field, a capacity of roughly 12 Gt of CO₂ is identified in 45 potential coal fields with a CO₂ storage capacity of more than 2 Mt.

Summarising all formations, a total capacity of 3,089 Gt of CO₂ is derived.

Study B

CO2CRC and APEC (2005) classify China’s sedimentary basins only qualitatively by considering high, intermediate or low prospectivity concerning CO₂ storage in *saline aquifers*. The focus is on the most developed and emission-rich Eastern part of the country (Figure 1). Most of the evaluated basins consist of delta sandstones from lakes or rivers. The sediment layers are heterogeneous, but are sealed by continuous mudstone layers as sufficient cap rock. Bohai basin, Songliao basin and Subei basin in north-east China have the highest prospectivity for storing CO₂. Songliao is ranked first. Offshore basins in south-east China

and close to Wuhan have intermediate or unresolved prospectivity. Other central Chinese basins such as Ordos, Sichuan and Nanpanjiang basins are assigned lower prospectivity. These basins consist of complex polycyclic basins that are strongly faulted. Moreover, their permeability and porosity values are poor. However, Ordos basin has the best prospectivity for storing CO₂ in *coal seams*. Most of the information about these basins originates from drilling for oil and gas exploration. It was therefore possible to calculate the storage capacity in *oil* and *gas fields*, which is given as 6.2 Gt and 3.5 Gt, respectively.

Figure 1: CO₂ sources and geological sinks in eastern China (CO2CRC and APEC, 2005)

Study C

China Geological Survey also investigated storage capacities (Zhang et al., 2005a, 2005b). Two methods are used to calculate storage capacity in *saline aquifers*. First, the *solubility*

method is used. Based on a basin area of 2.7 million km², this method yields a total capacity of 14,350 Gt of CO₂ for all basins. Assuming that saline aquifers make up 10 per cent of the total basin area, a capacity of 1,435 Gt of CO₂ is yielded, which is roughly half of that determined by study A, despite taking a similar approach. A total of 24 suitable aquifers are identified, located in four different regions of China: the Eastern Plain, the Yangtze Delta, the north-west arid inland basin and Sichuan basin. Second, a *volumetric method* is used. The average thickness is assumed to be 100 m and a porosity of 20 per cent is chosen (Hendriks et al., 2004), leading to a capacity of only 16.2 Gt of CO₂.

The capacity in 46 suitable *oil fields* is calculated by estimating China's oil reserves and additional recovery from EOR operations using CO₂. Capacities in *gas fields* are estimated to be much lower. In total, a capacity of 7.8 Gt of CO₂ in oil and gas fields is yielded with a proven capacity of 3.65 Gt of CO₂. In both cases, the highest capacities are available in Songliao basin, Jiyang depression (Bohai basin) and Ordos basin. Furthermore, the authors assume a total of 68 major promising *coalbeds* for CO₂ storage combined with the production of coalbed methane, categorised into ten different coal ranks. This yields a capacity of 12 Gt of CO₂ storage capacity.

Summarising all formations, a total capacity of 1,455 Gt of CO₂ is estimated if the solubility method for aquifers is applied and both proven and unproven oil and gas fields are included. If the volumetric method is used for aquifers and only proven oil and gas fields are considered, a much lower total capacity of 32 Gt is yielded.

Study D

In addition to these detailed reports, a fourth study by Dooley et al. (2005) is included for comparison, although it is only a very rough estimate that lacks any specific characteristics for China. It results in a storage capacity of 106 Gt, whereby onshore aquifers offer the greatest capacity. In an updated version, a storage capacity for China's saline aquifers can be derived from a figure resulting in 250 to 300 Gt of CO₂ (Dooley, 2013).

Summary

The four studies evaluate the CO₂ storage capacity at a theoretical level, which must therefore be classified as *theoretical capacity* on the techno-economic resource-reserve pyramid. While theoretical capacities in oil and gas fields are more or less in the same range (3–10 Gt), saline aquifer capacities vary between 16 and 3,068 Gt of CO₂. The results for coal seams range between 4 and 12 Gt.

Effective capacities cannot be derived directly from theoretical capacities because none of the relevant parameters used in equation (1) are given. For this reason, site- and basin-specific assessment studies are explored below to derive efficiency parameters that may be applied at the national level.

3.2 Overview of site-specific studies

Several research projects, such as CAGS (Jiang and Xu, 2010; Zhang, 2010), NZEC (Li et al., 2009a, 2009b; Li and Yang, 2010), COACH (Vincent et al., 2011; Zeng, 2009) and GeoCapacity (Chen et al., 2009), involved conducting site- and basin-specific investigations in China. Additional investigations have recently been undertaken by Chinese and Sino-US research groups (Jiao et al., 2011; Qiao et al., 2012; Su et al., 2013; Wei et al., 2013; Zhou et al., 2011).

These studies, which provide a much higher geographical resolution in their results, mainly consider five basins (Figure 1). The formations analysed are situated in the north-eastern part of China at the Bohai, Songliao and Subei basins, which are the three highly prospective basins according to CO₂CRC and APEC (2005). The authors also conducted assessments of Ordos basin and the Pearl River Mouth basin. These two basins were evaluated as having intermediate (Pearl River Mouth basin) and low prospectivity (Ordos basin). Since these five basins are those that have been studied most intensively, we select them for further analysis.

Bohai basin is situated in north-east China, mainly in Shandong Province and the Jing-Jin-Ji region, which includes the three provinces of *Beijing*, *Tianjin* and *Hebei (Ji)*. Much of the basin is off the coast in the Bohai Sea. Smaller parts are located in the region of Liaoning

and Henan provinces. Bohai basin is divided into several depressions. The Dagang oil field complex is located within the Huanghua depression. The Shengli oil field is located in the Jiyang depression. *Songliao basin* comprises the three north-easternmost provinces Jilin, Inner Mongolia and Heilongjiang. Jilin oil field complex is in Jilin Province; Daqing oil fields are located in Heilongjiang. *Ordos basin* covers Shaanxi, Shanxi and Gansu provinces, as well as the autonomous regions of Ningxia Hui and Inner Mongolia. *Subei* and *Pearl River Mouth basin* are two smaller basins. The *Subei basin* covers Jiangsu Province, as well as offshore areas (East China Sea). It includes the lower Yancheng and upper Sanduo formations with two depressions: Yanfu and Dongtai. The *Pearl River Mouth basin* is situated offshore from Guangdong in south-east China.

4 Results

4.1 Validation of CO₂ storage capacity in deep saline aquifers

4.1.1 Selection of the most suitable country-wide study

Table 2 provides an overview of storage capacity in deep saline aquifers in the selected five basins as given in the country-wide studies. Since there is no clear indication of the methodology used in Dooley et al. (2005), making it difficult to compare it with other studies, we exclude this study from the comparison. CO2CRC and APEC (2005) classify the aquifers qualitatively, meaning that no quantities are reported. The remaining studies yield very different figures, which is due in part to their use of different methodologies. However, different capacities are even yielded when a similar methodology (solubility) is used. Since Zhang et al. (2005b) provide insufficient background to their calculation and the solubility trapping capacity approach of Dahowski et al. (2009) virtually resembles the volumetric trapping capacity generated by the same research group (Wei et al., 2013), we select Dahowski et al. (2009) as the most detailed country-wide study. Additionally, this selected study incorporates important parameters from the volumetric approach (compare equation 1).

Table 2 Storage capacity of different formations in the five most researched sedimentary basins in China, selected from country-wide studies

Basin	Site	Prospectivity	Deep saline aquifers			Oil fields				Gas fields		CBM ^{b)} based
		CO2CRC and APEC (2005)	Zhang et al. (2005b)	Dahowski et al. (2009)		Zhang et al. (2005b) ^{a)}	Dahowski et al. (2009)	CO2CRC and APEC (2005)		Dahowski et al. (2009)	CO2CRC and APEC (2005)	Dahowski et al. (2009)
			Volumetric	Solubility	Solubility	Proven		Fields > 2 Mt CO ₂		Fields > 2 Mt CO ₂		
Bohai	Onshore	High	0.4	1,715	233	1.4	1.3	1.9	3.2	0.3	1.3	-
Songliao	Onshore	High	0.3	444	228	1.9	1.3	1.6	2.0	0.6	0.1	-
Subei	Onshore	High	0.9	73	90	0.3	0.1	0.1	-	0.0	-	-
Pearl River Mouth	Offshore	Intermediate	0.2	2,371	69	0.3	0.1	0.0	-	0.0	-	-
Ordos	Onshore	Low	0.4	733	257	0.7	0.4	0.4	0.1	1.1	0.4	4.5

All quantities are given in Gt CO₂

^{a)} Includes oil and gas fields

^{b)} CBM = coal bed methane

4.1.2 Selection of storage parameters for saline aquifers in China

A variety of studies is analysed for five Chinese sedimentary basins (Table 3) and compared with country-wide assessments, resulting in four key findings:

First, the studies argue that *geological constraints* could reduce the capacity considerably or would increase operating costs. This depends on the thickness of the sand layers at potential storage sites and the low permeabilities identified in promising formations (e.g. Ordos Basin). Additionally, if the aquifer is assumed to be a closed system, the efficiency selected should be at the low end of the percentage scale (0.16 to 2 per cent) in contrast to open systems with higher values (compare Table 3). However, this differentiation between open and closed systems is not made in most studies. According to the current state of knowledge, geological constraints do not exclude formations from an overall assessment per se, but increase the uncertainty of storage capacity evaluations.

Second, the studies calculate storage capacity using *different methodologies* (solubility or volumetric approach). However, it is not clear which approach yields higher or lower results (e.g. in Songliao and Pearl River Mouth basins). The huge variations between results are linked to different assumptions being made for storage efficiency and CO₂ density, as described below.

Third, very different findings can be extracted from the studies when identifying the range of *storage efficiency* recommendations. Studies on Bohai basin recommend applying low efficiency values to prevent the operator from having to conduct active pressure control by pumping out saline water. Although this may not be the case in all basins, there is a risk of such a need occurring without more in-depth knowledge of the geology. Similar values are given for Subei basin. In contrast, the basin-specific study for the Pearl River Mouth basin yields higher effective capacity values than the theoretical capacity generated by Dahowski et al. (2009) for this basin. Their theoretical capacity may therefore have underestimated capacity, and if low efficiency values were applied, this difference would become even

greater, showing the considerable uncertainties in these calculations. The studies analysed for Ordos basin demonstrate that efficiency should be below 30 per cent.

Table 3 Overview of different parameters and methodologies used to calculate CO₂ storage capacities in saline aquifers in Bohai, Songliao, Subei, Pearl River Mouth and Ordos Basins of China (in alphabetical order)

Author	Efficiency E %	CO ₂ density kg/m ³	Geological constraints		Extension			Methodology	
			Open	Closed	National	Basin	Site	Volumetric	Solubility
Chen et al. (2009)	0.16	670		x		x		x	
	3		x					x	
Jiang and Xu (2010)	1 to 4						x	Numerical model	
Jiao et al. (2011)	10–60	650					x	x	
Li et al. (2009b)	10	600					x	x	
Li et al. (2009a)	1							x	
	2	700				x		x	
	10							x	
Li and Yang (2010)	20								
	40						x		
	60								
Qiao et al. (2012)	1		x						x
	2.4	606	x			x			x
	4		x						x
Su et al. (2013)	0.51	407							x
	2	517							x
	5.5	562				x			x
		624							x
		653							x
Vincent et al. (2011)	2	650					x	x	
Wei et al. (2013)	2,7				x			x	
Zeng (2009)	2	700		x				x	
	20		x				x	x	
Zhang (2010)		560					x	Numerical model	
Zhou et al. (2011)	1							x	
	2.4	300–600				x		x	
	4							x	
Weighted mean	13	587^a							

^a Median CO₂ density = 606 kg/m³

Where information is missing, the field is left blank.

Fourth, the CO₂ density is an important factor in deriving the effective capacity in addition to the efficiency factor. Although it varies between 300 and 700 kg/m³ in the studies analysed, it varies less than the efficiency factor. While the figure averages at 588 kg/m³, its median is 606 kg/m³.

We conclude from the key findings that the efficiency values are the most important aspect when calculating effective storage capacities. However, it is not clear which level of efficiency should be applied. The analysis of 13 studies with 32 efficiency values (n=32) reveals a range from 0.16 to 60 per cent (see table 3). A frequency distribution is used to determine which efficiency values were used most frequently by grouping them into five classes (compare figure 2):

- 2.4 per cent is binned as 2 per cent;
- 2.7 per cent is binned as 3 per cent;
- 0.51 per cent is binned as 1 per cent,
- 1 to 4 per cent are binned separately as 1, 2, 3 and 4 per cent;
- 10 to 60 per cent are binned separately as 10, 20, 30, 40, 50 and 60 per cent.

Figure 2: Frequency distribution of efficiency factors for deep saline aquifers applied in storage capacity studies for China

Three efficiency ranges can be identified. It should be noted that we use the cut off points and the efficiency ranges for descriptive reasons only; they do not lead to elaborated statistical assessment. The binning of factors into ranges is used to show upper and lower limits of available efficiency factors from literature. These limits are fed into the storage scenario estimation from S3 to S1. The only derived statistical value is the probability: how often does one given efficiency fit into the three specific groups. The more values can be assigned to one group, the higher the probability that the weighted mean efficiency is suitable.

The first range consists of efficiencies from 0.16 to less than 10 per cent, with a weighted mean of 2 per cent. The probability for this group is highest with 62.5 per cent of all efficiencies. As Figure 2 illustrates, efficiencies of 1 and 2 per cent were applied most frequently. *The remaining efficiencies lie in the range of 10 to 60%. We split them in two groups:*

The second range includes values from 10 to 35 per cent, with a weighted mean of 17 per cent. 21.9 per cent of the analysed efficiencies are in this second range.

The third range integrates efficiencies from more than 35 to 60 per cent, with a weighted mean of 50 per cent. The probability of this third range is lowest with only 15.6 per cent of all efficiencies.

The weighted mean of all efficiency values is 13 per cent. Since it is assumed that the existing specific studies focus on the most promising and relevant parts of the basins, the efficiencies 2, 13 and 50 per cent are later used to develop storage scenarios for the whole of China.

4.2 Validation of CO₂ storage capacity in oil fields

Studies are not only analysed for aquifers, but also for oil fields. The capacity given in the country-wide studies ranges from 0.04 (Pearl River Mouth basin) to 3.19 Gt of CO₂ (Bohai basin) (Table 2). This range is much smaller than in the case of saline aquifers. Based on the regional studies, for each basin a “best guess” is derived:

- For Bohai the best guess of 2.0 Gt is derived using the mean estimate of the regional studies (compare Table 2).
- For Songliao it is based on the biggest oil field of Daqing with a capacity of 0.5 to 0.7 Gt (Li et al., 2008). Since this field provides about half of oil reserves in this basin, the figure is doubled, yielding a range of 1.0 to 1.4 Gt.
- The result for Subei basin is based on Pearce et al. (2010), who estimate a capacity of 20 to 40 Mt of CO₂ based on 70 per cent of estimations of oil in place. If this is upscaled to 100 per cent, a capacity of roughly 30 to 60 Mt of CO₂ is achieved.
- Regarding the Pearl River Mouth basin, Zhou et al. (2011a) suggest a storage capacity of 60 Mt of CO₂ based on proven oil reserves.
- The oil fields in Ordos basin have not yet been studied in detail.

Using the “best guess” figures, it is possible to validate the general results of site- and basin-specific assessments in four of the five selected basins (Table 4). For example, the “best guess” for Bohai basin was derived best by Dahowski et al. (2009). Ordos basin cannot be compared due to a lack of suitable studies.

In summary, the proven capacities analysed by Zhang et al. (2005b) yield the best estimate in three of the four cases where a detailed storage assessment was available. Thus it is assumed that this assessment is also the most valid one for all of China’s oil fields.

Table 4 Best approach when matching storage capacity assessments from country-wide studies with the “best guess” for individual formations

Name of basin	“Best guess” [in Gt]	Best approach		
		Zhang et al. (2005b)	Dahowski et al. (2009)	CO2CRC and APEC (2005)
Bohai	2.0	---	X	---
Songliao	1.0–1.4	X	---	---
Subei	0.03–0.06	X	---	---
Pearl River Mouth	0.06	X	X	---
Ordos	---	No basin- or site-specific assessments exist for oil fields		
X = study fits best to the “best guess”				

4.3 Validation of CO₂ storage capacity in natural gas fields

The storage capacity in natural gas fields is lower than that in aquifers and oil fields in the five selected basins (Table 2). Since China does not have very large gas reserves and CO₂-based EGR has not yet been applied, detailed investigations into the storage of CO₂ have yet to be conducted (Xie et al., 2013). The highest capacities are estimated to be 1.3 Gt of CO₂ by CO₂CRC and APEC (2005) for Bohai basin and 1.1 Gt of CO₂ for Ordos basin (Dahowski et al., 2009). Songliao basin offers a lower capacity; Subei basin and the Pearl River Mouth basin have no substantial gas reservoirs. Zhang et al. (2005b), which is assumed to be the best fit for oil fields, made no differentiation between oil and gas fields in their study. Thus the potential of gas fields is already included and is considered to be of minor importance only. Since this study was selected for oil fields in the storage scenarios, no additional estimate for gas fields is required.

4.4 Validation of CO₂ storage capacity in coal seams

Based on the study by Dahowski et al. (2009), of the five basins selected only Ordos basin provides storage capacity in coal seams. This capacity, related to coalbed methane production, amounts to 4.45 Gt of CO₂. Dahowski et al. (2009) assume that Bohai basin provides no capacity for coalfield sequestration; other studies investigate the capacity in Keiluan field in Hebei Province. Zheng et al. (2009) yield a capacity of 0.7 Gt of CO₂. Vincent et al. (2011) assume a capacity of 0.5 Gt of CO₂ in Keiluan mining areas, although it is an active coal mine with low permeability and porosity. Hence it can be assumed that Dahowski et al. (2009) did not include all seams in their analysis and underestimated the potential. Care must be taken not to contaminate the coal reserves with CO₂. Zhang et al. (2005a) estimate a capacity of 12 Gt of CO₂ for China, but do not define the basins where suitable coalfields can be found. The most recent results report a storage capacity of 9.9 Gt in China (Fang and Li, 2013), which may be considered the most detailed assessment to date because, despite the uncertainties involved, it is based on calculations for each basin.

4.5 Development of storage scenarios

Based on our previously conducted capacity assessment, an intermediate storage scenario (S2) is first developed, including the most suitable results described above. In order to consider the variety of assumptions determined and the range of uncertainties, one low (S3) and one high (S1) storage scenario is additionally provided (Table 5).

Table 5 Scenarios of effective CO₂ storage capacity in China

Formation	Location	Effective storage capacity			Based on
		S1: high	S2: intermediate	S3: low	
Oil and gas fields	Onshore and offshore	7.8	3.6	3.6	Zhang et al. (2005b), Dahowski et al. (2009)
Saline aquifers	Onshore	1,144	297	45.8	
	Offshore	389	101	15.6	Fang and Li (2013)
Coal seams	Onshore	9.9	-	-	
Total		1,551	402	65	

All quantities are given in Gt CO₂.

For aquifers, efficiency factors of 50 % (S1), 13 % (S2) and 2 % (S3) are applied.

The *intermediate scenario* S2 includes 3.6 Gt proven capacity for oil and gas fields assumed by Zhang et al. (2005b). For saline aquifers, the scenario is based on the average efficiency (13 per cent as weighted mean) and density figures (606 kg/m³ as median of selected CO₂ densities), generated in the previous analysis and applied on the theoretical storage capacity given by Dahowski et al. (2009). In this and the following scenarios, we make no differentiation between onshore and offshore basins since similar efficiency factors are applied both onshore and offshore in the literature under review. This yields a capacity of 398 Gt of CO₂ for saline aquifers. Coal seams are excluded in this scenario due to the uncertainties described in section 2.2 (Xie et al., 2013; Li and Fang, 2014). The total effective capacity amounts to 402 Gt of CO₂.

The *low storage scenario* (S3) includes the same proven capacity for oil and gas fields as used in the intermediate case because it is already at the lower end of the range available and provides basin-specific capacities. The effective capacity estimate for aquifers is derived by applying 2 per cent efficiency as the lowest mean. This yields a capacity of 61.4 Gt. The

potential capacity in coal seams is deemed to be too uncertain, and is therefore excluded from this scenario, too. In total, we derive an effective capacity of 65 Gt of CO₂.

The *high estimate (S1)* yields a total effective storage capacity of 1,551 Gt of CO₂. It includes the aquifer storage capacity by applying a 50 per cent efficiency as the highest mean, resulting in a capacity of 1,533 Gt. For oil and gas fields, unproven fields are considered in addition and the higher estimate by Zhang et al. (2005b), yielding 7.8 Gt of CO₂, is selected. 9.9 Gt storage in coal seams (Fang and Li, 2013) is included due to the optimistic approach of this scenario.

5 Discussion

In China, CCS has been discussed intensively, mainly by focusing on the concept to combine separation with the use of CO₂ (CCUS) for enhanced recovery of geological resources such as oil or gas. However, it must be specified whether the intention is to mitigate CO₂ or to recover additional resources. If CCS is undertaken for the purpose of CO₂ mitigation, a very important aspect for assessing this technology is having knowledge of adequate storage capacity (Dooley, 2011). This is especially crucial for policy makers in China. There are large uncertainties surrounding the existing country-wide estimates for available theoretical CO₂ storage capacity, which range widely from 32 to 3,090 Gt of CO₂. The upper values based on maximum assumptions even exceed the global capacity for aquifers of 1,000 Gt estimated by IPCC (2005). Hence, more detailed theoretical calculations are needed which may be achieved by applying a country-specific methodology due to China's unique geology. Furthermore, to our knowledge, no efficiency value has yet been derived to estimate an effective capacity on the national level. In particular, from our point of view, all considered studies should be thoroughly scrutinised and reviewed involving the authors and a board of international storage experts.

In order to cope with the prevailing uncertainties we recommend the use of storage scenarios in the first approximation as long as no more detailed storage capacity assessments are available. We developed three storage scenarios to provide a possible range of effective

storage capacity. The major contribution to efficient storage capacity is provided by deep saline aquifers, where we specially derived a China-specific efficiency factor based on an extensive literature review. It has to be pointed out that the derivation of parameters for country-wide storage calculation by looking at site- and basin-specific geological circumstances is a simplification. Nonetheless the weighty mean ensures at least a strong indication towards applicable parameters. Our intermediate scenario S2 uses an efficiency factor of 13 per cent. The lower and higher scenarios S3 and S1 were calculated using an efficiency factor of 2 and 50 per cent, respectively, for both onshore and offshore aquifers. These efficiencies are in a similar range as the capacity reduction figures applied by Dahowski et al. (2009) in a sensitivity analysis to their theoretical storage capacity (1, 10, and 50 per cent reduction, respectively). The proportion of oil and gas fields and coal seams is small in comparison to the prevailing large aquifers.

When considering the intermediate case, the effective storage capacity for China is estimated at 402 Gt of CO₂. Comparing this assessed storage capacity roughly with China's CO₂ emissions of approximately 10 Gt/yr in 2012 (JRC and PBL, 2013), CCS could be a viable long-term CO₂ mitigation technology. This will apply to an even greater extent if the highest capacity proves to be available. If, however, the lowest and cautious case (efficiency of 2 per cent) is more accurate, the derived capacity of 65 Gt will only last less than a decade. To our knowledge, only Wei et al. (2013) recommended such a low efficiency factor (2.7 per cent) for the national level. If low efficiency factors – which are used in about two third of all analysed studies (compare figure 2) – are confirmed in future research, it is debatable whether Chinese policy-makers should implement this technology as a major mitigation strategy for the power and industrial sector, considering its temporary nature. Instead, the discussion on how to manage the limited storage space properly and sustainably needs to be addressed, as CO₂ from industrial processes or biomass combustion would also need storage sites in the future. In contrast to the electricity sector, where known and feasible low-carbon alternatives exist (especially renewable energies), mitigation of process-

related industrial emissions provides less obvious alternatives. Biomass CCS could lead to net-negative emissions in the future (Ricci and Selosse, 2013).

6 Conclusion and policy implications

Due to the considerable uncertainties surrounding the capacity assessments, it is difficult for industry and policy-makers to decide how to proceed with this technology. Whilst conducting our analysis, we were surprised about the wide range of assumptions and parameter settings we found in the studies considered. Furthermore, the calculation methods applied and the method of selecting parameters are not always very transparent, which makes assessment difficult. However, it was out of the scope of this work to get to the bottom of the considered studies and to verify and improve each assumption, method and parameter involving the authors of the studies. Such uncertainties, which are not only restricted to China (Viebahn et al., 2012), reveal a need for action to harmonise storage capacity assessment approaches. Following the American example of providing “Quality Guidelines for Energy System Studies” (NETL, 2014), storage capacity assessment guidelines should be drawn up and used in all investigations. The International Energy Agency (IEA) tracks similar goals and has already started a process that could pave the way for the development of plausible and internationally consistent capacity assessment methods (IEA, 2013). Chinese research groups have recently been conducting a site- and basin-specific geological analysis for China in order to improve data availability and geological knowledge. The ongoing countrywide CO₂ storage capacity evaluations initiated by the Chinese Ministry of Land and Resources (Fang and Li, 2013) may create a more detailed and profound result for the whole of China in the future. These new findings for China should be harmonised with international guidelines and assessment methods to provide stronger consistence on global storage capacity assessments for underground storage of CO₂. Concluding, it is very difficult and merely impossible for decision-makers to come up with a profound and reliable decision, taking the current level of uncertainty into account. The provided storage scenarios illustrate the

difficulties in storage capacity assessment and may encourage decision-makers to strongly improve the data basis in the future.

Acknowledgements

This paper is based on the CCS Global research project, financially supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety. The results were updated for this article. We would like to thank Teresa Gehrs (LinguaConnect) for proof-reading the manuscript and the anonymous reviewers for their valuable comments and suggestions.

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