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The scientific case for large CO_2 storage projects worldwide: Where they should go, what they should look like, and how much they should cost

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Abstract

To achieve substantial GHG reductions through carbon capture and storage (CCS) requires 100's to 1000's of large volume injection facilities distributed globally with very low rates and volumes of leakage. Several large-scale projects exist (Weyburn, Sleipner, In-Salah) and each has revealed an important aspect of the geology that was not previously known. This reaffirms the notion that key geological thresholds in the earth's crust are sensitive to the magnitude and rate of excursions, (e.g., pressure build-up, pH). Because commercial-scale CCS will reach these thresholds, a suite of large-scale projects is needed to investigate the conditions for successful deployment. These projects must cover a range of geological and geographic settings and key plays. Moreover, they must be supported by a sufficiently large science and technology program to understand the key features, events, and processes in each case to address stakeholder concerns and develop operational guidelines for large-scale deployment.

Keywords: CO2, carbon storage, carbon sequestration, CCS, demonstration projects

Introduction

Carbon capture and storage (CCS) has emerged as a key technology pathway to substantially reduce greenhouse gas emissions while continuing to exploit the value of conventional fossil fuels. This will require the deployment of very large injection projects [1]. Such projects are likely to be of the order of today's three large projects (Sleipner, Weyburn, In Salah) or even substantially larger, requiring 100's to 1000's of large volume injection facilities. These will be distributed globally in a variety of geological and geographic settings. However, substantial uncertainties remain about the potential performance and risk associated with deployment at this scale. Similarly, uncertainties remain about what kinds of monitoring or mitigation protocols are reasonable or even of value to maintaining long-term performance and public acceptance.

The initiation and study of very large demonstration projects provides a swift, confident pathway to addressing these uncertainties and providing operational clarity to future projects [2]. It is not clear how many of these projects are needed to satisfy key stakeholder concerns or provide scientific answers to key questions. This paper argues that roughly 10 projects would suffice, provided that they provided enough richness in geology, geography, play type, and operational condition and are accompanied by substantial, sustained research programs. The cost of this kind of program is likely to be on the order of $3-5 billion over the next decade; however, the information would advise many trillions of dollars in energy infrastructure investment.

The importance of large projects

To achieve substantial GHG reductions through CCS requires 100's to 1000's of large volume injection facilities distributed globally with very low rates and volumes of leakage. Many such projects are planned, and several large-scale projects exist (Weyburn, Sleipner, In-Salah). Each has provided some demonstration of effectiveness, of monitoring technologies, and operational economics. Importantly, each large project also has revealed an important aspect of the geology that was not previously known, and in some cases incorrectly characterized. For example, at Sleipner,

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the importance of small flow heterogeneities was not anticipated but clearly seen [3]. At Weyburn, it appears that CO_2 migrated in unexpected ways along secondary fractures [4].

Such features would not have been revealed through a small (<100,000 ton CO_2/y) experiment. This is because geological thresholds in the earth's crust are sensitive to the magnitude and rate of excursions, (e.g., pressure build-up, pH). Unless those thresholds are reached, no effect occurs [e.g.,5]. Because the earth's crust is a complex, heterogeneous, non-linear system, field-based demonstrations are required to understand the likely range of crustal responses, including those that might allow CO_2 to escape from reservoirs. In addition, many important effects (e.g., corrosion, induced seismicity, mechanical failure of wells and cap-rocks) can only be understood in the context of large demonstrations and large experiments. Despite a substantial scientific effort at Weyburn and Sleipner, many parameters which could have been measured to circumscribe the most compelling scientific questions have not yet been collected. These include distribution of CO_2 saturation, stress changes, and well-bore leakage detection.

Substantial GHG abatement requires a geographically diverse portfolio of large injections. Importantly, the three largest demonstrations are distinct from a geological perspective and do cover a wide range of geological conditions. This helps to demonstrate that this technology may have broad application. However, key plays have not been tested yet at scale (e.g., Cenozoic basins of eastern China; Himalayan foreland; US Gulf Coast). In each active demonstration project to date, current measurement, monitoring, and verification (MMV) technology are not formally integrated and may not be sufficient to document either injection volumes or leakage risk and activity within the full necessary range of important geological or surface geographic conditions [2].

For this reason, it is helpful to define the necessary scale, scope, and cost of a portfolio of large projects. This paper attempts to do so strictly to provide a platform for discussion. The specific projects proposed should be viewed not as hard targets for immediate deployment, but rather as examples of the kinds of projects in the kinds of locations that would provide scientific and technical clarity to decision makers and investors in future commercial CCS projects.

Description of large projects: Scale and scope of work

To resolve key concerns, multiple large-volume, high-rate injection projects must proceed rapidly in order to serve two critical goals. The first is to demonstrate successful injection over a range of conditions, thereby testing "plays" for carbon storage. Towards this end, successful site characterization is absolutely critical [6]. Poor site selection that leads to technical failure or substantial leakage or negative effects would substantially reduce support for CCS amongst all stakeholders. The second is to develop and validate key science and technology to expedite the deployment of storage and improve the confidence of leakage monitoring and overall safety. Projects should assess pre-drill and post-injection the residual phase trapping, the detection threshold for leakage, the statistical, likelihood of well failure, and the maximum rate of CO_2 migration from the site through leakage pathways. In order meet these goals, a parallel science program is required. It should include substantial efforts at simulation of key processes and CO_2 fate, of monitoring, mitigation, and verification (MMV), and analysis and integration of results. These points are noted in Figure 1.

Draft budget for large projects

The following assumptions were used to estimate the likely costs of a large-scale experiment:

1. No CO_2 capture is needed: the available experimental source is a pure supply and sold at prices comparable to CO_2-EOR commodity prices.
2. Annual injection volumes would range from 500,000 to 1 million tons CO_2

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3. Projects would run 8 years, with two years of scoping and preparation, five years of injection and 1 year post-injection
4. There is no consideration of capital depreciation or discount rate

As such, this estimation is crude but attempts to be accurate. With this basis, Figure 1 lays out the range of estimated costs for various stages of a broad experimental program at between $107-255M each, with annual costs from $13-28M. These cost estimates are consistent with the incremental costs of the Sleipner program ($152 million in 1996 dollars) and Weyburn project ($48 M) [7]. The costs of well and monitoring are higher for the Sleipner case; these costs did not include a broad monitoring suite, extensive science program, or post-injection validation which represents $28M of Weyburn's costs.

Figure 1: Estimated costs of a large-scale CO_2 injection experiment

Program element	**Est. Cost ($M)**
Detailed pre-drill geological assessment	$ 2 - 4
Wells: injection (1-2) and monitoring (3-8)	$ 3 - 8
CO_2 (5 years injection)	$1.5 – 10 / yr
Compression (5 years)	$ 3 – 6 / yr
Monitoring and integration/inversion (5 years)	$ 2.2 – 6.4 /yr
Analysis and simulation	$ 5 - 7
Post injection sampling and recompletion	$ 3 - 8
Total Sum	**$107 - 255**
Average Annual Sum	**$ 13 - 28**

A Draft Portfolio of Large Projects for the World

In considering large CO_2 storage experiments, the first concerns must be injectivity, capacity, and effectiveness. In planning a set of experiments for a country or the world, the next consideration must be to accurately reflect the richness of geological settings for global deployment. In a global commercial context, the variance should include the following aspects:

- Critical plays defined by density of coal-fired power generation and other large point sources.
- A range of reservoir character (homogeneous and heterogeneous, siliciclastic and carbonate, high- and low-injectivity)
- A range of physical seals (mudstones, evaporites)
- A range of potential leakage mechanisms (faults, wells)

Thankfully, it is not necessary to test the entire matrix of possible parameters suggested by this list. The most important and representative cases can be represented by a handful of geological settings, and the number of critical plays is not enormous even on a global basis (Figure 2).

This table represents some portion of a multi-dimensional matrix that represents a subset of geological conditions and risk elements; six are represented here. The wide range of depositional types, reservoir classes and dispositions, permeability, cap-rock type, and well density are not correlated, such that much of the matrix is populated. More importantly, these conditions fairly represent the overwhelming majority of storage elements and opportunities world-wide, and as such would represent industrial-scale global storage variance well.

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Figure 2: Table of sites and key parameters

Site	Location	Reservoir class	Reservoir type	Permeability	Seal type	Well density
Sleipner	Norway	Offshore Saline Fm.	Deep-water Sandstone	V. high	Thick shale	Low
Weyburn	Canada	Onshore EOR	Ramp Carbonate	Moderate	Evaporate	V. high
In Salah	Algeria	Onshore Sandstone	Fluvial/tidal Sandstone	Low	Thick shale	Low
Illinois	US	Onshore Saline Fm.	Fluvial Sandstone	Moderate	Thick shales	Low
GOM	US	Onshore EOR/Saline	Fluvial/deltaic Sandstone	High	Shale	V. High
Wyoming	US	Onshore EOR/Saline	Eolian Sandstone / Platform Carbonate	Moderate	Shale/evap.	V. High
Alberta	Canada	Onshore EOR/Saline	Deep-water Sandstone/ Reefal Carbonate	Moderate	Shale/evap	V. High
DF1/Miller	UK	Offshore EOR	Deep-water sandstone	Moderate - high	Thick shale	Moderate
K12B	Neth.	Onshore	Eolian Sandstone	Moderate	Evaporite	Moderate
Latrobe Coal	Australia	Offshore EOR/Saline	Fluvial/deltaic Sandstone	High	Thin and thick shales	Moderate
Gorgon	Australia	Offshore Saline Fm	Deep-water Sandstone	Moderate	Thick shales	Low
Bohai	E China	Onshore/ Offshore Saline Fm.	Fluvial-lacustrine sandstone	High – V. high	Thick shales	High
Sichuan	S Central China	Onshore EGR	Shelf carbonates	Moderate-low	Evaporites/ carbonates	Moderate
Ganga	N. India	Onshore Saline Fm	Fluvial Sandstone	Moderate - high	Thin and thick shales	Low

These options are explored below. Key plays are locations with very large amounts of point source emissions, where sequestration could significantly reduce current and future emissions [8].In each case, a high concentration (low-cost) CO_2 supply exists nearby (figure 2) [8]. In some cases but not all, plans exist to execute a large-scale injection before 2010. A few plan large-scale science efforts in parallel. Below, named formations consider also stratigraphic equivalents.

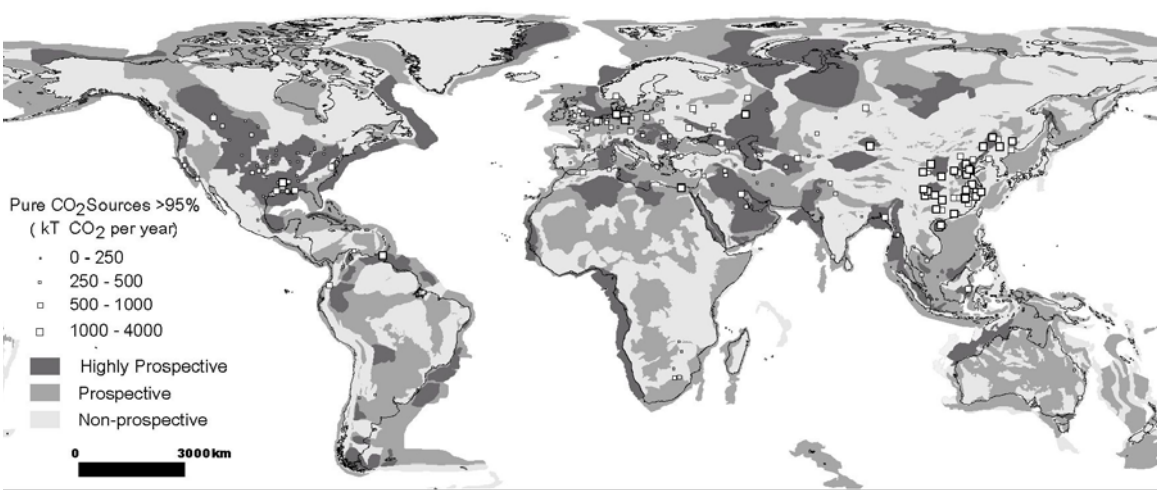

Figure 2: Global prospectivity map with pure CO2 sources [8]. Note: some large pure sources not rendered, chiefly gas processing facilities.

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North America

Given the concentration of large-point-sources in North America, five key plays emerge: The Ohio River Valley (ORV); the Gulf of Mexico (GOM), the Illinois Basin, the Alberta Basin, and the central Rocky Mountains. This would suggest at least five large projects in North America. However, the geology of the Illinois basin and the Ohio River Valley are substantively very similar in terms of target class; reservoir type, composition and age; seal type and composition; structural complexity; and well density On this basis, a project could proceed in either basin. The large number of fertilizer and ethanol plants in the Illinois basin (e.g., Equilon H_2 plant) suggests that this may provide more opportunities for early action [9].

- Illinois/ORV: Cambrian Mt. Simon Sandstone
- GOM: Miocene Frio or Vicksburg Fms.; other Neogene shelf sands
- Rocky Mts.: Mississippian Madison shelf carbonates or Pennsylvanian Tensleep/Weber eolian sandstones
- Alberta: Deep-water Triassic Viking Fm. or Devonian/Mississippian reef complexes

Europe

Despite attempts to map onshore opportunities, it appears that both early opportunities and large storage volumes will lie first and foremost in the North Sea. Importantly, the Sleipner project, DF1/Miller, and K12B all test different plays in and around the North Sea with different characteristics, depositional environments, seals, and locations around the perimeter. CO2SINK in Germany (Onshore Triassic-Jurassic sandstones) and Casablanca (Offshore Jurassic-Cretaceous carbonates) in Spain also test entirely different plays and conditions elsewhere in Europe, and would benefit from large experimental programs, but may not be key plays.

- UK: DF1/Miller: Jurassic Miller Fm. deep-water sandstone
- Netherlands: K12B: Permian Rotliegende eolian sandstone

China and India

It has long been recognized that substantial current and future GHG emissions reductions could come from rapid deployment of CCS in developing countries. China and India stand out for population, industrial base, and growth rate. Many workers have documented large pure sources in these countries [10], overall prospectivity [11] and even targets for EOR or storage in general [12]. In China, some 6 onshore and 3 offshore basins appear key and prospective [11]. Of these, some represent high injectivity and others low. One of each is chosen here: Bohai, because of its large oil fields, well understood geology, and proximity to Beijing and Tianjan; Sichuan, because of the low permeability units and potential for a commercial-scale enhanced gas recovery test. For India, the two most important plays are the Indo-Gangetic foreland and the Deccan Traps. Given the unconventional nature of basalt storage, the Indus or Ganga basins should be considered for large tests soon, and both have potential sources and targets.

- China: Bohai; Eocene-Miocene Shahejie - Guantao fluvial-lacustrine sandstones
- China: Sichuan: Triassic Jialingjiang Fm., shelf carbonates
- India: Ganga: Eocene-Miocene Murree – Siwalik Fms. fluvial sandstones

Australia

Although Australia's emissions are to small to consider key plays, their geology is representative of many continental shelf settings. Therefore, Australia's large pending commercial projects (Gorgon and Latrobe) provide an opportunity to test epicontinental shelf storage for much of the world.

- Monash/Latrobe Valley: Paleogene-Eocene Latrobe group fluvial/deltaic sandstones
- Gorgon: Jurassic Dupuy Fm. deep-water sandstones.

Discussion

The value of information derived from large scale injection studies relative to their cost would be enormous. For the three projects suggested above in the US, the price tag would range between

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$300 -700 million over eight years. Five large tests could be planned and executed for less than $1 billion, and address the chief concerns for roughly 70% of potential US capacity. Information from these projects would validate the commercial scalability of geological carbon storage and provide a basis for regulatory, legal, and financial decisions needed to ensure safe, reliable, economic sequestration. On a global basis, roughly ten storage tests might be run for a total price of between $2 and 5 billion, depending on the costs of local drilling, rig access, and offshore operations as well as the factors discussed above. This information would inform roughly $16 trillion in energy investment over the next 30 years. The case for OECD countries to help developing nations test their most important storage sites is strong, though mechanisms remain unresolved and are likely to vary case to case.

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