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The low cost of geological assessment for underground CO_2 storage: Policy and economic implications

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Abstract

The costs for carbon dioxide (CO_2) capture and storage (CCS) in geologic formations is estimated to be \$6–75/t CO_2. In the absence of a mandate to reduce greenhouse gas emissions or some other significant incentive for CCS deployment, this cost effectively limits CCS technology deployment to small niche markets and stymies the potential for further technological development through learning by doing until these disincentives for the free venting of CO_2 are in place. By far, the largest current fraction of these costs is capture (including compression and dehydration), commonly estimated at \$25–60/t CO_2 for power plant applications, followed by CO_2 transport and storage, estimated at \$0–15/t CO_2. Of the storage costs, only a small fraction of the cost will go to accurate geological characterization. These one time costs are probably on the order of \$0.1/t CO_2 or less as these costs are spread out over the many millions of tons likely to be injected into a field over many decades.

Geologic assessments include information central to capacity prediction, risk estimation for the target intervals and development facilities engineering. Since assessment costs are roughly two orders of magnitude smaller than capture costs, and assessment products carry other tangible societal benefits, such as improved accuracy in fossil fuel and ground water reserves estimates, government or joint private–public funding of major assessment initiatives should underpin early policy choices regarding CO_2 storage deployment and should serve as a point of entry for policy makers and regulators. Early assessment is also likely to improve the knowledge base upon which the first commercial CCS deployments will rest.

Keywords: Carbon sequestration; Fossil fuel; Energy policy; Zero emissions power

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1. Introduction

Carbon dioxide capture (CO_2) and storage (CCS) has emerged as a critical technology pathway to reduction of greenhouse gas (GHG) emissions [1]. This is because the option provides an opportunity for substantial emissions reduction while minimizing the cost of obtaining those reductions by allowing for the continued use

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of abundant high quality energy stocks, e.g. coal. CCS has also been shown to be a key enabling technology for a hydrogen economy [1,2], and it is this potential promise of CCS technologies that form the rationale behind large scale public–private sector efforts such as FutureGen [3] and the Carbon Sequestration Leadership Forum [4].

Conventional wisdom holds that one of the factors currently limiting the deployment of CCS technology is the cost of employing this technology. Although the cost of employing CCS is certainly higher than the cost of today's current practice of freely venting CO_2 to the atmosphere, it is not clear whether that is the relevant basis of comparison. If a decision is made to attempt the level of sustained large scale greenhouse gas emissions abatement needed to bring about a stable concentration of CO_2 in the atmosphere, then the cost of employing CCS would likely be comparable or lower relative to other carbon abatement technologies, such as deploying a fully decarbonized transportation sector [1]. Nonetheless, cost reduction and, in particular, reducing the cost of capture is a worthwhile and prominent goal in CCS research, as lower cost for deploying CCS imply lower overall GDP losses due to mitigation of greenhouse gas emissions [5]. There are indications that a well chosen combination of CCS and early investments into renewable energy sources could, in fact, lower GDP losses of an emissions mitigation policy to such an extent that these losses could become insignificant (about 0.5–1% net present value GDP losses compared to a business as usual scenario without mitigation policy for the next hundred years [6–8].

In contrast, relatively little effort has gone into scientific assessments of storage capacity. The nascent US Department of Energy led (USDOE) public private sector Carbon Sequestration Regional Partnerships are a rare example of a dedicated government led effort to better assess, at a national level, CO_2 storage capacity [4]. Others include Australia's GEODISC effort [9] and the European Union's Joule II effort [10]. These storage assessments have demonstrated the viability of CCS as a solution to local and regional emissions and have galvanized public and private sector interest on how CCS technology could enter the marketplace. They have also provided the data infrastructure needed for developing sites where storage might be deployed, and they have additional value to decision makers for long term planning in other areas, including water, hydrocarbon and environmental applications.

Such efforts should take place at least on a basin scale and ideally on the scale of individual target reservoirs. The cost of geologic CO_2 storage assessment is much smaller than the costs of capture or storage and is, therefore, much easier to initiate and execute. Indeed, these kinds of assessments can and likely should be launched before commercial deployment of CCS technologies begins. This makes the value of assessment high relative to its costs, making it an attractive early policy option for nations and regions confronted with uncertainties in geological storage.

2. The cost of employing CCS systems

There are numerous and varied cost estimates employing CCS systems with various power production and industrial facilities. The range spanned by these cost estimates reflects two different unknowns about the commercial deployment of CCS enabled systems. First, there is a broad consensus in the literature that the cost of employing CCS systems (and in particular the capture/separations cost component) should decrease with time as we accumulate more experience with commercially deployed CCS systems. The degree to which these costs might decline is unclear and is difficult to estimate given the truly small scale of today's deployment of CCS systems in comparison to the magnitude of their likely commercial deployment in a greenhouse gas constrained world. Second, these cost estimates also contain a degree of variability due to the highly site specific costs of employing CCS in the real world. This variability due to site specific considerations (e.g. is the source of CO_2 high purity, is there a so called value added reservoir nearby, how far is it and over what kind of terrain must the CO_2 be transported from the large CO_2 point source to a suitable geologic storage reservoir) could be quite large for some potential CCS configurations.

Nonetheless, it is from data such as those presented in Table 1 that an oft stated conclusion emerges: the costs of transport and storage are much less than the costs of capture. This conclusion has prompted significant focus and research in two areas. The first is reduction of capture costs, including new designs for zero emissions power plants. The second is economic research into regulation, emissions caps, or other government driven incentives that would ultimately make the cost of venting carbon emissions unattractive.

Table 1
Typical costs for various components of employing an integrated CCS system

	CO_2 capture and compression [16]	CO_2 transport and injection [5]	Measurement, monitoring and verification [17]
Steam Rankine power plant (chemical absorption with amines)	\$25–\$60/t CO_2	\$0–\$15/t CO_2	\$0.03/t CO_2
IGCC power plant (physical absorption)	\$25–\$40/t CO_2	“”	“”
Typical refinery flue gas, steel plant, cement plant (chemical absorption/flue gas recycling)	\$20–\$55/t CO_2	“”	“”
Gas stripped from the fermenter in an ethanol plant, process streams from ethylene and ethylene oxide plants, gas stripped from the reformer in an ammonia plant (principally compression)	\$6–\$12/t CO_2	“”	“”

Although it represents a smaller percentage of the life cycle cost of a CCS project, the cost of storage is nonetheless important. The good news is that a significant amount of research has gone into geological storage. Because of the low cost of storage relative to capture, most of this research has not focused on assessing the quality and quantity of the geologic CO_2 storage resource. Rather, the primary efforts have been to resolve uncertainties associated with storage efficacy, since they may limit the deployment of storage options. These included characterization of target sites [11,12], development and testing of monitoring and verification tools (e.g. [13]) and risks associated with leakage from subsurface reservoirs [14,15].

3. Prior assessments and their basic costs and benefits

Ultimately, the success of geological storage will depend heavily on reservoir and risk characterization. These, in turn, will require careful surface and subsurface mapping of target geological sites. However, despite the importance of and need for proper characterization, there has been little focused effort on basin wide or local assessment. This is particularly surprising given the low relative costs of assessment.

3.1. Geodisc

Following a workshop with industry, academia and governmental stakeholders in 1998, a proposal for GEODISC was funded in 1999 and began in July of that year. The 4 year program cost \$10 M and has produced a nationwide estimate for geological storage capacity in Australia. The assessment was iterative, basin specific, detailed and incorporated prior estimates from individual large oil and gas fields and basin wide studies of hydrocarbon systems [9]. These results were sufficiently specific to produce a preliminary risk analysis and ranking of prospective candidate CO_2 storage formations (e.g. [12,18]). The results of this modest effort have already been put to use in helping to inform the siting of a proposed liquefied natural gas (LNG) plant, proposed CO_2 storage projects associated with natural gas production and the creation of the follow-on public/private sector collaborative geological sequestration project known as the CO2CRC. The GEODISC program demonstrates that rapid, low cost, high quality assessment is possible on a national scale even given great geological complexity.

3.2. Alberta basin

The Alberta basin has served as a focus for hydrocarbon exploration and production for over 100 years. The government of Canada requires that cores and wells from hydrocarbon exploration and production enter the public domain rapidly. The organization of this data allowed a relatively small team to conduct a basin scale estimate of the storage potential [19,20]. This capability allowed for rapid screening within the Alberta basin based on the thermodynamic effects of CO_2 storage and rapid estimation of reasonable storage volume estimates and high grading of targets (e.g. [21]). Although the analysis was not keyed to individual reservoir or formations, it was extremely low in cost and time and presents planners with recommendations for action in further assessment and screening. The work also provides a short list of areas and targets likely to succeed and has stimulated new efforts at capture and storage of anthropogenic emissions in the region.

3.3. IEA GHG national CO_2 storage cost curves

The International Energy Agency's Greenhouse Gas R&D Programme (IEA GHG) has initiated a program of national basin level assessments to examine what the CO_2 storage capacity is for Western Europe [22] and Canada and the United States [23]. An integral component of this research was the computation of theoretical storage potentials in 100s of basins within these regions and modeling the potential use of these formations by the variety of large (i.e. greater than 100,000 t of CO_2 per year) anthropogenic point sources in both regions. These studies have established that CCS systems can play a very large role in delivering deep and sustained reductions in greenhouse gas emissions. The IEA GHG intends to extend these "national CO_2 storage cost curve studies" to other regions of the globe.

3.4. Regional partnerships

The US DOE announced the formation of seven regional carbon sequestration partnerships in 2003. The Partnerships cover 40 states and four Canadian provinces, including 160 academic, industrial, governmental and non-governmental entities [24]. The seven groups are charged with assessment and ranking of high grade source-sink matches with the goal of recommendation for new carbon storage demonstration projects. The assessment effort will include characterization and capacity estimation of important target reservoirs within the regions as well as preliminary risk analysis. Efforts are likely to proceed on a sub-basin scale or less and include preliminary capacity estimation for high value targets. The total public budget for this 2 year effort is $9.6 MM, and includes in-kind contributions from many groups. The Partnerships demonstrate that it is possible to collect and screen large volumes of data to produce preliminary estimates for planning and execution of new projects.

Part of the reason that the costs of assessment as a whole are small is that the volumes of storage are likely to be large for many industrialized nations [23,25]. For a nation likely to store 10s–100s of Gt CO_2 geologically over the course of this century, even $1 billion spent on assessment (a very high estimate) would only cost $0.1–0.001/t CO_2. In reality and as shown above, the costs of assessment are likely to be much less than that, as seen in the examples above. Even in nations with relatively little geologic CO_2 storage potential (e.g. Japan, South Korea), the costs for assessment will be less than the cost of capture, and the investment in assessing the nation's CO_2 storage potential will help establish the extent to which CCS can be relied upon as a cornerstone of the nation's greenhouse gas mitigation portfolio [23].

4. Levels of geologic CO_2 storage assessment

Comprehensive assessments of CO_2 storage potential must be seen as foundational climate change mitigation research undertaking to enable the deployment of these critical technologies. These geologic CO_2 storage assessments can be conducted at various levels of detail, with each corresponding to a different cost and reward. We offer here a taxonomy of three levels at which subsurface CO_2 storage assessments can be performed: by basin, by formation, or by sequence.

5. Basin level assessments

Basin assessments (100s–1000s of km^2 capable of generating CO_2 storage estimates accurate within 10s of Gt CO_2) proceed using bulk parameters for relatively thick sedimentary intervals and thermodynamic constraints of supercritical CO_2 injection (e.g. [19,26]). Often, bulk properties for interval thickness and porosity are used to determine pore volumes for a given unit or depth interval. Depth, temperature and geothermal gradient data generate contours of temperature at a given depth, which determine the volume, density and state of CO_2 at depth. This approach does not provide information on injectivity or permeability but allows for rapid screening of capacity over a large area and provides reasonable estimates for likely basin wide storage volumes. This type of assessment is needed to put CCS research on a nation's research and climate mitigation agendas, i.e. a nation that knows it has geologic CO_2 storage potential is likely to invest in CCS research and begin the needed rule making and regulatory steps that will define the context into which CCS enabled systems will begin their commercial deployment.

6. Individual formation evaluations and assessments

Estimates by formation (100s–1000s of km^2, but within a narrowly defined stratigraphic interval and typically accurate to within $+/- < 1$ Gt CO_2) are more data and time intensive, since they require detailed knowledge of formation tops, changes in thickness and porosity within a formation and the subtle changes in structural geology (formations are mappable geological units). Commonly, detailed formation data will include permeability and compositional data, which can be used to define local or regional injectivity trends. Similarly, depth/top information can be used to determine structural gradient, local geometric closures and other information to help evaluate the forces leading to leakage risk. However, there are important advantages to this approach. Specifically, it provides a mechanism to assess the capacity and injectivity on a more detailed level that can be used to inform site selection and preliminary risk screening and cost estimation. In other words, formation mapping is required to calculate the likely specific injectivity that will be encountered within the region of interest [11]. Formation mapping commonly requires time and work to condense and evaluate the data itself and may require careful evaluation of existing subsurface databases. The US Geological Survey has just completed a 3 year, \$5 M project of this kind for the San Joaquin basin in central California [27]. Knowledge of CO_2 storage potential along with estimates of specific injectivity at the formation level would most likely be needed to help narrow down a list of potential sites for a large potential CO_2 source, such as a new fossil fired power plant, to a smaller list of candidate sites that could be examined across a more comprehensive range of criteria.[1] Under the right geological conditions, this kind of assessment may be sufficient for site planning.

7. Individual geologic sequence evaluation and assessments

Mapping by geological sequence (10s–1000s of km^2 within a very narrow stratigraphic range and typically accurate to within $+/- \ll 1$ Gt CO_2) requires significantly more geological expertise and geological data (e.g. [28]). This approach separates individual formations and geological successions into genetically linked packages separated by unconformities and other stratal boundaries. This approach also allows a more accurate and precise rendering of key structural elements such as closures and faults. Commonly, geoscientists trained in sequence stratigraphic methods are needed for this level of detail, requiring more time and effort in order to map sub-units within a formation. However, sequence stratigraphy has been shown to reveal important information about porosity and permeability trends from scarce data, and a sequence stratigraphic framework can serve as a basis for extrapolation, interpolation, and geometric prediction. This approach underpins both exploration and production efforts in most major oil companies, who rely on this information for detailed reservoir prediction. Commonly, sequence based analyses are used to generate static geomodels and flow simulations. This level of assessment would likely be undertaken as a firm initiated the injection planning phase for an individual project at a specific site.

All three levels of assessment would also surely produce ancillary benefits. For example, detailed pore-volume and permeability estimates would serve as a basis for extractive industries (e.g. hydrocarbon industry, mining) to identify new plays or improve reserves estimates. Information on shallow or deep aquifers assessment can be used for long range planning of water resources and in environmental protection. These benefits will ultimately help to obviate the costs for assessment and encourage industry and geological surveys to participate in assessment work. These assessments, and in particular assessments at the geologic sequence level, would provide data that would underlie and inform the baseline that would be used for monitoring CO_2 during the injection and post-injection phases of a project.

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[1] It is important to note that the existence of a suitable CO_2 storage reservoir is only one of a number of criteria that would be used to site a CCS enabled power plant or other large CCS enabled industrial facility. Other criteria would include access to cooling water, rail and pipeline access to bring in fossil fuel, access to the electricity distribution grid, etc.

8. Policy implications

Assessment and characterization of geologic CO_2 storage capacity need to be seen and understood to be an investment in a nation or region's future economic and environmental well being in the way that estimates of hydrocarbon resources/reserves are viewed today. This knowledge of potential CO_2 storage capacities is integral in helping to define long term scenarios for how a region's energy infrastructure might evolve in a greenhouse gas constrained regime as the extent and quality of the geologic storage resource present speaks to what fraction of the region's energy mix can be decarbonized through CCS deployment and what the transportation and storage costs might be (e.g. [5]). This allows storage capacity to be treated as any other finite natural resource. Assessment information should serve as a resource for policy makers and long range planners. Examples include using capacity assessment products as inputs into plant siting, regional energy portfolio determination, or the development of large field experimental facilities [29].

As can be seen, the above taxonomy represents a refinement of knowledge about the potential to store CO_2 in a specific region as one moves from basin level assessments to assessments of individual sequences. The above taxonomy also implicitly suggests a potential allocation of burden sharing between the public and private sectors for these various levels of geologic CO_2 storage potential. At the most aggregate level, that of basin assessment, this would seem to be predominantly the domain of the public sector, as it would be difficult if not impossible for a firm to appropriate fully the returns of this kind of broad assessment. Moreover, the social rate of return would likely be quite high as these kinds of assessments can help to "put CCS on the table" and, therefore, allow a broader cross section of industry, non-governmental bodies and government to see a pathway forward into a greenhouse gas constrained future.

Assessments at the formation and geologic sequence level, on the other hand, are more closely linked to the needs of individual firms or entities that are considering employing CCS enabled systems as a part of their portfolio of climate mitigation activities. To be sure, this level of data is also needed by public sector bodies and regulatory agencies that would be called upon to assess the suitability and potential efficacy of a particular CCS deployment, but given that there is a strong and obvious private sector need for these data, it seems that arguments for public/private cost shared assessments are most strong at this end of the assessment spectrum. This level of assessment detail may also affect the value of financial instruments for carbon storage (e.g. [6]) by conditioning aspects of successful injection ranging over drilling requirements, uncertainty in injectivity and level of uncertainty in ascertaining risk.

Another element that speaks to the public sector nature of these assessments relates to the added value of early assessment in risk avoidance. Apart from pre-existing wells, most risks associated with leakage of CO_2 from a target reservoir are associated with subsurface geology (e.g. [14]). Lithologic, geometric and structural data are fundamental inputs to risking schema and are likely to be required by regulation and for certification of injection facilities [30]. These data would flow from assessments and are likely to present early low risk candidates for storage (e.g. [18]).

9. Recommendations

The value of geologic CO_2 storage assessments is large relative to their likely costs and, perhaps moreimportantly, small in comparison to the potential savings of trillions of dollars associated with being able to deploy CCS systems on a broad scale as a response to potential future climate change mandates [31]. The quicker this information can be obtained, the more the value of the knowledge gained through these assessments is maximized, as these assessments establish the degree to which CCS can play a role in a nation's or a region's portfolio of mitigation options. By establishing the role for CCS early, these assessments can reduce the overall welfare losses associated with delaying cost effective climate change mitigation.

1. Nations with significant current or future GHG emissions should embark on a well planned, thorough assessment of storage capacity at the basin scale. To the extent that it is appropriate, these basin scale assessments should be done in cooperation with national and regional geological surveys and subsurface

intensive industries (e.g. hydrocarbon, coal). Specialized international bodies such as the IEA GHG may serve as repositories for much of the needed data and supply expertise that will be needed to conduct the assessments and should be considered for early involvement.

2. These storage assessments should be initiated now. Rapid deployment will increase the value of the supplemental benefits of capacity assessment and reduce the costs associated with errors in starting CO_2 storage projects. The effort should take no more than 3–5 years and produce assessments that are basin specific and keyed to formations (at least) and chronostratigraphic sequences ideally. Countries such as China and India should be seen as high priorities for this kind of assessment.
3. The results of national and regional assessments should be housed in public domain repositories.[2]
4. Assessments should follow established, peer reviewed methodologies and should be modified, if necessary, to suit the available data and geological setting. It should be noted that any assessment is predicated on a set of assumptions concerning how CO_2 is stored and distributed within a pore volume (e.g. [26,33,34]). It is important that assessments are clear and transparent in their assumptions so that as new geochemical and geophysical studies produce constraints on processes and effects, capacity estimates can be readily recalculated.

Given the low cost and relative ease of action, policy makers should embrace the high return of this approach quickly. It is highly likely that information generated by early assessment will affect related areas and, as such, is likely to prompt subsequent assessments with greater detail suited to the task. Since assessment information can, thus, anchor choices in energy decision making and planning, preventing waste, error and uncertainty, early action is recommended.

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