CO_2 storage capacity estimation: issues and development of standards

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Abstract

Associated with the endeavours of geoscientists to pursue the promise that geological storage of CO_2 has of potentially making deep cuts into greenhouse gas emissions, Governments around the world are dependent on reliable estimates of CO_2 storage capacity and insightful indications of the viability of geological storage in their respective jurisdictions. Similarly, industry needs reliable estimates for business decisions regarding site selection and development. If such estimates are unreliable, and decisions are made based on poor advice, then valuable resources and time could be wasted. Policies that have been put in place to address CO_2 emissions could be jeopardised. Estimates need to clearly state the limitations that existed (data, time, knowledge) at the time of making the assessment and indicate the purpose and future use to which the estimates should be applied. A set of guidelines for estimation of storage capacity will greatly assist future deliberations by government and industry on the appropriateness of geological storage of CO_2 in different geological settings and political jurisdictions. This work has been initiated under the auspices of the Carbon Sequestration Leadership Forum (www.cslforum.org), and it is intended that it will be an ongoing taskforce to further examine issues associated with storage capacity estimation.

Keywords: CO_2, storage capacity, trapping efficiency

Introduction

Estimation of the capacity of a geological reservoir to store CO_2 is not a straightforward or simple process. Some authors have tried to make simplistic estimates at the regional or global level, but have largely been unsuccessful, as shown by widely conflicting results (Figure 1). At the worldwide level, estimates of the CO_2 storage potential are often quoted as “very large” with ranges for the estimates in the order of 100s to 10,000s Gt CO_2. Although in principle storage capacity estimation relies on a simple series of algorithms that depend on the storage mechanism under consideration to calculate the available capacity in a certain volume of sedimentary rock at a given depth, temperature and pressure, applying them to a specific region or site is complex. It is particularly difficult due to the various trap types and trapping mechanisms that can occur, the different time frames over which trapping becomes effective, and the different physical states in which the CO_2 might occur (Table 1). All these parameters affect the effectiveness of geological storage of CO_2, often in different directions. The highly variable nature of geological settings, rock characteristics, and reservoir performance combine to make some estimates unreliable when they are made with methodologies that generalise the inputs for evaluating potential storage capacity.

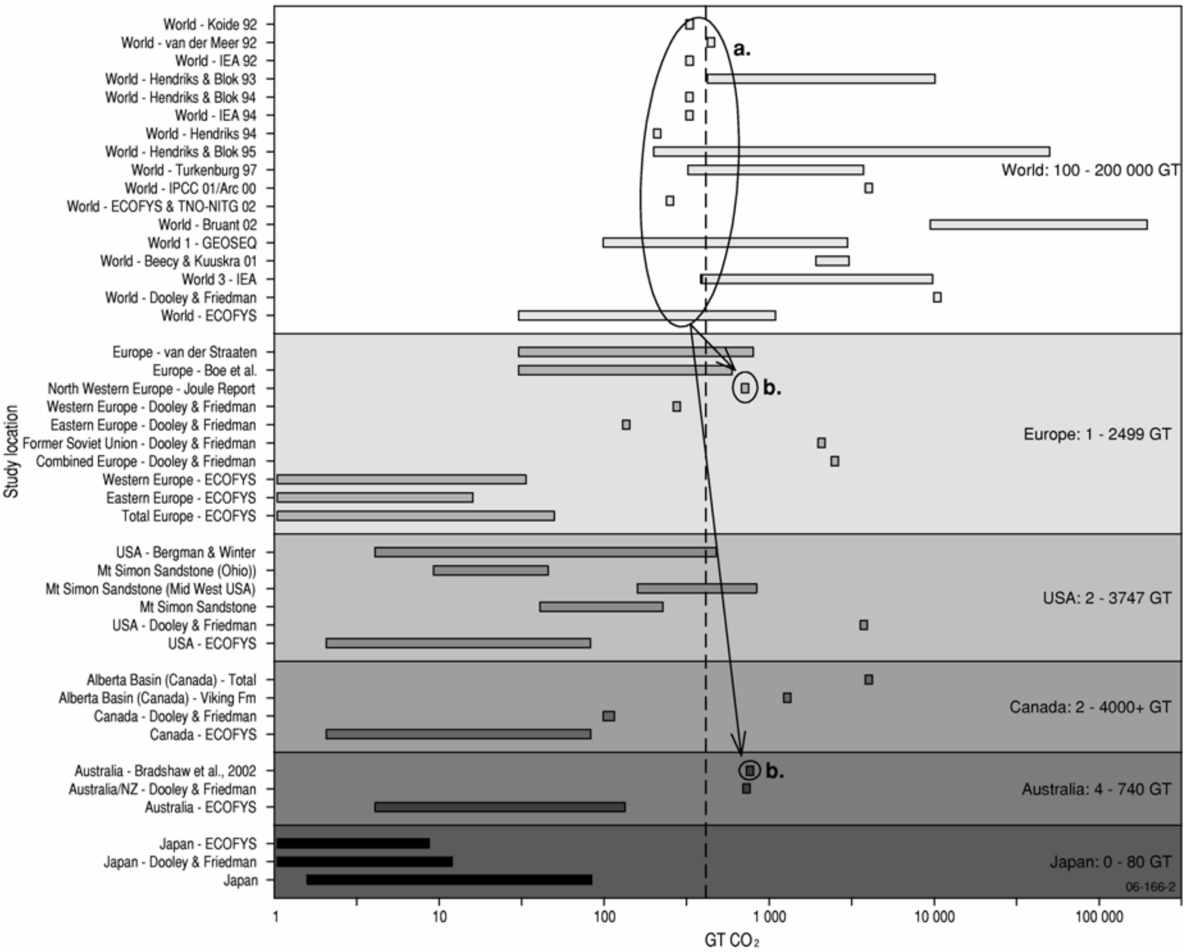

Figure 1 A listing of various estimates for CO_2 storage capacity for the world and regions of the world. Estimates are listed by region, and ordered internally by date of completion of the estimates. Note there are world estimates (a) that are smaller than some more "robust" regional estimates (b).

There are many levels of uncertainty within assessments of storage capacity. The different levels of assessment require extensive datasets from multiple disciplines that must be integrated to develop meaningful assessments. The most accurate way to estimate storage capacity at the local scale is through construction of a geological model and use of that information in reservoir simulations. Such analyses are resource, time and data intensive. Given the significant variability that exists in many estimates and in their underlying criteria, it is necessary to document the limitations of many of the assumptions used, and to make suggestions and give examples of how better and more reliable estimates can be determined. At the same time, a series of definitions needs to be established to provide consistency between capacity estimates and in understanding and comparing various capacity figures. This paper provides preliminary guidance on a number of issues associated with storage capacity estimation, and will be followed by further more detailed work.

Existing Capacity Estimates

A large proportion of existing capacity estimates are highly variable and in many instances are contradictory. Although geoscience professionals are able to examine the details and underlying assumptions of each report (if documented) to see if they have used appropriate and consistent methodologies, non-geoscientists will often only look at the final "bottom line" number and can be misled or subsequently mislead others if they use the values in a way for which they were never intended. This phenomenon is not uncommon in resource assessments of mineral and fossil fuel resources. Additional problems with the estimates of storage capacity relate to whether the assessments were conducted at the reserve or resource level, and the assumptions that were made to discriminate between these two tiers of assessment. Some of the contradictory estimates which are evident in Figure 1 are the result of using inappropriate methodology to derive rough estimates.

Many estimates use the surface area of a sedimentary basin to serve as a guide as to the storage potential of the basin. There is no reliable way to estimate or provide a guide as to the resources contained within a basin (including CO_2 storage capacity) by using surface area, as is documented for estimation of hydrocarbon resources around the world [1].

Table 1 Characteristics of physical and chemical trapping mechanisms. Note the different time frames & range of issues. Most mechanisms will operate alongside each other in each trap type. Oil and gas fields predominantly occur in structural and stratigraphic trapping mechanisms.

Characteristics / Trapping mechanism	Nature of trapping	Effective time frame	Areal size	Occurrence in basin	Issues	Capacity limitation/ benefits	Potential size	Capacity estimation method/ requirements
Structural & stratigraphic	Bouyancy trapping within anticline, fold, fault block, pinch-out. CO_2 remains as a fluid below physical trap (seal)	Immediate	10s km to 100s km	Dependent on basins tectonic evolution. 100s of small traps to single large traps per basin.	Faults may be sealed or open, dependent on stress regime, fault orientation & faults could be leak/spill points or compartmentalise trap.	If closed hydraulic system then limited by compression of fluid (few %) in reservoir. If open hydraulic system will displace formation fluid.	Significant	Simple volume calculation of available pore space in trap, allowing for factors that inhibit access to all the trap - eg. sweep efficiency, residual water saturation.
Residual gas	CO_2 fills interestices between pores of the grains of the rocks.	Immediate to thousands of years	Basin scale eg. 1000s km	Along migration pathway of CO_2	Will have to displace water in pores Dependent on CO_2 sweeping through reservoir to trap large volumes.	Can equal 15-20% of reservoir volume. Eventually dissolves into formation water.	Very large	Requires rock property data & reservoir simulation.
Dissolution	CO_2 migrates through reservoir beneath seal & eventually dissolves into formation fluid.	100s to 1000s of years if migrating more than 1000s of years if gas cap in structural trap & longer if reservoir is thin & has low permeability.	Basin scale eg. 10000s km	Along migration pathway of CO_2 both up dip & down dip.	Dependent on rate of migration (faster better) & contact with unsaturated water & pre-existing water chemistry (less saline water better) Rate of migrations depends on dip, pressure, injection rate, permeability, fractures, etc.	Once dissolved, CO_2 saturated water may migrate towards the basin centre thus giving the very large capacity. The limitation is contact between CO_2 & water & having highly permeable (vertical) & thick reservoirs.	Very large	Requires reservoir simulation & need to know CO_2 supply ratio & injection rate.
Mineral precipitation	CO_2 reacts with existing rock to form new stable minerals.	10s to 1000s of years.	Basin scale eg. 10000s km	Along migration pathway of CO_2	Dependent on presence of reactive minerals & formation water chemistry. Could precipitate or dissolve.	Rate of reaction slow. Precipitation could 'clog' up pore throats reducing injectivity. Approaches 'permanent' trapping.	Significant	Requires rock mineralogy
Hydrodynamic	CO_2 migrates through reservoir beneath seal, moving with or against the regional ground water flow system whilst other physical & chemical trapping mechanisms operate on the CO_2	Immediate	Basin scale eg. 10000s km	Along migration pathway of CO_2 with or against the direction of the flow system that may move at rates of cm per year.	Dependent on CO_2 migration after the injection period, being so slow that it will not reach the edges of the sedimentary basin where leakage could occur.	No physical trap may exist & thus totally reliant on slow transport mechanism & chemical processes. Can include all other trapping mechanisms along the migration pathway.	Very large	Requires reservoir simulation & regional reservoir flow model.
Coal adsorption	CO_2 preferentially adsorbs onto coal surface.	Immediate	10s km to 100s km	Limited to extent of thick coal seams in basins that are relatively shallow.	Coals can swell reducing injectivity. Difficult to predict permeability trends. CO_2 adsorption not 100% effective which raises issue of leakage if no physical seal is present.	Injectivity poor due to low permeability. Effective at shallower depths than porous sedimentary rocks, but not at deeper depths due to permeability issues. Many injection wells required. If methane liberated might not be net GHG mitigation.	Low	Requires gas sorption data & knowledge of permeability trends & coal 'reactivity' to CO_2

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Trapping Efficiency and Timing

The efficiency of trapping for many of the mechanisms described in Table 1 depends upon the migration rate of the CO_2, which itself is highly dependent on the rock and fluid properties and geological characteristics of each site. The conceptual geological settings that constitute the largest potential storage volumes are (in decreasing potential capacity) deep saline reservoirs, depleted gas reservoirs, oil reservoirs (with and without enhanced oil recovery), and coal beds. Trapping of CO_2 in geological formations in the subsurface can occur through various mechanisms. Estimates of storage capacity must take into account the range of trapping mechanisms that are possible at each site, the different geological constraints on each mechanism, and the fact that different trapping mechanisms operate on different time scales that range from instantaneous to tens of thousands of years. The complexity of these trapping mechanisms and the variations that occur within them individually and collectively demonstrate why simple capacity estimation methods will always have a range of uncertainties. Furthermore, estimates of storage capacity at specific sites may be highly sensitive to geological parameters that are poorly known or even unknown (such as relative permeability), requiring clear descriptions of surrogate values used in calculations.

Resource Pyramids

The concept of resource pyramids was advanced by McCabe [2] as a method to describe the accumulation around the world of hydrocarbons in different categories. This concept is proposed here to represent the similar issue of capacity for CO_2 storage in geological media. Because of the multi-faceted aspects of this issue, three resource pyramids have been proposed, representing a) High Level, b) Techno-Economic and c) Trap Type and Effectiveness aspects [1].

High Level Resource Pyramid

At the top of the High Level resource pyramid [1] are all the storage sites with good geological characteristics and that individually have large storage capacities, which are located close by to emission sites with low costs of capture. At the base of the pyramid are the extremely difficult sites, with problematic geological conditions, small storage capacity and that are located a great distance from sources with large capture costs. However, the total potential storage capacity of the sites at the base of the pyramid is very much greater than those at the top. Contradictory capacity estimate results have occurred when assessments do not adequately define the boundary conditions and assumptions that have been used, and so fail to describe their position on the resource pyramid.

Techno-Economic Resource Pyramid

Figure 2 shows an example of a techno-economic resource pyramid. When calculating capacity, several types of estimates can and often are made, depending on the nature and purpose of the assessment, and they all lie across different regions of the resource pyramid. The following nomenclature and definitions are a preliminary guide that should form the basis of further work. This pyramid considers 3 technical and economic categories, being Theoretical, Realistic and Viable Capacity;

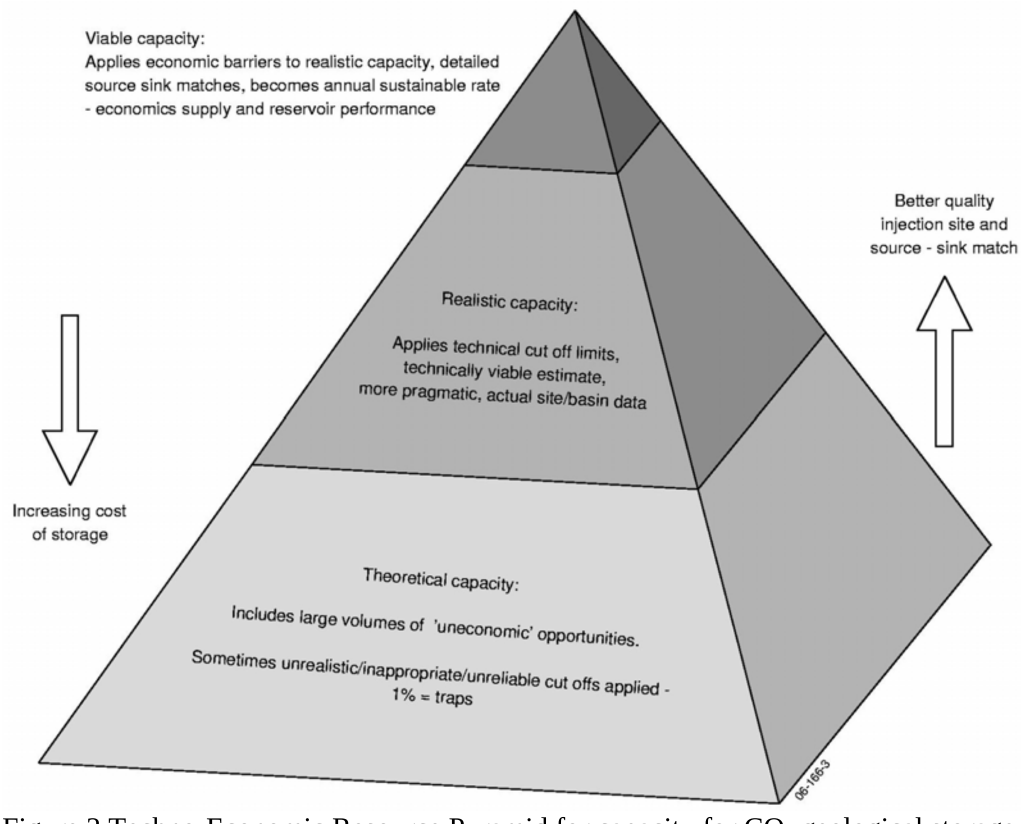

Figure 2 Techno-Economic Resource Pyramid for capacity for CO_2 geological storage, showing the three levels of Theoretical, Realistic and Viable estimates. Theoretical includes the entire pyramid, Realistic the top two portions and Viable only the top portion.

Theoretical capacity – assumes that the whole of a reservoir formation is accessible to store free-phase CO_2 in its pore volume, or the whole of the formation water in a reservoir formation is available to have CO_2 dissolved into it at maximum saturation, or the whole mass of coal is available to adsorb and store CO_2 at maximum adsorption capacity. This provides a maximum upper limit to a capacity estimate, however it is an unrealistic number as in practice there always will be technical and economic limitations across a region that prevent parts of the reservoir formation from being accessed and/or fully utilized. This represents the theoretical limit of the whole geological system. It occupies the whole of the resource pyramid.

Realistic capacity – applies a range of technical (geological and engineering) cut-off limits to elements of an assessment such as quality of the reservoir (e.g. permeability and porosity) and seal, depth of burial, pressure and stress regimes, size of the pore volume of the reservoir and trap, and whether there may be other competing interests that could be compromised by injection of CO_2 (e.g., existing resources such as oil, gas, coal, water, geothermal energy, minerals, national parks). This is a much more pragmatic estimate that can be done with some degree of precision, and gives important indications of technical viability of CO_2 storage. These estimates are within the main body of the resource pyramid, but exclude the basal parts of the resource pyramid.

Viable capacity –is the capacity arrived at by also considering economic, legal and regulatory barriers to CO_2 geological storage, and thus builds upon the realistic capacity assessment. Detailed source/sink matching is performed at this stage to match the best and nearest storage sites to large emission sources. The source-sink matching should extend beyond just geoscience and engineering aspects, and include social and environmental aspects of locating storage sites. Cost curves may also be derived and Monte Carlo simulations performed to help estimate the level of uncertainty and upper and lower ranges in the known and derived data versus the actual data that become available once a project is implemented. Once this level of assessment has been reached, it may be possible at a regional level to express the capacity as an annual sustainable rate of injection, not just as a total volume [3]. These capacity estimates are at the top of the resource pyramid.

<u>Trap Type and Effectiveness Resource Pyramid</u>

This version of the resource pyramid (Figure 3) attempts to represent the relationships between the reservoir quality and trap types (left vertical axis), trapping mechanisms (bottom axis) and the time that it takes until the trapping mechanism is effective (right horizontal axis). The characteristics of the trapping mechanisms are described in detail in Table 1. At least 3 qualifiers need to be documented in this resource pyramid to explain which storage capacity estimate method has been used. At any time at a particular storage site, some of these trapping mechanisms might be mutually exclusive (e.g. dissolution into the fluids and displacement of fluids), whilst others may partially act simultaneously (e.g. residual gas saturation and compression of fluids and the rock matrix with increasing pressure), and others will compete against each other (e.g. simple compression of fluids such as occurs in a closed system versus displacement of pore fluids in an open system). Over the long term "geological" life of a storage site, many of the trapping mechanisms may actually participate in the eventual trapping process.

Effect of Supply Volume and Injectivity on Storage Capacity

As described for the Techno-Economic Resource Pyramid, there is a need to clearly document whether storage capacity estimates are based upon source to sink matching (viable capacity), or whether injection sites are being considered in isolation from economics and in isolation from the likely supply volume (theoretical and realistic capacity). If the storage site is not a clearly defined structural trap that is immediately effective, and relies upon dissolution and residual trapping, then the Trap Type and Effectiveness Resource Pyramid needs to be considered to conceptualise what capacity estimate method is being described If a site is of poor quality in terms of permeability (and thus can only accept small rates of injection), but has a lot of pore space and potential storage volume, then there will be a limit to the rate at which the CO_2 can be injected for each well. This may limit its utility as a storage site because it will require large capital costs for many wells and compressors, and, hence, quoting such a site as having large storage capacity may be extremely misleading. As such, describing this capacity by expressing it in terms similar to the documentation of unconventional resources could help indicate that it might not be an economically or technically efficient option, but future changes in economics and technological advances could make it viable.

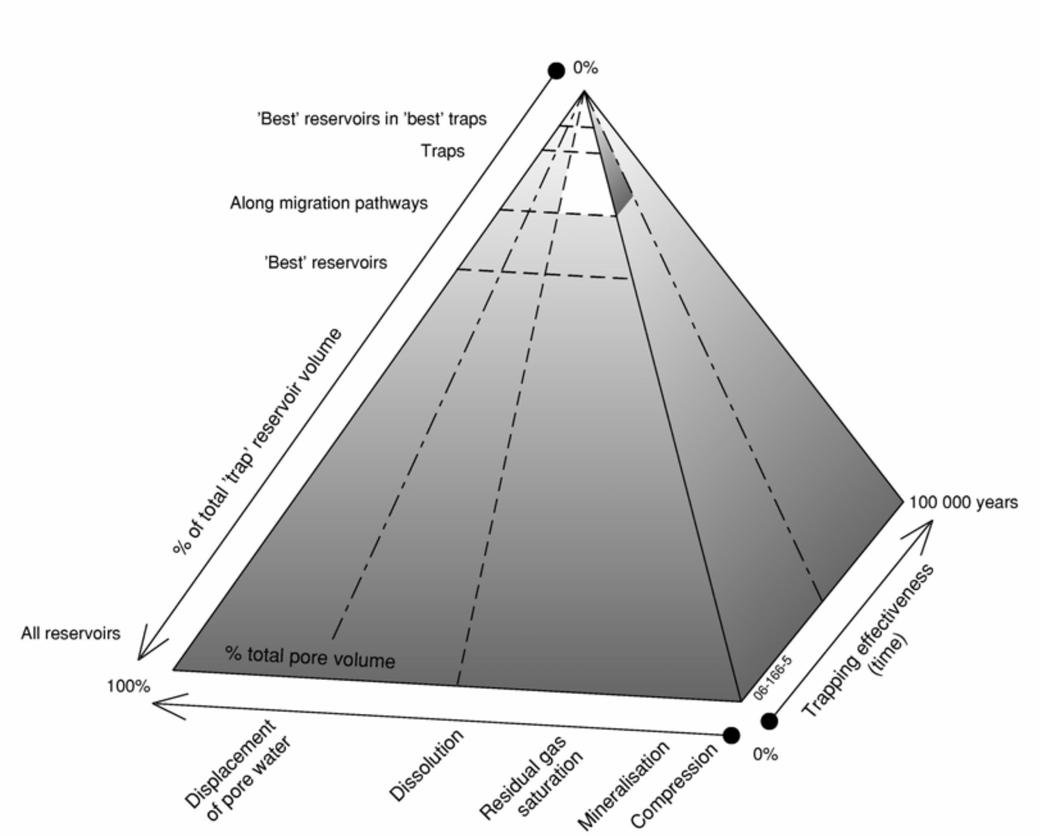

Figure 3 Trap/reservoir quality (as a proportion of all reservoir volume), and effectiveness resource pyramid showing the relationships between different trap and reservoir quality, trapping mechanisms and their effectiveness in terms of time (years). The highlighted inset pyramid corresponds to the proportion of the total resource pyramid that relates to dissolution trapping (see Table 1) that occurs along migration pathways over an effective time frame of up to 10,000s years.

Conclusions

Many of the contradictory assessments and errors in calculated storage capacity are due to the desire or need to make quick assessments with limited or no data. Such assessments might have a place, but they should not be used in setting forward looking strategy or for making investment decisions, nor should they be released in the public domain where they can be misunderstood and misused. Estimates need to clearly state the limitations that existed (data, time, knowledge) at the time of making the assessment and indicate the purpose and future use to which the estimates should be applied. Assessments that lack documentation of constraints (or justification for their use) cannot be easily compared with other assessments. A set of guidelines for estimation of storage capacity will greatly assist future deliberations by government and industry on the appropriateness of geological storage of CO_2 in different geological settings and political jurisdictions.

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