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Economic dimensions of geological CO_2 storage: key factors in an assessment of sub-seafloor and continental sequestration options

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Abstract

Geological sequestration offers long term storage opportunities that differ in terms of technical capacity and characteristics, and in terms of economic costs and benefits. In this paper we outline a simple economic framework that reflects the planning problem for sequestering CO_2 in alternative geological sinks and highlights the differences in the environmental risks and the economic costs of alternative sinks. The marginal costs of alternative geological sequestration options must be compared to measures of marginal benefits that take into account the probability of local and global environmental risks and other regulatory requirements. We direct our discussion of an application of this framework to the case of geological sequestration in deep-sea basalts and provide an initial assessment of how this framework could be implemented to quantify the long-term economic costs relative to other continental geological storage options.

Keywords: economic costs; environmental risks; basalts; sub-sea floor; marginal costs; marginal benefits

1. Introduction

1.1 Overview

Assuring long-term secure sequestration of anthropogenic carbon dioxide is one of our most pressing global scientific problems. Geological sequestration by injection of carbon dioxide into sub-surface formations offers long term storage opportunities that differ in terms of technical capacity and characteristics, and in terms of economic costs and benefits. Numerous studies have explored the technical aspects of geological storage, but there has been little systematic analysis of the economic costs and capacity for long-term storage. In this paper we outline a simple economic framework that reflects the planning problem for sequestering CO_2 in alternative geological sinks and

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highlights the differences in the environmental risks and the economic costs of alternative sinks. We compare alternative long-term disposal opportunities for a point source carbon emitter. The marginal costs of alternative geological sequestration options must be compared to an adjusted measure of marginal benefits that take into account the probability of local and global environmental risks and other regulatory requirements. From society's perspective, an optimal allocation among alternative sequestration sites requires that the marginal costs are equated across all sinks, and that these in turn are equated to the marginal benefits.

We direct our discussion of an application of this stylized framework to the case of geological sequestration in deep-sea basalts and provide an initial assessment of how this framework could be implemented to quantify the long-term economic costs relative to other continental geological storage options. The deep-sea basalt formations may provide unique and significant advantages such as: high porosity and permeability to accommodate large injected volumes, increased levels of chemical reactivity to produce stable carbonates, and reduced risk of post-injection leakage through geological, gravitational, and hydrate trapping mechanisms. With this information we are able to quantify the marginal benefits and marginal costs for alternative sub-seafloor sites and provide some preliminary comparisons of cost differences both among the set of deep-sea basalts and between continental and sub-seafloor options.

1.2 Literature review

The literature to date on the costs of carbon capture and sequestration has focused almost exclusively on the costs of capturing the CO_2, compressing and transporting via pipeline to a storage site, injection, and short term monitoring. The MIT (2007) [1]and the IPCC [2] report conclude that CCS is the critical enabling technology that would reduce CO_2 emissions significantly while also allowing coal to meet the world's pressing energy demands. The MIT report estimates that the average added cost for CCS (as defined above) is in the range of approximately \$30/t of CO_2 captured, although there are large uncertainties in that estimate. These uncertainties arise because the commercialization of this technology is still many years away, and many of the pilot projects are not of the scale and size required for large scale adaptation. In addition, there are many aspects of the true "social" costs of CCS that are omitted from the cost estimates in the literature. These include the long term costs and benefits of sequestration and monitoring and the scarcity rent from the use of the geological sinks. The notions of scarcity rents for carbon sequestration are discussed in a paper by Narita and Heal [3] . Thus, the key question that needs to be answered for planning purposes (private and social) is how much do the various technologies and options cost per ton of CO_2 reduced, on an all-else equal basis? That is if we want to be rationally allocation research dollars (capital) to options that are "least cost" we need to have a means for comparing apples and apples. This paper begins to identify some of the elements of the social costs, and explains why these cost components are important in our calculations of the costs of CCS vs. other alternatives, and even within the alternative options for storing the CO_2 underground. This is not about selecting winners for research dollars, but rather about designing a framework to be sure the key cost components are addressed.

2. Economic framework

2.1 *Setting the stage*

Consider the following problem facing a coal-fired power plant developer: Carbon management requires that the CO_2 emissions from the plant's facilities will need to be either offset with carbon credits or not emitted into the atmosphere in the form of CO_2 gasses. Assuming that the plant is responsible for the all of the costs of its actions with respect to a management regime, the planner will seek to minimize the cost of complying with the regulations, where the marginal conditions require that the marginal costs of sequestering the last unit of CO_2 be equal across or among the options. From a societal perspective, efficient policies for carbon management are also based on the marginal principles: equating marginal benefits and marginal costs across all of the alternatives. In this paper we address a subset of the alternatives (sub-sea basalts and conventional saline -- see Goldberg et al. [4] for description of subsea basalt), the choice among alternative sequestration sites assuming that the plant has made the decision to capture the CO_2 as opposed to purchasing carbon offsets, and that enhanced oil recovery options or other means of revenue from sale of CO_2 are not available.

2.2 Economic specification

We define two categories of costs for any given unit of CO_2 that is generated in period t: the costs that will be incurred in period t, (or in small time frame relative to period t,) which include capture and compression, transport, and injection; and the longer term costs associated with monitoring and verifying and any associated costs related to environmental damages. We assume that the plant would be responsible for damages, although these damages could be dealt with through insurance markets (not considered in this paper). In addition, this specification is static and meant to be illustrative of the tradeoffs between the CCS costs for two sinks which differ in short term costs and longer term costs associated with avoiding environmental damages. Further research will develop the dynamic counterpart to this specification.

2.3 Component costs

2.3.1. Capture and compression costs

These are frequently labelled the largest component of overall CCS costs. It includes the amortized capital costs of the capture facility and the parasitic load costs for operating the capture and compression operations.

Define V as the volume of CO_2 sequestered, $\overline{C_t}$ as the total amount of CO_2 emitted at period t, and $C_a(\bullet)$ as the capture and compression cost for a certain amount of CO_2.

Assume the costs are increasing in V, with a constant or decreasing rate ($\frac{d}{dV}C_a > 0$, $\frac{d^2}{dV^2}C_a \le 0$).

2.3.2. Transport costs

They include the cost of constructing pipelines; operation and maintenance costs and other costs. Off shore pipelines are about 40% to 70% more costly than onshore pipes of the same size. [2]

Define P_p as the cost of constructing a unit length of pipelines, L as the length of pipelines, $T_r^1(V^1, P_p^1, L^1)$ as the transportation cost function for sub-seafloor basalt carbon sequestration, $T_r^2(V^2, P_p^2, L^2)$ as the transportation cost function for continental saline carbon sequestration.

Assume the costs are increasing in V, with a decreasing rate ($\frac{\partial T_r}{\partial V} > 0$, $\frac{\partial^2 T_r}{\partial V^2} < 0$); are increasing in P_p, with a constant rate ($\frac{\partial T_r}{\partial P_p} > 0$, $\frac{\partial^2 T_r}{\partial P_p^2} = 0$); and are increasing in L, with a constant rate ($\frac{\partial T_r}{\partial L} > 0$, $\frac{\partial^2 T_r}{\partial L^2} = 0$). Also, assume that constructing a unit length of pipelines for sub-seafloor basalt carbon sequestration is more expensive than that for continental saline aquifers ($P_p^1 > P_p^2$), and the length of pipelines for sub-seafloor basalt is longer than that for continental saline aquifers ($L^1 > L^2$).

2.3.3. Injection costs

They include the cost of drilling wells; infrastructure; and project management. The unit injection cost is higher offshore than onshore. [2]

Define P_w as the cost of drilling a unit length of well, H as the depth/height of the well, and $In(V, P_w, H)$ as the injection cost function.

Assume the costs are increasing in V, with a decreasing rate ($\frac{\partial In}{\partial V} > 0$, $\frac{\partial^2 In}{\partial V^2} < 0$); are increasing in P_w and H ($\frac{\partial In}{\partial P_w} > 0$, $\frac{\partial In}{\partial H} > 0$).

2.3.4. Long-term costs

They include damages of leakage to the atmosphere or to the ground water aquifer.

Define $P_a(V)$ as the probability of CO_2 leakage to the atmosphere, D_a as the damage of CO_2 leakage to the atmosphere, $P_w(V)$ as the probability of CO_2 leakage to the ground water aquifers, and D_w as the damage of CO_2 leakage to the ground water aquifers.

Then we can specify:

$$E_D = P_a(V) \cdot D_a + P_w(V) \cdot D_w \tag{1}$$

as the expected damage function evaluated at time t. Note that the costs of monitoring can be subsumed into the probability, and the firm can lower the probability if it incurs additional costs associated with more careful monitoring. Further refinement to $P_a(V)$ will be to include site specific facts that could influence the probability of CO_2 leakage.

Assume that the probability of CO_2 leakage to the atmosphere will increase as the volume of CO_2 increases, with an increasing rate ($\frac{\partial P_a}{\partial V} > 0$, $\frac{\partial^2 P_a}{\partial V^2} > 0$). As suggested by Goldberg [4], we specify that $P_a^1(V) < P_a^2(V)$, because of the additional trapping mechanism that are likely to exist for trapping CO_2 within the deep-sea basalt.

We also specify that P_w will increase in V , with an increasing rate ($\frac{\partial P_w}{\partial V} > 0$, $\frac{\partial^2 P_w}{\partial V^2} > 0$ and $\frac{\partial P_w^1}{\partial V} \approx 0$), [4] and $D_w \gg D_a$, i.e. the damage of CO_2 leakage to the ground water is much higher than that to the atmosphere. Leakage to atmosphere would be valued at a unit cost of CO_2 traded in the carbon markets, damages of leakage to groundwater would be more problematic to value, and we hypothesize that the value is greater that unit carbon price. This can be a testable hypothesis and would require valuing damages to groundwater aquifers.

2.3.5. Total costs

The total cost function of CCS in the sub-seafloor basalt could be written as the summation of all the partial costs:

$$C^1(V^1) = C_a(V^1) + Tr(V^1, P_p^1, L^1) + In(V^1, P_w^1, H^1) + P_a^1(V^1) \cdot D_a + P_w^1(V^1) \cdot D_w \tag{2}$$

Similarly, the total cost function of CCS in the continental saline is:

$$C^2(V^2) = C_a(V^2) + Tr(V^2, P_p^2, L^2) + In(V^2, P_w^2, H^2) + P_a^2(V^2) \cdot D_a + P_w^2(V^2) \cdot D_w \tag{3}$$

2.4 The problem

Using these specifications we can return to the original motivation: given a certain amount of CO_2 to be sequestered, which is a least cost (better) option: Sub-seafloor or continental saline?

We construct a cost minimization problem as follows:

$$\begin{aligned} \min \quad & C^1(V^1) + C^2(V^2) \\ s.t. \quad & V^1 + V^2 = \overline{C_t} \\ & V^1 \geq 0 \\ & V^2 \geq 0 \end{aligned} \tag{4}$$

There are four possible solutions to the above problem:

a. $V^1 = 0$, $V^2 = 0$. It happens only when $\overline{C_t} = 0$;

b. $V^1 = 0$, $V^2 = \overline{C_t}$. I.e. we will sequester all of the CO_2 into continental saline aquifer. It happens when the marginal cost of CCS into sub-seafloor basalt is always higher than that of continental saline ($mc^1 \geq mc^2$).

c. $V^1 = \overline{C_t}$, $V^2 = 0$. I.e. we will sequester all of the CO_2 into subsea floor basalt. It happens when the marginal cost of CCS into continental saline is always higher than that of sub-seafloor basalt ($mc^2 \geq mc^1$).

d. $V^1 > 0$, $V^2 > 0$ so that they meet conditions $mc^1(V^1) = mc^2(V^2)$ and $V^1 + V^2 = \overline{C_t}$.

As we have seen, the marginal cost of CCS is a key figure in determining the preferable solution. Now let us write the marginal cost functions as the following:

$$mc^1(V^1) = \frac{dC_a(\cdot)}{dV^1} + \frac{\partial T_r(\cdot)}{\partial V^1} + \frac{\partial In(\cdot)}{\partial V^1} + \frac{\partial P_a^1(\cdot)}{\partial V^1} \cdot D_a + \frac{\partial P_w^1(\cdot)}{\partial V^1} \cdot D_w \quad (5)$$

$$mc^2(V^2) = \frac{dC_a(\cdot)}{dV^2} + \frac{\partial T_r(\cdot)}{\partial V^2} + \frac{\partial In(\cdot)}{\partial V^2} + \frac{\partial P_a^2(\cdot)}{\partial V^2} \cdot D_a + \frac{\partial P_w^2(\cdot)}{\partial V^2} \cdot D_w \quad (6)$$

In Table 1 we compare the value of each term in both of the cost functions:

Table 1

Short/Long Term	Marginal Costs	Analysis
Short Term	$\frac{dC_a(\cdot)}{dV}$	Decreasing function; $\frac{dC_a(\cdot)}{dV^1}\Big\|_{V^1=\overline{V}} = \frac{dC_a(\cdot)}{dV^2}\Big\|_{V^2=\overline{V}}$
	$\frac{\partial T_r(\cdot)}{\partial V}$	Decreasing function; $\frac{\partial T_r(\cdot)}{\partial V^1}\Big\|_{V^1=\overline{V}} > \frac{\partial T_r(\cdot)}{\partial V^2}\Big\|_{V^2=\overline{V}}$
	$\frac{\partial In(\cdot)}{\partial V}$	Decreasing function; $\frac{\partial In(\cdot)}{\partial V^1}\Big\|_{V^1=\overline{V}} > \frac{\partial In(\cdot)}{\partial V^2}\Big\|_{V^2=\overline{V}}$
Long Term	$\frac{\partial P_w(\cdot)}{\partial V}$	Increasing function; $\frac{\partial P_a^1(\cdot)}{\partial V^1}\Big\|_{V^1=\overline{V}} < \frac{\partial P_a^2(\cdot)}{\partial V^2}\Big\|_{V^2=\overline{V}}$
	$\frac{\partial P_w(\cdot)}{\partial V}$	Increasing function; $\frac{\partial P_w^1(\cdot)}{\partial V^1}\Big\|_{V^1=\overline{V}} \approx 0$, $\frac{\partial P_w^1(\cdot)}{\partial V^1}\Big\|_{V^1=\overline{V}} < \frac{\partial P_w^2(\cdot)}{\partial V^2}\Big\|_{V^2=\overline{V}}$

At time t, if the volume of CO_2 to be sequestered ($\overline{C_t}$) is small, then the short-term costs contribute most of the total cost, and continental saline aquifer may have an advantage. This is due to the fact that for small amounts of CO_2 the probability of damage is low, since the geological sinks are underutilized or stressed. As the amount of CO_2 is increasing, the long-term costs are becoming more and more important; therefore the subsea floor basalt may be preferable. We summarize this in Table 2.

Table 2

$\overline{C_t}$	Comparison between marginal costs	Choice
$\overline{C_t} < V^0$	$mc^1(V) > mc^2(V), 0 \le V < \overline{C_t}$	Continental saline aquifers
$\overline{C_t} \ge V^0$	$mc^2(V) < mc^1(V), 0 \le V < V^0$; $mc^2(V) \ge mc^1(V), V^0 \le V < \overline{C_t}$	Choose V^1, V^2 such that $mc^1(V^1) = mc^2(V^2)$
$\overline{C_t} \gg V^0$	$mc^2(V) \gg mc^1(V), V \gg \overline{C_t}$	Sub-seafloor basalts

3. Towards empirical assessments: sub-sea basalts

In the above specification, the pieces of critical information include (a) the location of the plant to the nearest continental site and the nearest sub-sea sequestration site; capture and compression costs, transport infrastructure and operating costs, injection costs by sink type, and (b) the types of damages that may occur, the probability of damages occurring and the value of the damages. We discuss the components of (b) as they related to the sub-sea basalts.

Damages and the probability of damages occurring are influenced by many factors including the capacity of the sink relative to the volume injected, the proximity to other resources that can be negatively impacted by migration of CO_2, the trapping mechanisms and the long run mobility of the injected CO_2. As noted by Goldberg et al [4], injection into deep-sea basalt formations provides unique and significant advantages over other potential geological storage options, including (i) vast reservoir capacities sufficient to accommodate centuries-long U.S. production of fossil fuel CO_2 at locations within pipeline distances to populated areas and CO_2 sources along the U.S. west coast; (ii) sufficiently closed water-rock circulation pathways for the chemical reaction of CO_2 and (iii) significant risk reduction for post-injection leakage by geological, gravitational, and hydrate-trapping mechanisms.

Important mechanisms for trapping CO_2 injected within subsea basalt also include (i) blanketing deep-sea sediments, which form a low-permeability stratigraphic barrier impeding vertical fluid migration; (ii) the formation of CO_2 hydrate, which is denser and less soluble than liquid CO_2 in seawater; and (iii) gravitational trapping at water depths 2,700 m, where injected CO_2 is denser than typical seawater. Goldberg et al [4] note that all three of these mechanisms are simultaneously available within ocean crust, providing independent protective barriers that could safely isolate the oceans, benthic ecosystems, and the atmosphere from leakage of CO_2 escaping from subsea basalt aquifers. To be useful in an economic assessment framework, additional research is needed on how these trapping mechanisms would impact (reduce) the probability of migration or leakage to the atmosphere.

Economists often conclude that the uncertainties associated with assessing many environmental problems are great and critical to policy design. (See excellent discussion in Pindyck [5] and related references) This problem – how to most effectively sequester CO_2 for long time frames -- is no exception. The complexity of the challenges is to deal with damage functions that may be highly nonlinear in CO_2 and the cost of damage abatement nonlinear as well. This may imply that our specification of expected values is in error: expected value of the damages may differ from the function of the expected value. Tipping points for CO_2 emissions into the atmosphere and leakages to environmental mediums are also problematic from a conventional cost benefit analysis (CBA). Finally, the extremely long time horizons also exacerbate the uncertainty over the costs and benefits. These complications are glossed over in our specification in section 2, but would need to be dealt with in a dynamic specification that would flow from this static example.

Preliminary information by Goldberg et al. [4] indicates that CO_2 volumes are extensive in the basalts on the Juan de Fuca plates. Depending upon the form and the fate of the injected CO_2 the capacity is estimated to be from 208 – 250 Gt of carbon. Thus the capacity potential is huge: at the current annual emission rate of 1.7 Gt of carbon per year by the United States, the basement on the Juan de Fuca plate alone would provide sufficient CO_2 sequestration capacity for nearly 150 years. Given its proximity to the U.S. west coast population centers a scenario may be to assess the Juan de Fuca reservoir as a sequestration option for CO_2 sources from western states, via pipeline transport. In Figure 1, Goldberg et al [4] showed the deep-sea basalt region for CO_2 sequestration on the Juan de Fuca plate. This possibility of using the deep-sea basalt is consistent with the planning model scenario we set up in section 2 of the paper. New fossil fuel power plants located near the coast may have many options for sequestration sinks. The parameters on capacity and injected volumes can be used in economic analysis of expected damages and compared to similar ratios for other saline (continental) formations. (*Economic approach to estimate the damage functions to be added in next version.*)

4. Concluding comments

The injection of CO_2 in deep-sea basalt offers critical advantages for sequestration that warrant comparison of the economic costs and benefits relative to other sequestration storage options. How one begins to quantify the analysis is in part dependent on the data, much of which can be gleamed from pilot injection studies. The framework in this paper provides a preliminary guideline on how information on leakages, trapping and volumes can be utilized to assess the costs of alternative sequestration options.

Important topics for ongoing integrative economic and geological research include *in situ* reaction rates for dissolution of injected CO_2, carbonate precipitation rates and the resulting rates of change in permeability, and site-specific hydrological testing, along with information on how these properties and the proximity of other environmental assets (like groundwater aquifers) will impact expected damages. A testable set of hypotheses evolve around the importance of the trade off between the short term costs and the long terms costs. In many ways this is

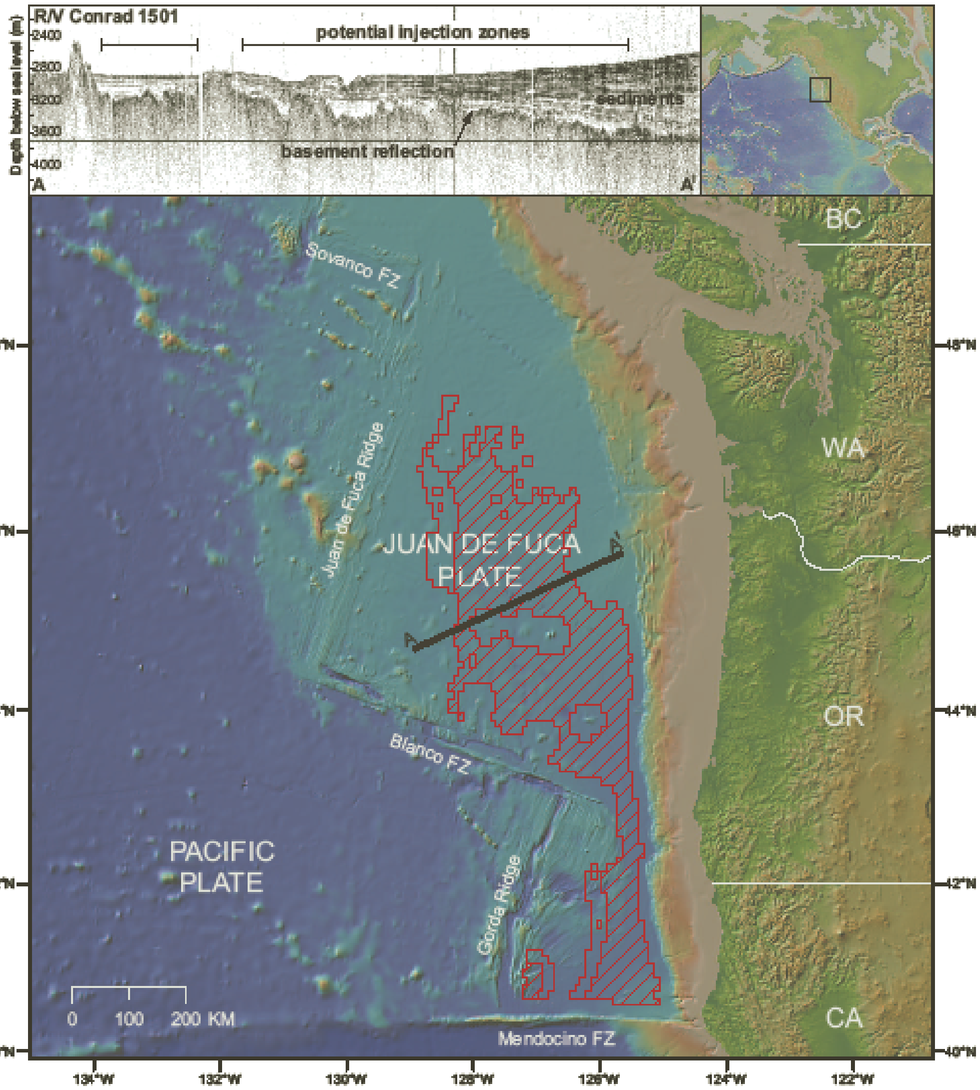

Figure 1. Location of Juan de Fuca plate for deep-sea basalt CO_2 sequestration. Goldberg et al. [4]

an empirical issue and only through further scientific investigation of these *in situ* effects combined with economic assessments can the viability of deep-sea basalt reservoirs such as the Juan de Fuca plate be determined.

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