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**Title**

CO2 Capture and Geologic Storage: The Possibilities

**Permalink**

<https://escholarship.org/uc/item/61b0513n>

**Journal**

Ground Water, 51(6)

**ISSN**

0017-467X

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**Publication Date**

2013-11-01

**DOI**

10.1111/gwat.12041

Peer reviewed

## CO<sub>2</sub> Capture and Geologic Storage: The Possibilities

by Hugo A. Loáiciga

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### Abstract

Carbon dioxide (CO<sub>2</sub>) capture and geologic storage has been postulated as one possible method to stabilize the atmospheric concentration of CO<sub>2</sub> by injecting and storing it in deep geologic formations. This issue paper analyzes the viability of capture and geologic storage of becoming an effective method to aid in stabilizing the atmospheric concentration of CO<sub>2</sub>. It is herein shown that such viability is contingent on overcoming major obstacles that are hydrogeological, technical, and economic in nature. Our analysis indicates that capture and geologic storage is likely to have negligible success in reducing the atmospheric buildup of CO<sub>2</sub> in the coming decades. The magnitude of the anthropogenic emissions of CO<sub>2</sub> indicates that a transition of the world economy away from reliance on fossil fuels might be the only path to stabilize its atmospheric concentration.

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### Introduction

The rapid increase of greenhouse gases in the atmosphere since the Industrial Revolution (ca. 1750) and concerns over its adverse impacts on Earth has prompted the search for methods to reduce their emission to the atmosphere by human activity (Loáiciga 2011; International Energy Agency 2012). Special attention has been given to carbon dioxide (CO<sub>2</sub>), the most voluminous among the anthropogenic greenhouse gases emitted to the atmosphere and the one with the largest contribution to the radiative forcing of the atmosphere (Intergovernmental Panel on Climate Change 2007). Capture and geologic storage of CO<sub>2</sub> has been proposed as a method (in combination with other measures) to reduce its atmospheric emissions by human actions (see, e.g., Bachu 2008; Haszeldine 2009; Lemieux 2011; Pollyea and Fairley 2012; Szulczewski et al. 2012; U.S. Department of Energy 2012; Warwick and Zhu 2012, for recent relevant reviews or studies related to this topic). This issue paper presents an analysis of CO<sub>2</sub> capture and

geologic storage (CCS) aimed at assessing its viability for reducing anthropogenic atmospheric CO<sub>2</sub> emissions in the coming decades and centuries. The analysis considers hydrogeologic, technical, and economic barriers to its large-scale implementation.

### A Typical System for CCS

Figure 1 depicts the components of a system for CCS. A typical capture and geologic storage system has the following physical components: (1) an emission source; (2) a system to capture CO<sub>2</sub> at the emission source; (3) conveyance infrastructure to transport the captured CO<sub>2</sub> from the capture point to the injection area; (4) an injection system; (5) monitoring of injected CO<sub>2</sub> to detect any leakage toward the surface. The requirements on the capture and geologic storage system's components for its feasibility are reviewed in the following sections.

### Capture and Conveyance

The capture component of the system shown in Figure 1 could be implemented with relative ease at point sources of CO<sub>2</sub>, such as fossil-fueled power plants, cement factories, and other such large, stationary, emitters of CO<sub>2</sub>. Geographically distributed sources of CO<sub>2</sub>, common

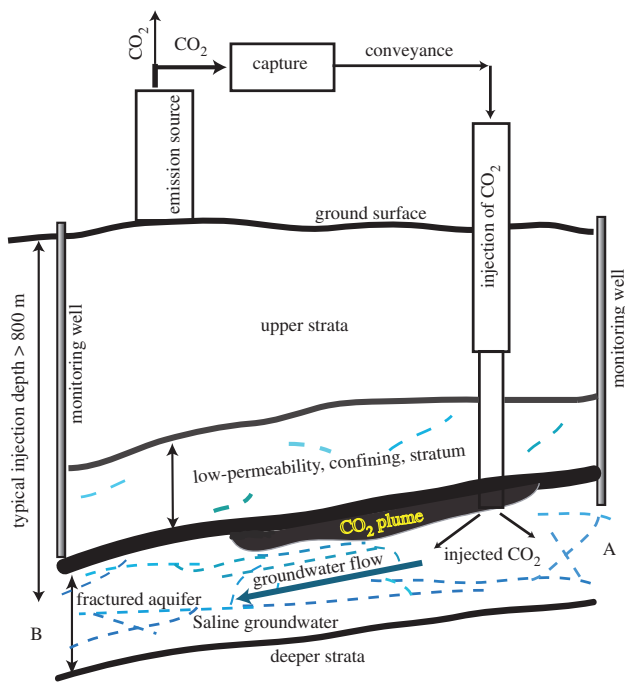
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Received November 2012, accepted January 2013.

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doi: 10.1111/gwat.12041

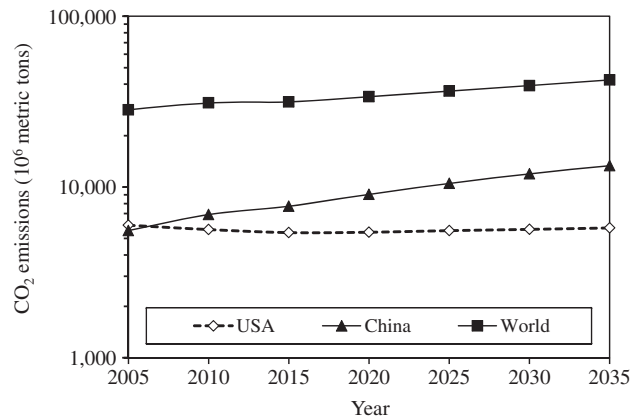


**Figure 1.** Schematic of a CO<sub>2</sub> capture and geologic storage system and its components. Elevation view not drawn to scale.

in the transportation sector of the economy (in which combustion engines of vehicles are main emitters), or sources in the residential and commercial sectors, would be more difficult, if not impossible, to tap onto. The transportation sector is particularly challenging from the viewpoint of the geologic storage, due to the high mobility of its CO<sub>2</sub> sources. At the same time, transportation is a major contributor of CO<sub>2</sub> emissions. In the United States, for example, whose economy is among the largest greenhouse gas emitters worldwide, the percent contribution of the commercial, industrial, residential, and transportation sectors to its total CO<sub>2</sub> equivalent<sup>1</sup> emissions are 18.5, 27.5, 20.7, and 33.3, respectively (Energy Information Administration 2012).

Although the efficiency of the combustion engines that power most motorized vehicles has improved, this gain is neutralized by the rapid increase in the number of vehicles driven worldwide, most of which are fossil-fuel powered wholly or partially. The potential for electric vehicles or ethanol-fueled vehicles to reduce CO<sub>2</sub> emissions in the transportation sector is questionable when vetted through a life-cycle energetic/emissions analysis. This is so because the sources of recharging electricity in the case of electric vehicles, or the dedication of water, land, and other inputs to the production of ethanol can easily result in a worsening of CO<sub>2</sub> emissions when compared with those from relatively efficient fossil-fuel powered vehicles (see a review of this topic in Loáiciga 2011).

<sup>1</sup>The CO<sub>2</sub> equivalent of a greenhouse gas is the amount of carbon dioxide by weight emitted into the atmosphere that would produce the same radiative forcing of the weight of the gas in question.



**Figure 2.** The annual (anthropogenic) total CO<sub>2</sub> equivalent emissions by China, the United States, and worldwide in the period 2005 to 2035. The 2005 and 2010 amounts were calculated from emissions data, whereas those for years 2015 to 2035 were estimated from model predictions. Amounts are in millions of metric tons. 1 metric ton = 1000 kg. Source: Energy Information Administration (2010).

The second component of a capture and geologic storage system is conveyance from the capture point to the injection point. It faces daunting obstacles to its implementation. One reason is that large point sources of CO<sub>2</sub> are not, commonly, found overlying or near suitable geologic formations in which to inject the captured gas and store it underground permanently. Szulczewski et al. (2012), for example, identified 11 aquifers in the United States with a potential for CO<sub>2</sub> storage. Four of these are in western states, relatively distant from large population centers. Capture and geologic storage would require conveyance of large amounts of CO<sub>2</sub> from sources to sinks. It is shown below that the magnitude of CO<sub>2</sub> conveyance would be in the order of tens of gigatons annually to stabilize CO<sub>2</sub> emissions worldwide. Of the 11 aquifers cited by Szulczewski et al. (2012), four underlie or are near densely populated areas. In this instance, the challenge for capture and geologic storage is the risk posed by large-scale burial of a toxic gas under heavily populated areas. The following section delves into the magnitude of anthropogenic CO<sub>2</sub> emissions. The section “Capture, Conveyance, and Injection Cost” expands on the analysis of capture and geologic storage costs.

### CO<sub>2</sub> Emissions and Its Atmospheric Mass Balance

Figure 2 shows the annual, anthropogenic, total CO<sub>2</sub> equivalent emissions by the United States and China, the world’s largest and second largest economies, respectively, and by the world’s community of countries. The emissions are expressed in millions of metric tons annually (1 metric ton = 1000 kg).

It is evident from Figure 2 that China has overtaken the United States as the country with the largest emission of atmospheric CO<sub>2</sub>. Its emissions will continue to rise as China undergoes economic modernization. The worldwide emissions are predicted to continue an upward trend through 2035, and are estimated to be slightly over

42,000 million metric tons (42 gigatons) annually by then. Also, the United States emissions are seen to have reached a nearly constant level at about 5500 million metric tons annually. Besides these trends, it is a remarkable feature of Figure 2 that the magnitude of worldwide anthropogenic CO<sub>2</sub> equivalent being added to the atmosphere annually. This feature is a sobering reminder of the effort facing any attempt to reduce atmospheric CO<sub>2</sub> by capture and geologic storage and by other means. Anthropogenic emissions of CO<sub>2</sub> have contributed to raising its atmospheric concentration from 280 parts per million by volume (ppmv) in the middle of the eighteenth century to 385 ppmv in 2010 (Loáiciga 2011). The mass of atmospheric CO<sub>2</sub> in 2010 was estimated by H.A.L. to be in the order of  $1000 \times 10^9$  metric tons (= 1000 gigatons) in 2012 (estimate based on data presented in Houghton 2004).

The atmospheric mass balance of CO<sub>2</sub> is governed by the CO<sub>2</sub> emissions to the atmosphere by human activities and by natural processes, which augment the atmospheric CO<sub>2</sub>, and by the removal of atmospheric CO<sub>2</sub> by natural processes and by human action, which lower the atmospheric CO<sub>2</sub>. The change in atmospheric CO<sub>2</sub> over a time interval equals the emissions to reduce the removals from the atmosphere during the same time interval. An obvious manner of stabilizing the mass of atmospheric CO<sub>2</sub> at a sustainable level would be to minimize anthropogenic emissions and maximize anthropogenic removal. Yet, current data show that worldwide anthropogenic emissions are rising, whereas CCS is at a developmental stage (International Energy Agency 2012; U.S. Department of Energy 2012).

## Injection, Geologic Storage, and Monitoring

The injection and geologic storage of CO<sub>2</sub> are interdependent: a high injection rate may be feasible when there is available interconnected pore volume in the host formation. This is contingent upon fluids present on the pore volume being displaceable by injected CO<sub>2</sub> without rising pore pressure beyond the levels that could fracture the host formation and confining ones. Hydrogeologists measure the interconnected pore volume in terms of effective porosity, which is the ratio of the volume of interconnected pore volume in a mass of rock to the bulk volume of the rock mass. Storage of injected CO<sub>2</sub> in the host formation—as depicted in Figure 1—can be attained if (1) the overlying confining formations (“cap rock” in the jargon) have sufficiently low hydraulic conductivity to reduce upward leakage to negligible levels, (2) there is no lateral migration of injected CO<sub>2</sub> to the exterior of the host formations, and (3) natural and man-made migration pathways to the surface (open boreholes are a case in point) are absent.

Lateral and vertical confinement of injected CO<sub>2</sub> can be an unrealistic proposition. It is shown in Figure 1 that typical injection (saline) aquifers feature groundwater flow in a general direction from an upstream region A to a downstream region B. Injection aquifers, except for rare, fossil, ones that become isolated from the global water

cycle, have a zone of recharge (i.e., a zone where water enters subsurface flow) and a zone of discharge (where groundwater leaves the soil-rock subsurface). Injected CO<sub>2</sub> will tend to migrate in the direction of groundwater flow toward a discharge zone by advection. The CO<sub>2</sub> will resurface by lateral migration unless it is physically trapped within the aquifer or chemically converted to other forms. Its density, being lighter than that of groundwater, would cause upward movement by buoyancy toward confining strata or recharge zones, also. Bachu (2008) has proposed mechanisms that may trap CO<sub>2</sub> in the injection aquifer on a long-term, perhaps permanent, basis. These mechanisms, however, remain to be proven at the scale of injection that consequential capture and geologic storage would demand.

The lateral migration and vertical leakage of injected CO<sub>2</sub> are unavoidable risks that must be carefully weighed prior to engaging in large-scale capture and geologic storage operations. Risk management can be aided by hydrogeologic and geophysical analyses, surveys, testing, and subsurface monitoring. Monitoring of injected CO<sub>2</sub> deployed as an early-warning system to detect failures in the containment of injected CO<sub>2</sub> must be a key component of capture and geologic storage. Testimony to the importance of injection monitoring is the 2010 U.S. Environmental Protection Agency’s regulations for CO<sub>2</sub> injection (class VI) wells that prescribe geologic site characterization, well construction, and monitoring requirements to protect underground sources of drinking water (U.S. Environmental Protection Agency 2010).

Assuming that deep confinement of injected CO<sub>2</sub> is feasible, a natural factor controlling the viability of geologic storage is the availability of interconnected pore volume in the host formation. At depths suitable for CO<sub>2</sub> injection (typically in excess of 800 m), the interconnected pore volume is associated with the occurrence of fractures, which are broadly defined as any natural break in a rock mass (U.S. Bureau of Reclamation 1998). Considering an injection depth equal to 1500 m, where injected CO<sub>2</sub> may have a density of about 700 kg/m<sup>3</sup> under certain subsurface conditions and injection conditions (see Bachu 2003; Lemieux 2011), the amount of interconnected formation pore volume that would be required to store the year-2035 worldwide, annual, anthropogenic CO<sub>2</sub> emissions would be approximately  $42,000 \times 10^6 \times 1000 \text{ kg} / (700 \text{ kg/m}^3) = 60 \times 10^9 \text{ m}^3 = 60 \text{ km}^3$ . Assume, for the sake of argument, that the annual rate of CO<sub>2</sub> injection is maintained at 42,000 million metric tons for 65 years beginning in 2035, and that the annual anthropogenic CO<sub>2</sub> emissions stabilize in 2035, and thereafter, at the 42,000 million metric-ton level. This injection program would require 3900 km<sup>3</sup> (= 65 × 60 km<sup>3</sup>) of interconnected pore space occupied by injected CO<sub>2</sub> by the end of the twenty-first century. Yet, upon completion, this injection program would not have reduced the amount of atmospheric CO<sub>2</sub> below that which existed at its inception in year 2035. Most likely, it would maintain the year-2035 atmospheric CO<sub>2</sub> content approximately constant for 65 years. The scenario

of atmospheric CO<sub>2</sub> stabilization just described is contingent on the natural rates of CO<sub>2</sub> emission and removal canceling each other out during the 65-year period.

The injection of tens of cubic kilometers of CO<sub>2</sub> annually in deep-fractured rocks detailed in the previous paragraph requires scrutiny from the viewpoint of injectivity. That is, can so much CO<sub>2</sub> be injected annually? Critical to answering this question is the nature of fracture connectivity, spacing, and fracture aperture at depth of 1000 m or deeper. The cubic law for subsurface laminar flow states that the hydraulic conductivity is proportional to the cube of fracture aperture. Bedrock fractures are commonly tight to slightly open at injection depths of 1000 m or deeper, with apertures in the order of 10<sup>-4</sup> m (U.S. Bureau of Reclamation 1998). This means that the hydraulic conductivity of fracture bedrock would be proportional to a magnitude in the order of 10<sup>-12</sup> m<sup>3</sup>, the proportionality constant being equal to one-twelfth of the product of the injected CO<sub>2</sub>'s density time the acceleration of gravity divided by the product of the injected CO<sub>2</sub>'s viscosity times the inter-fracture average separation (see de Marsily 1986). The resulting hydraulic conductivity of deep, fractured, bedrock aquifers is likely to be too small to allow sufficiently high injection rates of CO<sub>2</sub> to accommodate storage volumes in the order of tens of cubic kilometers annually. Detailed site-specific studies or injection tests would have to be conducted to judge the adequacy of a given geologic formation to receive large volumes of injected CO<sub>2</sub> in a timely fashion. In addition, the fate of displaced resident mineralized (saline) groundwater and the possible disruption of deep groundwater circulation processes must be carefully assessed to ensure sustainability of any proposed injection scheme.

### Porosity and Pore Volume of Deep Fractured Rocks

The amount of interconnected pore volume required to inject large amounts of CO<sub>2</sub> in the host formation deserves scrutiny. Table 1 shows the range of porosity in common rocks reported by Krynnine and Judd (1972). The lower values of the ranges of porosity shown in Table 1 for each rock type correspond to slightly fractured rocks, whereas the higher values are associated with moderately to intensely fractured rocks (U.S. Bureau of Reclamation 1998). The data in Table 1 indicate that porosity varies roughly between 0 and 25%. Yet, the porosity data in Table 1 are applicable to near-surface geostatic stress. The values on Table 1 must be reduced several-fold when dealing with deep bedrock aquifers where CO<sub>2</sub> might be injected.

Suppose that an injection formation has high-effective porosity equal to 10% and 1 km thickness. Injection pore volumes equal to 100 or 1000 km<sup>3</sup> would have to encompass areas of 1000 or 10 000 km<sup>2</sup>, respectively. A formation with only half the thickness would double the required areas. Another formation with 1 km thickness and porosity near 1%, would have to spread over 10 000 or 100 000 km<sup>2</sup> if the injection volumes were 100 or 1000 km<sup>3</sup>, respectively. An annual global injection rate of 3900 km<sup>3</sup>, as posited in the previous section, in bedrock

**Table 1**  
**Range of Porosity in Near-Surface Common Rocks (After Krynnine and Judd 1972)**

Rock Type	Range of Porosity (%)
Igneous	
Basalt	0.22 to 22.06
Granite	0.44 to 3.98
Sedimentary	
Sandstone	1.62 to 26.40
Breccia	0.78 to 18.73
Limestone	0.27 to 4.36
Metamorphic	
Gneiss	0.30 to 2.23
Marble	0.31 to 2.02

aquifers with average porosity equal to 5% would require an annual injection area equal to 78,000 km<sup>2</sup>. Maintaining this rate of injection for 65 years from 2035 to 2100 would imply an injection area of about 5.1 million km<sup>2</sup>. These calculated areas and volumes of CO<sub>2</sub> injection assume that it can be achieved safely, timely, and in a sustainable manner.

The previous examples of area-thickness-porosity requirements show the paramount importance of porosity and formation thickness in determining the area over which fractured, geologic formation must extend to offer the magnitude of pore volume needed for large-scale CO<sub>2</sub> injection. Assessment studies are underway in several countries to determine the available volume for the safe injection of CO<sub>2</sub> (International Energy Agency 2012; U.S. Department of Energy 2012; Warwick and Zhu 2012). A 2012 report by the International Energy Agency has shown that the current activity in CCS is small, mostly of an experimental nature. There is, however, substantial experience with commercial enhanced oil recovery and methane recovery operations involving the injection of CO<sub>2</sub>, and with other types of gaseous injections (natural gas, acid gases such as H<sub>2</sub>S) practiced to meet regulations. These injection practices, however, are insignificant in magnitude compared with the volume of injection required to stabilize global-scale anthropogenic emissions of CO<sub>2</sub> presented above.

### Injection, Hydraulic Fracturing, Induced Seismicity

Proponents of capture and geologic storage envision large volumes of CO<sub>2</sub> injection without undue creation of excess pore pressures that would further fracture the host and confining formations. The vast amount of CO<sub>2</sub> injection needed for it to be consequential casts doubt on the ability to maintain hydrostatic pressure conditions when engaging in large-scale injection. Therefore, this author ponders the possibility of a scenario whereby hydraulic fracturing may be caused by CO<sub>2</sub> injection. Hydraulic fracturing consists of increasing the (interconnected) pore volume of rocks by injecting pressurized fluids and sand into a rock mass. Hydraulic fracturing—also called



hydrofracturing or fracking—is widely used to mobilize hydrocarbons (natural gas, in particular) to extraction wells for removal and processing in dedicated facilities at ground level where they are converted into commercial fuels. An early analysis of the mechanics of hydrofracturing was reported by Hubert and Willis (1957). An updated analysis can be found in Fjaer et al. (2008). Hydrofracturing takes effect in two forms. First, high pressure created by injected fluids (could be CO<sub>2</sub>) fractures previously intact parts of rocks. Second, injected fluids enter existing (natural) fractures and increase their thickness and length thus enlarging the fracture-related pore volume.

Although the increment of secondary porosity by hydrofracturing might seem desirable from the viewpoint of storing CO<sub>2</sub> underground, it poses two concerns. First, high fluid pressure underground may exacerbate seismicity. The mechanisms linking high fluid pressure to induced seismicity in a variety of tectonic settings have been documented by several authors (see, e.g., Irwin and Barnes 1975; Keller and Loáiciga 1993, among others). The seismogenic depth of events with a moment magnitude in excess of five is typically between 5 and 50 km (Keller and Loáiciga 1993). Thus, CO<sub>2</sub> injection would have to be very deep and exert large fluid pressures to become a factor in triggering sizeable earthquakes. Nevertheless, the threat of induced (micro) seismicity in tectonically active areas deserves scrutiny prior to permitting large-scale geologic capture of CO<sub>2</sub>. A recent report by the National Research Council (2012) called for more in-depth study of the possible connection between hydrofracturing and induced seismicity.

The second concern stemming from hydrofracturing is that it could create pathways for CO<sub>2</sub> to return to the atmosphere or to contaminate fresh groundwater if extensive fracturing of the host rock takes place. The creation of these pathways (connected fractures) can be explained with the principles of rock mechanics. To do so, consider that the tensile strength of rocks has been measured to be as high as 7000 kPa in granite, and as low as 700 kPa in sandstone. These strengths are a fraction of the compressive strengths in the same rocks. For this reason, it is customary to assume that rocks have negligible tensile strength (Krynine and Judd 1972). The critical injection pressure of CO<sub>2</sub> at a depth  $z$  below the ground surface that would cause tensile failure in rock with a tensile strength  $\tau$  is derivable from the theory of elasticity applied to rock mechanics. The critical injection pressure ( $P_{\text{crit}}$ ) is approximated by the following equation:

$$P_{\text{crit}} \cong \frac{8}{5} \sigma'_z + \frac{3}{5} \tau \quad (1)$$

$\sigma'_z$  denotes the vertical effective stress at a depth  $z$ .

Assuming  $\sigma_z$  represents the total vertical stress and  $P$  be the pore pressure at depth  $z$ , the vertical effective stress  $\sigma'_z$  equals  $\sigma_z - \alpha P$  (Nur and Byerlee 1971) in which the coefficient  $\alpha = 1 - (c_s/c_b)$ , where  $c_b$  and  $c_s$  (with  $c_s < c_b$ ) denote the compressibility of the porous rock and

of the mineral grains, respectively. The coefficient  $\alpha$  is close to 1 in unconsolidated sediments. It is a smaller fraction in bedrock.

To illustrate the significance of Equation (1), suppose that the depth of injection  $z = 1000$  m, that the rocks' average unit weight  $\gamma = 25$  kN/m<sup>3</sup>,  $\alpha = 0.8$ ,  $\tau = 0$  (this is a typical, conservative, assumption of zero tension for rocks), and the pore pressure is hydrostatic (i.e.,  $P = 1000 \text{ m} \times 9.81 \text{ kN/m}^3 = 9.81$  MPa). The injection pressure required to cause hydrofracturing in this case would be close to 27 MPa according to Equation (1). This is an injection pressure that could be reached at the considered injection depth with existing technology.

## Capture, Conveyance, and Injection Costs

The examples of the previous section calculated the geographical extent of host formations capable of holding thousands of cubic kilometers of injected CO<sub>2</sub>. The calculated areas vary from thousands to millions of squared kilometers depending on the effective porosity, formation thickness, and injected volume. Yet, accurate worldwide assessments may reveal that safe storage capacity for large-scale capture and geologic storage that would be meaningful in reducing atmospheric CO<sub>2</sub> emissions may exist (U.S. Department of Energy 2012; Warwick and Zhu 2012). Why then the puny advance of capture and geologic storage? The answer may rest with economics.

Capture of CO<sub>2</sub> at point sources would impose an added cost of doing business to industries, power generators, and other major emitters. Yet, it has been argued extensively in the technical literature that those polluters would shift to cleaner energy sources if their CO<sub>2</sub> emissions were taxed to recover the costs exerted by their emissions (see an analysis of the economics of greenhouse gas abatement in IPCC 2007). Or, they would install capture technology that would reduce the effect of the carbon tax on their operations. In either case, higher operating costs would most likely be passed to consumers. To date, however, neither option has slowed the rise of anthropogenic CO<sub>2</sub> emissions. Instead, carbon-trading permit exchanges have been created that have proven unsuccessful in reducing CO<sub>2</sub> emissions at a global scale. On the clean-energy front, gains have been made in installing new power capacity (solar and eolian, primarily), but not enough to loosen the stranglehold of fossil fuels on worldwide energy production. Coal, petroleum, and natural gas currently produce nearly 80% of the world's primary energy (Energy Information Administration 2010; Loáiciga 2011).

Large-scale capture and geologic storage faces an array of costs that include permitting, capturing, conveying, injecting, monitoring, operating, maintaining, administering, securing right-of-ways, insuring, and financing. These costs most likely will vary significantly from operation to operation based on local or regional conditions. The U.S. Department of Energy (2012) has produced cost estimates for some aspects of CCS. The economic

viability of CCS remains to be proven given the costs that it would generate.

Many point sources of CO<sub>2</sub> are geographically separated from suitable injection areas. The conveyance of millions of tons of captured CO<sub>2</sub> poses significant challenges. The United States' failed experience in finding underground storage location(s) for its nuclear waste was partly due to the complexities of moving radioactive material throughout the country: the sources of pollution and the suitable injection areas were a geographical mismatch. Moreover, public acceptance of large-scale injection of CO<sub>2</sub> under densely populated areas is uncertain. While CO<sub>2</sub> does not pose the same level of risk associated with high-level radioactive waste, it is not risk free, and it is a health hazard in air beyond a concentration in the order of 10<sup>4</sup> ppmv in air (compare with the 385 ppmv CO<sub>2</sub> atmospheric concentration in 2010).

In summary, burdensome conveyance logistics and costs, the large volume of injection needed to stabilize atmospheric CO<sub>2</sub>, and the questionable feasibility of injecting safely large masses of CO<sub>2</sub> in deep formations weigh heavily against large-scale capture and geologic storage. Several authors have proposed roadmaps to a world economy that would stabilize atmospheric CO<sub>2</sub> at a sustainable level (e.g., Pacala and Socolow 2004). For this to happen, however, humans would have to lessen their reliance on fossil fuels and change their approach to building, transportation, and land-use management profoundly.

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