

Geologic CO₂ Storage—Can the Oil and Gas Industry Help Save the Planet?

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Abstract

Avoiding greenhouse-gas (GHG) emissions will require large-scale implementation of several technologies. One of them is storage of CO₂ in subsurface formations. This represents a substantial new business sector for the E&P industry. But taking advantage of this opportunity will require addressing several challenges, including characterizing target formations, developing a workforce, gaining confidence of the public and of regulators, and establishing CO₂ as a commodity. Of these challenges, the most critical will be to train enough engineers and geoscientists for this new industry.

Introduction

How Big Could a Geologic CO₂ Storage Industry Be? The concentration of CO₂ in the Earth's atmosphere has been rising steadily for a century, especially in the last 40 years. There is widespread, though not universal, evidence that the Earth is warming (Kerr 2006). Whether the first phenomenon is the cause of the second continues to be debated in some quarters, the latest consensus of the Intergovernmental Panel on Climate Change (IPCC) notwithstanding (IPCC 2007). Political considerations soon may override that debate, however, resulting in widespread implementation of GHG-emissions policies. Thus, it is timely to consider the implications of such policies here—that is, for the engineers and geoscientists currently engaged in finding and producing hydrocarbons.

If—and currently it must still be regarded as a big “if”—society embarks upon a serious campaign of GHG avoidance, it will have a tremendous effect on the oil and gas industry. The scale of the task is one compelling reason. To have any effect on the rate of anthropogenic CO₂ emissions, it will be necessary to avoid or store several hundred

Bcf/D of CO₂. This requirement follows from three factors: the current rate of global emissions, which is approximately 7 billion tonne per year of carbon (Gt/a C) or approximately 1.4 Tcf/D CO₂; the forecasted growth in emissions to 14 Gt/a C by 2050 under a “business as usual” scenario; and choosing a target atmospheric-CO₂ concentration of 500 ppm (the current value is approximately 370 ppm).

The rate of emission of anthropogenic CO₂ is a factor of ten smaller than the land/sea/air fluxes of Earth's carbon cycle. To set these fluxes in context of the E&P industry, consider one “wedge” (Pacala and Socolow 2004) of GHG emissions, which is 1 Gt/a C. Referring to **Tables 1 and 2**, a wedge is equivalent to 3.7 Gt/a CO₂. Converting to volumetric rates, a wedge corresponds to 190 Bcf/D of CO₂ or 105 million res. bbl/D of CO₂, where, for the sake of illustration, reservoir conditions correspond to typical deep-saline-aquifer conditions (e.g., at a depth of 5,000 ft). In 2006, global oil production was approximately 82 million STB/D, and global gas production was 280 Bcf/D. Thus, from the point of view of fluids moving in the subsurface, storing one wedge of CO₂ in deep saline aquifers or depleted oil and gas reservoirs would be at the same magnitude as the current global oil business.

From the point of view of fluids moving in surface facilities, transporting 1 Gt/a C from sources such as coal-fired power plants to injection wellheads would be comparable to the current global natural-gas business. Another point of reference: The infrastructure for transporting CO₂ from natural sources such as the McElmo dome to enhanced-oil-recovery projects in the Permian Basin currently can handle several Bcf/D. That infrastructure, the largest of its kind in the world, would have to be replicated fifty times to handle 1 wedge of anthropogenic CO₂.

The magnitude of these flow rates is sobering, but they are not beyond the technological capability of the oil and gas industry. In fact, few other industries deal with fluid volumes of this size. If society enacts a suitable regulatory framework for GHG mitigation, the industry could respond with an “off the shelf” geological-storage service in a short time—a key advantage given the urgency of the problem. This is not to dismiss the very real difficulty of finding and developing the financial and human resources for such an enterprise, nor of building the necessary infrastructure. But the oil and gas

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Quantities in Each Row are Equivalent		Notes
1	tonne carbon	Atomic mass of C is 12
3.7	tonne CO ₂	Molecular weight of CO ₂ is 44
69	Mscf CO ₂	Mscf=thousand standard cubic feet at oilfield standard conditions (60°F and 1 atm)
6.1	m ³ CO ₂	At typical deep-saline-aquifer conditions, CO ₂ is a supercritical fluid. Its density is 600 to 700 kg/m ³ .
38	res. bbl CO ₂	

1	"wedge"	Introduced by Pacala and Socolow (2004)
10 ⁹	tonne/a carbon	
3.7×10 ⁹	tonne/a CO ₂	
190	Bscf/D CO ₂	Billion (10 ⁹) standard cubic feet per day
105	million B/D CO ₂	Million barrels per day at typical deep-aquifer conditions (see Table 1)

industry will have an unrivaled technical advantage in meeting the needs of any serious campaign of GHG mitigation.

Leveraging this advantage into an economically viable business will not be straightforward. The E&P industry currently invests approximately USD 0.1 trillion/yr to renew and maintain hydrocarbon production. Storing CO₂ at rates large enough to make a difference—1 wedge—is likely to require comparable capital investment. At this price, the discussion usually turns quickly to the question, "What are the other options besides storage?"

An alternative to storage is not to produce the CO₂ in the first place. Options for avoiding CO₂ production exist,

but none are notably cheaper or easier than storage. For example, building enough nuclear power plants to replace 700 coal-fired plants each producing 1,000 MW would avoid 1 Gt/a C. Replacing the internal-combustion engines in 500 million cars with a hydrogen-fueled engine also would avoid 1 Gt/a C. (This avoidance assumes that any CO₂ emissions from the process of manufacturing hydrogen, for example by steam-reforming methane, would also be stored.) These options are technically feasible, just as is storage, but the costs are comparable.

All analyses lead to one simple fact: The world economy uses prodigious quantities of energy. And it is important to recall that the preceding discussion has considered just 1 wedge of CO₂. Effective GHG mitigation will require

Distribution of Global Energy Consumption by Fuel Type (Energy-Equivalent Basis)

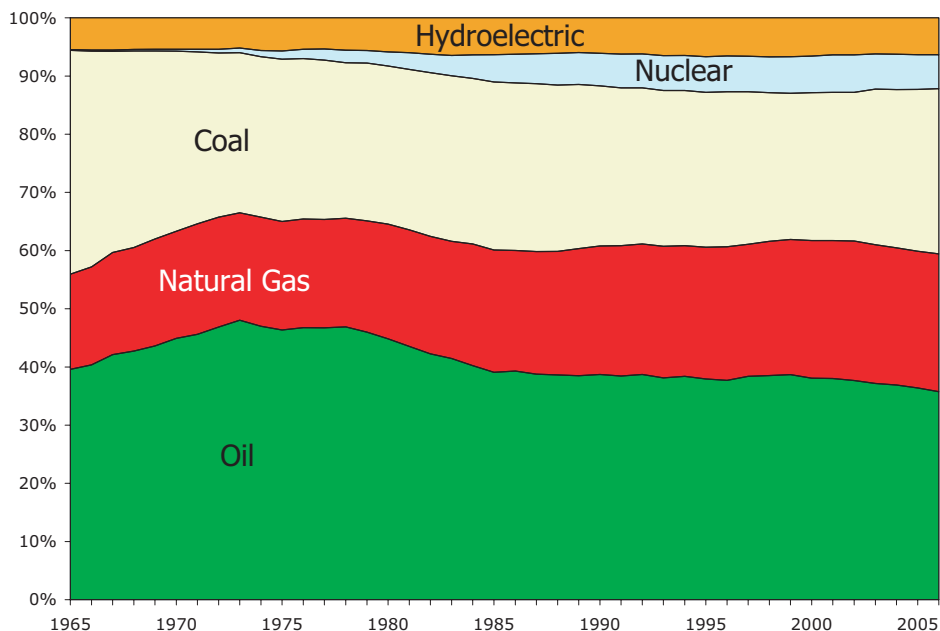


Fig. 1—The distribution of global energy consumption for the last 40 years confirms that the world economy runs almost entirely on fossil fuels. The contributions of solar, wind, and biofuels are not included here and are currently too small to affect this conclusion. The dominance of carbon-based fuels is one reason that shifting the balance away from them poses so large a task. Another reason is the sheer volume needed; see Fig. 2. Data source: BP (2007).

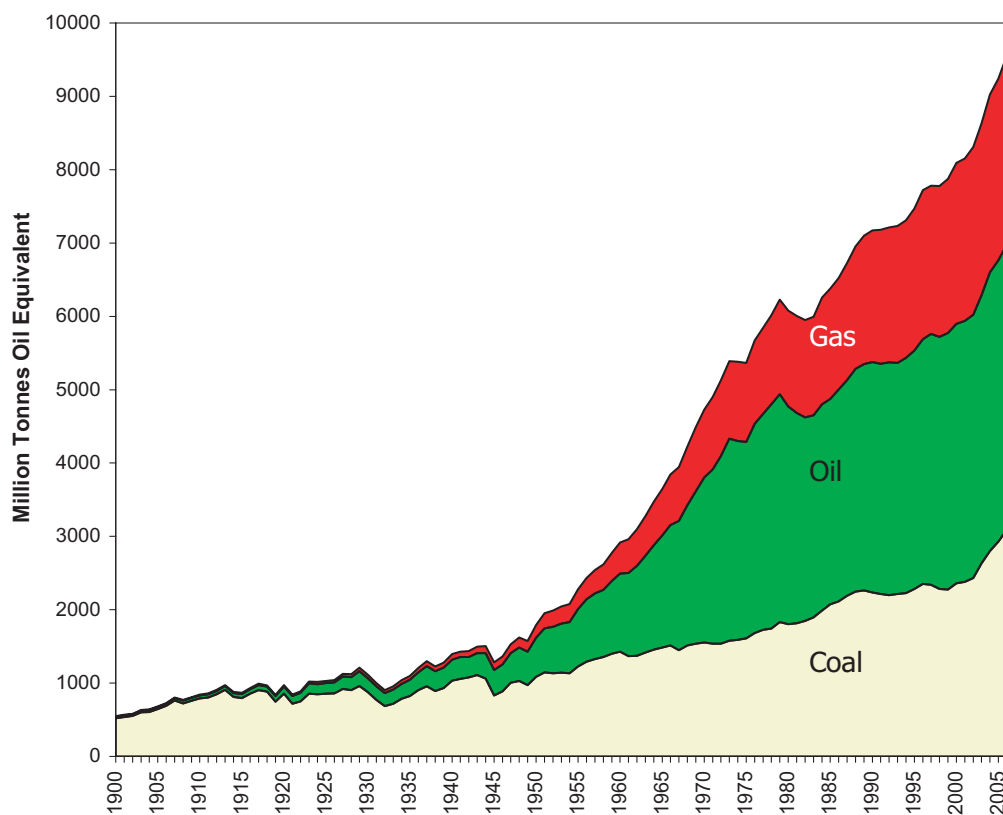


Fig. 2—In the second half of the twentieth century, annual fossil-fuel consumption increased rapidly. The scale of consumption defines the size of the GHG-emission rate, which in turn shows that meaningful geologic CO₂ storage would require an industry of size comparable to the current E&P industry. Because economic activity is linked so closely to energy consumption, trying to reduce CO₂ emissions solely by burning less fossil fuel is unlikely to be popular. Geologic storage is thus an important part of any realistic GHG-mitigation strategy. Data sources: Lomborg (2001) and BP (2007).

avoiding or removing 7 wedges simultaneously. Thus, if the problem of “which alternative do we implement” is posed as a multiple-choice question, the best answer is “all of the above.” GHG mitigation cannot be accomplished by CO₂ storage alone, but effective mitigation without storage would be much more difficult.

It is not surprising that the size of anthropogenic CO₂ emissions is of the same order as production rates of oil and gas. As shown in Fig. 1, on an energy-equivalent basis, coal, oil, and natural gas are consumed in similar quantities. Moreover, these fuels account for the great majority of the world’s energy supply. This has been the case for several decades. The fraction would exceed 90% had nuclear power not expanded during the 1980s. (Including wind, solar, biomass, and other fuels in Fig. 1 would not change the dominance of fossil fuels.)

Reinforcing the predominance of fossil fuels in the energy mix, the sheer scale of usage has risen five-fold since World War II (Fig. 2). Global coal consumption was 6.2 billion tonnes in 2006, and burning it produced approximately 12 billion tonnes of CO₂. The corresponding figures for oil were 31 billion bbl and approximately 9 billion tonnes of

CO₂. For natural gas, 101 Tcf were consumed, producing 5 billion tonnes of CO₂. Most oil is used for transportation, meaning its consumers are mobile and numerous. Coal consumption occurs in comparatively few locations that are fixed. Thus, coal consumers are the first choice for carbon capture and storage, even though oil and gas consumption collectively results in more GHG emissions.

Why Is Geologic Storage Inevitable? Regardless of whether consensus is reached on a link between anthropogenic CO₂ and global warming, many nations may soon choose to limit emissions of CO₂. Limiting emissions can be achieved in two ways: burning less carbon-containing fuel or continuing to burn carbon-rich fuels and storing the resulting CO₂.

The first approach continues to attract political and media attention and considerable research and development directed toward fuels without carbon, or at least with less carbon than current fuels. Indeed, one incentive for increased use of natural gas in recent years is that per unit energy produced, burning natural gas yields approximately half as much CO₂ as burning coal. However, except for nuclear power, no zero-carbon fuel or energy source is likely to be available

in the near future in sufficient quantities and at prices to displace a significant amount of coal, oil, or natural gas. A key phrase in this statement is “sufficient quantities.” As Fig. 2 illustrates, global fossil-energy consumption has more than doubled in the past 40 years. Even if the recent large growth rates in energy supplied by wind and sun could be sustained, the time for those sources to supply 2.5 billion tons of oil equivalent per year (the current natural-gas consumption) would be measured in decades.

Of course, energy demand will not be constant. Currently, approximately one-sixth of the world population (Europe, North America, and Japan) is responsible for half the total energy consumption. Half the world population (China, India, and Southeast Asia) consumes one-fifth of the energy. The latter statistic is the main reason for the forecast of continued increase in overall demand for energy. Thus wind, solar, and nuclear energy must grow even faster than fossil-fuel consumption to change the energy mix in Fig. 1. And because of spent-fuel issues, replacing substantial amounts of coal-fired electricity generation with nuclear plants is unlikely to happen rapidly. Consequently, the second approach—capturing and storing CO₂—will be an essential part of any effective GHG-avoidance strategy. In particular, a global effort to reduce the amount of CO₂ entering the atmosphere will primarily involve capturing CO₂ from fixed sources, such as coal-fired and gas-fired power plants, and injecting it into geological formations (Orr 2004).

If Geologic Storage Is So Important, Why Isn't Everyone Else Talking About It? Despite the compelling case in favor, only recently have articles about CO₂ storage begun to appear in the popular press. Ironically, GHG-mitigation efforts commonly reported often rely on storage. Consider hydrogen, for example. Currently, the most economical way to produce hydrogen is by reforming methane with steam. Implementing a “hydrogen economy” with current technologies would, therefore, increase the demand for natural gas significantly. Moreover, the carbon from which the hydrogen is separated must be stored. With current technologies, it is more energy efficient to burn the methane than to convert it into other molecules. Either way, CO₂ storage is needed. Next-generation technologies for coal-based power generation, such as the FutureGen project, have both capture and storage as integral parts of the process. Norway, which historically has met its electricity demand exclusively by hydroelectric generation, recently announced plans to build substantial new capacity for electricity generation, all of it fueled by natural gas. The CO₂ produced is to be captured and geologically stored.

Conservation, either in the sense of using less fuel or in the sense of creating more value for the same amount of fuel consumed, is prominent in many discussions of GHG policy. In terms of global fuel consumption, conservation in the first sense historically happens only during widespread economic downturns. (The downturns often follow jumps in the price of crude oil, but not always, as the last 2 years have shown.) Since 1960, each of the dips and

“flat spots” in global fossil-energy consumption in Fig. 2 corresponds to a recession in the US. The largest decrease in global fossil-fuel consumption since World War II was nearly 5% between 1979 and 1983. Reducing coal and oil consumption by 10% today—an unprecedented reduction in modern times, and one that would affect economic activity significantly—would avoid 2.1 Gt/a CO₂, or approximately two-thirds of a wedge (Table 2). This mode of conservation—simply using less—is, therefore, unlikely to eliminate the need for CO₂ storage over the time scale of interest (i.e., several decades).

The second mode of conservation is energy efficiency. Measured as gross domestic product (GDP) per unit of energy consumed, energy efficiency has increased steadily in countries with modern economies. This increase is particularly apparent over the last 3 decades, as energy consumers have responded to sporadic increases in oil price. Often, it is assumed that increasing energy efficiency will lead to a reduction in GHG emissions. But in terms of overall emissions, increased economic activity always outweighs increased energy efficiency (unless the activity involves large-scale substitution of nuclear or natural gas for coal and oil). Thus, greater efficiency reduces the rate of increase of GHG emissions, but historically it has not reduced the overall rate of emissions. Since 1990, the US has been almost twice as efficient in generating GDP with oil as it was between 1950 and 1979 (Tertzakian 2006). But growth in the US economy has resulted in greater total GHG emissions. In the UK, in contrast, total energy consumption has not increased as rapidly as in the US, and natural gas replaced approximately one-half of the coal consumption. Germany also halved its coal consumption over the same period and decreased its overall energy consumption also. Thus, GHG emissions from the UK have been essentially constant over the last 2 decades, and emissions from Germany have decreased. Globally, however, many more countries have increased their fossil-fuel consumption than have decreased it, and the net effect corresponds to the fossil-fuel-consumption trends in Fig. 2: a general increase in GHG emissions.

Any serious effort to limit GHG emissions to the atmosphere must involve CO₂ storage and, thus, will rely heavily on the technology and expertise of the oil and gas industry. Geologic storage is likely to be the dominant mode of storage, simply because ample space is available in deep saline aquifers, and transport costs can be held down by placing projects close to fixed sources. Storage is also possible in depleted oil and gas reservoirs. These have the advantage of being proven containers for buoyant fluids, but they are not always near CO₂ sources. More-exotic storage modes, such as injection into sediments in the deep ocean (water depths greater than 3000 m), would call upon the industry's experience in deepwater exploration and production. Indeed, to date, the most serious efforts to store substantial volumes of CO₂ have been conducted exclusively by oil and gas companies. The list includes the pioneering Sleipner and Weyburn projects and the scheduled Gorgon, In Salah, Draugen, and Snovit projects. The Weyburn and Draugen projects are unusual, with the use of CO₂ produced by fossil-fuel con-

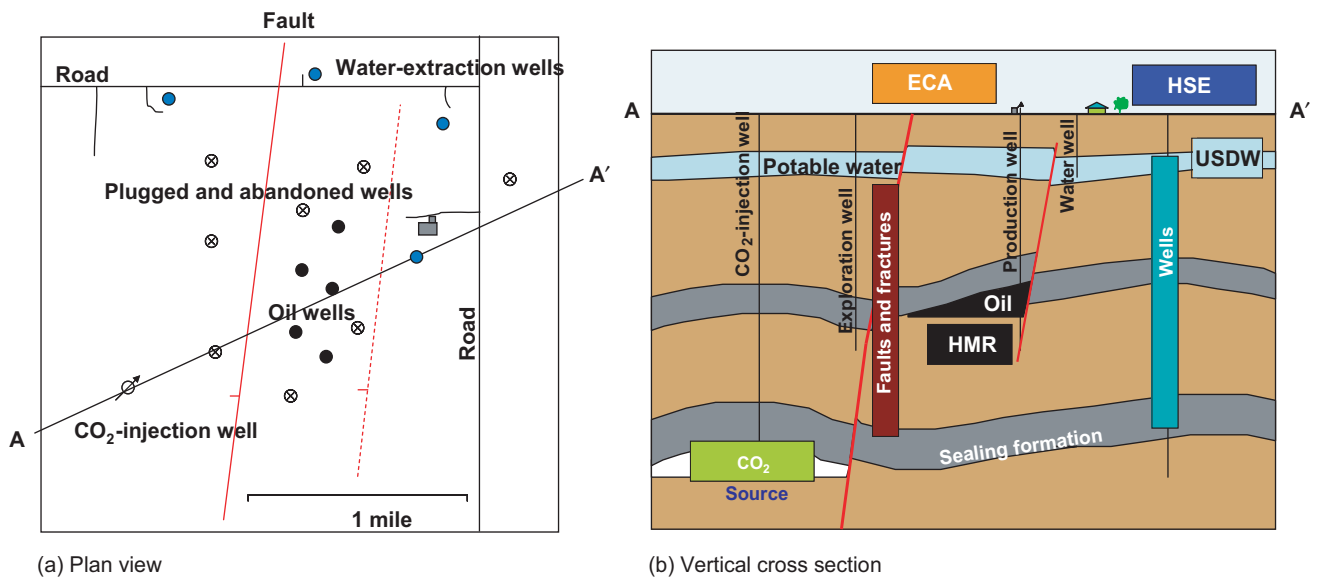


Fig. 3—(a) Plan view of a geologic CO₂-storage site (Oldenburg et al. 2007). The interactions of the operation with geologic features (faults, possibly reaching the surface) and human activity (buildings, homes, extraction of subsurface fluids or minerals) will be factors in assessing the risk associated with CO₂ storage. (b) Side view of Section AA' from (a). Schematic shows possible conduits for leakage (faults, fractures, existing wells) of CO₂ stored in a deep saline aquifer. In this scheme, leakage becomes a problem in three ways. One is if the CO₂ enters a “compartment” that has economic value, such as formations containing hydrocarbon or mineral resources (HMR) or underground sources of drinking water (USDW). Another is if the CO₂ affects health, safety, or environment (HSE), for example by entering basements of homes. The third is the re-entry of CO₂ into the atmosphere (ECA). Should the latter occur, emission credits would be reduced.

sumption. The CO₂ stream for the others is the result of purifying produced natural gas.

The oil and gas industry has few peers accustomed to the logistics of moving wedges of fluids, so it is natural to anticipate its leading role in geologic storage. But the industry's existing and planned storage efforts mentioned above are all associated with revenue-producing projects. In some cases, the infrastructure—which, for this discussion, includes hardware (such as wells and transport facilities) and knowledge (such as seismic surveys, core description, and drillstem tests)—existed when storage was implemented. In other cases, the necessary infrastructure would have been built or acquired as part of field development, regardless of whether storage would be implemented. Making the storage project part of the field project development keeps the cost of storage relatively low. For a greenfield storage project in which no revenue from produced hydrocarbons is available, the economics is less attractive, though studies indicate that the cost of capture is greater than the cost of transport and injection.

The cost of large-scale implementation of CO₂ storage, while not trivial, may be less of a constraint than logistics. One way to store one wedge (1 Gt/a C) would be to retrofit CO₂-capture and -storage facilities on one 1,000-MW coal-fired power plant every week—for 12 years. Even if each project were a simple off-the-shelf design, this would be a massive undertaking.

In the near term, fixed sources of CO₂ emissions (power generation by use of fossil fuel) are the main candidates for storage. Of these, coal-fired power plants are the first choice. CO₂ storage will, therefore, introduce a new kind of business relationship for the oil and gas industry: a partnership with coal producers, the transporters of coal, and power-generating companies. The natural-gas sector has established a relationship with power generators in competition with coal. The role of oil and gas companies, or of companies spun off by them, would be to offer the service of securely disposing the CO₂ produced by a power generator. The development of this service sector is likely to grow out of early projects in which enhanced-oil-recovery revenue is the primary motivation and credits for storage of CO₂ in the reservoir, if any, are secondary.

Technical Challenges for Large-Scale Geologic Storage

Will the CO₂ Stay Where We Put It? The major challenges facing geologic storage are associated with risk assessment. Can the probability that stored CO₂ will migrate from its intended container be assessed? If migration occurs, can the risk to other assets, to people, and to the environment be assessed? How can the storage be monitored to determine whether migration is occurring?

Under typical storage conditions (infinite-acting saline aquifers 1000 m below the surface), the density of the

CO₂ phase will be approximately two-thirds that of brine. Therefore, the stored fluid is buoyant, which provides a driving force for escape. The question then becomes whether stored CO₂ will encounter an escape route, and if encountered, what flux can occur along that route. Although many structures within the Earth's crust have trapped buoyant fluids (e.g., oil, natural gas, and thermogenic CO₂) for very long times, paths for leakage are also scattered throughout the crust. Indeed, drilling near surface seeps of oil or natural gas was a good exploration strategy in the early decades of the industry. In some parts of the world, many wells have been drilled into the Earth's crust, each creating a potential breach of sealing formations.

The combination of a driving force for migration and the possible existence of migration paths makes risk assessment necessary for certifying storage projects. But the magnitude of the job—several thousand projects with the magnitude of Sleipner, Weyburn, In Salah, and Gorgon would have to be implemented to make a difference—means that risk assessment should be as simple and inexpensive as possible. Moreover, the deep aquifers that will comprise most of the target formations for storage will not be nearly as well characterized as oil and gas reservoirs. This is a strong statement because even hydrocarbon reservoirs are often poorly characterized. How can simple physically grounded assessments of risk be produced when minimal information is available about the detailed structure of the target formation and its overburden? Can information acquired during CO₂ injection be used to reduce uncertainty in this assessment? Can regulations be developed for project certification and management that allow risk assessment to change during the project?

These questions and the phenomenon of buoyancy-driven flow in the subsurface are familiar to the oil and gas industry. The natural-gas-storage industry has accumulated a great deal of directly relevant experience, including the relative merits of using aquifers instead of depleted gas reservoirs. Their collective expertise could make a valuable contribution to enable large-scale CO₂ storage. However, geologic storage is not yet an enterprise, and prices for oil and natural gas are high and look to remain high. Industry managers may not commit scarce staff to storage issues, beyond what is being done as a part of natural-gas-field development.

One way to simplify risk assessment is to change the storage paradigm. The most straightforward approach to storage envisions a large gas cap of CO₂, held in place by structural seals. Secure long-term storage in this mode depends on the long-term integrity of the seal. An alternative approach reduces the risk of leakage through the seal by minimizing the mass of CO₂ in the gas cap. The idea is to maximize the amount of CO₂ dissolved in brine and trapped as a residual phase. The capillary forces that hold blobs of nonwetting phase in pore space are much larger than buoyancy forces, making the probability of migration small. Some injection strategies based on these alternative modes have been proposed (Kumar et al. 2005), and the topic remains an active area of research.

If Stored CO₂ Migrates Out of the Target Formation, How Fast and How Far Will It Go? Suppose a formation containing stored CO₂ did leak in an area with other human activity, as sketched in Fig. 3. How fast could CO₂ move along the leak path? How much CO₂ would reach assets such as aquifers used for drinking water or agriculture, or oil and gas reservoirs above the formation? Research to determine the relevant transport properties of wellbores, faults, and other features of leakage paths is being undertaken by many groups, but as discussed below, nontechnical aspects of the problem may prove at least as important as the technical issues. The properties of CO₂ also complicate this part of the risk assessment. Rising CO₂ will dissolve into brine, thus reducing the upward flux. But the solubility is a strong function of pressure: approximately 1 mol% at depth, but a factor of ten less in the shallow subsurface. The density of CO₂ decreases with pressure such that the buoyancy-driven flow becomes self-reinforcing. However, the decreasing density also increases the capillary pressure at the leading edge of a rising CO₂ plume. This situation increases the likelihood of drainage laterally into porous formations along the leakage path, which attenuates the upward flux but can widen the area influenced by the leak. Understanding the competition between these mechanisms will help bound the estimates of fluxes and concentrations that underlie risk assessment.

Can a Storage Project Be Monitored To Know About Leakage in Advance? To address the question of leakage, geologic-storage projects will require monitoring activities during injection and probably for some time afterward. Public and regulatory acceptance will depend on reliable and readily understood monitoring measurements. The cost of making those measurements will be critical. Once again, technology already developed in the oil and gas industry applies. The basic requirements of the measurement are sensitivity to the presence of a bulk CO₂ phase and good spatial resolution. The density contrast between CO₂ and brine makes seismic and acoustic methods a natural choice. While existing methods are adequate for initiating a storage industry, there is a need for novel techniques that could greatly reduce the length of time that monitoring is required and thus reduce the cost. For example, a measurement that could distinguish CO₂ trapped as a residual phase from CO₂ that is still potentially mobile would be extremely useful. The former mode of storage would require much less subsequent monitoring. Similarly, being able to distinguish brine saturated with dissolved CO₂ from native brine would be helpful in working out inventories of injected CO₂.

Nontechnical Challenges for Large-Scale CO₂ Storage

Will Governments Arrange for a Private-Sector Solution to a Global Problem? The effect of storage on the oil and gas industry also depends on political and economic challenges that will be at least as significant as technical challenges. Anthropogenic CO₂ emissions are strongly correlated to economic activity, but the atmosphere is common

to all countries. The international unanimity needed to avoid this dilemma has been difficult to achieve over the last 2 decades.

One way to ease this dilemma would be to establish CO₂ as a freely traded commodity. Several exchanges have been established for the trading of GHG reductions, anticipating the eventual decision by international bodies to set limits on emissions and attach credits to emission reductions. If a tonne of stored CO₂ has the same value as a tonne of CO₂ not produced, that is, if either tonne would earn a credit under the limits-and-trade scheme—then operators could evaluate the business case for geologic storage. A market could then evolve that would organize the most efficient overall means of limiting net CO₂ emissions. Experience in the US with a cap-and-trade program for sulfur dioxide emissions indicates that this approach could work for CO₂. Unlike CO₂, however, geologic storage is not one of the technologies used for sulfur dioxide emissions reduction. Another difference is that a market for large-scale fluxes of CO₂ already exists, but only for CO₂ taken from natural accumulations. This market is growing as more operators implement miscible-injection projects.

Will the Public Support—and Pay For—Large-Scale Geologic Storage? The challenge for establishing a storage business lies in the international community agreeing upon a price for a CO₂ credit. Different business sectors (coal producers, railroads that ship coal, electric utilities, industry on-site power generation) will have competing ideas of an appropriate price. Because coal-fired electricity production is likely to be the focus of GHG-emissions mitigation, consumers must decide how much extra they are willing to pay for electricity to cover the costs of capture at existing plants. Retrofitting existing plants with current capture technologies would consume approximately 30% of the power generated at those plants, thus adding approximately 30% to the cost of electricity. Surveys indicate significant resistance to increments of more than 10% on a monthly utility bill to pay for GHG mitigation. Moreover, many existing power plants are physically constrained from expansion. Such plants would, therefore, be derated by the amount of power required for capture, or power would have to be imported from new generation capacity constructed elsewhere. Balancing these competing interests, or at least sharing the pain equally, is difficult.

For the readership of *JPT*, the concept of geologic storage is likely to be greeted matter-of-factly. For the general public, the concept is almost completely unfamiliar. Even recent documentaries (including one that received an Academy Award in February 2007) and books addressing energy and environmental issues devote little time to the topic. Surveys in the US and the UK show that when informed of the concept, most people remain unsure whether storage should be implemented. This is troubling, given that storage is the most readily implemented technology for reducing emissions, and that the US Department of Energy has heralded the FutureGen project and is funding seven regional partnerships of industry and academia in the US

dedicated to field demonstration of storage. A more fundamental concern is that few of the people surveyed rank GHG emission as a high-priority problem. Getting broad public support for mitigating CO₂ emission in general and for geologic storage in particular will require remarkably effective communication.

Communicating risk assessment of storage projects to the public in a simple and transparent way will be particularly important. The fact that the Earth's crust is intrinsically leaky must be contrasted with the fact that CO₂ is a benign substance, except at large concentrations. Naturally occurring leaks of CO₂, natural gas, and oil to the Earth's surface are well documented, but so are naturally occurring traps that have endured over geologic time. This kind of ambiguity may not sit well with some stakeholders. Industry and regulators alike would like to choose secure storage sites with a very high probability of success. The existence of oil and gas reservoirs provides incontrovertible empirical support for the claim that large volumes of CO₂ can be stored without leakage for very long times. However, the existence of natural reservoirs does not necessarily tell us how to construct engineered reservoirs.

Nature enjoyed the luxury of creating reservoirs without regard for the probability of success: Good traps became reservoirs, poor traps did not, and much of the hydrocarbon generated at depth simply escaped to the atmosphere. A nascent CO₂-storage industry would not be allowed to take the analogous approach of "let's inject into a hundred aquifers and see which ones trap CO₂." The challenge here will be to ensure that "the perfect does not become the enemy of the good." If the objective is to limit the increase of CO₂ concentrations in the atmosphere in the coming decades, a slow leak that does not affect other assets in the subsurface or in near-surface environments is far preferable to not storing the CO₂ at all. Decreasing the risk of leakage from any given storage target is certainly achievable, but the cost of storage may increase correspondingly.

Will There Be Anybody To Actually Do the Work of Implementing Large-Scale Storage? Subscribers to this journal are the kind of people most likely to be involved in the practice of geologic storage. The skill sets that will be needed are similar if not identical to those needed in oil and gas exploration and production. This observation led to the theme of this article, that GHG-emissions mitigation would be a substantial new business opportunity for the E&P industry. But anyone familiar with the demographics of the E&P industry will immediately draw another, less optimistic conclusion: There simply will not be enough trained engineers to staff a geologic-storage industry and the E&P industry simultaneously.

On the basis of the magnitudes discussed in the Introduction, ramping up storage to the level needed to make a difference would require as many people as now work in the oil and gas business. Yet oil and gas operators and service companies are already scrambling to find qualified staff for existing and planned E&P projects. With continued high demand for oil and gas and high prices, com-

panies will continue to absorb all available graduates who know something about the subsurface. Where will graduates go when industry needs twice as many new hires?

Consider first the situation in the US, because it must play an active role if CO₂ storage is to be effective. The steady decline in the percentage of US students seeking science and engineering degrees has been widely lamented (National Academies 2007). Less widely noted, but of no less effect for this discussion, is the steady decline in public (i.e., federal and, in some cases, state) support for education, training, and research in petroleum engineering and related disciplines. Research funding is an integral part of higher education in science and engineering. The funding supports students who, while at school and then in the workforce, produce the technical innovations that ensure the health of a modern economy over the long term. Certainly the trend of declining public support bodes ill for the supply of graduates from US colleges for the E&P industry. The longer the trend continues, the more remote the possibility of also staffing a CO₂-storage industry with those graduates.

The situation in the rest of the world differs in detail from that in the US, but leads to a similarly gloomy prediction. Dozens of universities continue to educate petroleum engineers, and new institutions are opening, especially in oil-producing countries. But the primary mission of many of these programs is to supply graduates for an existing industry. The forecast demand for those graduates in the oil and gas sector necessarily dominates their planning process.

Institutions around the world that train subsurface engineers must expand substantially if geologic CO₂ storage is to play its role in GHG mitigation. But this seemingly easy remedy will not be easy to complete. In fact, it may prove the greatest obstacle to implementing CO₂ storage rapidly at a large enough scale to make a difference. Even if the technical, economic, and social challenges described above are addressed successfully, and even if citizens decide they want real GHG mitigation and are prepared to pay for it, geologic storage will not happen without engineers and geoscientists. They are the ones who must identify sites, design processes, certify permits, implement injection, interpret measurements, and carry out myriad other tasks associated with moving hundreds of Bcf/D of CO₂ from sources to storage formations. It is possible to expand the educational capacity to produce those workers, but society must start making that investment immediately.

Finally, climate change can be a politically and emotionally charged issue. It will not escape the notice of some stakeholders that the oil and gas industry will be well positioned to profit from geologic CO₂ storage. Consumers pay the industry once for hydrocarbons to

meet their personal transportation needs, and in the process they produce a quarter of global anthropogenic CO₂ emissions. In its most likely implementation, CO₂ storage would require consumers to pay the industry again, albeit indirectly, in the form of increased electricity bills. Initially, the payment would not be for CO₂ whose carbon was previously held in oil and gas molecules, although this would eventually change as capture and storage occurs at gas-fired power plants. Nevertheless, the public perception of the “fairness” of the industry’s role in geologic storage may distort or even overwhelm a rational evaluation of the challenges discussed above. Although it provides more than half of the energy needed to fuel the global economy, the oil and gas industry has never garnered much public sympathy for its efforts. Ironically, being uniquely qualified to help save the planet may not improve the industry’s image.

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