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Science **325**, 1658 (2009);
DOI: 10.1126/science.1175750

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20. I thank the Global Climate and Energy Project and the Precourt Institute for Energy, both at Stanford University, for support.

10.1126/science.1175677

PERSPECTIVE

Storage of Carbon Dioxide in Offshore Sediments

Daniel P. Schrag

The battle to reduce greenhouse gas emissions and prevent the most dangerous consequences of climate change will be waged across multiple fronts, including efforts to increase energy efficiency; efforts to deploy nonfossil fuel sources, including renewable and nuclear energy; and investment in adaptation to reduce the impacts of the climate change that will occur regardless of the actions we take. But with more than 80% of the world's energy coming from fossil fuel, winning the battle also requires capturing CO_2 from large stationary sources and storing that CO_2 in geologic repositories. Offshore geological repositories have received relatively little attention as potential CO_2 storage sites, despite their having a number of important advantages over onshore sites, and should be considered more closely.

There are some good reasons why carbon capture and storage (CCS) is attractive as a climate change mitigation strategy: A large fraction of CO_2 emissions comes from relatively few sources. In 2007, there were 2211 power plants that emitted at least 1 million metric tons of CO_2 per year: 1068 were in Asia (559 in China), 567 in North America (520 in the United States), 375 in Europe, and 157 in Africa (*1*). Together, these power plants released 10 billion metric tons of CO_2, or one-third of global emissions. If these plants could be retrofitted or rebuilt with capture technology, and if appropriate storage locations could be identified, then CCS would allow the world to reduce emissions while still using its fossil fuel reserves, at least until long-term substitutes can be developed. Widespread adoption of CCS in the United States and Europe over the next few decades would make it more likely that similar systems will be deployed in other countries, especially in rapidly growing economies with high present and future CO_2 emissions.

For the past 13 years, a Norwegian oil company has been running an experiment that leads the world in showing how CCS can play an important role in a broad portfolio of climate-mitigation strategies. Since 1996, in the North Sea, halfway between Scotland and Norway and far out of sight of land, StatoilHydro has been quietly injecting 1 million metric tons of CO_2 per year into a sandstone reservoir that lies 1000 m below the sea surface (Fig. 1). The CO_2 comes from a natural gas deposit called the Sleipner field. Extracting the gas for transport back to land requires separating the CO_2 anyway, so, faced with a carbon tax from the Norwegian government, StatoilHydro decided to turn a liability into an opportunity. As the longest-running, commercial-scale carbon-injection site, Sleipner serves as a demonstration for those who believe that this approach can help decarbonize our energy economy and serves as a laboratory for understanding how CO_2 migrates through the subsurface after injection, using techniques such as time-lapse seismic surveys (*2*).

One million metric tons of CO_2 per year is a start, but the demand for CCS is much more, perhaps as much as 10 billion metric tons of CO_2 per year or more. Finding storage locations for all that carbon will not be easy. Such amounts far exceed the capacity of old oil and gas fields, which will be among the first targets for sequestration projects because of additional revenues earned from enhanced oil recovery (EOR). Safe storage of CO_2 in a geologic formation requires a good reservoir with adequate porosity and permeability and thick, impermeable cap rocks that will prevent the CO_2 from escaping. Luckily, geologic storage does not have to last forever—only long enough to allow carbon sinks in the natural carbon cycle to reduce atmospheric CO_2 to near preindustrial levels [roughly 4000 years (*3*)].

Most investigations of CO_2 storage in the U.S. focus on terrestrial geologic formations, in particular, deep saline aquifers. Another approach to CO_2 storage is injection offshore into marine sediments, similar to what is done at Sleipner. Both approaches will ultimately be needed to accommodate all the large stationary sources of CO_2 in the United States, but there are several reasons why storing CO_2 in geologic formations offshore may be easier, safer, and less expensive than storing it in geologic formations on land, at least during the early days of commercialization.

CO_2 storage in offshore geologic formations is not ocean storage. The CO_2 injected into ocean sediments is stored deep beneath the ocean, avoiding the hazards of direct ocean injection, including effects on ocean ecology. Furthermore, marine sediments offer enormous storage potential. For example, a series of Cretaceous sandstones off New Jersey (*4*), which were drilled extensively in the 1970s as part of the oil and gas exploration program, appear to have the capacity to store at least several hundred billion tons of CO_2: enough to dispose of all the CO_2 from power plants within 250 km of the coast from Maryland to Massachusetts for the next century. Like on land, offshore storage sites require reservoirs with high permeability (typically sandstones), and thick, low-permeability cap rocks to prevent CO_2 from escaping (typically mudstone and shale). However, if one could find reservoirs with adequate permeability in deep water (that is, below 3000 m), the high pressure and low temperature would render the CO_2 denser than seawater, making the cap rock less important (*5*), although high-permeability sandstones are uncommon in deeper water environments. In many marine settings, the upper 1000 m of sediment, if it is dominated by clay, is unconsolidated, which means that faults and fractures do not persist as high-permeability pathways for CO_2 escape.

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Another advantage of offshore carbon storage is the potential to manage pressure within the geologic formation. Carbon storage is different from EOR in that EOR involves both the injection of CO_2 and the extraction of fluid—usually a mixture of water, CO_2, and oil (the CO_2 is usually reinjected). Injection of CO_2 into saline aquifers on land, however, without extraction of the saline water, increases pore pressures and changes the way CO_2 migrates in the subsurface. If the permeability of the reservoir is extremely high, then management of pressure is not a problem, because pressure transients near to the injection well are rapidly dispersed. As the scale of CCS increases, with as much as 100 million tons per year injected within a single formation, management of subsurface pressure will become a greater and greater challenge. Indeed, displacement of saline water and pressure management may prove the greatest overall challenge for CO_2 storage.

Fig. 1. Since 1996, StatoilHydro has been separating 1 million metric tons of CO_2 per year from a natural gas platform in the Sleipner Field in the North Sea and injecting it into a sandstone reservoir. Seismic monitoring has shown that the CO_2 is safely contained beneath a thick sequence of impermeable shales. [Photo: Dag Myrestrand/StatoilHydro]

This is where CCS in marine sediments offers an enormous advantage. An important difference between offshore and onshore storage of CO_2 is the nature of the fluid inside the geological formation. In sedimentary basins on land, where CO_2 sequestration has been proposed, the pore fluids are generally much saltier than seawater because of hydrologic cycling and evaporation over geologic time. The chemistry of these pore fluids is quite different from that of seawater because of chemical reactions in the sedimentary basin, and the pore fluids frequently contain high concentrations of toxic metals such as arsenic or lead. It would be undesirable to displace such pore fluid from the formation, similar to producing oil during EOR, and then discharge it, because one would merely be trading one disposal problem for another.

In most marine sediments, the pore fluid is much more similar to seawater, as it is essentially ancient seawater, modified slightly by diagenetic reactions and slow diffusive transport. Along continental margins with moderate organic matter content, the major differences from seawater are the presence of sulfide instead of sulfate and an increase in calcium with a corresponding drop in magnesium. Even when the salinity is high because of the influence of evaporites, the overall chemistry is not substantially different from that of seawater. As long as there are not high concentrations of oil or other hydrocarbons, the release of marine pore fluids to seawater to accommodate CO_2 injection will not cause any harm to the marine environment, as stipulated by the Environmental Protection Agency (EPA) regulations for oil platforms for their discharge of produced water to the ocean. The ability to manage pressure by drilling additional wells to release pore fluid to the ocean not only provides extra safety to prevent a fracture from allowing CO_2 to escape to the surface, but also allows for much more careful control and monitoring of the CO_2 plume during injection. This also allows a much higher fraction of the pore space to be used, reducing the footprint of an individual injection field.

Beyond the technical advantages, there are numerous social, political, and economic reasons why offshore storage of CO_2 is likely to be important during the early deployment of CCS, at least in heavily populated areas. In the United States, locating storage sites near populated areas where most CO_2 is created may be practically impossible, at least under current regulatory practices. In Europe, the situation is similar. For example, the town council of Barendrecht in the Netherlands recently opposed the permitting of a CO_2 storage site, arguing that the developers should not conduct an experiment underneath a place where so many people live. In contrast, offshore storage sites are in nobody's backyard.

In the United States, there is a debate over whether the surface landowner, the state, or the federal government owns the pore space within the storage reservoir. For offshore storage, there is no debate: Beyond 3 miles, the federal government owns the land. New EPA regulations for CCS focus on contamination of drinking water aquifers, which is not an issue for marine sediments far offshore. Although no regulations currently exist for leasing land offshore for CO_2 injection, the Minerals Management Service within the Department of the Interior leases land for industrial operations, such as oil and gas extraction, and will probably provide similar oversight for CCS. Offshore storage also offers a similar advantage in locating pipelines for CO_2 transport, which are difficult to site in heavily settled areas.

In general, working in the offshore environment is more expensive; drilling rigs, seismic surveys, and well manifolds are all much more expensive than for a comparable situation on land. The overall economics of CCS, however, make offshore storage very attractive. CCS costs are dominated by the cost of capture and compression. If offshore sites are easier to permit and easier to finance, after 13 years of demonstration at Sleipner, then the extra cost for characterization is more than justified. In addition, the high density of people near the coasts in U.S. regions such as the Northeast and California, combined with high electricity prices and stricter-than-average environmental regulations such as the Regional Greenhouse Gas Initiative, make these regions early targets for commercial power development involving CCS.

With all the advantages, including enormous capacity and the ability to actively manage pressure, CO_2 injected deep beneath the ocean floor is probably the best option for large population centers near the coast. It may take a long time before people are comfortable storing vast quantities of CO_2 near to where they live, even if the best science suggests that it is perfectly safe. Eventually, carbon storage fields will be needed in many different regions, and many of these sites will be onshore. But until there is more experience with CO_2 injection on larger and larger scales, it seems that StatoilHydro has the right idea.

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10.1126/science.1175750