

The Wedge from Capture CO₂ at Baseload Power Plant

A wedge can be achieved by carbon sequestration through

- 800 GW of baseload coal, or
- 1600 GW of baseload natural gas, or
- Equivalent biomass
- Less than perfect capture and storage ((both CO₂ not captured and extra energy to power the capture and storage) are considered

Comments

When energy is extracted from fossil fuels or biofuels by oxidizing its carbon to CO₂, there is no fundamental reason why that CO₂ should end up in the atmosphere. It is possible to capture the CO₂ at the energy conversion facility instead of venting it, and to store the captured CO₂ to prevent it from reaching the atmosphere for a long period of time. This strategy, carbon capture and storage (CCS), also known as fossil carbon sequestration, is being widely studied as a carbon mitigation strategy. The 2002 National Academy of Engineering symposium proceedings (S36) is a good source of introductory essays on many of the major issues; for more detailed information, we recommend the collection of papers prepared for a 2002 international conference in Kyoto, in two volumes (S37). The website of the International Energy Agency's Greenhouse Gas R&D Programme, www.ieagreen.org.uk, is particularly useful.

To achieve the objectives of CCS, several commercial technologies must be combined in new ways. Key carbon capture technologies are well known from their use in industrial hydrogen production at refineries and ammonia plants. Key carbon storage technologies are well known from their use for enhanced oil recovery (EOR). We consider carbon capture and carbon storage separately.

Carbon capture Carbon capture is possible as end-of-pipe technology ("post-combustion capture"): CO₂ is separated from the flue gases exiting a power plant or other industrial facility, for example by chemical absorption or adsorption. Alternatively, CO₂ may be captured at an early stage, prior to most of the energy generation ("pre-combustion capture"). Post-combustion capture is less disruptive of already established technological practice. However, in many cases, pre-combustion capture is less costly, because the key step of separating CO₂ from other gases may be accomplished at much higher partial pressure.

Pre-combustion CO₂ capture shares many technologies with the gasification of solid fuels (coal, petroleum coke, and various biofuels). The synthetic gas (syngas) exiting the gasifier contains, principally, CO and H₂, at high temperature and pressure, but it also contains impurities, like sulfur. For a gasification plant to become a pre-combustion capture plant, the CO and H₂ mixture must be converted to a CO₂ and H₂ mixture, via a shift reactor ($\text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{CO}_2 + \text{H}_2$). The technologies to remove impurities from syngas are similar to the technologies to remove CO₂ from a mixture of CO₂ and H₂.

When gasification is the first step in power production, if there is no CO₂ capture, the

CO-plus- H₂ syngas goes to a turbine, whereas if there is CO₂ capture, a much more H₂-rich syngas goes to the turbine. The incremental cost of CO₂ capture in power production, if gasification becomes established as the power conversion system of choice, is relatively low. Thus, the competition within coal-based power between steam power and power from gasification strongly affects and is affected by any requirement for carbon mitigation. The more gasification-based power is competitive, the less costly CO₂ capture will be, and the greater the societal demand for CO₂ capture, the more competitive gasification-based power will be.

Pre-combustion CO₂ capture also shares many technologies with H₂ production from coal or natural gas. Here, both a shift reactor to produce a mixture of CO₂ and H₂, and subsequent separation of the H₂ from the CO₂, are necessary to obtain a high-purity H₂ stream. The current scale of production of H₂, therefore, provides useful reference values for the task required to produce the “capture” part of a wedge of “capture and storage.”

Hydrogen is currently produced from fossil fuels at a rate of about 40 million tons per year. Most production is associated with two industries, ammonia fertilizer and petroleum refining, and, in both cases, H₂ is produced and used in the same complex. At 120 GJ/t (lower heating value) for H₂, the flow of secondary energy as H₂ is approximately 5 EJ/y. As a result, taking into account losses in conversion of primary energy to H₂, roughly two percent of the 400 EJ/y of global primary energy is used to make H₂. Since, at any plant where H₂ is produced from fossil fuels, a nearly pure stream of CO₂ can be captured at some stage, we estimate that 0.1 GtC/y of capturable CO₂ is generated at H₂ production plants (S38). Today, in every case, this CO₂ is vented, but only small changes could lead to capture. The scale of H₂ production today is only ten times smaller than the scale of a wedge of carbon capture in 2054.

We return to H₂ production later in this section, when we consider the decarbonization of fuels and the hydrogen economy.

Carbon storage The capture part of “capture and storage” results in a stream of relatively pure CO₂ at a plant gate, ready to be taken away. The CO₂ must be at high pressure, if it is to leave via gas pipeline, and the compression step is often the most expensive and energy-intensive step in the whole process. But, where can it be stored, and in what chemical form? Many novel proposals are receiving much attention, including storage in minerals and storage in the deep ocean, but, in the spirit of this paper, we consider only “geological storage,” because this is the one storage strategy for which there is already substantial relevant experience. The oil industry moves large quantities of CO₂ into underground formations for enhanced oil recovery (EOR), by far the largest industrial use of CO₂. The CO₂ is injected as a supercritical fluid, and much has been learned via EOR about migration of the fluid, dissolution into hydrocarbons and brine, and chemical interaction with host rock. The scale of current EOR provides useful reference values for the task required to produce the “storage” part of a capture-and-storage wedge.

In EOR, much of the CO₂ injected into a hydrocarbon formation reemerges with the oil it

has helped produce, and it is then separated and reinjected. We choose to describe EOR experience with CO₂ in terms of the total flow of new CO₂ brought to EOR sites, rather than the total flow of CO₂ injected at EOR sites, which includes recycled CO₂. About 10 MtC/y is brought to EOR sites in the U.S. today. Most of these sites are in the Permian Basin, West Texas, and most of the world's EOR is in the U.S. Therefore, a wedge of the storage part of capture-and-storage is a flow of CO₂ about 100 times larger than the current flow of CO₂ to EOR sites.

EOR today only rarely uses CO₂ captured from fossil fuels. Rather, most of the CO₂ used in EOR is drawn from *natural* CO₂ reservoirs. A large part of the CO₂ used for EOR in the Permian Basin is tied to the huge McElmo CO₂ reservoir in southwest Colorado via a 800-km-long CO₂ pipeline that runs across New Mexico. This pipeline carries somewhat more than 1 billion standard cubic feet per day (Bscfd) of CO₂, or about 5 MtC/y¹. Thus, a wedge is an activity that, during each of the next 50 years, adds a flow of carbon equal to the flow through four pipelines like the pipeline from McElmo Dome to the Permian Basin.

Much work remains to be done before there are good estimates of the total storage capacity for geological storage of CO₂, and before storage integrity and leakage are well understood. The storage part of a capture-and-storage wedge requires the storage of 25 GtC over the next 50 years. The global storage capacity in oil and gas reservoirs is estimated at 10 to 20 wedges. Estimates of the global storage capacity in large unconfined saline aquifers range from only four wedges to one hundred (S39).

Carbon storage has not been the objective of EOR. In the past ten years, however, demonstration projects designed to gain experience with geological sequestration have begun to come on line.

The first three of these are: 1) the Sleipner project, offshore Norway; 2) the Weyburn project, Saskatchewan, Canada; and 3) the In Salah project, Algeria. The Sleipner project demonstrates storage in a huge unconfined aquifer; the Weyburn project demonstrates storage associated with EOR; and the In Salah project demonstrates storage in the water leg beneath the same natural gas field from which the natural gas is being produced. All three projects involve approximately the same storage rate: one million tons of carbon dioxide per year (0.3 MtC/y). Thus, a wedge of storage is 3000 Sleipners, or 3000 Weyburns, or 3000 In Salahs.

It is possible that storage of CO₂ will be routinely accompanied by the storage of pollutants, like sulfur, as a single fluid mixture. For the past 15 years, "acid gas" (a mixture of CO₂ and hydrogen sulfide, or H₂S, obtained from the desulfurization of "sour gas," or gas with high sulfur content) has been disposed of in geological media in Western Canada. This method, which we call co-capture and co-storage, is being adopted

¹Note that, as a manifestation of the universal properties of gases at low pressure, a flow of 190 billion standard cubic feet of gas per day (Bscfd) is a carbon flow of 1 GtC/y, the carbon flow associated with a wedge, *whether the gas is CH₄ or CO₂*.

increasingly as the preferred strategy for sulfur management for many sour natural gas fields in western Canada and the U.S. The 2003 injection rate, summed over 41 active sites, was about 0.45 MtCO₂/y (0.12 MtC/y) and 0.55 MtH₂S/y. The cumulative storage through 2002 was 2.5 MtCO₂ (0.7 MtC) and 2.0 MtH₂S (S40).

Natural gas is stored in geologic reservoirs to buffer demand, providing further relevant experience in moving gases into and out of reservoirs below ground. In the U.S. alone, total gas in storage in 1999-2002 ranged, approximately, between five and seven trillion standard cubic feet, the minimum in March and the maximum in October (S41). The six-month-average flow in and out, therefore, is about 10 billion standard cubic feet per day (Bscfd). As noted above, a carbon flow of 1 GtC/y, whether as methane or CO₂, is a flow of 190 Bscfd. Therefore, ramping up the gas flow currently associated with seasonal natural gas storage in the U.S. to twenty times its current rate over the next fifty years is the storage part of a wedge of CO₂ capture and storage.

References

S36 National Academy of Engineering, 2003. *The Carbon Dioxide Dilemma: Promising Technologies and Policies*. Washington, D.C.: National Academies Press.

S37 Gale, J. and Y. Kaya, eds., 2003. *Proceedings of the 6th International Conference on Greenhouse Gas Control Technologies, 1-4 October, 2002, Kyoto, Japan*. Two volumes. Amsterdam: Pergamon.

S38 National Research Council, 2004. *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs*. Washington, D.C., National Academy Press.
<http://www.nap.edu/books/0309091632/html/>

S39 International Energy Agency, 2002. *Putting Carbon Back in the Ground*. Cheltenham, UK: International Energy Agency Greenhouse Gas R&D Programme.

S40 Bachu, S., et al., 2004. In J. Apps and C-F Tsang, eds., *Proceedings of the Second International Symposium on Underground Injection Science and Technology (UIST)*, Berkeley CA, October 2003. (in press).

S41 Website of the Energy Information Agency, "The Basics of Underground Natural Gas Storage":
http://www.eia.doe.gov/pub/oil_gas/natural_gas/analysis_publications/storagebasics/storagebasics.html. Accessed, April 9, 2004.