

CARBON CAPTURE TECHNOLOGIES: THE LONG PURSUIT OF LOCKING AWAY CARBON

Carbon capture technologies are designed to collect CO₂ from industrial smokestacks or directly from the air before it reaches the atmosphere. They represent one of our more straightforward approaches to fighting climate change. Yet despite their simple concept, these technologies remain difficult to implement on a large scale. This article looks at their history, how they work, and their limitations, as well as their potential role in our future efforts to reduce carbon emissions.

From Industrial Utility to Climate Solution

Carbon capture didn't start as a climate solution. Beginning in the 1920s, industries separated CO₂ from gas streams for practical reasons: to purify natural gas or help extract more oil from aging oil fields. The Terrell gas plant in Texas, which in 1972 began sending captured CO₂ to declining oil fields, is a good example of this early practical approach.

Only in the late 1970s did carbon capture begin to shift toward climate protection. Scientists like Cesare Marchetti suggested capturing power plant emissions and disposing of them—initially thinking about injecting them deep into the ocean, an idea later found to be environmentally harmful. Interest grew in the 1980s as concerns about global warming increased, leading to Norway's important Sleipner project in 1996, where Statoil (now Equinor) began injecting about one million tons of CO₂ each year into an underwater salt water reservoir, partly motivated by Norway's carbon tax.

The 2000s brought more investment, though progress was slow—about 70% of proposed carbon capture and storage (CCS) projects never made it past the planning stage. Notable successes included SaskPower's Boundary Dam in Canada (2014), the first commercial coal-fired power plant with CCS, and various facilities in China, Europe, Australia, and the Middle East.

Today's deployment remains modest. About 44 plants operate globally with CCS, together capturing only about 0.1% of global CO₂ emissions—a tiny fraction of the 35+ billion tons released annually. Nevertheless, many climate models predict that CCS could eventually contribute 14–19% of CO₂ reductions needed by 2050, especially in industries that are difficult to decarbonize like cement and steel manufacturing.

The Mechanics: Capture, Compress, Store

Carbon capture involves three main steps: separation, compression, and storage. First, CO₂ is isolated from exhaust gases or ambient air using chemical or physical processes. The extracted CO₂ is then compressed into a dense, liquid-like state and transported (usually through pipelines) to storage sites. Finally, it's injected deep underground into geological formations—often depleted oil reservoirs or salty water aquifers at least a kilometer below the surface—where impermeable rock prevents it from escaping. Over time, the CO₂ may dissolve into the salty water or react with minerals to form stable carbonates.

In some cases, rather than simply storing the CO₂, it's put to use—the “U” in CCUS (Carbon Capture, Utilization, and Storage). Enhanced oil recovery remains the main application, though CO₂ can also be used in beverage carbonation, synthetic fuel production, or building material manufacturing. Unless these uses permanently lock the carbon in stable compounds, however, it eventually returns to the atmosphere.

A well-equipped facility can capture approximately 90% of its CO₂ emissions—significant at the individual source level, though engineering and economic challenges make global-scale implementation difficult.

Four Approaches to Capture

Carbon capture technologies fall into four major categories, each with distinct applications and limitations:

- *Post-Combustion Capture:* The most common approach, particularly for updating existing facilities. After fuel is burned, exhaust gases (typically containing 5–15% CO₂) are passed through chemical solutions that selectively absorb CO₂. Later, the solution is heated to release pure CO₂ and regenerate the capture medium. This method's flexibility allows it to be applied to various sources—power plants, steel mills, cement factories—though the energy-intensive process and large equipment present challenges.
- *Pre-Combustion Capture:* In this approach, CO₂ is removed before combustion. Fuel is first converted into syngas (primarily carbon monoxide, hydrogen, and CO₂), then processed through a “shift” reaction producing more CO₂ and hydrogen. After the CO₂ is separated, the remaining hydrogen-rich fuel burns cleanly. This approach works well in certain industrial settings, particularly ammonia production and “blue hydrogen” manufacturing. While more efficient than post-combustion for CO₂-rich gas streams, it requires specialized equipment and processes, limiting retrofit potential.

- *Oxy-Fuel Combustion*: Rather than separating CO₂ from nitrogen-diluted exhaust, oxy-fuel combustion burns fuel in pure oxygen (often mixed with recycled CO₂ or water to moderate temperature). The resulting exhaust—primarily CO₂ and water vapor—yields nearly pure CO₂ after water condensation. This method simplifies separation but requires energy-intensive oxygen production. While tested in pilot projects like Germany’s Schwarze Pumpe plant (2008), oxy-fuel remains at the demonstration stage for power generation.
- *Direct Air Capture (DAC)*: Unlike the others, DAC extracts CO₂ directly from ambient air rather than from specific sources. Large industrial fans move air through filtration materials that chemically bind CO₂. Heat or electrical energy later releases the concentrated CO₂ for compression and storage. Companies like Climeworks (Switzerland) and Carbon Engineering (Canada) have developed commercial-scale facilities, though still small ones—Climeworks’ Orca plant in Iceland captures about 4,000 tons annually.

DAC offers location flexibility and can address diffuse emissions or even achieve negative emissions. Its main challenge lies in the extreme dilution of atmospheric CO₂ (0.04% versus concentrated industrial sources), making it energy-intensive and expensive—currently hundreds to over \$1,000 per ton, compared to tens of dollars for point-source capture.

Promise and Limitations

Carbon capture’s potential contribution to climate mitigation remains limited by several factors:

- *Scale Versus Need*: Current capacity (approximately 50 million tons annually) represents a tiny fraction of emissions. Meaningful climate impact would require gigatons-scale deployment—at least 1,000+ million tons yearly—requiring massive infrastructure expansion and investment.
- *Technical Efficiency*: While 90% capture rates are theoretically achievable, practical results often fall short due to operational issues or cost constraints. Additionally, CCS doesn’t address upstream emissions (like methane leaks) or eliminate all facility emissions.
- *Storage Capacity*: Geological storage capacity appears sufficient—likely hundreds of years’ worth at current emission rates. Most industrial regions have accessible storage formations, and experience from projects like Sleipner indicates that properly selected sites can retain over 99% of injected CO₂ for thousands of years.

However, comprehensive site surveys, monitoring protocols, and legal frameworks remain incomplete in many regions.

- *Economic Hurdles:* CCS imposes substantial costs. The energy penalty alone is significant—a coal-fired power plant with CCS requires 20–30% more fuel to generate the same electricity. Capital expenses for equipment and the absence of revenue from underground storage (except in enhanced oil recovery) further undermine economic viability without policy support. Current capture costs range from \$60–100 per ton for industrial sources to several hundred dollars for direct air capture.
- *Risk Management:* While generally considered safe, CCS involves potential risks, including CO₂ leakage and induced seismic activity from pressurized injection. Other environmental considerations include increased water consumption (up to 50% more for coal plants with CCS) and waste products from degraded chemicals. Public acceptance of pipelines and storage sites presents another hurdle, with some communities opposing CCS as prolonging fossil fuel dependence.

Strategic Role

Carbon capture represents one tool in a comprehensive climate strategy, not a complete solution. For sectors that can be electrified or use alternative energy sources, those options typically offer lower costs and additional benefits. However, CCS offers critical emissions reduction potential for hard-to-decarbonize industries like cement and steel manufacturing, where process emissions are inherent to current production methods.

Additionally, bioenergy with CCS (BECCS) and direct air capture with storage (DACCS) could potentially achieve negative emissions later this century, offsetting remaining emissions from other sectors. Their deployment at scale will depend on technological advancement, policy support, and international coordination.

Carbon capture technologies have evolved from industrial processes to potential climate solutions, with proven effectiveness at facility scale. Yet their global impact remains small, limited by economic, technical, and infrastructural challenges. With continued innovation and supportive policies, carbon capture could significantly contribute to emission reduction strategies, particularly in sectors where alternatives remain elusive, while complementing the broader transition to renewable energy and sustainable practices.