

Efficient power generation and LDES

CO₂ utilisation in the energy transition

By Stephen B. Harrison, sbh4 consulting

Too much carbon dioxide (CO₂) in the atmosphere causes problems with the earth's climate. But using the thermodynamic properties of this versatile molecule in modern power systems can support a climate-friendly energy transition.

Affordable, clean power is essential to drive sustainable economic development. Renewables such as wind, solar, hydro and tidal power

will be integral to a low-carbon energy mix. However, baseload power and long duration energy storage (LDES) will be required to supplement these non-programmable renewable power sources. CO₂ can support that in several ways.

The Allam-Fetvedt cycle enables thermal power generation from fossil fuels with zero CO₂ emissions to air. It uses supercritical CO₂ (sCO₂) from oxyfuel combustion as the main working

fluid in a semi-closed Brayton cycle. sCO₂ is also at the heart of the indirect-fired supercritical CO₂ recompression Brayton cycle which can be used with concentrated solar power, or on modern nuclear reactors.

In addition to its use as a working fluid in power generation, CO₂ can be used in a reversible power storage cycle to compliment non-programmable renewable power sources.

Concentrated solar power



Low-carbon power generation

The Allam-Fetvedt cycle can enable the use of natural gas or gasified coal to contribute to a Net Zero future. It offers high-efficiency power generation from traditional fossil fuels in an innovative cycle that avoids greenhouse gas (GHG) emissions.

In the Allam-Fetvedt cycle, sCO₂ is recirculated as the main component in the working fluid for power generation. The Allam-Fetvedt cycle relies on oxyfuel combustion which also ensures that pollutant emissions are avoided and enables post-combustion CO₂ to be captured at high pressure and low cost.

When gasified coal is used in the Allam-Fetvedt cycle, oxygen can also be used to simplify CO₂ capture from the gasification process. Large ASUs (air separation units) will be required to support this power generation cycle.

Conventional coal-fired power generation heats up steam, which is the working fluid within the power generation turbines. In conventional air-fed, gas-fired turbines, the nitrogen-rich combustion gases themselves drive the generator. In each case, post-combustion CO₂ capture would be required to ensure low-carbon power generation.

Post-combustion CO₂ capture generally takes place at the end of a power generation combustion process where the gas stream is very low pressure, and the CO₂ is often diluted with nitrogen from combustion air. The Petra Nova coal-fired power plant operated by NRG Energy in Texas and the SaskPower Boundary Dam Power Station coal-fired facility in Saskatchewan are well-documented case studies using amine solvents for post-combustion CO₂ capture.

The Petra Nova coal-fired power plant captures CO₂ for utilisation in enhanced oil recovery (EOR). It uses an amine-based solvent from Mitsubishi Heavy Industries in a twin-tower absorber and stripper system to capture post-

combustion CO₂ from the low-pressure flue gas.

Additional heat must be generated by the power plant to boil CO₂ from the amine solvent in the stripper, thus CO₂ capture comes at an additional cost. CO₂ capture at Petra Nova is economically viable when oil prices are high, but it becomes unprofitable when oil prices fall. Petra Nova ceased CO₂ capture in early 2020 when crude prices hit a low due to Covid, but restarted the CO₂ capture plant three years later in September 2023 as the price of West Texas crude broke through \$90 per barrel level.

One of the challenges of this mode of post-combustion CO₂ capture is the low pressure flue gas stream requires a very large CO₂ absorber tower to handle the high volume of low pressure flue gas. Additionally, a large CO₂ compressor is required to blow the captured CO₂ away to a suitable sequestration location.

Pre-combustion CO₂ capture (for example in steam methane reformers that are widely used by industrial gas companies for hydrogen production) can take place at high pressure and high CO₂ concentrations, thereby reducing the capital and operating costs of CO₂ capture. Uniquely, the Allam-Fetvedt cycle enables low-cost, high pressure,

“Renewables such as wind, solar, hydro and tidal power will be integral to a low-carbon energy mix...”

post-combustion CO₂ capture because CO₂ is released from the cycle at around 80 bar. This avoids the need for CO₂ compression.

The Allam-Fetvedt cycle is a semi-closed Brayton cycle. A high flow of CO₂ recirculates within the power generation cycles, but some pure CO₂ is released from the Allam-Fetvedt cycle. This avoids the need for CO₂ capture equipment to separate the CO₂ from nitrogen, oxygen and other typical flue gases. And, since there is no other route out of the process for the CO₂, the CO₂ capture rate from the Allam-Fetvedt cycle is very high at 100%.

CO₂ in the efficient recompression closed Brayton cycle

The US DOE-funded STEP demonstration project will operate a 10 MWe power plant using a ▶

© NRG Energy Inc | Petra-Nova's captured carbon dioxide pipeline



► recompression closed Brayton cycle (RCBC) with sCO₂ as the working fluid. STEP is the acronym for Supercritical Transformational Electric Power. This 10 MWe plant will be the world's largest indirect-fired sCO₂ power cycle test facility. Construction is scheduled to be complete in 2023, with operation and testing during at the end of 2024.

The STEP project is being executed by General Electric and the Gas Technology Institute (GTI) at the Southwest Research Institute (SwRI) site in San Antonio, Texas. Like the Allam-Fetvedt cycle, high efficiency heat exchangers and robust turbines are the key technology components in the indirect-fired sCO₂ recompression Brayton cycle. These are also key equipment items in modern high-efficiency air separation units. However, the equipment design and materials of construction differ.

Supercritical CO₂-based power cycles have the potential for increased heat-to-electricity conversion efficiencies. As a power generation working fluid, sCO₂ combines the best properties of both a liquid and a gas because it has a high density and low viscosity. A large amount of energy is lost when steam turns back into water in the Rankine cycle.

The implication is that only one third of the energy in the steam can be converted into electricity. In comparison, the sCO₂ Brayton cycle has a theoretical conversion efficiency of more than 50%.

CO₂ as a working fluid also offers high power density, and simplicity of operation compared to a steam-based power cycle – and can use more compact turbomachinery. This makes the cycle relevant to a wide range of applications. For example, the sCO₂ power cycle can be used for maritime propulsion and waste heat recovery.

The RCBC has the flexibility of being fuel agnostic and can generate power from fossil, geothermal and concentrated solar heat sources. CO₂ as a working fluid is also being considered for advanced nuclear reactors. When compared to the helium Brayton cycle, sCO₂ has the advantage of lower temperature operation. To achieve a similar heat to power conversion efficiency, helium would need to be heated to circa 850°C, whereas the sCO₂ is required to be heated to around 550°C. As a result, sCO₂ can be applied to nuclear reactors with a core outlet temperature above 500°C.

Liquid and gaseous CO₂ for grid balancing

The Italian start-up Energy Dome uses gaseous and liquid CO₂ in a closed cycle in its CO₂ Battery™. The technology is a form of long duration energy storage (LDES) that avoids the use of batteries.

The Energy Dome cycle expands vaporized liquid CO₂ across a turbine to generate power during periods of peak demand. The expanded CO₂ is stored in a large dome at atmospheric pressure.

When there is abundant renewable power generation from solar PV sources during the peak daylight hours, CO₂ gas is withdrawn from the dome. It is compressed and liquefied using excess power from the grid, which may otherwise be curtailed. Liquid CO₂ is stored in cryogenic tanks, like those used in industrial gas applications.

Energy Dome has developed a standard design that produces 20 MW of power over a 10-hour discharge period, meaning that it can store 200 MWh of power. The charging time is 10 hours, which can match well with the solar excess period in many renewables-led grids.

Low pressure CO₂ storage is an integral aspect of the Energy Dome concept. The amount of CO₂ gas that is stored determines the amount of power that the CO₂ Battery™ can release on demand. The standard 20 MW Energy Dome design would need many road-tanker loads of CO₂ to charge the system with the required amount of CO₂ gas.

To enable low-cost storage of a large volume of CO₂ gas at close to atmospheric pressure, Energy Dome uses the solution developed by another Italian company, Ecomembrane. The Ecomembrane is a PVC-coated polyester fabric membrane. This material has been used on more than 1,000 installations around the world to contain biogas in wastewater treatment plants or landfill sites. [EW](#)

Ecomembranes were developed for biogas processing



© NRG Energy Inc | Petra-Nova post combustion CO₂ capture facility



Nuclear reactor core

