Efficient power generation and LDES

CO_2 utilisation in the energy transition

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Too much carbon dioxide (CO_2) 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. CO_2 can support that in several ways.

The Allam-Fetvedt cycle enables thermal power generation from fossil fuels with zero CO_2 emissions to air. It uses supercritical CO_2 (sCO_2) from oxyfuel combustion as the main working fluid in a semi-closed Brayton cycle. sCO_2 is also at the heart of the indirect-fired supercritical CO_2 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, CO_2 can be used in a reversible power storage cycle to compliment non-programmable renewable power sources.

Concentrated solar power

Llow-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, sCO_2 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 CO_2 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 CO_2 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 CO_2 capture would be required to ensure low-carbon power generation.

Post-combustion CO_2 capture generally takes place at the end of a power generation combustion process where the gas stream is very low pressure, and the CO_2 is often diluted with nitrogen from combustion air. The Petra Nova coal-fired power plant operated by NGR 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 CO_2 capture.

The Petra Nova coal-fired power plant captures CO_2 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 CO_2 from the low-pressure flue gas.

Additional heat must be generated by the power plant to boil CO_2 from the amine solvent in the stripper, thus CO_2 capture comes at an additional cost. CO_2 capture at Petra Nova is economically viable when oil prices are high, but it becomes unprofitable when oil prices fall. Petra Nova ceased CO_2 capture in early 2020 when crude prices hit a low due to Covid, but restarted the CO_2 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 CO_2 capture is the low pressure flue gas stream requires a very large CO_2 absorber tower to handle the high volume of low pressure flue gas. Additionally, a large CO_2 compressor is required to blow the captured CO_2 away to a suitable sequestration location.

Pre-combustion CO_2 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 CO_2 concentrations, thereby reducing the capital and operating costs of CO_2 capture. Uniquely, the Allam-Fetvedt cycle enables low-cost, high pressure, post-combustion CO_2 capture because CO_2 is released from the cycle at around 80 bar. This avoids the need for CO_2 compression.

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

The Allam-Fetvedt cycle is a semi-closed Brayton cycle. A high flow of CO_2 recirculates within the power generation cycles, but some pure CO_2 is released from the Allam-Fetvedt cycle. This avoids the need for CO_2 capture equipment to separate the CO_2 from nitrogen, oxygen and other typical flue gases. And, since there is no other route out of the process for the CO_2, the CO_2 capture rate from the Allam-Fetvedt cycle is very high at 100%.

CO_2 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 sCO_2 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 sCO_2 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 sCO_2 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 CO_2-based power cycles have the potential for increased heat-to-electricity conversion efficiencies. As a power generation working fluid, sCO_2 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 sCO_2 Brayton cycle has a theoretical conversion efficiency of more than 50%.

CO_2 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 sCO_2 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. CO_2 as a working fluid is also being considered for advanced nuclear reactors. When compared to the helium Brayton cycle, sCO_2 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 sCO_2 is required to be heated to around 550°C. As a result, sCO_2 can be applied to nuclear reactors with a core outlet temperature above 500°C.

Liquid and gaseous CO_2 for grid balancing

The Italian start-up Energy Dome uses gaseous and liquid CO_2 in a closed cycle in its CO_2 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 CO_2 across a turbine to generate power during periods of peak demand. The expanded CO_2 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, CO_2 gas is withdrawn from the dome. It is compressed and liquefied using excess power from the grid, which may otherwise be curtailed. Liquid CO_2 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 CO_2 storage is an integral aspect of the Energy Dome concept. The amount of CO_2 gas that is stored determines the amount of power that the CO_2 Battery™ can release on demand. The standard 20 MW Energy Dome design would need many road-tanker loads of CO_2 to charge the system with the required amount of CO_2 gas.

To enable low-cost storage of a large volume of CO_2 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. gw

Ecomembranes were developed for biogas processing

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Nuclear reactor core