sCO_2 and CO_2 as working fluids for power generation and storage

Too much carbon dioxide in the atmosphere is clearly a problem. But using the thermodynamic properties of this versatile molecule in modern power systems can be an opportunity

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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 that can be used with concentrated solar power, or on modern nuclear reactors. Gaseous CO_2 can also be used as a working fluid in reversible power storage cycles to complement non-programmable renewable power generation.

sCO_2 as a working fluid in the Allam–Fetvedt cycle

The Allam–Fetvedt cycle can enable the use of gasified coal or natural gas 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 emissions. The process relies on oxy-fuel combustion, which also ensures that pollutant emissions are avoided and enables post-combustion CO_2 to be captured at high pressure and low cost.

Above: **Net Power La Porte demo site**

As in conventional air-fed, gas-fired turbines, combustion gases spin the main turbine in the Allam-Fetvedt cycle. However, in the Allam–Fetvedt case, they consist of a mixture of approximately 97.3% CO_2 and 2.7% water.

Supercritical CO_2 is recirculated within the Allam–Fetvedt cycle as the main component of the working fluid for power generation. Transfer of heat from the hot turbine exhaust gases to the burner inlet gases is essential to achieve efficient operation of the cycle. Printed circuit heat exchangers have been used for this application to combine high efficiency and process intensity.

The main turbine for the original Allam–Fetvedt cycle demonstration facility at La Porte, Texas, was built by Toshiba. Recently, Baker Hughes has taken on the role of turbine development and production for future deployments of the Allam-Fetvedt technology.

The temperature and pressure mean that the CO_2 is supercritical at the turbine inlet. And the presence of moisture means that carbonic acid formation is possible. Materials selection and coating technologies are the key to successful turbine operation in this environment.

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.

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 used 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 about 80 bar. This avoids the need for CO_2 compression.

Furthermore, pure CO_2 is released directly from the Allam–Fetvedt cycle avoiding 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, about 100%.

Supercritical CO_2 in the recompression closed Brayton cycle

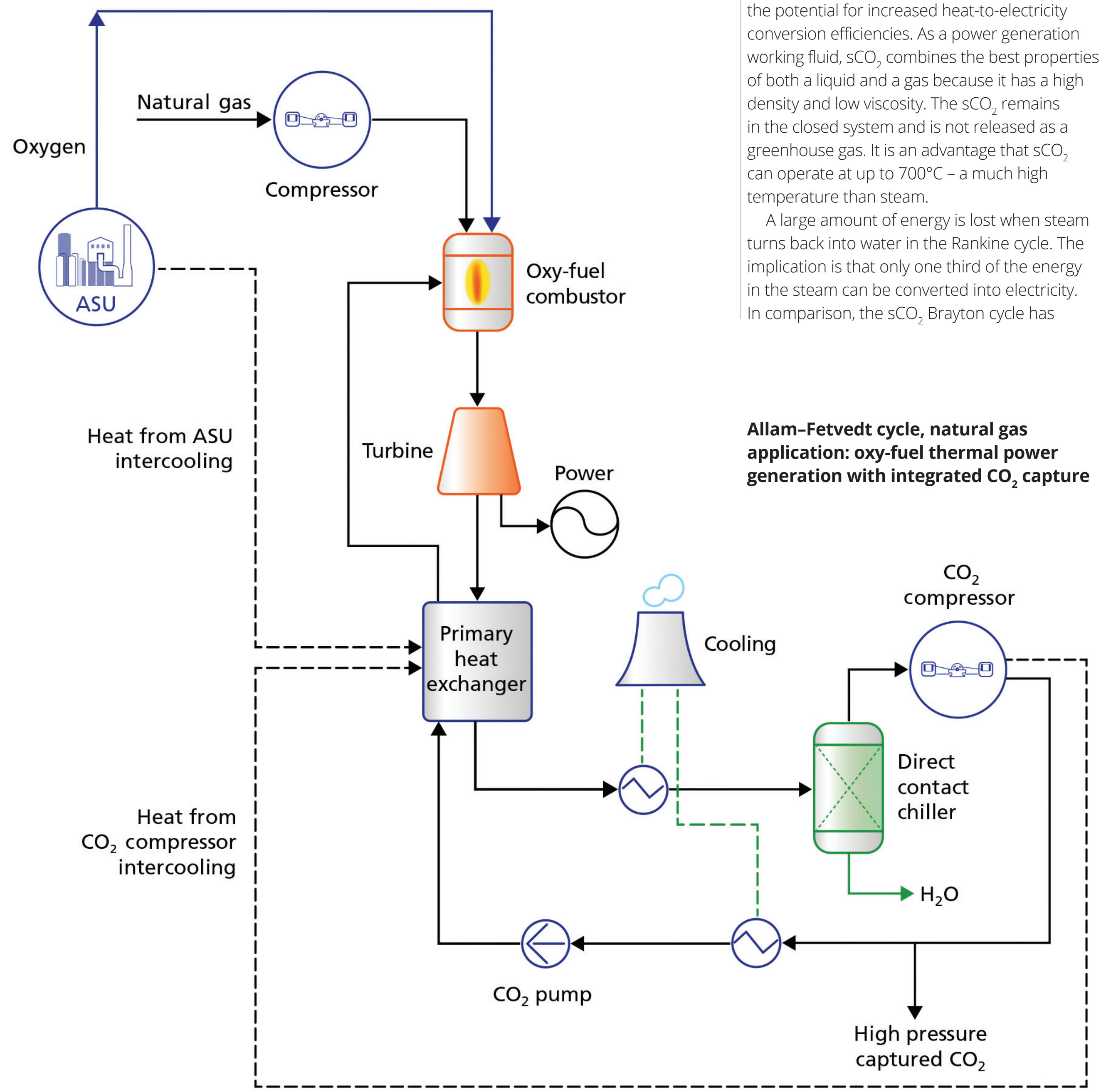
Sandia National Laboratories, Albuquerque, has researched and demonstrated a supercritical CO_2 recompression Brayton cycle and dispatched around 10 kW of power to the Sandia–Kirtland Air Force Base electrical grid for 50 minutes during a test in August 2022.

At a larger scale, the US DOE-funded STEP Demo project will see the operation of a 10 MWe power plant using similar technology (see *Modern Power Systems*, Nov/Dec 2023, pp 14-18). This plant will be the world's largest indirect-fired sCO_2 power cycle test facility and will use a recompression closed Brayton cycle (RCBC) with sCO_2 as the working fluid.

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 and these are two of the main research areas within the STEP programme.

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. The sCO_2 remains in the closed system and is not released as a greenhouse gas. It is an advantage that sCO_2 can operate at up to 700°C – a much high temperature than steam.

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



Allam–Fetvedt cycle, natural gas application: oxy-fuel thermal power generation with integrated CO_2 capture

Stream composition, referenced to combustor feed						
	Temperature (°C)	Pressure (bar)	CO_2 (wt%)	Natural gas (wt%)	Oxygen (wt%)	H_2O (wt%)
Oxy-fuel combustor feed	700	300	94	1.25	4.75	0
Expansion turbine feed	1150	300	97.25	0	0	2.75
Primary heat exchanger feed	720	30	97.25	0	0	2.75
High pressure captured CO_2	60	80	100	0	0	0
Direct contact chiller drain	20	30	0	0	0	100

a theoretical conversion efficiency of more than 50%. The RCBC has the potential to be significantly more efficient than the traditional steam-based Rankine cycle because sCO_2 can operate between low and high temperatures and low and high pressures without a phase change.

Unlike the Allam–Fetvedt cycle, fuel combustion takes place outside the RCBC since it is an indirectly heated process. The RCBC therefore has the flexibility of being fuel agnostic, but if CO_2 is generated by fossil fuel combustion, the resultant CO_2 would need to be captured to yield climate-neutral power generation.

Supercritical CO_2 as a working fluid 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 in addition to power generation from nuclear, fossil, geothermal and concentrated solar heat sources. For example, the sCO_2 power cycle can be used for maritime propulsion and waste heat recovery.

Supercritical 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 sCO_2 is required to be heated to around 550°C. sCO_2 can therefore be applied to nuclear reactors with a core outlet temperature above 500°C.

Above: **Ecomembrane**

Left: **Air Separation Unit for oxygen production for oxyfuel combustion**

Gaseous CO_2 cycle for LDES and grid balancing

The Italian startup Energy Dome uses subcritical gaseous CO_2 in a closed cycle in its CO_2 Battery™ (see also page 29). The technology is a form of long duration energy storage (LDES) that avoids the use of conventional batteries. The Energy Dome cycle expands vaporised liquid CO_2 across a turbine to generate power during periods of peak demand, typically overnight and in the early morning when power is drawn from the grid before solar generation has begun. 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. Heat energy from the compression is stored in a thermal energy storage system. This heat is subsequently used to revaporise the liquid CO_2 to ensure maximum cycle efficiency. The whole cycle operates below the triple point of CO_2, avoiding supercritical operation.

Energy Dome has developed a standard design that produces 20 MW of power over a 10 hour discharge period. The charging time is 10 hours, which can match well with the solar excess period in many renewables-led grids. The duration of discharge is longer than most battery systems can offer and is a complementary fit to solar-heavy grids. Excess solar generation is increasingly common in areas with a high percentage of rooftop solar generation, such as South Australia.

Furthermore, green hydrogen systems based on solar power without overnight wind power integration may benefit from the Energy Dome for overnight power to the electrolysers to ensure high utilisation and avoid periods of shutdown. The daily cycling of the Energy Dome system is also a good fit to the LDES business model, which relies on high utilisation of the capital asset to ensure maximum revenue generation with frequent charging and discharge cycles. Revenue can also be generated through grid management services and excess power withdrawal to avoid power surges on the grid.

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. To enable low-cost storage of a large volume of CO_2 gas at close to atmospheric pressure, Energy Dome can use the concept developed by another Italian company, Ecomembrane.

The Ecomembrane technology relies on a PVC-coated polyester fabric membrane. This material has been used for decades as a low-cost means to contain biogas in wastewater treatment plants and store recovered landfill gas. The Ecomembrane has been used on more than 1000 installations around the world for these purposes. MPS

NET Power focuses on Project Permian

Lummus Technology has signed a strategic supply agreement with NET Power to design and supply recuperative heat exchangers (HXR) for utility scale power plants employing the Allam–Fetvedt cycle (also now sometimes referred to as the NET Power Cycle). The first planned utility scale plant is Project Permian (300 MWe), located near Midland-Odessa in Texas, with initial power generation envisaged in the second half of 2027/first half of 2028. NET Power says it is "engaging its strategic shareholders to support the project": Baker Hughes (key integrated process equipment and technologies); Oxy (CO_2 transport & sequestration and power off-take); Constellation (expertise in plant operations and power off-take); and 8 Rivers (project development support).

Front-end engineering and design (FEED) for Project Permian is underway in partnership with Zachry Group. It is expected to conclude in 2024 and will form the basis for NET Power's standardised utility-scale plant design. Site related permitting is also progressing for Project Permian.

The HXR recovers energy from the turboexpander exhaust and air separation unit to reheat recirculated CO_2, making it one of the most important pieces of equipment in the NET Power Cycle.

Upon completing the FEED for Project Permian, NET Power says intends to issue a purchase order to Lummus for that plant.

Under the terms of the strategic supply agreement, Lummus, in its role as the licensed NET Power HXR supplier, intends "to leverage its global supply chain network to increase global HXR manufacturing capacity, enabling NET Power deployments at scale to help countries and communities around the world rapidly achieve their energy and environmental goals."

Heatric, part of Meggitt, now a division of the Parker Hannifin Filtration Group, supplied printed circuit heat exchangers for NET Power's La Porte Allam–Fetvedt demo facility.

The La Porte test facility site is currently being prepared for combustor and turboexpander demonstrations to be carried out in conjunction with Baker Hughes, with the aim of de-risking the first utility-scale project and further refining NET Power's proprietary plant controls architecture.

Looking beyond Project Permian, NET Power also reports progress on what it calls its "first originated project" (OP1), which will be "located in North America." A technical feasibility study has been completed and NET Power says it is preparing to submit permits for grid interconnection and carbon sequestration, in 2024. ●