POWER

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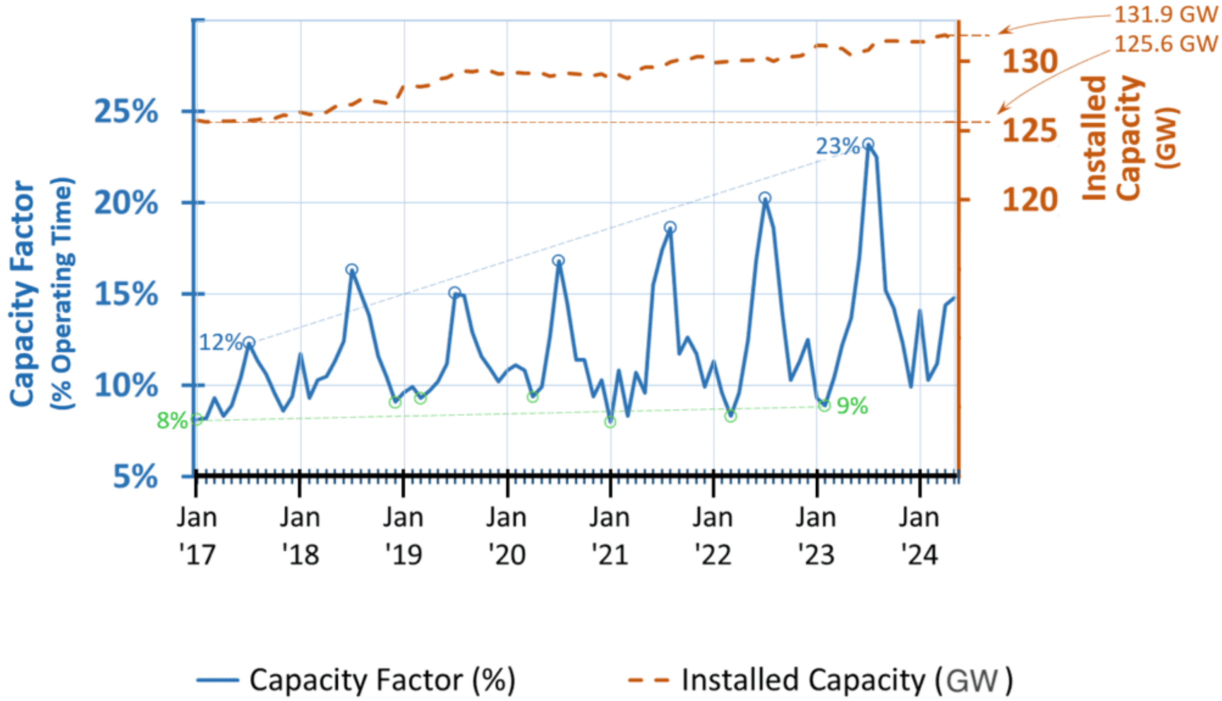
Simple Cycle, Combined Cycle, or a Hybrid Approach?

Simple cycle gas turbines provide efficiency levels of around 35% to 40%. Combined cycle units boost efficiency to 60% and beyond. But another option is emerging that combines the attributes of simple and combined cycle designs. This hybrid configuration uses a single power turbine expander and recycles exhaust heat back to the combustor to combine the best of both worlds. Known as the VAST (Value Added Steam Technologies) Power Cycle, it promises efficiency levels above 50%. It holds the potential to become the most cost-effective backup option for grids where renewable energy dominates. Further, it achieves emissions levels that are cleaner than California's stringent limits without catalysts.

Traditional Power Cycles

Though infrequently used, simple cycle (Brayton) peakers operate on standby and provide vital backup power supporting grid reliability. They offer operational flexibility with fast ramp capabilities. The U.S. Energy Information Administration (EIA) reports that capacity factors of simple cycle plants averaged 9.6% to 14.1% from 2017 through 2023. However, summer peaks have surged above 12%, reaching up to 23% at times (Figure 1). Summer utilization peaks have been rapidly increasing while the winter utilization increased only slightly. This has resulted in winter to summer capacity factor swing of 4% in 2017 increasing to 14% in 2023.



1. Monthly U.S. simple cycle natural gas turbine capacity factor and installed capacity (January 2017–May 2024). Source: EIA

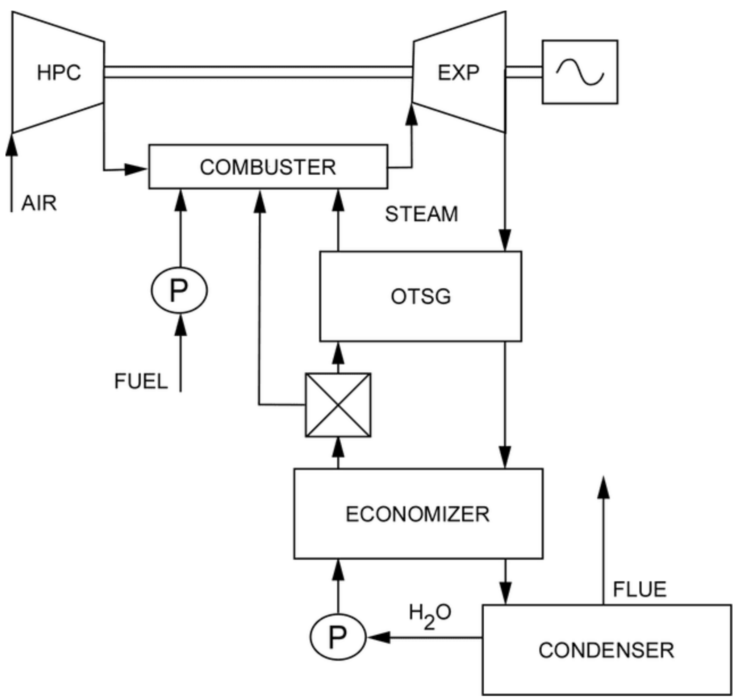
U.S. peaking capacity rose slowly to 132 GW through early 2024. About 3 GW of peaking capacity has been added over the last three years. An additional 2.8 GW is planned for 2024 and 2025 with about half of that addition in Texas. The Lone Star State needs more fast-starting dispatchable backup capacity to support a flood of renewables coming onto the grid that bring about greater variability of supply. The EIA predicts 14 times higher increase in non-dispatchable solar and wind generation compared to dispatchable peaking power and nuclear power in 2024 (37% solar and 6% wind vs. 2% natural gas and 1% nuclear). This shows a rapidly rising need for dispatchable backup of growing solar and wind power.

The other traditional power plant design is combined cycle. Such plants feed exhaust heat from gas turbines through a heat recovery steam generator (HRSG) that uses the Rankine cycle to produce steam that is fed to a steam turbine. This raises the efficiency by a considerable margin over simple cycle plants. It can approach 65% under ideal conditions. The average capacity factor for the U.S. combined cycle fleet rose to 57% in 2022, according to the EIA. During 2022 and 2023, a total of 13 new combined cycle plants with a combined capacity of 12.4 GW entered service. About 5 GW more is due online in 2024 and 2025.

As a great many more systems and components are involved, combined cycle plants are more complex than simple cycle facilities. Gearboxes and clutches are sometimes included. Thus, capital costs are higher and maintenance issues multiply. Further, the presence of more renewable energy on the grid is forcing many combined cycle plants to cycle constantly. This causes serious maintenance and degradation issues. In some cases, coping with frequent solar and wind fluctuations reduces combined cycle efficiency below 50% due to slow steam turbine response from rapid cycling.

A New Hybrid Cycle

A middle ground is emerging, which is a hybrid of simple and combined cycle. The VAST Power Cycle uses a gas turbine expander to meld the Brayton cycle with the Rankine cycle, eliminating the steam turbine of the combined cycle (Figure 2). The single gas turbine expander operates on about 46% steam, and about 54% nitrogen (N_2), carbon dioxide (CO_2), and oxygen (O_2), as the hot working fluid that generates system power.



2. The VAST Power Cycle. (Exp = expander; P = pump; HPC = high-pressure compressor; OTSG = once-through steam generator). Source: VAST

The gas turbine is transformed into a hybrid gas/steam turbine, increasing expander power by 60% to 80% depending on pressure. Exhaust heat is recovered and recycled back into the combustor with steam and hot water. This displaces excess compressed cooling air and its losses. The system achieves more than 50% efficiency while delivering lower-cost electricity. The elimination of excess cooling air also reduces the compressor flow and size by 50% or more. The energy used to compress cooling air is now available for power generation.

This significantly increases system efficiency while lowering capital expenditure per kW below that of both simple and combined cycle units. The system's annual capacity factor can then shift from less than 10% for simple cycles to 10% to 60% to backup non-dispatchable solar and wind.

Overcoming Wet Combustion Barriers

Wet combustion was historically limited by flame quenching, the cost of water purification, and lower efficiency. Makeup boiler quality water to replace water lost in the exhaust had previously made continuous NO_x control via water injection far too expensive. Historically, water injection improved power but reduced efficiency. The hybrid cycle has overcome this issue.

This new hybrid cycle recovers net water, eliminating continuous boiler quality water treatment. By recycling cooling water and steam, it displaces more than 75% of the compressed air normally required to cool gas turbines. All the injected cooling water is recycled while recovering net water from combustion.

"Recovering and recycling ultra-pure water overcomes the greatest objection to using wet cycle gas turbines," said VAST Co-Founder and Chief Scientist Dr. David Hagen. "This new power cycle recycles injected steam and hot water, plus a portion of the water formed by combustion."

Emissions Control

In 2023, Sargent & Lundy reviewed conventional water injection for NO_x gas turbine emission control. The firm found, "Water injection is a well-established technology and … can offer NO_x emissions of below 42 ppm (0.05 lb/MMBtu), with the lowest practical emissions of 25 ppm (0.03 lb/MMBtu)." Such high emissions levels exceed U.S. Environmental Protection Agency (EPA) requirements for power generation. Poor mixing of air, fuel, and water in conventional combustion systems caused hot spots and NO_x.

The VAST Cycle combustor improves mixing, reduces O_2, controls combustion temperatures with steam and water, and lowers peak temperatures. Sufficient oxygen with improved mixing and adequate residence time simultaneously cuts carbon monoxide (CO). Modeling found NO_x and CO formation below 1 ppmvd (parts per million by volume diluted to 15% O_2 on a dry basis).

The system was modeled through two Department of Energy (DOE) reactive computational fluid dynamics (CFD) grants using 1.1 million core hours of supercomputer time and 8,900 person-hours of Argonne and Lawrence Livermore National Lab personnel. Modeling achieved more than two orders of magnitude lower NO_x and CO than emitted by conventional gas turbines.

"The gas turbine combustor has been the most difficult component to scale," said Hagen. "We designed a scalable combustor that overcomes this challenge. It achieves more uniform fluid mixing and 10-fold better temperature control while improving durability."

Argonne Lab's CFD modeling and Lawrence Livermore's data reduction predict sub-2 ppmvd NO_x and CO emissions over a wide range of turbine operating parameters. These emissions are projected for 10 MW to 500 MW and for turbine inlet temperatures ranging from 1,100C to 1,500C.

According to the Argonne National Lab report on the new combustor: "Wet combustion using water and steam is a promising technology to strongly reduce harmful emissions while boosting Brayton cycle efficiency by ~24%. VAST provides a new, more cost-effective backup power generation system essential to enable increasing penetration of intermittent renewable solar and wind power. It offers new technology for the rapidly growing market of renewable power backup—beyond peaker turbines. Clean combustion eliminates 6% to 9% emission cleanup capital costs plus ongoing ammonia operating costs."

Initial projections on cost savings indicate that this approach could boost efficiency 24% higher than simple cycle machines. The EIA estimates that a simple cycle plant costs about $389/kW. It is projected to cost about $295/kW at 70 MW capacity, or 37% below simple cycle peaker costs.

Next Steps

The NASA Technical Readiness Level (TRL) system lays out the commercialization progress of new technology. VAST has reached TRL 4 and is looking for partners to take it through the pilot phase on to commercialization. This hybrid system has the potential to solve some of the problems that have emerged during the energy transition. With so many coal plants being shut down, and many areas reluctant to invest heavily in natural gas facilities, anything that has the potential to reduce the cost per kW of traditional power and drastically lower emissions should attract interest. If this new approach to wet combustion moves through to commercialization rapidly, it could fill the gap of dispatchable power that is growing each year as more wind and solar resources are added to the grid.

Author: ***Drew Robb*** *(drewrobb@sbcglobal.net) has been a full-time freelance writer for more than 25 years specializing in engineering and technology.*