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Compressed air energy storage (CAES)

A proven solution for cost-effective, grid-scale and long-duration power storage

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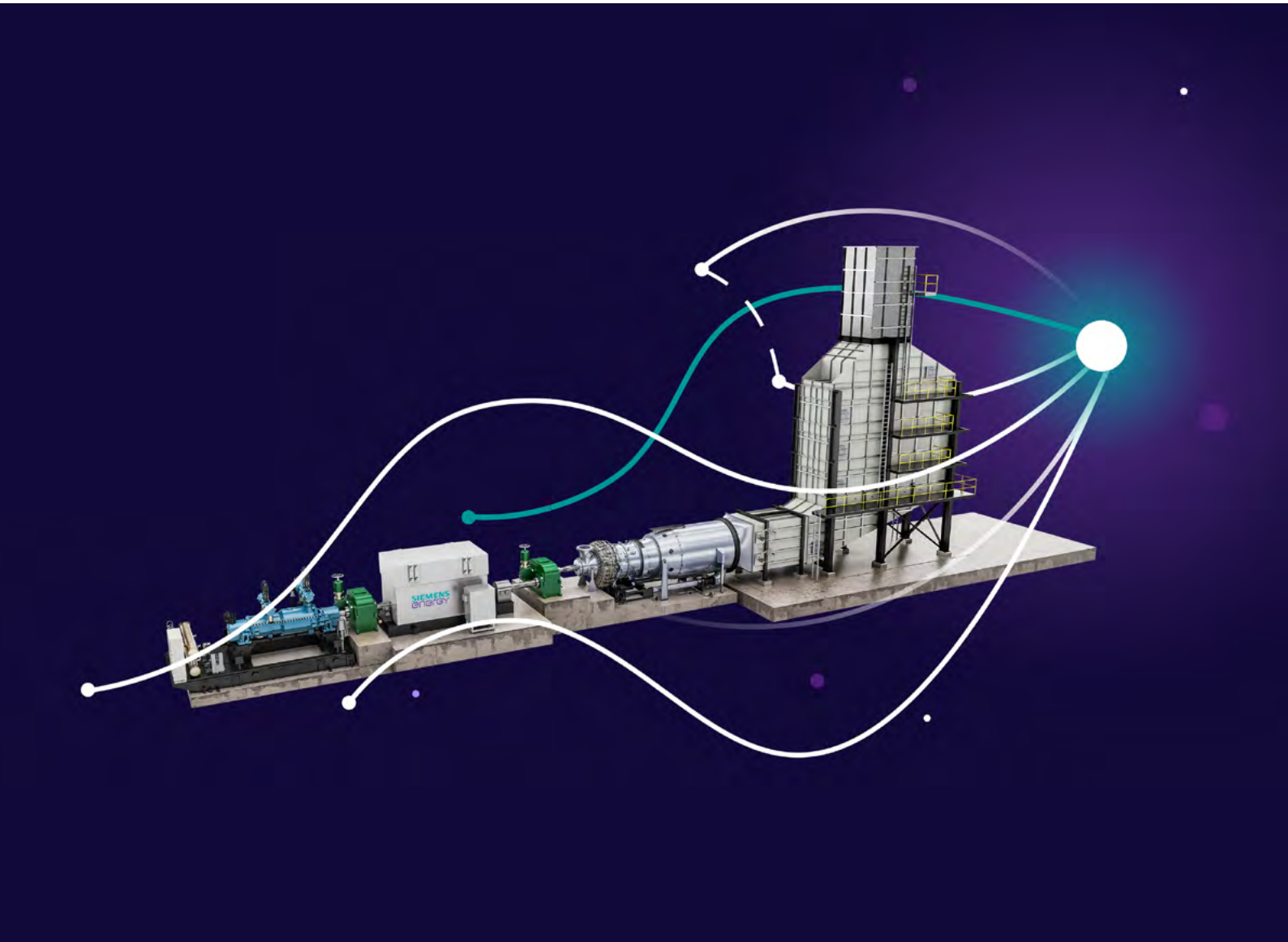

Abstract

As renewable power generation from wind and solar grows in its contribution to the world's energy mix, utilities will need to balance the generation variability of these sustainable resources with demand fluctuations. This paper describes how power-generation operators can use compressed air energy storage (CAES) technology for a reliable, cost-effective, and long-duration energy storage solution at grid scale. Further, it explains how CAES can provide a path to deep grid decarbonization via hydrogen as fuel. The two major components of a CAES system — a compression train and an expander train — are explained. Also included is a comparison of the advantages of CAES technology over lithium ion battery solutions in achieving sufficient storage duration to support high renewable penetration.

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Growth in renewable power generation is exploding across the U.S and around the world. By the end of 2021, the U.S. Energy Information Administration (EIA) expects renewables, especially wind and solar, to be the nation's fastest growing sector of power generation. By 2050, the agency expects renewables' share of wind and solar in the U.S. power-generation mix to grow to 38 percent, double its 2019 proportion. Worldwide, wind and solar grid installations are outpacing fossil fuels, accounting for 67 percent of new global power-generation capacity in 2019.

In addition to a continuing fall in the installed costs of wind and solar technologies, advantageous tax and governmental policy benefits, regulatory emissions compliance requirements, and corporate social responsibility expectations are helping to drive the growth in adoption of renewable energy sources.

> **"We know that climate risk is investment risk. But we also believe the climate transition presents a historic investment opportunity."**
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> Laurence D. Fink, Founder, Chairman and Chief Executive Officer of BlackRock, world's largest investment management firm

Blackrock, the world's largest investment management firm with nearly $9 trillion in assets, made an explicit commitment to sustainability when Founder, Chairman and CEO Laurence D. Fink said in his 2021 letter to CEOs, "We know that climate risk is investment risk. But we also believe the climate transition presents a historic investment opportunity."

Addressing intermittency. Wind and solar share a big shortcoming that must be factored into their deployment scenarios and, ultimately, their continued growth as fully decarbonized and sustainable power-generating resources: intermittency. Although both resources can deliver power with no fuel costs and zero emissions — an ideal combination for electricity's decarbonization — they depend on a key variant of weather, as in whether (and the degree to which) the wind is blowing or sun is shining.

Without a cost-effective, grid-scale energy storage solution, it is virtually impossible for utilities to align the variability in renewable power generation with daily and seasonal demand fluctuations.

Historically, electric utilities have used pumped storage as a mechanism to balance grid supply and demand. However, pumped storage is not technically or economically feasible in regions lacking the appropriate geographical features, or where water resources are scarce. Lithium-ion battery banks are increasingly being applied at grid level, but they are not well suited for energy storage duration levels beyond approximately four hours.

This whitepaper will demonstrate that Compressed Air Energy Storage (CAES), a proven technology with a long list of competitive advantages, can represent a compelling energy storage solution in regions with geological features suitable for underground storage of high-pressure air.

McIntosh 110-MW CAES plant in Alabama, built in 1991 with Siemens Energy technology and since operating smoothly, economically and with 98.9% reliability.

Siemens Energy, a global pioneer in power generation and CAES

Siemens Energy, a world leader in power generation, with a broad portfolio and global installed base of thousands of utility- and industrial-grade gas turbines and compressors, is at the forefront of CAES technology. Our pioneering roots in CAES extend back decades. We helped build the 110-MW plant in McIntosh, Alabama, USA in 1991. Today, proven grid-scale CAES technology from Siemens Energy stands ready for additional deployments in power grids across the globe to help utilities take greater advantage of wind and solar renewable energy resources.

How a Siemens Energy CAES solution works

Simply put, a Siemens Energy CAES solution uses electric motor driven compressors to capture the excess energy generated by renewables, storing the compressed air underground. Then, during hours of higher grid demand, the compressed air is withdrawn from storage, heated and routed to expansion turbines to generate electricity.

The CAES facility thus engages in "energy time shifting" — producing economic value by taking advantage of the price differential between low and higher demand periods. In addition, a CAES facility can be designed to accommodate storage duration extending to multiple days — ensuring the availability of a firm energy resource, dispatchable as needed to meet system demand, as well as to provide grid support services such as regulation, spinning reserves, and transmission optimization.

Three expansion stages. In a typical CAES cycle, as shown in Figure 1, there are three stages of expansion. Compressed air, upon exiting the storage cavern, is first

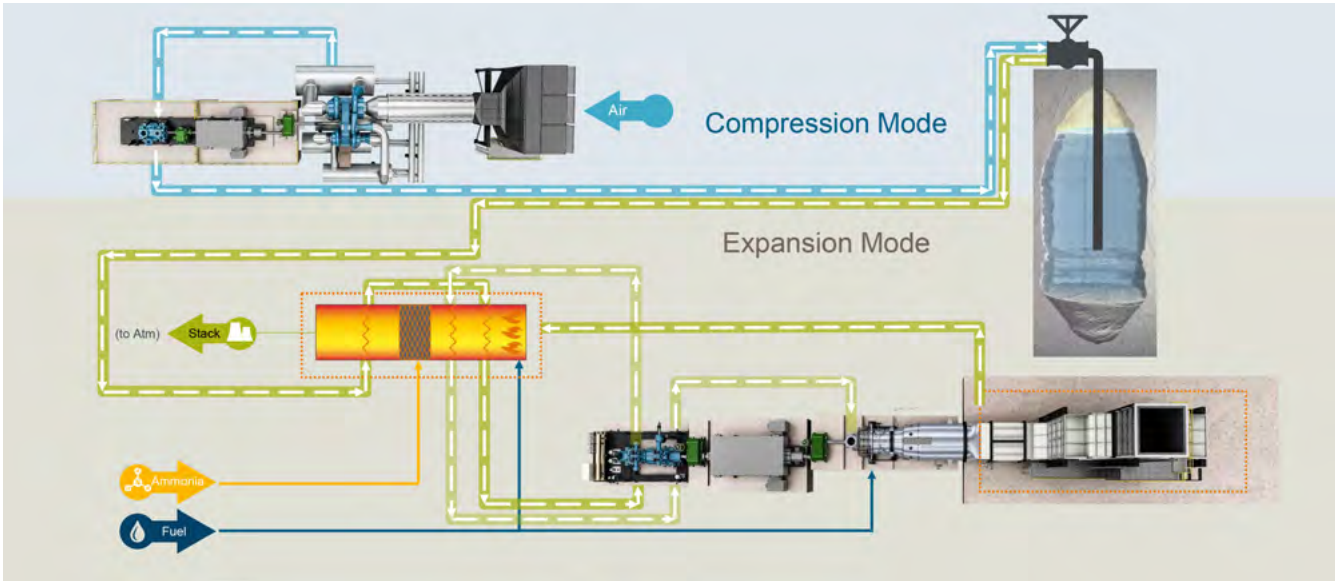

Figure 1. CAES cycle schematic showing simultaneous compression and expansion operating modes.

pre-heated by the expander's exhaust in a waste heat recovery exchanger or recuperator. Supplemental firing in the recuperator further increases the temperature of the air to 1000°F before it flows through the first-stage expander to produce 20 MW. The first-stage exhaust is then reheated in the recuperator and routed through the second-stage expander, producing an additional 32 MW.

Upon exiting the second-stage expander, the air is directed to a dry low-NOx combustor system, where direct firing increases the temperature before entering the third and final stage expander. The third-stage expander generates an additional 108 MW, resulting in a rated output of 160 MW.

More fuel efficiency. The use of recuperation, coupled with high air storage pressures (up to 3,000 psi), results in excellent energy efficiency for the CAES power block. Compared to conventional simple-cycle combustion turbines or "peakers" that many utilities use to provide rapid load response, the Siemens Energy CAES power block consumes about 67 percent less fuel, thereby producing that much less CO_2 per kW-hr.

What's more, a standard gas turbine operates in tandem with a compressor section. A CAES facility decouples the expansion and compression functions — resulting in a superior heat rate curve during partial load operation. This enables the economical operation of the unit at minimum load — as low as 10 percent of nameplate — while waiting to be dispatched by the grid operator.

Compression train

The CAES compression train, shown in Figure 2, uses Siemens Energy's Siemens STC-GV or DATUM compressors, with thousands of units installed worldwide in air separation and other industries. Depending on site requirements, compressor selection can be configured up to 125 MW per train, with the capability to turn down air flow rate by up to 30 percent on demand. Compression ramp rate is 30 percent per minute, allowing rapid change in response to fluctuation in available power — a performance characteristic that is well-suited for intermittent renewable power. So, when desired, the compressor train can transition from offline to full load within four minutes. Finally, the compressor motor can be interrupted by an underfrequency relay — and thus is capable of offering reserve capacity to the grid in the form of near instantaneous demand reduction.

Expansion train

The Siemens Energy CAES expansion train, shown in Figure 3, generates electricity over a wide operating range.

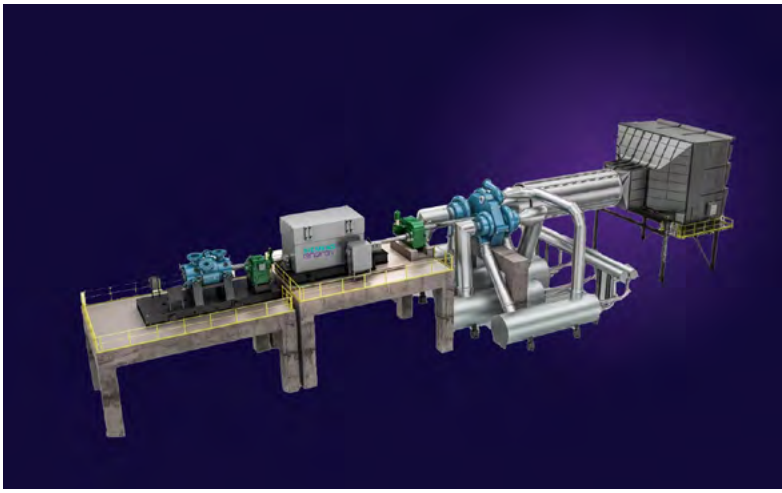

Figure 2. **Siemens Energy CAES compression train can reach full load from startup within four minutes**

It features an integrated (single case) VHP and HP expander derived from a Siemen's Energy SST-800 steam turbine. The train's LP expander is derived from Siemens Energy's SGT-800 gas turbine. Both turbine models are proven in use with many hundreds of units installed worldwide for power generation and other industrial applications.

The expansion train is capable of approximately 160 MW maximum power output with exceptional operating flexibility — able to ramp up over a range of 10–100 percent of rated capacity within five minutes. The plant can achieve full power from start in less than 10 minutes of a request for dispatch. Finally, in comparison to a combined cycle gas turbine installation, start costs are exceptionally low, as there is no need to burn fuel to bring the steam cycle up to operating temperatures.

Figure 3. Siemens Energy CAES expansion train can achieve full power within 10 minutes of startup.

Path to a 100-percent hydrogen future

Utilization of the SGT-800 hot section for the third stage expander provides reliability and service-part commonality with the large, global installed fleet of these engines. The SGT-800 also enables operators to co-fire their expansion trains with up to 50 percent hydrogen, with a retrofit path to 100 percent hydrogen by 2030. The ability to co-fire with hydrogen today with a path to 100 percent hydrogen in the future enables a CAES plant to evolve over time as carbon reduction efforts evolve to a deeply decarbonized power supply. In addition, CAES facilities located on salt domes are well positioned to accommodate onsite hydrogen storage.

Equipment benefits: Long life, fast startups and ramps, low emissions

CAES plant equipment from Siemens Energy is designed for a long life of 30 years or more. It is capable of long duration grid-scale storage — ranging from 8 hours to several days — and can provide numerous ancillary services to the grid with low associated fuel consumption and emissions. The plant has excellent load following capability with a nearly flat heat rate across an extremely broad operating range. Designed for fast startup and ramp rates, independent operation of compression and expansion trains allows operators to quickly respond to changing grid and market conditions.

Comparative advantages of a CAES solution

A Siemens Energy CAES solution offers utility operators a wide range of advantages, especially compared with lithium-ion battery solutions. These include:

- **Superior flexibility.** CAES offers operators a wide operating range of up to 90 percent with a low sustainable low (LSL) rating of 10 percent of plant output. By comparison, a combined cycle gas turbine has an LSL rating of just 50 percent of plant output.
- **Lower cost.** Where suitable storage geology is present, CAES can achieve long duration power storage at a far lower cost than other options, including pumped storage or lithium ion batteries. According to the U.S. Department of Energy's 2020 Grid Energy Storage Technology Cost and Performance Assessment: "CAES remains the most cost-effective [energy storage system] on a total installed cost basis as well as an annualized cost basis for a 100 MW, 10-hour system."
- **High reliability.** For example, the McIntosh CAES plant uses Siemens compressors and generators, which have operated smoothly, economically, and reliably for 30 years and provide a current plant reliability rate of 98.9 percent.

Siemens Energy, a pioneering world leader in power generation and CAES technology

Siemens Energy has a long history of providing reliable, utility-grade equipment and services to the power-generation industry around the world. Our heritage includes such venerable companies as Westinghouse and Dresser-Rand. We invest heavily into R&D each year to drive innovation across our portfolio of advanced energy technology. This includes the decarbonization of more than 50 percent of that portfolio.

Based on our expertise and experience, Siemens Energy has a deep appreciation for the requirements that utility operators have with regard to reliability and maintainability of power generation equipment. That's why we can offer

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>
> U.S. Department of Energy December 2020

our CAES technology on a turn-key basis for the surface "power block" equipment, with industry-standard equipment warranties and performance guarantees backed by the financial strength and staying power of a company with roots going back to 1847.

Siemens can also support ongoing service needs of the CAES process equipment under a Long Term Service Agreement, inclusive of real-time equipment monitoring accompanied by proprietary analytical software.

To find out more, please visit https://www.siemens-energy.com/global/en/offerings/renewable-energy/energy-storage-solutions/caes.html.

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