Fuel-Free Geologic Compressed Air Energy Storage from Renewable Power

Task #7 Final Report

For:
New Technology Implementation Grant Program

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Submitted by:
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Abstract/Executive Summary

General Compression (GC) has completed the design and installation of a General Compression Advanced Energy Storage (GCAES™) machine, and its integration with a 2MW Gamesa G97 wind turbine, a pre-existing geologic salt cavern, and the Lea County Electric Cooperative electrical grid.

This GCAES™ machine was then operated across a wide range of operating speeds and pressures, and data from hundreds of sensors were collected. These data were used to analyze, among other things, thermodynamic and hydraulic performance, machine pressure and flow rates, cavern interaction, and energy flows between the wind turbine generator, the GCAES™ machine and the grid to assess the technological and commercial viability of the machine.

Throughout commissioning and initial operations, multiple technical issues were uncovered, improvements designed, and upgrades made, improving the overall GCAES™ design and informing its future operations.

The GCAES™ technology has been proven to be successful, demonstrating, as called for under the TCEQ NTIG, its value for reducing air pollution by integrating renewable energy generators (such as wind turbines) with energy storage to provide a firm energy output and providing other grid benefits.

General Compression is now seeking the resources to build its production intent design machine as it aims towards commercial opportunities.
**Introduction/Background**

General Compression (GC) has developed a near-isothermal compressor/expander module that allows utility-scale energy storage systems to operate fuel-free for long durations (from 10 to 100+ hours) at a variety of power ratings (from 5 megawatts to 1,000+ megawatts).

Long-duration GCAES™ addresses three market needs not met by short-term energy storage:

1. Enables wind energy to compete with natural gas, coal and nuclear generation for new firm generation requirements in many markets;

2. Provides flexibility and optionality to solve many grid related problems including: (i) meeting peak demand, (ii) making base-load plants load-following, (iii) integrating wind, (iv) avoiding new build generation and transmission costs, (v) overcoming fossil fuel and transmission permitting issues, and (vi) providing other ancillary services; and

3. Provides trading organizations with optionality not inherent in traditional generation resources or short duration energy storage.

Long-duration GCAES™ technology meets market needs that cannot be met by batteries, other CAES technologies or pumped hydropower, and can meet varying market needs, including by using above- and below-ground storage mediums. GCAES™ technology is protected by 14 issued patents and nearly 50 patent applications filed in the United States, Canada, Europe, and Asia. GCAES™ development is ahead of competing fuel-free CAES technologies.

Building on the previously proven core intellectual property and technology, the completed and operating facility in Gaines County, Texas is the first fuel-free and third utility-scale CAES project in the world. It demonstrates the scalability of GCAES™, its integration with the power grid, wind turbine, and geologic & thermal storage, and system-level functionality and performance on a continuing basis.

**Project Objectives/Technical Approach**

As articulated from the project’s beginning, the objectives of this project were:

*Installation of GCAES™ and integration with 3MW of wind turbine(s) at the specific project site or an adjacent site that includes an existing geologic salt cavern in West Texas, allowing a minimum of 500 megawatt-hours (MWh) of stored, renewable energy to be delivered to the grid.*
**Tasks**

As set forth in the original Grant Agreement, the Grant Activities and Scope of Work were detailed in seven tasks, as follows:

- Task 1: Finalize agreements for ownership and operation of the overall project site;
- Task 2: Secure necessary permits to install and operate the GCAES™ at the specific project site and 3-MW of wind turbine(s) at specific project site or an adjacent site;
- Task 3: Specific project site preparation;
- Task 4: Prototype accumulation of 1000 operating hours;
- Task 5: Finalize GCAES™ design;
- Task 6: Procure components for, build, and install GCAES™ and 3-MW of wind turbine(s); and
- Task 7: Reporting

The first six tasks have been completed, and deliverable reports have been submitted and approved by TCEQ.

This deliverable report is being submitted to satisfy the Task 7 requirement for a final report.

**Task 7: Reporting**

Task 7 requires reporting quarterly and in a “comprehensive final report,” as set forth in the Grant Activities (Scope of Work):

2.7 *The PERFORMING PARTY will prepare and submit quarterly detailed project reports and a comprehensive final report while ensuring compliance with all the TCEQ’s program requirements.*

2.7.1 *The PERFORMING PARTY will coordinate all project resources to ensure compliance with NTIG program requirements while providing deliverables on-schedule and on-budget.*

2.7.2 *The PERFORMING PARTY will generate quarterly progress reports and a final report summarizing all aspects of the project based on data from the task completion reports.*

2.7.3 *Schedule: The PERFORMING PARTY shall submit quarterly reports to the TCEQ by no later than 10 days after the end of each calendar quarter (March 31, June 30, September 30, December 31). The PERFORMING PARTY shall submit the final report to complete this task within 19 months of the signed Notice to Proceed Date as issued by the TCEQ.*
2.7.4 Deliverables: The PERFORMING PARTY shall submit progress reports with associated billing statements and a final report to the TCEQ upon completion of this task.

This deliverable report constitutes the “comprehensive final report” required for Task 7. The remainder of this section of this report details GC’s completion of the required Grant Activities and Scope of Work for each Task.

**Task 1** Finalize agreements for ownership and operation of the overall project site

General Compression and its project partner ConocoPhillips Company secured an overall project site in Gaines County, Texas for the project and for potential future commercial operation. The overall site includes all necessary assets located on the defined land area, including the GCAES™ machine, wind turbine, overhead electrical line to interconnection point, salt cavern, thermal storage pond, brine pond, and piping, wellheads and other balance of plant elements. GC can extend its leasehold rights for more than five years without landlord consent.

The Task 1 Deliverables Report was approved on February 6, 2013.

![Overall Project Site (aerial view)](image)

**Task 2** Secure necessary permits to install and operate the GCAES™ at the specific project site and 3-MW of wind turbine(s) at specific project site or an adjacent site
General Compression and its project partners hold the permits to install and operate the GCAES™ machine and wind turbine, including the following:

**Project:**
- Exempt Wholesale Generator Status (Federal Energy Regulatory Commission)
- Market Based Rate Authority (Federal Energy Regulatory Commission)
- Electrical Interconnect Agreement (Lea County Electric Cooperative)
- Net Metering Agreement (Lea County Electric Cooperative)

**Salt Cavern:**
- Rule 97 Permit (Texas Railroad Commission)

**Wind Turbine:**
- Determination of No Hazard to Air Navigation (Federal Aviation Administration)
- No Identified Interference (National Telecommunications and Information Administration)

General Compression also evaluated the suitability of the site for the project by studying the following:
- Existence of state or federal protected species,
- Presence of hazardous materials (Phase 1), and
- Activity of avian (bird) and bat species and potential for atypical impacts

The Task 2 Deliverables Report (with confidential appendices) was approved on June 12, 2012.

![Figure 2. Overall Project Site (panoramic view)](image)

Key: (1) wind turbine; (2) overhead electrical line to interconnection point (not visible); (3) thermal storage pond; (4) GCAES™ machine (inside building); (5) air pipe to air wellhead (not visible); (6) brine pipe; (7) brine wellhead; & (8) brine pond.

**Task 3 Specific project site preparation**

The GCAES™ machine is located on the site of an existing salt cavern formerly used as a liquid hydrocarbon storage facility. General Compression, along with project partner ConocoPhillips,
and engineering, procurement, and construction contractors Waldron Engineering and Lonquist & Co., prepared the site for installing the GCAES™ machine and constructing the balance of plant. In addition to repurposing and re-commissioning the salt cavern, this work included the following:

- Foundation and building for GCAES™ machine;
- Overhead electrical line to interconnection point;
- Thermal storage pond;
- Brine pond; and
- Piping, wellheads and other balance of plant elements.

MPR Associates, as General Compression’s Owner’s Engineer, certified the project (including the wind turbine) to be “In Service” on December 19, 2012.

Task 3 Deliverables Report (with confidential appendices) was approved on April 18, 2013.

**Task 4 Prototype accumulation of 1000 operating hours**

The Task 4 requirement for 1000 operating hours was achieved using the Advanced System Prototype machine in Gaines County, Texas, as well as the Proof of Concept and First Stage Demonstrator machines in Watertown, Massachusetts. The first 1000 operating hours on a prototype machine are typically the most crucial for proving a new technology; therefore, a detailed runtime plan was developed to achieve this task, with runtime hours progressing from more conservative, highly-observable operation up to full pressure and faster stroke times.

These machines have continued to run since submission of the Task 4 Deliverables Report, accumulating additional hours. The machines ran successfully in both compression and expansion modes, at a variety of speeds and operating pressures.

The data file from the first compression stroke on ASP can be seen in Figure 3. The data from hundreds of sensors throughout the ASP machine are collected, both for long-term storage and detailed analysis, as well as for instantaneous display and machine control. Figure 3 shows an instantaneous display available through GC’s data collection system that the controls engineers and machine operators utilize.

Figure 4 shows the cavern pressure rising as a result of the GCAES™ machine running in compression and pumping air into the underground cavern. The cavern pressure is the orange line, and can be seen in this plot rising up to 950 psi as measured in real-time with pressure transducers in the cavern pipe.

These pressure sensors in the cavern have also been used to measure the losses associated with long-term air storage in the underground cavern. For lengths of time up to months, there has
been no measurable pressure decay in the stored air. Therefore, the storage efficiency of GCAES™ technology is measurable at 100%.

The Task 4 Deliverables Report (with confidential appendices) was approved on January 7, 2014.

Figure 3. First Compression Stroke

Figure 4. Cavern Pressure Rise during Compression
**Task 5  Finalize the GCAES™ design**

General Compression decided to pursue its first opportunity for a commercially functioning GCAES™ machine by upgrading the Advanced System Prototype in Gaines County, Texas rather than building an entirely new machine at another location in Texas that was to be determined.

Virtually every major subsystem in the machine was upgraded, modified, or repaired subsequent of the original design. Significantly improved machine output, performance, and durability resulted from upgrading the major components and subsystems as follows:

*Hydraulic System*
- Boost Circuit
- Pilot Circuit
- Water Exchange Circuit
- Decompression Valves
- Controls

*First Stage Pressure Vessel*
- Piston
- Rolling Sock Seal

*Second Stage Pressure Vessel*
- Ram
- Structural Support System

*Electrical System*
- Switchgear
- SCADA System interface with Wind Turbine

*Balance of Plant*
- Above Ground Cavern Pipe
- Thermal Storage Pond

The Task 5 Deliverables Report (with confidential appendices) was approved on January 23, 2014.

**Task 6  Procure components for, build, and install GCAES™ and 3MW of wind turbine(s)**

General Compression completed the procurement, construction, and installation (including mechanical and electrical integration) of the GCAES™ machine and a Gamesa G97 2MW wind turbine. General Compression secured permission to operate (and other required approvals) and thereafter interconnected and synchronized both the GCAES™ machine and the wind turbine to the electrical grid.

Through the sophisticated supervisory control and data acquisition (SCADA) system used for GCAES™, the controls have shown the ability to take the input signal from the wind turbine and react to this signal by compressing or expanding.
The Task 6 Deliverables Report (with confidential appendices) was approved on March 10, 2014.

Discussion/Observations

Objectives vs. Results

According to the Request for Grant Applications, the primary objective of the New Technology Implementation Grant program is to

...offset the incremental cost of emissions reductions of pollutants from facilities and other stationary sources in the State of Texas, [by, among other things,] adequately funding the implementation of new technologies that will make the state a leader in new technologies that can solve the state’s environmental challenges while creating new business and industry in the state.

As demonstrated by General Compression’s project in Gaines County, Texas, the GCAES™ technology, as explained below, aims directly at emission reduction by allowing emission-free generation from a wind turbine to be stored and used when grid demand would otherwise require energy from a fossil-fuel generation source. More specifically, the Grant Activities and Scope of Work required by TCEQ allowed and encouraged General Compression to advance its understanding and development of its energy storage technology in a way that advances its commercial prospects in Texas and elsewhere.
The GCAES™ system is a fuel-free compressed air energy storage technology. When charging, electricity is used to drive an electric motor/generator (EMG), operating as a motor. The EMG directly drives a high-efficiency hydraulic pump/motor. The hydraulic pump/motor generates high-pressure oil flow, which drives a hydraulic linear actuator, thereby converting the rotational energy of the EMG to reciprocating motion. The hydraulic linear actuator is directly coupled to a piston in the compression/expansion cylinder. The reciprocating motion of the piston displaces water in the cylinder. The changing water level, along with the opening and closing of valves, causes air to be compressed at nearly constant temperature and then pushed into storage. During compression, the heat from compression is transferred to the water in the vessel. A portion of the water is moved into a thermal pond (for later use in the expansion process) and replaced with a volume of cool water. During expansion, when electricity is demanded, the system valves are operated in a sequence that allows the high-pressure air from storage to drive the piston, hydraulics, and EMG (operating as a generator) to deliver power. The warmed water from compression, stored in the thermal pond, is returned to the system during expansion, preventing the air from cooling significantly. This energy flow can be seen in Figure 6.

Figure 6. GCAES™ energy flow

Through working with the Lea County Electrical Cooperative, General Compression successfully connected the GCAES™ machine and the Gamesa G97 wind turbine to the electrical grid. These three systems were then connected and controlled by the SCADA system.

The SCADA system takes real-time data from the on-site wind turbine, the GCAES™ machine, and signals provided by the grid operator to determine the optimal operation of the GCAES™. The SCADA system will tell the machine to turn on, turn off, increase load, or decrease load based on what the wind turbine is providing and the grid is requesting.
Figure 7 shows the SCADA system overview, detailing the connection between the South Hobbs grid, the wind turbine, and the GCAES™ generators. The machine is controlled from this screen, and from the other SCADA screen tabs at the top.

Critical Issues

The learning from the GCAES™ Advanced System Prototype is invaluable for the future of compressed air energy storage, both from understanding the successes and addressing the continuing practical problems.

An in-depth formal analysis of the potential issues with the machine has been conducted in the form of a design failure mode and effect analysis (dFMEA). Thirty-eight major components were analyzed in detail to discover failure modes and potential failure effects. Failure prevention and detection already designed into the system was identified for each failure mode, and additional ideas fixes for the future were developed. The severity, probability, and detectability of each of the causes of failure were set, and a full priority matrix was calculated. The results are being used for both ASP risk mitigation as well as for future GCAES™ designs.

A discussion of a selection of these critical issues can be found in detail in the Task 4 Report Appendices, and an overview of a few important issues can be seen below. In addition to what is listed below, significant lessons were learned regarding water and thermal management within the piston vessels, hydraulic system simplification and architecture, and hydraulic and process
valve design and operation. Extensive learning has also been accomplished on the machine control system. For each of these items, an improvement has been developed for the next GCAEST™ machine design.

**Hydraulic Cylinder Connection Rods**

Early in the process of calibrating the machine after it was initially energized, it became apparent that the high-pressure hydraulic cylinder connection rods needed to be redesigned to withstand the expected high-cycle fatigue. The machine was taken down for a period of time, the upgrade was successfully implemented, and there have been no subsequent problems with the hydraulic cylinder connection rods.

**Hydraulic System Contamination**

Upon first startup of the machine, accidental macro-contamination was found in the hydraulic oil lines, and resulted in damage to hydraulic pumps. The pumps were removed from the system, disassembled, and repaired before they were reinstalled. Three phases of hydraulic system flushing were required to remove the remaining contamination, through the use of an external filtration system. This was accomplished in full, and no issues with hydraulic contamination have been experienced since.

**Large Vessel Seal**

An innovative solution for sealing large-diameter piston-vessel assemblies, an inflatable rubber rolling seal was used to isolate the upper and lower chambers between the Stage 1 piston and vessel. An ideal solution, with zero leakage and almost zero frictional losses, this sealing innovation is important for machine efficiency and for manufacturing costs. However, as it is the first of its kind, it has required ongoing iterative improvements to make the design and manufacturing processes support the durability requirements.

Multiple design iterations have been developed, installed, and tested, each resulting in more learning and more statistically significant results.

**Hydraulic Control Valves**

Due to the machine’s hydraulic circuit architecture, very large hydraulic fluid flows were required through the control valves. This required custom valve design and prototype hydraulic valves to be installed in the machine. With these prototype parts came efficiency challenges. These challenges have currently been solved for this machine but, in an added layer of protection, prototype-resultant issues will be avoided on future machines due to a simpler hydraulic circuit architecture design in which commercial off-the-shelf hydraulic valves can be used.

**Process Valves**

GC has unique air process valve requirements, and has seen some challenges with slipping and breaking of the couplings between the valves and the actuators. However, all of the couplings that have had issues have been replaced, and long-term design changes are in place for future machines to avoid this issue.
Technical and Commercial Viability of the Proposed Approach

General Compression’s project in Gaines County, Texas has provided valuable data affirming the viability of GCAES™ and the use of GCAES™ to firm wind generators as commercial technology.

The kilowatt-scale Proof of Concept and First Stage Demonstrator machines in Watertown, Massachusetts proved that the core technology innovations worked in concept. But two non-trivial questions remained to be answered, as only a full-scale prototype could demonstrate: do the thermodynamics at scale work? and does the cavern integration work?

Even with the challenges encountered, the Gaines County, Texas project has demonstrated that the answer to each question is ‘yes.’

One of the main innovations of the GCAES™ machine is the novel near-isothermal compression/expansion. Based on data from sensors throughout the machine, the thermodynamic results are very close and slightly better than the analytical thermodynamic model predictions, as detailed in the Task 4 Deliverables Report. These data are significant, showing that one of GC’s most important innovations is performing even better than expected.

The cavern integration performs precisely as predicted based on models of pressure compensation and air injection.

Based on these results, and operating experience in both compression and expansion modes, at varying stroke rates and pressures, with no cavern pressure losses or machine rating degradation over time, the Gaines County, Texas project has successfully established the technical viability of long-duration storage with GCAES™.

Moreover, the learning occurring during construction, commissioning and operation of this machine has improved GCAES™ design and operations. The upgrades installed in this machine have improved the performance and availability of GCAES™. The result is a commercially viable technology.

Scope for Future Work

Informed by the experiences while performing the Grant Activities and Scope of Work, and contingent on obtaining the necessary resources, General Compression plans to build its production-intent design machine. This next model will incorporate the design improvements for increased rating, availability and efficiency. It will be built with production-intent suppliers with production-intent components. It will take advantage of further economies of scale, and it will be operated in a commercial-intent method.
Intellectual Properties/Publications/Presentations

The following list includes those published US patents and US patent applications that cover intellectual property related to core GCAES™ and project technologies.

Published US Patents

1. **8,522,538**
   Systems and methods for compressing and/or expanding a gas utilizing a bi-directional piston and hydraulic actuator

2. **8,454,321**
   Methods and devices for optimizing heat transfer within a compression and/or expansion device

3. **8,387,375**
   Systems and methods for optimizing thermal efficiency of a compressed air energy storage system

4. **8,359,857**
   Compressor and/or expander device

5. **8,286,659**
   Compressor and/or expander device

6. **8,272,212**
   Systems and methods for optimizing thermal efficiency of a compressed air energy storage system

7. **8,161,741**
   System and methods for optimizing efficiency of a hydraulically actuated system

8. **8,096,117**
   Compressor and/or expander device

Published US Patent Applications

1. **20120222424**
   Compressor and/or expander device

2. **20120174569**
   Compensated compressed gas storage systems

3. **20120102954**
Compression/expansion process that allows temperature to vary independent of pressure

4 20120102935
Systems, methods, and devices for the management of heat removal within a compression and/or expansion device or system

5 20120096845
Systems and methods for compressing and/or expanding a gas utilizing a bi-directional piston and hydraulic actuator

6 20120073432
Compressor and/or expander device with rolling piston seal

7 20120057998
System and methods for optimizing efficiency of a hydraulically actuated system

8 20120057997
Systems and methods for optimizing thermal efficiency of a compressed air energy storage system

9 20120055145
Systems and methods for optimizing thermal efficiency of a compressed air energy storage system

10 20110258999
Methods and devices for optimizing heat transfer within a compression and/or expansion device

11 20110258996
System and methods for optimizing efficiency of a hydraulically actuated system
Summary/Conclusions

As noted above, the GCAES™ machine can help with emissions reductions by allowing intermittent generation from wind turbines to meet load demands. It can address other important electric system needs, including addressing transmission constraints and lessening the need for new build generation. The Gaines County, Texas project has significantly advanced the GCAESTM technology by demonstrating performance at scale and as integrated with a wind turbine and a salt cavern; it has also meaningfully informed design and operating improvements that will allow commercially viable GCAESTM projects. For these reasons, and others as detailed in this and its prior reports, General Compression is pleased to conclude it has fully achieved all the objectives set out by TCEQ in the Grant Activities and Scope of Work.
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