Fuel-Free Geologic Compressed Air Energy Storage from Renewable Power

Task #4 Deliverable Report

For:

New Technology Implementation Grant Program

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Submitted by:

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Abstract/Executive Summary

General Compression (GC) has successfully operated the 2MW commercial-scale Advanced System Prototype (ASP) and Proof of Concept and First Stage Demonstrator (POC) for over 1000 hours, pointedly substantiating the promise of General Compression Advanced Energy Storage (GCAES™) technology. These critical first hours have provided GC with a wealth of learning, both for improvements to the current prototype machines and for future GCAES™ designs.

The hours at the POC have demonstrated near isothermal compression and expansion, hydraulic drivetrain function and performance, key component durability, and autonomous operation. The POC has also informed performance model validation, as well as provided a test bed for component and subsystem development.

ASP operation has proven two-stage, double-acting compression and expansion with thermal management, full geologic storage and wind turbine integration; these have together taken to a new level the confidence in renewable power output smoothing. The project clearly demonstrates the commercial-scale viability of the core GCAES™ technology. Moreover, the data collected from ASP will serve to validate system-level function and performance on a continuing basis and inform GCAES™ product development and commercialization with ongoing operational data and experience.

The many challenges encountered during initial operation have allowed GC to gain invaluable understanding about the new energy storage technology. Issues were experienced with individual component durability, system integration, component interaction, and machine control. The overall system efficiency posed a challenge both in measurement and in the value of the result. These challenges have all prompted solutions, both for the short and long term, advancing the technology readiness to the point of confidence in near-term commercialization. Solving these problems has helped GC define its place in an emerging market.

To date, ASP has operated over a wide range of stroke speeds and output pressures, resulting in a broad and deep data set for informing, calibrating, and validating analytical models. The ASP machine reached the full cavern pressure through continuous compression runtime. After reaching full pressure and storing the energy successfully in the cavern, the machine was then switched into expansion mode and demonstrated the full energy lifecycle. The success of this operation shows a significant step toward allowing renewable power sources to displace high-emission fossil fuel-fired power plants by providing fuel-free dispatchable power.

Introduction / Background

General Compression has developed a near-isothermal compressor/expander module that will allow the construction of utility-scale storage projects from a minimum of 2MW to over 1,000 MW in power rating and over 300 hours of storage. The General Compression Advanced Energy Storage (GCAES™) project enables renewable generators to output energy to almost any power curve required by a customer. These modules use electricity as an input, either from intermittent renewable generators such as wind turbines and solar arrays, or from off-peak grid generators. The projects are carbon-free and require no fuel to turn the air into energy, lowering operating and permitting costs compared to other compressed air energy storage technologies and expanding the number of potential project sites. Commercial GCAES™ units will have a round-trip electrical efficiency of 66% and an installed cost of between $881-$1,010/kW.

GCAES™ projects are targeted at increasing the value of renewables, eliminating curtailment, enhancing transmission utilization, and making dispatchable renewable power available to customers, thus making it possible for renewables to displace coal or natural gas on the grid and significantly reduce total state-wide emissions. Projects can be built in remote areas, allowing renewables to more completely utilize remote transmission lines. GCAES™ coupled with conventional power generation also reduces the need for peaking power plants and may eliminate the need for future fossil fuel power plant construction.

General Compression plans to partner with utilities and developers of wind farms, existing underground storage facilities, transmission lines, etc. to develop integrated wind/storage projects. Standalone storage projects can also be built within urban power constraint areas, where peak/off-peak power arbitrage opportunities are highest because of the difficulty of siting new generation and transmission. The compressed air is stored in geologic formations and then expanded on demand to convert it to electric power. Value is created by absorbing power when it is not required by customers and generating power when it is. Unlike conventional compressed air energy storage projects, no fuel is burned when air is expanded and power is generated.

GCAES™ projects are responsive enough to be eligible in various markets for their ability to provide spinning reserves, capacity, voltage support, frequency regulation, and other services. GCAES™ projects are carbon-free and do not have gas line connections, air pollutant or CO2 emissions, radioactive risks, or coal ash containment. They are ideally suited to areas where conventional power projects cannot receive air permits.

Project Objectives / Technical Approach

As set forth from its initial application, General Compression has eight operational goals and objectives related to the project for which it is seeking TCEQ funding:

1) Build and install a commercial unit of the General Compression Advanced Energy Storage™ at a demonstration facility being developed jointly between General Compression and ConocoPhillips Company.

2) Integrate the GCAES™ system into an existing cavern formation at the demonstration facility.

3) Build and install approximately 2 to 10 MW of wind turbines at the same site.

4) Integrate electricity generation from the wind turbine into the GCAES™ system for optimal delivery of wind power to the grid.

5) Provide and maintain energy storage and generation services to supply power to the Texas electrical grid over multiple timeframes.

6) Work with the Bureau of Economic Geology at the University of Texas ("BEG") to develop the test protocol to analyze the function of the GCAES™ unit and the wind turbine together as a project so that they respond to appropriate market signals.

7) Work with BEG to analyze the further integration of renewables into the electrical grid throughout the state of Texas in order to support the reduction of emissions and create opportunities for existing and future clean energy industry expansion within the state.

8) Reduce emissions by displacing baseload power generated from fossil fuels with renewable resources thus improving overall air quality in the state of Texas.

Tasks

Task 4: Prototype accumulation of 1000 operating hours

From the Grant Activities (Scope of Work):

> *2.4 The PERFORMING PARTY will operate the 2.4 MW Advanced Systems Prototype for at least 1000 hours to confirm that GCAES™ is ready for commercial operation.*
>
> *2.4.1 The PERFORMING PARTY will take the necessary steps to commission the 2.4 MW Advanced Systems Prototype including but not limited to control system debugging and calibration, data collection, and post-processing.*
>
> *2.4.2 The PERFORMING PARTY will ensure that the accumulation of 1000 hours of operation on the 2.4 MW Advanced Systems Prototype is completed before GCAES™ installation.*
>
> *2.4.3 Schedule: The PERFORMING PARTY shall complete this task within 5 months of the signed Notice to Proceed Date as issued by the TCEQ.*
>
> *2.4.4 Deliverables: The PERFORMING PARTY shall submit a report to the TCEQ upon completion of this task. This report will include a summary of the performance and durability of the 2.4 MW Advanced Systems Prototype for the 1000 hours of operation, problems experienced during the 1000 hours of operation, proposed solutions to the problems, and whether the GCAES™ is ready for commercial operation.*

As noted in the regular quarterly updates, items 2.4.2 and 2.4.3 will be achieved differently than originally stated above. Instead of accumulating 1000 hours on ASP as stated in 2.4.2, at least 950 hours were to be accumulated on POC and at least 50 on ASP. And, instead of completion in 5 months from the signed Notice to Proceed Date, it was agreed in Amendment No. 4 (September 23, 2013) that completion would occur prior to December 31, 2013 for Task 4.

General Compression has two working facilities that will contribute to these objectives: the Advanced System Prototype (ASP) in Gaines County, Texas, and the Proof of Concept and First Stage Demonstrator (POC) in Watertown, Massachusetts. The successful completion of this task will provide significant controls and operational learning for both POC and ASP, as well as for the design of the next GCAES™.

To make the older POC more representative of the future of GCAES™, multiple upgrades have been made, as can be seen in Appendix A: POC Upgrades.

Task 4: Deliverables

The first 1000 operating hours on a prototype machine are the most crucial for proving a new technology. Any fundamental flaws, major deviations, or significant unexpected results will appear in these first hours of running, and upon success, a dramatic increase in confidence in the technology will follow. Therefore, General Compression has put significant planning, priority, and resources into this task. The analysis of challenges encountered and overcome in the first 1000 hours can be found in the Discussion/Observations section.

Plan for 1000 hours

General Compression has stated that a minimum of 950 hours will be accumulated on the Watertown POC and that a minimum of 50 hours will be accumulated on the Gaines County ASP. The POC hours will serve to prove the endurance of key components, while the ASP hours will show the full-scale working system. The endurance testing is straightforward, with hour accumulation being the highest priority. The first 50 hours for ASP will give a much more thorough, deep insight into the GCAES™ technology and hence required a detailed plan for accumulation, progressing all the way from low pressure to full pressure operation. The detailed plan can be seen in Appendix B: Plan for 1000 hours.

Discussion/Observations

The General Compression Advanced Energy Storage™ (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 1.

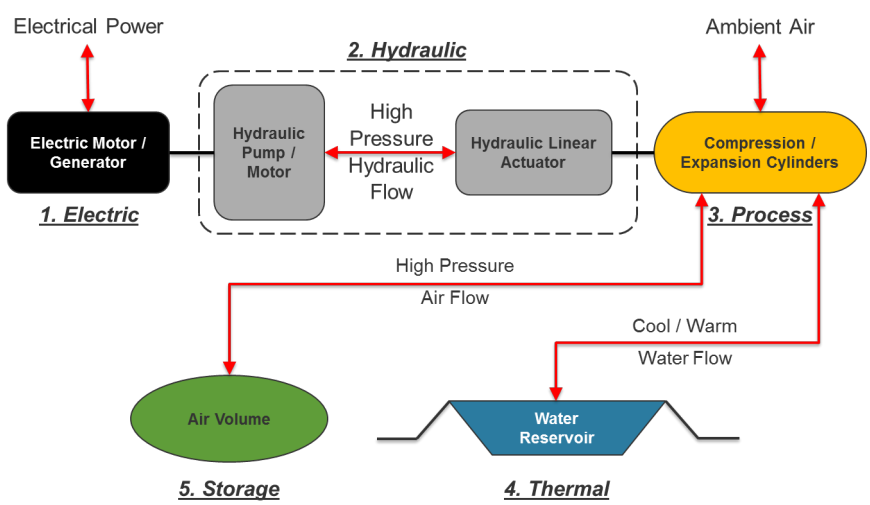

Figure 1. GCAES™ energy flow

Objectives vs. Results

The 1000 total operating hours on the GCAES™ machines has been achieved in full, with greater than 1000 hours on POC and greater than 65 hours on ASP. The detailed results can be seen in Appendix C: Objectives vs. Results.

Critical issues

The learning from the 1000 operating hours at ASP and POC 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 possible failure effects. Failure prevention and detection already designed into the system was identified for each failure mode, and additional ideas on how to fix in 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 Appendix D: Critical Issues

Details or attachment of final results/deliverables

The following documents are submitted as Confidential/Proprietary: inform applicant & seek AG opinion before releasing:

> TCEQ Task 4 Final Report Appendices (69 pages, dated November 5, 2013) submitted as ***Confidential/Proprietary: inform applicant & seek AG opinion before releasing.***

Technical and commercial viability of the proposed approach

The Task 4 goals of the GCAES™ compressed air energy storage project in Gaines County, Texas, as outlined in the Task section above, were all achieved by General Compression. The quality of the design, detail of modeling, and prudent ramping and testing approach all set GC up for success in running both ASP and POC to meet the goals.

ASP and POC have proven to be invaluable resources for both uncovering technical barriers and for testing their solutions. There are continuing testing plans for better machine understanding and model calibration, and there are upgrade schedules in place for addressing remaining issues. These are discussed in more detail in Appendix E: Technical and Commercial Viability.

The successes of both ASP and POC have pointedly proven the promise of GCAES™ technology. The first machines of their kind, they have shown a level of functionality unparalleled by any other new fuel-free, large-scale energy storage technology. The full system, from atmospheric air intake, to compressed

air storage, and back to atmospheric air and electric power output has been successfully demonstrated up to full pressure capability at ASP. With the next design iteration, GC believes that a pre-production model ready for the commercialization path will be built and run at a market-ready utility level.

Scope for future work

Future work is planned for the design of the next GCAES™ machine. A full design process, from concept development to the ongoing operations and maintenance procedure is currently underway. A detailed discussion of future work can be found in Appendix F: Scope for Future Work.

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

The 1000 hours of combined operation on ASP and POC have provided a wealth of knowledge for the future of GCAES™. Durability testing, component and system characterization, model calibration and validation, and control and operational improvements have all been key to furthering machine understanding.

The hours at the POC have demonstrated near isothermal compression and expansion, hydraulic drivetrain function and performance, key component durability, and autonomous operation. The POC also informed performance model validation, as well as for provided a test bed for component and subsystem development.

The hours run so far at ASP are proving two-stage, double-acting compression and expansion with thermal management and full geologic storage and wind turbine integration. ASP operation has increased the level of confidence in renewable power output smoothing. The project clearly demonstrates the scaling of the core GCAES™ technology to commercial proportions. Moreover, the data from these hours of runtime so far will be used to validate system-level function and performance on a continuing basis and inform GCAES™ product development with ongoing operational data and experience.

The component, system, and controls challenges discussed in this report all have a plan in place for near-term solutions for the current prototypes, as well as design changes for the next GCAES™ machine iterations. General Compression has confidence that these solutions will pave the way for the next step to product commercialization.

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