Compressed Air Energy Storage (CAES)

3rd Thermal-Mechanical-Chemical Energy Storage Workshop
August 2021
Energy Storage @ Siemens Energy

- Hydrogen
- Thermal
- Hydro
- Battery
- Grid Stabilizer
- Supercapacitor
- Thermal-mechanical
- Mechanical

Discharge duration:
- Weeks
- Days
- Hours
- Minutes
- Seconds
- Milliseconds

Power:
- 100 kW
- 1 MW
- 100 MW
- 1000 MW

Compressed Air Energy Storage

Introduction

Overview

• Improves utilization of renewable energy resources by absorbing energy that might otherwise be curtailed
• Increases grid capacity utilization, balancing, and reserve services
• GW-hr energy storage for supporting base load generators and load management
• Includes: Above ground systems, plant engineering, procurement, construction, installation, start-up services, long term service support

Client Value Proposition

• Long duration storage
• Energy and ancillary services with low fuel consumption
• Excellent load-following capacity and part-load efficiency
• High ramp rates and fast start-up
• Independent operation of compression and expansion
• Significant plant scope available from single source

APPLICATIONS

Cycle flexibility and long storage duration – key to grid scale energy storage offerings

• Regulation & ancillary services
• Transmission optimization
• Avoidance of renewable curtailment

August 2021
Compressed Air Energy Storage
Simple Concept - cut gas turbine into two pieces

Absorb and store excess energy

10+ GW-hrs storage

Precise air flow management allows for wide operating range (16 – 160 MW)

“Air Battery” – Time Shift Load Absorbing Compressor from Power Generating Turbine

• Modular concept
• Significant Siemens OEM product scope
• Up to turnkey offering
• Performance, delivery and emission guarantees
Compressed Air Energy Storage Reference - McIntosh CAES Plant

Scope of Supply

CAES
- Expander: 154.7 kg/s, 110 MW
- Compressor: 89.5 kg/s, 49 MW
- Storage: Salt Dome @ 540,000 m³
- Pressure Range: 45-75 bara

Siemens overall
- 2x W501F gas turbines
- 2x V84.2 gas turbines
- T3000 plant-wide control system
- Fuel gas booster compressors
- RG3 brushless excitation system
- D3000 vibration monitoring package
- D4 static excitation

Project Background

- PowerSouth had issues meeting electricity demands during peak usage periods
- Operating smoothly, economically and reliably for nearly 30 years
- Plant reliability rate now at 98.9%

Client Benefit

- Quick start capability during critical power outages
- Cost-effective power and a strong backup resource
- Operate their base-load plants more efficiently
- Control of entire plant from a single interface

Application: CAES
Country: USA
Commercial Operation Year: 1991
Client: PowerSouth Energy Cooperative

Note: Refer to EPRI Report TR-101751 V1&V2 for extensive documentation concerning the McIntosh CAES Project
Compressed Air Energy Storage
Grid Scale Interruptible, Controllable Load Absorption

- Six-stage Integrally Geared LP Compressor
- Two-stage Inline Type HP Compressor
- Double-ended Drive 2-pole Electric Motor
- Water-cooled heat exchangers
- Up to 125 MW
- 30% turndown & 30% ramp rate per minute
- 4 minutes from offline to full load
- Interruptible demand response

Compression Train

DATUM - over 1,200 installed
STC-GV - over 2,000 installed

Efficient and Flexible Demand Response with GW-hrs of Energy Storage
Compressed Air Energy Storage
Equipment Configured to Operate as a “Super Peaker”

Unmatched Operating Range Provides Needed Flexibility to Balance Complicated Generation Mix

- 160MW and 140MW max design output
- Less 20MW min generation output.
- VHP and HP Expander derived from Siemens SST-800 steam turbine
- LP Expander with DLE combustion system derived from Siemens SGT-800 gas turbine
- Double-ended Drive 2-pole Electric Generator
- 20% ramp rate per minute
- Full generation in 10 minutes
- 90% effective recuperator with duct burner and Selective Catalytic Reduction system
- Up to 50% H2 co-firing; path to 100%

Expansion Train

SST-800 - over 130 installed
SGT-800 - over 350 installed
LP Expander derived from SGT-800 Gas Turbine (SXT-800)

Advantages of SXT-800 CAES Solution

- Large installed base and operating experience with the combustion and high-temperature turbine hardware
- State-of-the-art emissions achievable with DLE (no water injection)
- Performance improvement of the expander system due to higher turbine inlet temperature
- Smaller air piping for the same power output level leading to lower cost in the plant and potentially in the cavern and wellbore
- Experience of service personnel in installation, commissioning, and long-term maintenance of the SGT-800 hardware
- Significant size, experience, and capability of the SGT-800 core unit engineering teams to help solve any problems that may arise in the field
Compressed Air Energy Storage Expander Cycle Flexibility

Performance demonstrates wide operating range

<table>
<thead>
<tr>
<th>Power (MW)</th>
<th>Heat Rate (kJ/kWh)</th>
<th>System Flow (kg/s)</th>
<th>Fuel Usage* (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>160</td>
<td>4067</td>
<td>144</td>
<td>3.9</td>
</tr>
<tr>
<td>105</td>
<td>4095</td>
<td>103</td>
<td>2.5</td>
</tr>
<tr>
<td>85</td>
<td>4120</td>
<td>91</td>
<td>2.1</td>
</tr>
<tr>
<td>65</td>
<td>4157</td>
<td>76</td>
<td>1.6</td>
</tr>
<tr>
<td>50</td>
<td>4199</td>
<td>67</td>
<td>1.2</td>
</tr>
<tr>
<td>35</td>
<td>4257</td>
<td>52</td>
<td>0.9</td>
</tr>
<tr>
<td>20</td>
<td>4440</td>
<td>40</td>
<td>0.5</td>
</tr>
</tbody>
</table>

*natural gas lower heating value

Near Flat Heat Rate, High Turndown, Rapid Regulation Response Allows An Unmatched Balancing Asset
Siemens Hydrogen Gas Turbines for our sustainable future
The mission is to burn 100% hydrogen

<table>
<thead>
<tr>
<th>Gas turbine model</th>
<th>Power Output¹</th>
<th>H₂ capabilities in vol. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>50Hz</td>
<td>593 MW</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>450 MW</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>329 MW</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>187 MW</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>405 MW</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>310 MW</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>215 to 260 MW</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>117 MW</td>
<td>30</td>
</tr>
<tr>
<td>60Hz</td>
<td>60 to 71/58 to 62 MW</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>48 to 62 MW</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>41 to 44 MW</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>40/34 to 41 MW</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>33/34 MW</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>27 to 37/28 to 38 MW</td>
<td>40</td>
</tr>
<tr>
<td></td>
<td>24/25 MW</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>10 to 14/11 to 15 MW</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>8/8 to 9 MW</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>5/6 MW</td>
<td>65</td>
</tr>
<tr>
<td>50Hz or 60Hz</td>
<td>4 to 6 MW</td>
<td>65</td>
</tr>
</tbody>
</table>

Values shown are indicative for new unit applications and depend on local conditions and requirements. Some operating restrictions/special hardware and package modifications may apply.

Higher H₂ contents to be discussed on a project specific basis

1 ISO, Base Load, Natural Gas; Version 3.4, July 2020
EU-Turbines Commitment to drive the transition towards a decarbonized Energy Mix

Hydrogen co-firing commitment from EU-Turbines

In January 2019, Siemens signed a commitment on H₂ co-firing in gas turbines at the #PowerTheEU summit

**Today:** Operation with 3 – 5% H₂ content
(→ already achieved for all new GT models)

**2020:** Operation with 20% H₂ content
(→ already achieved for most GT models)

**2030:** Commercial availability of turbines for 100% H₂
(→ already achieved for AD-GTs, R&D and implementation plans in place to cover more GT models until 2030)

https://powertheeu.eu/

Siemens R&D activities to increase hydrogen capabilities

Siemens lately invested in in-house H₂ testing capabilities at Clean Energy Center in Berlin – Single burner tests at engine conditions

**Engine Tests for SGT-600/700/800 running on H₂ in DLE (dry low emissions) combustion systems has resulted in sales release of 60/55/50 vol-H₂ respectively**

Ongoing development to increase capabilities of our engines
Salt formations – North America

- Pressure holding capability is our main question. Can be sized to whatever client desires. Size equates to MW-hrs of storage.

- Rule of thumb is 0.8psi max cavern pressure per ft of depth to top of salt. So, 3200 ft to top of salt, then 2560 psi max holding pressure.

- Domal salt preferred over salt beds. Typically, domal can handle 160MW 3-stage. Salt beds at shallower depth, so 140MW 2-stage.

- Depleted gas fields – question of remaining entrained HCs.
Compressed Air Energy Storage
Commercial Considerations

CAPEX equates to three (3) major components

- **Power Island** = [$400-600 / kW]
  - Numerous configurations w/ train quantities and compression sizing

- **Balance of Plant (BoP) / Engineering, Procurement & Construction (EPC)** = [$425-625 / kW]
  - Location, labor rates, building/site permitting, transmission interconnection, fuel pipeline, construction contingency

- **Reservoir** = [$50-150 / kW]
  - Salt cavern, aquifer, or hard rock mine
  - Greenfield vs. existing
  - Declines in $/kW-hr as cavern size increases

~5 acres per
1x compressor &
1x expander train plant

- **Not Siemens Scope**
  - Cavern
  - Balance of Plant
  - Trains
  - Detailed Design & Materials Order
  - Equipment Build
  - Installation & Commissioning

- **Year 1**
  - Leach Plant & Cavern Creation

- **Year 2**
  - Build BOP & Mechanical Complete

- **Year 3**
### 1x1 Power Train

<table>
<thead>
<tr>
<th>Component</th>
<th>Amount ($MM USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CAES Core Equipment</strong></td>
<td></td>
</tr>
<tr>
<td>160MW Expansion train</td>
<td>$ 55</td>
</tr>
<tr>
<td>105 MW Compression train*</td>
<td>$ 35</td>
</tr>
<tr>
<td><strong>Balance of Plant (BoP)</strong></td>
<td>$ 30</td>
</tr>
<tr>
<td><strong>Construction</strong></td>
<td>$ 75</td>
</tr>
<tr>
<td><strong>Subtotal - 1x1 Power Train</strong></td>
<td>$ 195</td>
</tr>
</tbody>
</table>

### Each additional 1x1

<table>
<thead>
<tr>
<th>Component</th>
<th>Amount ($MM USD)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CAES Core Equipment</strong></td>
<td></td>
</tr>
<tr>
<td>160 MW Expansion train</td>
<td>$ 50</td>
</tr>
<tr>
<td>105 MW Compression train*</td>
<td>$ 30</td>
</tr>
<tr>
<td><strong>Balance of Plant (BoP)</strong></td>
<td>$ 25</td>
</tr>
<tr>
<td><strong>Construction</strong></td>
<td>$ 65</td>
</tr>
<tr>
<td><strong>Subtotal - additional 1x1</strong></td>
<td>$ 170</td>
</tr>
</tbody>
</table>

**Notes:**
- CAES core +/-10%
- BoP +/-15%
- Construction +/-20%
- BoP and Construction ~50/50% cost split between comp & exp
- 140MW equivalent is ~7.5% less cost for CAES Core and ~5% less cost for BoP and Construction.
- Typical cavern development range = $35 – 65 MM
- Each 1x1 = ~5 acres

* Assumes similar max mass flow for compression as expansion. Compression can be sized to lower or higher mass flow.
Energy (Storage) Transformation – CAES + H2

Can be replaced by H2 cavern storage

CAES facility

Electrolyzer facility
Published by Siemens Energy

**Bobby Bailie**

Business Development Director – Energy Storage
Siemens Energy | Industrial Applications

15375 Memorial Drive, Ste. 600
Houston, TX 77079, USA
Mobile: +1 281 513-3878

robert.bailie@siemens-energy.com

siemens-energy.com