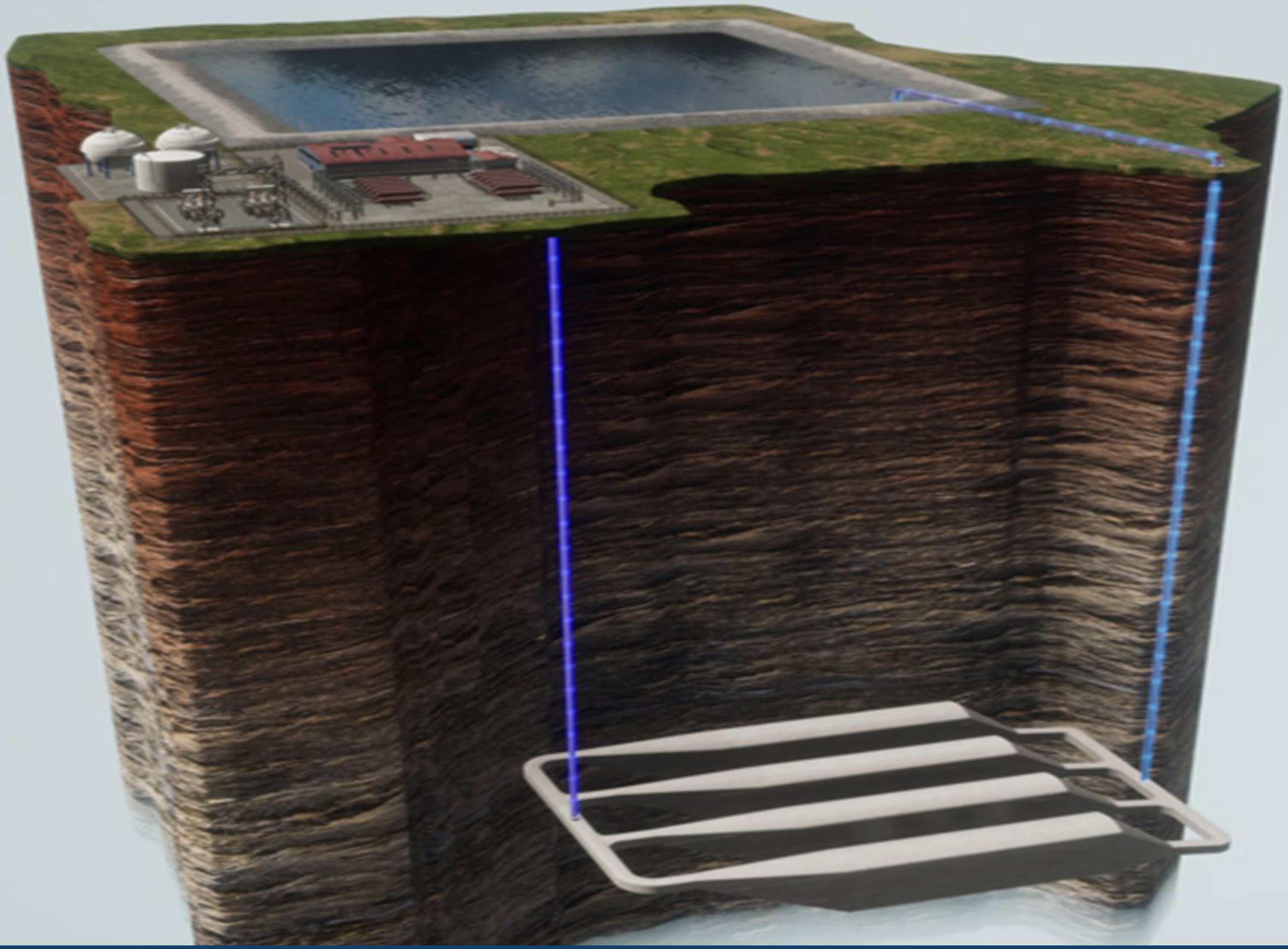
To: Nova Scotia Power (NSP) – Integrated, Resource Planning Team
From: Jon Sorenson, Hydrostor
Re: Advanced Compressed Air Energy Storage (A-CAES)

As communicated on our teleconference, Hydrostor, provides Advanced Compressed Air Energy Storage, which is a patent pending technology that can be incredibly advantageous to Nova Scotia Power in its Integration Planning effort, as you retire assets, focus on renewable energy but must have balance and reliability with new intermittent connected assets. Please see attached pdf included in the download and please note the following for some of the benefits of the Hydrostor technology:

- **Siting Flexibility:** A-CAES assets can be sited flexibly, meaning they can be constructed at the site of decommissioned / decommissioning coal plants to take advantage of the existing robust interconnection capacity and provide dispatchable generation where it is required (unliked pumped hydro which might).
- **Superior Economics:** To replace the reliability provide by coal plants through the use of energy-storage assets, long storage durations are required (8–12+ hours). With very low marginal costs for storage capacity, the economics of A-CAES are superior to alternative storage solutions for providing these long-duration reliability services at scale.
- **Analogous Grid Security Services:** Similar to coal-fired power stations, A-CAES facilities generate power using synchronous generators, meaning they provide all of the same grid security services previously provided by traditional generators, such as synchronous inertia, reactive voltage support, and system strength / fault-current contribution, as well as providing a higher power quality, without harmonics (unliked inverter-based generation). A-CAES systems can even operate their generators as synchronous condensers when they are not otherwise generating, providing these security services on an uninterrupted basis.
- **Flexible Capacity for Grid Balancing:** With abundant storage capacity and flexible turbomachinery, A-CAES assets can operate through a wide range of net power export to balance the grid. As an example, a system with a 500-MW charge rating and a 500-MW discharge rating, could operate across a 1000-MW range (500 MW import to 500 MW export) to balance supply and demand, effectively integrating abundant amounts of low-cost, intermittent renewable generation (e.g. on- or off-shore wind), while maintaining reliability and security of supply.

Additionally, we believe that a portfolio based on A-CAES and wind generation would be capital intensive but would have much lower operating costs relative to something based on flexible gas-fired generation. This means that the NSP rate base / regulated asset base, on which you typically earn a rate of return, would be greater, while still offering a highly competitive cost of supply to all of your customers. This model would be a better economic model for rate payers as you would not be passing through the costs of the gas that your purchase without any approved mark-ups for administrating the gas. If NSP can only earn profits on their capital assets, in the form of a regulated rate of return, then the deployment of wind combined with A-CAES makes strong economic sense to both the utility and the rate payers.



HYDROSTOR

Advanced Compressed Air Energy Storage:
Technical Inputs Summary

January 2020

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Executive Summary

Hydrostor has undertaken extensive research, development, and prototyping, leading to the development of Advanced Compressed Air Energy Storage (A-CAES). This technology is now one of the leading bulk-scale energy storage solutions globally. Much like traditional compressed air energy storage (CAES) systems, the technology functions by using electricity to compress air into underground caverns, storing the energy for later use. Later, when energy is required, the air is released back to the surface, where it drives a turbine, generating electricity.

Innovative A-CAES Technology

Traditional CAES technology has been around for over forty years: the first CAES plant was developed in Huntorf, Germany in 1978 and is still in operation. The implementation of CAES, however, has been hindered by two major impediments:

1. Much of the energy used to compress the air in the process is wasted, leading to the need to burn natural gas to heat the air that is used to drive the turbine and generate power onto the grid; and
2. The caverns used to store air for traditional CAES can only be deployed cost effectively in domal salt formations, which are rare and not necessarily aligned with the areas where energy storage is required.

Hydrostor's innovations enable A-CAES to recycle much of the energy consumed during charging, enhancing its efficiency, eliminating the need for natural gas combustion in the process, and facilitate the development of air storage caverns in many geologies, including both salt and common hard rock.

When a CAES system charges, compressing air into the storage cavern, both the pressure and temperature of the air increase. In traditional CAES, the heat that is developed (the "heat of compression") is exhausted to the atmosphere, as the air cannot be stored at high temperatures. This wastes much of the energy that is used to compress the air. Later, when the plant is discharging and the air flows through the turbine, both the air pressure and air temperature decrease. To provide adequate power to the turbine, the air must be heated through the combustion of natural gas, generating emissions and exposing the plant to volatile natural gas prices or costly long-term gas supply contracts. To address this issue, A-CAES systems are designed to capture and store the heat of compression for later re-use during discharging.

Traditional CAES systems store air in fixed-volume salt caverns. The pressure within the cavern increases as more air is pumped into the same volume and decreases as air is released. Both the cavern and the turbomachinery—the compressors and turbines—have limits on the operating pressures within which they can operate. The resulting range of acceptable pressures limits the amount of air that can be compressed into or extracted from the cavern, reducing the volumetric energy density. Consequently, these caverns must be developed for very low prices per unit of volume in order to be cost effective, which can typically only be accomplished in domal salt formations, through a process called solution mining. Because these salt formations are rare, this greatly limits the geographic range within which these systems can be developed, preventing the use of CAES for bulk-scale energy storage in many high-value applications.

A-CAES, in contrast, uses the principle of hydrostatic compensation to maintain a constant pressure within the storage cavern. This is accomplished by connecting the cavern to a water reservoir at surface level through a large conduit, resulting in a flooded cavern pressurized by the weight of water. As air is compressed into the cavern, it displaces water up the conduit and into the water reservoir. As air is released from the cavern, the water floods back into the cavern, displacing the air to the surface. Throughout each process, the movement of water into and out of the cavern results in a near-constant pressure within the cavern. This hydrostatic compensation greatly enhances the volumetric energy density of these caverns, enabling systems to use caverns with a higher capital cost per unit of volume excavated. Taking advantage of this, Hydrostor A-CAES can be developed cost effectively in most geologies, using mined hard-rock caverns.

Once constructed, A-CAES systems operate in much the same manner as natural gas–fired generating stations and, through the use of analogous turbines, can deliver the same suite of ancillary services and capacity, without any greenhouse-gas emissions. Specifically, A-CAES systems can provide frequency regulation, spinning and non-spinning reserve, demand response, voltage support, synchronous inertia, and black-start capability, serving as an effective replacement for much of the traditional fossil fuel–fired generating stations that are being decommissioned—forced out of operation by increasingly stringent environmental regulations, including carbon pricing, and an inability to compete with low-marginal-cost generators such as wind and solar.

Importantly, A-CAES operation is a mechanical process and is not plagued by the same issues inherent to inverter-based generators based on electrochemical reactions, such as batteries and photovoltaic solar: A-CAES performance does not degrade over its lifespan, there are no depth-of-discharge restrictions, and the system does not cause damaging harmonics on the grid when generating power. The caverns and turbomachinery employed by A-CAES can have a 50+ year asset life with appropriate maintenance.

While the current A-CAES design is already capable of being deployed at industry-leading capital costs, with strong performance characteristics, flexible siting, and a long lifespan, Hydrostor's technical team continues to collaborate with its consultants and suppliers to identify opportunities for improvement. Through these efforts, Hydrostor has already identified a list of viable value-engineering opportunities, which it is currently pursuing, and continues to add to this list. These efforts will result in steady improvements in capital and operating costs, technical performance, delivery schedule, and siting flexibility.

A-CAES Overview

Hydrostor's A-CAES technology is uniquely suited to enable the transition to a cleaner, more reliable electricity grid. As a flexibly-sited, long duration, and synchronous storage resource, A-CAES provides grid services that, in aggregate, are not readily replicated by other storage technologies. It is a highly flexible and customizable tool to address bulk electricity system needs for dispatchable capacity, renewable integration and grid optimization, and as such it is already finding application globally as a near-term resource with a well-proven supply chain to directly replace fossil fuel plants and act as a cost-effective transmission alternative.

A-CAES delivers low-cost, long-duration bulk energy storage (hundreds of MW's, 4-24+ hours) that is 100% emissions-free and can be flexibly located where required by the grid. It does so with large-scale rotating generators that deliver traditional grid stability services sought by utilities such as spinning reserves, voltage support, and synchronous inertia, while also being able to deliver reliable capacity (resource adequacy) as a long duration storage resource. Importantly, A-CAES can typically be constructed in places where other forms of large-scale synchronous storage cannot (like pumped hydro and traditional CAES) and provides grid benefits that other forms of non-synchronous storage cannot (like batteries).

A-CAES utilizes standard, off-the-shelf equipment that has been rigorously deployed in a variety of other applications and industries (e.g. pipeline compressor and let-down stations) and is supplied exclusively by Tier 1 original equipment manufacturers (e.g. Baker Hughes is a global leading supplier of core equipment and is an invested corporate partner to the Consortium on delivery of its systems). Capital investment for A-CAES is significantly lower per kWh than other storage technologies, in part because of its significant economies-of-scale, and by combining the well-established expertise and supply chains of the mining sector with those of proven, bankable, industry-standard generating and process equipment to offer a compelling solution at scale.

Large-scale deployment of energy storage technologies has been challenged by several factors, including total installed cost, scalability, and/or geographic constraints (such as topography and footprint). In the case of traditional CAES, it has been further constrained by the reliance on burning fossil fuels. Hydrostor's A-CAES technology has been specifically designed to address these factors relying only on a well-proven supply chain and the use of standard industrial equipment/construction approaches. A-CAES is based conceptually on the same basic design and process as traditional CAES with its multi-decade operating history, and incorporates two key improvements to allow it to be emissions-free and flexibly-sited: 1) the development of a patented thermal storage system that eliminates the need for a fuel source, and 2) the construction of hydrostatically compensated, hard rock air storage caverns.

Electrical Conversion	▪ A-CAES uses standard electrically driven air processing equipment (compressors, motors, turbines, and generators) routinely used in power and oil & gas applications, where they offer exceptional reliability ▪ Tier 1 original equipment manufacturers (Baker Hughes, MAN Energy Solutions, Hanwha Power Systems) offer best-in-class warranties and performance guarantees ▪ Established supply chains and global support services for this equipment mean that they can be deployed on any scale at a competitive cost
Fuel Free Operation ***Unique to Hydrostor***	▪ Hydrostor has developed an adiabatic process, enabling fossil fuel-free and emission-free CAES ▪ The thermal management subsystem captures heat developed as the air is compressed, stores it, and reinjects it into the air on expansion, boosting electricity production and system efficiency ▪ While the system is proprietary, it relies on well-proven, industry-standard heat processing equipment available from Tier 1 original equipment manufacturers (Alfa Laval, Therco-Serck, Exchanger Industries)
Flexibly Sited Air Storage ***Unique to Hydrostor***	▪ A-CAES stores air in purpose-built mined caverns, analogous to those used for the storage of hydrocarbons, enabling siting flexibility in almost all common geologies ▪ Mined caverns are a mature storage solution with 190 deployments worldwide with design and construction by global experts (Geostock, Agapito Associates, Lane Power Solutions) ▪ Hydrostor's storage solution uses a water flooded cavern, which drastically reduces the mined volume required and enables fully recoverable, near constant pressure air storage

Figure 1: A-CAES Sub-systems

How A-CAES Works

As the A-CAES system is charged, off-peak or surplus electricity from the grid (or a renewable source) is used to power an air compressor, which converts the electrical energy into potential energy and heat stored by the compressed air. The heat generated during compression is captured by a set of heat exchangers and stored separately for later use. The air stream is compressed to match the pressure needed to inject it into a constructed underground storage cavern. Once in the cavern, the air can be stored until electricity is required.

Hydrostatic compensation (using water head, analogous to a pumped hydro facility, in order to maintain a constant air pressure underground) is provided by a surface reservoir of water, connected to the cavern through the construction access facilities (either a shaft or a helical decline, depending on geology). As air is charged into the storage cavern, water is displaced up the access decline or shaft and into the surface reservoir, storing substantial potential energy in the large elevation difference. With hydrostatic compensation, the air pressure within the cavern is maintained at a near constant level. This is essential for the efficient performance of the air handling equipment (whereas in traditional CAES the storage pressure varies significantly, which limits system efficiency and performance).

When energy is required, the compressed air is permitted to flow back to surface, which it does so under the process of the compensation water re-flooding the cavern. The stored heat is reinjected through the same heat exchangers before the compressed air is used to drive a turbine, generating electricity and supplying it back to the grid. As turbines require heat for both adequate power production and thermal protection, it is only through the use of the thermal storage system that Hydrostor's A-CAES can be fossil fuel and emissions free.

Because of the use of hydrostatic compensation, all of the stored air is fully recoverable; this is unlike traditional CAES which requires a substantial portion of the air to maintain a minimum storage pressure for either cavern protection or turbine operation. This drastically reduces storage volume requirements. Therefore, hydrostatic compensation enables Hydrostor's A-CAES to utilize economically-constructed mined storage caverns (at lower volume requirements) and benefit from the ability to be constructed in most geologies.

An animation illustrating how Hydrostor's A-CAES system works can be found at hydrostor.ca.

How Advanced Compressed Air Energy Storage (A-CAES) Works

1

Compress Air Using Electricity

Off-peak or surplus electricity from the grid or a renewable source is used to operate a compressor that produces heated compressed air.

2

Capture Heat in Thermal System

Heat is extracted from the air stream and stored inside proprietary thermal store. This adiabatic process increases overall efficiency and eliminates the need for burning fossil fuels during expansion.

3

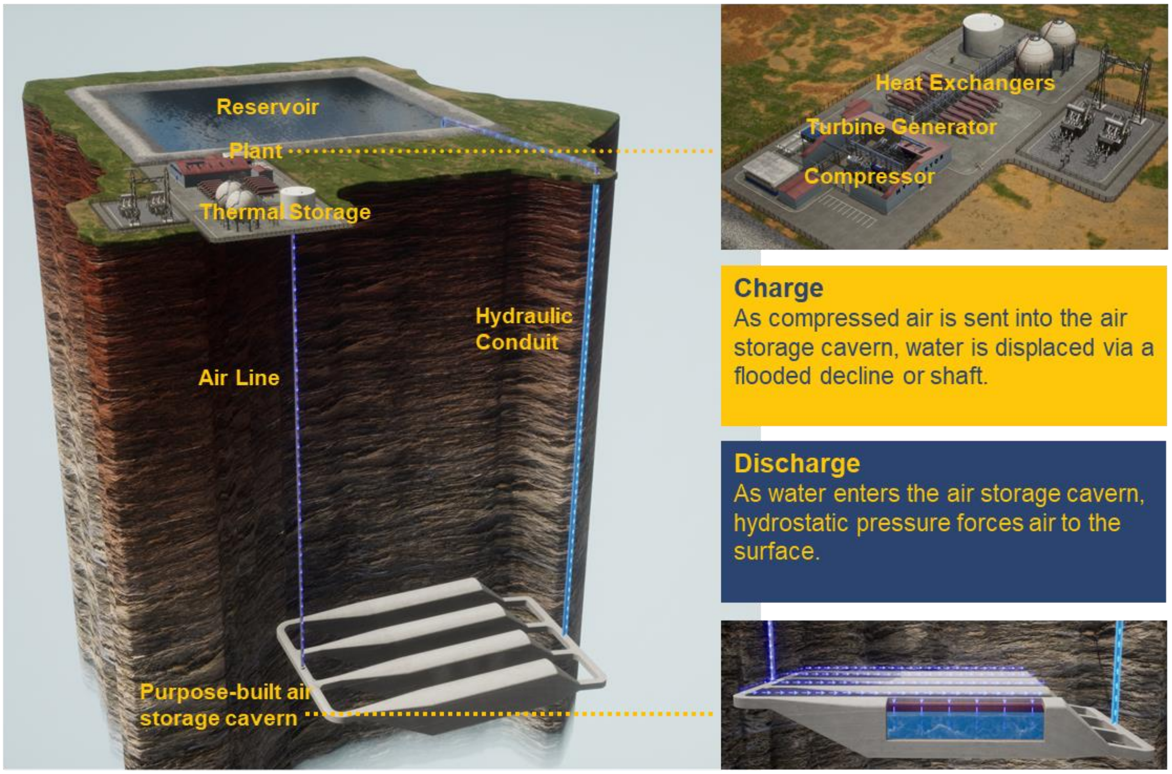
Store Compressed Air

Air is stored in purpose-built storage caverns where hydrostatic compensation is used to maintain the system at a constant pressure during operation.

4

Convert Compressed Air to Electricity

Hydrostatic pressure forces air to the surface where it is recombined with the stored heat and expanded through a turbine to generate electricity on demand.



Charge
As compressed air is sent into the air storage cavern, water is displaced via a flooded decline or shaft.

Discharge
As water enters the air storage cavern, hydrostatic pressure forces air to the surface.

Industry-proven air and heat processing equipment with decades of operational history in power and oil & gas sectors.

Well-established mining techniques for storage cavern construction based on precedents of more than 190 analogous storage caverns globally.

Proven application of hydrostatic compensation and thermal management systems.

Figure 2: How A-CAES Works

Benefits of Hydrostor A-CAES Technology

The characteristics of Hydrostor's A-CAES technology provide it with a competitive advantage over other technologies in several applications. The key benefits of Hydrostor's technology are summarized below:

- **Long Asset Life:** The hard-rock caverns and turbomachines at the heart of Hydrostor's A-CAES system have exceptionally long service lives of 50+ years, with appropriate design and maintenance.
- **Project Siting Flexibility:** Hydrostor's proprietary use of hard-rock caverns for air storage untethers A-CAES from the need for sites with suitable salt formations, enabling the development of bulk storage in areas where geological, topographical, and regulatory conditions do not permit the development of traditional CAES or pumped-hydro storage projects.
- **Low Cost:** At full scale (100+ MW), Hydrostor A-CAES offers one of the lowest installed costs on a dollar-per-kWh basis available today for bulk energy storage. Notably, A-CAES has *the* lowest installed cost of any bulk energy storage solution that can be flexibly sited.
- **Proven, Reliable Equipment:** The Hydrostor A-CAES solution uses only proven equipment that has been used in industry for decades and is provided by competing Tier 1 equipment suppliers. Hydrostor has a strong supply chain relationship with these suppliers.
- **Scalability:** By using industry-standard equipment, Hydrostor leverages the significant economies of scale, well-established supply chains and expertise of the mining and oil-and-gas sectors, enabling deployment of A-CAES on a massive scale without the need to develop new supply chains.
- **Fuel and Emission Free:** Hydrostor's proprietary thermal management system is environmentally friendly, uses no hazardous chemicals, and enables fossil-fuel-free CAES, resulting in a zero-emission system with greatly reduced overall operating costs.
- **Ancillary Grid Services:** A-CAES provides ancillary services by leveraging synchronous generation to deliver voltage support whilst also providing frequency regulation where required for improved power quality, as well as offering black-start capability.
- **Synchronous Generation:** Hydrostor A-CAES utilizes large-scale rotating synchronous generators (and motors) that deliver traditional grid stability services sought by utilities, including voltage support and synchronous inertia[1], while also reducing damaging harmonics produced by battery and solar PV inverters. As thermal generation facilities retire, removing synchronous generators from the grid, A-CAES can play a vital role in minimizing impacts to the grid by delivering these essential services, often in the very same locations as the retiring assets.
- **Flexible, Dispatchable Capacity:** Hydrostor's technology can help maintain system reliability as the penetration of intermittent generators, like wind and solar, increases and as thermal generators are retired. Hydrostor A-CAES has the flexibility to provide fast ramp rates and long-duration dispatchable capacity to meet the increasingly unpredictable requirements of the grid more cost effectively than gas-fired generators. The system can also be paired directly with large intermittent generators to optimize renewables integration and avoid curtailed power output.
- **System Design Flexibility:** Charge, discharge, and storage capacities can be set independently of each other to optimize system design, reduce costs, and maximize efficiency. In addition, modularity in design (i.e., using several smaller units versus one larger unit) and equipment selection allows for built-in redundancy and the ability to operate over a wider range, depending on the system's intended use.

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1. Synchronous inertia refers to the rotational inertia of a spinning synchronous generator that is coupled to the electrical grid and its resistance to changes in grid frequency which are caused by supply and demand imbalances. This resistance results in a reduction in the rate of change of frequency, affording grid operators time to correct before an outage.

Technical and Performance Specifications

The performance of Hydrostor's A-CAES is similar to other rotating power generation equipment such as natural gas–fired facilities. Specific performance metrics for a typical full-scale (100+ MW) A-CAES project are shown in Table 2. Many of these metrics can be optimized to meet project requirements.

Table 2: Performance Specifications & System and Site Specifications

Summary of A-CAES Performance Specifications		**Performance(1)**
Response Time	Time from signal to charge (electrical power consumption)	3-5 min
	Time from signal to initial discharge (electrical power generation)	5 min (2)
Response Time with Hybrid Battery	A short duration battery system can provide rapid power consumption or delivery during charge and discharge response	100 ms
Synchronous Condenser Mode	Auxiliary power draw to operate the system as a synchronous condenser for continuous voltage support and provide faster response times.	0.5–2% of power rating
Parasitic Losses	Auxiliary and standby power requirements under regular (standby) operating mode.	Negligible (included in RTE)
Ramp Rate	Maximum rate of change on electrical consumption / generation	25% / min (2)
Reactive Power Delivery	Maximum reactive power during charge or discharge (3)	1.6 MVA_r/MW
	Maximum reactive power during standby in synchronous condenser mode (3)	1.75 MVA_r/MW
Efficiency	Steady-state round-trip efficiency (AC-to-AC), including all auxiliary loads, assuming daily cycle	>60%
Lifetime	Cycle life	20,000 cycles (4)
	Equipment useful life (with appropriate maintenance)	30–50+ years
Inertia, System Strength	Provided by compressor and turbine while charging, discharging, or in synchronous condenser mode	

(1) *Metrics can be optimized to meet project requirements.*
(2) *Response times can be improved to meet customer needs at FEED stage.*
(3) *Based on machines with a power factor of 0.8; reactive power delivery per machine of ~0.75 MVAr/MW during operation and ~0.88 MVAr/MW while acting as a synchronous condenser*
(4) *Cycle life can be extended with standard maintenance overhaul for turbomachinery (included in 50 year project option).*

Siting Criteria

The A-CAES surface footprint can be divided into four categories:

1. Base system: the electrical conversion equipment, thermal management system (excluding fluid storage) and building,
2. The thermal fluid storage, if utilizing an above-ground thermal storage design,
3. The surface reservoir, and
4. On-site waste rock storage, if waste rock cannot be reused or an off-take cannot be secured.

Approximate surface footprints for 100, 250, 300, and 500 MW A-CAES installations with 8 hours of discharge duration are outlined in Table 1.

Table 1: Surface Footprints for A-CAES Components (in acres)

System Size	Base System	Thermal Fluid Storage	Reservoir	Waste Rock Pile
100 MW / 800 MWh	3.3	1.5	8.4	4.1
250 MW / 2,000 MWh	6.0	3.1	14.3	10.7
300 MW / 2,400 MWh	6.9	3.8	16.0	12.9
500 MW / 4,000 MWh	10.5	6.1	22.8	21.6

Fresh, salt or non-potable water, including the use of groundwater where available, can be used as compensation water to provide hydrostatic pressure. This can be done as an open-loop system if an existing water source is nearby or as a closed-loop system with a purpose-built reservoir.

- If a nearby natural body of water is to be used for compensation:
  - Water should be accessible at high flow rates.
  - No temperature or chemical impact on water should occur in the cavern.
  - Space and easement must be available for a water channel or underground pipes.
- Otherwise, if a compensation reservoir will be constructed:
  - The area required for the surface reservoir will depend on the depth and storage capacity of the system (see table for typical requirements).
  - One-time water requirement includes necessary freeboard for closed-loop systems:
    - 100 MW / 800 MWh: 120,000 m^3 (100 acre-ft)
    - 250 MW / 2,000 MWh: 300,000 m^3 (240 acre-ft)
    - 300 MW / 2,400 MWh: 360,000 m^3 (290 acre-ft)
    - 500 MW / 4,000 MWh: 595,000 m^3 (480 acre-ft)
  - Annual top-up as required for evaporative losses. Evaporative losses are site-specific, and in some cases, precipitation exceeds evaporative losses, particularly if the pond is doubled as a stormwater reservoir for the overall site.

Geology

For a greenfield site, the subsurface location is dictated solely by the geology and geotechnical properties of the rock. For a preliminary assessment of the site, sufficient public/private data must be available, otherwise, an exploratory program, including borehole investigation, must be carried out to determine viability. More information about the requirements of an exploratory drilling program can be found in the data room.

Available data sources may include but are not limited to:

- Regional geographic mapping & cross-sections.
- Local/regional water well data.
- Local/regional borehole data.
- Local/regional geophysical data.

A FEED study of a greenfield site uses boreholes and detailed analysis to confirm existing geotechnical characteristics.

Overburden

Depending on its nature, increased overburden (unconsolidated material above bedrock) thickness can increase the cost of cavern construction. A minimal amount of overburden is preferred and a thickness of less than 50 m of overburden of any nature is considered feasible for siting depending on other costs and factors. However, overburdens which contain a high clay content or highly consolidated soils do not pose the same difficulties as loose, unconsolidated soils and can support development of caverns even with overburden depths of a few hundred meters, as long as the cavern itself is situated in consolidated rock.

Geotechnical

The subsurface components of the Hydrostor A-CAES system can be constructed and installed in a variety of geotechnical conditions. Preference is given to sites with hard-rock geology, given the structural stability and integrity of open excavations in these rock types under unsupported or minimal-support conditions.

Locations with soft-rock (lower strength rock, such as certain types of sedimentary) geology could be considered; however, considerations will need to be made for additional support to satisfy the structural requirements inside the air storage and thermal storage caverns, which may increase capital costs.

Below is a summary of geo-tech requirements to consider when siting potential A-CAES systems:

- Preference for hard-rock and high rock strength.
- Preference for rock types with low permeability.
- Preference for rock masses with minor jointing and cracks.
- Avoid crossing faults with a history of high magnitude seismic events.
- Areas with limited time dependency/swelling potential.
- Sub-surface geology where low in-situ stresses exist. Suggested max horizontal stress is 15 MPa for suitable locations.
- Avoid intersecting aquifers in the air storage region to minimize dewatering cost and avoid possible regulatory issues.

Project Capital Costs

The economies of scale that are achievable for the major components of A-CAES enable it to be a leading low-cost storage solution for large-scale (100+ MW) storage applications with a service life of over 50 years. To demonstrate the varying cost of A-CAES systems, Hydrostor has developed cost estimates for hard-rock cavern A-CAES systems ranging from 200 MW to 500 MW of discharge power capacity, with discharge durations from 4 to 12 hours, which are shown below in Figures 3 and 4 (for salt geology) and in Figures 5 and 6 (for hard-rock geology).

These numbers represent all-in capital costs, incorporating all engineering, procurement, construction, commissioning, and interconnection costs as well as substantial contingency reserves and other project-delivery costs such as bonding and insurance. Similar to the base costs above, a range of costs has been shown where the upper end of each range represents the cost at which Hydrostor can deliver projects today in average geological conditions, while the lower end of each range represents the cost at which Hydrostor anticipates delivering projects in the future—accounting for technological and project-delivery improvements—in above-average geological conditions. Further savings can be achieved in situations with brownfield infrastructure such as existing caverns or interconnection infrastructure.

Salt Geology

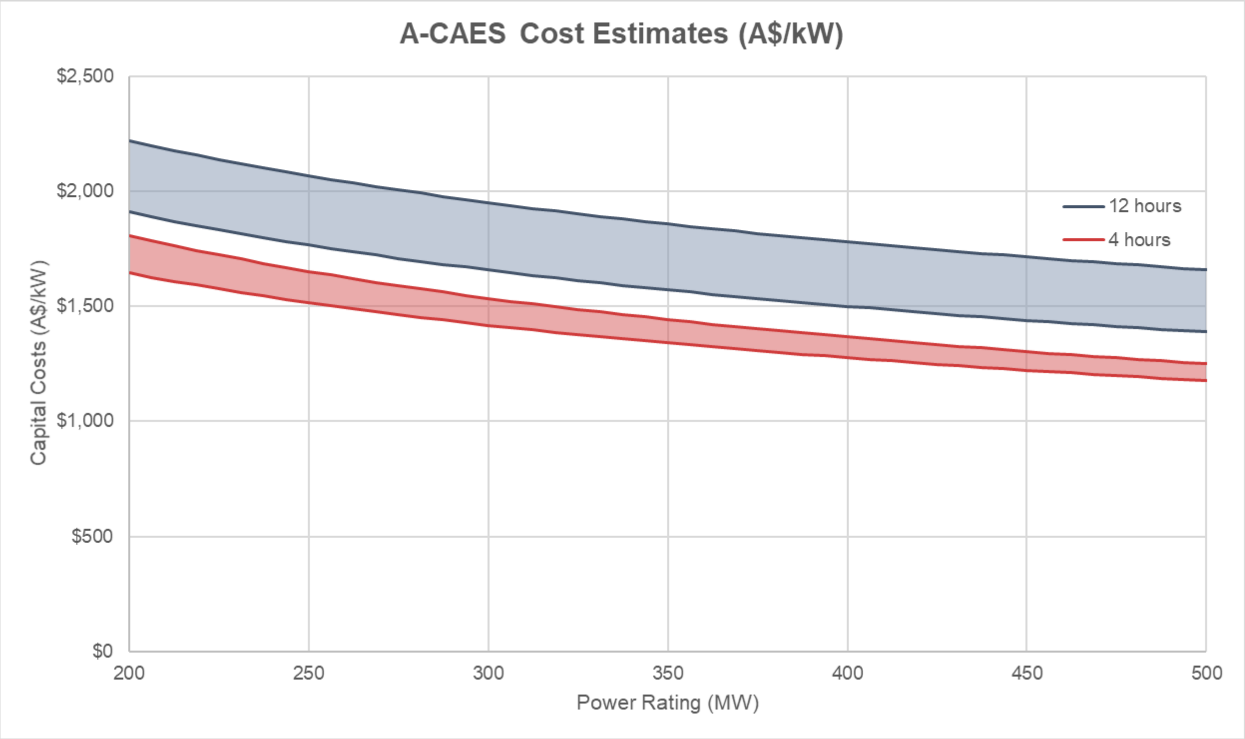

Figure 3: Salt-Based A-CAES All-in Capital Cost Estimates (US$/kW)

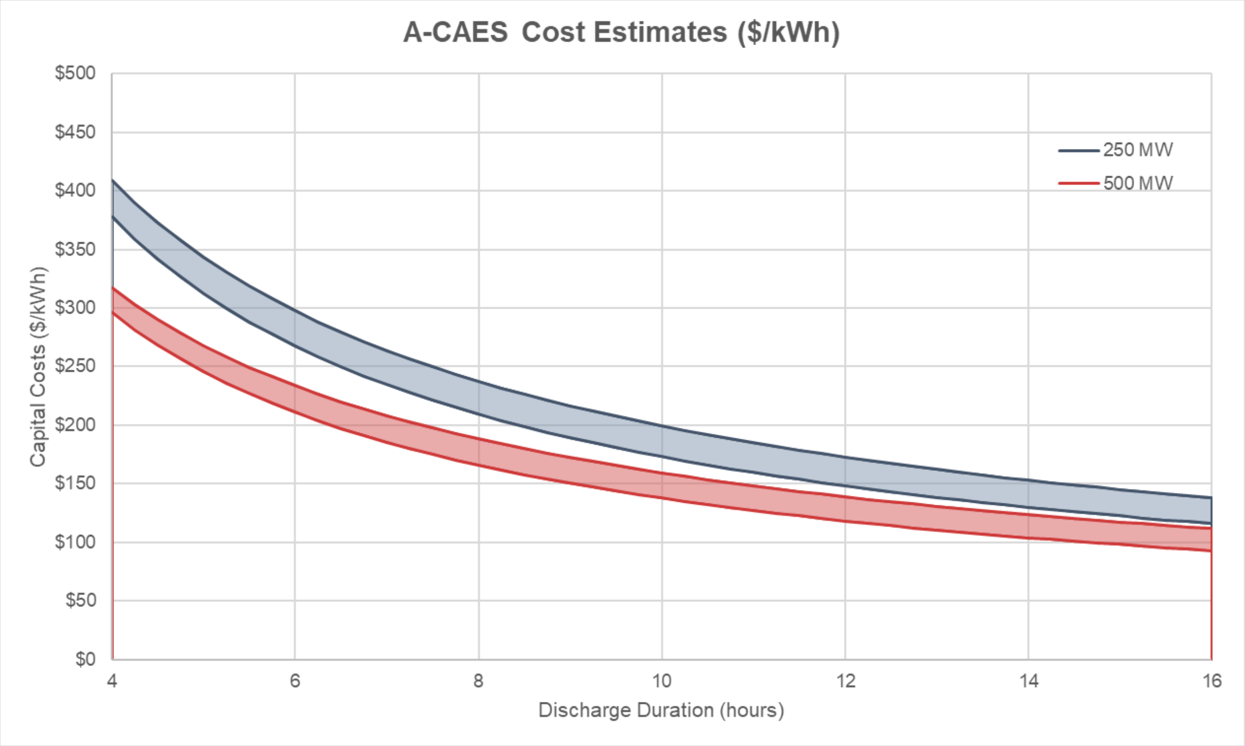

Figure 4: Salt-Based A-CAES All-in Capital Cost Estimates (US$/kWh)

Hard Rock Geology

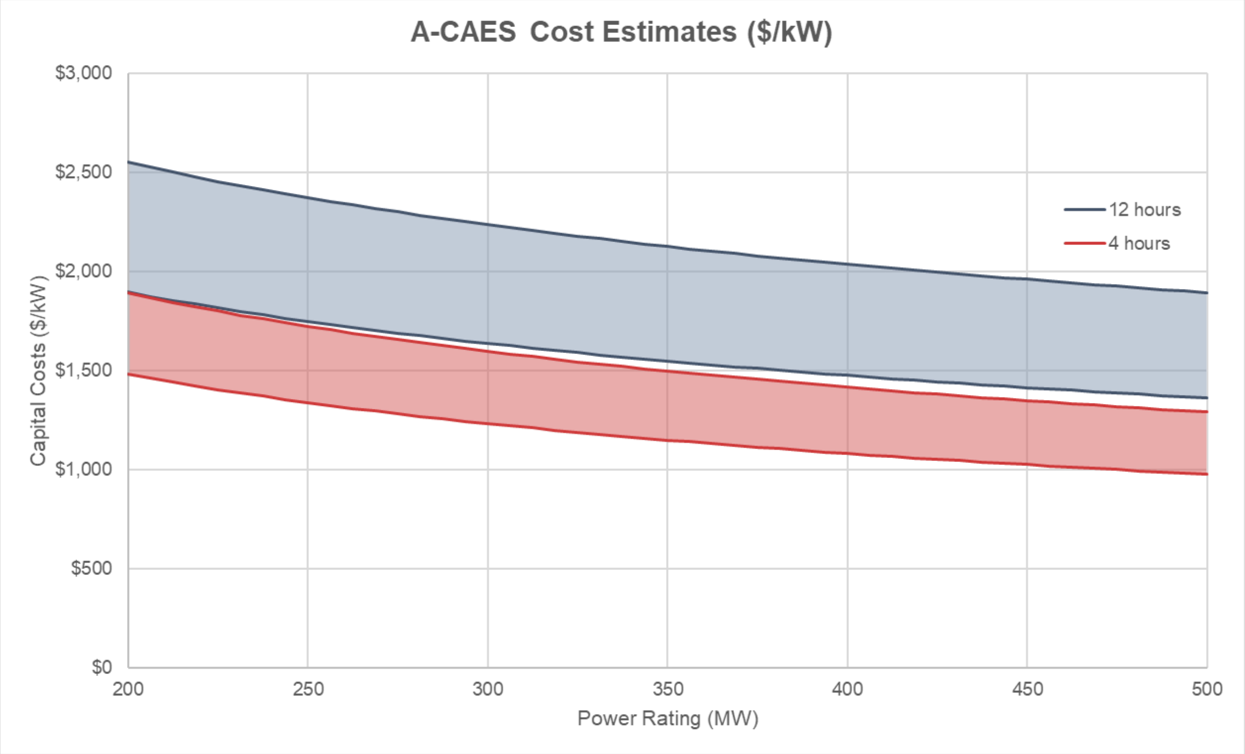

Figure 5: Hard-Rock-Based A-CAES All-in Capital Cost Estimates (US$/kW)

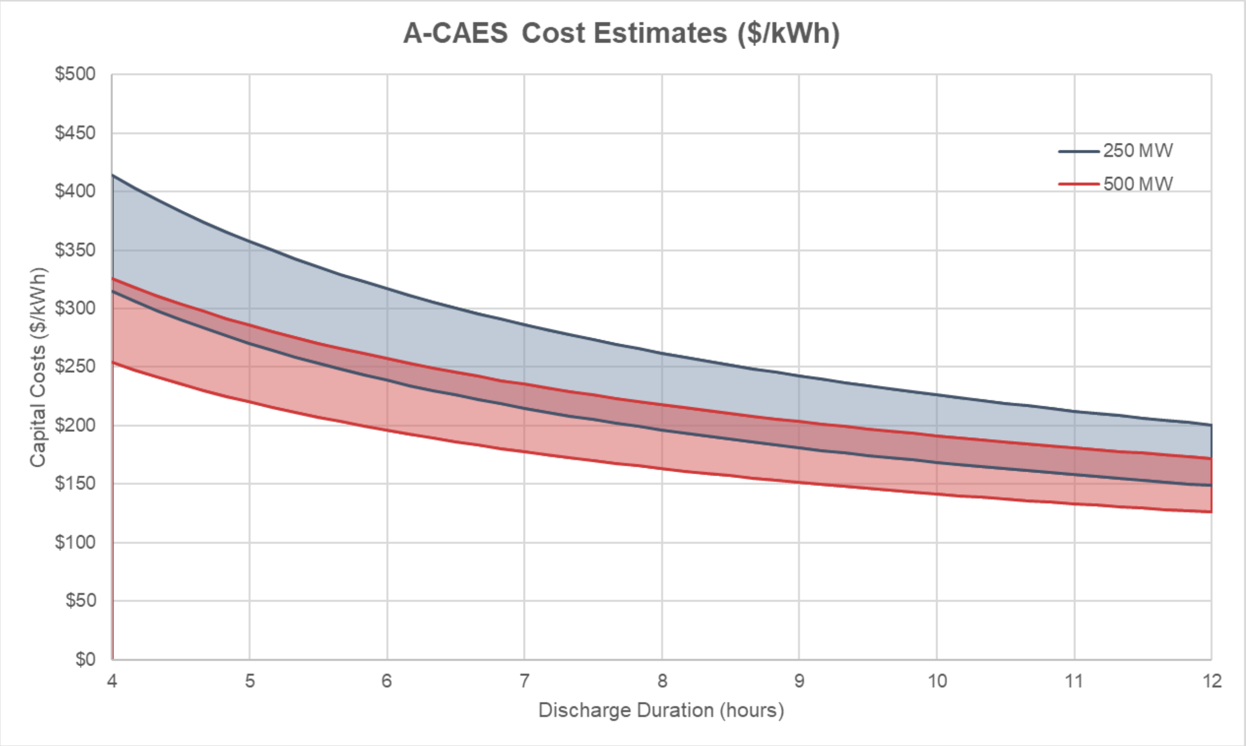

Figure 6: Hard-Rock-Based A-CAES All-in Capital Cost Estimates (US$/kWh)

Operating Costs

Due to the similarities between the configuration of an A-CAES process plant and that of a simple-cycle gas-turbine plant (“SCGT”), the annual operations and maintenance (“O&M”) costs of the two are comparable. While non-fuel annual O&M costs for an SCGT vary between 1% and 2% of the plant’s capital cost, depending on factors such as the local labour costs and the plant’s capacity factor[2], the equivalent costs for an A-CAES plant are expected to differ for two primary reasons: a lack of combustion in the process and a large portion of capital cost being related to subsurface infrastructure with negligible maintenance costs.

Because no combustion occurs in the A-CAES process, the system’s equipment cycles through a much lower temperature range when alternating between operating states. Whereas SCGTs experience internal temperatures up to 1200°C, A-CAES infrastructure is never exposed to temperatures greater than 250°C. Additionally, because no combustion occurs in the process, no combustion by-products accumulate in the system’s turbine, significantly reducing maintenance requirements.

The capital costs to develop the subsurface infrastructure of an A-CAES plant are on the order of 50% of the overall system capital cost, depending on the system parameters. The O&M costs for this subsurface infrastructure are negligible, so, as a percentage of overall system capital costs, the O&M costs of an A-CAES plant is projected to be substantially lower than those for an SCGT.

The all-in O&M costs for an A-CAES plant are thus estimated at 1% of the full-system capital costs (equivalent to roughly 2% of the capital cost for the aboveground infrastructure) per annum.

For direct-sale opportunities on which Hydrostor provides long-term maintenance services, the costs of providing these services would not include many of the costs that would be incurred for self-developed opportunities, such as operators, land leases, insurance, and capital projects. Thus, it is reasonable to estimate the costs of providing these services at 0.5% of the full-system capital costs per annum.

Hybrid A-CAES / Lithium-Ion Options

A-CAES can be paired with lithium-ion batteries in order to deliver enhanced services to end-users. Improvements offered by a hybrid A-CAES / lithium-ion solution include optimized delivery timelines and improved performance (e.g. reduced operational response times to enable frequency response, and potential efficiency improvements). Hybridizing with a lithium-ion battery will make the Project dispatchable in <1 second, positioning it as a long-duration storage solution that can also provide frequency regulation and control services. The size of the lithium-ion battery can be tailored to meet grids specific requirements for these types of services to minimize this option’s incremental cost. An option is also provided to enable improved round-trip efficiency for the combined A-CAES/battery system.

~ end of memo ~

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[2] 2017 PSE Integrated Resource Plan – Gas-Fired Resource Costs;
Fuel and Technology Cost Review Report, ACIL Allen, June 2014;
Lazard’s Levelized Cost of Energy – Version 12.0, November 2018;