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Hybrid Integration of Energy Storage for Affordable and Expeditious Decarbonization, Reliability and Resiliency

Additional submitted attachment is included below.

Hybrid Integration of Energy Storage for Affordable and Expeditious Decarbonization, Reliability and Resiliency

California Energy Commission
Workshop on Incremental Efficiency Improvements to the Natural Gas Powerplant Fleet for Electric System Reliability and Resiliency
Docket No. 20-SIT-01

Response 20-012

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Pintail Power LLC

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1 Executive Summary

The California Energy Commission (CEC) opened docket number 20-SIT-01 to explore potential technology options for increasing the efficiency and flexibility of the existing natural gas powerplant fleet to help meet near-term electric system reliability and the longer-term transition to renewable and zero-carbon resources.

Pintail Power LLC, based in Palo Alto, California is a provider of hybrid energy storage technology that bridges renewable and conventional power. Our patented technologies store grid-sourced renewable energy to dramatically cut the Heat Rate and emissions of combined cycle power plants, while adding flexibility, and ancillary services. Pintail Power's approach to integrating variable renewable energy with dispatchable power can be instrumental in California's transition to 60% renewable power by 2030 and the ultimate decarbonization of the electric power sector.

1.1 Short-term Challenges

California needs dispatchable capacity to reliably meet demand while facing climate change resiliency challenges:

- region wide extreme hot weather events that reduce the capacity of the gas fleet and the availability of imported power;
- reduced precipitation and snow-pack related water storage that reduces the availability of hydro power within the state and potentially region-wide,
- widespread wildfires that have the potential to cut solar PV production for many consecutive days and result in Public Safety Power Shutoffs that jeopardize public health and wealth and potentially undermine public confidence in the State's electric infrastructure.

At the CEC workshop, presentations from gas turbine vendors, operators, load serving entities, regulators and community/environmental groups, and questions and comments from Commissioners and the public illuminated the dilemma faced by California.

- On the one hand, the natural gas fleet in California and the west is an essential provider of energy and reliability services, and there is a short-term need to augment capacity;
- On the other hand, the need to decarbonize and reduce air emissions in impacted communities necessitates reduction in use of natural gas.

1.2 Long-term Challenges

To meet California's climate goals, a combination of new wind and solar resources and energy storage will be needed according to the CPUC's Reference System Portfolio (RSP) [1] used to guide the 2019/20 IRP and Transmission Planning decision. Of the approximately 27,000 MW of gas capacity in the CPUC baseline modeling assumptions [2], only about 4,500 MW would be retired by 2045. "The RSP retains nearly all existing gas generation because natural gas capacity is needed for reliability before and immediately after 2030, despite being dispatched for relatively few hours of the day." [1]

> To remain economically viable with low capacity factors, the gas fleet will require billions of dollars per year from California electricity customers, either in capacity-like subsidies or in higher real-time electricity prices. Moreover, the gas fleet is ill-suited for the role

> anticipated by the CPUC, with cycling increasing emissions, reducing fuel efficiency, increasing the Forced Outage Rate, and raising Operations and Maintenance expenses.

To displace the gas, the RSP anticipates the build-out of 14,500 MW of new renewable resources, along with about 44 GWh[1] of energy storage at a capital investment in excess of $25 billion[2]. Whether electricity customers see rate increases will be determined by the balance between fuel cost savings and the investor returns required to support this build-out.

Storage is essential to manage oversupply of renewable resources because CAISO already curtails large amounts of renewables for operational reasons and "*is seeking solutions to avoid or reduce the amount of curtailment of renewable power to maximize the use of clean energy sources.*" [3]

Indeed on 21 April 2019, before the Covid-19 pandemic, CAISO curtailed 32 GWh of renewables during the solar operating day [4]. Just 1,200 MW of new solar would fill the proposed storage, so virtually all additional renewable energy would face substantial curtailment. Curtailment impairs return on investment and necessitates higher energy prices.

1.3 Holistic Solution

Unifying the renewable and conventional grids via hybrid energy storage provides a holistic solution to expeditiously meet California's climate objectives and maintain reliability at the lowest cost. Pintail Power's hybrid technology provides safe, low-cost storage of renewable energy and low-carbon dispatchable power by transforming the gas fleet to

- Provide tens to hundreds of GWh of low-cost energy storage to integrate the planned increases in variable renewable resources;
- Cut fuel consumption and emissions by displacing gas-fired with zero-carbon capacity;
- Increase flexibility and responsiveness and reduce emissions during startup and part-load operation of the gas fleet.
- Provide reserves, frequency regulation, and voltage support without burning fuel.
- Provide resiliency against extreme events.
- Position the fleet to affordably switch to renewable fuels.

Pintail Power's technology is the Liquid Salt Combined Cycle (LSCC™), which integrates proven two-tank molten salt thermal energy storage with combustion turbine exhaust heat in a novel combined cycle arrangement that synergistically:

- Increases the capacity (power) output
- Reduces the fuel heat rate
- Reduces the storage cost
- Increases operating flexibility to serve the grid while charging and discharging.

The LSCC technology, described in Section 2, rearranges proven power equipment to deliver exceptionally low fuel consumption (<4500 Btu/kWh) and marginal storage cost (<$25/kWh-AC). The molten salt is safe, non-toxic, non-flammable, non-explosive, and does not degrade,

[1] 8,900 MW of batteries and 1,000 of long-duration storage. Assumes 4-hour duration batteries and 8-hour duration Pumped Storage.

[2] Assumes $250/kWh for storage and $1/watt for renewables.

no matter the rate or state of charge, making it a perpetual asset. The technology can be incorporated into existing plants, enhancing value by providing multiple grid services throughout each operating day.

The LSCC technology can be applied to any gas turbine, from any vendor, at any scale. Pintail Power has identified more than 100 CAISO-connected units with sufficient land for storage tanks, to provide more than 200 GWh of low-cost energy storage. Section 3 discusses opportunities to deploy LSCC technology at existing peaking and combined cycle facilities, at the Once-Through Units, and in cogeneration.

Section 4 summarizes the capabilities and value proposition, including

- Solar time-shifting and arbitrage
- Flexibility and regulation
- Low-carbon resource adequacy
- Congestion and curtailment relief
- Frequency and voltage support
- Resiliency during extreme events

Section 5 provides a framework for understanding and analyzing the cost, performance, and value of hybrid energy storage. The distinctive characteristics of hybrid storage, such as LSCC and Compressed Air Energy Storage (CAES), that are often overlooked:

- Cost and scale advantages of bulk storage in tanks, reservoirs and caverns.
- Hybrid systems discharge using both fuel and stored electricity, so two performance metrics are needed, because Round Trip Efficiency becomes confusing when more electricity is discharged than was used to charge.
- De-coupling of charge and discharge power enhances flexibility and is especially valuable when the charging profile can match the solar PV generation profile.

1.4 Action Planning

LSCC technology offers both low-cost long-duration storage and fast charging beyond the capabilities of the battery and pumped storage solutions considered by the CPUC. The LSCC technology is poised for commercialization at projects in California and CEC support of hybrid storage is timely.

- Pintail Power's technical approach is supported by a broad range of equipment suppliers and EPCs, and has been featured in industry publications [5, 6].
- The Electric Power Research Institute, and supported by Pintail Power, Southern Company and Nexant, has been selected by the U.S. Department of Energy to design a Liquid Salt Combined Cycle at LM6000 scale.
- The U.S. Department of Defense AFWERX program has selected Pintail Power's technology for advancement in its Re-imagining Energy Challenge.

Pintail Power looks forward to working with the California Energy Commission and stake-holders to unify the renewable and conventional supplies, affordably and safely improve the economics and operations of the California electric supply, and accelerate decarbonization of California's power grid.

2 LSCC Technology is Based on Proven Equipment

Pintail Power's patented Liquid Salt Combined Cycle™ (LSCC™) technology synergistically integrates molten salt thermal energy storage with combustion turbine exhaust heat, as shown in Figure 2. The hybrid combined cycle adds a conventional two-tank molten salt storage system, an electrical resistance heater for charging, and a molten salt steam generator (evaporator) that uses stored energy to boil water.

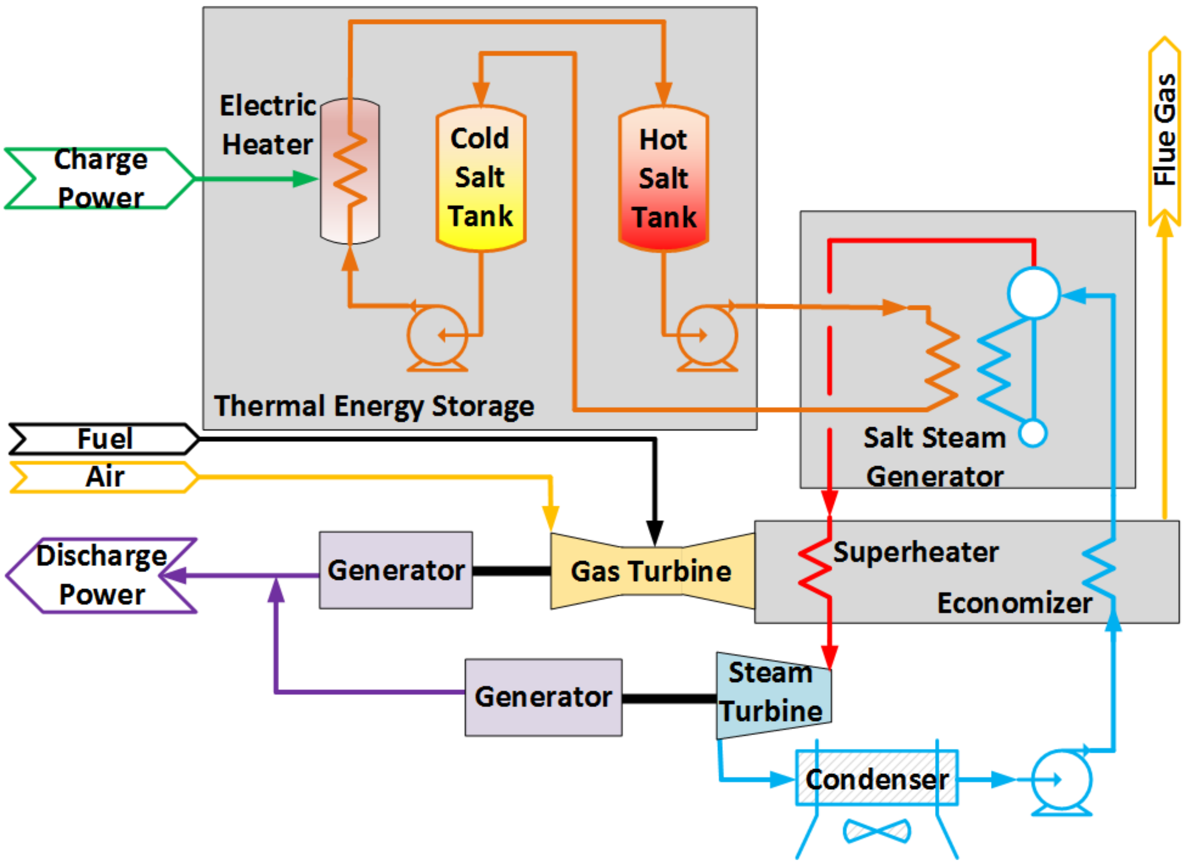

Figure 1. The patented Liquid Salt Combined Cycle (LSCC) integrates proven equipment in a novel system to create technical, economic and operational synergies.

By removing evaporative heating duty from the exhaust heat recovery equipment, this patented arrangement removes pinch constraints so 2.5 to 3 times more superheated steam can be delivered to the steam turbine. By reserving turbine exhaust gas for superheating, this approach increases overall power output and reduces fuel-based Heat Rate (kJ/kWh-e) and the Primary Energy Rate (kWh-e charge energy per kWh-e discharge energy).

Having exhaust heat available for superheating also allows the salt storage temperature to be reduced, so carbon steel tanks and piping be utilized with substantial cost savings over stainless steel needed with high temperature salt storage.

Fuel integration also increases the specific utilization of stored energy (kWh-e/kg salt) by more than 5x compared to Concentrated Solar Power (CSP), reducing the capital cost and volume of storage media needed.

The non-reheat steam cycle is simple and flexible, with the steam pressure and flow rate optimized based on combustion turbine exhaust temperature to assure acceptable steam turbine exhaust moisture content.

Fast, low emission, startup is enabled by removing heavy-wall components from the exhaust gas path and using low-cost excess renewable energy to keep the steam cycle ready to run or using stored energy to pre-heat the steam cycle to readiness before gas turbine startup. [The startup heaters are not shown in the simplified diagram of Figure 1].

> LSCC units can achieve emissions compliance and design heat rate faster than conventional combined cycles.

2.1 Works with any Combustion Turbine

LSCC technology works with any turbine, from any manufacturer, at any scale. Whatever the turbine, hybrid integration results in substantial fuel savings, more bottoming-cycle capacity, and efficient recovery of stored energy. The fuel heat rate is generally about half that of a simple cycle gas turbine, and the Stored Energy Rate is less than one, meaning more electricity is delivered than stored.

The performance of some common gas turbines in the California fleet is shown in Table 1. Although the thermodynamic efficiency is not improved, LSCC technology enables large reductions in fuel Heat Rate, and is an effective decarbonization strategy.

	Simple Cycle			LSCC – Air Cooled			
Combustion Turbine	Power (kW)	Heat Rate (kJ/kWh)	Exh. Temp (°C)	Net Power (kW)	Fuel Heat Rate (kJ/kWh) (Btu/kWh)	Stored Energy Rate (kJ/kWh) (kWh/kWh)	Salt Flow (kg/kWh)
GE 7FA.04	200,277	9342	624	414,555	4513 4278	3333 0.926	9.8
Siemens SGT-800	56,700	8540	565	111,896	4566 4327	3332 0.93	9.8
GE LM6000	49,955	8513	450	91,991	4877 4623	3249 0.90	12.5

Table 1. Comparison of estimated performance of new or upgraded gas turbines in simple cycle and LSCC. [Prepared using Ebsilon Professional power plant design software, at ISO, 60 Hz, air-cooled, net of plant load, Lower Heating Value.]

Whether paired with a fast-starting aero-derivative gas turbine (LM6000), industrial gas turbine (SGT-800), or large frame gas turbine (7F), LSCC technology dramatically reduces fuel consumption, similar to the way a Toyota Prius does.

2.2 Molten Salt Storage Is Safe, Proven, Cost-effective, and Flexible

The LSCC technology is based on integration of mature components from CSP and the Chemical and Process Industry (CPI), with salts suitable for heat transfer and storage available from multiple suppliers. . Two-tank molten salt storage technology has been proven in CSP, such as shown in Figure 2, which shows six pairs of hot and cold salt storage. In LSCC service, each pair of these tanks would provide between 1.6 to 2.1 GWh-AC of discharge energy

Figure 2. Molten salt storage tanks at the Solana CSP plant in Arizona, USA.

Pintail Power specifies a commercially available low-freezing point eutectic mixture of nitrate salts, known by the trade name Hitec®. This salt has a six-decade track record in petrochemical applications, a long, trouble-free life in service conditions up to 450°C/842°F, a low freezing point (142°C/288°F) that reduces freeze protection costs, chemical stability and compatibility with carbon steel vessels and piping, along with favorable handling characteristics (non-toxic, non-flammable). At LSCC conditions, carbon steel is suitable for tanks and piping, to reduce materials cost and the hot and cold storage tanks can be identical to reduce construction cost.

> The molten salt is chemically stable at LSCC operating conditions and is a perpetual-life asset that can be re-used, recycled or re-sold at the project's end of life.

Hot salt at 800°F (427°C) is kept in an insulated carbon-steel hot tank. During discharge, the salt is circulated through a molten salt steam generator, available from a range of suppliers with experience on CSP projects. The salt exit temperature depends on the associated gas turbine but is always greater than 200°C, far above its freezing point. Thermal losses are typically less than 1°C per day, or < 1%/day, so it is feasible for an LSCC system to remain idle for a month or more.

Depending on the combustion turbine salt, usage ranges from 9.8 to 12.5 metric tons per MWh-e of delivered energy. At a cost of $2,000 per metric ton, the marginal storage cost with LSCC technology ranges from $20 to $25 per kWh-e, a fraction of the marginal cost of lithium batteries.

2.3 Electric Heating Is Compact, Efficient, Flexible, and Cost-effective

The salt is heated by parallel trains of electric heaters, such as the 10-MW, medium voltage units available from Chromalox. Electric heaters provide a relatively inexpensive charging process and are nearly 100% efficient in conversion of electric to thermal energy. Because the incremental capital cost of heaters is small, and the heater capacity is independent of the discharge capacity, it is practical and economical to increase the charging capacity to be able to absorb over-generation – subject to grid interconnect constraints.

> Asymmetric charge/discharge sizing provides a better match to the solar PV production profile to reduce congestion and curtailment, and reduce the marginal cost of energy discharged from storage.

Electric heating is flexible, offering high turn-down for demand response, single or sub-cycle response for frequency control and is coordinated with variable flow control to provide accurate temperature regulation. To enable fast startup, the steam generator can be kept in hot standby using stored energy, without requiring exhaust heat from the combustion turbine.

2.4 Synergies Deliver Value and Benefits

LSCC technology provides novel synergies that improve efficiency, while reducing size, capital, and operating costs. By integrating proven thermal storage systems and thermal generation systems already deployed in utility service around the world, LSCC technology offers the following advantages:

- Very high energy density stores more energy on the available land to assure availability of energy for discharge, while also reducing curtailment of renewable energy.
- Safe thermal energy storage eliminates the fire, explosion, toxicity, disposal, and environmental issues of lithium batteries.
- Low capital cost by reducing the quantity of bulk storage medium and using low-cost electric heaters.
- Leverage of existing infrastructure by upgrading existing power plants with LSCC technology.
- Long lifetime without degradation of storage media.
- Flexible charging and discharging without the rate of charge or state of charge constraints of batteries.
- Low fuel heat rate makes LSCC the use of high-cost renewable fuels or Hydrogen more competitive to achieve full decarbonization.

> Pintail Power's hybrid Liquid Salt Combined Cycle can provide large-scale storage of otherwise curtailed renewable energy to decarbonize at lower cost than alternatives.

2.5 Top-tier Supply Chain

The LSCC technology integrates equipment already used in the California fleet with proven thermal energy technology and process equipment used in the concentrated solar power and Chemical Process Industries.

- A new steam turbine generator and condenser will be added to peaker units. The LSCC technology permits existing steam turbines to achieve full output, using a single combustion turbine, which may permit retirement of one unit from the 2-on-1 configuration commonly installed in California.

- Combustion turbines can generally be used as is, or upgraded with compressor, combustor, and hot gas path options which are available from the OEMs or from third parties. Upgrades to meet California's Summer 2021 reliability needs will also be beneficial for LSCC.
- Heat transfer equipment is available from customary suppliers. Existing peaker units would require new heat transfer equipment including Deaerator, exhaust heat recovery system, stack and bypass stack, blowdown system, Molten Salt Steam Generator, and startup superheater. At existing combined cycle plants, the auxiliary systems, emission controls, and stacks would be reused, with new heat transfer coils inserted in the ductwork.
- The molten salt storage system is comprised of one or more pairs of field-erected hot and cold storage tanks of customary design, such as shown in Figure 2.
- Salt pumps and electric heaters are widely available.

Engineering, Procurement, and Construction (EPC) involves customary processes and methods, and there are many qualified firms capable of designing and building LSCC systems.

> As a vendor-agnostic technology provider, Pintail Power can team with any OEMs and EPCs to deliver LSCC systems.

Pintail Power has teamed with EPRI, Southern Company, and Nexant on the design of the Liquid Salt Combined Cycle, and is confident in the commercial readiness of LSCC technology.

2.6 Transforming the grid with LSCC

Two key elements are needed to transform the solar dominant California grid to accelerate decarbonization:

- Large storage capacity (many hours discharge) to absorb solar over-generation during the day, and especially on weekends, so it can be dispatched after dark.
- Fast charging capability so solar over-generation can be captured when available while maintaining reliability.

LSCC can effect this transformation sooner and at lower cost than alternatives by transforming the gas fleet into large-scale storage assets.

- There are more than one hundred suitable CAISO connected sites that provide the potential for hundreds of GWh of LSCC storage.
- The CAISO grid and its nodes will increasingly value the load provided by storage, which will be needed to match supply and demand. The low marginal cost of LSCC storage can provide an almost unlimited load to manage increasing over-generation.
- Decoupling of charge from discharge enables another degree of freedom to optimize the charge rate and enable economical long-duration discharge.

A typical project would pair an existing gas turbine with a steam turbine of roughly the same capacity, add 18 to 48 hours of storage, and size electric heaters at the existing interconnect capacity. Some examples are provided in Section 3.

3 LSCC Deployment

California has abundant opportunity to deploy Liquid Salt Combined Cycle technology at more than one hundred suitable CAISO-connected gas plants within the fleet, including:

- Peaking units
- Combined Cycle power plants
- The Once-through units or successor units
- Cogeneration projects

Each project is unique, but would typically pair a gas turbine with a steam turbine of roughly the same capacity, add 18 to 48 hours of storage, and size electric heaters sized at the existing interconnect capacity. Interconnect capacity might be increased at some projects in order to absorb more over-generation. Duct burners, if present, would be retired, and as well as an unneeded gas turbine. Some examples are described next.

3.1 Peaker fleet

The peaker fleet is largely comprised fast-starting aero-derivative gas turbines, frequently deployed in multiple units, such as the two-unit project shown in Figure 3. Many of these projects have sufficient land for storage tanks. As the figure illustrates, 1600 MWh of discharge energy could be in the pair of salt tanks to provide 18-hours of discharge at full power.

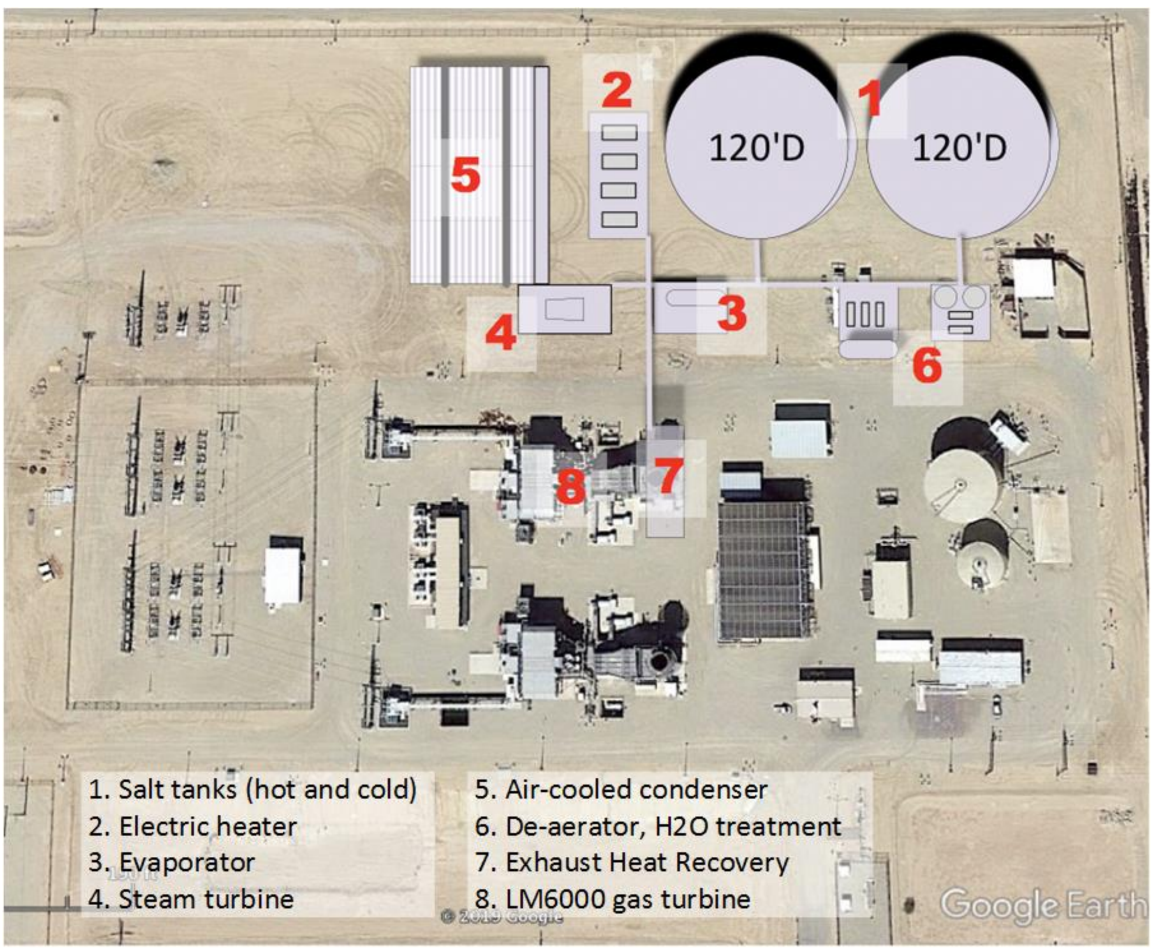

Figure 3. Conceptual general arrangement showing the upgrade of one out of two units at an existing peaking plant.

Using the existing 100 MW interconnect, the 1600 MWh of storage could be fully charged in less than 15 hours (1600 MWh * 0.93 MWh charge per MWh discharge / 100 MW). The system could be fully charged on a weekend-day when demand is low, Locational Marginal Price is low, and the carbon intensity of grid energy is also low.

The system could provide 4-hour Resource Adequacy for four consecutive days, without needing to recharge, although it could recharge as needed, ideally from low-cost solar over-generation. A bypass damper would permit the unit to operate as simple cycle unit should storage be depleted. To assure peak capacity is available during extreme events, a salt heating coil could be installed in the bypass stack to enable self-charging using a combination of electric power and exhaust heat from the LM6000.

If the interconnect was upgraded, overnight de-carbonization would be another use. For example, the unit shown could discharge for 92 MW for 16 hours while requiring 1370 MWh of charging (92 MW * 16 hours * 0.93 MWh charge per MWh discharge). To accomplish this in an 8-hour day would require 171 MW of charging power, which could be readily accommodated at modest cost by adding heaters and increasing pumping capacity.

3.2 Combined cycle fleet

The combined cycle power fleet in California is generally configured with a much larger steam turbine than can be supplied from a single gas turbine. Many plants use duct burners and often multiple gas turbines and Heat Recovery Steam Generators to produce enough steam. The large interconnect provides capability for fast charging.

Converting a large combined cycle to LSCC technology will necessarily be more capital intensive and will require more technical and economic trade-offs with respect to modifications to existing Heat Recovery Steam Generators, considering their age and condition, and the lack of startup and load-following flexibility of the existing steam bottoming cycles.

> Consideration should be given to repowering combined cycle plants as LSCC units using modern combustion turbines capable of burning Hydrogen. The use of existing interconnect and condenser cooling would help reduce capital cost, and the low fuel Heat Rate would reduce the cost of energy when consuming more expensive fuel. Such a re-powered plant could be designed to provide the flexibility needed by the grid.

3.3 Once Through Units

The once-through units at LADWP’s Haynes, Harbor, and Scattergood Generating Stations urgently require a solution. Originally oil-fired, there is land available for storage tanks at location.

3.3.1 Harbor Generating Station

Figure 4, shows a hypothetical installation of six 120-foot diameter tanks arrayed within the existing fuel-oil storage tank area at Harbor Generating Station. Five LM6000 peaking units are installed adjacent to the existing berm for the oil storage. These tanks could provide approximately 5 GWh of storage for a 460-MW LSCC plant.

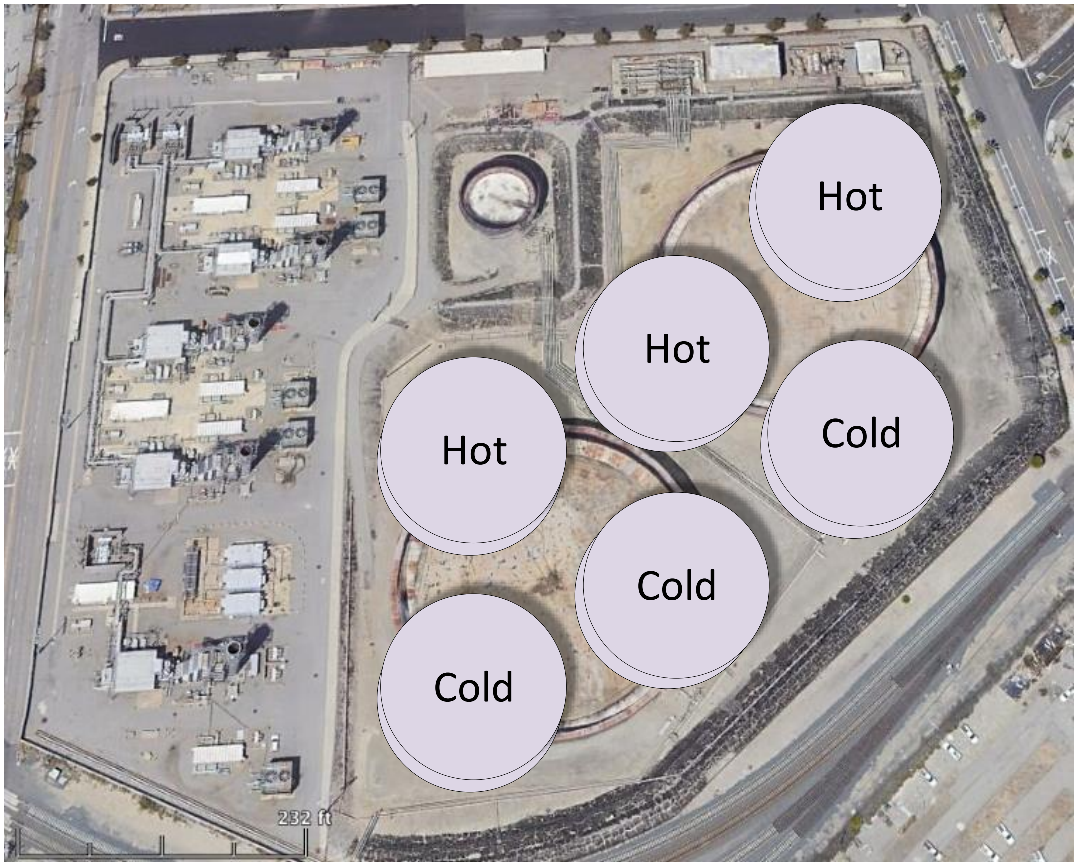

Figure 4. An 11,000 MWh energy storage system could be deployed at Harbor Generating Station, using six molten salt storage tanks, similar in design and construction to the 12 tanks installed at the Solana CSP station in Arizona. Similar systems could also be installed at the Scattergood and Haynes Generating Stations.

3.3.2 Scattergood Generating Station

Scattergood Generating Station located in El Segundo is shown in Figure 5. Units 1 and 2 at the bottom (closer to the beach) are conventional steam plants fired by natural gas. The 460 MW Unit 3 was replaced by about 500 MW of combustion turbine capacity including a combined cycle power plant based on the GE 7F.05 gas turbine and two LMS-100 peakers.

The LMS-100 units could be upgraded to LSCC technology to provide LADWP with 110 MW net new zero carbon capacity. About 3.2 GWh storage could be provided in storage tanks within the existing berm to the south of West Grand Avenue. The Molten Salt Steam Generator (MSSG) would provide steam to accelerate startup of the Unit 3 combined cycle, until it was also upgraded, following demolition of Units 1 and 2.

Figure 5. Scattergood Generating Station aerial view. The rectangular area including the boiler house and turbine hall for Units 1-3 and adjacent vacant land, is approximately 750 feet x 500 feet, and could be used for about 10 GWh of energy storage to support the existing combined cycle.

3.3.3 Haynes Generating Station

The Haynes Generating Station in Long Beach has been upgraded with combined cycle units and includes LMS-100 peaking units that could be integrated with thermal energy storage.

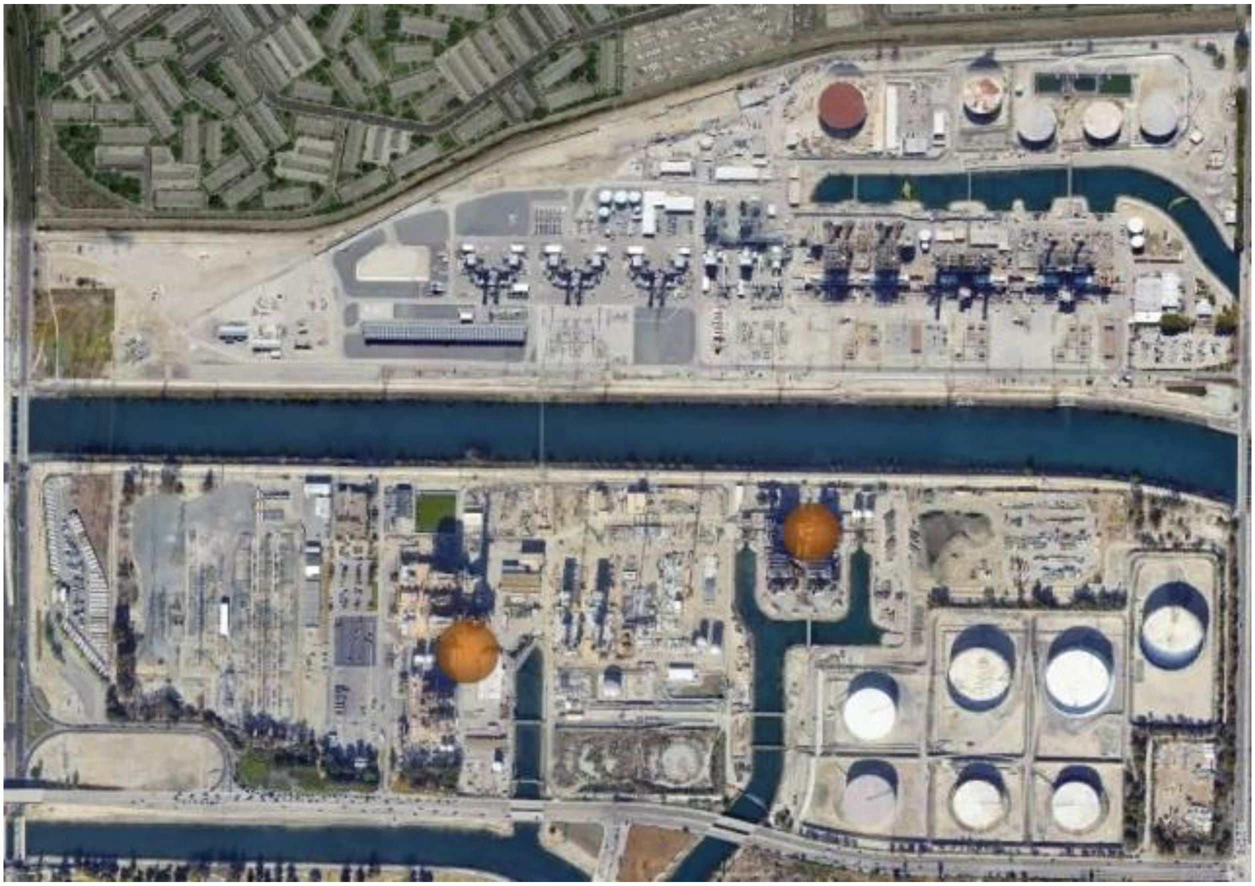

Figure 6. Haynes Generating Stations includes a large fuel oil tank farm in the lower right that could be redeveloped for hybrid thermal energy storage.

3.4 Cogeneration Units

LSCC technology presents some unique opportunities for gas turbine cogeneration facilities. Units that have lost their thermal host, such as those providing enhanced oil recovery, could be re-purposed to provide storage and flexible capacity.

4 LSCC Technology Enhances Asset Value

The LSCC technology, described in Section 2, offers a unique combination of features to enhance the value of a transformed gas fleet:

- Use of proven, safe, non-toxic, non-degrading, components to reduce risk, and extend the project life.
- Use of low-cost liquid salt storage bulk media to decouple discharge power and energy thereby reducing the cost of long duration storage.
- Integration of stored energy in the combined cycle to increase efficiency and storage density to deliver more energy from the storage media.
- Decoupling the charging process from the storage media and discharge process via efficient and flexible medium voltage heating technology to provide charging flexibility.
- Operational flexibility to enable ramping, frequency regulation, and voltage support, along with minimal standby power requirements and low losses.
- Synergistic use of stored energy and exhaust heat to displace fuel and discharge more energy than was stored.

By upgrading to LSCC technology, assets will realize multiple revenue streams to increase value and permit overall lower cost of electricity:

- Time-shifting and arbitrage.
- Regulation while charging and discharging
- Multiple day resource adequacy without the need to recharge each day.
- Voltage support and operating reserves.
- Congestion and curtailment relief
- Self-charge capability for economic or emergency reasons.
- Upside opportunities to sell into the market and downside protection against energy scarcity.

4.1 Solar Time Shifting and Arbitrage

Long-duration storage enables large quantities of solar energy to be stored for time-shifting. Fast charging capability allows more energy to be stored when electricity prices are low to reduce the marginal cost of energy discharged from an LSCC system. Together, these make low-carbon energy more competitive in the Day Ahead Market to increase the capacity factor and revenue of an LSCC plant.

4.2 Flexibility and Regulation

The LSCC technology provides exceptional ramping capability because there are no rate of charge or state of charge constraints on the operation of the storage system during charging or discharging, and because the steam and gas turbines are only loosely coupled.

- During charging, resistive heater load can be quickly added or dropped in response to real-time grid requirements. The flow rate of salt can be adjusted using a variable speed drive on the pump as well as by recycling to the cold tank, while maintaining precise temperature control of salt going to the Hot Tank.
- During discharging, the loose coupling between the steam turbine and gas turbine permits more flexible part-load operation, with fuel Heat Rate improving at part load. This occurs because steam turbine flow rate and pressure can be maintained by varying the heat from storage, unlike conventional combined cycle plants.

- The independence of the charging and discharging equipment (heaters and turbine-generators, respectively) provides additional flexibility during transitions between charging and discharging. For example, instead of a fast runback of power output, some molten salt can be sent through heaters to reduce the net power output.

4.3 *Multi-day Resource Adequacy*

Long-duration storage assures that RA can be available on successive days, without the need to re-charge from expensive or high-carbon electricity.

4.4 *Congestion and Curtailment Relief*

Congestion results in higher electricity prices and occasional curtailment of renewables. One effect has been a persistent spread between NP-15 and SP-15 Locational Marginal Prices. Appropriate siting of LSCC storage can alleviate congestion and curtailment to reduce electricity for Californians and improve returns for renewable investors.

4.5 *Ancillary Services*

LSCC system can provide a broad range of Ancillary Services per the CAISO Tariff:

- Non-spinning reserve can be provided by the gas and steam turbines as “multi-stage generators”.
- Regulation Up and Regulation Down is provided by a combination of the charging heaters and the discharging generators. The long-duration, and fast charging provides additional opportunity to deliver regulation during charging without the risk of the facility being short of stored energy needed for RA or energy. For example, the peaking facility described in Section 3.2 could charge at 70 MW and offer 30 MW of down regulation (by increasing charge power) and 70 MW of up regulation (by decreasing charge power).
- Voltage Support can be provided by the voltage regulator of each generator when discharging and by a synchronous condenser capability enabled by a SSS clutch connecting the Steam Turbine to its Generator. The synchronous inertia of this rotating machine is also expected to become a more valuable grid service during periods when renewable generation dominates.

4.6 *Resiliency During Extreme Events*

Recent extreme events have shown the need for resiliency: Public Safety Power Shutoffs, wildfire smoke suppression of solar PV production, and multi-day heat waves throughout the region. Even long-duration storage could be exhausted and difficult to replenish under such conditions, so the LSCC system can be equipped to offer exceptional resilience:

- When storage is depleted, the gas turbine can continue operating to provide its simple-cycle capacity, diverting exhaust gas through the bypass damper and up the auxiliary stack.
- If there are periods when the gas turbine power is not needed, the capacity power can be delivered to storage for later use when demand increases.
- An optional heating coil could be inserted in the bypass stack to recover and store additional energy.

> These features provide additional capability that can be especially valuable during Flex Alerts when power prices are at their highest.

5 Hybrid Storage Offers Unique Benefits

The abundance of low-cost renewable energy is creating opportunities for energy storage to reduce GHG intensity while serving the over-arching principles of the electric service compact: Safety, Reliability, Affordability, and Sustainability. This section is drawn from the recent ASME Advanced Clean Energy Summit webinar [7] by Dr. Conlon and provides perspectives for evaluation of energy storage systems that may be proposed in response to future RFOs.

5.1 Storing Electricity Requires Transformation

All Energy Storage Systems (ESS) transform electric energy to another form of energy in order to be stored:

- Electrochemical energy, as in a battery which changes the charge of ions.
- Gravitational potential energy, as in Pumped Storage Hydro (PSH), which changes the elevation of water.
- Mechanical energy, as in Compressed Air Energy Storage (CAES), which changes the pressure of air, or flywheels which change the kinetic energy of a rotating disk.
- Chemical Storage, such as in Hydrogen or Ammonia, which use the energy of molecular bonds (e.g. two H_2O water molecules to two H_2 Hydrogen Molecules and one O_2 oxygen molecule).
- Thermal storage, which has two forms:
  - Sensible heat, where temperature is changed, as in molten salt or hot rocks
  - Latent, where phase is changed, as in cryogenic liquefaction of air.

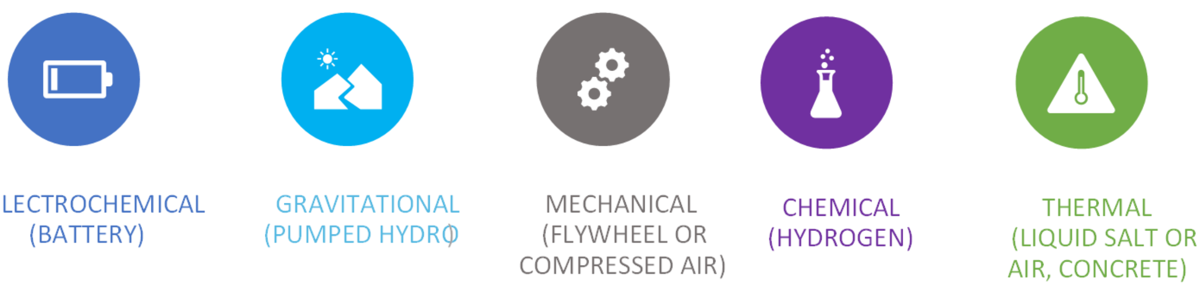

Figure 7. Electricity is transformed into internal energy appropriate to the type of storage medium

Accordingly, all ESS require transformation processes that convert electricity to (charging) and from (discharging) the internal energy of the storage medium as illustrated in Figure 8. The storage medium determines the kinds of equipment used by the charging and discharging processes, and hence the capital cost of the system and the performance (power and efficiency) of the overall ESS.

> Pintail Power's system optimizes the operating conditions to minimize the cost and maximize the performance of the charging and discharging processes and employs proven utility scale equipment and storage media.

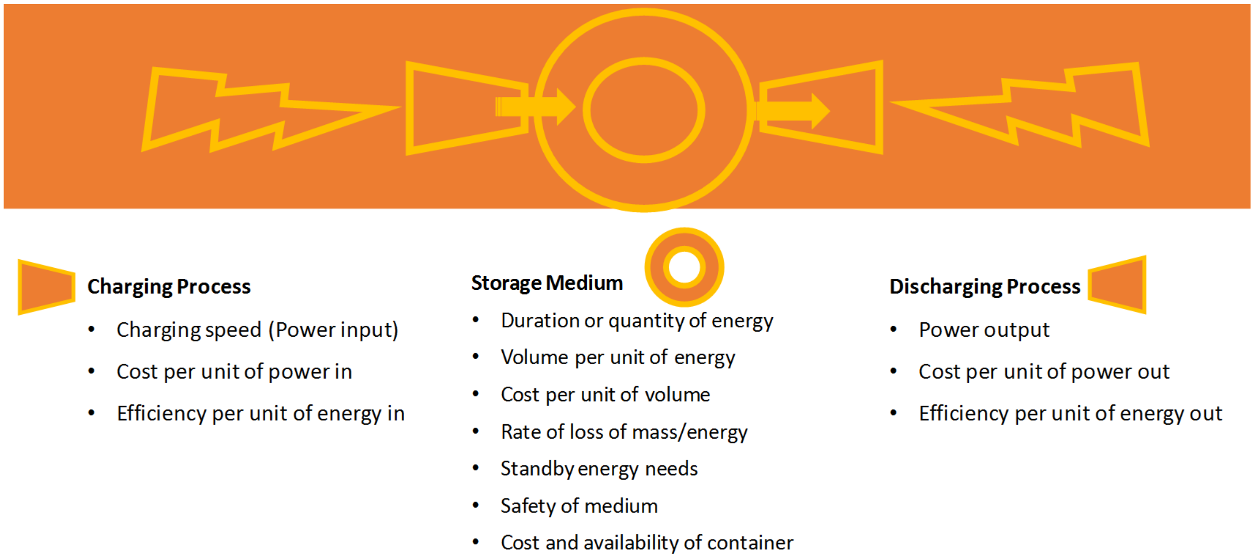

Figure 8. Electricity must be transformed into internal energy during charging and transformed back to electricity during discharging

5.2 The Storage Medium Drives the Design, Performance and Costs

There are many considerations in selection of the storage medium:

- Discharge duration multiplied by the discharge power is the quantity of energy that can be delivered from the ESS and is the major determinant of cost.
- Storage conditions and density (volume per unit of energy) determine the cost and physical size of the storage container. Some systems like CAES and Pumped Hydro require geological reservoirs, which may not be conveniently located or may have significant environmental impacts. Other systems may require expensive or exotic materials to contain the storage medium.
- Because large volumes are required, low cost materials and bulk storage are preferred.
- Loss rates of mass (air or water leaks) or energy (heat transfer from the environment or battery leakage currents) reduce round trip efficiency. Losses are proportional to area, so low surface to volume ratio bulk storage typically has lower losses.
- Passive systems (hydro, compressed air or thermal) which do not require active thermal management (and HVAC electrical loads) during standby have lower operating costs because they don't use electricity when it is expensive.
- Stable storage media with perpetual life (water, air, or molten salt) are preferred over those that degrade with use, have limited lifetimes and require replacement, or have operational constraints on rate of charge or state of charge, like batteries.
- Safe, non-toxic, and chemically stable (non-flammable, non-explosive) media are preferred to minimize risk to the public and reduce the cost of hazard mitigation.

> Pintail Power hybrid technology enables superior performance and cost by increasing storage density to reduce the media and reservoir cost and operating at conditions where low-cost carbon steel is suitable. The molten salt is non-toxic, non-flammable, non-

> explosive, has a perpetual life with salvage value, has low daily loss rates and minimal standby energy requirements.

5.3 *Bulk Storage Reduces Cost at Large Scale*

The storage medium can take two forms and exhibit different behaviors with scale as shown in Figure 9.

- Cellular batteries, including Lithium, benefit from manufacturing economy, with high production volume reducing unit cost.
- Bulk storage relies on an inexpensive storage medium (air and water are free, molten salts and flow battery electrolytes have low cost) that benefit from economy of scale.

Representative costs for the charging and discharging processes (proportional to power) and the storage medium (proportional to energy or power times duration) are also shown in the Figure. Capital cost increases with the duration, but the lower cost of bulk storage wins out at longer duration. This is shown in the upper curve as the total capital cost in dollars, and in the lower curve as the specific capital cost in $/kWh. Above about 5 hours of storage, bulk systems tend to be more cost-effective.

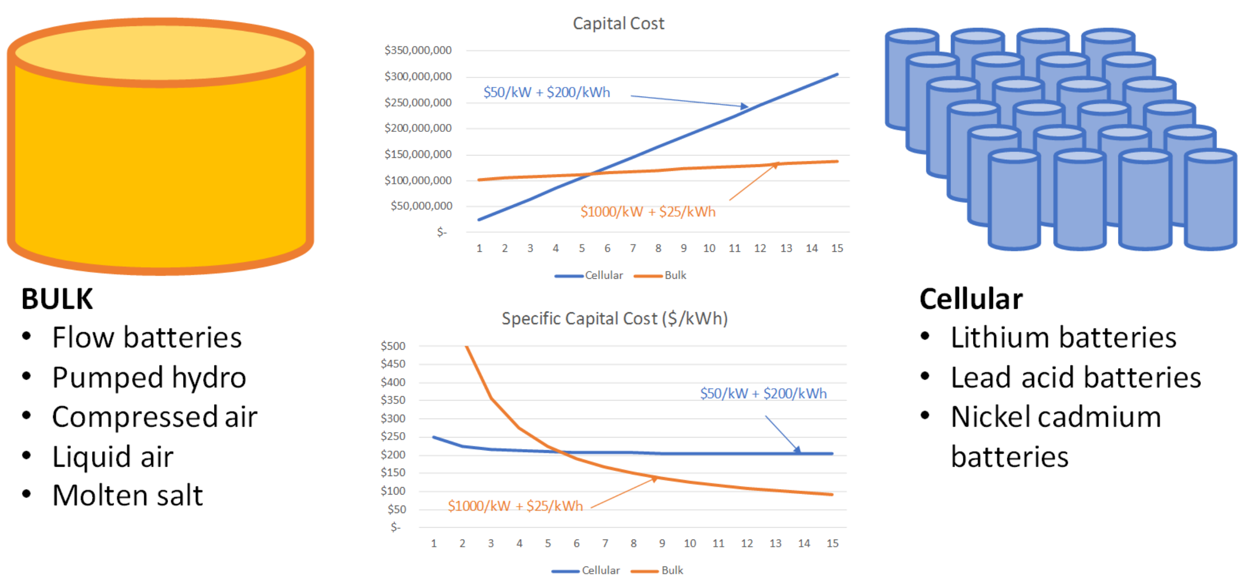

Figure 9. The form factor of the storage medium affects cost and specific cost.

5.4 *The Case for Hybrid Storage*

In a hybrid storage system, an external source of energy is used to boost the efficiency of transforming stored energy back to electricity as shown in Figure 10. The external energy source allows hybrid systems to produce more electricity than was stored, but their primary advantage is that the higher transformation efficiency reduces the quantity of storage medium, which in turn reduces the size and cost of the storage vessel and the cost of the charging equipment.

Compressed Air Energy Storage (CAES) uses exhaust heat from a combustion turbine to improve the efficiency of producing electricity from compressed air. In turn, the stored energy reduces the amount of fuel used per unit of electric energy delivered, and these synergistic effects lower the cost of hybrid storage projects.

Pintail Power's Liquid Salt Combined Cycle (LSCC), described in the Technology Section delivers the same hybrid synergies as CAES, while offering the locational flexibility of high-density storage in above ground tanks, and avoiding the development risk of underground caverns.

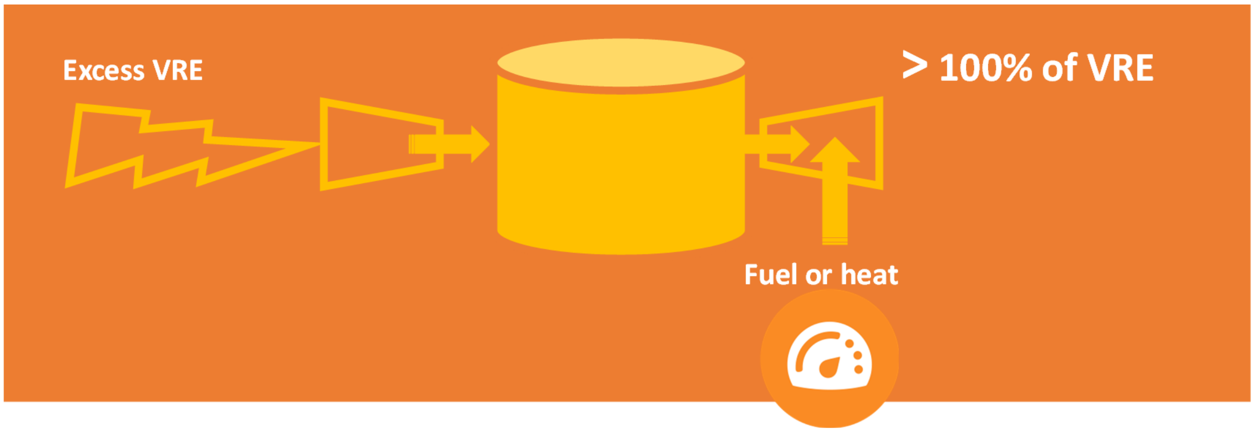

Figure 10. Hybrids use fuel or heat to boost the performance and reduce the cost of energy storage

5.5 Hybrids Deliver the Lowest Cost Storage

By combining inexpensive bulk storage media, efficient utilization of the storage medium, and the economy of scale of charging/discharging processes, hybrid systems deliver the lowest cost energy storage at long duration. Figure 11 compares the Levelized Cost of Storage for different technologies using the methodology and data assembled by Lazard for its annual cost of storage report.

> The key take-aways are that hybrid technologies – Pintail Power's LSCC technology (described in the Technology Section) and the generic CAES technology – deliver the lowest levelized cost

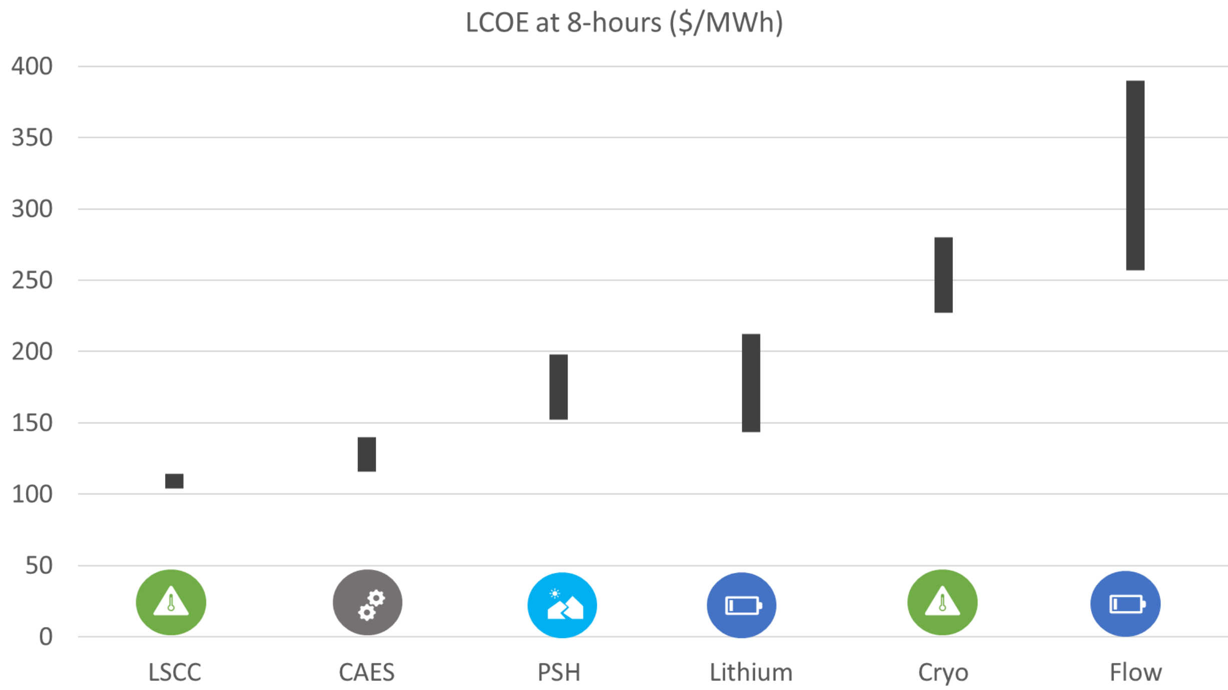

Figure 11. Bulk storage systems have the lowest Levelized Cost of Energy at 8-hours and above for 100MW capacity. Liquid Salt Combined Cycle technology is the cost leader.[3]

5.6 *Metrics*

Comparison of Energy Storage Systems (ESS) to determine Levelized Cost or Net Present Value should use uniform metrics that apply to all technologies.

> Most of the cost-related metrics are familiar and customary. Performance-related metrics are taken from ASME PTC-53 Performance Test Code for Energy Storage Systems.
>
> Pintail Power has found that an additional charging rate metric, the "T-Rate" is also essential for evaluating storage in markets with price volatility.

5.6.1 ESS Discharge Capability

The storage system capability is customarily specified by reference to discharge:

- Discharge Power, measured in kilowatts (kW)
- Discharge Energy, measured in kilowatt-hours (kWh)

> The discharge duration is the Discharge Energy divided by the Discharge Power.

5.6.2 ESS Capital Cost

The capital cost of energy storage systems has these independent design factors:

- Discharge Specific Power, measured as $/kW like any conventional power plant

[3] LCOE was calculated per Lazard methods and data. CAES, PSH and LAES (Highview Liquid Air Energy Storage), were last reported by Lazard in 2016. Flow batteries are from 2018 report, when Lazard last broke them out by technology. Lithium extrapolated to 8-hours from Lazard 2020 study. LCOE of LSCC is based on Pintail Power's cost and performance estimates.

- Discharge Specific Energy, measured as \$/kWh, is the cost of the storage medium and storage containment
- Charge Specific Power, measured as \$/kW, is the cost of the charging system

> Some systems reduce capital cost by using the same equipment for charging and discharging, such as inverter/charger for batteries or reversible pump/turbine for Pumped Hydro. Other systems use compressors for charging (CAES, LAES) and turbo-expanders for discharging. Pintail Power's LSCC uses electric heaters for charging, which are much lower cost and more flexible than compressors.

5.6.3 Marginal Cost of Energy

The marginal cost of energy discharged from the ESS is:

$$MCOE = Fuel\ Heat\ Rate * Fuel\ Cost + \mathrm{P}ER * Power\ Cost$$

- Fuel Heat Rate, expressed as $MMBtu/MWh_D$, is the ratio of fuel energy consumed per electricity discharged. This is the customary efficiency metric for thermal power plants and is zero for non-hybrid ESS.
- Primary Energy Rate (PER), expressed as MWh_C/MWh_D, is the ratio of electrical energy consumed during charging to electricity produced during discharging. PER is the inverse of roundtrip efficiency used for single input storage systems.
- Fuel Cost (\$/MMBtu) is the cost of fuel at the burner tip
- Power Cost (\$/MWh) is the cost of charging electricity. Because stored energy is fungible, the MCOE uses the average cost of charging electricity.

> It is vital to compare Primary Energy Rate (or Round-Trip Efficiency in the case of non-hybrid systems) at the same reference conditions, with adjustment to account for performance variation due to ambient conditions.

5.6.4 Time Rate (TR)

The Time Rate is the ratio of charge duration to discharge duration, or hours of charging per hour of discharging

$$\mathrm{TR} = \frac{t_C}{t_D} = PER * \frac{P_D}{P_C}$$

The TR is a critically important parameter to the economic evaluation of ESS, and as with the fuel Heat Rate and Primary Energy Rate, a smaller number is better. Until now, this ratio has not been considered because the most commonly deployed ESS (Pumped Storage and electrochemical batteries) have shared the charging and discharging equipment, so TR was fixed by the technology and was not a design choice.

A low TR is important for two reasons:

1. It indicates that the ESS can charge faster while low-cost energy is available to reduce the Power Cost component of MCOE.

2. It permits a higher discharge capacity factor, because fewer hours per day are used for charging, making more hours available for discharging. More discharge means lower levelized cost, since the discharge energy is in the denominator.

TR can be improved (lowered) by increasing the charge power P_C (subject to interconnect limits) and/or by decreasing the Primary Energy Rate.

> Pintail Power's hybrid LSCC has a Primary Energy Rate less than 1. As shown in the Technology Section, PER is 0.92 for an LM6000-based LSCC and can be as low as 0.6 for larger systems. Non-hybrid systems all have PER>1.
>
> Pintail Power's LSCC uses electric heaters for charging, which are more flexible and cost less per unit of charge power than turbomachinery used to charge CAES or LAES systems. This make it economically practical to increase the charge power up to the interconnect capacity to further reduce Marginal Cost of Energy and increase discharge capacity factor.

5.6.5 Operations and Maintenance Metrics

O&M metrics are also needed to undertake a full evaluation of a storage system.

- Startup cost, which may depend on whether the system is cold, warm or hot upon startup, ultimately expressed as $/start.
- Variable O&M expense, which is proportional to the usage of the system, and is expressed as $/kWh of discharge energy.
- Fixed O&M expense, which is proportional to the size of the system, and is expressed as $/kW of discharge capability.

> In the case of batteries that require thermal management, it is important to clarify if the standby energy costs are included in the efficiency calculation or are a separate cost. The cost of electricity during standby and discharge periods is likely more than during charging periods, so thermal management could be a significant O&M cost for batteries.

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