EXPANSION ENERGY

Cost-Effective, High-Efficiency 70 MW Energy Storage Plant Based on Patented Pressurized Liquid Air Energy Storage (LAES) Technology Has Lower Cost of Energy Compared to Battery Energy Storage Systems

Presented to the **POWER-GEN International Conference**
December 2017

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Abstract

Expansion Energy LLC's patented "VPS[TM] Cycle" technology converts surplus grid power into moderate-pressure liquefied air stored in above-ground cryogenic tanks, which is later converted back into power during peak demand periods through an innovative, highly efficient discharge process. In addition to being a liquid air energy storage (LAES) system, the VPS Cycle is a new type of advanced combined cycle power generation plant which does not use water or steam for its bottoming cycle and which has significantly higher thermal efficiency (72%+) versus standard combined cycle power plants (55-60%).

The VPS Cycle effectively utilizes waste cold and waste heat from within the power cycle to generate significantly more power by incorporating a patented Organic Rankine Cycle (ORC) process. This ability to convert more of the potential energy stored in the moderately pressurized cryogenic liquid air into electricity results in a substantially higher "round-trip efficiency" (RTE) than other LAES cycles and other bulk power storage systems, as high as 90%+. Discharge times can be 2-10 hours per day. Scales range from 10 MW to 500+ MW.

Using industry-standard economic methodologies, it has been determined that the VPS Cycle has the lowest Levelized Cost of Energy (LCOE) of any power storage system available today. VPS's LCOE is typically $125-$135/MWh versus $200-$400/MWh for compressed air energy storage (CAES); $185-$275/MWh for pumped hydro; and $350-$750/MWh for lithium ion batteries (in each case assuming a power "charging" price of $50/MWh). VPS's LCOE is also lower than simple-cycle peaker plants ($220-$300/MWh).

The VPS Cycle technology is presently being considered for commercial deployments by several large North American utilities.

One 70 MW VPS project is expected to reduce CO_2 emissions by > 10 million metric tons over its lifetime and to stimulate > 200 MW of new wind power as the VPS plant's "charging" (liquefaction) electricity source.

In addition to stand-alone VPS plants deployed on the grid, the integration of the VPS technology "behind-the-meter" at industrial facilities that have some amount of waste heat and/or surplus cryogenic fluid (especially liquid nitrogen or liquid oxygen from air separation plants) which can be utilized by the Cycle are particularly attractive, both for technical/efficiency reasons and for optimal economics.

VPS integrations can also convert gas-fired peaker plants into daily, long-duration energy storage plants with approximately 2X the efficiency of the peaker itself and with no additional greenhouse gas emissions (GHGs).

VPS™ Cycle Technology Overview

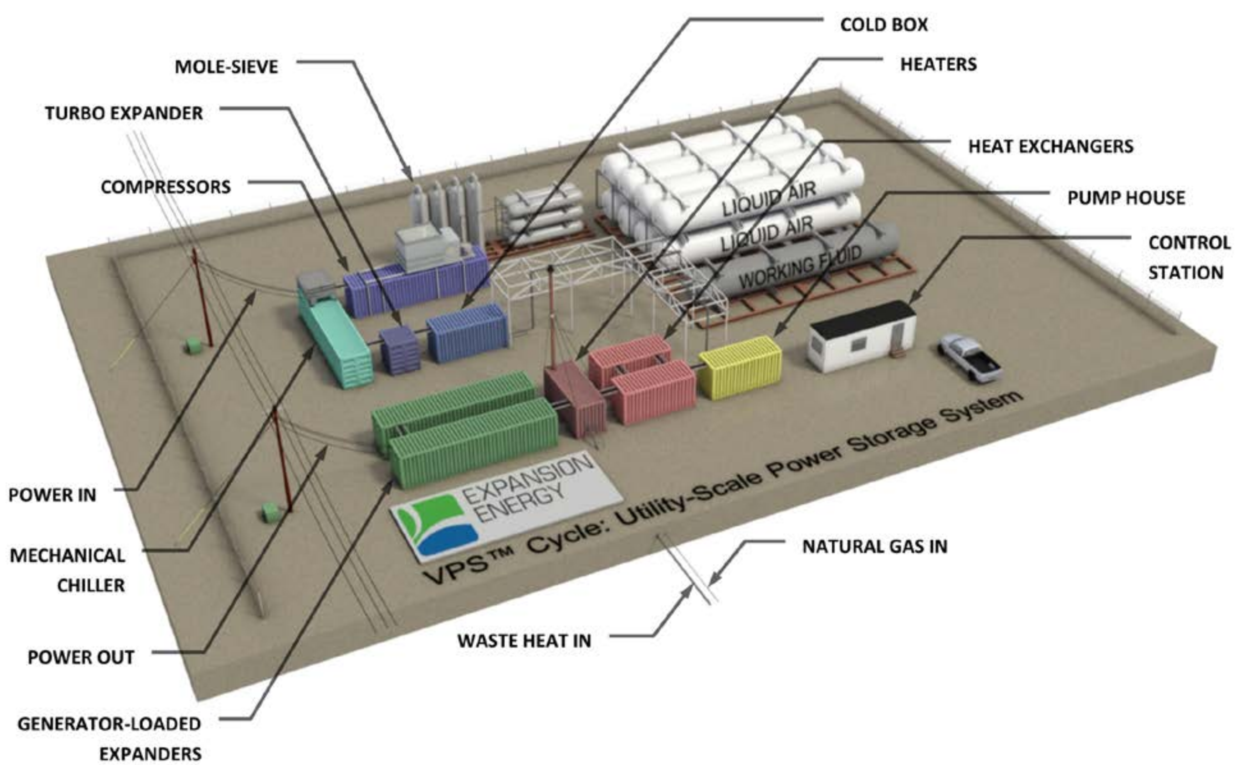
The patented VPS™ Cycle liquid air energy storage (LAES) and combined cycle power generation technology consists of two distinct "modes":

1) Inflow-to-Storage ("charging") Mode

2) Outflow-from-Storage ("discharging") Mode

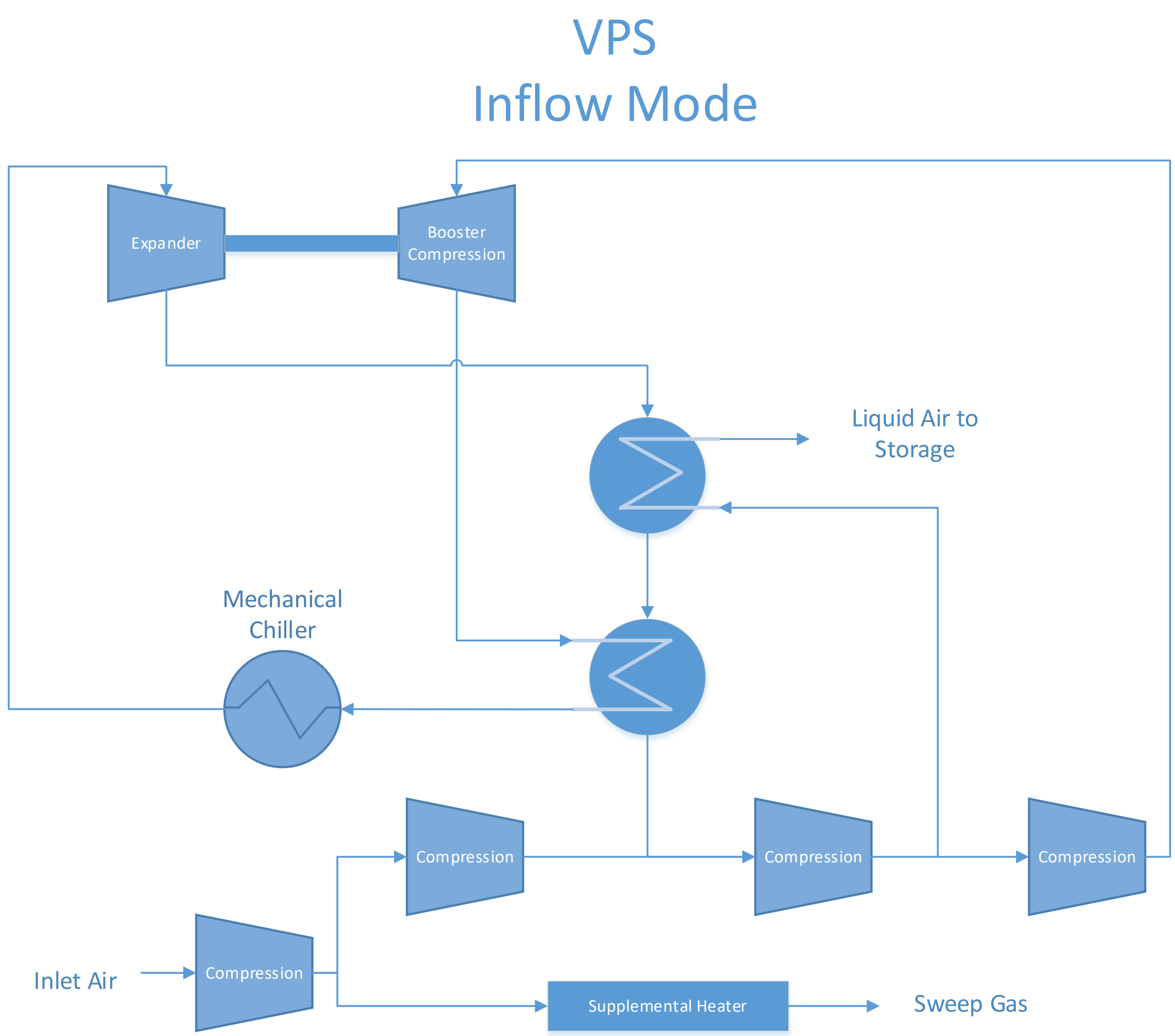
The Inflow and Outflow Modes are "connected" by cryogenic fluid **Storage Tanks** which store **cryogenic liquid air (L-Air)** produced by the Inflow Mode. In every other respect, the Inflow and the Outflow Modes operate independent of one another and at different times of the day. A rendering of a typical VPS Cycle plant design is shown below.

Figure 1: VPS™ Cycle Plant Rendering



During the **Inflow Mode**, low-cost, off-peak electricity is converted to L-Air in a cryogenic process, much like air separation plants which produce industrial liquid gases, except that with VPS the air is not separated into its elemental components. Ambient air is compressed and then deeply refrigerated by a cryogenic turbo expander to liquefy the air, which is then stored in cryogenic tanks. The Inflow Mode is optimized through a judicious balance of the compression and refrigeration, along with heat and cold recovery steps, which produce the L-Air in a highly efficient manner. This efficient design maximizes the amount of L-Air that can be produced and stored from the electricity input ("charging"). A simplified process flow diagram (PFD) of the VPS Cycle's Inflow Mode is shown below.

Figure 2: VPS Cycle Inflow Mode PFD *



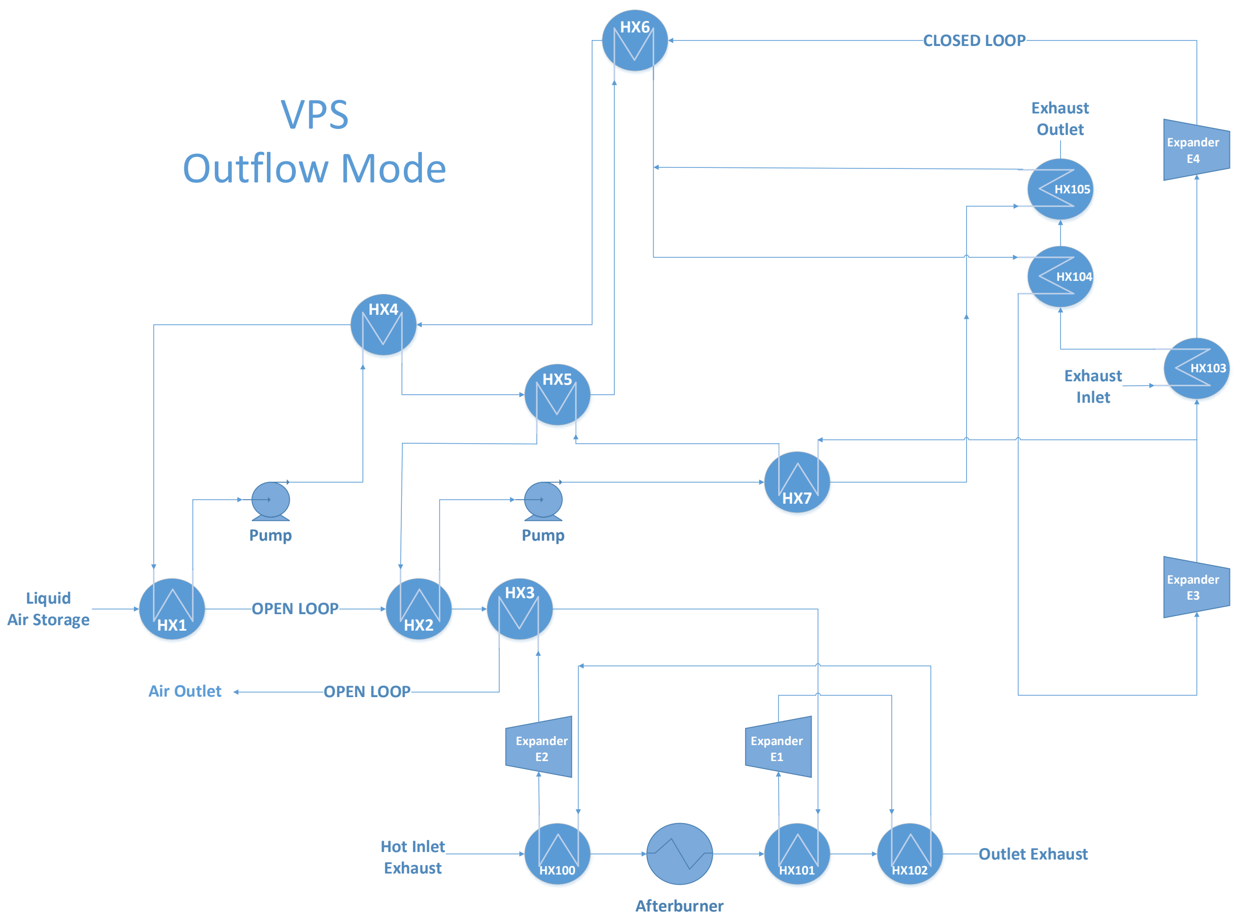
During the **Outflow Mode**, the energy stored in the L-Air is released through two “heat engine” processes—one an open loop and one a closed loop. First, in the **open loop** portion of the Cycle, the L-Air stored in the cryogenic tanks is pumped to pressure and its refrigeration is recovered by condensing a counter-flowing working fluid within the closed loop ORC “bottoming cycle.” Simultaneously, the L-Air is vaporized to return it to a gaseous state, now at high pressure. The pressurized air is further heated by an external source of high-grade waste heat (such as from a simple cycle gas turbine peaker plant) and/or the heat from combustion of natural gas. The now-pressurized and warmed air is then expanded in generator-loaded hot gas expanders. The external heat content added to the pressurized air allows more work to be performed by the hot gas expanders, and thus more electricity to be produced by the generators.

Still in the Outflow Mode, the deep refrigeration from the beginning of the open-loop portion of the Outflow Mode is recovered through heat exchangers to condense the working fluid within VPS’s **closed loop** ORC bottoming cycle. That condensed working fluid within the ORC is also pumped to pressure and heated by waste heat and/or the heat from natural gas combustion. Similar to the open loop portion, that working fluid is expanded in a generator-loaded hot gas expander to produce even more electricity. This proprietary bottoming cycle concept is a key advantage of VPS over other LAES systems and over other combined cycle power generation systems, as explained further below in this paper.

The Outflow Mode can have several variations, depending on the heat source, such as waste heat from a simple cycle gas turbine (GT), with or without an afterburner, and/or a free-standing natural gas-fired combustion chamber, or a combination of the above. The outbound air can be sent to a combustion chamber, thus producing hot, high-pressure products of combustion, or it can merely be heated, in which it leaves the Cycle as low-pressure, near ambient air.

A simplified process flow diagram (PFD) of the VPS Cycle’s Outflow Mode is shown below.

Figure 3: VPS Cycle Outflow Mode PFD *



** Note that both the Inflow and Outflow PFDs presented above are simplified schematics. Proprietary/trade secret information is not presented here. For example, not all pumps, valves, heat exchangers or the generators that load the expanders in the Outflow Mode are shown, nor are the motors that drive the compressors and chiller in the Inflow Mode. Fully engineered designs and process packages for the VPS Cycle are available for license and can be disclosed under a confidentiality agreement with interested parties.*

Optimal VPS Deployment Options

In addition to new-build, stand-alone VPS plants for energy storage and/or high-efficiency combined cycle generation, the VPS technology can **turn existing (often idle) gas-fired peaker plants (GTs), combined-cycle plants (CCPPs) or CHP plants into baseload energy storage assets and "boost" the overall efficiency of those plants** substantially, by utilizing the waste heat from the GT. In other words, the VPS technology can **convert GT, CCPP, or CHP plants into ultra-high efficiency, long-duration storage assets** by deploying VPS equipment adjacent to those existing facilities. Each of these embodiments of the VPS Cycle allow low-value, off-peak renewable and/or baseload power to be "absorbed" rather than dissipated, and released later to the grid during higher-value peak demand periods.

Note that, if paired with a GT, a VPS plant can "re-charge" itself (air liquefaction) with power generated off-peak when power is cheap using both the GT and the closed-loop ORC portion of VPS (using waste heat from the GT).

In addition to utility-owned or independent power producer (IPP)-owned VPS plants for grid applications, VPS can also be effectively deployed for a variety of **"behind-the-meter" applications at industrial facilities and certain large commercial facilities.** This can aid utility demand-side management programs; lower power demand charges; lower energy charges; etc.

Among the most attractive industrial sites for deploying the VPS technology is **at existing air separation plants** owned by manufacturers of industrial gases. Many air separation plants are designed and operated to produce one industrial gas, either nitrogen or oxygen. In those cases, the air separation plants have surplus nitrogen or surplus oxygen, depending on which product is in demand in the nearby market or by the captive "over-the-fence" customer. Therefore, the surplus cryogenic nitrogen or surplus cryogenic oxygen can be stored in VPS's cryogenic tanks instead of air, but used the same way as L-Air in VPS's Outflow Mode. This means that the existing air separation plant essentially acts at the Inflow Mode for VPS, thus saving that capital cost and operating cost and making for an even more economical VPS plant.

Enabling Greater Deployment of Intermittent Renewable Energy

One key goal of deploying energy storage assets, including the VPS Cycle, is to "firm up" intermittent renewable energy sources such as wind and solar power generation. Properly deployed, storage systems integrated with intermittent renewables provide most or all of the benefits of renewable energy but with the reliability of traditional baseload power plants.

One 70 MW VPS project is expected to reduce CO_2 emissions by > 10 million metric tons over its lifetime and to stimulate > 200 MW of new wind power or other renewable power source of the VPS plant's "charging" (liquefaction). The VPS plant would also provide ~ 70 MW of low-emission, high-efficiency peaking generation—**the most efficient gas-fired peaking generation available**.

Similar GHG emission reduction outcomes are expected for other VPS Cycle deployments of similar scale and purpose.

Other Storage Applications for VPS

In addition to "load shifting" application, the VPS technology has the potential to be applied for numerous applications in the electrical grid. These applications include the provision of ancillary services, deferral or elimination of transmission and distribution upgrades, retrofitting existing peaking plants to improve economics and reduce emissions, reducing grid congestion and line losses, enhancing grid reliability, and enabling micro grids.

Deployment Scales & Fabricated Modules

The VPS technology is applicable to a wide range of scales, from **10 MW to 100s of MW**. However, XE is designing standard-sized, pre-designed/**pre-fabricated VPS Cycle modules** of approx. **20 MW, 50 MW** and **70 MW**. Multiple modules can be deployed side by side if greater total capacities are required. Custom deployments can be designed also, particularly for projects > 100 MW in scale.

XE is also partnering with global EPC & fabrication companies to provide lump-sum, turnkey (LSTK) contracts with performance guarantees for pre-designed, shop-fabricated VPS modules.

VPS Cycle Capital Costs & ROI

At scales > 100 MW, the VPS Cycle's **CAPEX is ~ $150 per kWh** of daily output capacity. **At lower scales, CAPEX is ~ $200-250 per kWh** of daily output capacity.

On a $/kW basis, the VPS Cycle's **CAPEX is ~ $900 - $1,300/kW** (depending on the scale), **similar to the CAPEX of simple-cycle GT peaker plants**.

Note that for long-duration "bulk" energy storage assets (10s or 100s of MW for 2-10 hours/day) such as the VPS Cycle, the $/kWh metric is more important than the $/kW metric, and VPS has one of the lowest $/kWh of any storage technology available today.

Because of these relatively low capital costs and VPS's inherently high efficiency, when properly deployed, VPS plants have the potential to deliver very attractive ROIs. As an example of the magnitude of economic value the VPS Cycle can deliver, XE completed an extensive feasibility study with Con Edison (NYC) and the New York State Energy Research & Development Authority (NYSERDA) for the potential deployment of a VPS plant in or near New York City to support the Con Edison utility's service territory. Projected economic benefits from the study were compelling—a potential **net present value (NPV) of $218 million** per project. A copy of that report can be obtained on NYSERDA's website: http://www.nyserda.ny.gov/About/Publications/Research-and-Development-Technical-Reports/Electric-Power-Transmission-and-Distribution-Reports

Round-Trip Efficiency

Round-trip efficiency (RTE) is an important metric for energy storage technologies. However, it is very important to understand the specific methodology chosen for calculating RTE in order to ensure "apples-to-apples" comparisons. The VPS Cycle's RTE is calculated by dividing the MWh released during the Outflow Mode by the MWh consumed during Inflow Mode, after first subtracting from the Outflow the MWh which would have been produced if any natural gas consumed during the Outflow Mode were instead used by a simple cycle power plant. The remaining Outflow MWh is attributed to the electricity that was used to produce the L-Air during the Inflow phase. The calculation of the RTE for a proposed 70 MW VPS project discussed later in this paper is shown here:

Electric Energy released during Outflow Mode (5 days/week x 4 hrs/day x 68.8 MW)	=	**1,376 MWh/week**
Less Energy which would have been produced by a GT (5 days/week x 4 hrs x 121 MMBtu/hr x 11,500 Btu/kWh)	=	**210 MWh/week**
Net Energy Outflow attributed to Stored Power		**1,166 MWh/week**
Inflow Power to liquefy the air (7 days/week x 10 hrs/day x 16.9 MW)	=	**1,183 MWh/week**
RTE is Net Outflow Power/Inflow Power (1,166 MWh/1,183 MWh)	=	**98.6%**

The ~ 98% RTE shown above is achieved in part by using high-grade waste heat from a GT peaker plant as part of the thermal energy content of VPS's Outflow Mode.

In the proposed ~ 70 MW VPS project discussed later in this paper, approximately 1,960,000 lb/hr of 1,000° F (538° C) waste heat from a GT would supply the pre-heating requirement of the air and the ORC working fluid streams in the project's Outflow Mode. This level of waste heat could be provided by 65 MW - 75 MW of simple cycle GT. For example, 3-GE 2500P turbines each rated at 21.8 MW would be sufficient. Reduced volumes or lower temperature waste heat would reduce the VPS plant's efficiency and raise the heat rate somewhat. However, VPS would benefit from any amount of waste heat above 500° F (260° C).

There are many suitable sources of such high volume, high grade waste heat, within the electric generation, industrial process, gas compression, oil and gas processing and petrochemical sectors. In the event that the proposed 70 MW VPS project is unable to secure a suitable external source of waste heat, the RTE of that VPS project will be reduced to ~ 72% and the heat rate would rise to ~ 4,300 Btu/kWh. These efficiency numbers are still quite good relative to other storage options.

Thermal Efficiency / Heat Rate

As important a metric as RTE is to the storage industry, it may be even more important to understand and compare VPS's **thermal efficiency** and **heat rate** to other thermal power systems. Primarily because of its innovative closed-loop ORC bottoming cycle as described in the next section, the **VPS Cycle achieves ultra-high thermal efficiency of 72-75%** (on a stand-alone basis without utilizing waste heat from an external source such as a GT) **versus a standard CCGT's thermal efficiency of 55-60%.** This means that the VPS Cycle uses substantially less natural gas (NG) for each MWh released during the Outflow Mode versus CCGTs (and GTs). As a result, VPS releases far fewer emissions per MWh versus CCGTs and GTs.

Commensurately, **VPS has a low Heat Rate of 1,710-4,500 Btu/kWh** depending on whether high temperature waste heat is available such as from a GT. This is in contrast to Heat Rates of ~ 6,600-7,700 BTU/kWh for standard CCGTs and 10,000-12,000 BTU/kWh for simple-cycle GTs). A VPS plant integrated with an existing peaker plant can generate up to **2 X more power than the GT itself**—with no additional natural gas consumption or emissions (i.e., no new air permits needed).

A comparison of heat rate and thermal efficiency of a VPS plant versus other common power generation systems is show in the table below.

Table 1: VPS Heat Rate & Thermal Efficiency vs. Other Power Systems

Natural Gas Power Generation Technologies	Heat Rate (Btu/kWh)	Thermal Efficiency
Average Heat Rate of US Simple Cycle GTs (EIA, 2014)	**11,378**	**30.0%**
Typical US Combined Cycle Power Plant	**7,615**	**44.8%**
VPS Integrated 1:2 with GT-to-VPS (No additional NG; Large or Small Scale)	**5,903**	**57.8%**
Best in Class, **Large Scale** CCPP at Ideal Operating Conditions	**5,690**	**60.0%**
VPS Stand-Alone, without GT; w/ Direct-fired NG Combustion (Large or Small)	**4,500**	**75.8%**
Stand-Alone **VPS** with GT Exhaust + Afterburner / Duct Heater (Large or Small)	**1,710**	**199.5% ***

** 199.5% is possible because of the use of external GT waste heat, not just the new NG used by VPS.*

How Does the VPS Cycle Achieve Such High Levels of Efficiency?

VPS achieves the high thermal efficiency and low heat rate described above by effectively utilizing both waste cold and waste heat from within the open-loop portion (essentially a “deconstructed Brayton cycle”) of the VPS Cycle to run **a closed-loop Organic Rankine Cycle (ORC)** process, which is a core portion of the VPS patents. Because the waste cold is at deep, cryogenic temperature and the waste heat is typically on the order of 900-1,000° F**, the VPS ORC’s “delta-T”** (i.e., the difference between the highest and lowest temperature within the ORC) **is far larger than any standard commercial ORC system**, where the low end of their delta-T is ambient temperature (typically 50-80° F).

More specifically, in typical Rankine cycle applications for power generation (i.e., steam generation), the highest temperature is about 1,000° F (538° C), and condensation is at ambient temp, around 50° F (10° C), a delta T of about 950° F (528° C). By comparison, in the VPS Cycle, the highest temperature is higher, about 1,400° F (760° C) and, with the use of refrigerated air, the temperature of condensation for VPS’s closed loop ORC is much lower, about -60° F (-51° C), resulting in **a larger delta T of 1,460° F (811° C) for VPS’s ORC**, and much higher efficiency.

VPS Cycle as a Next-Generation Combined Cycle Power Plant

Because VPS’s highly efficient ORC acts as a “bottoming cycle” and because VPS’s thermal efficiency is so high relative to other thermal generation systems (~ 72% VPS thermal efficiency vs. 55-60% thermal efficiency for standard CCPPs), the VPS Cycle is not just a LAES storage technology, but also a type of **next-generation combined cycle power plant (CCPP)** which **does not use water or steam**. Instead, the working fluid in VPS’s closed-loop ORC bottoming cycle is typically a commercial refrigerant which is never vented to the atmosphere. Therefore, VPS can be described as **an ultra-high efficiency combined cycle power plant with storage built in**. (Other LAES systems cannot claim this.) However, unlike standard combined cycle power plants (CCGTs), the VPS Cycle **uses zero water**; **does not require cooling towers**; and **can be deployed in modules at much smaller scales** (e.g., increments of 20 MW) than standard combined cycles can.

In perhaps the most likely VPS deployment, where a VPS plant is sited adjacent to an existing simple cycle GT, the VPS Outflow Mode becomes **a highly efficient combined cycle with three sets of generators**, rather than the two sets in standard CCPPs—the GT, the open loop for the L-Air, and the closed loop ORC refrigerant. Those two cycles under the GT are more efficient (with lower heat rates) than the steam cycle in a standard CCPP. Increased efficiency results in lower fuel costs and lower emissions per MWH of output.

All of the above VPS Combined Cycle generation configurations still preserve all of the benefits of VPS as a storage technology.

Why Is A New Type of Combined Cycle Power Plant Like VPS Needed?

Just like standard CCPPs, the VPS technology can be used to design and build large-scale combined cycle generation plants (e.g., 200-500 MW) to serve the grid from a centralized location. However, unlike standard CCPPs, VPS Combined Cycle plants can be used for the following additional applications (which standard CCPPs cannot) because **VPS plants can be deployed at much smaller scales cost-effectively versus CCPPs**:

- Distributed power generation (an important industry trend)
- Alleviating tight load pockets in utility distribution systems
- Micro-grids
- Combined heat and power (CHP)
- “Behind-the-meter” at industrial and large commercial consumers

In part because VPS can be deployed cost-effectively at much smaller scales than standard CCPPs, VPS plants **can readily be shop-fabricated as pre-designed modules**, saving on capital costs versus field-erected CCPPs which are subject to more CAPEX variability and longer project timelines.

Importantly, in many wholesale markets/ISOs the generation assets with lowest heat rate are first to be dispatched by the system operator. With its very low heat rates, VPS plants would be deployed before GT peakers and CCPPs, making VPS’s low heat rate an even more beneficial feature.

Also, unlike standard CCPPs and GTs, VPS plants **do not lose efficiency in hot and/or humid conditions. This can be a very important economic factor in most regions which experience any significant humidity and/or high temperatures.**

Because of its higher thermal efficiency and low heat rate, air emissions—NOX, CO_2, etc.—from a VPS plant are **reduced 25-40%** per MWh versus CCPPs, and **50-65%** vs. GTs. In fact, a VPS plant produces no additional greenhouse gas (GHG) emissions if the VPS plant uses only the waste heat from an existing GT as its thermal energy source. With environmental concerns rising in many regions/markets, this important benefit of the VPS technology cannot be overlooked.

Also regarding environmental concerns and costs, unlike standard CCPPs, a VPS Cycle plant **uses no water for cooling or for other purposes.** This not only lowers the environmental impact of the plant, it also reduces capital costs (e.g., no cooling towers required) and operating costs, and reduces staffing costs/complexity because VPS plants to do not require specialized, high-cost labor like CCPPs do (for their HRSG boilers, etc.)

VPS Cycle Integrations with Existing (or New) Combined Cycle Power Plants

Though beyond the scope of this paper, it is important to note that the VPS Cycle can also be integrated with existing or new standard CCGTs to improve CCGT performance and/or lower their CAPEX. Examples of such integrations include, but are not limited to:

- More efficient utilization of the CCGT's steam content
- Pressurized, low-temperature air sent to GT front-end to reduce compressor load and thereby raise MW or reduce NG
- Increase CCGT value during off-peak
- Allow heat recovery steam generation (HRSG) turn-down during peak period
- Use HRSG waste heat to pre-heat VPS's ORC (for higher efficiency)
- Reduce or eliminate need for the CCGT's cooling towers

VPS Cycle vs. Other LAES Systems

Other LAES systems have been proposed by other companies in recent years. However, **the VPS Cycle is substantially different than those other LAES systems** because VPS **utilizes "waste cold"** from its Outflow Mode not to make more liquid air (L-Air) for its Inflow Mode as other LAES designs do, but **instead to release substantially more power by using that refrigeration in the closed loop ORC portion of VPS's Outflow Mode** during the discharge period—which is of course the main objective of any energy storage system.

"Standard" LAES designs have been reported to achieve approximately 60% round-trip efficiency (RTE) on a stand-alone basis. In contrast, VPS can achieve RTE of approximately **75% on a stand-alone basis**. Moreover, by using a high-grade source of waste heat, such as from a GT peaker, the VPS Cycle can achieve **RTE of more than 90%**. This is largely due VPS's patented utilization of waste cold (refrigeration) for its closed loop ORC.

Just as important as the RTE metric are the thermal efficiency and heat rate of any LAES system. Because of its closed loop ORC bottoming cycle, **the VPS technology has superior thermal efficiency and heat rate versus other LAES systems**. See also the "Efficiency / Heat Rate" section above.

VPS Cycle vs. Other Energy Storage Technologies

Different storage technologies have different strengths and different targeted applications. Nonetheless, the VPS Cycle has important advantages versus other power storage technologies for many applications, as discussed below.

***Batteries*.** Compared to battery energy storage systems, the VPS Cycle has a much longer life—30-40 years of useful life vs. only 5-7 years for batteries—and virtually unlimited cycling. Moreover, the VPS technology can be easily scaled to 10's or 100's of MW. Battery storage systems have practical limitations above 40-50 MW. Regarding discharge duration, battery energy storage systems are typically designed for and limited to a maximum of 1-2 hours per day of discharge capacity. VPS plants have a much longer discharge (outflow) period each day—4-10 hours per day, which is necessary for load shifting and the "firming" of intermittent renewables such as wind power to deliver baseload type reliability. Finally, battery energy storage systems have substantially higher cost, especially as measured on a levelized cost of energy (LCOE) basis. See also the **"VPS Cycle LCOE vs. Battery & Other LCOE"** section.

Compressed Air Energy Storage (CAES). CAES systems are capable of long duration discharge periods and of high capacity (100s of MW). However, commercial CAES projects require special geologic conditions such as underground caverns that can store high-pressure air. Suitable caverns are rare and can be difficult to identify and qualify. In contrast, VPS Cycle LAES plants are entirely man-made systems using "off-the-shelf" equipment, making them predictable and repeatable. Of course, CAES's reliance on underground caverns also means that the CAES plant must be sited where the suitable cavern is—not necessarily where the load or need is. In contrast, a VPS Cycle LAES plant can be sited virtually anywhere (above ground) that has 10,000 to 50,000 feet of available space, depending on the scale of the plant, partly because L-Air is multiples more dense that CAES's compressed air, making it suitable for storage in above-ground tanks. Siting close to the load (and/or near a source of waste heat) brings multiple additional system benefits, including reserving T&D capacity for other generation assets, so this locational advantage can be critical. Regarding efficiency, CAES plants have RTEs of 45-65%, whereas VPS plants have RTEs from 72% to 90+%, depending on whether a waste heat source is available. All of the above factors also mean that VPS plants have a lower capital cost per MW and MWh of storage capacity.

In addition, with a CAES project, the air pressure within the cavern falls as air is withdrawn during the power generation phase. As a result, additional equipment is required to operate over a wide range of air pressures. This need for additional equipment increases capital cost and makes it difficult to maintain a steady electric power output. There are no such constraints with a VPS Cycle LAES plant, as it can constantly maintain its full rated capacity until the storage tanks are completely empty.

Pumped Hydro Energy Storage. Pumped hydro energy storage systems have a long and successful track record for high MW applications. However, this approach requires specific geological conditions which are rare, and require very large tracts of land plus water rights. As such, pumped hydro projects have very long lead times (as much as 10 years), challenging permit requirements and very high capital costs, making them more like large civil infrastructure projects than typical power industry projects. Since lakes, reservoirs and/or streams are involved, there can be significant environmental, fish and wildlife issues. Moreover, as with CAES, the specific geological conditions that would support a pumped hydro project are usually not found where storage is need the most—typically near the load, not in a remote location.

VPS Cycle LCOE vs. Battery & Other LCOE

An important measure of cost-effectiveness of any storage or generation system in the power industry is its Levelized Cost of Energy (LCOE). Based on third party analyses of the LCOE of a typical 70 MW VPS Cycle plant, and comparing the VPS LCOE to the published LCOEs of other storage or peaking systems, the VPS Cycle showed the lowest LCOE of any system studied—about **1/3 of lithium ion batteries' LCOE** and about **1/2 of a GT peaker plant's LCOE**.

VPS's LCOE was also substantially lower than the LCOE of both CAES and pumped hydro storage technologies, as shown in the table below.

Table 2: VPS™ Cycle LCOE versus Other Storage & Generation Technologies

Technology	CAPEX/kWh of Daily Discharge Capacity	Charging $/MWh (assumption)	LCOE ($/MWh)
VPS™ Cycle LAES	$173	$50	**$125 – $135 ***
CAES	$197	$50	**$192**
Pumped Hydro	$244 – $359	$50	**$188 – $274**
Lithium Ion Battery	$486 – $1,236	$50	**$347 – $739**
Flow Battery	$372 – $1,115	$50	**$290 – $892**
Gas Turbine Peaker	N/A	N/A	**$220 – $300**

** The $125/MWh VPS LCOE value assumes that waste heat from a GT is available for the VPS plant.*

** The $135/MWh VPS LCOE value assumes only direct heat of combustion is available (no waste heat).*

LCOE Methodology & Analysis

Levelized Cost of Energy (or Levelized Cost of Storage) is an industry standard technique that attempts to achieve an “apples-to-apples” comparison—usually on a $/MWh basis—of power generation or storage systems/projects which may be inherently dissimilar. LCOE analyses allow decision-makers to determine which systems or projects bring the most total value (considering both costs and benefits) to the asset owner, ratepayers, etc. over the lifetime of the project.

LCOE calculations consider such major variables as CAPEX; OPEX; hours per day and days per week of operation; expected project lifetime; power output (MW); fuel consumed; and, in the case of storage, the amount (MWh) and cost of energy consumed during the “charging” portion of the asset’s daily/weekly/monthly cycle.

The LCOE table in the previous section uses published industry data for the LCOE ranges of the other energy storage systems listed and for GT peaker plants.

The VPS Cycle LCOE range was calculated using the results of the 70 MW VPS plant commercial case study described in the last sections of this paper. The following specific VPS plant characteristics and variables from that case study were utilized:

- Inflow (charging) hours = **10 hours/day**
- Inflow days/week = **7 days**
- Outflow (discharge) days per week = **5 days**
- Outflow rate = **69 MW**
- Natural Gas cost = **$3.00/MMBtu**
- Plant lifetime = **25 years**

Note that the assumed **$50/MWh charging cost** is likely quite high for off-peak power values in most North American regions. However, XE also used the $50/MWh charging cost assumption in its LCOE calculations to ensure that the LCOE analysis is an “apples-to-apples” comparison.

VPS Cycle Technology Risk Assessment

Every component of a VPS Cycle plant is already available "off the shelf" today from multiple, well-qualified manufacturers. Standard program logic control (PLCs) systems are used to operate and control the plant. These components have been deployed for decades at thousands of locations worldwide, and have a long track record of successful performance at power plants, industrial process plants and air separation plants, among other applications.

As such, the only significant remaining technology risk for the VPS technology is integration risk—i.e., deploying these components in a way that has not traditional been done, but not too different than how these components are used for the other applications mentioned above.

The subsections below explain why the technology risks of a VPS plant's main segments—the Inflow Mode, the Storage Tanks, and the Outflow Mode—are mitigated and manageable. The integration of those three elements does not require new science, new engineering methods, or any new or exotic equipment or materials.

1) Inflow Mode

VPS's Inflow Mode is akin to any air separation plant that produces industrial gases, of which there are thousands deployed world-wide. However, VPS Inflow is simpler because:

- There is no need to fractionate the air into its constituent components of nitrogen, oxygen, argon
- The stored liquid air (L-Air) in VPS is not as cold as the L-N2 and other products of air separation plants

As at air separation plants, VPS stores refrigerated air that is derived from ambient air, and from which the CO_2 and moisture have been removed by a **molecular sieve.** Mole sieves are ubiquitous in air separation plants and other gas processing facilities.

The main **air compressor** and the **compressor-loaded cryogenic turbo expander** in VPS are no different than those in air separation or LNG plants.

The optional **mechanical chiller** in VPS, used to provide moderate-grade refrigeration (pre-cooling), is of a standard design, with thousands of similar units deployed world-wide.

In short, the design, construction, and operation of the VPS Inflow Mode have less technical risk than air separation plants at the same scale.

2) Outflow Mode

VPS's Outflow Mode is **akin to steam cycles** at power plants, including at coal-fired power plants and the steam side of combined cycle power plants. All such systems use high-grade heat to boil a pressurized working fluid — water in closed-loop steam plants; air in the open-loop portion VPS as well as a secondary working fluid (an appropriate refrigerant) in a closed loop.

Steam cycles generally operate with pressures ending at less than atmospheric (a vacuum), which require specialized union operators. In contrast, nothing in VPS requires a vacuum or operators with special skills.

VPS's secondary working fluid loop is **akin to any ORC** system, or bottoming cycle, deployed at CHP facilities or where waste heat is converted to kW output. **Bottoming cycles** are well understood and use essentially the same components as the "topping" steam cycle.

The **pumps** used in VPS are similar to those used for steam cycles and ORC plants, but the VPS pumps are designed for the cryogenic conditions of the stored L-Air and for the counter-flowing refrigerant. Thousands of such cryogenic pumps are in use world-wide at air separation plants, LNG plants, LNG import terminals, and in the oil and gas industry where L-N2 is used for various purposes.

The various **heat exchangers** used in steam cycles and ORC plants have their equivalent in VPS, with the exception that the VPS heat exchangers are designed to operate at colder temperatures, just like those used in the thousands of air separation and LNG plants around the world.

The **generator-loaded, multi-stage hot gas expanders** in steam cycles and ORC systems have their equivalent in VPS. However, unlike steam cycles, VPS does not require water treatment, cooling towers or make-up water, which reduces CAPEX and OPEX/operational complexity.

In other words, the three main components of the VPS Outflow Mode — **liquid pumps, heat exchangers and generator-loaded hot gas expanders** — are not especially different from equipment used in existing steam cycles and ORC systems. All of the components will be provided by suppliers with deep experience in the manufacture and deployment of those components, with performance guarantees that are based on many years of successful operation.

3) Storage Tanks

The "link" between Inflow and Outflow Modes are the cryogenic L-Air storage tanks, and to lesser extent a single buffer tank for the ~~R410A~~ refrigerant. The L-Air storage pressure (about 500 psia) and storage temperature (about -230 F) is well within the capability of standard tanks. Nothing about those storage conditions requires new materials, new science or new engineering.

The stacking of those tanks (if necessary) requires no special structural considerations.

The interconnection of the tanks and the Inflow and Outflow equipment, through manifolds and piping, requires nothing more than routine "plumbing."

The insulation of the tanks, the manifold and the piping connections to the Inflow and Outflow equipment requires no special materials or engineering practices. Insulation of cold equipment is done routinely in many industries.

System Performance & Validation

Both the Inflow and Outflow Modes have been extensively simulated by four independent engineering firms using software such as HYSYS and CHEMCAD software. Those simulations have established the material and energy balances and have confirmed the thermodynamic validity of both the Inflow and the Outflow Modes.

The individual components tested by those software simulations were based on specific equipment manufactured by global equipment suppliers with deep track records, using data points for each component provided by the vendor.

Technology Risk Conclusions

Viewed in the context of the above, the limited and easily managed risks within the Inflow Mode are less than at air separation plants. The Outflow Mode risks are equally manageable, and are about the same as standard steam cycle plants and ORC power plants. There is virtually no technical risk in the Storage Tanks portion, as they have almost no moving parts and are standard cryogenic vessels. Thus, the integration risk of connecting and operating the three systems — Inflow, Outflow, and Storage Tanks — by way of a standard PLC system is no greater than any other integrated industrial process, including other thermal power cycles.

Case Study: 70 MW VPS^{TM} Cycle Project Overview

A large North American electric utility company asked Expansion Energy to design an approximately 70 MW VPS Cycle plant (preferably which would utilize high-grade waste heat from an existing GT) to enable the utility to achieve its mandate of adding > 200 MW of intermittent wind power into its power sourcing mix without sacrificing the reliability of its traditional baseload power sources.

As part of this utility's due diligence on the VPS technology, the independent firm of Audubon Engineering (Houston, TX; www.auduboncompanies.com) was commissioned to do a detailed technical review of the VPS technology for this particular deployment, analyzing such important factors as thermodynamics and energy balance; capital costs; operating costs; equipment/components availability; expected project lifetime; and other important matters. The results of Audubon's technical review are summarized in the remainder of this paper.

SNC-Lavalin (www.snclavalin.com) was selected by the utility client to serve as their Owners Engineer during that study to validate (or dispute) the Audubon findings and to suggest alternative methodologies as necessary. As part of its engagement as Owners Engineer, SNC-Lavalin also reviewed the findings presented in the remainder of this paper, and generally validated the work of Audubon presented herein.

Case Study Project Description & Objectives

The utility client's development plans were to design, construct, test and operate a grid-scale VPS Cycle plant with approximately **17 MW x 10 hours for the Inflow Mode** (charging) and **69 MW x 4 hours for the Outflow Mode** (discharging) capabilities.

The VPS technology was chosen over other LAES and non-LAES technologies because the VPS technology is expected to achieve a higher round-trip efficiency (RTE) of up to 95% and a lower heat rate of approximately 1,700 Btu/kWh.

One main purpose of the proposed project is to demonstrate technical and commercial viability of VPS LAES in enhancing the market competitiveness and economic viability of wind generation, by storing surplus wind energy during periods of low market prices or low demand, and releasing that energy during periods of high prices or high demand.

Relatedly, the VPS project will enable significant GHG emission reductions in two ways:

- The electricity generated by new wind generation enabled by the VPS project would displace electricity produced by existing fossil fuel generation (coal and natural gas). It is expected that by shifting this stored wind energy from low price periods to higher price periods, the VPS project would **enable an additional 200 MW of new wind generation** to proceed, as a result of higher market price revenue and improved economic viability—both enabled by the VPS asset. The resulting **GHG emission reduction is estimated to be 372,670 tonnes per year and 9.3 million tonnes over the estimated 25-year life of the VPS project.**

- The 69 MW of electricity produced by the VPS project would **reduce the need for fossil fueled peaking generation**, especially natural gas-fired simple cycle GTs. The resulting **GHG emission reduction is estimated to be 38,900 tonnes per year and 1.0 million tonnes over the 25-year life of the VPS project.** The proposed **VPS Project will emit approximately 0.089 tonnes of CO_2 per MWh** of electricity produced. This compares to about 0.65 tonnes per MWh of the generation displaced by the VPS project, based on the average grid emission factor typically used for GHG emission calculations in this region. Therefore, for each MWh produced, the VPS project will reduce CO_2 emissions by about 0.561 tonnes per MWh, **an 86% reduction of GHG intensity.**
- The combined reduction in CO_2 emissions from the above two categories is 412,480 tonnes per year and 10.3 million tonnes over the project life. Other than CO_2, no other GHGs will be emitted by the LAES Project.

On a **capital cost basis**, over the project's 25-year lifetime, the **cost per metric ton of GHG reduction is about $6.06/ton**.

On an **operating costs basis**, the project's annual **cost per metric ton of GHG reduction is estimated to be about $5.96/ton**.

Audubon Engineering's VPS Cycle Evaluation Tasks & Results

The specific Audubon Engineering tasks and findings for the above project are described in the remainder of this paper.

1. ***VPS (Inflow Mode & Outflow Mode) Simulation Modeling Verification.***

   Audubon independently analyzed and developed a simulation to model the design of the VPS process using Aspentech's HYSYS software. The model was developed from input provided by Expansion Energy, at the request of the client, to validate both the VPS Inflow Mode and the Outflow Mode. The purpose of the review was to substantiate the following from Audubon's independent evaluation:

   a. Confirm the Power input requirements for VPS's Inflow Mode
   b. Confirm the Power output from VPS's Outflow Mode
   c. Confirm VPS Heat Rate
   d. Calculate Round-trip efficiency % (RTE)
   e. Calculate VPS Total Conversion Efficiency / Thermal Efficiency
   f. Calculate expected CO_2 emissions

As per the developed models, Audubon confirmed the design basis and process modeling for the commercial VPS deployment. Audubon's analysis verified and developed consistent results for both the Inflow and Outflow Modes. Per the independent review, power input requirements, power outflow, heat rates, efficiencies, and emissions were all consistently achieved in Audubon's analysis.

Audubon confirmed that the VPS Cycle provides a reliable and predictable method to store power during off-peak periods and then re-deploy (discharge) the power during peak times. The basic premise is the liquefaction of air in the "Inflow" Mode and the release of the stored energy within the liquid air by re-vaporizing in the "Outflow" Mode. The driving factor to make the VPS Cycle economically viable is the conversion efficiency. Other technologies for power storage have a lower RTE range of 50% to 80%. Audubon's review and analysis confirmed that the VPS Cycle can achieve 90% or greater RTE, plus high conversion efficiency and thermal efficiency.

The following Inflow/Outflow sections provide an analysis of Audubon's results for VPS's efficiency.

Inflow Mode Evaluation

The basis of the Inflow Mode for this project is to produce approximately 136.9K lb/hr (224,000 gallons) of liquid stored at -230 F and 496 psia. This assumes a 10-hour inflow for storage. The Inflow Mode would operate during off-peak periods at night. The power requirements for the Inflow Mode were calculated per the following for the major power-consuming components:

Table 3: VPS Cycle Inflow Power Demand

Inflow Power Demand	MW
C1	2.28
C2	1.27
C3	3.75
C4	2.65
C5	3.24
C6	2.15
Booster Compressor	0.44
Fin Fan Coolers	0.50
Mechanical Chiller	0.57
Total	**16.9 MW**

Outflow Mode Evaluation

Using the amount of liquid air produced during the Inflow Mode as quantified above, two power release scenarios were evaluated for the Outflow design:

- **171,000 lb/hr of liquid air outflow over an 8 hour period, 5-days**
- **479,000 lb/hr of liquid air outflow over a 4 hour period, 5-days**

The liquid air created in the Inflow Mode is used as stored energy. The Outflow model predicts the expected energy recovery through the use of expansion and heat cycles with R410A, a common refrigerant, in the closed loop ORC portion of the Outflow Mode.

The power outputs for the two outflow scenarios are calculated per the following:

Table 4: VPS Cycle Outflow Capacity

	479,000 lb/hr (4 hour)	171,000 lb/hr (8 hour)
E2 Power Output	95,896,714	34,250,234
E1 Power Output	73,768,432	26,346,952
E3 Power Output	38,997,876	13,927,589
E4 Power Output	30,310,348	10,832,360
P2 Power	-1,420,529	-510,707
P3 Power	-1,192,983	-426,059
P1 Power	-1,569,149	-560,434
Total (BTU/hr)	**234,790,708**	**83,859,937**
Total (MW)	**68.8 MW**	**24.6 MW**
MWH	**275.2 MWH**	**196.8 MWH**

The **round-trip efficiency (RTE)** result for the VPS Cycle in this configuration was **72%** when there is **no waste heat input,** but approximately **95%+ where waste heat at about 1,000 F is available, for example from a GT**. Other RTE values in between can be achieved depending on the amount and the grade of waste heat available. **Audubon therefore confirmed that the VPS design is extremely efficient for power recovery** as per the developed and confirmed design.

2. *Industrial Equipment Selection and Viability*

In review and validation of the process design for the VPS Cycle, Audubon performed a preliminary evaluation of the equipment required for this ~ **70 MW VPS deployment** per industry standards and practicality. The main components of the VPS system were broken out in the following major equipment categories:

- Fin Fan Coolers
- Inflow Compressors (6 stages required)
- Molecular Sieve
- Heat Exchangers (brazed aluminum, shell & tube, plate & frame)
- Mechanical Refrigeration
- Hot Gas Expanders, Generator-loaded
- Compressor-loaded, Cryogenic Turbo-Expander
- Cryogenic Liquid Pumps
- Cryogenic Storage Tanks

Audubon confirmed that all of the components and sub-units within the VPS system are common industrial equipment within the power and gas processing industries. All individual equipment and subsystems can be readily purchased and manufactured in North America and are available for supply. All of the individual components and subunits are proven technology and currently in operation in industrial facilities. The prime mover efficiencies are in-line with industry standards of 70-85% for design efficiencies.

Similar CHP and ORC systems and equipment are commonly deployed with a wide range of refrigerants acting as working fluids. Potential cost and operational efficiencies may be achieved through other commercially available cooling mediums. VPS's counter-flowing refrigerant can be selected from a wide array of evolving refrigerants, none of which are ozone-depleting.

The overall facility utilizing the VPS Cycle is predicted to deploy a modular design approach. Manufacturing and designing the equipment and process subunits in a controlled fabrication area allows for overall superior quality and reduction in construction costs. The anticipated market manufacturers that Audubon would recommend all provide modular solutions. The main engineering contactor would also implement a modular approach to consolidate the equipment into discrete packages for expedited site installation.

3. ***Confirm That Daily Start-up and Shut-down of Both the Inflow and Outflow Modes Is Viable.***

   The Inflow and Outflow Modes operate for limited durations during each 24-hour period. As noted above, the Inflow Mode operates during off-peak times at night, and the Outflow Mode operates at peak times, typically during the day. Because of the somewhat intermittent operation, startup & shutdown feasibility of the facility is critical to the viability. Audubon advised that the Inflow system can be expected to be readily turned on and off with minimal operational issues due to the main component being the electric-motor driven 6-stage air compressor. Audubon also advised that the mechanical chiller and liquid air storage could avoid a short cool down period by keeping residual liquid-air in the system and through optimal insulation of all heat exchangers, pipes and other components. The liquid air is stored in a double wall, vacuum jacketed bullet tank(s). A cool-down period would be required as part of the Inflow Mode's start up and as a precursor for full operation of the Inflow Mode. Because of the use of air as the main fluid, any residual amounts can be easily vented to the atmosphere with no environmental impact.

   Audubon determined that the Outflow Mode would also predictively require minimal startup and shutdown time. The Outflow component requiring the longest startup period (but which can still be measured in minutes) is the pre-start and circulation of the R410A refrigeration system, which would be in a liquid state in a moderately sized buffer tank. The R410A loop is closed and associated equipment would need to be circulating before the liquid air is heat exchanged against the R410A stream. However, because R410A is a liquid at ambient temperatures and moderate pressures, and because it can be sub-cooled, it can be stored at an optimal pressure and temperature, ready for its role in the next Outflow sequence.

4. ***Confirm That Expansion Energy's VPS CAPEX Budget Contains All Major Components and Reasonably Estimates the EPC Services and Other Expenses That Will Be Required to Permit and Build the VPS Plant.***

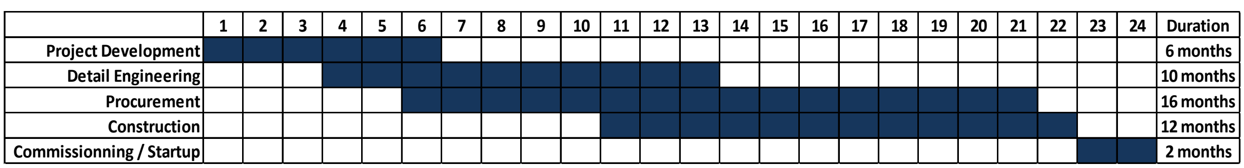
   Utilizing in-house and industry indices for equipment and material pricing, Audubon performed a high level review of the estimated CAPEX budget and applied cost sensitivities and variables to each major line item. Audubon currently designs industrial facilities in-house and purchases third party equipment of the same type that makes up the VPS Cycle design. Based on Audubon's in-house experience and project data, the VPS CAPEX evaluation was performed.

The CAPEX estimate utilized Expansion Energy's component line items and cross referenced those components with Audubon's in-house costing data. A low and high range was applied with a line item cost sensitivity percentage to each line item. The results concluded that Audubon's preliminary estimate was in-line with Expansion Energy's VPS capital cost estimate—**approximately $70 million** (all in) or ~ **$1,000/kW of Outflow capacity**. The equipment and material had less variability, with the construction portion having the largest risk and cost unpredictability due to the project being in preliminary design stages, and considering that construction costs can vary significantly from region to region. For that reason, Audubon recommends shop-fabricating as much of the project content as possible, to reduce and control costs.

5. Project Timeline

If field-erected using a traditional construction approach, the project's development & construction period is estimated at approximately 24 months. A project development stage of approximately 6 months would be utilized to finalize the design basis and optimize the VPS design for the commercial deployment. Detailed engineering would commence approximately midway through the development phase with a duration of approximately 10 months. Procurement durations and project critical path would be dictated by the long lead equipment including the compressors and expanders.

Figure 4: VPS Cycle Project Development Timeline



However, **if a modular design and maximizing shop fabrication are utilized**, the construction is estimated to shrink to **12 months, with a 2 month commissioning and startup period**.

6. Project Lifetime

Audubon's standard design criteria for the equipment, materials of construction and engineering designs for a project of this nature are for a **30 year life cycle.** Recommended O&M and preventative maintenance best practices should be followed for minimum downtimes and optimal operational efficiencies, as well as prolonging equipment life. The proposed equipment and material for a VPS Cycle plant have been readily installed and currently operated worldwide in many industrial environments and for many applications.

Key Findings & Conclusions

Expansion Energy's VPS Cycle technology is quite distinct from other energy storage systems (including other LAES energy storage systems) and from other types of combined cycle generation systems as a result of VPS's patented elements, including (but not limited to) its novel use of **a unique ORC bottoming cycle** which has a **delta-T that is far wider than other ORCs** and which therefore **performs significantly more work and produces/releases substantially more power**.

These VPS distinctions yield **higher RTE** (up to 90% or more) **than most other energy storage systems**, as well as a significantly **higher thermal efficiency and lower heat rate** (1,710-4,500 Btu/kWh) **than other types of thermal power generation systems**, including standard combined cycle power plants (CCPPs). This means that VPS plants will have significantly lower GHG emissions per MWh than other thermal power systems. The fact that the VPS combined cycle **does not consume water and does not require cooling towers** lowers its environmental footprint even further versus other thermal power systems.

In addition to its efficiency advantages and environmental benefits, the VPS Cycle can be built for **lower CAPEX per kW and kWh than most other energy storage systems or standard combined cycle power plants**; and for about the same CAPEX per kW of capacity as a GT peaker plant. This translates into significantly **lower CAPEX per kWh vs. GT peakers, CCPPs or other energy storage systems**. The $/kWh metric is much more important than the $/kW metric for "bulk," long-duration energy storage systems and for utility-scale power systems, which VPS is designed for.

As a result of the above distinctions and advantages, the **LCOE calculated for the VPS Cycle is substantially lower than all other energy storage systems** (CAES, pumped hydro, lithium ion batteries, flow batteries) to which VPS was compared, and **also much lower than GT peaker plants**.

Many of the above VPS advantages were validated by the 70 MW commercial case study described in this paper. For example, in the 70 MW case study, the VPS Cycle's **CAPEX** was estimated to be about **$70 million**, or ~**$1,000/kW**, which is similar to most GT peaker plants even though **VPS offers much greater efficiency and total value**.

These VPS CAPEX findings also confirm that VPS plants will have **substantially lower CAPEX on a $/kW basis than standard combined cycle power plants**, while delivering a significantly **higher thermal efficiency**—**72% for VPS vs. 55-60% for a standard CCPP**).

As a result of the evaluations presented herein and other completed and ongoing work, the VPS Cycle technology is increasingly being established as a **cost-effective energy storage technology covering a wide range of scales and applications**, and as a **next-generation combined cycle power plant with low/manageable technology and construction risk**. Indeed, because VPS can be **shop-fabricated as modules and deployed cost-effectively at substantially smaller scales than standard**

CCPPs (which typically are field-erected with greater construction cost variability), the VPS technology can have somewhat lower construction risk versus CCPPs, **can be built and deployed more quickly, and are suitable for smaller, distributed generation needs and opportunities** which are becoming more common in the power generation industry today.

All of the above factors also increase the likelihood that the **VPS technology will support the broader deployment of intermittent renewable energy** such as wind and solar power, both by being able to "absorb" and utilize surplus renewable power generated in low-demand periods and by being able to ramp up quickly to serve the grid when those intermittent renewable power sources are not producing during high demand periods, such as on calm or cloudy days.

Contact Information

Interested parties are invited to contact Expansion Energy LLC for more information on the VPS Cycle technology. Confidential information regarding the content of this paper may be disclosed after signing a mutual non-disclosure agreement (NDA).

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