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Engineering and Cost Study of an Offshore Wind Farm Compressed Air Energy Storage System

William Hurley
Hurley Maritime Consulting
Seattle, WA USA
wlhurley01@gmail.com

Alan Orthmann
Glosten, Inc.
Seattle, WA USA
ajorthmann@glosten.com

Paul Lieberman
Lieberman Research Associates
and EnisEnerGen LLC
Henderson, NV USA
lieberman.lra@gmail.com

Ben Enis
EnisEnerGen LLC
Henderson, NV USA
benenis@cox.net

ABSTRACT

This paper presents an engineering and cost study investigating a novel concept for combining a compressed air energy storage system with an offshore electrical substation serving a deep-water floating offshore wind farm. The study investigates a solution that combines existing offshore technologies with emerging compressed air energy storage (CAES) systems seeking synergies with wind farm energy production, higher efficiencies and lower levelized cost of storage. A cost analysis is presented including a worked model of an economic comparison between this offshore CAES system and electro-chemical (Li-Ion) battery storage. A variant of the Levelized Cost of Storage (LCOS) comparison metric is presented.

Keywords— Compressed Air Energy Storage, CAES, Offshore Wind, Floating Substation, Turret Mooring, Levelized Cost of Storage, LCOS

I. INTRODUCTION

Energy storage is now universally recognized as an important supplemental capability to the renewable energy sources of wind and solar. These renewable energy sources are intermittent and benefit by having integrated energy storage to better manage how electricity is provided to the electrical grid. Storing available energy during off-peak periods of low demand and providing that stored power during peak high-demand periods, or when the market prices are higher, is one of many benefits provided by a storage system. Energy storage helps wind and solar become more like baseload energy systems.

Offshore wind farms are being installed worldwide at a rapid pace. Costs have dropped rapidly thanks to innovation and competition. There is growing interest in deep-water wind: the next-generation of offshore wind where floating turbine foundations provide access to better wind quality further from shore, and site selection is not restrained by the maximum water depth practical to build bottom-fixed turbine foundations.

Commercial interest in energy storage systems for wind farms is also building. The initial storage type selections are tending toward electro-chemical, or battery, as lithium-ion (LI) battery technology is advanced and reliable systems can be built today. Norwegian company Equinor teamed with Masdar and have developed Hywind Scotland, a 25MW pilot wind farm of floating spar platforms near Peterhead off the east coast of Scotland, and they are prototyping a battery storage system termed “Batwind.” The shoreside battery bank capacity is small at 1MW and 1.3MWh, but the primary purpose is to develop software that “will incorporate various data sources including weather forecasting, market pricing, maintenance, expected consumption data and how, when and if to provide grid services [1].”

Danish company Orsted is looking at a 55MW and 110 MWh battery storage facility for their bottom-fixed 800MW Bay State wind farm currently under development off the coast of Massachusetts in the US. This would be the largest combined wind/storage plant in the world [2].

Compressed Air Energy Storage (CAES) is a viable alternate to battery storage and may well be preferable over the long term.

This paper investigates the technical and economic feasibility of an offshore CAES system supporting an offshore wind farm. This investigation is conducted by engineers working towards the practical application of CAES technology with a platform design concept. Ship and platform design expertise is applied to develop a practical concept based on sound naval architecture and marine engineering principles and practices. The synergies from combining a CAES system with a floating offshore substation, moored in deep water and serving a floating wind farm, are evaluated. In addition to sharing the floating platform’s support structure, the CAES system benefits by using the seawater as a heat source during the expansion / power generation cycle, and the system provides energy for platform services using the waste heat from the compression cycle. The platform also utilizes the CAES cold air exhaust for cooling transformers and other electrical equipment, as well as cooling accommodation spaces.

The Transportable CAES system concept (T-CAES) developed by EnisEnerGen [3] is applied in an initial engineering design cycle to obtain first indications of performance and cost. Steel pressure vessels are installed on the platform and store the compressed air.

The paper concludes with a cost comparison to a shoreside LI installation of the same energy capacity.

II. Substation Platform with Integrated Energy Storage

A. *Substation Description*

The offshore substation is the central electrical hub for an offshore wind farm. Array cables from the turbines run on the seabed and are pulled up to the station where they terminate and power is transformed to a higher voltage, typically from 33kV or 66kV to 138kV). Power is then fed to one export cable that runs from the station back to the seabed and on to the onshore substation where it is connected to the grid. Offshore substations both stabilize and maximize the power generated and equipment includes switchgear, protection and control components, and a transformer to provide power to the station services. In current bottom-fixed shallow water (less than 50 meters) wind farms have one or sometimes two offshore substations mounted on large monopiles or jacket structures and fixed to the bottom [4].

Fig. 1 – Substation installed on a platform at the Baltic Sea 2 offshore wind site (Credit: Alstom/GE)

B. *Floating Platform with Turret Mooring*

As deep-water floating offshore wind farms are today entering pre-commercial stage, concepts for floating offshore substations are starting to be conceived. A deep-water floating substation presents particular challenges:

- dynamic power cables are needed, designed to be suspended in the water column and be flexible to accommodate the motions of the platform
- the platform mooring system needs to avoid clashing with the many power cables entering the platform
- electrical equipment design needs to consider the motions and accelerations that will be encountered on a floating platform

To address these challenges, a turret-mooring system and a large floating pontoon, non-self-propelled, is proposed to be the substation platform. Turret moorings, developed by SBM Offshore and others, have served the offshore oil and gas industry for many years. Their principal application has been to Floating Production Storage and Offloading (FPSO) facilities, where pipelines feed oil from the wells in a field to the turret and onto the platform where it is processed, the product is stored, and then offloaded to tankers for export delivery.

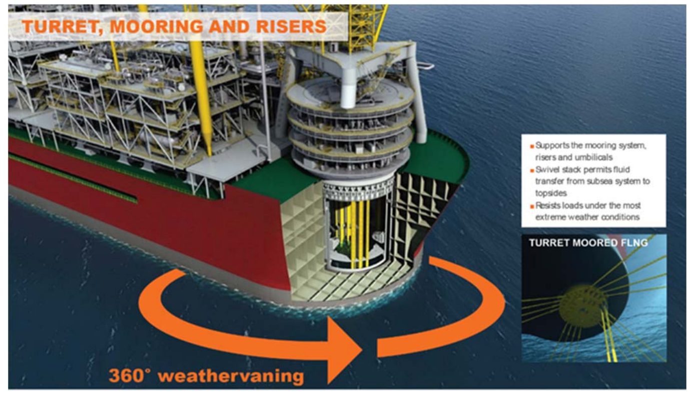

Fig. 2 –FPSO on a turret mooring – Courtesy of SBM Offshore

Fig. 3 – Cantilevered Arm with Turret – Courtesy of SBM Offshore

Turret moorings allow the platform to swing around the turret to face into the wind and waves, and the turret remains relatively stationary with a spread mooring system. Oil is transferred through the turret using swivel couplings; electrical power is transferred using electrical swivels, traditionally known as slip rings.

Substation equipment manufacturers will need to consider new design requirements for installing their electrical equipment on a floating platform subjected to motions, accelerations and that is closer to the water surface than they are accustomed to. Their standard equipment will need some "marinization," however excess freeboard and enclosed superstructures can be provided, and standards implemented that apply typical installation engineering and design used to install sensitive electrical equipment in complex ships that transit the globe in all weather conditions.

Turret moorings have the advantage as the bow is always headed into the wind and waves, hence platform motions are primarily pitch and heave with roll motions largely avoided.

C. Integration with Energy Storage

The floating offshore substation platform provides the opportunity to integrate the CAES Submerged Tank System (CAES-STS) on the same basic hull. A variety of pressure vessel (tank) configurations were investigated to find the best approach to integrate the tanks with the hull. One end of the tank needs to be in a dry, accessible space so the access hatch, valve connection, sensor connections, drain connection and all other fittings are located near one end of the tank, and the rest of the tank is submerged. The preferred solution was to orient the tanks vertically, with the end of the tanks extending into an inner bottom structure under the basic hull. See Fig. 7.

The inner-bottom structure module is fabricated separately from the hull by a manufacturer skilled in high-pressure compressed air piping, and the tanks are welded to the module which in turn is attached to the bottom of the hull structure. The submerged tanks add buoyancy to the overall platform, and although the tanks have a net weight when submerged (weight exceeds buoyancy), the combination of the tanks and the inner bottom module provides net buoyancy and the freeboard of the platform increases by 1.7m (5.6ft). This is a positive contribution to the integrated platform.

The platform size selected for this study considers the typical fabrication capabilities of medium sized shipyards around the world, recognizes the heavy-weather environment it will operate in, and also seeks to maximize total compressed air capacity all within a reasonable cost-effective envelope. This results in a platform with adequate deck area for both the substation modules and the compressed air system machinery.

As a result of the integration, the complete power management system can take place on the platform avoiding the need for a separate, independent stored energy facility on shore. All power, whether direct from the turbine or from the stored energy system or a mix of both is managed and fed to the export cable which terminates at a small onshore substation for grid connection.

D. Pressure Vessel Design and Procurement

Pressure vessel manufacturers were solicited in the US and China to determine the most practical and cost-effective tank solution. The intent is to maximize the surface area/volume ratio to maximized heat transfer efficiency. For cylindrical tanks this ratio changes linearly with diameter, increasing with decreasing diameter. Smaller diameter tanks are more efficient for heat transfer.

In order to be installed on an offshore platform the tanks must meet the ASME Pressure Vessel Code and be certified and tested. A corrosion allowance of 20% on shell thickness was specified, as well as coatings for seawater immersion and external pads for the attachment of cathodic protection anodes.

It was found that tank fabrication facilities are typically limited by total weight of the tank, for handling at the factory, and in some cases by overall length. Ultimately a tank design from Wuxi Lanxing Pressure Vessel Co., Ltd., of Wuxi City in Jiangsu Province, China, was selected. They proposed a tank that could fit inside a standard 12.2m (40ft) long ISO container and meet the container weight limitations to allow standard and low-cost shipment from the tank fabricator to any location.

Tank characteristics are listed as follows.

Material:	SA516 steel
Inner diameter:	2000mm (6.56ft)
Total Length:	10.95m (35.93ft)
Shell Thickness:	75mm (2.95in)
Hemisphere thickness:	50mm (1.97in)
Internal Volume:	31.3 cu m (1,152 cu ft)
Weight:	40,000 kg (88,200 lbs)
Cost:	$120,000 per unit

There is the potential for marine growth on the tank walls that would negatively impact the heat transfer coefficient relied on for system efficiency gains. However there have been recent developments in robotic, submerged hull-cleaning mechanisms that could be adapted to continually clean the exterior of the tanks. Compressed air enters the tanks at 50°C and then cools to the ambient seawater temperature. The tank walls cool further as the air is discharged. These temperature variations in the tank wall will help reduce marine growth.

E. Platform Description

The platform is arranged with the substation modules aft and the CAES machinery forward. Other modules include an accommodation block, control center and communication equipment. The platform is designed to accommodate wind farm technicians stationed on the platform to support and maintain the turbines, as well accommodating operating engineers running the substation and energy storage system from a centralized control room. Ultimately the substation and energy storage system can be operated remotely from shore with the platform un-manned, but the initial intent is to provide comfortable accommodations for personnel to be stationed offshore.

There are a variety of wind farm maintenance strategies being explored currently in the industry, and one includes a large offshore vessel stationed at the farm supporting technicians to provide continual turbine maintenance. The floating substation / CAES system platform could serve this role. Boat access arrangements are provided at the stern for personnel access. Connection for an articulated boarding ladder is also provided, deck cranes for loading and off-loading equipment, and a helicopter landing area is provided forward.

The platform principal characteristics are:

Length, overall, hull	136m (447ft)
Beam, overall	40.2m (132ft)
Depth, hull only	10.7m (35ft)
Depth, overall	19.9m (65.4ft)
Draft, operating, overall	12.9m (42.4ft)
Freeboard, to main deck	7.0m (23ft)

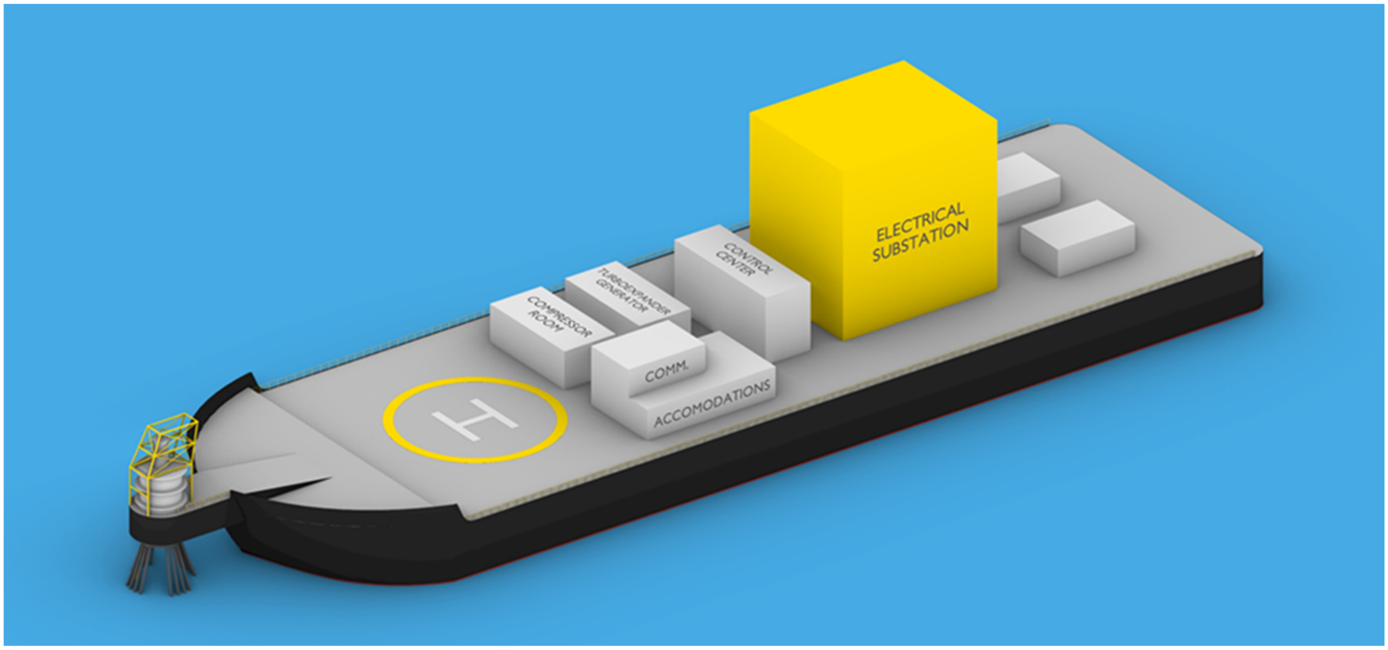

Fig. 4 – The Substation Platform with Integrated Energy Storage

The platform mooring system utilizes the turret style mooring system (Fig. 5) and is designed to withstand severe storm conditions and survive a 100-year event. In areas that experience typhoons and hurricanes the design criteria will be developed accordingly.

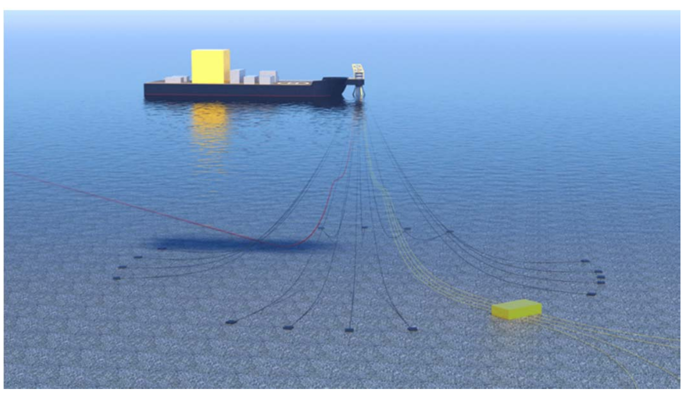

Fig. 5 – The turret mooring spread showing array and export power cables

The submerged tanks are arranged as follows:

- Tank Configuration: 10 across by 30 lengthwise for 300 tanks, arranged in 20 banks of 15 tanks
- Tank Spacing: 3.66m (12.0ft)
- Tank Area: 110m long x 36.6m wide (360ft x120ft)

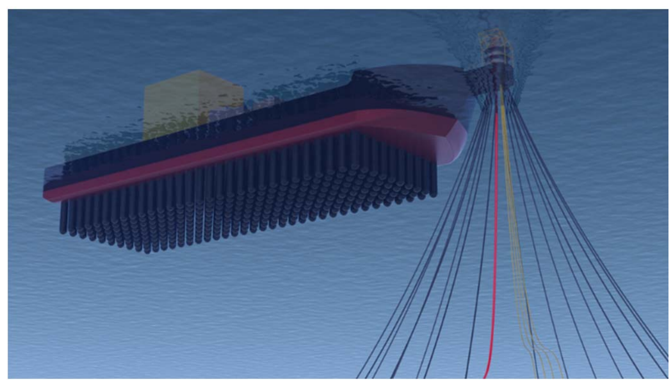

Fig. 6 – Underwater view showing submerged compressed air tanks

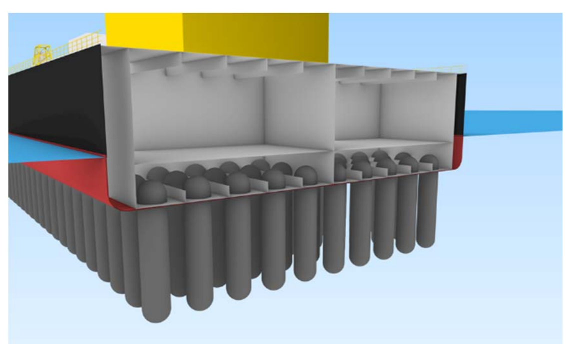

Fig. 7 – Cutaway view showing inner bottom tank spaces

III. CAES System

A. Description

The CAES Submerged Tank System (CAES-STS) is similar to the traditional CAES except the geological storage cavern of an aquifer, salt cavern or hard rock storage reservoir is replaced by steel pressure vessels. The STS total volumetric storage capacity is very small compared to typical caverns and although stored pressure is higher, the STS standard cubic volume available is only 667,328 SCM - 4.6% of the Huntorf facility with 14,373,688 [5], for example.

The STS provides some distinct advantages realized during the expansion process: 1) cleaner air than cavern storage, for improved turboexpander operation, and 2) a drier air provided by the higher pressure.

The compression cycle employs a waste heat recovery system which is utilized to support the platform's energy needs such as accommodation heating, accommodation hot water, fuel oil heating and steam production for the generation of ship's service electricity. Waste heat recovery systems are very common on ships and standard commercially available systems are considered.

Additionally the waste heat supports a Thermal Energy Storage (TES) system to heat the air during expansion process. No specific TES is identified but there are many options presented in literature that are being researched, Houssainy [6] and Garvey [7], among others.

The expansion cycle is fairly traditional where the inlet air is preheated by the TES. There is the potential for adding an external heat source to build heat in the TES.

The STS benefits from the ability of the submerged tanks to draw heat from direct contact with the seawater. Warm seawater is continuously supplied by tidal current and water flow from induced convection. The repeated performance of the compression/expansion cycle depends on the return of initial pressure/temperature conditions after each cycle. This return to initial conditions after each cycle is the result of the water/steel interface contact and its very highly efficient heat transfer by direct contact with water. This heat transfer warms the tank air during the expansion cycle as they exhaust from 1,200- to 200-psig steadying the electrical power output from the turboexpander/generator set and adding efficiency of the overall system.

It is important to consider the wind turbines, substation and CAES-STS system all part of one integrated energy system. The substation energy needs are fed by turbine power although the station has diesel generators as backup. Waste heat from the CAES system supports substation services, including electrical power from a steam turbine generator, although that electrical power could also be fed back to the substation for export. There is a myriad of power-sharing and power-management scenarios and a well-designed system will optimize overall power utilization and energy efficiency.

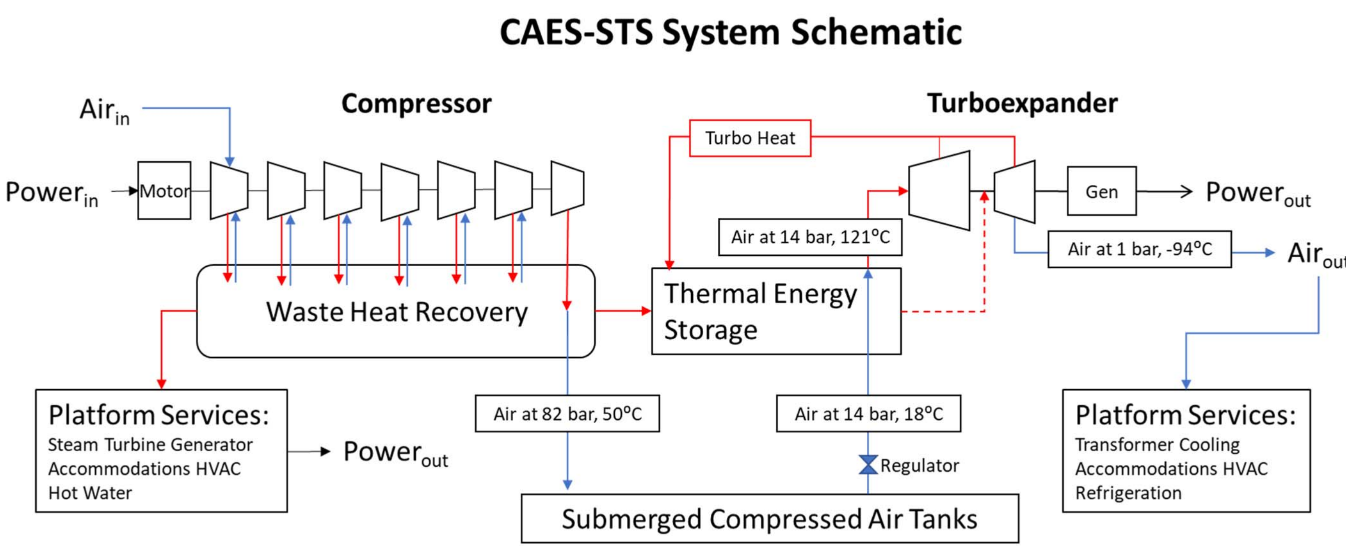

Fig. 8 – CAES-STS System Schematic

B. Multi-Stage Compressors

A multi-stage reciprocating compressor takes input power from the wind farm array during periods of high energy production and low grid demand. The energy draw for air compression is only about 0.5% of the rated capacity of an 800MW wind farm, and the system concept developed takes about 32 hours to reach full charge from the discharge level, so it may prove practical, and desirable, to charge the system while providing energy to the grid.

The multi-stage arrangement primarily allows heat to be removed and recovered between each stage of compression using intercoolers. This both improves the compressor efficiency by reducing the work of compression required, as compression is near isothermal, and allows progressive heat recovery throughout the compression process. Heat recovered between each compressor stage is primarily stored as thermal energy, to be later used during the expansion/power generation process. Heat recovered can also be utilized for platform services.

The multi-stage arrangement also reduces the compression ratio of each stage, minimizing the mechanical loading on the compressor. In a remote, offshore environment, this configuration should improve maintenance and service costs, and ensure a more reliable machine.

For this system concept we have considered two compressor options: 1) one 7-stage compressor or 2) three compressor lines. The latter provides redundancy and flexibility in power demand and charging duration. Each compressor line consists of one primary 3-stage centrifugal compressor and two reciprocating booster compressors. With all 3 compressor lines powered up the system is rated at 4,650kW and 20,899 SCMH (12,300 SCFM).

C. Turboexpander-Generator

A turboexpander-generator runs the compression process in reverse, receiving compressed air and expanding it through a turbine to generate power. Turboexpanders are used in a variety of industries, for gas production and separation, refrigeration, and power generation. The CAES-STS would utilize a turboexpander configured for power generation. A two-stage turboexpander-generator is needed for the pressure change considered (14 bar to 1 bar). Expansion where the input to output ratio exceeds 4:1 can result in boundary layer separation at the turbine impeller vanes, reducing efficiency and potentially damaging the assembly. The first stage reduces the air from 14 bar to 3.5 bar, the second stage from 3.5 bar to 1 bar, or atmospheric pressure.

The two turbines are connected to a single output shaft that runs a synchronous generator. Turbine speed is typically higher than required generator input speed, so the turboexpander typically connects to the generator through a reduction gear.

Turboexpander efficiency increases with input air temperature, benefiting from preheating air or reducing the loss of heat from the stored air to the surrounding environment during expansion.

D. CAES Capacity

The design point for the CAES-STS for the purposes of this paper is 6.4MW output power and 40 MWh capacity. Generator output power can be selected based on grid demand characteristics, but the 40MWh capacity is set by the total storage capacity, turboexpander efficiency, and generator efficiency.

E. Thermodynamic Efficiency of the Submerged Tank System

As compressed air stored in ambient air conditions is expanded, in a near-isentropic process, the temperature decreases. The thermodynamic efficiency of a turboexpander depends on incoming air temperature, and the efficiency decreases with decreased temperature. The air supply from CAES to a turboexpander generator must therefore be heated to improve the equipment performance. A plot of turboexpander volume/power efficiency is provided in Fig. 9.

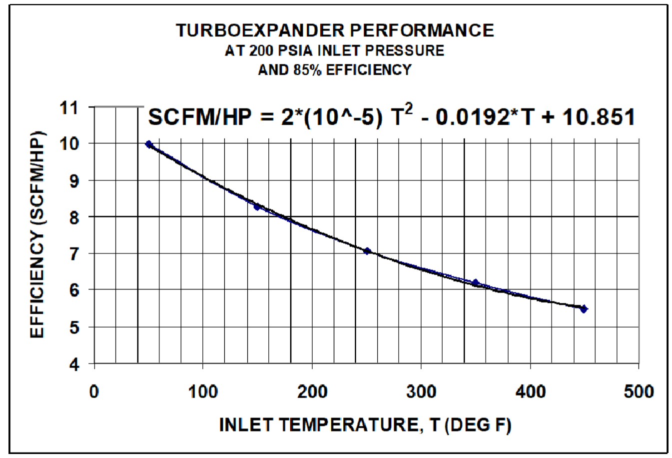

Fig. 9 – Temperature vs. Turboexpander Volume/Power efficiency

Compressed air storage tanks located in ambient air cannot absorb heat from the surrounding environment at a sufficient rate to control the internal compressed air temperature. Vessels located in ambient air are also subject to day-to-night temperature swings that results in an irregular temperature output from the storage tank.

The CAES-STS configuration submerges the storage vessels in seawater, where the air supply can benefit from a high convective coefficient between the seawater and storage tank surface. The positioning of the CAES-STS in open water also provides current flow over the pressure vessels, increasing the convective coefficient further and ensuring the surrounding environment does not stagnate and reduce in temperature as the stored air temperature drops during expansion.

A simple time sequence analysis comparing temperature behavior of storage tanks in ambient air and seawater was developed to determine the energy benefit from the CAES-STS configuration. The expansion of air and resulting temperature decrease for each time step is assumed isentropic. Fixed convective heat transfer coefficients are assumed for ambient outside air to tank wall and seawater to tank wall, while a density-dependent heat transfer coefficient is assumed for tank wall to internal compressed air. The analysis does not account for daily and seasonal air temperature variations; ambient seawater and air temperatures are assumed equal.

The analysis was performed for the following environmental temperatures, which vary depending on the surface seawater temperature associated with the wind farm site.

- 21°C (70°F), representing a semi-tropical STS installation
- 18°C (65°F), representing a Taiwan or Korea installation
- 13°C (55°F), representing a North America or Northern Europe installation

The in-water and in-air temperature results for 13°C (55°F) environmental temperature are plotted in Fig. 10.

The analysis indicates that submerging the tanks in seawater rather than open air has an appreciable effect on the internal air temperature. The final in-water internal tank temperature was approximately 5.6°C (10°F) higher than the in-air tank temperature.

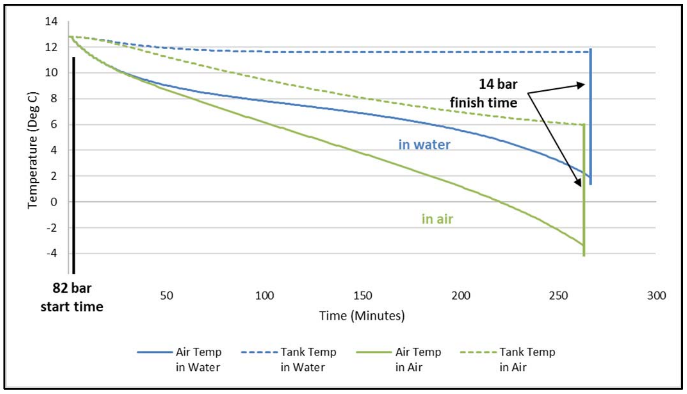

Fig. 10 – Internal air temperature for storage tanks submerged in water vs. air, 13°C (55°F) ambient

Average turboexpander efficiency and overall thermodynamic efficiency values for the considered environmental temperatures are provided in Table 1.

TABLE 1 - V/P AND THERMODYNAMIC EFFICIENCIES, IN-WATER VS IN-AIR STORAGE

Ambient Temp	*(°F)*	70.0	65.0	55.0
	(°C)	21.1	18.3	12.8
Volume/Power Ratio				
In Water	*(SCMH/kW)*	22.3	22.5	22.9
In Air	*(SCMH/kW)*	22.5	22.7	23.0
Thermodynamic Efficiency				
In Water	*(%)*	29.7%	29.4%	28.9%
In Air	*(%)*	29.4%	29.2%	28.7%

The air is pre-heated by the Thermal Energy Storage unit to achieve 121°C (250°F) at the turboexpander inlet before entering the turboexpander. The impact of the submerged tanks on the required heat recovery energy is provided in Table 2.

TABLE 2 - REQUIRED HEAT RECOVERY TO ACHIEVE 121 °C (250 °F) AT THE TURBOEXPANDER INLET

Ambient Temp	*(°F)*	70.0	65.0	55.0
	(°C)	21.1	18.3	12.8
Heat Required				
In Water	*(MW-hr)*	23.2	24.0	25.6
In Air	*(MW-hr)*	23.6	24.4	26.0

While the internal temperature for in-water tanks was maintained at a higher level due to improved heat transfer from the environment, the volume/power ratio and required heat recovery were not reduced significantly. As indicated in Fig. 8 a temperature increase of ~5.6°C (~10°F) reduces the volume/power ratio by less than 2 percent. For comparison, a temperature increase of 111°C (200°F), to the turboexpander inlet design temperature of 121°C (250°F), reduces the volume power ratio by 27 percent.

Similarly, the in-water temperature only reduced the heat recovery required to achieve the inlet design temp by ~0.4 MWh for each environmental temperature condition, or less than 2 percent.

For an installation with waste heat recovery/pre-heating to 121°C (250°F), submerging the storage tanks in seawater does not appreciably increase the storage system's energy output, nor does it appreciably increase the system's thermodynamic efficiency.

This result calls to question the value of submerging the tanks. It would of course be possible to enclose the tanks in the hull, as shown in Fig. 11, but this may have a higher capital cost than the exposed tanks. A careful trade-off study could be conducted to determine preferred design.

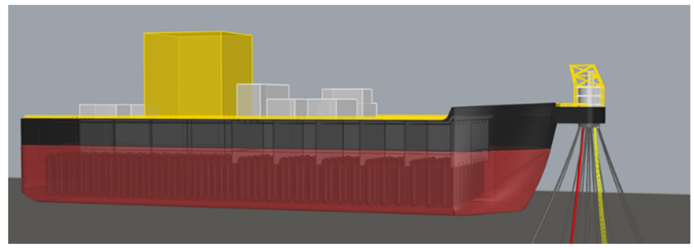

Fig. 11 – Platform option with tanks enclosed inside the hull

IV. LEVELIZED COST OF STORAGE

There are various metrics for comparison of storage technologies. This study applies a Levelized Cost of Storage (LCOS) metric to compare the CAES-STS system with a Lithium-Ion (LI) battery storage system installed on shore.

LCOS is calculated for the specific CAES-STS system described in the earlier sections with a LI system of the same energy capacity.

This analysis borrows from a Levelized Cost of Energy (LCOE) model developed by the United States Department of Energy for offshore wind energy comparisons [8]. Equation 1 is the LCOE formulation, which uses a simple capital recovery factor. The capital recovery factor (CRF) is defined in Equation 2, and accounts for the return on investment (cost of capital) and project lifetime.

To transfer the LCOE model to a LCOS model the cost of the energy that the storage system "buys" from the wind farm is included in the cost. By adding this cost all the operating efficiencies of the system are accounted for on a cost basis.

$$(1)\ LCOS = \frac{(ICCxCRF) + O\&M + COE_{wf}}{AEP_{net}}; \text{ where}$$

LCOS is levelized cost of storage in $/MWh
ICC is initial capital cost (CAPEX)
CRF is the capital recovery, defined in Equation (2)
O&M is the annual operations and maintenance cost in $
COEwf is the annual cost of the energy from the wind farm
AEPnet is the net annual energy produced from storage, after losses and availability

$$(2)\quad CRF = \frac{ROIx(1+ROI)^N}{\{(1+ROI)^N-1\}}\text{; where}$$

CRF is the capital recovery factor
ROI is the average annual return on investment (%)
N is the project life in years

Another LCOS calculation method has been proposed by the World Energy Council [9] which has some minor differences. Their method does not include the COEwf factor but they do state it could be included.

Including COEwf in the LCOS model is consistent with the wind farm LCOE cost model assumption that whatever energy is being produced will be purchased, and there are no market forces at work. The Annual Energy Production (AEP) in the offshore wind LCOE estimates energy production based on wind characteristics, quality and turbine availability and does not include market demand. Directing wind power to generating storage capacity may need to occur concurrently with market demand from the grid, hence the value of building storage needs to be on par with the revenue provided from the grid. Generating storage when there is low market demand will help preserve the wind farm LCOE model.

Storage technology comparison needs to consider the different Energy to Power (E2P) ratios that are specific to each technology. E2P is essentially the duration of discharge of the full energy capacity, in hours, set by the either the generator size or inverter size. CAES tends to have an E2P ratio of 6 [9], (the STS has a 6.27 E2P) while lithium ion (LI) systems range from 1 to 4 [9] (the Bay State Wind example has a 2.0 E2P). Since LCOS is cost of energy delivered, systems are compared with the same energy capacity, and power capacity is then set by the E2P ratio. The E2P for the LI system was set to 2.0 in this study.

TABLE 3 - ENERGY TO POWER (E2P) RATIOS

	STS	LI
Energy Capacity	40 MWh	40 MWh
E2P	6.27	2
Power Rating	6.38 MW	20 MW
Duration of Discharge	6.3 hr	2 hr

Underlying this cost comparison is the assumption that the "capability based" system design will match the power delivery requirements of the wind farm. It is recognized that this assumption is unrealistic because ultimately a stored energy facility will be designed around a complex set of requirements, but this approach is taken as there is a defined "capability" in the presented STS-CAES design. For the purposes of comparing LCOS between system types this assumption is acceptable, however should be treated with caution. In actual application wind farm requirements would be set and each system type would be optimized to try and meet those requirements, suitability as well as cost would be assessed and a selection made. It is important to note that wind farm power delivery requirements would be determined in consideration of value of ancillary benefits including:

- Grid Services
- Frequency regulation
- Compensation for load imbalance
- Peak shaving, valley filling, load shifting
- Correction of forecast errors of wind farm production
- Prevention of re-dispatch
- Opportunity of spot market price fluctuations

In the evaluation of the value of ancillary benefits, "cheapest is not always best." [9]

Hence the comparison is made between CAES-STS and LI systems each with a one-cycle discharge energy capacity of 40 MW-hr. Applying the E2P ratios the STS power capacity is 6.4 MW and the LI power capacity is 20 MW. This LI power capacity is 36% of the size under consideration for Bay State Wind [2]. The (unrealistic) assumption is that either system, providing 6.4 MW for 6.25 hours or providing 20 MW for 2 hours, would meet the power delivery requirements of the wind farm and have ancillary benefits of equivalent value.

It is recognized that these energy and power capacities are low compared to what may be required by the wind farm, but the comparisons should be scalable.

Another important economic factor in the comparison is the number of cycles in a year. This factor is also dependent on wind farm power delivery requirements and varies significantly with location and energy demand requirements. In the Mediterranean Sea wind strength tends to cycle daily in the summer months, where it is calm in the mornings and wind builds in the afternoon and into the evening. This is typical off the coast of California, where wind is generated by thermal energy. The coast of the UK is more dominated by large weather systems with winds lasting for 4 days, followed by a period of calm weather. In most all areas the duration of calm conditions varies with season.

A range of number of cycles per year is investigated. This range is from a daily cycle (365 cycles a year) to a 4-day cycle (91 cycles a year). Given that this represents a factor of 4 on energy produced each year, the LCOS range will vary significantly. A comparison of the maximum number of cycles possible for each technology is not made, as advised in [9]. This kind of capability comparison would favor the STS-CAES system as it does not wear out at the rate LI does but is somewhat meaningless as it does not relate to the requirements of a specific wind farm.

The compressor or battery charger needs to be sized to re-charge the storage within the design number of cycles. The compressor modeled for the STS-CAES system, in terms of characteristics and cost, is sized to recharge the tanks in 2 days.

A. Assumptions in LCOS Analysis

1) Capital Costs and Finance Parameters

For the CAES-STS system the capital cost estimate includes the materials and labor to fabricate a hull module containing the tanks and piping system, as well as the machinery modules on deck with the compressor(s), turboexpander(s), heat recovery system and the thermal energy storage system. Control and monitoring systems are also included. These elements are appended to the floating substation platform and turret mooring that is accounted in the wind farm cost.

For the LI system the capital cost includes the cost of an onshore building, batteries, charger(s), inverter(s), control and monitoring systems. A year 2020 LI battery cost of $130/kWh is used [10].

The battery bank size is determined by including an 80% depth of discharge (DOD) factor [11] and a reduction to 90% capacity which can be expected after 1,000 cycles [11]. Additionally, the inverter efficiency estimated at 96.5%, is included as the energy is measured after the inverter. Hence to provide 40MWh of energy capacity 58MWh of battery capacity is installed.

Additional financial assumptions include:

- Project life is 45 years.
- Cost of capital or return on investment (ROI) is assumed at 8%.
- Cost of Energy generated by the wind farm is assumed at $60/MWh.
- All costs are in 2020 US Dollars and inflation is not considered.
- For the initial capital cost inflation can be considered part of the cost of capital percentage.

2) Operations and Maintenance

Average annual costs are determined and additionally the costs of major overhauls and battery replacements are included.

CAES-STS platform overhauls: Year 15, Year 30: In addition to annual maintenance, 15-year overhaul periods are typical for shipboard equipment. Overhaul periods are planned Year 15 and Year 30. Equipment items are overhauled in Year 15 and Year 30 includes a new compressor and new turboexpander, reflecting new technology, but at 20% less cost.

LI System Battery Replacements: Year 8, Year 18, Year 30: In addition to annual maintenance, battery replacements are included. The first replacement after 8 years reflects either 3,000 cycles or 730 cycles, depending on a daily cycle requirement or a 4-day cycle requirement. Regardless of number of cycles, it is assumed that the batteries will need replacement at the end of an 8-year calendar life [11].

Table 4 shows battery replacement costs, with future costs projected by BloombergNEF [10]. Increasing intervals reflect improvements in battery life. The battery bank purchase in Year 30 will last until the end of the project in Year 45.

TABLE 4 - LI BATTERY REPLACEMENT SCHEDULE AND COST, BASED ON A 58MWH BATTERY BANK

Year #	Year	Cost per kWh	Battery Cost
1	2020	$130	$7,540,000
8	2027	$78	$4,524,000
18	2037	$57.66	$3,344,280
30	2049	$50.22	$2,912,760

Other materials, labor and disposal cost for the old batteries are added to the basic battery cost in the overall annual O&M cost estimate.

3) Other Assumptions

Energy Capacities are for one full cycle of discharge, where battery discharge is to the maximum depth of discharge (DOD), assumed to be 80%, and the CAES-STS system discharges from full pressure at 82bar (1,200psig) to 14bar (200psig), an 83% depth of discharge.

The CAES-STS cold discharge air benefits to the platform systems have not been accounted for in the comparison.

The cost of purchasing land on shore for the battery storage facility is included at $2M.

B. LCOS Comparison Summary

Results of this economic analysis are presented in Table 5. This table assumes an average of one cycle every 2 days.

TABLE 5 - LCOS COMPARISON – 2-DAY CYCLE FREQUENCY

		CAES-STS	LI
Levelized Cost of Storage	**$/MWh**	$453	$435
Initial Capital Cost, $	ICC	$57,186,000	$19,441,000
Ops and Maint, annual, $	O&M	$464,362	$960,275
Cost of Wind Energy, annual,	COE	$1,625,884	$610,185
Annual Energy Production from Storage, MWh/yr	AEP	15,026	7,300
Cycle frequency, days	2	2	2
Cycles per year	182.5	182.5	182.5
Return on Investment, after taxes and inflation	8%	8%	8%
Life of Project, years	45	45	45
Capital Recovery Factor, CRF	8.26%	8.26%	8.26%
Wind Farm LCOE, per MWh	$60	$60	$60
Electricity Produced			
from turboexpander generator or inverter	MWh/cycle	40	40
from Platf. Services (steam turbine generator)	MWh/cycle	42.3	0
Total per cycle	MWh/cycle	82.3	40.0
Total per year, Annual Energy Production (AEP)	MWh/yr	15,026	7,300
Power input per cycle	MWh/cycle	148	56
Net Efficiencies - Power out/Power in		55%	72%

- The capital cost of the STS-CAES system is almost 3 times the capital cost for the LI system. This difference will probably increase over time as battery costs continue to come down.

- The average annual O&M cost is higher for the LI system due to battery replacements over the 45-year project life.
- Waste heat energy usage by platform services is critical for this application, as the turboexpander selected for this concept design has limited capability to reheat the air between the first and second stages, and thermodynamic efficiency gain is limited. This model assumes that the waste heat not used for TES is used to generate electricity for the platform or exported to the grid, and the efficiencies associated with this process are included. Further work would refine the turboexpander selection, and the net efficiency of the CAES-STS system should improve. The comparative results should not change appreciably.

Table 6 shows the impact of cycle frequency.

TABLE 6 – IMPACT OF CYCLE FREQUENCY ON LCOS

Cycle Frequency	LCOS, $/MWh	
Days	CAES-STS	LI
1	$281	$259
2	$453	$435
3	$626	$611
4	$799	$787

In a report by the World Energy Council [9] it is estimated that for a CAES system co-located with wind, and in their 2015 study period, LCOS ranges between €150 and €300/MWh for a daily cycle system. The cost numbers generated in this report fall within that range.

V. CONCLUSIONS

The platform design development presented in this study demonstrates the technical feasibility and cost of an offshore CAES system supporting an offshore wind farm. The findings are summarized as follows:

A. Thermodynamic Advantages:

Submerged steel tanks in 65 deg seawater were thought to improve efficiency of CAES system due to the heat transfer rate of seawater to the steel walls. The cooling of the tanks from air expansion would be mitigated by the relatively warm seawater. However, analysis indicated submerged tanks only resulted in less than a 2% efficiency improvement.

B. Efficiency Benefits:

Overall efficiency of the CAES system is 55%. This compares with published CAES efficiencies of 60-70% [9].

C. Synergistic advantages from sharing platform with the wind farm offshore substation:

Using the deep-water floating substation platform for the wind farm to also support the CAES system shares the cost of the platform, and the operational cost (total operating personnel, maintenance) is also shared.

Shoreside energy storage facilities are not required as all systems are combined offshore, including power management functions. This eliminates shoreside property permitting, leasing or acquisition that would be otherwise needed.

Waste heat captured from the compressor can be utilized by the substation systems, reducing fuel use and emissions. A steam turbine generator can be utilized to supplement the substation electricity demand.

The overall concept design of the deep-water offshore wind substation integrated with CAES is a viable marine system developed using Naval Architecture and Marine Engineering principles and practices.

D. Levelized Cost of Storage and Capital Cost:

The LCOS for the CAES-STS system is comparable to a shore-based Lithium Ion battery storage system. The capital costs are much higher, but the operations and maintenance costs are lower, due to battery replacements over time.

The estimated costs have a variety of sensitivities, and a tolerance should be applied to the numbers recognizing that this study is at a feasibility level.

This study has confirmed that CAES is a viable option for stored energy in combination with an offshore wind farm.

E. Next Steps

Another design cycle should be performed and the engineering and design effort should be applied to a specific set of wind farm storage requirements. A trade study could be performed again looking at battery or other energy storage options.

A sensitivity analysis would help understand the cost impact of various items.

This is a novel platform concept and the next step would be to follow the standard process to progress a floating marine system. This would include a hazard identification process and address the risk levels and consequences of failures, such as a ruptured tank. A design evaluation by a marine classification society such as Det Norske Veritas or American Bureau of Shipping could be conducted leading to an Approval in Principle (AiP) certification.

CLOSING

It is the intention of the authors that this paper engender discussion, thought and continued study. The authors hope the paper is enlightening and moves us down the path towards practical application of CAES systems to the challenge of wind energy storage.

NOTATIONS AND ABBREVIATIONS

ASME	American Society of Mechanical Engineers
CAES	Compressed Air Energy Storage
CAES-STS	Compressed Air Energy Storage – Submerged Tank System
E2P	Energy to Power
Freeboard	Distance from water surface to main deck
ISO	International Standards Organization
LI	Lithium Ion
MWh	Mega-Watt hour
O&M	Operations and Maintenance
SCFM	Standard Cubic Foot per Minute
SCMH	Standard Cubic Meter per Hour
T-CAES	Transportable – Compressed Air Energy Storage
TES	Thermal Energy Storage
V/P	Volume/Pressure

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