ENERGY STORAGE SYSTEM FOR FLOATING WIND TURBINES

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Abstract- World has witnessed the growth of wind energy in recent years, increasing approximately at an annual rate of 25-30%. Majority of wind power is generated from onshore wind farms. The growth of onshore wind farms are limited due to their visual impact and lack of inexpensive land near major population centres. Wind energy generated from offshore wind farms is the next frontier. But, a major problem associated with wind power is its intermittency. Even if it is somewhat predictable, it is still difficult to match generation with demand. Energy storage can alleviate this intermittency problem thus smoothening the power output fluctuations. Concrete spheres at ocean depths can be used as a complement to Floating Wind Turbines (FWT) for energy storage. Water is pumped out of the concrete spheres during periods of low demand thus storing energy. During periods of high demand water flows back to the spheres through a turbine to generate electricity. The fly ash from conventional coal power plants can be utilized for concrete manufacture thus reducing its impact on environment. The concrete spheres can also serve as artificial reefs for the marine population.

Index Terms—Fly ash, Artificial Reefs, Concrete Spheres, Energy Storage, Floating Wind Turbines, Wind Energy

I. INTRODUCTION

With the advent of industrial revolution, the demand of electricity has increased tremendously. Currently, majority of power generated in the world is from fossil fuelled power plants. Fossil fuels are the largest greenhouse gas emitters in the world, contributing 3/4th of all carbon, methane and other greenhouse gas emissions .Also, world's fossil fuel reserve is being depleted drastically. Within a short span of time, world will have to depend on renewable energy sources to meet most of its electricity demand.

Wind is a rapidly growing renewable energy source. Major portion of the wind power in the world is generated from onshore wind farms. The growth of onshore wind farms is limited due to requirement of large area and also due to the lack of inexpensive land near major population centre. Offshore wind turbines are the next frontier for the extraction of wind energy. Bottom mounted offshore wind turbines are restricted for use in shallow waters. For greater sea depths where the wind velocity is higher, Floating Wind Turbines (FWTs) are preferred. A recent National Renewable Energy Laboratory (NREL) study of U.S. offshore wind estimates that there are over 4000 GW in offshore wind potential, including over 2400-GW potential in areas with average wind speeds greater than7 m/s at water depths greater than 60 m, where FWTs are more likely to be deployed.

A major problem associated with wind power is the intermittency of wind. The intermittency of wind power may cause grid instability due to imbalance between local power demand and power generation. So, the integration of wind power to power systems is confronted with many challenges, including reduction or elimination of power fluctuations, maintaining power quality and voltage profile when connecting to weak grids, prediction of wind power, and changes in the way conventional power plants are operated. This in turn may lead to adverse voltage variations and other effects. The feasible solutions for this problem include implementation of an Energy Storage System (ESS) and better wind forecast. The wind forecast, although much improved, still suffers from problems such as complexity and poor accuracy. ESS can provide steady and predictable power by storing excess energy and releasing it when the demand is greater than the supply. The capacity factor of current offshore wind turbines without energy storage is very low, typically less than 50%.

Offshore wind power with integrated energy storage could satisfy greater than 20% of world's electricity demand because of its higher capacity factor and proximity to densely populated areas. The objective of this paper is to develop an Ocean Renewable Energy Storage (ORES) system for the floating offshore wind turbines. Ocean Renewable Energy Storage System is an ideal complement to Floating Wind Turbines (FWT). ORES system is used for storing energy deep underwater in concrete spheres which can act as moorings for the FWTs. The offshore environment can be used for unobstructive, safe and economic utility energy storage by taking the advantage of hydrostatic pressure at the ocean depths to store energy by pumping water out of the concrete spheres and later allowing it to flow back in through a turbine to generate electricity. The use of energy storage as a power and energy buffer can smooth the power output fluctuations. Energy storage has been considered as a solution for improving power flows from wind turbine generator, and can potentially make wind a more viable and competitive energy resources. Also, energy storage has got several benefits including improved renewable energy integration, avoidance/deferral of new fossil fuelled peaking plants and transmission upgrades, reduced emissions from reduced peaker plant operations and ancillary services typically provided by fossil-fuelled plant. .

II. LITERATURE REVIEW

The background that leads to an ocean renewable energy storage system is described here. The concrete spheres can serve as moorings for the FWTs which help them to be installed in rocky seafloor conditions where it is difficult to deploy suction anchors for the mooring lines. The conventional storage methodologies including Pumped Hydro Storage and Compressed Air Energy Storage are also included here.

A. Floating Wind Turbines

Bottom mounted offshore wind turbines can be used only for shallow waters. They are not feasible for deeper areas of the sea where the wind velocity is higher. This leads to the development of Floating Wind Turbines. A Floating Wind Turbine is an offshore wind turbine mounted on a floating structure that allows the turbine to generate electricity in water depths where bottom-mounted towers are not feasible. Floating wind energy systems seem to have some advantages over bottom mounted wind energy systems, like lower cost installation (in a harbour), lower maintenance cost, lower removal cost [1].

Support Structures for FWTs

Variety of offshore support structures that are in use are illustrated in fig.1. The first is a gravity foundation which, as the name implies, relies on gravity to secure it to the bottom. This work well in very shallow water where the seabed can be prepared using surface vessels and the foundation can be cast in concrete and floated to the site for placement.

The second is by far the most popular. It is a "monopile" and has been used in waters around Denmark and the United Kingdom. The third is a tripod. This could be used in water with depths of more than 20 m. A jacket structure, which is more common to oil and gas truss structures, was used in the Beatrice project in 45 m water depths off the coast of Scotland. The fourth example is a floating support structure. It can be used in deep waters.

Wind Turbine Platforms

There are three main types of floating wind platforms. One type, known as 'ballast stabilized,' uses spar buoy platforms with catenary mooring drag-enabled anchors. A second, called 'Tension Leg Platforms' or 'Mooring Line Stabilized Platforms' is attached to the seabed with suction pile anchors.The third type is the 'Buoyancy Stabilized' platform, which employs a 'barge' type device with catenary mooring

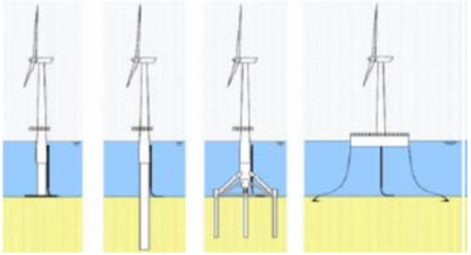

Fig. 1 Different types of support structures

lines. Energy Storage System employing concrete spheres is a good complement to FWTs. The TLP wind turbine floater consists of a slender cylindrical buoy connected to the seafloor with vertical tethers attached to the buoy in the vicinity of the waterline. The buoy displacement is larger than the weight of the wind turbine and the steel weight of the buoy structure. The Taught Leg Buoy (TLB) concept also consists of a slender cylindrical buoy free of permanent ballast with reserve buoyancy necessary to pre-tension two layers of mooring lines inclined relative to the seafloor where they are connected to gravity anchors [2].

Engineering Considerations

The triangular platform of FWT is moored using a conventional catenary mooring consisting of four lines, two of which are connected to the column supporting the turbine, thus creating an asymmetric mooring. Undersea mooring of floating wind turbines are accomplished with three principal mooring systems. Two common types of engineered design for anchoring floating structures include tension leg and catenary loose mooring systems. Tension leg mooring systems have vertical tethers under tension providing large restoring moments in pitch and roll. Catenary mooring systems provide station keeping for an offshore structure yet provide little stiffness at low tensions. A third form of mooring system is the Ballasted catenary configuration, created by adding multiple-tonne weights hanging from the midsection of each anchor cable in order to provide additional cable tension and therefore increase stiffness of the above-water floating structure [1].

B. Pressurised Storage Technologies

There are numerous energy storage technologies currently available ranging from short-term methods for second-to second variations in renewable output, to longer term utility-scale methods of which Pumped Storage Hydroelectricity (PSH) is the most well known and robust. PSH is a type of hydroelectric power generation used by some power systems for load balancing. The method stores energy in the form of potential energy of water, pumped from a lower elevation reservoir to a higher elevation. At times of low electrical demand, excess generation capacity is used to pump water into the higher reservoir. When there is higher demand, water is released back into the lower reservoir through a turbine, generating electricity. Reversible turbine/generator assemblies act as pump and turbine (usually a Francis turbine design.). Nearly all facilities use the height difference between two natural bodies of water or artificial reservoirs. Pure pumped-storage plants just shift the water between reservoirs, while the "pump-back" approach is a combination of pumped storage and conventional hydroelectric plants that use natural stream-flow. The energy capacity is proportional to the volume of reservoirs available for the turbine.

Taking into account evaporation losses from the exposed water surface and conversion losses, approximately 70% to 85% of the electrical energy used to pump the water into the elevated reservoir can be regained. The technique is currently the most cost-effective means of storing large amounts of electrical energy on an operating basis, but capital costs and the presence of appropriate geography are critical decision factors. Round trip efficiencies of PSH range from 75% to 85%.

This system may be economical because it flattens out load variations on the power grid, permitting thermal power stations such as coal-fired plants and nuclear power plants that provide base-load electricity to continue operating at peak efficiency (Base load power plants), while reducing the need for "peaking" power plants that use the same fuels as many base load thermal plants, gas and oil, but have been designed for flexibility rather than maximal thermal efficiency. However, capital costs for purpose-built hydro storage are relatively high.

Compressed Air Energy Storage (CAES) is newer and there are just two CAES plants in the world: a 320-MW, 1.2-GWh plant in Bremen, Germany, built in 1978, and the McIntosh Project in Alabama, a 110-MW, 2.9-GWh plant. In a conventional CAES system, excess electricity is used to drive an air compressor that compresses air into an underground salt cavern; and the energy is then retrieved by pre-compressing and improving the efficiency of natural gas combustion in a gas fired turbine. Such a system is relatively inefficient (< 50%), requires use of hydrocarbon fuel, and depends on geological sites. Using natural gas to preheat the air entering the turbine, the round trip energy efficiency can be as high as 71% [3].

Another concept has been that 280-m diameter spheres be placed at 2000-m depths to provide energy storage for FWTs and onshore wind turbines.

C. Submerged Generation and Storage System

A Submerged Generation and Storage system (SubGenStor) composed of multi- megawatt turbines or pump/ turbines are capable of storing and generating renewable energy. The goal of this invention is to create virtually invisible and environmentally friendly renewable energy storage and generation. It has the advantage that the pump or generating units are located underwater out of visual range and can be located in close proximity to the load centre [4].

This system allows multiple, modular units to be used. By the novel idea of mounting these at the bottom of a lake or ocean (any body of water) the units do not require water channels (penstocks or tailrace) of any great length. The turbine or pump/turbine units are mounted in a watertight structure beneath a body of water and with the use of air vents the lower storage reservoir is kept at normal atmospheric pressure while the storage reservoir fills during generation. At the end of a period of generation or when the lower storage reservoir is filled the lower reservoir is pumped clear or forced clear of water by mechanical or pressure means. Vent tubes floating at the surface and/or access caissons will be equipped with all necessary warning devices for marine traffic. Underwater cables will carry the generated energy to inverters, converters, transformers, switchgear etc. located on the shore as required and then into the electricity grid.

D. Concrete structures for 2000m depth

At greater depths, the deep sea environmental forces are far different than near-surface structures. Wave forces are negligible but seismic forces are fully effective, accelerating both the structure and the added mass of water. Soils are generally extremely weak, characterized by bottom ooze, with low bearing pressure and shear strength. Bottom currents may reach one-half knot. Mooring lines or risers etc.will impose uplift and lateral forces. The installation of a structure at great depths presents extremely difficult problems of high hydrostatic pressures, density changes in the seawater, compression of the structure and its contained fluids or gasses due to pressure and temperature changes, and absorption of water into concrete under the high pressure. Such a structure will usually be of large size and hence problems of stability, orientation and positioning will occur during installation. The weight of any lowering lines becomes significant. These lines will be subject to large dynamic effects as elastic connectors between the surface control vessel and the mass of the block with its added mass of water. Problems of control are rendered difficult because of the pressure and dynamics [5].

Steel Fibre Reinforced Concrete (SFRC) and Glass Fibre Reinforced Concrete structures (GFRC) are preferred for undersea concrete structures. Both SFRC and GFRC have been shown to mitigate cracking. SFRC has been shown to handle much greater cyclic stresses than unreinforced concrete [6].

The conventional storage methodologies have several disadvantages including increased cost of installation. Thus a new method is proposed which uses concrete spheres to store energy. A reversible pump/turbine assembly is used with concrete spheres for generation and storage.

III. UNDERSEA ENERGY STORAGE

Numerous advantages and challenges for offshore wind has been identified and well documented including proximity to major population centres, greater capacity factors, smoother air flow and potential for rebuilding heavy manufacturing industries in coastal areas. Energy storage can help address the intermittency problem inherent in wind and thus improves grid stability. The ORES system provides unobstructive, safe and economic utility energy storage. The storage can be economically feasible at depths as shallow as 200 m.

A. Arrangement and Operation

The schematic cross sectional view of the energy storage sphere which can also act as moorings to the FWTs is shown in figure 2. Water is pumped out of the spheres to store energy, and allowed to flow back in through a turbine to generate electricity[7].

For a Tension Leg Platform (TLP) FWT, the number and size of the storage spheres needed to anchor them would depend on the specific design of the tension leg system. Tension legs can be in the form of steel tubing which offers a protected conduit for cables; in addition, the legs can serve as snorkels so 1-atm pressure could always be present in the sphere which can enable simpler pumps to be used by eliminating cavitations as a concern. The ORES concept makes it simpler to deploy tension leg FWTs in rocky seafloor conditions where suction anchors would be difficult to deploy. When excess power is available and the spheres are to be charged, power is sent from a wind turbine, wave energy harvester, ocean current turbine, or even the grid to operate the pump/turbine and water is pumped out of the structure.

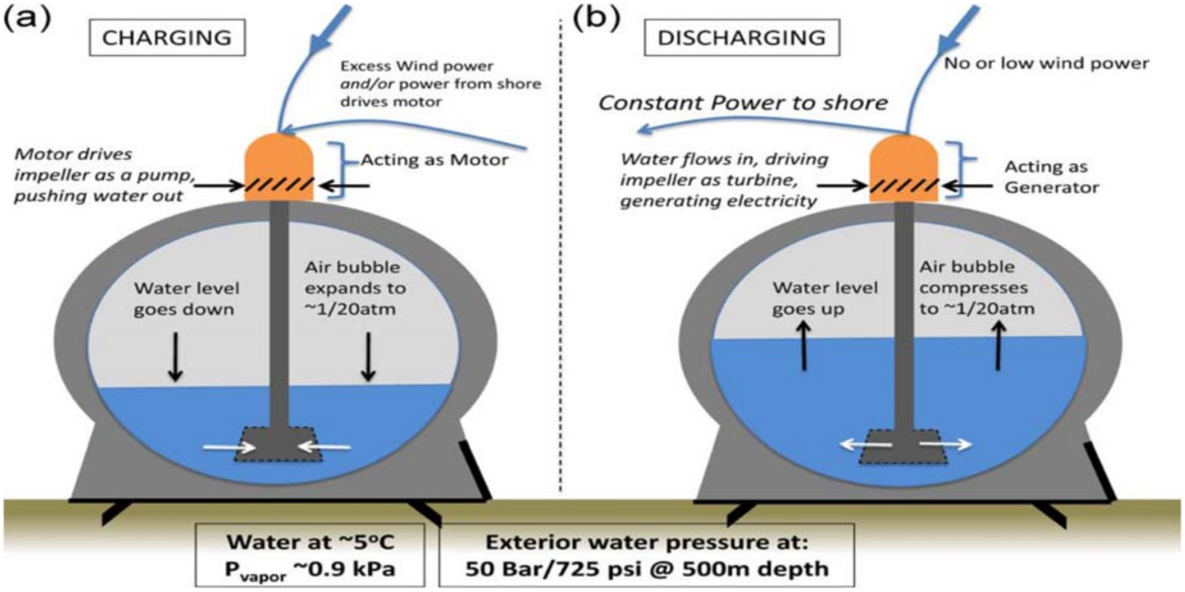

Fig.3.1 Internal view of ORES system during (a) charging and (b) discharging operations

B. ORES Concept

The concept of Pumped Storage Hydroelectricity is used. Pumped hydro units pump water out of the structures during high-wind/low-demand periods, and water flows back into the evacuated structures through turbines during periods of high demand. The inside volume remains at or below atmospheric pressure so the total charge capacity (in megawatt hours) of the storage cylinder can be related to the sphere inner volume, efficiency of the pump/turbine unit, and depth as

$$\mathrm{C_{max}} = \frac{\rho_{\mathrm{sw}}\eta_{\mathrm{turb}}\mathrm{dgV_{inner}}}{3.69\mathrm{E}^{9}} \tag{1}$$

where ρ_{sw} is density of seawater (1025 kg/m3); η_{turb} is the turbine efficiency (85%); g is 9.81 m/s^2; d is depth in meters; V_{inner} is the interior volume of the sphere; and $3.6E^9$ is the conversion from Joules to megawatt hours.

Since pressure increases by 10 bar every 100 m (0.44 psi/ft), deeper locations are preferable to maximize the storage capacity for a given volume. When fully discharged, a 5% of total volume 1-atm air pocket would remain, so when the water is pumped out, a 1/20-atm environment remains to prevent pump cavitations. Since energy is extracted by water flowing through the turbine into the sphere, compression of the air volume back to 1 atm causes actual capacity to differ from theoretical maximum capacity by about 5%. A vent line to thesurface, e.g., through tension legs for a TLP FWT, could mitigate pump cavitation concerns.

The first concept was to use a thin-shelled concrete sphere with an outer retaining wall to hold ballast. An evacuated ribbed thin-shell 25-m diameter sphere would require 5000 mt of ballast in order to remain on the bottom when empty. An additional 500 mt of ballast is required as a gravity mooring for each anchor line of an FWT. If a tension leg system is used, up to 3000 mt of ballast may be required for a 5 MW FWT. Incorporating the ballast in the design by a thick wall yields a robust structure that should be less prone to damage during manufacture and transport, while also providing an extra margin of structural safety so it can be deployed without modification at greater operating depths. In addition, since ballast requirements do not change appreciably with depth, energy density increases significantly at greater depths without a proportionate increase in structure or deployment costs, decreasing the cost per megawatt hour of storage.

Potential sites

Using a combination of bottom contour maps available from the National Oceanographic and Atmospheric Administration (NOAA) and Google Earth, areas were identified that appear most conducive (more than 200-m depths) to deep-water energy storage within 125 NM of large population centres. Sites should have large areas with excellent wind resources, good bottom topography conditions, reasonable distance from shore, and not in conflict with use by other groups (fishing, military, etc.). In order to mitigate conflicts, storage units could be placed remotely from the wind turbines. In such a concept, the spheres are deployed as a storage-only farm where the required excess ballast is minimized and the spheres are clustered closer together. Transmission lines connect the storage farm with the wind farm and then onto shore.

C. Structure strength and ballasting requirements

The maximum safe depth d is a function of the concrete strength S, the sphere's inner and outer radii r_i and r_o, respectively, seawater density (ϱ), gravity (g), and a factor of safety FOS as

$$d=\frac{2S(r_0^3-r_i^3)}{3FOS.\rho g r_0^3} \tag{2}$$

For example, using standard values for g and ρ equal to1025 kg/m3, a 25-m diameter sphere with a wall thickness of 2.0 m, a safety factor of 1.5, and 34.5-MPa (5000-psi) concrete could be safely deployed to a depth of 548 m.

In order for the sphere to remain on the bottom of the ocean and still provide sufficient ballast for the FWT, its weight has to be500 mt greater than its displacement. The interior volume V_{inner} was determined from the desired energy storage, using eqn.3.1, while the inner radius is given by

$$r_{inner} = \sqrt[3]{\frac{V_{inner}}{4\pi}} \tag{3}$$

The volume of shell V_{shell} is given by,

$$V_{shell} = \frac{4}{3}\pi((r_{inner} + t)^3 - r_{inner}^3) \tag{4}$$

The volume of a conical base to which the sphere is attached is based on a cone of height $2r_{inner}$ and base diameter of $2r_{inner}$ intersecting a sphere of radius $r_{inner} + t$ is given by

$$V_{base} = \frac{14\pi(r_{inner}^3)}{75} \tag{5}$$

The weight W_t and the displacement Δ of the resulting sphere with the conical base are given by

$$W_t = (V_{shell} + V_{base}).\rho_{concrete} \tag{6}$$

$$\Delta = \frac{(V_{base}+\frac{4}{3}\pi\,(r_{inner}+t)^3))}{75} \tag{7}$$

Fig.3. ORES Hemisphere Concept

Hemispherical substructure

The original design concept was based on making six equal sections (i.e., staves) which would be brought together and banded with steel cables analogous to making a barrel. Although the size of each section would be very manageable, due to the complexity of assembly, risks of installing top and bottom caps, and fragility of the individual staves between demoulding and assembly, it was finally converged to a hemispherical design assembly as shown fig.3. Each hemisphere is very robust and can be made using a simple two-piece mould. The need for top and bottom caps was eliminated, with only a small hole retained for the pump/turbine unit access. The mating surfaces both have grooves which allow epoxy grout to be pumped around the circumferential interface to seal the two hemispheres together. The simple conical base allows the spheres to rest on bottoms with up to a 10% gradient.

Fig.3. ORES Hemisphere Concept

To facilitate manufacturing, the bottom of each hemisphere can be a steel plate or a precast post-tensioned concrete acting as part of the mould during concrete casting. It also provides structure for holding buoyancy modules or for lowering from a barge. In addition it provides attachment pad eyes for the FWT mooring lines and power cables.

The underside of the plate must be able to remain anchored in the soil under dynamic loading conditions while minimizing the transference of any stresses to the concrete and resisting movement of the sphere due to any underwater currents th at may be present. The concrete of the sphere, as far as the moorings are concerned, only acts as the weight to press the bottom plate firmly onto the soil suction will also help resist dynamic loads.

D. Large Scale Manufacturing

SFRC and GFRC are preferred for undersea concrete structures. Both SFRC and GFRC have been shown to mitigate cracking. SFRC has been shown to handle much greater cyclic stresses than unreinforced concrete. One of the important properties of steel fibre reinforced concrete (SFRC) is its superior resistance to cracking and crack propagation. As a result of this ability to arrest cracks, fibre composites possess increased extensibility and tensile strength, both at first crack and at ultimate, particular under flexural loading; and the fibres are able to hold the matrix together even after extensive cracking. The net result of all these is to impart to the fibre composite pronounced post – cracking ductility which is unheard of in ordinary concrete. The transformation from a brittle to a ductile type of material would increase substantially the energy absorption characteristics of the fibre composite and its ability to withstand repeatedly applied, shock or impact loading.

Self Consolidating Concrete (SCC) is also in consideration for use in the construction of storage spheres. The behaviour of SCC as a structural material can be improved if adequate steel fibre reinforcement is added to SCC mix composition. In fact, the fibre reinforcement mechanisms can convert the brittle behaviour of this cement based material into a pseudo-ductile behaviour up to a crack width that is acceptable under the structural design point-of-view. Fibre addition, however, increases the complexity of the mix design process, due to the s-trong perturbation effect that steel fibres cause on fresh concrete flow. In the present work, a mix design method is proposed to develop cost effective and high performance Steel Fibre Reinforced Self-Compacting Concrete (SFRSCC). However, the properties that make SFRC best (typically longer larger fibres) make the product less capable of self-consolidating(where shorter or no fibres would be preferred).The optimum point of fibre size, number, and shape for best self-consolidating and best crack-mitigation/cyclic stress performance remains a major point of research.

A 25-m inside diameter sphere requires approximately 10 000 mt of concrete, poured in two 5000-mt hemispheres over a 21-h period; a 30-m diameter sphere requires approximately 20000 mt of concrete, poured in two 10000-mt hemispheres over a 42-h period.4 The vision is for this concrete to be poured continuously. As recently as 2009, for the construction of the high-rise towers, some of the largest SCC single pours have been on the order of 16000 m3 or nearly 40000 mt.

Pump/Turbine System

A turbine or pump/turbine essentially comprises of multi-vane input and output stator (the water distributor), a rotating turbine/impeller unit and a multi-pole rotor in a motor/generator stator. Some or all of the units may include direct or gear drive from the turbine/impeller to a variable (or constant) speed electrical rotor. It is possible that a torque converter could take the place of or assist the gearbox. These turbines or pump/turbines are mounted in a water tight structure beneath the water and discharge into a vented lower storage reservoir also located beneath the water anchored onto the bottom of the body of water and typically including a "dead storage" water area used as ballast. The body of water will usually be large enough such that operation of the system will not lower or increase the upper water level by any substantial amount [4].

Single-stage pump/turbines that can handle up to700-m head have been designed and tested. Additionally, submersible pumps are often used in water wells and in the oil and gas industry. However, the unique requirements for the storage sphere require a design that can be removed by ROV for replacement or repair. Three major concerns that must still be addressed are corrosion, clogging from sediment ingestion during turbine operation, and effects on nearby marine life during pumping and turbine operation. A self-clearing feature will be required for the pump/turbine unit to maintain maximum efficiency. In addition, a reliable mechanism must be incorporated into the pump/turbine design to allow it to differential pressure for long periods of time and then be able to pump or act as a turbine with minimal mechanical shock and minimal efficiency loss.

IV. BENEFITS OF STORAGE

Energy storage improves grid stability. The integration of energy storage into wind power generation system could increase system operation efficiency, enhance wind power absorption, achieve fuel cost savings, and reduce CO_2 emissions[8].

A. *Wind Model*

The wind distribution can be described mathematically by atypical Weibull distribution. A random variable v has a distribution if its Probability Density Function (PDF) is defined by equation (8) as follows,

$$f(v,c,k) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} e^{-}\left(\frac{v}{c}\right)^{k} \qquad (8)$$

where c is a scale parameter with the same units as the random variable and k is a shape parameter[8].

Electricity generated from wind power can be highly variable from hour to hour, from day to day and from month to month. Annual variation also exists, but is not considered as significant. Because instantaneous electrical generation and consumption must remain in balance to maintain grid stability, this variability can present substantial challenges to incorporating large amounts of wind power into a grid system. Intermittency and the non dispatchable nature of wind energy production can result ill higher costs associated with regulation of voltage and power flow. It contributes to requirement for higher operating reserve. At high penetration levels, it could also cause problems to the existing energy demand management, load shedding, or storage.

B. Advantages of Storage

Energy storage provides additional flexibility for the system: at times of low load, energy storage may be used to increase the overall system load by storing energy, whereas the stored energy can be released to the system at times of high load. From a market perspective, this means that energy will be stored at times of low prices and being sold at high prices (usually peak load). Fig.3 shows effect of energy storage in wind power generation system.

Analysis of the Benefits of Energy Storage

The application of ESS to wind power can bring many benefits to both power grids and wind power developers. The grid benefits from more friendly wind farms while the developers benefit from increased wind power revenues. The benefits of energy storage can be modelled as follows,

$$XPRO = XSAV+XGEN+XTEC+XEN - XCOST \qquad (9)$$

where,

XPRO	Overall benefits of energy storage, £/year
XSAV	Benefits of saving and integrating an amount of wind power into existing power system that otherwise not integrated, £/year.
XGEN	Benefits result from avoiding the need to add other generation sources, £/year
XTEC	Benefits result from improvement in power system performance with wind power due to presence of energy storage, £/year
XEN	Revenue related to environmental benefits, £/year
XCOST	Total cost of energy storage, including capital cost

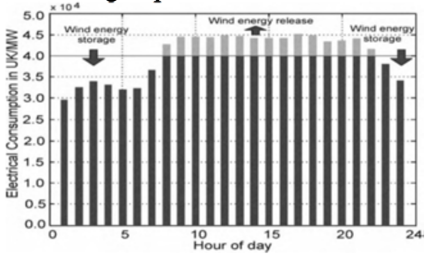

Fig .4. Impact of Energy Storage on Wind Power Generation

C. Synergistic Benefits

Fly ash from coal-fired power plants can be utilized for the construction of concrete spheres. Concrete spheres can also serve as artificial reefs which can help replenish the fish stocks. About 40% of the fly ash produced is used for industrial purposes, including as a substitute for cement in concrete, while the rest is stored until it can be disposed off. This can cause problems for the local environment.

Grade F fly ash from burning older anthracite and bituminous coal has been shown to be a viable, low-cost to Portland cement. Grade C fly ash, from burning of younger lignite or sub bituminous coal, has some self-cementing properties and with moisture will harden and gain strength over time so it can also be used as a Portland cement replacement. Use of fly ash lowers both the cost and CO2emissions associated with concrete manufacture, and reduces heat build up during curing. As offshore wind energy farms are built with storages systems, the fly ash from coal burning power plants can be assimilated. ORES structures could thus be an important new market for fly ash.

The creation of FWT farms with bottom-based energy storage spheres could also help repopulate the marine species. FWT pedestals just below the surface could act as floating reefs. Near the surface at the wind turbine structure, Fish Aggregation Devices (FADs) and floating structures could be used to attract fish in the open sea. Small fish are attracted by the shade or potential hiding spots of the FAD and large pelagic fish are attracted to the small fish as well as a way to orient themselves in the large, unvaried landscape of the ocean. A group of FWTs would act as a weak FAD, attracting some fish, but additional features could greatly enhance habitat. To provide this habitat, submerged, semi submerged, and/or floating surfaces can be suspended from the floating buoys that support the wind turbines. These would be planted with sea grasses or kelp to provide an environment that juveniles could hide.

V. REVIEW OF TEST SYSTEM

In order to test the hypothesis that concrete hemispheres can be cast joined together into spheres, and used as underwater pumped storage, a simple 75-cm inner-diameter sphere was designed and constructed. The results obtained by the analysis of test system are being discussed here.

To create the concrete hemispheres, a steel mould was made from the hemi-heads used for 1000- and 2000-L LPG tanks. The hemi-heads were modified to fit inside each other to allow pouring of concrete, removal of each mould, and handling of each hemisphere by chain fall. The mould was affixed to a vibration table and Kevlar fibre reinforced concrete was poured in and vibrated. Stud sockets and a groove were made in the joining faces of the concrete hemispheres using a steel ring and studs to aid in bonding the concrete halves together.

Two concrete hemispheres were created in this way, joined and sealed on the exterior. The joint plane for the spheres is horizontal to facilitate casting and the addition of features to the mating faces.

Because of its small size, manipulating and positioning the hemispheres to join them was not a major concern. For the full sized device, the joint plane will be vertical to minimize manipulation and avoid crane use; hence other strategies will need to be developed for bonding and sealing the two halves together such as those used to bond modular bridge segments together.

The installed test system is shown in fig.5.. To simulate depth, a high reservoir was created a 240-L (63 gal) barrel on a tower, 10 m (34.5 ft) above the inlet to the turbine. The energy conversion system is built using a separate pump and micro-hydro turbine. Due to its small size, a combination pump/turbine was not available so separate units were used.

The pump used was a rotary vane type capable of 38 L/min (10 gal/min) at a broad pressure range including the prototype's operating head of 11 m (36 ft). The turbine is a Turgo type). Despite having a very low head relative to the planned storage units, the height here is still considered high for micro systems as micro-hydro units can be built with as little as 60 cm (2 ft) of head. The flow to the turbine was adjusted by using different diameter nozzles to maximize efficiency. Electrical output from the turbine unit is measured as it is dumped to an adjustable load resistor which was also optimized for maximum efficiency by varying its nozzle size.

Testing of the micro device consisted of two phases: storing energy. First, water was allowed to flow through the turbine into the sphere, discharging the energy, until either 190 L (50 gal) had flowed or atmospheric pressure was reached inside the sphere. 190 L (50 gal) was the maximum volume this smaller system could accommodate without losing water through the vent line; a larger version would be able to fill completely. The valves were then switched to close off the turbine and deliver water to the pump and water was pumped back the sphere was empty again, and thus fully charged with energy.

Fig. 5 Installed Test System

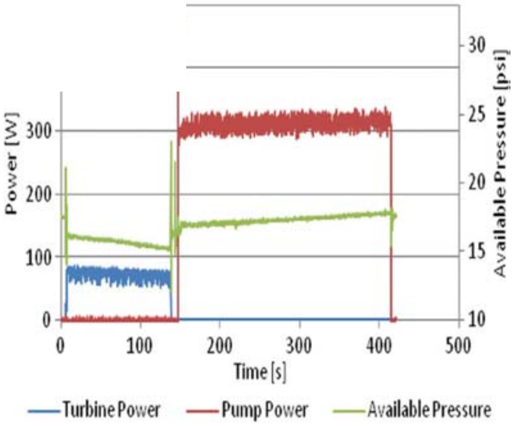

Fig.6. Power from a typical cycle with vent line

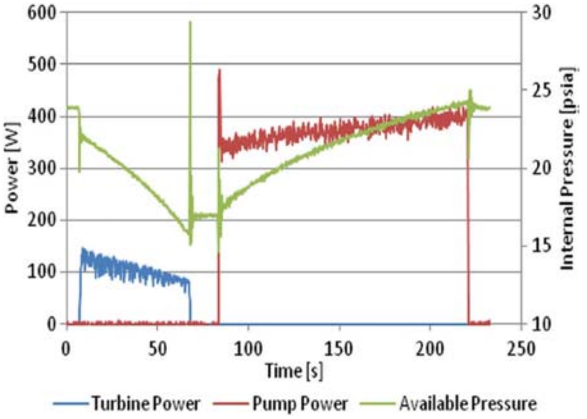

Fig.7. Power from a typical cycle without a vent line

The spikes in pressure are due to the opening and closing of the valves; either sending water to the turbine or the pump. The pump motor starting current can also be seen in the spike of power it consumes as it begins pumping. Finally, piping losses are seen in the quick change in pressure as the water gets up to speed entering the turbine. The same is not seen as clearly when the pump is running as it takes more time to get up to speed and the flow rate is much lower than when the turbine is running.

Without the vent line, a vacuum is drawn inside the sphere significantly increasing the available pressure. One particular advantage of the vent line is that it delivers power at a constant level whereas, without it, the turbine output will vary with the internal pressure. The test unit was found to have low round trip efficiency but the hydro installations can successfully achieve round trip efficiencies in excess of 70%.Furthermore, since the device is tested on land with atmospheric pressure on the exterior, the internal pressure was not permitted above 1.01 bar (14.7 psi) in any testing to avoid internal pressure on the airtight seal. This pressure limitation reduced both the usable volume of the sphere and the storage capacity; however, any device placed on the seafloor would not be subjected to this limitation.

VII. CONCLUSION

A storage methodology employing concrete spheres which can complement FWTs is developed. Energy storage has the potential to improve system operational performance such as reducing power loss and improving voltage profile. The conclusions drawn from this discussion are listed below:

- Energy storage can help address the intermittency problem inherent in wind.
- The concrete spheres can serve as moorings for FWTs which helps them to be erected in deep sea areas where the wind velocity is higher.
- The concrete spheres must be able to withstand seismic forces to which it is subjected when placed in the sea bed. SFRC and GFRC are preferred for concrete structures since both of these have been shown to mitigate cracking.
- Vent line to the surface is used to maintain pressure inside the spheres at

atmospheric pressure and to avoid cavitation.

- Fly ash from coal burning power plants can be put to productive use in the concrete used to fabricate the storage spheres.
- FWT pedestals can serve as artificial reefs which can help replenish the marine environment.

As offshore wind energy farms are built with storage systems, fly ash from coal burning power plants can be put to productive use in the concrete used to fabricate the storage spheres. In parallel, facilities can be built to liquefy coal previously used for power generation into transportation fuels. One day in a more renewable energy future coal fired power plants can be replaced with offshore wind, and coal can be the source for our transportation fuels. Energy ‘‘independence’’ might actually be a realistic goal.

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