Ocean Renewable Energy System (ORES) – Analysis of an Undersea Energy Storage Concept (July 2011)

Alexander H. Slocum, Member, IEEE, Gregory E. Fennell, Gökhan Dündar, Brian G. Hodder, James D. C. Meredith, and Monique Sager

Abstract—Due to its higher capacity factor and proximity to densely populated areas, offshore wind power with integrated energy storage could satisfy >20% of US electricity demand. Similar results could also be obtained in many parts of the world. The offshore environment can be used for unobtrusive, safe, and economical utility-scale energy storage by taking advantage of the hydrostatic pressure at ocean depths to store energy by pumping water out of concrete spheres and later allowing it to flow back in through a turbine to generate electricity. The storage spheres are an ideal complement to energy harvesting machines, such as floating wind turbines (FWTs). The system could provide near baseline quality utility-scale renewable energy and do double-duty as the anchoring point for the generation platforms. Analysis indicates storage can be economically feasible at depths as shallow as 200 m, with cost/MWh of storage dropping until 1,500 m before beginning to trend upward. The sweet spot occurs when the concrete wall thickness to withstand the hydrostatic pressure provides enough ballast mass, and this will depend on the strength of concrete and reinforcement used. In addition, the concrete required would use significant amounts of fly ash from coal-fired power plants, and the spheres can serve as artificial reefs.

Index Terms—energy harvesting, energy storage, undersea energy, wind integration, renewable energy, sustainable energy, grid storage

I. INTRODUCTION

A recent NREL study of US offshore wind estimates there are over 4,000 GW in offshore wind potential, including over 2,400 GW potential in areas with average wind speeds > 7 m/s at water depths greater than 60 m where FWTs are more likely to be deployed [1]. Numerous advantages and challenges for offshore wind have been identified and are well documented, including proximity to major population centers, greater capacity factors, smoother airflow, and potential for rebuilding heavy manufacturing industries in coastal states [1].

Recently, a $6B, 5 GW undersea transmission cable between New Jersey and Virginia intended to facilitate offshore wind development was announced [2] and the United States Department of the Interior announced plans to start pre-approving sites for offshore wind, which offers the prospect of greatly reducing the time for offshore wind projects to gain federal approval. By comparison, Cape Wind, a 130 MW offshore wind farm planned for Nantucket Sound south of Cape Cod, took approximately nine years to obtain final federal approval [3].

Energy storage can help address the intermittency problem inherent in wind and reduce the impact of diurnal wind patterns, when high winds/low demand occur at night which can require wind power to be curtailed or thermal power plants idled. Utility-scale energy storage can also help with load-leveling power plants for more efficient fuel use [4]. California’s energy storage bill AB 2514 [5] sets the stage for increased energy storage requirements and also allows for flexibility in how energy storage is achieved, including thermal energy storage for air conditioning, centralized or distributed storage, and different schemes of ownership. It also focuses on the benefits of storage [4] including: 1) Improved renewable energy integration; 2) Avoidance/deferral of new fossil-fueled peaking plants and transmission upgrades; 3) Reduced emissions from reduced peaker plant operations; and 4) Ancillary services typically provided by fossil-fueled plants.

Accordingly, this paper describes a system for storing energy deep underwater in concrete spheres which also can act as moorings for Floating Wind Turbines. Water is pumped out of the spheres to store energy, and allowed to flow back in through a turbine to generate electricity. Fig. 1 presents schematic cross-section views of an energy storage sphere as currently envisioned charging (a) and discharging (b).

Fig. 2 shows how energy storage spheres and their electrical interconnections could be arranged in a hexagonal pattern on
the ocean bottom, with the FWTs moored to them. For a tension leg FWT [6], the number and size of the storage spheres 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 cavitation 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.

Fig. 2. Conceptual ORES configuration with FWTs.

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.

II. BACKGROUND: PRESSURIZED STORAGE TECHNOLOGIES

There are numerous energy storage technologies currently available ranging from short-term methods for second-to-second variations in renewable output [7], to longer term utility-scale methods of which pumped storage hydroelectric (PSH) is the most well-known and robust.

PSH is the oldest and most common form of utility-scale energy storage [8]. During low demand, energy is used to pump water from a lower reservoir to a higher reservoir. During peak demand, the water in the higher reservoir flows back down to the lower reservoir through the same pump (typically a Francis pump, now acting as a turbine) to generate electricity. The power capacity of the system is proportional to the head (height difference between the upper reservoir and the turbine) and flow rate. The energy capacity is further proportional to the volume of reservoirs available for the turbine. Round trip efficiencies of PSH range from 75% to 85% [9]. The most recent large-scale energy storage device in the US is the Rocky Mountain Facility, a 760 MW, 6.1 GWh PSH unit in Armuchee, GA completed in 1995 [8] and [10]. For underground energy storing PSH, water is kept on the ground level rather than keeping it in a high reservoir and when energy is needed water runs down to the underground generators. The first sea water PSH was built in Japan in 1999 (Yanbaru, 30 MW) which pumps seawater 600 m to an artificially excavated upper reservoir 150 m above sea level. It is interesting to note that in the late 1970’s, Morishige, at Mitsubishi Heavy Industries proposed the concept of bottom mounted large structures for PSH [11]. Japan has many land-based PH facilities which can be used in conjunction with their nuclear power plants to meet peak demand. With additional offshore PSH and offshore windparks, perhaps an alternative to many of the nuclear plants can be achieved. Others [12-18] have since then attempted to propose seafloor mounted PSH systems to work with offshore wind turbines but none appears to have moved forward likely because of practicality constraints.

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 built in 1991 [19]. Using natural gas to heat the air entering the turbine, the round trip energy efficiency can be as high as 71% [8]. Both plants use storage in underground caverns, requiring specific geologic conditions.

Bright Energy Storage Technologies, based in Denver, CO, is pursuing a CAES concept that uses a thin-walled air storage vessel on the sea floor. When energy generation exceeds demand, air is pumped into the reservoir; when energy demand exceeds generation, the water pressure is used to force the air back up to the surface to drive the compressor in reverse [20]. Note that the seafloor unit will have to be ballasted or attached to the seafloor with sufficient force to counter the buoyant forces, but only one high pressure air line to the surface will be required. SustainX, a company based in West Lebanon, NH, is developing isothermic CAES using storage in cylinders at pressures up to 210 bar (3,000 psi) [21]. Another concept has been recently proposed that 280 m diameter spheres be placed at 2000 m depths to provide energy storage for FWTs and onshore wind turbines [22].

A. Value of Storage

The California Independent System Operator (CAISO) believes energy storage is one of three pillars required for renewables integration [23]; and the California Energy Commission (CEC) found two- to four-hour storage technically superior in lieu of similarly sized gas turbine generators for regulation of renewable power to the grid [24]. Sandia National Laboratories has also conducted extensive research on multiple benefits of long- and short-term energy storage (beyond arbitrage) and have concluded that there are at least seventeen important benefits of energy storage. As Eyer reports, it is difficult to assess the combined economic benefits when storage takes advantage of more than one of these listed benefits [4].

Storage can also help defer transmission line upgrades. In Texas, a $5B upgrade is planned to better integrate wind into the electric grid [25]. In California, the addition of 5.8 GW wind to the Tehachapi wind farms may require up to $6.2 billion of transmission line upgrades [26]. Either of these upgrades could be reduced and/or deferred if storage were available at the wind farm, allowing a steadier (albeit lower) power level to reach the largest load centers. If the high-demand areas are near the coastline, offshore wind coupled with a deep-water storage system could offer a synergistic solution providing renewable energy reliably and steadily.

Storage for arbitrage alone is not likely to cover the capital costs [10] and [27]. Positive net operating revenue requires a year-round price differential of 20-30% between peak and off-
peak rates. An additional point about arbitrage that numerous authors have highlighted is that storing large amounts of off-peak energy then using it during on-peak times effectively raises the off-peak prices and lowers the on-peak prices. Electricity prices typically follow marginal fuel costs, so as demand goes up during off-peak times, marginal prices are expected to rise [10] and [28].

In New England, reserves are required as contingency in case large power plants shutdown or other emergencies occur. TMSR (Ten Minute Spinning Reserve), TMNSR (Non-Spinning Reserve) and TMOR (Thirty Minute Operating Reserve) are set based on history and operating units. Spinning Reserve means the power plant is actually running and synchronized with the grid. Non-Spinning Reserve may be operating, but is not synchronized with the grid. In 2009/2010, typical values for TMSR and TMNSR were both 850 MW. TMOR was typically 750 MW, with net reserves of 2,450 MW. For ISO-NE, the Locational Forward Reserve Market costs were approximately $144M throughout the year [28].

III. OCEAN RENEWABLE ENERGY STORAGE (ORES) CONCEPT

PSH are well-proven on land, and in 2008 we began to investigate the concept of locating large concrete structures on the seafloor where 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 MWh) of the storage cylinder can be related to the sphere inner volume, efficiency of the pump/turbine unit, and depth:

\[
C_{\text{max}} = \frac{\rho \eta_{\text{tur}} d g V_{\text{inner}}}{3.69 \times 10^6} \tag{1}
\]

Since pressure increases by 10 bar every 100 m (0.44psi/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 cavitation. As 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 in (1) by about 5%. A vent line to the surface, e.g., through tension legs for a TLP FWP could mitigate pump cavitation concerns and let the spheres work to theoretical maximum capacity. Individual spheres could each have a dedicated pump/turbine unit, or several spheres could share a modular common pump/turbine unit through piping interconnections.

Our 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 (Note: All references to sphere diameter are interior diameter unless otherwise specified.) would require 5,000 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 a FWT [30]. If a tension leg system is used, up to 3,000 mt of ballast may be required for a 5 MW FWT [6]. We found the cost of ballast, its transport and deployment, and the cost of the additional structure to contain it favored a simpler approach of making the sphere wall thicker and uniform, as discussed in detail later. Incorporating the ballast in the design by making 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 MWh of storage.

A. Potential Sites

Using a combination of bottom contour maps available from the National Oceanographic and Atmospheric Administration (www.noaa.gov) and Google Earth, areas were identified that appear most conducive (200+ m depths) to deep-water energy storage within 125 NM of large population centers. A summary of the areas considered with potential wind farm capacities is shown in Table I. The wind farm capacity used the same 5 MW/km² as in [1]. This may be optimistic, where the wind densities along the southern coasts of Spain and France appear to be lower than those assumed by Musial and Ram for US offshore sites. These areas, like those evaluated off the coast of the US, were limited to those where wind farms and storage would be co-located in bottom depths most economical to storage. Separating storage from the wind farms would open up additional areas for future evaluation.

<table>
<thead>
<tr>
<th>Location</th>
<th>Area (km²)</th>
<th>Distance from Shore (NM)</th>
<th>Depth (m)</th>
<th>GW (MW/km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gulf of Maine</td>
<td>1,170</td>
<td>50-75</td>
<td>200-300</td>
<td>5.8</td>
</tr>
<tr>
<td>San Diego</td>
<td>51</td>
<td>6-8</td>
<td>400-600</td>
<td>N/A²</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>580</td>
<td>20 &amp; 85 ³</td>
<td>200-600</td>
<td>2.9</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>25</td>
<td>30</td>
<td>800-900</td>
<td>N/A</td>
</tr>
<tr>
<td>San Francisco</td>
<td>500</td>
<td>15</td>
<td>200-600</td>
<td>2.5</td>
</tr>
<tr>
<td>Hawaii (Oahu)</td>
<td>40</td>
<td>3</td>
<td>500-600</td>
<td>N/A</td>
</tr>
<tr>
<td>Hawaii (Big Island)</td>
<td>200</td>
<td>3</td>
<td>400-600</td>
<td>1</td>
</tr>
<tr>
<td>Lake Michigan</td>
<td>1,000</td>
<td>30</td>
<td>200-300</td>
<td>15</td>
</tr>
<tr>
<td>Bay of Biscay</td>
<td>1,700</td>
<td>15-25</td>
<td>400-500</td>
<td>5.4</td>
</tr>
<tr>
<td>Med Coast of Spain</td>
<td>6,000</td>
<td>15-30</td>
<td>400-500</td>
<td>30</td>
</tr>
<tr>
<td>South France</td>
<td>3,000</td>
<td>5-40</td>
<td>400-500</td>
<td>15</td>
</tr>
<tr>
<td>Taiwan</td>
<td>4,000</td>
<td>10-125</td>
<td>100-400</td>
<td>20</td>
</tr>
<tr>
<td>Hong Kong, PRC</td>
<td>4,000</td>
<td>80-150</td>
<td>200-500</td>
<td>20</td>
</tr>
<tr>
<td>Japan (Hokkaido)</td>
<td>4,000</td>
<td>3-60</td>
<td>200-500</td>
<td>20</td>
</tr>
<tr>
<td>Japan (Tokyo/Chiba)</td>
<td>400</td>
<td>45-55</td>
<td>200-400</td>
<td>2</td>
</tr>
<tr>
<td>Japan (Kyoto)</td>
<td>1,800</td>
<td>20-30</td>
<td>300-500</td>
<td>9</td>
</tr>
<tr>
<td>Turkey (Izmir)</td>
<td>200</td>
<td>3</td>
<td>300-800</td>
<td>1</td>
</tr>
<tr>
<td>Turkey (Hatay)</td>
<td>250</td>
<td>8</td>
<td>200-1,000</td>
<td>1.2</td>
</tr>
<tr>
<td>Turkey (Canakkale)</td>
<td>250</td>
<td>2-3</td>
<td>200-300</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Our initial surveys show it can be challenging to find large areas with excellent wind resources, good bottom topography

1 Where \( \rho_{sw} \) is density of seawater (1025 kg/m³), \( \eta_{\text{tur}} \) is the turbine efficiency (85%), \( g \) is 9.81 m/s², \( d \) is depth in meters, \( V_{\text{inner}} \) is the interior volume of the sphere, and 3.69E9 is the conversion from Joules to MWh.

2 Storage-only, either due to proximity to land or poor wind conditions.

3 The two distances reflect two areas in 300-500 m deep water.
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. The total cost for such a system would likely be more than the original concept described previously because the FWTs would then require anchors and additional transmission lines would also be required.

The sites we evaluated included New England (Fig. 3), Southeast US coast (South Carolina, Georgia, and Florida), Gulf of Mexico, Northern California (Fig. 4), Southern California (Fig. 5), Lake Michigan, and portions of Hawaii (Fig. 6). Focused analysis on the most cost-effective set-up for wind farms in any location has been limited to publically available historical wind data\(^4\). Storage-only scenarios, however, could be investigated for nearly any site where bottom topography details are available.

Hawaii has committed to supplying up to 70% of its energy needs from renewable energy sources by 2030 [31] and [32]. In 2008, plans were announced to install 400 MW of wind turbines on the islands of Molokai and Lanai to provide power to the island of Oahu via an underwater power cable\(^5\). This power cable passes through the Ka’iwi channel South and East of Oahu with depths of water between 500 m and 700 m. Large-scale energy storage could thus play a vital role in integrating the large wind penetration into the existing Hawaii grids [33].

### IV. 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 \((\rho)\), gravity \((g)\), and a Factor of Safety \((FOS)\):

\[
d = \frac{2 \cdot S(r_o^3 - r_i^3)}{3 \cdot (FOS) \cdot \rho \cdot g \cdot r_o^3}
\] (2)

For example, using standard values for \(g\) and \(\rho\)=1025 kg/m\(^3\), a 25 m diameter sphere with a wall thickness of 2.0 m, a safety factor of 1.5 and 34.5 MPa (5,000 psi) concrete could be safely deployed to a depth of 548m. To be self-ballasting for a tension leg FWT, however, requires a wall thickness of 2.6 m.

Ballast requirements are determined by estimating the total displacement of the sphere based on the volume of the sphere and its conical base, and the total weight of the concrete and any structural steel used. In order for the sphere to remain on

\(^4\) Wind data was downloaded from the National Data Buoy Center (www.ndbc.noaa.gov) for numerous weather buoys. Supplementary materials on how wind data was height corrected from the standard 5 m anemometer height are available on http://pergatory.mit.edu/ores

\(^5\) The addition of the 400MW wind farm on Molokai and Lanai plus another 100MW of potential wind and/or solar power on Oahu would achieve a renewable penetration of 78% of the minimal load condition on Oahu (Matsuura, 2009).
the bottom of the ocean and still provide sufficient ballast for the FWT, its weight has to be 500 mt greater than its displacement. The interior volume $V_{inner}$ was determined from the desired energy storage, using (1) while the inner radius is:

$$r_{inner} = \frac{3V_{inner}}{4\pi}$$  \hspace{1cm} (3)

The volume of shell, $V_{shell}$, volume of base, $V_{base}$, and displacement, $\Delta$, however, requires knowledge of the shell thickness:

$$V_{shell} = \frac{4}{3}\pi(r_{inner} + t)^3 - r_{inner}^3$$  \hspace{1cm} (4)

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

$$V_{base} = \frac{14\pi (r_{inner} + t)^3}{75}$$  \hspace{1cm} (5)

The weight and displacement of the resulting sphere with conical base are:

$$Wt = (V_{shell} + V_{base})\rho_{concrete} = \Delta + \text{Ballast}$$  \hspace{1cm} (6)

$$\Delta = \frac{V_{base} + \frac{4}{3}\pi (r_{inner} + t)^3}{\rho_{sw}}$$  \hspace{1cm} (7)

Table II shows placing a single sphere as the gravity base for a TLP FWT in deep water may be the most economical.

### Table II Spherical Chamber with Conical Base Deployment Scenarios (INPUTS, OUTPUTS)

<table>
<thead>
<tr>
<th></th>
<th>Density sea water (kg/m³)</th>
<th>Density concrete (kg/m³)</th>
<th>Inside diameter (m)</th>
<th>Concrete strength (MPa, psi)</th>
<th>Strength Factor of Safety</th>
<th>Minimum ballast safety factor</th>
<th>Inner volume (m³)</th>
<th>Required ballast for total inner volume (mt)</th>
<th>Volume - conical base: height=base Diameter (m³) (Eq. 4)</th>
<th>FWT anchor system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1025</td>
<td>2400</td>
<td>25</td>
<td>34.5 5000</td>
<td>1.5</td>
<td>1</td>
<td>8181</td>
<td>8386</td>
<td>1145</td>
<td>Moored</td>
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<tr>
<td>Required ballast for anchoring FWT (mt)</td>
<td>500</td>
<td>3000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TLP</td>
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<tr>
<td>Total required submerged ballast (mt)</td>
<td>8886</td>
<td>11386</td>
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<td></td>
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<tr>
<td>Volume of concrete required for ballast (m³)</td>
<td>6462</td>
<td>8281</td>
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<td>Sphere wall thickness to self-ballast (m)</td>
<td>2.7</td>
<td>3.6</td>
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<td></td>
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<td>Actual submerged weight of concrete (mt)</td>
<td>10584</td>
<td>14514</td>
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<td></td>
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<tr>
<td>Actual dry land weight (mt)</td>
<td>18474</td>
<td>25334</td>
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<td></td>
<td></td>
<td></td>
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<td>Actual ballast safety factor</td>
<td>1.2</td>
<td>1.3</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Pump/turbine efficiency</td>
<td>70%</td>
<td>70%</td>
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<tr>
<td>Percent usable volume (to maintain pump head height)</td>
<td>95%</td>
<td>95%</td>
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<tr>
<td>Planned deployment depth (m)</td>
<td>400</td>
<td>400</td>
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<td></td>
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<tr>
<td>Charge capacity at 400m (MWh) (Eq. 1)</td>
<td>6.1</td>
<td>6.1</td>
<td></td>
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<td></td>
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<tr>
<td>Maximum safe depth (m)</td>
<td>678</td>
<td>815</td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>Charge capacity at maximum safe depth (MWh)</td>
<td>10.3</td>
<td>12.4</td>
<td></td>
<td></td>
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</tbody>
</table>

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 de-molding and assembly, we converged on a hemispherical assembly design shown in Fig. 7. Each hemisphere is very robust and can be made using a simple two-piece mold. 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.

To facilitate manufacturing, the bottom of each hemisphere can be a steel plate or a pre-cast post-tensioned concrete plate acting as part of the mold during concrete casting. It also provides structure for holding buoyancy modules or for lowering from a barge. In addition it provides attachment padeyes 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 transfer of any stresses to the concrete and resisting movement of the sphere due to any underwater currents that 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 where suction will also help resist dynamic loads.

Figs. 8 & 9 show the effects of gravity alone on a hemisphere section on land prior to assembly. Plain unreinforced concrete was used as the material (a specific self-consolidating, steel-fiber reinforced concrete or SC-SFRC blend has not yet been analyzed). While simple FEA verified our initial calculations, it also provided confidence that the hemi-shell will be safe and stable when de-molded.

### A. Modular Hemispherical Sub-structure

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.
Fig. 8. Hemisphere free-standing, gravity effects only; maximum displacement ~6-7 mm

Fig. 9. Hemisphere free-standing, gravity effects only, maximum stress (2.9 MPa)

Fig. 10. Displacement of full sphere (1.5mm max.) at 500 m depth

Fig. 11. Compressive stresses (24 MPa max.) due to hydrostatic pressure and maximum buoyancy at 500m depth

V. MODEL TESTS

In order to test our 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 then constructed by Iron Dragon Corp. and Newstress Corp. of New Hampshire. The small inner-diameter (75cm) sphere under a small head does not provide much energy storage; on the order of one millionth the energy storage capacity of the planned spheres. However, the lessons learned from manufacturing, handling, and assembly were tremendous and will lead towards successful, larger demonstration models we propose to test in the Gulf of Maine.

To create the concrete hemispheres, a steel mold was made from the hemi-heads used for 1,000 liter and 2,000 liter LPG tanks. The hemi-heads were modified to fit inside of each other to allow pouring of concrete, removal of each mold, and
handling of each hemisphere by chain-fall. The mold was affixed to a vibration table and Kevlar fiber 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. When the two halves were brought together and the area around the groove was sealed, epoxy could be injected into the groove. However, it was found to be difficult to achieve a seal on the interior of the groove so epoxy could not successfully be injected. A pipe coupling was also embedded in the pole to facilitate connections to the piping system. Fig. 12 shows the mold (a) and a concrete hemisphere (b).

Two concrete hemispheres were created in this way, joined and sealed on the exterior with Sikadur 32 High-Mod, from Sika Corporation. 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 (as shown in Fig. 7) 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. Fig. 13 presents the Solidworks model of the test system.

The actual test sphere assembly is shown in Fig. 14.
To simulate depth, a high reservoir was created by placing a 240 L (63 gallon) barrel on a tower, 10 m (34.5 feet) above the inlet to the turbine, as shown in Fig. 15. 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 is a PO4060 Clark Solutions Inc. rotary vane type capable of 38 L/min (10 gpm) at a broad pressure range including the prototype’s operating head of 11 m (36 feet). The turbine is a Turgo type from Hydro Induction Power Inc. 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 feet) of head. The flow to the turbine was adjusted by using different diameter nozzles to maximize efficiency as presented in Fig. 16. Electrical output from the turbine unit is measured as it is dumped to an adjustable load resistor which was also optimized for maximum efficiency as shown in Fig. 17.

Testing of the micro device consisted of two phases: discharging and storing energy. First, water was allowed to flow through the turbine into the sphere, discharging the energy, until either 190 L (50 gallons) had flowed or atmospheric pressure was reached inside the sphere. 190 L (50 gallons) 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 up until the sphere was empty again, and thus fully charged with energy.

Data was collected for two test cases: with a vent line and without. A full sized ORES device could be fitted with a vent line from the sphere to the atmosphere ensuring that the pressure inside the sphere remained near atmospheric (aside from piping losses) as the sphere was charged and discharged. The vent line would thus allow the sphere to be fully filled without leaving space for compressing gasses. In the case without a vent line, a fully charged (empty of water) sphere is evacuated to low pressure and as the device cycles, the gases within are allowed to compress and expand. The available pressure is defined as the difference in pressure from the inside of the sphere to the outside which, in this case, is the pressure at the nozzle minus the internal pressure. Data from
typical runs of each case are shown in Figs. 18-19 and tabulated in Table III.

![Fig. 18. Power from a typical cycle with a vent line](image)

![Fig. 19. Power from a typical cycle without a vent line](image)

The power output for the turbine and the pump can be seen to change with the available pressure, increasing and decreasing with it. Without the vent line, the change in power output of the pump and turbine are evident with the changing available pressure. With the vent line open, the available pressure still changes a small amount due to the changing height of the water column as the barrel empties and fills. In this case as well, the turbine and pump powers follow the available pressure accordingly. 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 as clearly seen 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. As such, the total amount of energy stored per gallon and the power output of the turbine are larger however, the pump’s power consumption is as well. By reducing the pressure inside the sphere to 0.55 bar (8 psi), we were able to add 0.46 bar (6.7 psi) to the available pressure which allowed an 81% increase in power per liter. However, in deeper water, the 0.46 bar (6.7 psi) increase will be less significant compared to the total head.

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. Comparing the costs associated with a varying output and a difference in storage capacity with the price of installation and maintenance of a vent line is outside the scope of this paper but may have to be done on a site by site basis as an optimal solution will depend on the depth of the site.

While the test unit has low round trip efficiency, it should be kept in mind that pumped hydro installations successfully achieve round trip efficiencies in excess of 70%. Future devices will have several improvements. The first improvement will be to use more efficient turbines and pumps. Rotary vane pumps have inherent friction losses between the vanes and the pump casing. Future versions will also be able to pump more slowly reducing piping losses. Furthermore, since the device tested here is 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 air-tight seal. This pressure limitation reduced both the usable volume of the sphere and the storage capacity; however, any device placed on the sea floor would not be subject to this limitation. Finally, the leak rate for these experiments was 0.3 kPa/min and future spheres will improve upon this. A vent line would allow filling to a higher level than without it, which becomes more significant as the head becomes higher.

### Table III Data from a typical discharge and storage cycle

<table>
<thead>
<tr>
<th></th>
<th>Vent Line</th>
<th>No Vent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head, average water column (m)</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>Head, vacuum (m)</td>
<td>0</td>
<td>4.8</td>
</tr>
<tr>
<td>Head, total (m)</td>
<td>12</td>
<td>16.8</td>
</tr>
<tr>
<td>Cycle water volume (L)</td>
<td>189</td>
<td>75.7</td>
</tr>
<tr>
<td>Sphere volume (L)</td>
<td>208.5</td>
<td>208.5</td>
</tr>
<tr>
<td>Volume utilization</td>
<td>91%</td>
<td>36%</td>
</tr>
<tr>
<td><strong>Turbine</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total energy produced (J)</td>
<td>9,434</td>
<td>6,203</td>
</tr>
<tr>
<td>Average power (W)</td>
<td>73</td>
<td>103</td>
</tr>
<tr>
<td>Average flow rate (L/min)</td>
<td>64</td>
<td>68</td>
</tr>
<tr>
<td>Run time (s)</td>
<td>130</td>
<td>60</td>
</tr>
<tr>
<td>Average efficiency</td>
<td>61%</td>
<td>67%</td>
</tr>
<tr>
<td><strong>Pump</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total energy consumed (J)</td>
<td>83,294</td>
<td>51,196</td>
</tr>
<tr>
<td>Average power (W)</td>
<td>312</td>
<td>374</td>
</tr>
<tr>
<td>Average flow rate (L/min)</td>
<td>30</td>
<td>34</td>
</tr>
<tr>
<td>Run time (s)</td>
<td>267</td>
<td>137</td>
</tr>
<tr>
<td>Average efficiency</td>
<td>21%</td>
<td>24%</td>
</tr>
<tr>
<td><strong>Overall System</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total recovered energy (J)</td>
<td>9,434</td>
<td>6,203</td>
</tr>
<tr>
<td>Energy recovered per liter (J/L)</td>
<td>50</td>
<td>83</td>
</tr>
<tr>
<td>Total recovered energy (Wh)</td>
<td>2.6</td>
<td>1.7</td>
</tr>
<tr>
<td>Roundtrip storage efficiency</td>
<td>11%</td>
<td>12%</td>
</tr>
</tbody>
</table>
VI. LARGE SCALE MANUFACTURING

A. Concrete

Significant research has been conducted in academia and industry on steel-fiber reinforced concrete (SFRC) and glass-fiber reinforced concrete (GFRC). Long-term performance of these high-performance concretes in marine environments is still an ongoing research topic. Both SFRC and GFRC have been shown to mitigate cracking; SFRC has been shown to handle much greater cyclic stresses than un-reinforced concrete [36] and [37]. While the costs for SFRC can be estimated using available publications [38], cost estimations for large volumes of GFRC were more difficult to obtain. The concrete used in the simulation was assumed to contain 44.5 kg of steel fiber per cubic meter.

Another assumption for this concept is the use of self-consolidating concrete (SCC), also known as self-compacting concrete, in order to reduce labor costs, simplify mold construction, increase productivity, and reduce probability of voids developing in the poured concrete. SCC has been used in construction since approximately 1985 [39]; fairly recently, SC-SFRC has been researched for different applications. However, most research shows the properties that make SFRC best (typically longer, larger fibers) make the product less capable of self-consolidating (where shorter or no fibers would be preferred). The optimum point of fiber size, number, and shape for best self-consolidating and best crack-mitigation/cyclic stress performance remains a major point of research [27] and [40].

B. Pump/Turbine System

Single-stage pump/turbines that can handle up to 700 m head have been designed and tested [41]. 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. We believe 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 maintain 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. This may be as simple as an actuated gate or ball valve.

C. Manufacturing

A 25 m inside diameter sphere requires approximately 10,000 mt of concrete, poured in two 5,000 mt hemispheres over a 21-hour period; a 30 m-diameter sphere requires approximately 20,000 mt of concrete, poured in two 10,000 mt hemispheres over a 42 hour period. 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 16,000 m^3 or nearly 40,000 mt [42].

Constructing thousands of spheres will require such pours on a daily basis: 2,400 spheres over five years, averages out to over two spheres per working day which, combined with cure times, means many forms will be required to manufacture units in parallel. Shipping such large quantities of material is not new; the largest coal power plants in the United States consume over 33,000 mt of coal every day they are operating at full power.\(^8\) Also, in 2005, approximately 1 billion mt of concrete was manufactured; implementing a 3 GW, 10 hour storage system would require approximately 10 million mt of concrete every year, requiring only a 1% increase in concrete production [43].

As Fig. 20 shows, a shipyard type area would be required for manufacturing the storage spheres.

Fig. 20. Storage sphere casting and assembly concept of manufacturing

Some of the major factors that we believe will drive choices of manufacturing sites include:

1. Sufficient acreage for lay-down areas, on-site mold assembly, on-site buoyancy module assembly, segment curing and sphere assembly. For the simulation where 2,400 spheres are created in five years, over two spheres must be manufactured and launched every day. If built at one manufacturing site, this requires space for 26 mold assemblies plus lay-down or holding areas for two sets of base-plates and two pump/turbine units per day and material holding areas able to accept 40,000 mt of concrete (cement, fly ash, aggregate, etc) and a to-be-determined amount of grout and mold-release per day.

2. Sufficient channel width to allow for 40+ m wide barges or spheres with buoyancy modules attached to safely clear.

3. Sufficiently long quay for loading spheres onto 170+ m barges. If buoyancy modules or pontoons are used, a marine railway or Syncrolift-type drydock for launching the spheres with attached buoyancy modules.

\(^8\) On average, 0.47 mt of coal is required per MWh electricity. The largest coal power plants in the United States can generate over 3,000MW, which requires 3000 * 24 * 0.47 = 33,840 mt coal per day at 100% power. (Ref: http://web.mit.edu/mitel/docs/reports/table-plants.pdf, accessed 02/18/2011)
4. Maximum depth channel to minimize the size of barges required to tow through the channel (we have analyzed depths between 8 m and 12 m).
   a. Storage capital costs increase by approximately 2% for every 2 m shallower channel due to the increased size of barge required to lift the large spheres up.
5. Proximity to concrete supplier by railway or barge.
   a. For our scenario where a 3 GW, 10-hr storage farm is built in five years, 40,000 mt of concrete is required per day. Obviously, multiple manufacturing sites would each require lesser amounts.
   b. In the US, it is estimated that 1 billion tons of concrete are used every year, so the amounts listed above constitute at most 1% of the total concrete production in the US every day. Past examples of such large resource consumption include the Hoover Dam and US Liberty ship production in World War II.
7. Adequate water supply: while actual water usage can vary considerably depending on various additives and desired working and cured characteristics of the concrete, water constitutes up to 40% of the weight of the Portland Cement/fly ash used when mixing concrete [36]. This equates to ~1,760 cubic meters/day for concrete, plus whatever is used for clean-up, etc.

The cost of the modifications to a manufacturing site required to meet some or all of the above criteria were not estimated for this paper but will be addressed in future research.

Although a sphere is the most structurally efficient system, earlier cited references for other underwater storage structures would require similar manufacturing efforts. The key for any shape structure is that many will be required, and in some cases assembled and fluidically coupled together either on the surface or on the seafloor so high volume manufacturing and assembly techniques will have to be developed and deployed.

D. Towing and Deployment

In order for the spheres to be towed from their manufacturing site to a deployment site, some form of significant buoyancy will be required as most ports have channel depths of only 15 m. We have looked at ideas for using barges, buoyancy modules, floating drydocks, and docking ships and believe the two most feasible methods will be to use a barge or buoyancy modules. The economic simulations assume a barge that can carry up to 45,000 mt of spheres then lower the spheres by winch assemblies through moon-pools built into the barge. A potential loading and deployment sequence is illustrated in Fig. 21.

Once a sphere is towed out to the site, it must be lowered to its proper location to anchor a FWT. If the delivery of the FWT does not coincide with delivery of the spheres, then the spheres could be lowered first and cable, mooring line, and connections can later be made up by ROV. Alternatively, the connections can be made up prior to lowering and tied off to a temporary buoy prior to delivery of the FWT.

The barge concept with moon-pool would allow the spheres to be lowered by winch to the sea bottom. If buoyancy modules are used, they could be designed to flood down to allow a controlled descent to the bottom, removed by remote pelican hook operation, then lifted in a controlled manner using high pressure air, much like how a submarine surfaces.

Alternatively, individual pieces can be cast and brought to the offshore site and assembled, where each part added increases the total weight, but also the buoyancy. Epoxy and post tension cables could be used to hold the assembled structure together as is done with precast bridge and building segments.

Since large thick concrete sections often require cooling channels and several weeks to obtain full strength, it is estimated that it could take a month from start to finish to build and deploy a unit; hence any large scale effort will require manufacturing of multiple units concurrently. This increases capital costs, but given the tens of thousands of spheres that would be required to complete an offshore wind energy system that provides a significant portion of a country’s electric power needs, such costs should be strategically justifiable.
E. End of Life Analysis

For a Life Cycle Analysis (LCA) of the ORES system, our initial minimum assumption is for a twenty-year life; however, various concrete offshore platforms built in the North Sea have proven themselves for over forty years. Assuming one complete storage cycle every day, a forty-year life results in approximately 14,600 cycles over its lifetime. If we find that utilization of SFRC or GFRC allows for greater cyclic loading, and the performance of the concrete still meets our design criteria, then the spheres should continue to provide storage even beyond forty years. Pump/turbine unit replacement or refurbishment would likely be required more frequently but better maintenance estimates have not been determined yet.

With regard to maintenance costs, the assumption is the pump/turbine unit would be over-engineered for reliability and its maintenance costs would consequently be minimized. Tension legs would serve as guide rails for ROVs to facilitate maintenance when required. In addition, all underwater connections will be designed to simplify ROV tasks. The expectation is that pump/turbine units would be swapped out for repairs. The design of the ORES device will draw on the expertise of subsea oil production systems which are designed to operate at ocean depths for extended periods with minimal maintenance. Our analysis assumed annual maintenance costs equal to 1% of total storage system capital costs.

For eventual end-of-life/decommissioning of the storage spheres, it is assumed the sphere will act as an artificial reef with positive benefits towards cultivating deep sea marine life. When or if the storage spheres have served their purpose, or if normal wear and tear have lessened their efficiency (leaks) to the point of being ineffective, the vision is for the pump/turbine units and transmission lines to be salvaged but the actual spheres left in-place to continue to serve as artificial reefs since the structural materials are themselves benign.

VII. SYNERGISTIC BENEFITS

In addition to deployment of the energy storage structures reinvigorating coastal manufacturing industries, fly ash from coal-fired power plants will be consumed and artificial reefs which can help replenish fish stocks will be created.

A. Utilization of Fly Ash in Concrete

Approximately 57 million metric tons of fly ash/year is produced in the United States [45]. About 40% is used for industrial purposes, including as a substitute for cement in concrete, while the rest is stored until it can be disposed of. This can cause problems for the local environment, as experienced by Tennessee’s Kingston plant on December 22, 2008 after a fly ash retention pond gave way, releasing 5.4 M cubic meters of fly ash into the Emory River; the cost of clean-up has been estimated at up to $825 million, not including regulatory action, litigation, or long-term remediation [46].

Grade F fly ash from burning older anthracite and bituminous coal, has been shown to be a viable, low cost alternative to Portland Cement. Grade C fly ash, from burning of younger lignite or subbituminous 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. Portland Cement makes up approximately 11% of the weight of concrete, in marine applications. Up to 30% by weight of Portland cement can typically be replaced by fly ash, or 3% of the total weight of concrete. Use of fly ash lowers both the cost and CO₂ emissions associated with concrete manufacture, improves workability and strength development, and reduces heat build-up during curing [47].

Up to 50% fly ash has been tested and shown to have improved resistance to chloride penetration [40], [48] and [49]. Some research has been done on concrete created with 100% fly ash at strengths up to 30 MPa (4,000 psi). When using aggregates of crushed glass (essentially producing a nearly 100% fully recycled material concrete), strengths in excess of 48 MPa have been achieved [50]. However, the carbon content must be low, and some older power plants do not burn hot enough to produce low carbon fly ash, although this could help motivate their conversion to a cleaner (hotter) burning process. ORES structures could thus be an important new market for fly ash as shown in Table IV. The total concrete weight varies slightly less than the inverse of depth due to the weight of a (steel or heavily reinforced concrete) baseplate assumed to be part of the sphere bottom. Note that for depths below the maximum deployment depth shown in Table 2, higher strength concrete should be used instead of just increasing the wall thickness (e.g., 50 MPa concrete can increase the maximum deployable depth for the TLP sphere of Table II to 1000 m).

Table IV Concrete and fly ash required for varying storage only/wind farm scenarios

<table>
<thead>
<tr>
<th>Hours of storage</th>
<th>Wind Farm Size (GW)</th>
<th>Water Depth (m)</th>
<th>Concrete (MMT)</th>
<th>Fly Ash Content (MMT)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>30%</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>500</td>
<td>82.4</td>
<td>2.7</td>
</tr>
<tr>
<td>10</td>
<td>1.5</td>
<td>500</td>
<td>41.2</td>
<td>1.4</td>
</tr>
<tr>
<td>10</td>
<td>6</td>
<td>500</td>
<td>164.8</td>
<td>5.4</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>250</td>
<td>164.8</td>
<td>5.4</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>375</td>
<td>109.9</td>
<td>3.6</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>625</td>
<td>65.9</td>
<td>2.2</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>750</td>
<td>54.9</td>
<td>1.8</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>875</td>
<td>47.1</td>
<td>1.6</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>1000</td>
<td>41.2</td>
<td>1.4</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>500</td>
<td>65.9</td>
<td>2.2</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>500</td>
<td>49.4</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Approximately 843 million metric tons of coal was used to generate 1.8 billion MWh of electricity in the US in 2009 [51] as well as 53 million metric tons of fly ash. Thus, 30 kg fly ash is produced per MWh. At 80% capacity factor, a 2,500 MW coal plant produces 525,600 Mt of fly ash per year. ORES storage spheres used with tension leg FWT, at 500 m depth with 10 hours storage requires 4.1 MMT of fly ash per GW wind farm. Assuming a capacity factor for the offshore wind farm of 50%, a 4 GW wind farm with storage equates to a 2,500 MW coal plant at 80% capacity factor; or slightly over 10 years worth of fly ash output from the 2,500 MW coal plant it might eventually replace. Hence, as offshore wind farms are phased in, the storage spheres can utilize the waste from coal-fired plants as coal plants are phased out. Based on the annual US production of fly ash, once storage sphere production is
ramped up, in a decade, about 1/3 of US electricity needs could be reliably provided by offshore wind energy.

As offshore wind energy farms are built with storage systems, the fly ash from coal burning power plants can be assimilated. In parallel, facilities to liquefy coal into transportation fuels can be built. One day in a more energy independent future, the coal fired power plants can be replaced with offshore wind, and coal will be the source for our transportation fuels. Energy “independence” might actually be a realistic goal.

B. Fisheries

The Gulf of Maine was once one of the most productive fisheries in the world. However a number of trends have greatly decreased the populations of some of the most desirable fish: Coastal Development - has ruined many key habitats of larvae and juveniles of fish, and increased pollution of rivers due to runoff [52]; Temperature Trends – warmer water has significantly reduced habitat for key species; Salinity Trends - Due to changing weather patterns, there has been a notable increase in rainfall in the Northeast and additional fresh water flowing from rivers has worked to decrease the salinity in the Gulf of Maine coastal area. This is problematic for species survival, as many species require a very specific salinity range to thrive.

With certain enhancements, the creation of FWT farms with bottom based energy storage spheres could help re-populate the Gulf of Maine and other locations. Sphere deployment in the Gulf of Maine would likely be at 200-350 m depths, offering cooler temperatures and increased salinity. Also FWT pedestals just below the surface could act as floating reefs. Table V illustrates the habitat requirements for some important species at various stages of life and shows wind farm enhancements would satisfy the habitat requirements for various life stages of targeted species. Halibut, Monkfish, Whiting and Pollack all go at least 300 m deep, and are viable species to examine further for our 300-350 m deep artificial reefs. Pollock live all the way down to 365 m and <14 degrees C, and are known to live in artificial reefs. Cod typically live down to 150 m, yet can tolerate the salinities associated with much deeper depths, so they also could potentially survive in this environment [53].

Near the surface at the wind turbine structure, Fish Aggregation Devices (FADs), 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. Juveniles prefer habitats closer to the water's surface providing warmth and many places to hide. 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 in since, for example, juvenile flounder prefer inland marshes [54]. This environment might be able to support juveniles brought in from hatcheries. Furthermore, these floating surfaces might be configured as wave energy harvesters.

![Fig. 22. Effect of depth and distance from shore on cost per kWh](image)

VIII. Economic Viability

The economics concerning ORES appear to be very favorable. Preliminary analysis indicates ORES will be price competitive with conventional PSH and CAES at about $0.10-$0.15/kWh. ORES can be viable at depths of as little as 200 m. However, by incorporating the ballast into a thick wall, it can be used without modification at depths up to approximately 700 m. Over this range, performance increases with depth, but cable and deployment costs increase only marginally; hence deeper is better. Other critical factors include distance from shore and distance to metropolitan or industrial areas with high energy demand which affect transmission and deployment costs, material costs, fabrication costs. Fig. 22 illustrates the effects of depth and distance from shore on cost per kWh for storage.
of storage rises. Other economic viability factors include the variety of utility-scale storage benefits related to grid integration of renewable generation and grid-wide load-leveling of all generation [4], alternative models for managing energy storage, and significant synergistic benefits associated with fabrication and deployment.

Optimization of storage levels and control is an area of further research. This is a complex issue that is affected by modeling of generation profiles if ORES is to be partnered with offshore generation platforms, as well as consideration of grid-wide storage benefits.

When deployed in conjunction with floating generation platforms ORES also doubles as the anchoring point. The actual Cost of Storage is not the full deployment cost; more accurately it is the incremental cost of deploying ORES over the cost of an alternative anchoring system that does not provide the same storage benefit.

As detailed previously, there are also synergistic benefits of fabrication and deployment: The spheres will use significant amounts of fly ash as a substitute for 30-50% of the Portland cement in the concrete. The submerged spheres can also sometimes serve as artificial reefs which can have a positive impact on fisheries and the communities that rely on them for their livelihood. Surface features could potentially be modified using attachments and/or coatings to favor particular species.

The manufacture and deployment of ORES will also help to revitalize local economies. New jobs required for the manufacture, deployment, and maintenance of FWT farms and energy storage spheres could be significant. NREL estimated that a factory that produces 100 MW/year of wind turbines, can create up to 2,000 jobs9 [1] and [55]. We estimate the manufacturing of a large-scale storage system could increase both factors (jobs and economic activity) by up to 25% based on the additional manufacturing requirements for the storage spheres and ancillary equipment; return on investment (ROI) comes from the harvest, storage, and sale of wind energy.

Using NREL’s job estimate and applying it to a scenario where a 3 GW wind farm with 10-hrs storage is built and installed over five years (or an average of 600 MW of installed capacity per year), approximately 12,000 jobs are required to support the production of floating wind-turbines, cabling, and associated equipment and infrastructure for just the wind farm. Approximately 3,000 jobs could be required at or near a sphere manufacturing site for construction and assembly of the spheres, steel-work, and pump/turbine units. An additional 1,000 people may be required to build the towing barges and installation vessels needed prior to sphere manufacturing for deployment and installation of the spheres. Thus as many as 16,000 jobs could be created for the entire project. 10 If simple concrete anchors are used instead of the ORES spheres they would also contribute to employment, but at a level well below the 25% level estimated for the storage spheres.

Ancillary benefits of this scale of project would include reigniting manufacturing in and around US ports, re-capitalization of US shipbuilding to build the necessary support vessels, and other infrastructure upgrades required to deliver significant amounts of raw materials to the manufacturing sites.

Preliminary site assessments indicate ORES can be applicable globally11. Possible sites for ORES development, either in conjunction with generation or as Storage-Only projects, thus far considered include the Gulf of Maine, coastal areas adjacent to San Diego, Los Angeles and San Francisco, Hawaii, Lake Michigan, as well as Argentina, Brazil, China, United Kingdom, France, Spain, Turkey, Ireland, Norway, Hong Kong, Japan, and Taiwan.

IX. CONCLUSIONS

ORES can provide storage to complement offshore wind energy farms so power can be provided on a more reliable and predictable basis, facilitating grid integration. When viewed on a grid-wide basis storage capacity can play a critical role in stabilizing the grid, providing ready reserves to displace standby losses and reduce reliance on generation by peaker plants. The ORES system also provides other synergistic benefits: the spheres can act as moorings for FWTs, serve as artificial reefs for sea-life, make productive use of large quantities of fly ash, and be a significant source of quality sustainable employment.

The design theory was verified by FEA and feasibility investigated by fabrication and testing of a small-scale concrete sphere with small head hydro turbine and pump located at the base of a water tower. Notably the sphere was made using fiber reinforced concrete with minimal need for epoxy coated (corrosion resistant) steel reinforcing bars which if scalable, should help to reduce cost and increase life. The turbine efficiency of the small system was good for its size and pressure limits, but the round trip efficiency of the system was low (11%) due to the use of a vane pump instead of a reversible turbine.

PSH round trip efficiencies are in the range of 70-85% [56], with a long history dating back to the 1890's in Italy and Switzerland, and the 1930's in the U.S. and Japan. Taking what we believe to be a conservative approach we adopted the 70% lower bound of the round trip efficiency range. State of the art designs imply 85% turbine efficiency for a round trip efficiency of 70%. If a more modest 80% efficiency is assumed, then round trip efficiency will be 65% and there is a corresponding decrease in storage value and ROI, but the result is still compelling.

When the test system was run closed to the atmosphere so low pressure was generated as the water was pumped out, the vane pump became very noisy, possibly due to cavitation although the pressure inside the sphere was above that where cavitation should occur; however, this shows that more work is needed in the area of pump selection and deployment. If an

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9 These jobs are required as long as primary production of the wind turbines and support equipment continues. Operations and maintenance jobs that are manned as the wind farms are operating were not calculated separately.

10 This does not include establishment of the manufacturing site, bottom surveys, environmental studies and other work required prior to engaging in full-scale production nor does it assume all the jobs will remain once production is complete. For instance, the jobs required for production of barges, tugs and deployment vessels might not be required once the spheres commence production.

11 Supplementary materials on suitability of other sites as well as other synergistic benefits are available on http://pergatory.mit.edu/ores
ORES sphere was deployed as the energy storage unit and anchor for a tension leg platform FWT, the tension legs could be tubes, which could also serve as snorkels and power cable conduits.

Based on the design and fabrication of the small scale test unit, concepts for large scale production and deployment were generated and presented that indicate shoreline based facilities could achieve production rates required for large scale ramp-up of offshore energy systems. Further work is required to develop these systems in more detail, and the next step would be to design, build, deploy and test offshore a 3 m diameter sphere in 30-40 m of water.

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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REFERENCES


[16] Cassidy US Patent 4,211,077


[18] M. Kubb Canadian patent publication 2 467 287


Dr. Slocum has received numerous R&D 100 awards for his contributions to technology and innovation. For example, he created 11 products that have been awarded R&D 100 awards, each for material innovation and efficiency. In 1995, he was awarded the Martin Luther King Jr. Leadership Award. He has also received the SME Frederick W. Taylor Research Medal, and the ASME Leonardo da Vinci and Machine Design Awards. Dr. Slocum has completed numerous Ironman triathlon events, is a rescue certified SCUBA diver, an avid snowboarder, woodworker, and has for many years helped coach a FIRST robotics team with his wife Debra.

**Gökhan Dündar** was born in Ankara, Turkey in 1984. He received his B.S. (2006) in mechanical engineering from the Turkish Naval Academy in Istanbul, Turkey and is a S.M. candidate (2012) in mechanical engineering at MIT in Cambridge, MA. He entered the Turkish Naval Academy in 2002, graduated in 2006 and has served 3 years as an officer in the Turkish Navy, where he is currently a Lieutenant Jr. Grade. His research interests are renewable energy and large-scale energy storage.

**Brian G. Hodder** received his B.S. in public policy (1983) and MBA (1988) from Cornell University in Ithaca, NY where he received the Hemmeter Award for Entrepreneurship. He owns UCP Consulting (www.ucpcons.com) based in Bedford, MA which is focused on clean-tech and emerging technology start-ups. Prior to founding UCP Consulting he worked with Genasun LLC, a high-efficiency solar charge controller start-up, served as COO of a start-up retail natural gas company, and was Applications Manager for Edison Mission Marketing & Trading, Inc. His current area of interest is utility-scale energy storage and business sustainability.

Mr. Hodder is a member of the International Society of Sustainability Professionals (ISSP), ASME, and Toastmasters.

**James D. C. Meredith** received his S.M. in echanical engineering at MIT in Cambridge, MA and B. Eng. (2008) in mechanical engineering from McGill University, in Montreal, Quebec, Canada. He is a fellow of the Energy Initiative at MIT and has published papers on composite materials, combustion and medical devices. His S.M. research focused on large-scale energy storage.

Monique A. Sager is an undergraduate at the University of Pennsylvania, Philadelphia, PA. She worked in the MIT Energy Initiative under Professor Slocum the summers of 2009 and 2010. Ms. Sager is a Henry David Thoreau Foundation Scholar and a member of the National Honors Society. She was president of her FIRST Robotics team at Wayland High School, and was a coxswain for the varsity crew team.