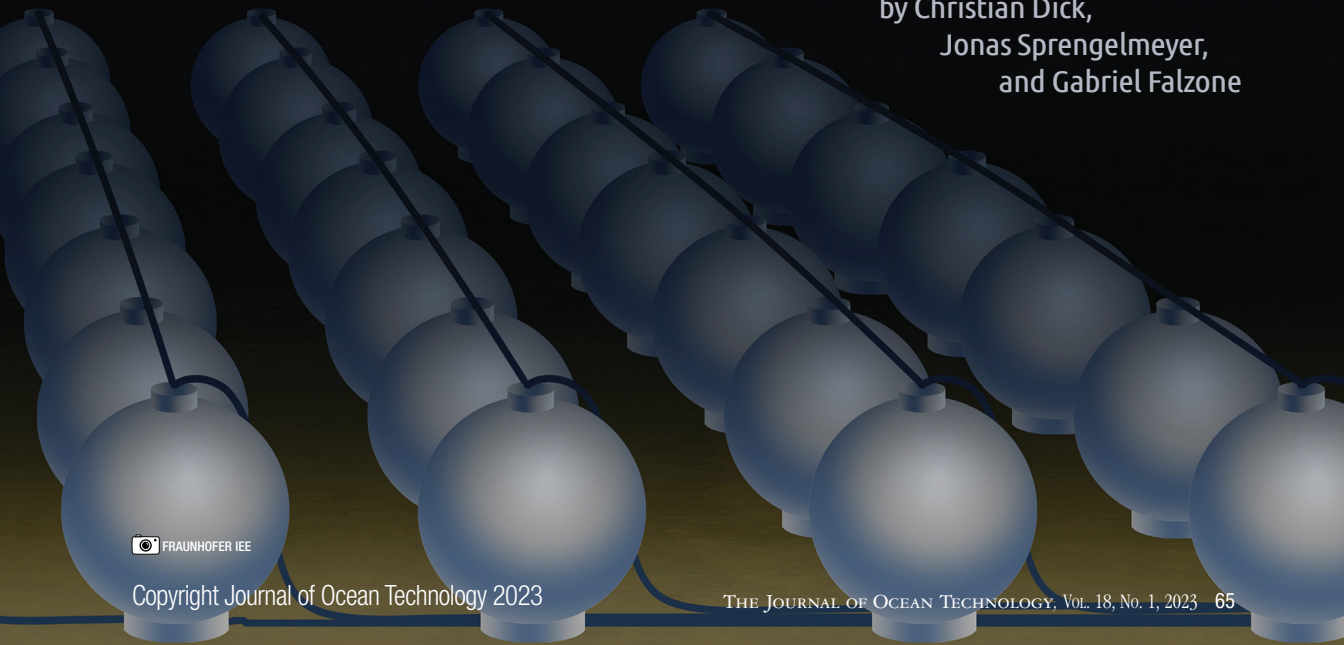




Stored Energy in the Sea

Combining 3D Printed Pumped Hydro
Energy Storage Systems with Floating
Offshore Wind in California

by Christian Dick,
Jonas Sprengelmeyer,
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Introduction

The energy production of wind turbines increases when they are located near the shore or even offshore since the wind speeds are higher and the wind blows more freely compared to locations in the countryside.

The installation site has an impact on the design of the turbine, which generally leads to higher rotor diameter but lower hub heights for offshore or nearshore wind turbines, but also affects several other design parameters due to the harsher environment. Neglecting these differences, the increased wind speed and quality at offshore locations have the potential to nearly double the energy yield of a wind turbine installed at an offshore site compared to an installation of the same turbine in the countryside. Consequently, there are widespread efforts to increase the number of offshore wind plants worldwide. While most offshore wind plants are installed in shallow water up to 50 m water depth, there are many coastlines where the water depth increases to higher depths near the shoreline. In these regions, floating offshore wind turbines are an option to utilize the wind energy potential.

One of these regions is California in the United States of America. California has set itself ambitious climate targets and is planning to reduce CO₂ emissions. For this reason, Senate Bill 350 increases California's renewable electricity procurement goal from 33% by 2020 to 50% by 2030 and to 100% by 2045 as mandated by Senate Bill 100. To achieve this goal, California must advance the development of diverse renewable energy generation and storage technologies. Among other technologies, floating offshore wind (FOW) will play a key role in this strategy. For this reason, there are currently two advertised wind energy areas (WEA) for FOW off the California coast. One of the regions stands out for its potential to install an innovative offshore pumped hydro energy storage system, which is being developed by the Fraunhofer Institute for Energy Economics and Energy System Technology IEE. In this essay, we explain the

basic working principle of this storage system and highlight the advantages of a combination with an offshore wind farm in one of the wind energy areas in California. Additionally, we introduce RCAM Technologies' approach to 3D concrete printing of renewable energy infrastructure and discuss the potential applications in manufacturing FOW anchors and the StEnSea system.

StEnSea System

The innovative offshore pumped hydro energy storage system, also known as StEnSea system (Stored Energy in the Sea system), has been proven in a field test in a [first research project](#). The StEnSea system consists of two main components. The first one is a hollow concrete sphere representing the storage tank and the other is the cylindrical technical unit holding the pump turbine, a controllable valve, and the components of the Supervisory Control and Data Acquisition system. The technical unit is removable and can be recovered separately, which facilitates maintenance and repairs.

The working principle and operating modes of the StEnSea system are similar to conventional pumped hydro energy storage systems (PHES), which use the pressure difference resulting from a height difference between an upper and a lower storage reservoir or lake. In StEnSea, the water body surrounding the sphere represents the upper storage reservoir, while the sphere interior represents the lower reservoir.

An empty sphere corresponds to a fully charged storage unit, while a filled sphere corresponds to a fully discharged one. During discharge, opening the controllable valve enables water to flow through the technical unit into the sphere. The inflowing water drives a turbine and a generator that feeds electricity into the grid. Using energy from the grid to pump the water out of the sphere against the surrounding water pressure recharges the storage system. Figure 1 illustrates this working principle.

The dimensions of the full-scale system are given in Table 1. They are the result of a

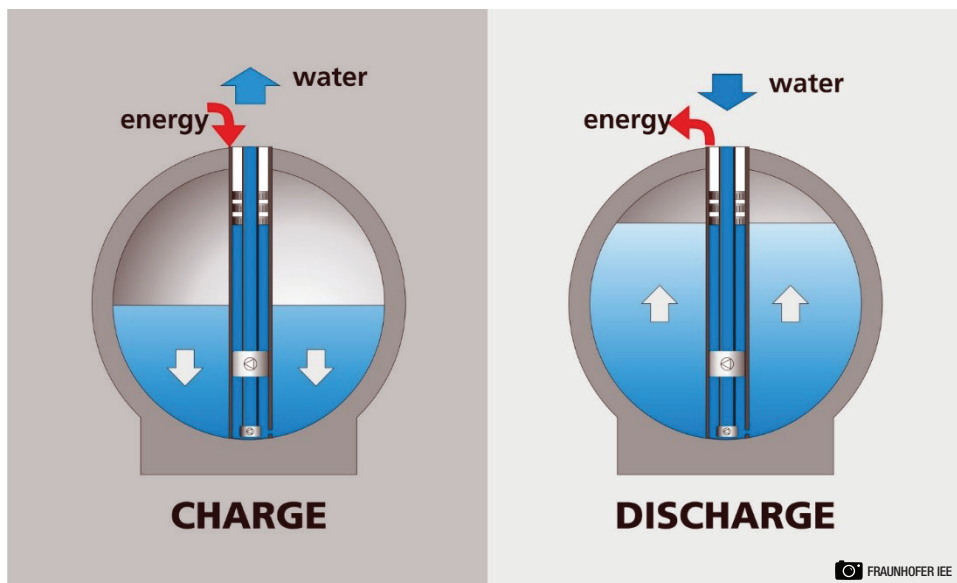


Figure 1: Working principle of the Stored Energy in the Sea (StEnSea) system.

Table 1: Technical data of the Stored Energy in the Sea (StEnSea) system.

Parameter	Value
Outer diameter	34.32 m
Inner diameter	28.6 m
Inner volume	12,249 m ³
Wall thickness	2.86 m
Concrete quantity	9,260 m ³
Concrete density	2,500 kg/m ³
Weight of the concrete sphere	23,150 t
Installation depth	750 m
Charge capacity	31.1 MWh
Discharge capacity	22.4 MWh
Power	5 MW
Discharge time	4.5 h
Full cycle efficiency	0.72
$\eta_{cycle} = \eta_{pump} \cdot \eta_{turbine}$	

feasibility study carried out by HOCHTIEF Solutions AG before the start of the first research project to determine the size and weight of the sphere, which is still manageable with the existing offshore logistics, resulting in an outer diameter of approximately 35 m. Following the selection of the diameter, two main criteria in the design of the sphere have to be ensured. On one hand, the sphere must

withstand the ambient water pressure; on the other hand, the weight of the system must be larger than its buoyancy to ensure that the sphere remains on the seabed even when it is empty. Both conditions are addressed by varying the wall thickness, since the weight and, thus, the compressive strength of the sphere increases with the wall thickness. Up to a certain water depth, the buoyancy condition

Country	Area in km ²	Capacity TWh
Total area	111,659	817
TOP 10	64,965	475
United States	10,226	75
Japan	9,511	70
Saudi Arabia	8,535	62
Indonesia	8,002	59
Bahamas	6,201	45
Libya	5,836	43
Italy	5,572	41
Spain	4,299	31
Greece	3,476	25
Kenya	3,307	24

Table 2: Worldwide Stored Energy in the Sea (StEnSea) potential.

is decisive for the wall thickness, as it depends solely on the amount of water displaced and is, therefore, independent of the water depth itself. Once the depth exceeds this threshold, the wall thickness must be increased to ensure that the sphere withstands the water pressure. This water depth threshold is approximately 750 m, which is, therefore, chosen as the rated installation depth. However, it is possible to install the sphere in lower or higher water depths. In deeper water, the capital costs would increase due to a higher amount of concrete for the required wall thickness and with it the costs for installation and transport. An installation in a lower water depth would be possible without a constructive change of the concrete sphere, but due to the lower pressure difference between the interior of the sphere and the surrounding water, the pump turbine would have to be adjusted and the energy storage capacity would decrease.

A key advantage of the StEnSea system over conventional PHES is that it offers large areas for new installation sites in deepsea waters with very limited conflicts of use, while the potential of conventional PHES is closely connected to geographical conditions and often raises environmental issues due to land use conflicts and the impact on the water regime. A site evaluation with a geographical

information system was carried out to identify potential installation sites worldwide. The following values and thresholds were used to derive the worldwide potential of the StEnSea system:

- Water depth: 600 m-800 m
- Slope: $\leq 1^\circ$
- Distance to the electrical grid: ≤ 100 km
- Distance to maintenance bases: ≤ 100 km
- Distance to installation bases: ≤ 500 km
- Unsuitable geomorphology such as trenches, spreading ridges, rift valleys, canyons, seamounts, escarpments, fans

The results in Table 2 show a worldwide potential, which exceeds the required storage need by far. Of course, there are more and less suitable locations within the resulting areas, but the techno-economic assessment must be performed individually for each site.

During the first research project in 2016, a 1:10 scaled prototype was built and successfully tested in Lake Constance. Figure 2 shows a photo of the installation. Additional simulations and analysis regarding the full-scale system moved the StEnSea system from Technology Readiness Level (TRL) 2 to 5. The investigations showed that the technical implementation in the targeted scale is possible.

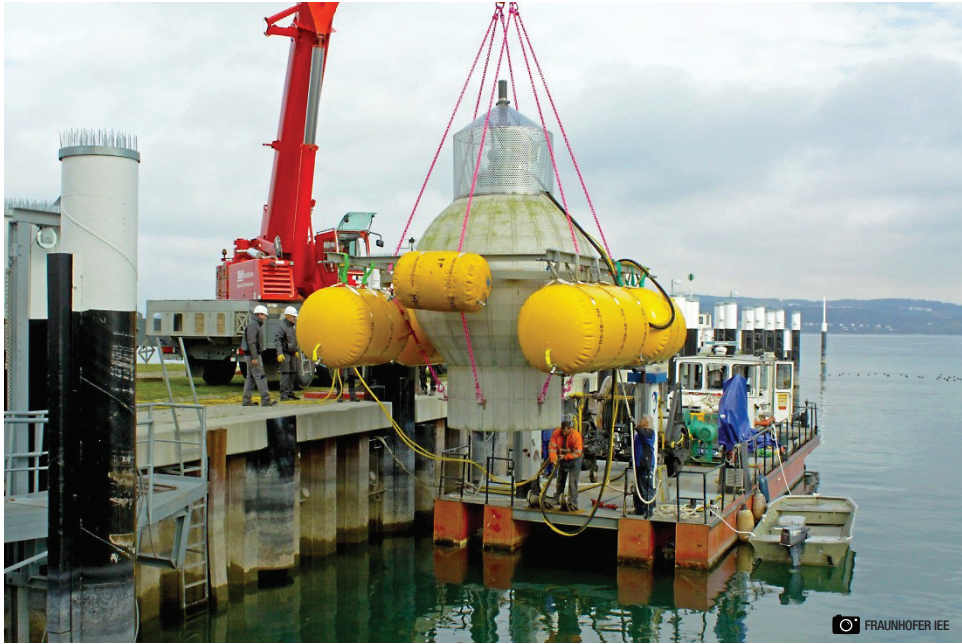


Figure 2: Installation of 1:10 scaled Stored Energy in the Sea (StEnSea) model in Lake Constance.

A follow-up research project, which is currently being negotiated with the funding agencies, aims to demonstrate the possibility to install the system in the intended water depth. It will help to gain new insights into the offshore installation and operation. Through continuous operation, it will be possible to analyze and assess long-term effects on the concrete sphere and pump turbine. The planned work would move the technology to TRL 6, preparing the realization of commercial full-scale systems. If the promising results of the first research project can be continued, the StEnSea system could become an important component of the future energy storage portfolio.

Floating Offshore Wind Areas in California

The wind resources off the coast of California have the potential to make a significant contribution to California's electricity generation and to diversify the state's energy mix. There are currently two advertised WEA for FOW in California: Humboldt WEA and Morro Bay WEA. In December 2022, an auction was held for the two areas, auctioning offshore areas with a potential of 4.5 GW and an area of 1,500 km². The potentially installed

FOW turbines at these sites could supply more than 1.5 million households with electricity.

In California, high offshore wind speeds at short distances from the coast meet great water depths between 500-1,300 m. This makes the region not only attractive for the use of FOW but also for the StEnSea system. The entire area in the Morro Bay WEA is at least 900 m deep, which would require an altered technical unit. However, an analysis by Fraunhofer IEE shows that there are great matches between the potential StEnSea system locations and the Humboldt WEA. Figure 3 shows the results of the location analysis.

As shown in Figure 3, the call area is divided into lease blocks and aliquots, with each aliquot being a square of 1,200 m by 1,200 m, equal to 1.44 km², and each block containing 16 aliquots in four rows of four, equal to 23.04 km².

The potential StEnSea system locations in the Humboldt WEA sum up to an area of approximately 120 km², which is about 20% of the total WEA. Assuming the installation of 400 spheres in an area of one km², the

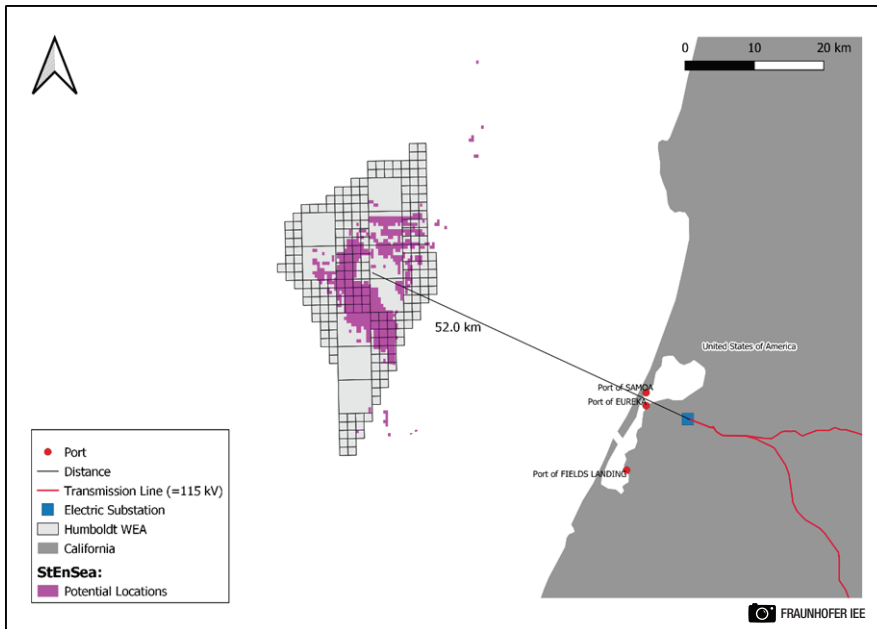


Figure 3: Stored Energy in the Sea (StEnSea) locations in Humboldt wind energy area (WEA).

total capacity would be about 1.5 TWh, which is equal to the annual consumption of approximately 150,000 households in the U.S. This exceeds the storage demand in this region by far.

Within the techno-economic analysis, the standard size of a StEnSea system park considers 80 spheres, which sum up to a power of 400 MW and a capacity of 2.5 GWh. This StEnSea system park would require an area of approximately 0.2 km² and would, therefore, easily fit in the WEA without limiting the wind energy potential. This is particularly true due to the required distances in between the wind turbines. Figure 4 shows four 15 MW wind turbines with their required distances drawn to scale. In the direction of wave, wind, and current the turbine spacing should be at least 7 rotor diameters and at least 4 rotor diameters in the perpendicular direction to reduce wake effects. Each wind turbine has three anchors that are installed in a specific distance to the wind turbine. This distance varies with the chosen mooring system, but even for the catenary mooring system with the longest distances, it is easily possible to fit a 400 MW StEnSea system park in between the wind turbines.

The combined installation enables a couple of operation modes. The first one is to combine both technologies, but to operate them separately. This would offer the chance to share the cost for the offshore infrastructure as well as the grid connection including the subsea cables. Additionally, the wind farm could be operated in combination with the StEnSea system park. Floating offshore wind farms, like other renewable technologies, are also weather dependent and there is a chance that there is no demand for electricity during particularly strong winds. The generated wind energy would then have to be curtailed or stored. Adding a StEnSea system park with additional storage capacity would allow for a significantly smoother and more reliable energy feed-in as changes in wind speed could be compensated.

Other advantages of the StEnSea system locations in the advertised WEA are an easier granting of permit for the installation and the joint use of the infrastructure for the grid integration, operation, and maintenance between the wind farm and the storage system. Furthermore, mooring systems in which the spheres could theoretically be used as anchors themselves are not applicable, since

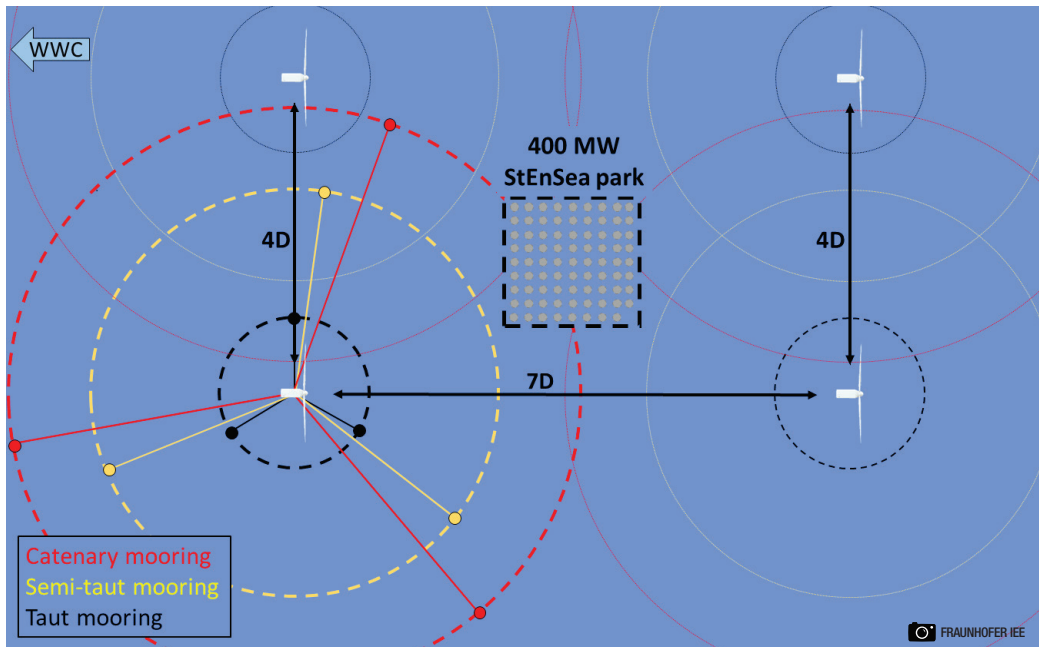


Figure 4: Wind turbine area with different mooring systems. WWC = wave, winds, currents. 4D = 4 rotor diameters. 7D = 7 rotor diameters.

the distance between two anchors is much larger than the distance between two spheres within the original layout of the storage park. The design of the sphere itself would have to change due to the installation in a variety of depths and, hence, additional load.

Considering these aspects led to the conclusion that it is preferable to use separate anchoring and storage systems. RCAM Technologies is developing innovative anchor systems for FOW plants that are made using 3D concrete printing technology. 3D concrete printing uses an automated robotic system to create complex concrete structures without the labour needs of conventional concrete forming. Compared to conventional casting, 3D concrete printing can reduce the cost of manufacturing complex designs, reduce labour cost, increase safety, and enable lean and sustainable manufacturing in a port. RCAM's designs include concrete suction anchors and torpedo anchors, which are projected to reduce costs, reduce carbon emissions, and create more local jobs than typical steel anchors. Figure 5 shows representations of RCAM's torpedo and suction anchors and the 3D concrete printing process.

As the construction of the StEnSea sphere is one of the largest costs of the system, there is potential to apply new construction methodologies such as 3D concrete printing to reduce costs. RCAM completed a proof-of-concept print with its partner Vertico in the Netherlands, which demonstrated that it is possible to print a spherical structure using present day 3D concrete printers. Figure 6 shows photographs of this completed print. RCAM is continuing to scale up and demonstrate the 3D concrete printing technology.

Conclusion

The wind resources off the coast of California have the potential to make a significant contribution to California's electricity generation and to diversify the state's energy mix. Additionally, the Humboldt WEA stands out for its potential to install an innovative offshore pumped hydro energy storage system, which is being developed by the Fraunhofer Institute for Energy Economics and Energy System Technology IEE. A combined use could have several benefits such as:

- Cost reduction through shared use of



Figure 5: Artist's renderings of 3D concrete printed torpedo and suction anchor technologies for floating offshore wind.



Figure 6: Photographs of 3D Stored Energy in the Sea (StEnSea) proof-of-concept print by RCAM Technologies and Vertico.

infrastructure for the grid integration, operation, and maintenance.

- Easier permission progress within borders of WEA without a loss of production capacity.
- Increased quality of the energy production through balancing services with the storage system.
- Higher capacity utilization or optimization of the export cable.

Furthermore, 3D concrete printing has the potential to:

- Reduce cost of manufacturing complex designs
- Reduce labour cost
- Increase safety
- Enable lean and sustainable manufacturing in a port

This essay shows that a successful development of the StEnSea system combined with modern 3D printing construction will benefit the key technology of floating offshore wind and its expansion to reduce CO₂ emissions and can have a significant impact on the sustainable energy supply system of the future. ~



Dipl.-Ing. Christian Dick is an electrical engineer working at Fraunhofer IEE in Kassel since 2013. As a member of the Energy Storage department, his research topics cover the design and development of energy storage systems as well as the optimization of the control management, their grid integration, and techno-economic analysis. He has been involved in the development of the StEnSea system since the beginning and was the technical project manager for the first research project.



Jonas Sprengelmeyer is a student at Clausthal University of Technology and is currently writing his master thesis at Fraunhofer IEE in Kassel on a techno-economic feasibility study of StEnSea system. He has a background in industrial engineering with a focus on energy and raw materials. His expertise and areas of interest are grid integration of renewable energy and underground hydrogen storage.



Dr. Gabriel Falzone is the director of operations at RCAM Technologies. He has a PhD in materials engineering from University of California, Los Angeles, specializing in sustainable and low carbon concrete, with over 25 published papers. Dr. Falzone has experience in scaling up concrete technology pilots as the former VP, technology at CO2Concrete (now CarbonBuilt) – a winner of the \$7.5 M NRG COSIA Carbon XPRIZE in 2020.