Storing energy at sea (StEnSea)

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***Abstract*—For the transformation of the electricity system to a renewable energy system it will be necessary to expand the grid and to increase the storage capacities. Pumped hydro energy storage systems are currently and will be the dominant storage technology to store surplus energy in the future. A major challenge for the further expansion of conventional pumped hydro energy systems on land is the identification of suitable and conflict-free locations. The development of an offshore pumped hydro storage concept, which was tested for the first time at the Fraunhofer Institute for Energy Economics and Energy Systems technology IEE (former IWES Kassel) in the project StEnSEA (Storing Energy at sea), could enable the use of new locations at sea. The main requirement for this new technology is a sufficient depth of water at a small distance to the shore. Based on a feasibility study, the StEnSEA project carried out a detailed system analysis with the development of the design, construction and logistics concept. Additionally the pump turbine unit itself and its integration into the storage system has been investigated. Furthermore the integration into the electricity network has been analyzed and a techno-economic assessment has been carried out to develop a roadmap for the technical implementation of the novel offshore storage systems. A major part of the project was the installation of a prototype in scale 1:10, which was successfully tested in the winter of 2016 in Lake Constance. Apart from the huge worldwide potential, another main advantage of the offshore pumped hydro storage system is that the power of the system can be adjusted by the number of units installed in a plant. This enables various operating concepts for the application of the offshore pumped hydro storage system, which could cause this new technology to be an important part of the future energy supply.**

Keywords: Energy Storage, Pumped Hydro, integration of VG

I. INTRODUCTION

The goal of the project "Storing Energy at Sea (StEnSea)" was to develop and test a novel pumped storage concept for storing large amounts of electrical energy offshore. The project builds up on a feasibility study (phase I) conducted by the project partners and comprises a detailed system analysis (phase II) including construction, manufacturing and logistics concepts of the pressure reservoir, development and detailed design of the pump/turbine unit, grid integration on the basis of load calculations, market analyses and economic viability calculations for an international market as well as the development of a commercialisation strategy and a roadmap for technical implementation.

Furthermore, in the project phase II field testing of a 1:10 scale model with 3m in diameter was conducted in Lake Constance in Germany. In this context details regarding construction and manufacturing, installation and logistics as well as operation & maintenance of the storage system was investigated.

The paper presents the design parameters of the full-scale system and a concept how to operate this new kind of storage system in an electricity grid and market.

II. THE STENSEA SYSTEM

In contrast to well-known conventional pumped-hydro power plants, which use two separated water reservoirs of different heights, the StEnSea concept uses the static pressure of the water column in deep waters. In order to use this potential a hollow concrete sphere is installed in deep water. A pump-turbine in the hollow sphere enables to store electrical energy. When the water is flowing into the sphere the storage is discharged. In this case the pump-turbine is running in turbine mode generating electricity. In order to re-charge the storage system the water is pumped out of the sphere against the pressure of the surrounding water column.

A schematic cross sectional view of an energy storage sphere is presented in figure 1.

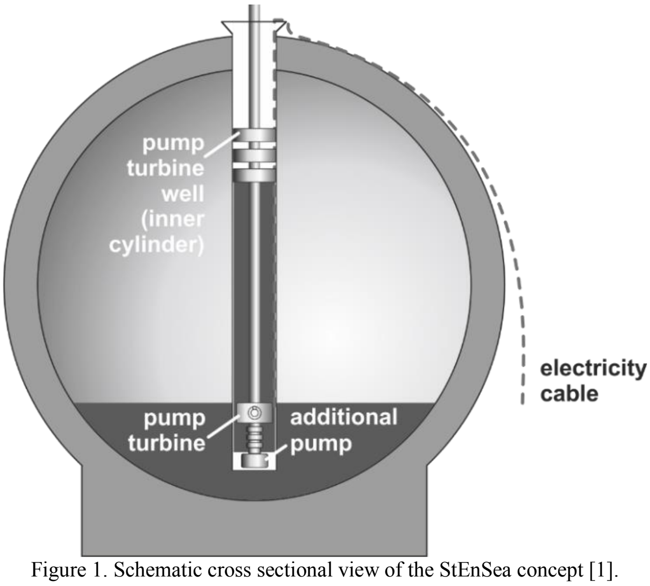

Figure 1. Schematic cross sectional view of the StEnSea concept [1].

As the inner volume stays below atmospheric pressure while pumping the water out of the sphere a feed pump is required. This auxiliary pump fills a cylinder which contains the pump turbine and other electrical equipment of the storage system. Both pumps require an input pressure above the net positive suction head to avoid cavitation while pumping water from the inner volume into the cylinder or from the cylinder out of the sphere. As the pressure difference for the additional pump is much lower than for the pump turbine the required input pressure is lower as well. The input pressure of both pumps is given by the water column above them. For the additional pump this is the water column in the sphere and for the pump turbine it is the water column in the cylinder.

The total charge capacity (C_max in MWh) can be related to the inner volume of the sphere (V_inner in m³), the pump and turbine efficiency (η_turb) and the installation depth (d in m) (Eq. (1)).

$$C_{max} = (\rho_{water} \times \eta_{turb} \times d \times g \times V_{inner}) \times \frac{1}{3.6E9} \quad (1)$$

In the first phase of the project a feasibility analysis resulted in the physical design parameters for the energy storage system. An advantage of the system is that the power and energy can be designed separately. While the power increases with the installation depth the energy for one given installation depth can be increased by scaling up the inner volume of the sphere.

The diameters are primarily depending on two different design criteria. The first one is that the gravitational force of the device has to be higher than the buoyancy force of the device to ensure that it stays on the seabed. The second design criterion is the force of the pressure from the surrounding water. The sphere has to withstand this pressure. There is an optimum between those two design criteria. While the pressure on the sphere increases with the installation depth the buoyancy force is not dependent on depth. Obviously, most straight forward to maximize the power and capacity of the storage system for a given diameter is to install it as deep as possible. For the project and the first Full-Scale prototype the diameters were the results of an optimization. Based on the fact that higher volumes lead to higher capacity it may be assumed that it is advisable to build the spheres as huge as possible, but in contrast to that the size of the sphere has a big impact on the logistics of a project. Therefore, it has advantages to install several smaller spheres instead of one extremely large sphere. The feasibility analysis lead to a compromise. The StEnSea system was designed with an electrical power of 5 MW. The feasibility analysis lead to a corresponding inner diameter of 28.6 m with a wall thickness of 2.72 m providing a volume (V_inner) of around 12,000 m³. The techno-economic assessment is discussed in detail in [1]. The calculations are based on the assumption that the pump has an efficiency of 81 % and the turbine has an efficiency of 89 %. This results in a total efficiency (η_turb) of 73 %, including the generator efficiency (transformer efficiency is not considered). Applying Eq. 1 and using the acceleration (g) 9.81 m/s², a seawater density (ρ_water) of 1,025 kg/m³ and an installation depth (d) of 750 m, the pump turbine has the desired nominal power of 5 MW. In this case the storage capacity is 18.3 MWh with a charging and discharging time of approximately 4 hours, which is sufficient long to participate on the wholesale electricity and balance power market in Europe. Table 1 summarizes the relevant technical parameters of a full scale StEnSea unit.

Table 1. Relevant technical parameters of a StEnSea unit [1].

Parameter	*Value*	*Unit*
Construction depth	750	m
Inner diameter of the hollow sphere	28.6	m
Hollow sphere volumina	12,200	m³/unit
Electrical storage capacity	18.3	MWh/unit
Installed electrical capacity	5	MW/unit
Specific storage capacity	0.715	kWh/m³
Units per storage farm	5-120	units
Turbine efficiency	0.81	
Pump efficiency	0.89	
Total efficiency	0.72	

For the identification of potential installation sites, the main variable in Eq. (1) is the installation depth, but obviously there are several other criteria that have to be taken into account.

III. POTENTIAL INSTALLATION SITES

In order to identify potential installation sites for the full-scale StEnSea system the following steps were undertaken: First a number of parameters were identified which describe the quality of suitable sites for the deployment of submarine energy storage systems in general. These are the following parameters:

- water depth,
- slope,
- geomorphology,
- distance to the electrical grid,
- distance to installation and maintenance bases,
- existence of marine protected areas which could obstruct the installation or operation of StEnSEA systems,
- need for electric storage capacity in the vicinity.

In the next step specific threshold values were identified for each parameter which determine the suitability of a site for the deployment of a full-scale StEnSea system. Basis for these values were derived from the feasibility analysis. However, for some parameters estimations had to be made. In this context the required values were derived from similar use cases from the offshore Oil & Gas (O&G), the offshore wind and the marine energy industries. It turned out that the application of specific values was not possible or sensible for every parameter. Consequently the parameters were separated into “hard” and “soft” parameters. While hard parameters had specific values assigned and were utilized in the process of site identification, soft parameters with no values assigned were in a consecutive step utilized for the qualitative description and discussion of the sites. The following values were used for the hard parameters:

- Water depth: 600-800 m,
- Slope: <= 1°,
- Unsuitable geomorphology:

  - trenches,
  - spreading ridges,
  - rift valleys,
  - canyons,
  - seamounts,
  - escarpments,
  - fans,
- Distance to the electrical grid: <= 100 km,
- Distance to maintenance bases: <= 100 km,
- Distance to installation bases: <= 500 km.

In the next step suitable geo-datasets were identified and acquired, containing the required parameters in sufficient ranges of values and resolution at a global extent ([2]-[8]). These datasets were consecutively processed with a Geographical Information System (GIS), taking into account the previously identified restrictions. The resulting geographical areas were finally allocated to the Exclusive Economic Zones (EEZ) of countries worldwide. Table 2 shows the areas and storage capacities for the TOP 10 countries worldwide. Table 3 shows the results for the TOP10 countries in the European region.

Table 2. TOP 10 countries worldwide

Country	*Area [km^2]*	*Share of total area*	*Capacity [GWh]*
Total area	111,659	100%	817,344
TOP 10	85,925	77%	628,971
United States	10,226	9%	74,854
Japan	9,511	9%	69,621
Saudi Arabia	8,535	8%	62,476
Indonesia	8,002	7%	58,575
Bahamas	6,201	6%	45,391
Libya	5,836	5%	42,720
Italy	5,572	5%	40,787
Spain	4,299	4%	31,469
Greece	3,476	3%	25,444
Kenya	3,307	3%	24,207

Table 3. TOP10 countries in the European region

Country	*Area [km^2]*	*Share of total area*	*Capacity [GWh]*
TOP 10 Europe	22,705	20%	166,201
Italy	5,572	5%	40,787
Spain	4,299	4%	31,469
Greece	3,476	3%	25,444
Cyprus	2342	2%	17,143
Portugal	2093	2%	15,321
Malta	2084	2%	15,255
Faeroe Islands	1,223	1%	8,952
Norway	844	1%	6,178
France	772	1%	5,651
Iceland	471	0.4%	3,448

IV. FLEXIBLE PLANT SIZE

As shown in the last section there is a huge technical potential worldwide for the StEnSea concept. The goal of the project was to develop and test the system. Several studies and simulations for the full-scale device were carried out in the process. Especially the grid integration and operational management of the system were investigated. In this context one important topic is the sizing of the single device and future plant concepts. As shown in figure 2 several units are combined to one plant. Therefore the possible plant size has a wide range. It is even possible to expand an existing plant if needed. For the techno-economic assessment in [1] different farm sizes from 25 MW to 600 MW devices were analyzed.

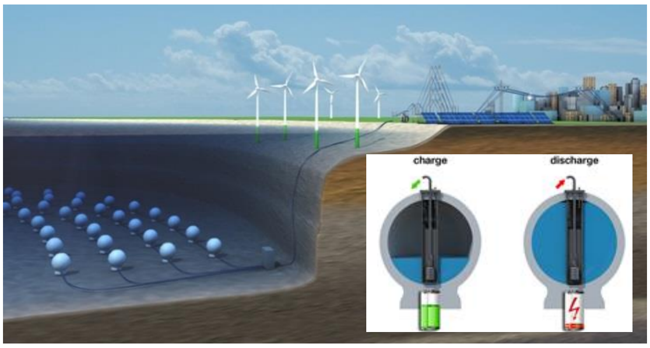

Figure 2: Principal layout and functions of a StEnSea plant

While the studies and calculations aim towards the development of the system the testing was mainly linked to the prototype testing of a 1:10 scale model of the storage system. The test itself ran for 4 weeks in a depth of 100 m in lake Constance in the south of Germany.

V. CONCLUSIONS

The StEnSEA system is a new pump storage concept that has great potential worldwide and represents an alternative to conventional pumped storage power plants through comparable specific investment and operating costs, at appropriate locations. Especially on islands that use a high percentage of renewable energies for energy production, the StEnSEA system has the advantage that it works with salt water, which in contrast to fresh water is always available in sufficient quantity.

In addition, the StEnSEA concept is unlikely to experience conflicts of use and acceptance problems, which could be used to capture relevant parts of a rapidly growing storage market.

The model test showed that the technology can be put into practice. Together with the results from the study, this allows for the next steps towards full-scale systems. Currently, a follow-up project is under negotiation with the funding agencies and industrial partners in which a prototype is to be realized on a scale of 1: 3 and tested in significantly greater water depth in the sea.

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