Comparison of underwater with conventional pumped hydro-energy storage systems

D. Dubbers
Physikalisches Institut, Heidelberg University, Im Neuenheimer Feld 226, 69120 Heidelberg, Germany

Dated: 07 December 2020
Keywords: Renewable energy, hydroelectric storage, underwater storage, stored energy at sea, StEnSea
E-mail address: dubbers@physi.uni-heidelberg.de

Abstract. The laws of fluid mechanics imply that modular offshore pumped hydro-energy storage systems like StEnSea have no advantage over similar but much cheaper modular onshore systems.

The large-scale storage of surplus electrical energy from renewable sources is an unsolved problem. Among the four technologies used for energy storage: mechanical, electrical, thermal, and chemical, mechanical pumped hydro energy storage (PHS) in water reservoirs at high altitude provides 94% of the world's energy storage capacity [1]. Unfortunately, in many industrialized countries, the potential of PHS has been largely exhausted (although worldwide reserves may be large [2]). As an alternative, high hopes are placed on the chemical storage of electrical energy in the form of hydrogen gas by means of water electrolysis. However, the hydrogen round-trip efficiency – electricity-gas-electricity – is only 19%, see Table 2 in [3], which implies that one needs more than five wind turbines to store and retrieve the energy of a single turbine. Therefore, new ideas on efficient energy storage are highly welcome.

In recent years, offshore underwater PHS [4], [5] has been proposed as an efficient method to store large amounts of energy, and is described as an emerging technology with significant potential, see the reviews [6], [7]. To store electrical energy, water-filled spheres of volume V are evacuated by pumping the water out against the high pressure p of the water surrounding the spheres deep undersea. For a lossless setup, the work done, and with it the energy stored, is

$$|E| = pV. \quad (1)$$

The water pressure at depth H is

$$p = g\rho H, \quad (2)$$

with water density ρ and gravitational acceleration g. In SI-units, the value of E, given in J = Ws, is converted to MWh by division with 3.6×10^{-9}. To recover the energy, the spheres are refilled with the surrounding ocean water streaming onto the pumps, which then act as generators. Energy flows back and forth to a sphere through an underwater cable.

Evidently, deep in the ocean, pressure p is immense, and so is the sphere's storage capacity E. Taking into account that there is a maximum pressure a hollow concrete sphere can withstand, and that the buoyancy of the empty spheres must be counteracted by their weight, one finds a viable depth of H = 600 to 800 m [8].

The StEnSEA project plans to use concrete spheres of outer diameter 34 m and wall thickness 2.7 m, each with a mass of about 12 000 tons, installed at depth H = 750 m at the bottom of the ocean, which must be flat to better than one degree [5]. With a round-trip efficiency of 73%, the storage capacity then is E =18 MWh per sphere [4,5]. In a full-scale offshore PHS system, farms of large numbers of spheres are planned. To double the world-wide conventional PHS capacity of order 10 TWh would require about one half million such spheres. In 2017, a prototype storage sphere of diameter D = 3 m was tested in Lake Constance at depth H = 100 m, with storage capacity E =2 kWh. A similar project, named Ocean Renewable Energy Storage (ORES) of the Massachusetts Institute of Technology, had been proposed some years ago, but apparently is not being followed up [8].

The StEnSEA proposal was recently extended to the case of concrete spheres submerged not offshore, but in a deep artificial lake created by further excavating and flooding an exhausted open-pit coal mine named "Hambacher Loch" in North Rhine-Westphalia, Germany [9], [10].

At first sight, the idea of a modular underwater PHS system is seducing. However, an important feature is not mentioned in any publication on StenSea: In fluid mechanics, the law of Torricelli states that the speed υ of a fluid, streaming out of an opening in the bottom of a tank filled to a height H, is the same as the speed the same fluid would acquire in falling freely from an equal height H. Hence when, with the ocean seen as a big tank, the water at depth H is streaming under high pressure onto the underwater turbine, it has the same speed as the water from a reservoir installed onshore at elevation H, emptied via a downpipe onto a turbine at some ground level H = 0. Both setups are sketched in Fig. 1.

The power of a turbine is proportional to the speed υ of water falling onto the turbine,

$$P = \dot{m}gH \,, \tag{3}$$

with mass flow rate

$$\dot{m} = \rho \dot{V} = \rho A \upsilon \tag{4}$$

for a water flux through area *A*, which brings us back to Eqs. 1 and 2. Therefore both PHS systems, offshore and onshore, have the same energy storage capacity. The only advantage of the offshore system then is that it requires no land area that could be better used otherwise.

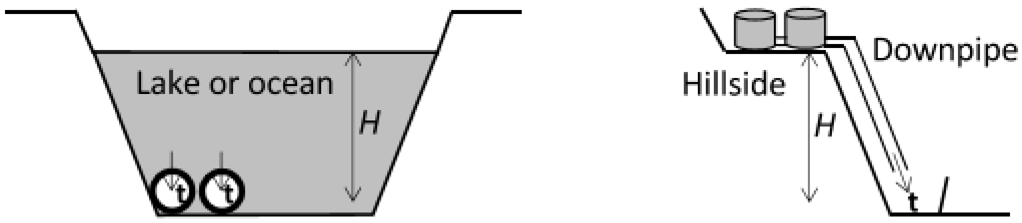

Fig. 1. Two modular pumped hydro-energy storage systems of equal storage capacity. Left panel: The underwater StEnSea setup with thick-walled storage spheres, installed offshore at depth *H*, with ambient water feeding the turbines **t** under high pressure. Right panel: Thin-walled conventional water reservoirs, installed onshore at elevation *H*, emptied through a downpipe onto a turbine **t** at ground level. Both panels show the energy recovery step.

In the onshore scenario, the water reservoirs need not be thick-walled concrete spheres, but can be thin steel reservoirs of any shape, open or closed. With a wall thickness of only 6 mm, see page 19 of Ref. [11], their weight is less than one percent of that of the thick concrete spheres. To the low fabrication cost one can add the ease of installation and maintenance, and the absence of a harsh maritime environment. Furthermore, there are no tight restrictions on the elevation *H* nor on the volume *V* of the modular steel reservoirs.

In addition, for many steep hillsides onshore, there is no competing land use, and the environmental impact of the rather small modular reservoirs on them is low. Worldwide, steep hillsides abound, be it at coast lines or further inland. In the offshore scenario, viable locations for StEnSea underwater systems may be sufficient in number, but are limited to rather singular spots on the world's oceans, see Fig. 2 of Ref. [5]. Also for the open-pit Hambacher Loch, it is much easier to put the water reservoirs on the edge of the empty hole rather than to fill the hole over several years with water from the Rhein River before submerging the heavy concrete spheres therein.

Certainly, one should keep the underwater PHS proposition in mind, because beneficial applications of specialized offshore PHS systems may turn up, for instance as an energy buffer in deep-sea mineral exploitation. But for general use as a storage facility for surplus energy, an onshore modular PHS system is clearly preferable to an underwater modular system. The question whether modular PHS systems are a useful concept at all would require separate discussion. Unfortunately, the interested public seems not to be aware of this state of affairs, and tends to misinterpret often repeated statements of the type "the system takes advantage of high hydrostatic pressure of deep water" [7], thinking that high pressure is a decisive advantage of the underwater method, while it is an unnecessary burden.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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