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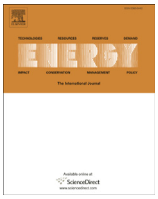

Techno-economic assessment of a subsea energy storage technology for power balancing services

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ABSTRACT

Large scale deployment of intermittent renewable energy induces new challenges for energy systems. They have to balance the volatile energy consumption with the variable power generation. Thus all other components of a renewable energy system are required to be more flexible than they are at present. Storing surplus energy to meet demands when required is one technical solution of balancing this demand. This study analyses the economic performance of an innovative storage technology, known as stored energy in the sea (StEnSea), and compares the findings of the economic analysis with the costs of alternative storage technology options, namely compressed air energy storage (CAES) and pumped hydro storage (PHES) plants, which are comparable in capacity and their balancing performances. Results have shown that the required price arbitrage for the economic operation of the StEnSea technology at a storage farm with 80 storage units and 400 MW ranges from 4 €ct kWh-1 to 20 €ct kWh-1 and strongly depends on the annual operation cycles. The comparison of costs for storing surplus electricity providing power during demand periods when using the StEnSea technology with the costs of CAES and PHES for equivalent services have shown that the StEnSea technology is cost competitive.

1. Introduction

The transformation of the electricity system to a renewable energy (RE) system will mainly be based on high proportions of electricity from wind and photovoltaics. This introduces a new layer of complexity, since wind farms and photovoltaic systems generate electricity depending on weather influences. Thus, all other components of a renewable electricity system need to become more flexible in order to be able to balance the varying residual power. These includes demand side management [1], the extension of the transmission grid [2] as well as electricity generation management, for instance using flexibly operated biogas plants [3]. If the power generation stills exceeds the demand, electricity energy storage (EES) systems are able to store surplus electricity and generate electricity whenever needed to balance the demand. Furthermore, EES are able to provide a variety of system services for grid stability. Accordingly, the European Commission has recognized EES as one of the strategic future energy technologies, that will be necessary to achieve the EU's energy target by 2050 [4].

Today, there is a wide spectrum of EES technologies available. All technologies can be characterised and differentiated according to their technical characteristics, functional limitations and possible operational strategies. In order to smooth large-scale volatile renewable energy generation from wind and sun in the electrical grid, the power rating and time shifting of EES should have according to Gallo et al. [5] 1–100 MW as well as being able to balance minutes to several hours. Nevertheless, most of the technologies with a sufficient power rating and time shifting potential have no or only little large scale operational experience (for instance, liquid air energy storage [6], pumped thermal energy storage [7], power to methane storage [8] and others). Other EES, for instance batteries use raw materials such as lithium and lead, which can present environmental hazards if they are not disposed of or recycled properly.

Well-established long-term, large-scale utility-scale storage systems are pumped-hydro energy storage (PHES) plants having a capacity ranging from several MW to several GW, while having relatively high electrical conversion efficiencies of about 80% [9,10].

Abbreviations: CAES, Compressed air energy storage; EES, Electricity energy storage; Eq., Equation; HVDC, High voltage direct current; Investm., Investment; PHES, Pumped-hydro energy storage; RE, Renewable energy; StEnSea, Stored Energy in the Sea; SU, Storage unit; TS, Transformer station; VDI, Association of German engineers.

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However the potential of PHES is closely connected with geographical conditions and always connected with land demand for the storage reservoir that consequently impacts the environment.

Another commercially proven large utility-scale EES option is compressed air energy storage (CAES). Underground salt caverns, natural aquifers or depleted natural gas reservoirs are cost-effective storage unit options for capacities up to several hundred megawatts. Nevertheless, also the implementation of CAES requires appropriate geological formations which represent one of the major challenges for the implementation of such projects and restricts the potential. Overground CAES may generally have a reduced capacity and higher costs but also easier project implementation and higher energy efficiency [11].

In numerous studies for a pan European energy system experts have analysed the balancing power demand in partly or fully RE systems [12–16]. In this context Heide et al. [17] have analysed the required energy storage capacity for a simplified 100% wind and solar power generation scenario with 400–480 TWh per year. This would exceed the available storage capacity of PHES and CAES in Europe [16,18]. Furthermore, the installation of storage systems next to generation sites reduces the expansion of grid capacities; for instance at offshore wind farms that need to be connected with onshore grids.

An innovative concept, with sufficient power rating and time shifting potential could help to complete the available storage portfolio, is “StEnSea” (Stored Energy in the Sea) where energy is stored deep underwater in hollow spherical concrete storage tanks. Implemented in combination with offshore wind energy farms, subsea storage could be able to store the generated electricity next to the generation site during surplus periods. The physical principle of these storage tanks is based on the physical concept of pumped-hydro storage plants. A hollow concrete sphere with a pump-turbine is plunged onto the sea ground where it generates electricity with inflowing water and stores electricity while the water is pumped out. The storage capacity depends on the sphere's hollow volume and increases proportionally with the water pressure and the installation's depth [19,20]. However, the “StEnSea” storage concept is quite innovative and first practical tests with a small scale prototype hollow sphere are in currently under investigation.

Storing electricity is presumed to be one solution for stabilizing the electricity supply and averting uneconomical power generation and high prices in peak times. Currently there are many storage concepts providing balancing services from short to long periods (from seconds to several days and weeks). In general all systems can participate in the wholesale electricity markets in a number of ways, depending on their energy storage and delivery characteristics. However, uncertainties about the future electricity market development influenced by other flexibility options competing with EES systems bring doubts about the future market potential and income structure. A comprehensive cost and economic analysis of specific energy storage systems is required. Thus, this study calculates the necessary price arbitrage for operating the subsea energy storage commercially analyses the cost structure and compares it with alternative EES options. A sensitivity analysis was conducted in order to assess the influence of different cost parameters as well as the number of storage units per storage farm and depth of storage location below sea level.

Conducting this study is a first approach assessing the cost competitiveness of the StEnSea technology compared to alternative storage technologies with similar storage capacities and storage periods and is answering the following questions:

i. Which price arbitrage is required for its economic operation and convinces investors to invest in the StEnSea technology?
ii. Which cost parameters have the highest influence on the economic operation of a StEnSea plant?
iii. Is the economic performance of the StEnSea technology cost competitive compared with alternative EES options providing equivalent power services?

2. Material and methods

2.1. Technical description of the StEnSea concept

The physical principle of the StEnSea concept is based on the concept of pumped-hydro storage plants (cf. [21]). A concrete hollow sphere is placed deep underwater on the seabed where a pump turbine pumps water out of the hollow sphere during periods when wind and/or photovoltaic systems produce a high amount of electricity by wind- or photovoltaic-systems and consequently the price of electricity on the wholesale market is low. During periods of high electricity demand when the electricity prices are high, water is allowed to flow back into the hollow sphere through a pump turbine which generates electricity. The volume of the concrete hollow sphere remains at or below atmospheric pressure. Hence the total charge capacity (C_{max}) can be related to the hollow inner volume, pump and turbine efficiency and depth of the storage location (Eq. (1)).

$$C_{max} = \frac{\rho_{\mathrm{water}} \cdot \eta_{\mathrm{turb}} \cdot d \cdot g \cdot V_{\mathrm{inner}}}{3.69E9} \quad (1)$$

Following the findings of Schmidt-Böcking et al. [20], Slocum et al. [19] as well as the ones from a feasibility study of Hochtief AG and their patent application (EP 2700 594 A1) we consider a large-scale StEnSea storage unit for the techno-economic analyses with an inner diameter of the concrete hollow of 28.6 m with a wall thickness of 2.72 m providing a volume (V_{inner}) of 12,200 m^3 for the commercial operation of the storage system. The pump efficiency is 82%, the efficiency of the turbine is 89% (cf. [22,23]). This results in a total efficiency (η_{turb}) of 73%, including generator and engine efficiency (transformer efficiency is not considered). Considering the gravity acceleration (g) 9.81 m s^{-2}, a conversion factor of 3.69^9 from Joules to megawatt hours, a seawater density (ρ_{water}) of 1025 kg m^{-3} and a depth (d) of 750 m. The pump turbine has a nominal power of 5 MW, if implemented with the described technical characteristics at a depth of 750 m. The storage capacity is approximately 18.3 MWh with a charging and discharging time of about 4 h. A schematic cross sectional view of an energy storage sphere is presented in Fig. 1.

Electricity transmission losses via the electricity grid are not considered since they are negligible. Relevant technical parameters of a StEnSea unit are summarized in Table 1.

2.2. Economic analysis

In order to assess the economic operation of the StEnSea project, an economic simulation model was developed based on the annuity method [24] and a guideline developed by the association of German engineers (VDI) (c.f. [25]). This allows calculating the necessary revenues for StEnSea storage to be operated economically. Applying this method makes it possible to compare the results with other calculations based on this standardized method. Furthermore, the annuity method enables the transformation of the initial investment as well as non-recurring and regular payments during the complete assessment period of an investment into a periodically constant business ratio. Discounts and changes in interest rates or price can be considered in the cost simulation.