Applied Energy 155 (2015) 315–322

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

# A techno-economic assessment of offshore wind coupled to offshore compressed air energy storage

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## HIGHLIGHTS

- This paper examines the economics of offshore compressed air energy storage (OCAES).
- A mixed integer linear programming model is used to quantify OCAES performance.
- A hypothetical wind-OCAES system off the North Carolina coast is analyzed.
- The resultant levelized cost depends strongly on the OCAES cost assumptions.
- OCAES is more expensive than gas turbine backup at carbon costs exceeding $1000/tC.

## ARTICLE INFO

*Article history:*
Received 23 September 2014
Received in revised form 29 May 2015
Accepted 30 May 2015

*Keywords:*
Offshore energy storage
Wind energy
Mathematical modeling

## ABSTRACT

A critical challenge associated with renewable energy is managing its variable and intermittent output. Offshore compressed air energy storage (OCAES) is a carbon-free storage technology that can used to support renewable energy generation in marine environments. This paper provides the first economic characterization of OCAES performance when coupled to an offshore wind farm by employing a mixed integer programming model. The model seeks the minimum levelized cost of electricity by optimizing the grid-tied cable capacity and OCAES component sizes across a range of specified cable capacity factors. OCAES can be used to increase the capacity factor of the grid-tied transmission cable, but the resultant levelized cost of electricity strongly depends on the OCAES cost assumptions. Compared to using a land-based gas turbine as backup, OCAES is significantly more expensive, even when the price of carbon exceeds 1000 $/tC.



## 1. Introduction

A key challenge with intermittent renewables such as wind and solar photovoltaics is managing their variable output in power systems where supply must meet demand in real time. Output from intermittent renewables is largely dictated by prevailing meteorological conditions. Fast-ramping, dispatchable generation can be used to backup variable generation sources such as wind or to follow load [1]. Such fast-ramping ability is typically provided by gas turbines, which often run at low capacity factors on the order of 10% [2], producing high marginal costs (e.g., ~80 $/MWh) compared to baseload technologies, such as nuclear (~10 $/MWh) and large coal fired or co-generation plants (20–50 $/MWh) [3].

Energy storage systems (ESSs) represent an alternative way to increase the reliability and stability of renewable energy systems and may play a critical role in their large scale utilization [4–6]. For large scale energy storage applications at the level of several hundred megawatts (MWs), pumped hydro and compressed air energy storage are currently the most commercially viable technologies [7–10]. Air and water provide the most inexpensive storage mediums, and can therefore be applied most cost-effectively at such a large scale [11].

Compressed air energy storage (CAES) has received significant attention as a result of its relatively low capital and maintenance costs [7,8,10–16], broad geographical coverage [11,14,17–19], and low environmental impacts [14,17]. It is estimated that around 75–80% of the continental US has suitable geology for CAES development [15,16]. Several previous efforts have used optimization models to characterize the economic performance of CAES coupled with renewables [20–24]. Research indicates that wind coupled to CAES and serving as baseload is not currently economically competitive in the U.S. under prevailing fuel prices and technology costs [21,25].

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http://dx.doi.org/10.1016/j.apenergy.2015.05.111
0306-2619/

While renewables coupled to CAES have received significant attention in the academic literature, little work has focused on the possibility of offshore CAES (OCAES), which can operate in conjunction with offshore renewables such as wind and wave power. The concept of OCAES was originally discussed by Seymour [26–28] and involved coupling platform-mounted turbomachinery to an engineered storage reservoir located on the ocean floor. One advantage of locating energy storage offshore is the proximity to high grade offshore renewable resources, such as offshore wind, where resources are significantly stronger than their on-shore counterparts [26]. Because undersea transmission cabling has high installation and capital cost [29], utilizing OCAES can increase the cable's capacity factor[1], potentially lowering the average cost of offshore wind power while increasing the reliability and economic value of delivered power. In the limit where the cable capacity factor approaches unity, it enables baseload offshore wind power similar to that studied by Greenblatt et al. [21] for the onshore case. In addition, less variable output from offshore wind farms can increase the associated market value of electricity.

This paper represents the first cost and performance assessment of OCAES coupled with an offshore wind farm. We have developed a mixed-integer programming (MIP) model that optimizes OCAES component sizes and undersea transmission line capacity given a fixed offshore wind capacity of 200 MW. We utilize North Carolina as our study location. North Carolina serves as an ideal case study because offshore wind resources are significantly stronger than onshore: in a report published by NREL in 2012 [30], the total estimated NC wind power potential is 1300 TWh offshore and only 2 TWh onshore. In addition, North Carolina may be suitable for the development of ocean-based geologic reservoirs for CAES [15,27]. Given the lack of experience and deep uncertainty associated with technology performance, this paper is intended as a screening analysis to determine whether OCAES can be economically viable.

This paper is structured as follows. Section 2 gives a brief introduction to CAES mechanics and provides a description of OCAES. Section 3 details assumptions regarding the modeled system configuration, presents cost and performance estimates, and introduces the model formulation. Section 4 presents results from the optimization model, and Section 5 describes the insights and conclusions from this study.

## 2. Potential OCAES design

### 2.1. Conventional CAES design

Commercial experience with CAES is limited to two plants currently in operation: one in Huntorf, Germany and the other in MacIntosh, Alabama. These two land-based CAES units consist of three major components: a compressor, a turboexpander, and a storage reservoir. During the storage cycle, the compressor is powered by electricity to pump pressurized air into a storage reservoir, which is generally located underground in a natural geologic formation. The two existing CAES plants use solution-mined cavities in salt domes as their storage reservoirs [15]. More generally, suitable geology structures include salt domes, depleted oil or gas reservoirs, mined spaces in hard rock, or aquifers [15,16]. To generate electricity, the compressed air is released and mixed with natural gas before entering the combustion chamber of the turboexpander, where the hot exhaust gases spin the expander blades and shaft, which is connected to an electric generator. The natural gas is used to preheat the air to prevent the turboexpander blades from freezing during the adiabatic expansion process [31].

### 2.2. Adiabatic and isothermal CAES

A critical challenge with OCAES is designing the system to work on an offshore platform without natural gas, which requires compression and expansion processes that are either adiabatic or isothermal. By collecting the rejected heat during the compression cycle and using it to reheat the gas during the expansion cycle, advanced adiabatic CAES (AA-CAES) can avoid using natural gas (NG) [32,33].

By contrast, isothermal compression takes place without a temperature change, and therefore requires the least amount of thermodynamic work. There is no need for an external heat source, such as NG combustion or a thermal energy storage (TES) system because there is no heat loss. Several isothermal CAES concepts have been proposed, such as the water spray [34], hydraulic piston [35], and liquid-flooded Ericson cycle [36]. Liquid pistons represent another implementation of isothermal CAES. As described by Van de Ven et al. [4,37], a liquid piston uses a column of liquid to directly compress a gas in a fixed volume chamber. An advantage of the liquid piston design is that the heat transfer is enhanced to a near-isothermal condition since the water in the piston can act as a heat sink. By simulating the heat transfer and frictional forces, Van de Ven et al. [37] found that the liquid piston exhibited a round-trip efficiency between 70% and 83%.

### 2.3. The storage reservoir

There are two basic approaches to the design of the OCAES storage reservoir: utilize a suitable geologic formation (if it exists) or deploy an engineered structure on the ocean floor in order to store the compressed air. Geologic storage options associated with land-based CAES are also available offshore, including rock caverns and aquifers [26,38]. The advantages of a geologic storage reservoir are the relatively high potential storage volumes and the relatively low development costs. For the two existing CAES plants utilizing salt caverns as their storage reservoirs, the cost estimate is approximately \$1/kWh [15,16]. However, porous aquifers have the potential to be the cheapest option for large scale storage volumes at approximately \$0.1/kWh [16]. While estimates for offshore geological storage are scarce, Boehme et al. [38] shows that for a large-scale solution-mined salt cavity, the cost is around 43 £/m$^3$. Assuming a compressed air energy density of 60 bar, which is the suggested operating pressure for OCAES [26,27], the capital cost for the solution-mined cavity would be approximately 10 \$/kWh, roughly an order of magnitude higher than the equivalent land-based version.

## 3. The modeled system

### 3.1. Wind farms and system layout

In order to estimate the economic performance of the aforementioned wind-OCAES system, it is critical to acquire wind power time series data in order to test the operational performance of OCAES. Since wind power can experience rapid fluctuations over relatively short timescales, wind power data with an hourly time resolution are needed. In this analysis, hourly data are used for computational tractability, and as such we do not consider fluctuations at shorter time scales. In addition, the model assumes perfect foresight (i.e., no forecast error).

To test the cost performance of a hypothetical wind-OCAES system, we model 10 interconnected 20 MW wind sites that in

[1] In this paper, 'cable capacity factor' is used to indicate the capacity factor of the grid-tied transmission cable and the 'wind farm capacity factor' represents the capacity factor of the wind farm itself based on available resources.