Underwater Compressed Gas Energy Storage

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Underwater compressed air energy storage was developed from its terrestrial counterpart. It has also evolved to underwater compressed natural gas and hydrogen energy storage in recent years. Underwater compressed air energy storage (UWCGES) is a promising energy storage technology for the marine environment and subsequently of recent significant interest attention.

Keywords: energy storage ; underwater compressed air energy storage ; compressed gas

1. Introduction

COVID-19 and the Russia–Ukraine conflict are changing the energy landscape. Many countries are forced to accelerate their processes of the energy transition. Developing local sustainable and renewable energies has long shown strategic value. It is known that intermittent and stochastic renewable energies challenge the grid security and stability. This highlights the need for energy storage, particularly flexible-scale long-duration energy storage (LDES) [1]. Currently, PHS (Pumped Hydro Storage) is the most mature and prolific form of LDES, holding more than 95% of the worldwide market. In the absence of disruptive breakthroughs, this is unlikely to change for the foreseeable future. While dominant, PHS is not without its detractions of geographical restrictions, potential ecological and environmental disturbances, and high initial investment [2]. Compressed air energy storage (CAES), battery energy storage (BES), and hydrogen energy storage (HES) are regarded as promising alternatives to PHS and continue to evolve in market and government planning. Many demonstration and commercial projects have been deployed in recent years [3][4][5]. BES possesses obvious advantages in terms of flexibility and fast response. However, reliability, service life, and environmental concerns still require attention. Although BES is presently the most widely utilized and studied energy storage technology, it is still not competitive in terms of large-scale long-duration energy storage. CAES technology presently is favored in terms of projected service life reliability and environmental footprint. CAES challenges include relatively low round-trip energy efficiency and energy density. CAES economics are still rather variable, depending on the specific application. Generally, the cost of CAES is lower than BES and higher than PHS in terms of large-scale storage [6][7]. There are many different types of CAES technology, including traditional diabatic CAES, adiabatic CAES, isothermal CAES, and LAES (liquid air energy storage). According to the storage modes of air, CAES can be divided into underground CAES with salt caverns and rock caves, above-ground CAES with artificial pressure vessels, and underwater CAES (UWCAES) with subsea storage caverns and artificial storage accumulators. HES is trailing behind due to various challenges in hydrogen production, storage, transportation, and utilization. Nevertheless, hydrogen energy pathways are receiving growing attention as more pressure is put on the availability of natural gas [8].

The rapid development of onshore renewable energies drives the booming of onshore energy storage technologies. The ocean, which occupies 71% of the surface of this planet, provides a vast source of renewable energies. Accordingly, offshore renewable energies are predicted to drive the development of corresponding offshore energy storage technologies. Offshore energy storage technologies can often leverage onshore technology counterparts. However, the harsh marine environment poses additional unique challenges [9]. In recent years, many novel offshore energy storage concepts have been proposed and investigated, such as UWCAES [10][11], subsea PHS [12], subsea HES [13][14], buoyancy energy storage [15][16], floating energy storage [17], hydropneumatics energy storage [18], etc. Storing underwater/subsea is a significant feature of most offshore energy storage concepts. Compared with floating storage, underwater storage sustains less harsh environment loads from wave, wind, and current.

UWCAES derives from onshore CAES and is one of the earliest developed offshore energy storage technologies. Compared with onshore CAES, the unique property of UWCAES is that the compressed air is stored and transmitted underwater. This brings both advantages and disadvantages. In onshore CAES systems, compressed air is generally stored in a constant volume, thereby contributing to fluctuating pressure and temperature in charging and discharging processes and the obvious off-design operations of compression plants, heat exchangers, and expansion plants [19].

Either throttling or sliding pressure operation is needed, which pulls down the round-trip energy efficiency. In contrast, the isobaric storage of compressed air can be achieved in UWCAES systems by taking advantage of hydrostatic pressure in deep water. This allows the system to be steadily operated at designed points and the throttling and sliding pressure operation are avoided, thereby contributing to a higher round-trip energy efficiency. On the other hand, many barriers hinder the development of UWCAES, such as the harsh marine environment, complex and expensive underwater systems, and lagging offshore renewable energy technologies. Overcoming these challenges would make UWCAES a promising solution for flexible-scale energy storage for coastal cities, islands, offshore platforms, offshore renewable energy farms, etc.

Natural gas and hydrogen will play more important roles in the future energy landscape. Due to the similar physical properties of air, hydrogen, and natural gas, they can be stored in similar ways: small-scale artificial pressure vessels in the high-pressure gaseous state, thermally insulated containers in the liquid state, and large-scale underground caverns in the high-pressure gaseous state. Beyond this, natural gas and hydrogen possess much higher volume exergy density than compressed air with a ratio of about 70:20:1 [20]. Thus, in recent years, UWCAES has been expanded to underwater compressed gas (air, hydrogen, natural gas, carbon dioxide, etc.) energy storage (UWCGES) [21][22].

2. UWCAES

UWCGES derives from UWCAES. Thus, the working principle and milestones of UWCAES are briefly introduced.

In general, there are two technical routes for achieving UWCAES. One is UWCAES with adiabatic compression and expansion and another is UWCAES with isothermal compression and expansion. This is like onshore CAES. In an adiabatic UWCAES system, no heat is exchanged with the surroundings. The thermal energy of hot compressed air is stored in the thermal energy storage unit. When needed, the storage compressed air is released and the stored thermal energy retrieved. The hot compressed air then expands adiabatically and drives the expansion train to generate electricity. In an isothermal UWCAES system, the compressor is cooled and the compressed air is discharged at a low temperature. Similarly, the expander is heated and the compressed air expands isothermally. It is worth noting that the water body of the ocean/lake is an ideal heat sink/source which could facilitate isothermal compression and expansion. This advantage should be fully exploited in UWCAES systems. This is the reason why many studies on UWCAES are focusing on implementing isothermal compression. Generally, the compressed air can be stored in either human-make accumulators or subseabed caverns/saline aquifers. UWCAES with subseabed caverns/saline aquifers/depleted oil and gas fields are similar to traditional onshore underground CAES. The pressure of compressed air cycles over relatively large pressure ranges in the charging and discharging processes. An important advantage of subseabed storage is a higher storage pressure could be achieved due to the additional hydrostatic pressure of deep water. In addition, the investigation cost could be significantly reduced if depleted offshore gas/oil reservoirs could be reused. The storage volume of artificial accumulators is much less than that of subseabed caverns/saline aquifers/depleted oil and gas fields. Nevertheless, the storage pressure of artificial accumulators can maintain nearly constant levels based on the hydrostatic pressure associated with that depth. Artificial accumulators can be divided into flexible, rigid, and hybrid variants. The flexible accumulator is generally made from polymer composite materials and the shape of the accumulator changes with the changing storage volume of compressed air. The rigid accumulator is generally a steel-reinforced concrete structure. The hybrid accumulator combines the advantages of flexible and rigid ones but is more complex in structure. More details are discussed in the following sections.

As a subbranch of CAES, UWCAES is not a new idea. To the best knowledge, early in 1987, Laing and Laing proposed and improved the UWCAES concept for storing off-peak wind electricity [23][24]. In the first UWCAES concept, human-make accumulators made from flexible material were used for storing compressed air. Many follow-up concepts are very similar to Laing and Liang's concept. In 1997, Seymour at UCSD (University of California, San Diego) proposed the first simple rigid accumulator concept which could be a long pipe or a compact tank with ballast bins [25][26]. In 2011, a team from the University of Windsor and Hydrostor tested a tiny-scale UWCAES pilot project in Lake Ontario that showed the concept was feasible and promising. The compressed air storage accumulator was a commercial lift bag that is widely used in ocean engineering [27]. In 2012, a team from the University of Nottingham tested their prototype 5 m diameter energy bag in 25 m of seawater at the European Marine Energy Centre off the coast of Orkney [28]. Twenty-eight years after the first UWCAES concept, in 2015, Hydrostor successfully built and tested the world's first grid-connected 1 MW demonstration of UWCAES in Lake Ontario on Toronto Island.

3. Isothermal UWCAES

Patil and Ro et al. from North Carolina State University and Baylor University continue their studies on UWCAES while concentrating on investigating isothermal compression technologies [29][30][31][32][33]. Similarly, a team from the University of Nantes and SEGULA Technologies is also developing a UWCAES project "REMORA" and focuses on isothermal compression/expansion [34][35][36]. There is little doubt that the round-trip energy efficiency could be significantly improved with isothermal compression and expansion. Beyond this, requisite thermal energy storage facilities could be omitted by taking advantage of the highly accessible water heat sink. Overall, for enhancing heat transfer and achieving isothermal processes, most studies are based on the liquid piston concept accompanied by liquid spray, wire mesh, porous media, water–gas two-phase foam, etc. From quasi-steady-state theoretical studies and low-speed experiments, a very high exergy efficiency of compression could be achieved in the range of 85~95% [37][38]. However, the performance degenerates when considering the transient operation of the system and the off-design operation of hydraulic facilities. There is still a shortage of studies that consider real operating conditions. Further, it is very difficult to achieve isothermal compression/expansion when the rotational speed of the liquid piston compressor is close to the engineering practical rotational speed. The bankruptcies of well-known SustainX and Lightsail highlight the uncertainties surrounding isothermal CAES.

4. Adiabatic UWCAES

The majority of studies have gone in different directions based on more mature adiabatic CAES (A-CAES) with thermal energy storage. Since 2019, several onshore commercial A-CAES systems have been successfully operated worldwide, such as Goderich A-CAES facility (2.2 MW, 10 MWh) [39], Jintan A-CAES facility (60 MW, 300 MWh) [40], Zhangjiakou A-CAES facility (100 MW, 400 MWh) [41], etc. Thus, for now, the pathway of A-CAES is more feasible than the isothermal CAES pathway. Based on the world's first grid-connected UWCAES facility, Carriveau et al. from the University of Windsor and Hydrostor revealed that the real round-trip exergy efficiency could reach about 53%. About 75~82% of the exergy destruction was avoidable, thereby showing significant potential for improvement [42][43]. Wang et al. from Dalian Maritime University designed a hybrid energy system for the island that integrates marine renewable energy with UWCAES, BES and diesel generation. It was found that an efficiency of 59% was achievable in terms of UWCAES subsystem [44]. Tiano and Rizzo from the University of Salerno investigated the feasibility of carbon-free renewable energy feeding in Sicily by introducing UWCAES [45]. Guandalini et al. from Polytechnic University of Milan conducted a preliminary design and performance assessment of UWCAES considering the off-design properties of the overall system and realistic power input. It was found that a round-trip efficiency in the range of 75~85% could be achieved [46][47]. Dai et al. from Xi'an Jiaotong University designed an autonomous renewable seawater reverse osmosis system by introducing underwater compressed air energy storage and investigated the feasibility from perspectives of technology and economy [48][49]. They also proposed underwater compressed CO_2 energy storage by replacing air with CO_2 [22]. Liu et al. from Qingdao University of Science and Technology and Xi'an Jiaotong University proposed a trigeneration system with UWCAES. It was found that an overall exergy efficiency of about 56% could be obtained [50]. Cheater from GustoMSC proposed the ECO concept with UWCAES [51]. The results showed that it was economically competitive with PHS when the compressed air was stored in ultra-deep water [51].

The underwater system is the distinction between UWCAES and onshore CAES. The underwater system can be divided into the gas storage unit and the gas transportation unit. Researchers from the University of Windsor and Dalian Maritime University are still collaborating on evolving UWCAES. Wang et al. investigated the numerical and experimental properties of flow around a balloon-shaped flexible accumulator [52]. Moreover, they proposed a general accumulator concept that could be used for storing fluids less dense than seawater. The general accumulator combined the advantages of traditional flexible and rigid ones. A large-eddy simulation and modal analysis of a 1000 m^3 model revealed that the risk of vortex-induced vibration fatigue damage was very low [21]. Hu et al. designed flexible risers for gas transportation in UWCAES systems. The catenary riser and lazy wave riser were compared under different environments and internal pressure levels [53]. Liang et al. established a theoretical model for describing slugging flow in a hilly-terrain tube. This was a step toward accurately predicting the status of liquid accumulation in gas transportation pipelines of UWCAES [54]. After the investigation on flexible energy bags in 2012 [28], Garvey et al. from the University of Nottingham stopped updating their progress along this line.

Subsea geological storage of compressed air and hydrogen has emerged as an advanced variant of CAES in just the last 4 years. Researchers from the University of Edinburgh conducted several pioneering studies in this field. Mouli-Castillo et al. revealed that UWCAES in porous rocks of sedimentary basins could completely satisfy the seasonal energy storage demand of the United Kingdom with acceptable economy [55]. Furthermore, they investigated the feasibility of balancing the entire seasonal demand of UK domestic heating with subseabed gas field hydrogen storage. It was found that only a few offshore gas fields were required and hydrogen storage would not compete for the subsurface space required for carbon storage or CAES [56]. Scafidi et al. determined that a value of 6900 TWh of available hydrogen storage capacity was present in gas fields and 2200 TWh in saline aquifers on the UK continental shelf [57]. Hassanpouryouzband et al. analyzed the prospects and scientific challenges in subseabed hydrogen geological storage and concluded that there was great potential to achieve net-zero by 2050 with subseabed hydrogen geological storage [58]. Dinh et al. from University College Cork also integrated subseabed hydrogen geological storage with offshore wind farms [59]. Gasanzade et al. from Kiel University and Flensburg University of Applied Sciences assessed subsurface renewable energy storage capacity for hydrogen, methane, and compressed air in the North German Basin [20]. Bennett et al. from the University of Virginia investigated the techno-economic performance of UWCAES in subseabed saline aquifers for balancing offshore wind power [11]. The result showed that the levelized cost of electricity of a 350 MW UWCAES system with 168 h of storage could be 81% less than that with 10 h lithium-ion battery energy storage [11].

Industrial progress in this space is trailing far behind academic studies. Too many enterprises begin well but fall off towards the close. Hydrostor's world's first UWCAES demonstration is the only existing commercial UWCAES facility. The critical issue is that the onshore section works well but the underwater section remains problematic. The marine components of UWCAES are still the greatest challenge to large margin returns on investment. Thus planned UWCAES projects in Lake Huron and Aruba were terminated. Instead, several onshore CAES projects based on adiabatic compression/expansion and thermal energy storage have been built and contracted in recent years [60]. Another UWCAES project in Hawaii with 12 MW (56 MWh) capacity was announced by Brayton Energy several years ago [61]. However, no detailed engineering progress has been revealed in recent years In addition, SEGULA Technologies is developing a UWCAES concept named "REMORA" [62]. They are now focusing on isothermal compression/expansion while not on underwater systems. TechnipFMC is leading an underwater hydrogen energy storage project named "Deep Purple" [14]. Green hydrogen is produced with offshore wind power and subsequently stored in artificial pressure vessels on the seabed. In 2021, Tractebel and partner companies developed an offshore infrastructure and processing facilities concept for storing hydrogen at large scale in the subseabed caverns [13].

It is understandable that the UWCAES is trailing behind the onshore CAES, not to mention underwater natural gas, hydrogen, and CO_2 energy storage. That said, flourishing offshore renewable energies are pushing UWCGES forward and there is a trend of resurgence. Before large-scale applications of UWCGES will proliferate, many challenges must be addressed.

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