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Review

Underwater Compressed Gas Energy Storage (UWCGES): Current Status, Challenges, and Future Perspectives

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Abstract: 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. UWCGES is a promising energy storage technology for the marine environment and subsequently of recent significant interest attention. However, it is still immature. In this study, the latest progress in both academic and industrial fields is summarized. Additionally, challenges facing this emerging technology are analyzed. The pros and cons of UWCGES are provided and are differentiated from the terrestrial variant. Technical, economic, environmental, and policy challenges are examined. In particular, the critical issues for developing artificial large and ultra-large underwater gas storage accumulators and effective underwater gas transportation are comprehensively analyzed. Finally, the demand for marine energy storage technology is briefly summarized, and the potential application scenarios and application modes of underwater compressed gas energy storage technology are prospected. This study aims to highlight the current state of the UWCGES sector and provide some guidance and reference for theoretical research and industrial development.

Keywords: energy storage; underwater compressed air energy storage; compressed gas; offshore renewable energy; hydrogen; natural gas; UWCGES

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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 [3–5]. 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].

Overall, UWCGES is still embryonic and faces many uncertainties. In this review, the latest studies and industrial progress of UWCGES in recent years are updated. Challenges are summarized and discussed. Finally, possible application modes and perspectives are presented.

2. UWCAES

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

In general, there are two technical routes for achieving UWCAES, as shown in Figure 1. 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.

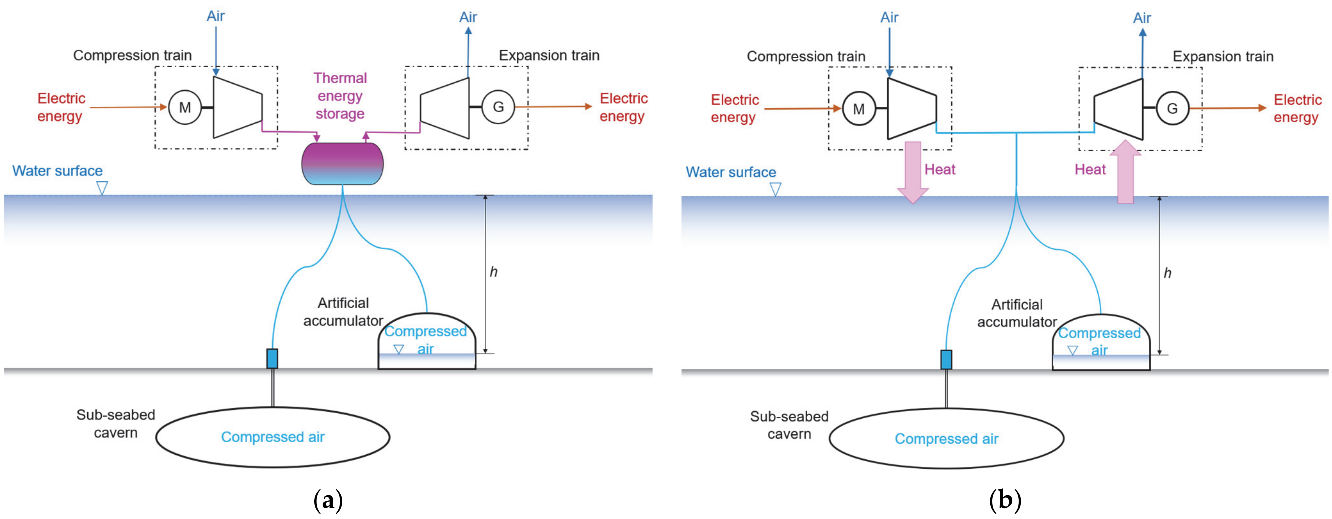


Figure 1. Schematic diagrams of UWCAES: (**a**) UWCAES with adiabatic compression and expansion; (**b**) UWCAES with isothermal compression and expansion.

Figure 2 shows the timeline of the major academic and industrial milestones of UWCAES. As a subbranch of CAES, UWCAES is not a new idea. To our 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.

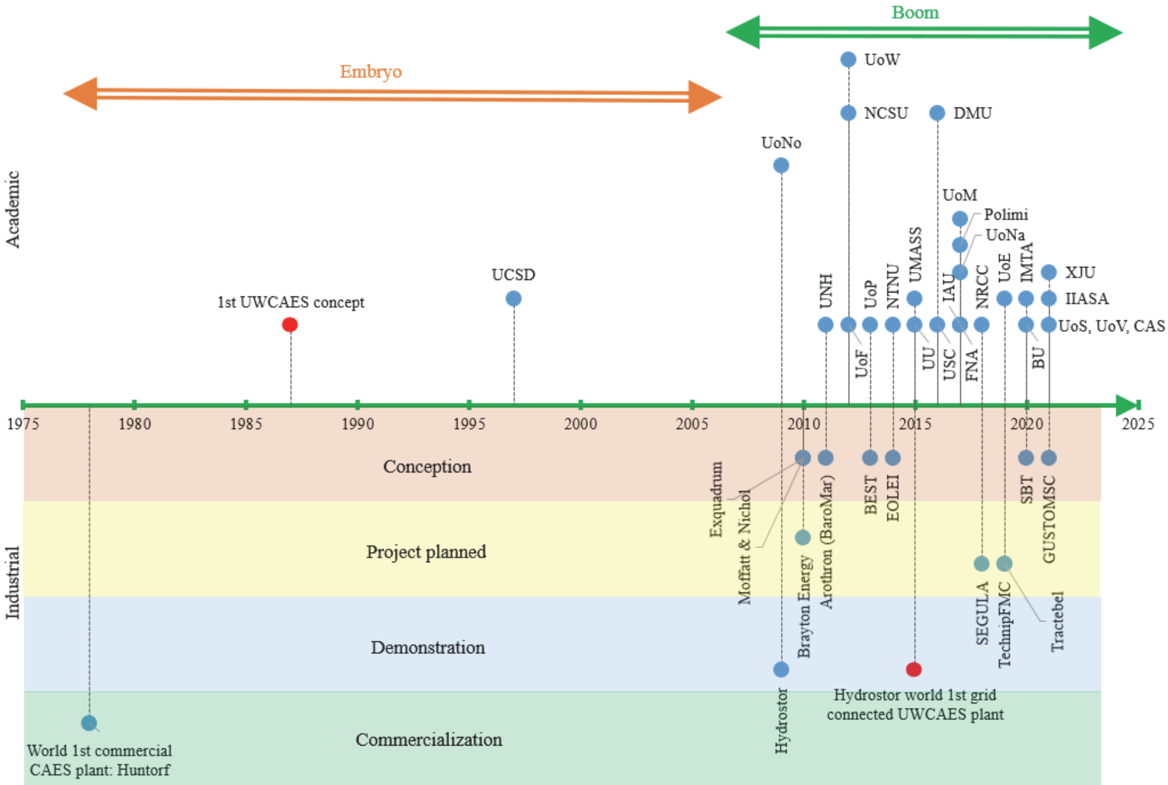


Figure 2. Timeline of major academic and industrial milestones of UWCAES. The point-in-time is confirmed according to the earliest traceable publications or announcements. The data go through June 2020. For the upper academic area, the length of the dotted line is related to the number of publications of various institutes of corresponding authors. For the lower industrial area, the length of the dotted line means the development status of various enterprises. Red points show the most important milestones of UWCAES. Several important underwater hydrogen energy storage cases are also included, such as TechnipFMC, Tractebel, and SBT. (BEST: Bright Energy Storage Technologies; BU: Baylor University; CAS: Chinese Academy of Science; DMU: Dalian Maritime University; FNA: French Naval Academy; IAU: Islamic Azad University; IIASA: International Institute for Applied Systems Analysis; IMTA: IMT Atlantique; NCSU: North Carolina State University; NRCC: Natl Res Council Canada; NTNU: Norwegian University of Science and Technology; Polimi: Politecnico di Milano; SBT: SBT Energy; UCSD: University of California San Diego; UMASS: University of Massachusetts; UNH: University of New Hampshire; UoE: University of Edinburgh; UoF: University of Florence; UoM: University of Malta; UoNa: Université de Nantes; UoNo: University of Nottingham; UoP: University of Padova; UoS: University of Salerno; UoV: University of Virginia; UoW: University of Windsor; USC: Universidade de Santiago de Compostela; UU: Utrecht University; XJU: Xi'an Jiaotong University).

3. Current Status

Reference [9] provides a brief literature review on UWCAES before 2018. However, the situation has changed a lot in recent years. Thus, the latest studies and industrial progress are updated and analyzed in this section.

From the perspective of academic research, it is evident that more scholars are paying attention to UWCAES. Overall, the latest publications on UWCAES can still be divided into two pathways, as shown in Figure 1. Many studies are common technologies that could also be used in both onshore and underwater CAES systems.

3.1. 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 [29–33]. Similarly, a team from the University of Nantes and SEGULA Technologies is also developing a UWCAES project "REMORA" and focuses on isothermal compression/expansion [34–36]. 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.

3.2. 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.

4. Challenges

The current status of UWCGES highlights that there remain many challenges to overcome. The developmental state of many marine renewable energy technologies hinders the development of corresponding marine energy storage technologies. Some challenges, such as the practical realization of isothermal compression and expansion and the improvement of round-trip energy efficiency, are commonly faced by both offshore compressed gas storage and onshore compressed gas storage. Many publications on onshore compressed gas storage have been released in recent years [4,7,63–67]. Thus, in this study, only the unique challenges faced by UWCGES are discussed from various perspectives. The challenges of developing UWCGES are shown in Figure 3 and are discussed in the following subsections.

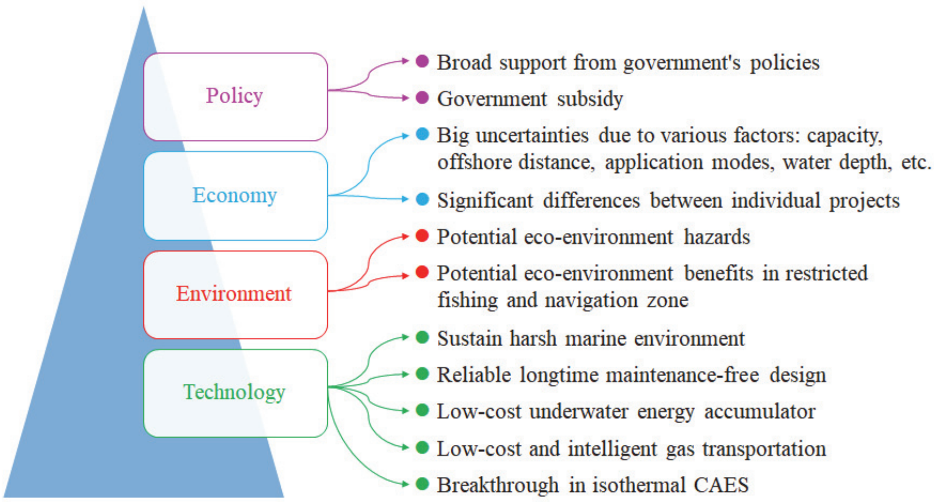


Figure 3. Challenges for developing UWCGES.

4.1. Technical Aspects

At present, the technical challenges of UWCGES are mainly associated with operating the system underwater, i.e., underwater gas storage and underwater transportation. The saline marine environment makes corrosion a major concern for system components. The installation and maintenance of all offshore infrastructures are characterized by high difficulty and high cost and UWCGES components will need to reliably perform in the harsh marine environment over the long term. In order to save investment costs and reduce maintenance difficulty, the design of an underwater system must be highly reliable, easy to maintain or maintenance-free, which is also an important foundation for the further development of UWCGES. The increasingly mature ocean engineering technology provides a good reference for the development of UWCGES technology. Overall, these problems of underwater systems could be solved both theoretically and technically.

4.1.1. Underwater Gas Storage

As aforementioned, there are mainly two types of underwater gas storage, underwater fabricated accumulator storage and subseabed geological storage. Although the research on seabed geological structure gas storage has gradually evolved in recent years, the research is rather limited. Fabricated underwater accumulator storage remains the primary research topic in this field. Generally, artificial accumulators can be divided into two categories: flexible and rigid. Flexible gas storage accumulators based on flexible composite materials have been studied and applied in academia and industrial demonstration. The field testing of small-scale (1~100 m^3 scale) flexible gas storage accumulators reveals that the concept is feasible. Unfortunately, flexible gas storage accumulators are still not reliable in a harsh and complex marine environment. There is not yet evidence to support long-duration storage and critical maintenance is not often convenient or economic. Large-scale gas storage accumulators are required for large-scale underwater compressed gas energy storage. Subsequently, this heightens challenges to the reliability of large and super large flexible gas storage accumulators [9,28].

Comparatively, rigid gas storage accumulators based on reinforced concrete or steel structures have higher marine reliability and feasibility. That said, because the gas storage accumulator must sustain current flow, high salinity, high pressure, scouring, and other complex effects, a series of problems such as concrete cracking and reinforcement corrosion may occur after long periods [68–71]. These may lead to the structural failure of these underwater gas storage accumulators. Underwater gas storage accumulators must be highly reliable and potentially even maintenance-free. Therefore, it is necessary to investigate the structural durability, failure mechanism, and life prediction of gas storage accumulators [72]. In view of the durability of reinforced concrete structures used in ocean engineering, researchers have proposed the use of fiber-reinforced polymer, sustainable alkali-activated cementitious materials, and other ways to improve the durability of steel concrete structures [73–75]. The interaction mechanisms between rigid gas storage structures and the marine environment are complex, and accurate prediction is very difficult. Therefore, the durability of both reinforced concrete structures and steel structures is still facing severe challenges and uncertainties. In recent years, offshore engineering projects using steel concrete structures have emerged, such as concrete support structures for offshore wind turbines, sea crossing bridges, submarine immersed tunnels, and offshore floating platforms [76–78]. The success of these projects marks the increasingly widespread application of reinforced concrete structures in the field of offshore engineering. With the advancement of research, the underwater gas storage accumulator made of reinforced concrete will be feasible in the near future.

In order to ensure the structural integrity of underwater gas storage accumulators, detailed structural design and structural dynamic analysis should be conducted. This includes the static, dynamic, and fatigue considerations related to cyclic charging and discharging loads, hydrodynamic loads, and gravitational and geotechnical loads [79]. Detailed structural dynamics analysis can also minimize the manufacturing, installation, and maintenance costs of gas storage accumulators. Achieving the balance between structural strength and cost is extremely important for the commercial application of underwater gas storage accumulators.

Compared with surface structures, underwater storage accumulators can largely avoid the impacts of adverse environmental conditions such as wind, waves, currents, icebergs, ice flows, and ships on the sea surface. The equipment is located on the seabed with relatively stable conditions, but it is still necessary to analyze the hydrodynamic stability of gas storage accumulators. Large gas storage accumulators have a large characteristic scale and large flow Reynolds number, which may lead to fatigue damage due to vortex-induced vibration caused by currents. Wang et al. studied the hydrodynamic characteristics of an underwater gas storage accumulator with a gas storage volume of 1000 m^3 under different flow conditions through fluid–structure coupling and modal analysis [21]. However, the study considers the underwater gas storage accumulator as a rigid body. Only the one-way impact of ocean current on the gas storage accumulator is considered, while the two-way fluid–structure coupling between the ocean current and accumulator is not considered. In fact, the volume of commercially acceptable underwater gas storage accumulators should be much larger than 1000 m^3. Due to the large scale of large or super large underwater gas storage accumulators, these accumulators should be regarded as a non-rigid structures, and the fluid–structure coupling research should be carried out to study the fluid force and wake flow field under different water flows and accumulator structures [80]. Potential solutions to avoid the vortex-induced vibration phenomenon should be explored. In addition, when the gas storage accumulator is in different gas storage states of varying volume and pressure, its natural frequency will change. This should also be considered in further research.

Because the gas is circularly charged and discharged into and out of the accumulators, huge buoyancy loads fluctuate dramatically. Although the underwater gas storage accumulator is not a pressure vessel, the cyclic buoyancy load may lead to fatigue damage to the accumulator structure. The concrete structure is likely to produce large cracks, especially under the action of tensile stress, which will further affect the safety and stability of the accumulator. Thus, it is necessary to analyze structural weaknesses and locally strengthen the accumulator structure.

During the design of large underwater gas storage accumulators, the impacts of submarine geological disasters and dropped falling object impact on the safety of the accumulator should also be considered. The sliding of seabed sediment and the change in geotechnical characteristics caused by submarine geological disasters are likely to lead to the instability and even destruction of gas storage accumulators. Falling objects may cause direct damage to the accumulators. Thus, specific protective structures need to be designed. If an underwater gas storage accumulator is damaged, it can lead to a large, rapid escape of compressed gas. The volume of this compressed gas will expand rapidly during the acceleration process, which will pose a potential hazard to the safety of the surface and underwater vehicles and sea creatures [81–83]. It is necessary to conduct relevant research and evaluation to mitigate this potential.

In addition to the requirements of structural durability, the large underwater gas storage accumulators have extremely high requirements for foundation stability. The marine environment and geological conditions in deep water are complex and there is a large density difference between gas and water. Therefore, underwater gas storage accumulators must be effectively ballasted and anchored. Accumulators must withstand the loads caused by the huge buoyancy generated by a large amount of compressed gas in the water, as well as the complex marine environmental load, and even force majeure load such as undersea earthquakes and tsunamis [84]. In general, reinforced concrete structures should take advantage of their gravity ballast, and steel structures should utilize gravity ballasts or foundation structure anchorage [9,21]. Gravity ballasting is the simplest and most reliable ballasting method, which can balance the huge buoyancy of gas by increasing the self-weight of the accumulator itself. The infrastructure to fix the gas storage accumulator on the seabed depends on the local seabed conditions. For soft and super soft seabed conditions (clay/sand), the foundation structure of the suction anchor or suction caisson can be used [85]. At present, suction caissons are widely used as the foundation structure of offshore wind turbines because of their technical feasibility, convenient transportation and installation, and cost-effectiveness [86]. Many scholars have conducted detailed research on offshore wind turbine foundations which can serve as a reference when designing underwater accumulators [87–93]. The loads on the foundation structure of underwater gas storage accumulators are similar to those of the offshore wind turbine foundations, but there are significant distinctions. A load diagram is shown in Figure 4. The foundation of an underwater gas storage accumulator is mainly subject to the coupling effects of vertical cyclic loading caused by self-weight and cyclic charging/discharging and horizontal loading caused by ocean current and overturning moment. If the gas storage accumulator is in deep-water soft soil, there is concomitant soil rheological effect [94]. Whether it is anchored by its own gravity ballast or by external forces, the stability of the foundation has to endure the trials of soil creep, relaxation, and local scour over time. Therefore, the design of the foundation structure is critically important. A suitable foundation structure can not only reduce the investment cost but also increase the ability of the accumulator to resist vertical, horizontal, and overturning effects and improve the corrosion and erosion resistance around the foundation, thereby ensuring the safe and stable operation of the gas storage accumulator over the long term.

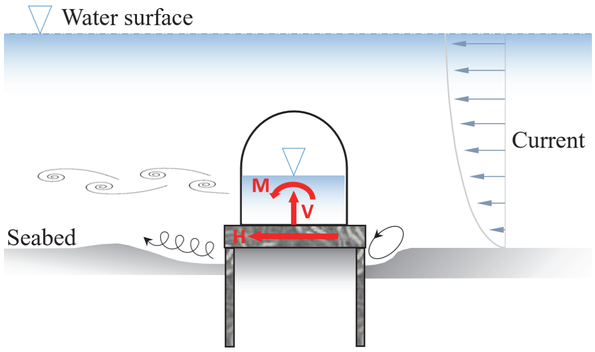


Figure 4. An underwater gas storage accumulator founded on a suction caisson transmitting V-H-M loading at the top of the foundation. (H: horizontal load; V: vertical load; M: moment load).

Separation vortices generated by the ocean current around the gas storage accumulator will erode the soil near the foundation, thereby affecting its stability. Therefore, it is important to understand the local scouring characteristics and predict the scouring depth around the foundation [95,96]. Protection measures for controlling local scour should be investigated after clarifying the mechanism of local scour around the foundation. Currently, there are two commonly used anti-scour measures; one is to use hard marine engineering materials to make physical anti-scour plates, and another is to change the flow field around the subsea structures to make the scour area away from the foundations [95]. Studies have shown that the anti-sinking plate support structure with a skirt can effectively alleviate the local erosion effect [97]. There are complex interactions between the foundation of the accumulator, the ocean current, and the seabed rock/soil. Thus, it is necessary to conduct a coupling analysis of sea–soil–structure interactions.

In addition, the biofouling of marine organisms must also be considered, especially in several important seawater vents on the accumulator. Currently, materials such as titanium alloy and copper nickel alloy can be considered to prevent the adhesion and accumulation of marine organisms from blocking the channel [98].

Generally, the service life of the offshore platform is between 20 and 30 years by comprehensively considering the coupling effects of wind, wave, current, and corrosion. However, the operating environment of the underwater energy storage accumulators is much more moderate than that of surface platforms. Therefore, a longer lifetime between 25 and 35 years can be expected. When out of service, these accumulators do not need to be demolished and can be used as artificial reefs for marine organisms and anchors for offshore wind turbines.

4.1.2. Underwater Gas Transportation

Subsea fluid transportation is relatively mature and widely utilized in the offshore oil and gas industry. However, the processes are generally rather complex, and the investment cost is very high. Comparatively, underwater gas transportation in UWCGES systems should be easier because there are fewer detrimental impurities and the operating conditions are more moderate.

Multiphase flow is the main challenge in the gas transportation of UWCGES. Figure 5 shows a typical gas transportation process. Compressed gas enters the underwater gas transportation pipeline after pressure regulation and drying at gas stations. The temperature of seawater decreases with the increasing water depth. The heat exchange between the pipeline and seawater causes the temperature of the compressed gas in the pipeline to decrease gradually. After reaching the dew point, the water vapor condenses and precipitates, thereby forming liquid accumulation in the low-lying part of the pipeline due to gravity. This may lead to a complex and harmful gas–liquid two-phase flow and even gas–liquid–hydrate three-phase flow. Due to the turbulent nature of fluid flow and the complex interaction of gas–liquid–solid multiphase flow, the complex changes of various flow patterns and fluid pressure fluctuations will present and further result in a series of hazards. First, liquid accumulation will inevitably lead to a reduction in pipeline flowrate, a decline in transportation efficiency, and an increase in pressure drop and energy consumption; secondly, the existence of water will aggravate the corrosion in the gas transportation pipeline and there is a risk of water hammer. At the same time, the fluctuation in pressure and flowrate will induce pipeline vibration and the surge of pressure-regulating equipment. In turn, pipeline vibration will affect the two-phase flow in the pipeline and further aggravate the fluctuation in pressure and flowrate. If the liquid accumulation is not treated, it will seriously affect the safe and efficient operation of the underwater gas transportation system and even cause accidents. For example, during the operations of the UWCAES demonstration system and the underwater testing experiments, the liquid accumulation issues persist without exception, which significantly interferes with system operation [28]. Therefore, the accumulated liquid in the gas transportation pipeline must be removed through pigging. The actual pigging operation mainly depends on experience and is regularly planned. Unplanned/unnecessary pigging operations not only increase the operation cost but also increase the frequency of shutdown. Therefore, the optimal method is to accurately predict the state of liquid accumulation and determine the pigging scheme before the liquid accumulation leads to the deterioration or failure of the system. Therefore, it is necessary to develop low-cost gas transportation support technologies, such as online monitoring and the removal of liquid accumulation in underwater pipelines.

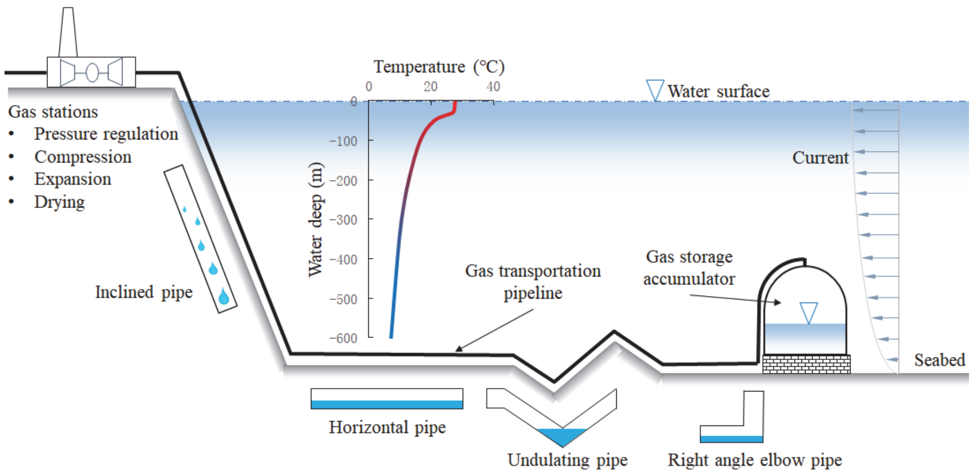


Figure 5. Schematic diagram of underwater gas transportation system.

4.2. Environmental Aspects

At present, marine energy storage technology, though largely embryonic in its development, is undergoing significant progress. Considering the complexity of the bathymetry, the harshness of the environment, and the randomness of the seabed flow direction, the impact of underwater gas storage on marine ecology is also uncertain. A principal risk is the potential for the destruction of habitat for marine organisms and seabed microorganisms. Studies have shown that most microorganisms live 2 cm above the seabed sediment [99]. Installations of large underwater gas storage accumulators on the deep seabed are bound to occupy the habitats of the original marine organisms. At the same time, during the working process of the gas storage system, the seawater flow around the gas storage accumulator forms vortex streets and wakes, causing long-term disturbance to the microorganisms in the seabed upper sediment. At the same time, the arrangement of multiple large-scale underwater gas storage accumulators will also increase the range of influence. The construction of the seabed ecological balance is an extremely long process, and the components and physical and chemical properties are different before and after reconstruction [100]. The long-term disturbance to the seabed sediments may cause a permanent imbalance in the local ecology of the seabed. A reasonable and effective environmental assessment system of underwater gas storage systems needs to be developed. This could be a complement and extension of the existing frameworks of the ecological risk assessment of marine renewable energy [101].

Studies have also shown that underwater systems can have a series of positive effects on the marine ecological environment, such as acting as artificial reefs and promoting local ecological diversity under the protection of closed fishing and restricted navigation areas [102].

4.3. Economic Aspects

The precondition of the successful commercialization of UWCGES depends on economics. Many theoretical studies support the potential acceptable economy of UWCGES technology [51,103–106]. At the significant stage of the energy transition, the utilization of marine renewable energy is accelerating. By integrating UWCGES technology, the contradiction between the rapid growth of marine renewable energy power generation and the slow speed of power grid construction can be effectively solved, which is conducive to solving the consumption of marine renewable energy and improving the utilization rate of marine renewable energy. Marine renewable energy power generation is an integrated system integrating UWCGES technology, which helps to accelerate the reduction in the price of marine renewable energy power. Furthermore, it can also help the development of marine renewable energy and UWCGES technology to achieve sustainable development in the economy, society, people, and nature. However, when commercial companies disclose the economy of their UWCGES technology, they lack transparency in specific details. It could be inferred the technical and economic indicators disclosed by commercial companies are the results obtained under relatively ideal conditions. For example, the deployment site is always ideally deep-water or ultra-deep-water, and the overall efficiency of the system is always very high. In fact, like the onshore systems, the technical economy of UWCGES mainly depends on the specific application mode, technical scheme, energy storage scale, gas storage depth, and distance from the application site. In particular, the UWCGES is generally limited by the local water depth conditions. Specific and detailed technical and economic analysis is needed for specific applications.

4.4. Policy Aspects

The emergence and development of novel energy storage technologies are often inseparable from the encouragement of government policies. Energy storage policy can promote the development of energy storage technology through incentives, loans, and a fair competitive environment. Marine energy storage technology has developed rapidly, but it is still in its infancy, facing strategic problems such as the return of investment, core technology, and the market mechanism. The technical economy is an important obstacle to the promotion and application of energy storage technology, especially for offshore energy storage technologies. UWCGES projects at the initial stages of research tend to lack predictable revenues to attract capital to follow up. Government can provide appropriate incentives to help attract this capital. Policies on energy storage are closely related to economic development and energy storage technology research. Currently, countries with relatively mature energy storage policies include the US, China, Germany, Australia, and Japan [107]. UWCGES has not yet formed a mature theoretical system, especially the core technology related to underwater systems. The government should play an active role, refer to the land energy storage policy, learn from the experience of mature energy storage commercialization projects and demonstration projects, and introduce policies to focus on the research and development of the core technologies of UWCGES, thereby breaking through the technical barriers. Through the extensive support of policies, emerging energy storage projects can carry out technical research and continue to build demonstration projects to promote commercialization. In the diversified application scenarios in the future, there will be great differences in the income mode and scale of UWCGES technology. The government could try to promote market competition through policy incentives to reduce costs and promote sustainable development and large-scale promotion and application of UWCGES technology. However, at present, relatively few countries have introduced policies supporting energy storage, especially countries in emerging economies [107,108]. The policies on onshore energy storage are evolving while offshore policy lags worldwide. Pressure should be on the government to improve policies, promote UWCGES technology research, and construct a better business model, thereby clearing the obstacles to the development of UWCGES.

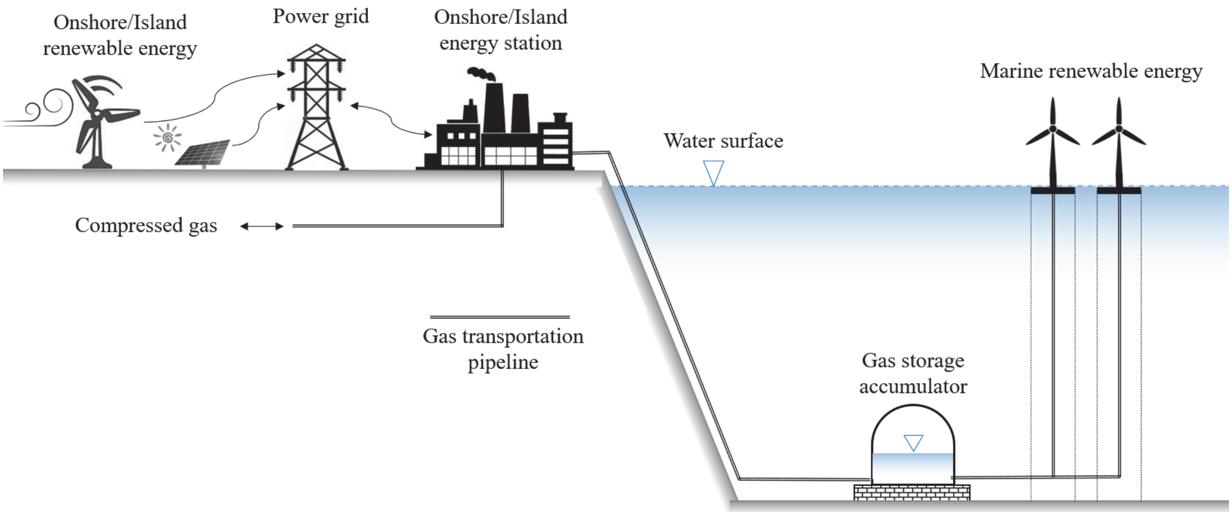
5. Future Perspectives

With the accelerating exploitation of marine resources, marine activities continue to extend to the deep sea. An increasing density of marine infrastructure has been deployed, and more and more energy is consumed. At present time, almost all marine activities rely on long-distance electrical power transmission by submarine cables and power supply from self-contained fuels/batteries. Submarine cables transmit electric energy from onshore grids to the seabed and provide continuous energy supply to underwater equipment in dendritic and radial structures. The high-voltage direct current transmission is the primary underwater cable power transmission mode. However, expensive submarine cable power transmission is not practical for distributed offshore energy demands and far deep-sea demands [109]. In addition, many studies have found that the electromagnetic fields generated by submarine cables have obvious impacts on marine invertebrates and affect the marine environment temporarily or permanently [110,111]. An alternative to submarine cables is a traditional self-contained energy supply, such as batteries or fuels. Energy storage with a battery has been widely used by most underwater devices, especially those working in the far deep sea [112]. However, limited by the capacity of a battery, it is more suitable for small devices or devices requiring a short-time power supply. The energy demands of many large underwater infrastructures cannot be met with batteries. Therefore, there is a clear present need for an energy supply mode with acceptable economy and environmental protection. Marine renewable energy with energy storage may be such a solution. The advantages of marine renewable energy power supply are obvious for far deep-sea demands. It follows then that there is a corresponding demand for marine energy storage technology. The harsh marine environment demands more stringent requirements for offshore energy storage than onshore storage. The UWCGES technology discussed in this study is an alternative that can be integrated to serve a variety of marine application scenarios.

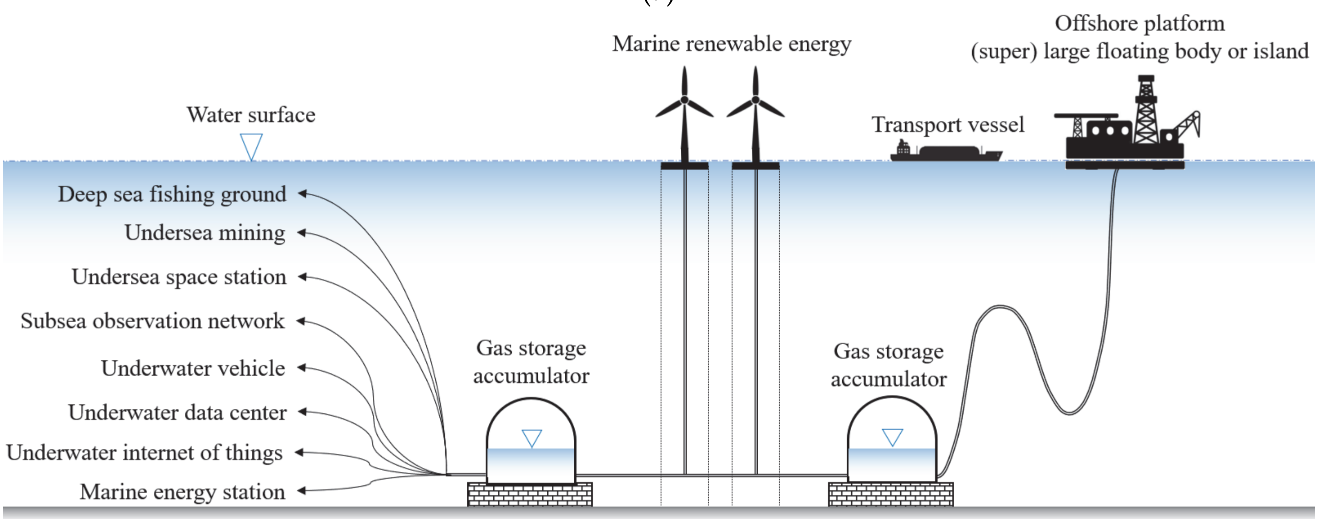
In the short term, UWCGES technology can serve the application scenarios shown in Figure 6a. Air, natural gas, and hydrogen compressed in gas stations with renewable energy can be stored in underwater gas storage accumulators through underwater gas transportation pipelines. When needed, the compressed gas stored in the underwater accumulators can be fed back to the energy system.

With the continuous development and the breakthrough of new technologies in various fields of ocean engineering, UWCGES can serve more application scenarios as shown in Figure 6b in the medium and long term. In the mode of marine renewable energy with energy storage, it can provide energy storage services for marine platforms, large or super large floating bodies, and islands at sea. It can also serve as a marine energy station to provide long-term uninterrupted energy supply for seabed mining, deep-sea fisheries, seabed space stations, subsea observation networks, underwater vehicles, underwater data centers, underwater Internet of Things, etc. [113–119].

Hydrogen energy is a focal candidate for future low-carbon and renewable energy infrastructure. Offshore renewable energies can be used for producing green hydrogen [120]. Underwater storage underpins this chain and can be treated as a complement to traditional storage and transportation modes. Figure 7 shows an integrated application mode of UWCGES in the future marine clean energy system. Marine renewable energy power can not only be directly supplied to the power grid but also be used to support seawater desalination and green hydrogen production. The freshwater produced in the seawater desalination system can be used for electrolytic hydrogen production. The produced green hydrogen can be compressed by efficient isothermal compression and stored in large underwater gas storage accumulators. At the same time, it can also be directly used for compressed air storage as needed. Finally, according to different demands, stored compressed gas will be directly supplied to end users or used for power generation. Hydrogen production from marine renewables could be an important part of the energy transition in the global marine sector. This integrated application mode combines UWCGES with marine renewable energy, seawater desalination, green hydrogen production, and other technologies to provide renewable energy, fresh water, green hydrogen, compressed air, oxygen, and other clean resources. This application mode can be adapted to meet different needs according to various application scenarios shown in Figure 6.



(**a**)



(**b**)

Figure 6. Potential application scenarios of UWCGES: (**a**) Short term service scenarios; (**b**) Medium and long term service scenarios.

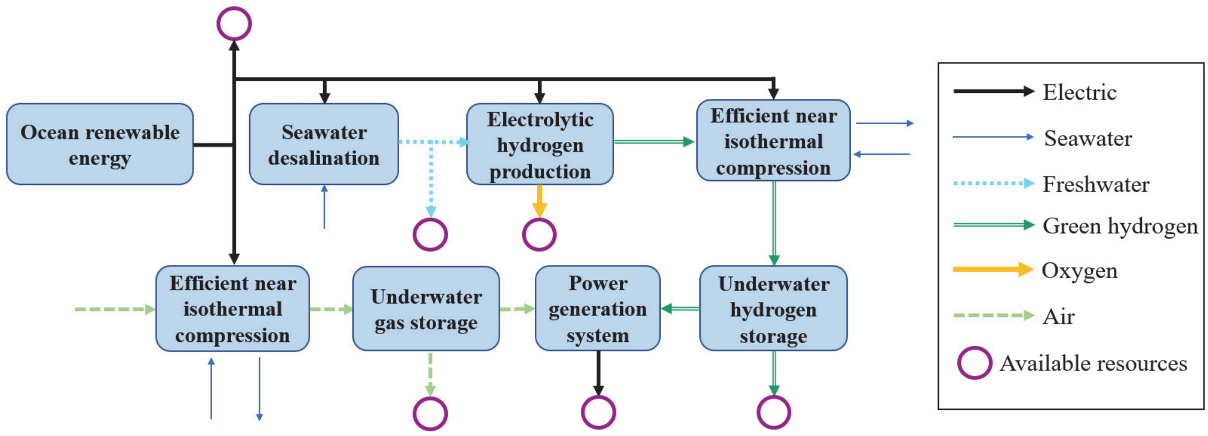


Figure 7. An integrated application mode of UWCGES.

6. Conclusions

UWCGES is one of the most feasible solutions for large-scale offshore energy storage. Though facing many challenges, its potential has driven significant recent attention. Technical challenge considerations include: effective ballast anchoring, structural stability under complex and cyclic loads, safety under the impacts of falling objects and gas escape, vortex-induced vibration under different ocean current conditions, local scouring near the foundation, low-cost gas transportation support technologies, as well as the biofouling of marine organisms. In terms of the environment, the potential hazards of underwater gas storage accumulators are to destroy the habitat of marine organisms and the ecological balance of seabed microorganisms. However, the underwater system may also have a series of positive impacts on the marine ecological environment with proper protection and regulations. In terms of economy, UWCGES is affected by many factors, such as application mode, technical scheme, energy storage scale, etc. There remains a great uncertainty in the return on investment, and there are significant differences between individual projects. In terms of policy, there should be a distinction between onshore and offshore energy storage. Offshore energy storage policy is lacking globally and is subsequently hampering development.

Despite various challenges, it is likely that the strength of energy demand and clean resource demand at large should help to advance the development of marine renewable energy technology. UWCGES is a highly feasible offshore energy storage solution. It can make up for the shortages in traditional energy storage and supply measures in the far and deep sea. With strategic research and development investment, UWCGES can become a critical building block in the next generation of clean energy infrastructure that our planet will depend on.

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