Comparing UWCAES and VRFB for Energy Storage Based on Characteristics

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Abstract. Energy storage technology has always been an important direction of modern industrial development. As a relatively new energy storage technology, UWCAES and VRFB have been studied and discussed respectively on their roles and characteristics, but there are few studies on the comparison of their technical characteristics. Therefore, by introducing the operation principle of UWCAES and VRFB, and comparing their application characteristics respectively, this thesis summarizes and compares the performance of these two energy storage technologies in terms of availability and reliability, facility configuration and location choices, and sustainable development. It is found that both UWCAES and VRFB have high efficiency. Due to their characteristics that are less restricted by geology and adjustable facilities, UWCAES and VRFB are highly applicable. UWCAES has achieved sustainability goals by replacing nonrenewable sources with greener energy and VRFB has enabled the use of recyclable and low-degradation materials to achieve sustainable and long-lasting uses. But both technologies are still in the development stage and have their problems to solve, such as the placement and tightness of tanks in UWCAES and the low energy density of VRFB.

Keywords: UWCAES, VRFB, Characteristics Comparison, Efficiency, Sustainability.

1. Introduction

Energy systems are in a state of constant change and evolution due to the presence of alternative energy sources, advancements in technology, shifting demands, cost considerations, and environmental impacts. While traditional energy generation has historically relied on fossil fuels, there has been a gradual shift towards more modern and inventive techniques, particularly focusing on green resources, for example, solar and wind power. In spite of the continuous rise in energy costs, customer requirements are rapidly increasing due to population growth, economic progress, higher per capita consumption, the need for supply in remote areas, and energy consumption for various devices. Implementing energy storage solutions can enable adaptable electricity generation and reliable delivery, effectively catering to the growing demands of consumers [1]. The necessity of energy storage is underscored through the rising population along with consumers' increasing demands, particularly pursuing for flexible and long-lasting solutions. Currently, Pumped Hydro Storage (PHS) stands as the most developed and widespread type of storage, controlling over 95% of the global market. Unless there are significant disruptions, this situation is likely to persist in the foreseeable future. Despite its dominant position, PHS has drawbacks such geographical restrictions, the possibility of ecological and environmental consequences, and high starting expenses. Alternatives to PHS that are considered as promising include battery energy storage (BES), hydrogen energy storage (HES), and compressed air energy storage (CAES), all of which are making progress in both commercial and governmental programs [2]. The present review aims to assess and compare the existing devices and systems currently in operation, along with those expected to be utilized in the future. By extensively referencing literature, prior research, reports, and journals, detailed insights into economic and environmental concerns have been provided, as well as the challenges and constraints associated with these techniques. Flow batteries, supercapacitors, superconducting magnetic energy storage (SMES), flywheel energy storage (FES), pumped hydro storage (PHS), thermal energy storage (TES), compressed air energy storage (CAES), and hybrid energy storage (HES) are just a few of the many techniques for storing energy that have been analyzed [1].

However, most current literature studies focus on analyzing the development, application and characteristics of old and emerging energy storage technologies. Few works of literature compare the performance of two or more energy storage techniques in terms of availability and reliability, facility configuration and location choices, and sustainability. In this thesis, Underwater Compressed Air Energy Storage (UWCAES) and Vanadium redox flow battery (VRFB) will be discussed and compared. From its terrestrial equivalent, CAES, underwater CAES has evolved. In recent years, technology has also advanced for undersea gas compression as well as energy storage of hydrogen. Many people are interested in UWCAES because it is an encouraging energy storage solution in the maritime circumstances [2]. VRFB, which has been adopted worldwide and incorporated with microgrids (MGs), green power plants, and residential usage, is one of the most prospective huge-scale storage methods for energy. Unlike solid-state batteries, VRFB stores its electrolytes in tanks, making it different from those batteries [3].

A comparison between UWCAES and VRFB in terms of their performances on applications will be shown. This thesis will give the reader a clearer understanding of the advantages and weaknesses of UWCAES and VRFB in each of the different application aspects. The methods of the thesis are comparing the availability between UWCAES and VRFB through the analysis of round-trip efficiency and the constraints of the construction geographical location, etc. At the end, a comprehensive summary and comparison of the application characteristics of UWCAES and VRFB are shown.

2. General Principles and Development of UWCAES

CAES has been modified in a novel way called underwater compressed air energy storage (UWCAES), a technique that brings about energy storage by pressurizing and storing air in reservoirs. It functions and operates similarly to CAES. Air expanders combined with generators can turn pressurized air back into power as necessary. Unlike CAES, UWCAES utilizes a submerged and distensible air accumulator to facilitate energy storage. This accumulator in UWCAES technology offers a critical design feature that addresses the restrictions of the storage reservoir application of traditional CAES systems. These restrictions are specifically the system capacity constrained by geological factors and the pressure fluctuations associated with capacity. The notable feature of this accumulator is its scalable and isobaric nature, which mitigates the need to select an ideal construction site. The general structure of a UWCAES system can be observed in Fig.1. Compressors, turbines, motors/generators, a thermal recovery unit (TRU) made up of several of heat exchangers (HEX), as well as a system of storage containing both air and thermal components make up the basic layout of a UWCAES arrangement. An assortment of air accumulators that are all connected to a network of air delivery pipes make up the air storage system. During the energy storage stage, the outside air is compressed and delivered into the air accumulators. The TRU, as a important energy collector, stores the heat generated throughout the air compression process in a thermal storage media. It is made up of numerous HEX units. The stored air is taken out of storage and expanded by a turbine while being heated by the TRU during the discharge phase. The terminal produces electricity by connecting a generator to a turbine [4]. UWCAES, a novel technology derived from CAES, has been developed over the past decade and has found successful applications in various cases worldwide.

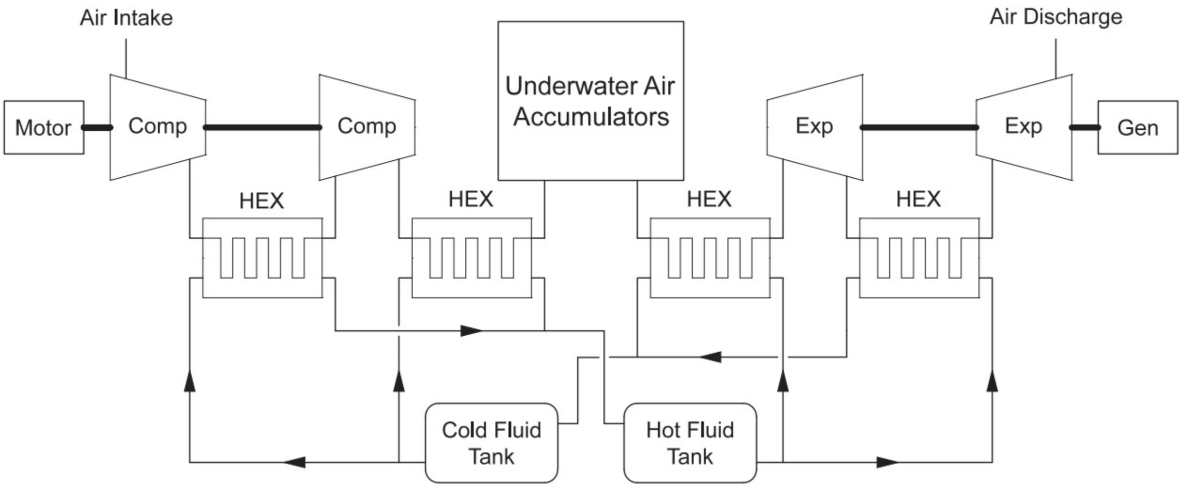

Figure 1. UWCAES process diagram [1].

3. General Principles and Development of VRFB:

Redox flow battery (RFB), a revitalizing energy-storing technology in terms of its distinctive features, is more appealing than traditional batteries because it can store vast amounts of electrical energy in a manner that is both reasonably efficient and affordable [5]. Redox flow batteries normally require a large-scale setup to deploy exterior tanks which used to store the electrolytes rather than been stored in the battery center, which is the primary distinction between RFB and most common electrochemical batteries. In Figure 2, a fundamental diagram of a RFB is depicted. The RFB technology that has received the greatest attention is the vanadium redox flow battery (VRFB). Vanadium ions used as electrolyte solutions generally have four distinct oxidation states which are V2+, V3+, VO2+(V4+), and VO2 +(V5+), where electrons are transferred back and forth. The two half-cells in the central battery are used to supply the electrolytes which then flow cyclically from the positive electrolyte tank to the negative electrolyte tank in the battery reactor. The VRFB battery cell is made up of two half cells, each of which has an electrode and a bipolar plate. A unique membrane is sandwiched in between the two half cells to allow for selective ion exchange while guarding against contamination from the mixture of electrolytes. The fundamental chemical principles of oxidation reaction (negative cell reaction) and reduction reaction (positive cell reaction) are given in Equation (1) and (2). The overall reaction is depicted in Equation (3). In a typical VRFB application, multiple stacks of battery cells are deployed, in which parallel cells share a bipolar plate with adjacent cells. In the discharging phase, the negative electrolytes contain V3+ and the positive electrolytes contain V4+(VO2+); while the negative side will go through reduction to be reduced to V2+ and the positive side will go through oxidation to be oxidized to V5+ (VO2 +) during charging periods. When the battery is being recharged, electrons flow across the bipolar plate from the positive side to the negative side, leading hydrogen ions (H+) pass cross the membrane and enter the negative half-cell [6]. Overall, VRFB has been widely applied just as UWCAES because of its high efficiency and eco-friendly characteristics.

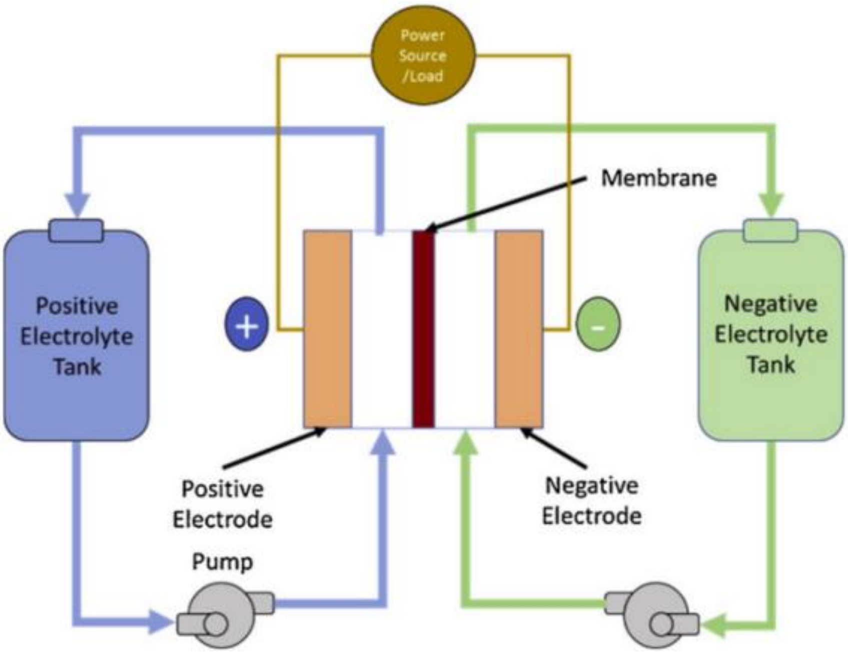

Figure 2. Redox flow battery diagram [3].

Positive cell reaction:

$$VO_2^+ + 2H^+ + e^- \rightleftharpoons VO^{2+} + H_2O \tag{1}$$

Negative cell reaction:

$$V^{2+} \rightleftharpoons V^{3+} + e^- \tag{2}$$

Overall cell reaction:

$$VO_2^+ + V^{2+} + 2H^+ \rightleftharpoons VO^{2+} + V^{3+} + H_2O \tag{3}$$

4. Comparison of Technology Availability and Reliability

UWCAES and VRFB are both favorable by the goal of reaching a sustainable industry. They both possess exclusive characteristics and privileges in application as energy-storing technology. A comparison between UWCAES and VRFB based on their characteristics will be made in the following contents of the thesis. The overall availability and reliability of UWCAES and VRFB will be first analyzed. One of the most important factors in determining the usability of an energy storing technology is to check its efficiency. The system efficiency of a two-level UWCAES system is within the range from 62% to 81%. The efficiency of UWCAES system is close to be at its highest (81%), when energy is stored in the battery pack at a high density, while at its lowest (62%) in the frequent operations in the modes like LM-LM, LHM-HM, and LHM-LHM [7]. The redox reaction happens in batteries significantly influenced the energy efficiency of VRFB. The positive electrode will experience an oxygen evolution reaction during the charging phase, and subsequent hydrogen evolution and oxygen evolution reactions may result, which can reduce electrode efficiency and limit the use of VRFB on a broad scale. But the efficiency of VRFB could still be enhanced by increasing surface roughness by using pristine graphite felt (GF) at 400 ◦C for 30h thus increasing electrochemical activity and finally battery efficiency [8]. Based on the second law of thermodynamics, the VRFB's overall energy efficiency has a storage efficiency of at least 61% [9]. Therefore, the general efficiency of UWCAES and VRFB are relatively similar, and are higher than other energy-storing counterparts such as pumped-hydro energy storage systems. UWCAES is a comparatively novel energy-storing technology but with high availability because of its abundant installation sites and existing and extendable constructed application principles from CAES. VRFB is also highly available. The VRFB has a straightforward structure, and the majority of the materials used are readily accessible and reasonably priced. Additionally, there aren't many geographical restrictions, and the installation site only needs to use renewable energy for the power generation equipment. Finally, the VRFB's building area is also relatively small compared to other fixed energy storage applications, saving space [5]. Hence, UWCAES and VRFB are both widely available to apply.

5. Comparison of Facility Configurations and Locations

The discussion of this paragraph focuses on the equipment and infrastructure needed for a UWCAES system and a VRFB system, and then how they are deployed in terms of location and facility configuration. Single/multistage, adiabatic/diabatic, and other configurations that are thought to be suitable for subterranean CAES can all be employed with UWCAES systems. The decision of where to put UWCAES (conversion equipment and heat storage) is primarily influenced by the distance between the ships and the land as well as the expense of transferring power via cables and high-pressure air via pipes [10]. Installation sizes for VRFB range from a few kilowatts to a few megawatts, and commercial techniques have been successfully used in a number of projects at diverse sites. The charging transfer takes place in the VRFB's central storage tank, which can be expanded depending on the uses and available space. So, increasing the capacity of the system according to corresponding industrial-scale applications is relatively manageable without high initial costs since expanding the tanks is the only requirement if a capacity increase is needed [11]. The location and facility configuration of UWCAES are comparatively sterner than VRFB. In some regions of the world, there are limited spots where deep water is found within a few kilometers of shore, so in these places, an onshore electricity substation and a floating platform are needed, which means additional cost and strict sealing requirements occur. For VRFB, the size of the system is adjustable and there is no need to consider the vertical height as an application influencing factor. But the location and facility configuration of the technology setup are determined mainly by the location of the energy-requiring places and the amount of power needed from there. Therefore, both of the technologies have their privileges in specific situations.

6. Comparison of Technology Sustainability

Sustainability is a crucial concern in the energy sector, particularly energy storage. For UWCAES, sustainability is reflected in optimized efficiency and cost-effectiveness, ensuring wasting as little energy as possible. UWCAES has a relatively smaller scale than CAES while eliminating fossil fuel use. The combustion chamber of a CAES system is substituted by thermal energy storage, much as adiabatic CAES [4]. The sustainable advancement of battery performance hinges not solely on the discovery of new materials, but also on the reduction of resource consumption. When compared to lithium-based batteries, studies have indicated that VRFB is more recyclable when the pathways for recycling steel and copper are taken. Experts believe that VRFB has little degradation difficulties, hence it can probably be completely reused [12]. UWCAES is upgraded from CAES and VRFB is also derived from traditional lithium-based batteries, thus they both possess better performances in achieving the sustainable goal of the energy sector. UWCAES discourages the use of fossil fuels as an electrical source and instead uses thermal energy for operational energy. Because VRFBs can be charged and discharged multiple times without significant degradation, and because they use vanadium which is recyclable as a main component, they are generally regarded as a more sustainable and environmentally friendly option for energy storage compared to some other types of batteries that utilize materials that have a greater environmental impact. However, it is significant to consider factors like the environmental impacts of manufacturing, maintenance, and end-of-life disposal when estimating the overall sustainability of these technologies. But the costs associated with these factors can vary between regions, environmental regulations, and different manufacturers. Specific circumstances require specific analysis.

7. A Summary of Three Comparisons

The limitations of CAES's capacity-linked storage variations in pressure and geology-restricted system capacity are addressed by UWCAES. UWCAES is easier to scale up in industry and its isobaric nature enables a better performance in efficiency and simplified control by maintaining a constant pressure throughout the expansion and compression cycles which reduces energy losses and leads to simpler and more reliable control systems. VRFB as a promising energy-storing technology has the unique characteristics of storing the electrolytes in exterior tanks instead of the battery center and uses electrolytes containing vanadium ions with high recyclability. Different operational modes and amounts of energy stored in UWCAES systems lead to different efficiencies of UWCAES, and the redox reaction of vanadium ions and surface roughness also will result in different efficiency of VRFB, but the overall average efficiency of UWCAES and VRFB are relatively similar that is around 80%, which are generally higher than most of other energy storing technologies. Both of the two technologies are relatively accessible to scale up and are highly available in terms of their less geology-restricted systems. Both of the technologies can be adjusted to satisfy the needs of different amounts of energy stored by simply adding up or cutting down the number of accumulators (UWCAES) or storing tanks (VRFB). Both UWCAES and VRFB are reaching the goal of sustainable development: UWCAES eliminates the use of fossil fuel by replacing the combustion chamber with thermal energy storage underwater; VRFB has minimal issues with degradation and higher recyclability compared to other types of batteries. However, some application issues are still associated with these two technologies. For UWCAES, there are issues with placing tanks at the bottom of lakes, oceans, and seas, as well as issues with the pressure drop and the tightness of the tanks themselves [13]. The advancement and use of VRFB are constrained by the low energy density brought on by elements such resistance polarization, concentration polarization, and electrolyte transmission delay [14]. Research is continuing and UWCAES and VRFB are still in the development phase, therefore, upgrades and innovations of these two energy-storing technologies can be expected.

8. Conclusion

This thesis compares the application performances and deployment characteristics of two relatively emerging technologies in storing energy, UWCAES and VRFB, which were characterized in terms of round-trip efficiencies, installation environments, facility configurations, and sustainability. The result of the analysis of availability and reliability shows that the general efficiency of UWCAES is from 62% to 81% and the general efficiency of VRFB is at least 61%, suggesting the efficiency of these two technologies is similar; the highly abundant installation sites, less geology-restriction, cost-effective and available materials characteristics of the two technologies enable the two technologies highly available and reliable. Facility configurations of UWCAES focus on the core component - underwater air accumulators - which could be added up or cut out based on the amount of the need for energy storage; same as the UWCAES, the facility configurations of VRFB could be adjusted by simply increasing or deleting the number of tanks in VRFB according to the energy stored. Each technology has its geographic preferences, and UWCAES is suitable for offshore energy storage, but both technologies will choose the right location based on their material needs and transportation costs. When considering achieving sustainability, UWCAES decreases the use of nonrenewable energy in its system by using thermal energy instead and VRFB has a long service life and uses highly recyclable materials inside, meaning both of them are approaching sustainable development among the energy storage technologies. Therefore, UWCAES and VRFB in general have similar aspects in terms of availability, reliability and sustainability, and both have good performance in these aspects. This article gives the reader an intuitive look at the characteristics of both technologies and the similarities of their characteristics. The two technologies still have some drawbacks to be solved: UWCAES has problems with its tanks' placements and tightness, and VRFB has low energy density. The thesis only covers some directions of comparison of characteristics between these two technologies and there are still many other worth discussing aspects to analyze. More researches and discussions could be done in the future about the comparison between two or even more energy storage technologies in terms of multiple aspects related to their characteristics.

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