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Views & Comments

The Flow Battery for Stationary Large-Scale Energy Storage

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Energy decarbonization is critical for the sustainable development of human society. The large-scale use of renewable energy in the future can both meet the growing energy demand and reduce carbon dioxide emissions, and is thus becoming increasingly important [1]. Renewable energy (e.g., wind and solar power) has the characteristics of discontinuity, instability, and uncontrollability; therefore, it cannot be directly connected to the power grid [2]. It is essential to employ energy storage devices for amplitude/frequency modulation, smooth output, tracking power generation plans and so on. At present, energy storage is the key bottleneck in the promotion and application of renewable energy [3,4]. Even though non-aqueous lithium-ion batteries dominate the power and consumer battery markets and non-aqueous sodium- and potassium-ion batteries are developing rapidly, the use of an organic electrolyte in stationary large-scale energy storage would inevitably introduce a serious security risk [5–8].

The concept of flow batteries was proposed in 1974 by Thaller at the National Aeronautics and Space Administration (NASA) Lewis Research Center Cleveland [9]. The flow battery realizes the mutual conversion of electrical energy and chemical energy through a reversible redox reaction (i.e., a reversible change of the valence state) of the active materials in the anolyte and catholyte [10]. Flow batteries–vanadium flow batteries in particular–are well suited for grid energy storage and are attracting increasing attention due to their advantages of flexible power and capacity design, high safety levels, and a long charge/discharge cycle life.

The vanadium flow battery was first suggested by Skyllas-Kazacos and coworkers in 1985 [11,12]. In recent years, remarkable progress has been achieved in vanadium flow battery electrodes [13,14], electrolytes [15–17], membranes [18–20], and bipolar plates [21–23]. Numerical modeling methods have been built to investigate stack geometry [24], the uniformity of transfer current density [25], mass transport [26], vanadium ion crossover [27], the flow field [28], and so forth. Moreover, machine learning algorithms have been successfully introduced to assist in the design of flow fields [29], cost prediction, and performance optimization [30]. The vanadium flow battery has now been accepted as a promising energy storage solution by an increasing number of scientists and entrepreneurs. Stimulated by the success of vanadium flow batteries, research on various other flow battery systems (e.g., zinc–iron flow batteries, zinc–bromine flow batteries, zinc–nickel single-flow batteries, organic flow batteries, iron–chromium flow batteries, and zinc–cerium flow batteries) is booming [3,31–34] and achieving very impressive progress. The large-scale application of flow batteries in renewable energy generation will greatly reduce the abandonment rate of wind and solar energy and the consumption of fossil fuels, and will thereby help in decreasing carbon emissions. Against the background of climate change, urgent market demand, and strong policy support, flow batteries are arriving at the right time.

We firmly believe that flow batteries will play a very important role in the stationary energy storage market. Herein, based on our many years of experience in the research and application of flow batteries, we briefly share our views on their development in terms of energy density, cost, safety, and the environment. The pictorial summary of our views on flow batteries is displayed in Fig. 1.

1. Energy density

Energy density refers to the energy released per unit mass or unit volume of a battery—that is, the mass-specific energy or volume-specific energy. According to the convention of flow batteries, the energy density is calculated based on the volume of electrolyte, which differs from calculations for portable or power batteries. Frankly speaking, the energy density of flow batteries is not dominant in comparison with lithium-ion batteries. However, energy density should not be a major concern for flow batteries due to

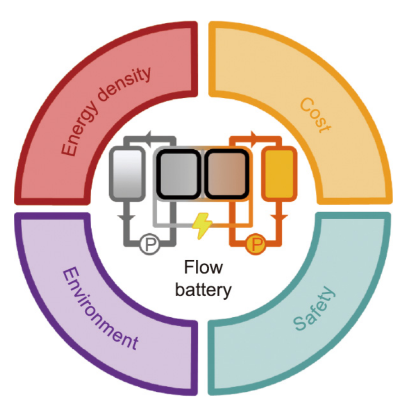

Fig. 1. A pictorial summary of our views on flow batteries. P: pump.

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their obvious and unquestionable advantages in terms of reliability and stability. Furthermore, for large-scale stationary energy storage technology, the flow battery system plays the role of infrastructure, rather than functioning as a portable consumable. In addition, large-scale energy storage projects are usually built in low-cost spaces, which means that the costs of land occupation using flow batteries is not high. Optimizing the layout of the flow battery can also effectively save the costs. Therefore, mass- and volume-specific energies are less critical for stationary energy storage than for power batteries. Nevertheless, a higher energy density is always beneficial in saving space and will extend a battery's application fields. The energy density based on electrolyte volume can be used as an indicator to help in the development of a more advanced flow battery system.

To increase the energy density of a flow battery, new compositions or additives should be tried in order to endow a high-concentration electrolyte with better physical and kinetic properties. In parallel, the novel redox couples for flow batteries must be further developed, with the aim of increasing concentration and more electron transfer. Moreover, the energy consumption of normal battery operation cannot be ignored. Compared with other types of batteries, such as the lithium-ion battery, lead acid battery, and zinc–nickel battery, the flow of the electrolyte through the stack during charging and discharging is an important feature of the flow battery, which inevitably leads to additional energy consumption. To reduce the energy consumption of the circulation of the electrolyte, a stack structure with low fluid resistance and an advanced flow type can be designed. Furthermore, utilizing a proper operation mode is an even more important way to reduce energy consumption.

2. Cost

Product cost is a comprehensive index of a technology, its business model, and its management that directly determines price and competitiveness. For example, the high safety levels, high degree of reliability, and ultralong lifespan of vanadium flow batteries are indisputable. Based our calculations, the cost of a vanadium flow battery system at an energy/power of 4 h can reach around 223 USD·$(kW·h)^{-1}$ when the operating current density reaches 200 mA·cm^{-2}, while the voltage efficiency and utilization ratio of the electrolyte are respectively maintained at above 90% and 80% [30]. If the cost is greatly reduced, it will open up a wider market. Healthy competition, technological progress, and large-scale production in the flow battery industry can indeed partially reduce cost. However, the cost of the vanadium electrolyte, which accounts for a large proportion of the entire system, is not controlled by these factors. In fact, the vanadium electrolyte is recoverable and recyclable, making the vanadium battery different from other energy storage systems. Vanadium electrolyte can thus be regarded as a financial asset, hedging the cost of a vanadium flow battery. Electrolyte rental for vanadium flow batteries is a promising business model that can dramatically reduce the investment and further reduce the operation cost. Even after years of heavy-duty use, the electrolyte of a vanadium flow battery can be fully recycled and reused after simple treatment. The electrolyte rental solution is feasible in terms of both capital and technology, and deserves promotion. If this model is successful, its application to other flow battery systems could be attempted. From the market's perspective, an acceptable cost of flow batteries should be comparable with the cost of lithium-ion batteries—which is the ultimate goal of flow battery developers. Establishing a clear and reasonable business model will stimulate the enthusiasm of all links in the flow battery supply chain and contribute to the sustainable development of flow batteries.

Encouraged by energy policies in recent years, a large amount of capital has been poured into the energy storage industry. The investment in flow batteries is bound to increase, thanks to their significant advantages in safety and reliability. Their upstream and downstream industrial chains should quickly be improved. The competition mechanism in the raw material and component supply market will form rapidly. Undoubtedly, the cost of flow batteries will decrease further, resulting in a huge profit space. For investors, this is the right time for capital layout in the field of flow batteries. Interestingly, the appropriate use of capital can attract numerous talents, introduce advanced equipment, promote technological progress, improve market competition, and reduce product costs. Driven by capital, downstream flow battery products will mature in a short period of time, provoking the rapid formation of the entire industry. The reasonable introduction and utilization of capital is the key to cutting costs, increasing the product added value, and promoting the healthy and rapid development of flow batteries.

3. Safety

Renewable energy requires a very safe and reliable storage solution, which is also very important for the future smart grid. Safety is a prerequisite for any advanced electrochemical energy storage technology. Mainstream flow batteries usually use aqueous electrolytes, giving them the common characteristic of a high degree of safety. Compared with various other existing energy storage technologies with organic electrolytes, flow batteries are safer and more reliable. Increasing attention to production safety, life safety, and property safety is activating a broad market space for flow batteries—especially vanadium flow batteries—in the field of large-capacity energy storage technology. Improving technical standards and testing/certification systems, strengthening the online monitoring of component and system operating statuses, promoting the establishment of technical safety standards and management systems, strengthening safety management, and clarifying the main body of safety responsibility in each link of the industrial chain will further promote the safe operation of flow batteries and ensure their sustained, healthy, and rapid development. As long as the bottom line of safety is maintained, the market competitiveness of flow batteries will flourish, which will facilitate an unprecedented market explosion.

4. Environment

Flow batteries have strong environmental advantages. Taking vanadium flow batteries as an example, these batteries usually employ an aqueous electrolyte, which does not impose a burden on the environment during the preparation, use, and post-processing of the electrolyte. No harmful substances are released during the operation and storage of the electrolyte. However, a possible risk from battery system operation stems from electrolyte leakage, which not only harms the electric circuit of the battery system and makes the performance rapidly decay but also causes a waste of vanadium resources and environmental pollution. Fortunately, advanced flow battery system manufacturing technology, mature fluid transport technology from the chemical industry, and developed detection/monitoring technology can greatly reduce the risk of electrolyte leakage and resulting accidents. Importantly, aqueous flow batteries have a very low risk of explosion and fire, which reduces the possibility of the combustion of combustibles in the battery system and the release of toxic gases. Moreover, from a structural perspective, the components of flow batteries are independent and easily separable from each other. Many of the components of decommissioned flow batteries—including the high-cost electrolyte—are recyclable. Compared with lithium-ion batteries, the recycling of flow batteries is likely to be simpler, the resource recovery rate may be higher, and the economy may be better. That is to say, decommissioned flow batteries are not waste but a resource.

In recent years, plenty of demonstration projects for flow batteries have been implemented around the world, and huge advancement has occurred in this field. However, it must be admitted that there is still a gap between the current level of development and large-scale marketization. Solid technology support is the foundation required for flow batteries to be put into and adapted to the market. Continuous technological progress and innovation are an effective path to not only better meet market demand but also inject infinite vitality into flow batteries, regardless of their stage of commercialization. In the face of strong market demand and high-quality standards, more and more research institutions and enterprises are increasing their investment in improving the efficiency, power density, energy density, and high/low temperature stability of flow batteries. Increased effort is still needed in some aspects of flow batteries (e.g., electrolytes, electrode/bipolar plates, ion conducting membranes, and stack system technology), even though great progress has been made. Significantly, reducing the costs of flow battery systems has become the focus of attention in recent years. Establishing or updating a flexible competitive raw material supply system and developing efficient standardized production technology from raw materials to flow battery stack systems are urgently needed and beneficial to improving the quality and competitiveness of flow batteries. It is a fact that vanadium flow batterie are more mature than other flow battery systems. Even so, the next generation of flow battery technology must still be continuously researched and developed to solve the problems of the low energy density and high cost of vanadium flow batteries. Among such battery systems, aqueous zinc-based flow batteries are expected to have a great future due to their low cost, high energy density, environmental friendliness, and high safety level.

In this paper, we have shared our thoughts on flow batteries from four aspects–namely, energy density, cost, safety, and the environment. We firmly believe that, with the deepening of research and development, the commercialization of vanadium flow batteries will speed up, which is likely to promote the rapid advancement of other flow battery systems. The stationary large-scale electrochemical energy storage market will eventually choose flow battery technology.

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