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White Paper

Vanadium Redox Flow Batteries

Identifying Market Opportunities and Enablers

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Introduction

Vanadium redox flow battery (VRFB) technology is a leading energy storage option. Although lithium-ion (Li-ion) still leads the industry in deployed capacity, VRFBs offer new capabilities that enable a new wave of industry growth. Flow batteries are durable and have a long lifespan, low operating costs, safe operation, and a low environmental impact in manufacturing and recycling. The technology can work in tandem with existing chemistries to fill demand in a growing energy storage market.

Flow battery technology has advanced considerably in recent years, driven by major R&D efforts from both private companies and publicly funded universities and laboratories. The technology is an ideal fit for many storage applications requiring longer duration discharge and more than 20 years of operation with minimal maintenance.

Flow batteries are durable and have a long lifespan, low operating costs, safe operation, and a low environmental impact in manufacturing and recycling.

Key advantages of VRFBs include the flexibility and scalability of the technology, allowing it to cover several applications in the storage market. These advantages, combined with the durable and reusable nature of VRFBs, make for a sustainable energy storage solution that adds to its value proposition. Of note is also the high safety rating of VRFBs, which is due to its nonflammable design. In addition, VRFBs have existing synergies with industries such as steel alloy production, which also uses vanadium. This existing means of production could be expanded to provide accessible supplies for VRFBs as well.

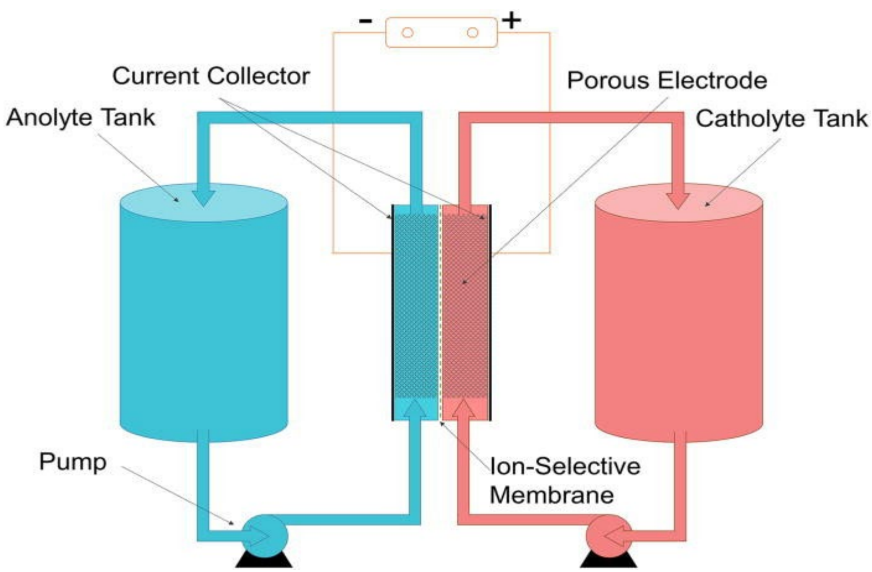
Despite the many advantages, VRFB markets still face commercial challenges. Misconceptions about costs and comparisons based purely on capital rather than cost of energy, and an overreliance on Li-ion batteries are significant barriers for VRFBs. Building confidence and understanding and reaching economies of scale to overcome these barriers could lead to VRFBs' continuous growth in the storage industry.

This white paper provides an overview of the state of the global flow battery market, including market trends around deployments, supply chain issues, and partnerships for VRFB stakeholders. It also outlines VRFB case studies of note and lays out recommendations for stakeholders.

Vanadium Redox Flow Batteries: Technology Considerations

Flow batteries are generally defined as batteries that transform the electron flow from activated electrolyte into electric current. They achieve charge and discharge by pumping a liquid anolyte (negative electrolyte) and catholyte (positive electrolyte) adjacent to each other across a membrane as Figure 1 shows. Because the electrolytes contain compounds in different oxidation states, flow batteries use reduction and oxidation (redox for short) reactions where electrons are transferred between the two solutions.

Figure 1 Flow Battery Schematic

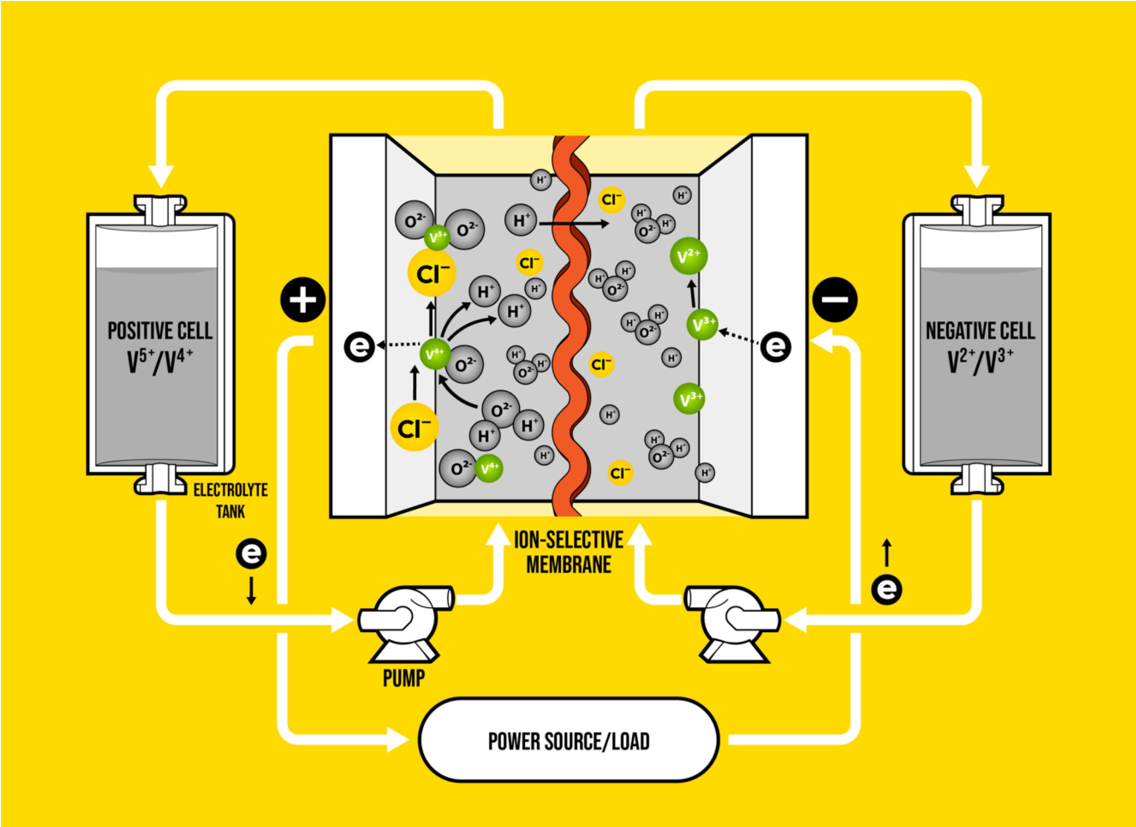


(Source: Journal of Vacuum Science and Technology B)

There are several inherent advantages to flow batteries compared with other storage technologies. Flow batteries are naturally flexible and expandable by design because they can be designed with decoupled power output (determined by the size of the power stack) and energy capacity (determined by the volume of liquid electrolyte) with long discharge durations. Increasing the energy storage capacity is a matter of adding more electrolyte without needing to expand the core system components. Increasing the energy storage capacity enables a flow battery system to reduce its levelized cost per kilowatt-hour delivered over the course of its lifetime, something that Li-ion battery systems are not able to do. Flow battery systems also require little to no thermal management and therefore do not present the same fire risk as Li-ion or molten salt batteries.

Although there are many different flow battery chemistries, vanadium redox flow batteries (VRFBs) are the most widely deployed type of flow battery because of decades of research, development, and testing. VRFBs use electrolyte solutions with vanadium ions in four different oxidation states to carry charge as Figure 2 shows.

Figure 2 ***VRFB Schematic***



(Source: Vanitec)

The first successful VRFBs were developed in the 1980s. Since then the technology has evolved to include several subchemistries and design variations. Unlike other flow batteries, the anolyte and catholyte used in VRFBs are both based on the same parent compound making use of vanadium's four most common oxidation states. As a result, if electrolytes are mixed, there is no permanent reduction in capacity or damage to the battery. As is the case with other flow battery chemistries, VRFBs are capable of being left completely discharged for long periods of time with no ill effects such as self-discharge. The electrolytes are stored in separate tanks and not in the power cell of the battery, therefore there is no interaction unless the pumps are turned on. The aqueous electrolyte used in VRFBs is inherently nonflammable; it is therefore impossible for it to catch fire. In addition, VRFB technology has a high cycle life, with many vendors predicting ranges of 15,000-20,000 full cycles with 100% depth of discharge (DoD) availability. VRFBs can also switch between charge and discharge states without a rest period and without capacity degradation, resulting in increased operational availability.

VRFB technology does have downsides. Like most flow battery technologies, VRFB energy and power densities are relatively low, requiring heavier and physically large systems. The environment where the system is to be installed must be able to house the required electrolyte tanks and pumping systems, which can be large depending on the desired energy storage capacity. Figure 3 shows the size of the electrolyte tanks used for a 3 MW/12 MWh VRFB demonstration project from VRB Energy in Hubei.

Although the technology presents minimal fire risk, in addition to vanadium, the electrolyte compounds primarily consist of water along with additives such as sulfuric acid or hydrochloric acid, which are corrosive and toxic in nature. The risk of electrolyte leakage or spillage as well as fumes venting from a VRFB system presents a safety risk that must be properly managed.

Perhaps the most pressing barrier for greater VRFB adoption is the cost. There is a need to substantially reduce costs due to the relatively high capital cost and volatility of the price of vanadium used in the electrolyte, which accounts for a large portion of a battery system's overall cost.

Figure 3 Electrolyte Tanks for a 3 MW/12 MWh VRFB

(Source: VRB Energy)

Value Proposition and Market Drivers

VRFBs continue to find markets where they are a viable choice for new projects. The key drivers for VRFBs relate mainly to their durability and safety, as well as their synergistic ability to complement existing vanadium mining practices.

Applications

VRFBs' flexible design enables large-scale and long-duration energy storage (i.e., the ability to increase energy storage capacity by adding more tanks of electrolyte). As such, utility-scale applications are one of the key use cases for VRFBs. Because of the size and complexity of the systems required for VRFBs, they are primarily suited for stationary applications where large systems can be accommodated. By pairing variable renewable energy sources such as wind turbines and solar PV arrays with VRFBs, large amounts of excess renewable energy can be captured and utilized later when the sun isn't shining or the wind isn't blowing, effectively turning them into dispatchable resources for peak periods. VRFBs could be crucial as the decade progresses with more renewable generation sources coming online and longer duration energy storage (i.e., longer than 4 hours) is required to balance the grid. Several states in the US have also set aggressive energy storage capacity targets for the coming decade. As demand for longer duration storage applications grows, the deep discharge cycle abilities and long lifetimes of VRFBs are expected to be critical.

Additionally, in grid congested areas where new transmission and distribution lines may be needed, VRFBs can alleviate stress without the same capital investment and environmental disruption required to build out new lines. Because of VRFBs' ability to independently scale power and energy capacity, applications are possible in which VRFBs act as replacements to diesel generators, such as microgrids for remote or isolated communities. In acting as a backup generator, VRFBs could increase grid resiliency in the wake of more frequent extreme weather events without the harmful air pollution effects associated with diesel generators. There have also been trial projects in South Korea and Australia where VRFBs are being used as EV charging stations because of their ability to be cycled frequently without experiencing capacity degradation. EV charging stations often experience frequent and unpredictable use depending on their location, meaning the full DoD and ability to cycle frequently and for long durations of VRFBs would be advantageous. VRFBs can be added to existing charging infrastructure in urban areas, and in remote areas, VRFBs can be paired with solar PV systems to form standalone charging systems.

In large industrial applications such as manufacturing processes, VRFBs can be used to shift energy-intensive processes to off-peak hours to relieve strain on the grid. Energy arbitrage wherein VRFBs are charged during off-peak periods using low cost electricity and then discharged during peak times can lead to revenue opportunities for the owners. In the UK, VRFBs are also being used to provide ancillary services such as balancing and frequency response.

Durability

A key advantage for VRFBs over Li-ion is the durability and flexibility of the technology. Li-ion batteries are notorious across many industries for their relatively short lifespan due to degradation of energy capacity. Although there is a range of cycle lives across various Li-ion battery types, on average, the technology offers around 3,000 cycles before significant degradation occurs. Furthermore, Li-ion batteries are not designed to sit idle for extended periods of time or discharge completely to a 0% state of charge. These limitations can affect the economics of an energy storage project by requiring an oversized battery system for a given application and requiring periodic replacement of degraded battery modules to maintain rated capacity. VRFBs do not experience capacity degradation with each discharge cycle leading to significantly longer cycle lifetimes than Li-ion technology. That means VRFBs could be discharged multiple times each day for short duration needs, discharged once in a day for a longer period, or some combination in between without affecting the longevity of the system.

Reusability and Recyclability

Another key advantage for VRFBs specifically over other types of batteries is the reusability of the electrolyte. Liquid electrolyte used in VRFBs can be nearly 100% recovered and, with minimal processing steps and cost, reused in another battery application. If spent electrolyte can't be recycled to another electrolyte application, it can be recycled into commodity-grade vanadium products, including vanadium pentoxide (V_2O_5), which can be used in other applications resulting in an economic return for the electrolyte supplier and, in some instances, the battery owner. Because the electrolyte chemistry does not significantly degrade during use, alternative financing options for the electrolyte are also possible.

Bushveld Energy is working to develop their electrolyte leasing business wherein they retain ownership of the compound and lease it to VRFB system users or buyers. At the end of the VRFB's operating life, the electrolyte is recovered, reprocessed, and either leased to another VRFB user or recycled into commodity-grade vanadium products for a financial return. This option helps lower the high upfront cost of the VRFB system.

Safety

The inherent safety risks associated with Li-ion batteries due to overheating and thermal runaway have always been a concern in the industry. However, fires and explosions in grid-scale energy storage systems (ESSs) around the world over the past several years have heightened efforts to maintain safety and is driving greater interest in flow batteries and nonflammable ESS technologies.

According to the South Korea Ministry of Trade, Industry, and Energy, 21 ESS fires occurred in the country between May 2018 and January 2019 resulting in the government suspending operations at many ESS sites across the country. In June 2019, the Ministry released the results of its investigation into the fires and concluded there were four major causes: insufficient battery protection against electric shock, inadequate management of operating environment, faulty installations, and insufficient integrated protection and management systems.

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Outside of South Korea, perhaps the highest profile ESS fire in the US occurred in Arizona in April 2019 at a plant owned by the utility Arizona Public Service. That fire and subsequent explosion critically injured four firefighters. The cause of the fire was determined to be dendritic growth on a single Li-ion cell causing a short circuit which in turn resulted in the cell heating up and catching fire. After the cell caught fire, the suppressing agent was dispensed but was unable to stop the fire as it spread to neighboring cells. As the cells continued to burn, they released explosive gas that built up inside the housing container and eventually combusted when first responders opened the door and added oxygen to the system.

Because flow batteries do not generate significant amounts of heat during operation and therefore do not require HVAC systems for thermal management or risk overheating, they don't present the same explosion or fire risks that Li-ion systems do. Furthermore, most flow battery chemistries use aqueous electrolytes, which are largely composed of water and are inherently nonflammable though they do contain acid additives. Although VRFBs present safety risks due to the toxicity and corrosive nature of chemicals used, these risks can be well mitigated with proper design and maintenance and would likely not result in the same type of catastrophic damage as an explosion or fire.

Complement Existing Vanadium Mining Practices

In addition to the benefits of the technology, synergies across industries are helping drive the development of flow batteries. Many stakeholders in the vanadium industry see VRFBs as a major source of new demand for the metal that has traditionally been used in steel alloys. This dynamic has resulted in government programs to support the technology's development in China. Several Chinese provinces contain large vanadium reserves that the government is hoping to exploit by encouraging new industries to use the metal. The Chinese government is supporting the development of several large VRFB projects including the 100 MW/500 MWh system with VRB Energy in Hubei Province and the 200 MW/800 MWh system in Dalian with Rongke Power.

In addition to government-level support for vanadium industries and technologies, several vendors view VRFBs as a complementary business to existing mining activities and have direct or indirect ties to vanadium mining interests. South Africa-based Bushveld Minerals is one of the main vanadium producers in the world. In August 2020, a consortium, which includes Bushveld Minerals, acquired the majority shares in CellCube, a VRFB developer, manufacturer, and distributor. Largo Resources, another one of the major vanadium producers in the world, also has plans to set up its own vertically integrated energy storage company through its subsidiary Largo Clean Resources. Similarly, vendor VRB Energy is majority owned by Ivanhoe Electric, a metal-focused minerals exploration and development company. Australian Vanadium Limited, another vanadium producer, also entered the VRFB market through its formation of subsidiary company VSUN Energy.

Market Barriers

VRFBs are continuing to gain traction for various storage applications due to their durability and advantages providing long-duration energy storage. Although momentum has grown, obstacles remain for the technology to overcome, primarily around capital cost and market demand.

Despite the advantages and overall potential of the technology, VRFBs have not been used often in short-duration (i.e., less 4 hours) applications. The short-duration energy storage applications that are in high demand in today's market have been dominated by Li-ion batteries because of their drastic drop in capital cost over the past two decades. The lower power and energy densities of VRFBs compared with alternative battery storage technologies means VRFB systems must be physically larger and heavier than Li-ion battery systems of comparable specifications. VRFBs require large electrolyte tanks and pumping systems meaning they are primarily suited for stationary applications where such systems can be accommodated. Li-ion batteries have proven to be versatile in numerous applications, being used in both grid-scale and distributed energy storage applications, EVs, and consumer electronics. As a result, VRFBs have not enjoyed the same widespread project portfolio, market growth, or media attention. Consequently, many flow battery vendors that started in the past 5-10 years have been unable to compete in the battery storage marketplace. Bankruptcies at hopeful flow battery vendors have ensued, including Imergy, EnerVault, and EnStorage.

The lower round-trip efficiency of VRFBs compared with Li-ion battery systems can affect revenue for applications such as arbitrage that rely on high margins between the price of energy being discharged and the cost of energy for charging. Flow batteries average between 70%-85% round-trip efficiency, compared with 90%-95% average for Li-ion batteries, potentially affecting the economics of projects based around bulk shifting of energy. To alleviate this, some flow battery companies are designing the stack to automatically drain the electrolyte when it is not being used in an effort to reduce unnecessary chemical reactions. Additionally, the long cycle lifetimes and deep discharge capabilities of VRFBs enable more revenue to be earned over the operational lifetime of a single VRFB helping to offset the lower round-trip efficiency.

However, the most significant challenge not just for VRFBs but for flow batteries in general has been the limited number of successfully deployed systems in operation partially due to the low demand for applications in which VRFBs offer more advantageous economics. In 2021, flow batteries made up only 3% of the battery market. And although there are a few established VRFB manufacturers, there are many that are still either early stage or startups. These early stage companies are unable to offer the same type of performance guarantees that come with Li-ion batteries from the widespread network of global suppliers. This has limited demand from highly risk averse utilities and project developers looking to secure long-term business deals with manufacturers.

Although VRFBs can complement existing vanadium mining practices, they are also subject to the volatility of vanadium price and the constrained nature of a less mature supply chain. Because vanadium is not openly traded, the prices are negotiated privately between buyers and sellers when required and has historically fluctuated significantly in response to changes in global supply and demand. However, spot prices for commodity-grade vanadium products are published weekly by organizations in Europe and the US. The price of the vanadium for the electrolyte solution can make up a significant percentage of the required capital cost for the overall system (30-50% depending on the price of vanadium and amount of electrolyte used), more than any single key mineral in other comparable battery technologies. Additionally, although there are several established suppliers for each part of the VRFB value chain, it is still a new ecosystem and may not be as resilient as Li-ion battery supply chains in the face of disruptions. For example, there are only a small number of producers capable of producing vanadium that meets the specifications required to be used in vanadium electrolyte for VRFBs.

Market Opportunities

Global Deployment

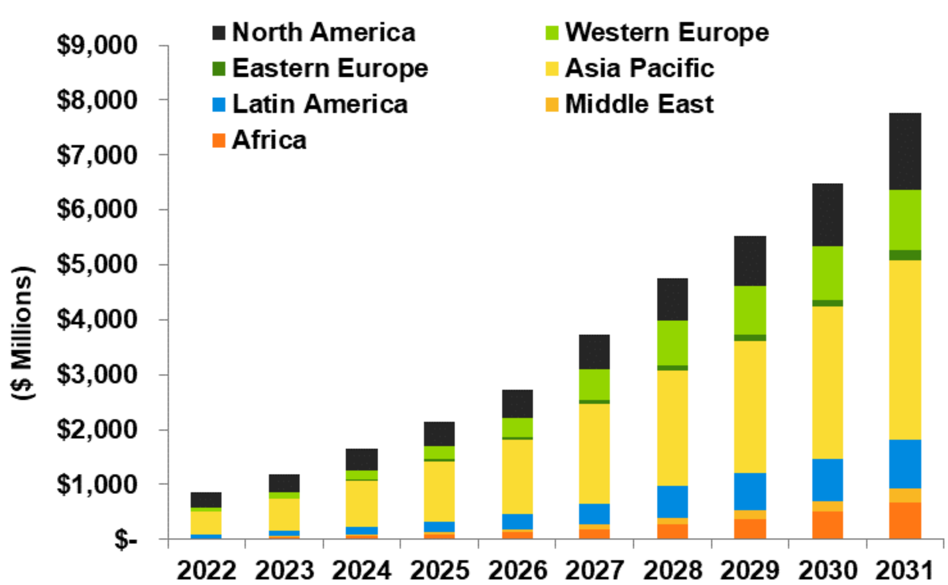
Although flow batteries have had a gradual pace of implementation, future projects are taking advantage of economies of scale and are expected to lead the way for increased market share. One of these large projects was a planned deployment for Dalian, China, where an 800 MWh plant is scheduled to come online in 2022. The vendor to this project, Rongke Power/UniEnergy, also has plans for a manufacturing plant for additional flow batteries.

A 50 MW/200 MWh flow battery is also in progress in Australia. The Pangea Storage Project plans to invest $200 million and use technology provided by CellCube. The company promises a 25-year guarantee on its battery system with no degradation. These projects are evidence of the growing interest in flow batteries globally. As Chart 1 shows, annual VRFB project deployment revenue is projected to grow from $856.4 million in 2022 to $7.76 billion by 2031. Another large deployment by Sumitomo that is 15 MW/60 MWh is also a notable project and mentioned later in this paper as a highlighted case study.

Market Forecasts

Guidehouse Insights' industry analysts use a variety of research sources in preparing white papers. To create and model energy storage forecasts, a variety of factors and assumptions are prepared to understand and accurately assess the market of interest. For VRFBs, inputs are entered to analyze total addressable market, the competitiveness of energy storage against alternatives, the split of VRFB technology, duration, and CAPEX investment. Likewise, revenue is calculated using a bottom-up approach based on average prices for battery system components across the stationary energy storage and EV markets. The system sizes are based on industry averages. The following forecasts were independently developed by Guidehouse Insights.

Chart 1 Annual Installed VRFB Utility-Scale and Commercial and Industrial Deployment Revenue by Region, All Application Segments, World Markets: 2022-2031

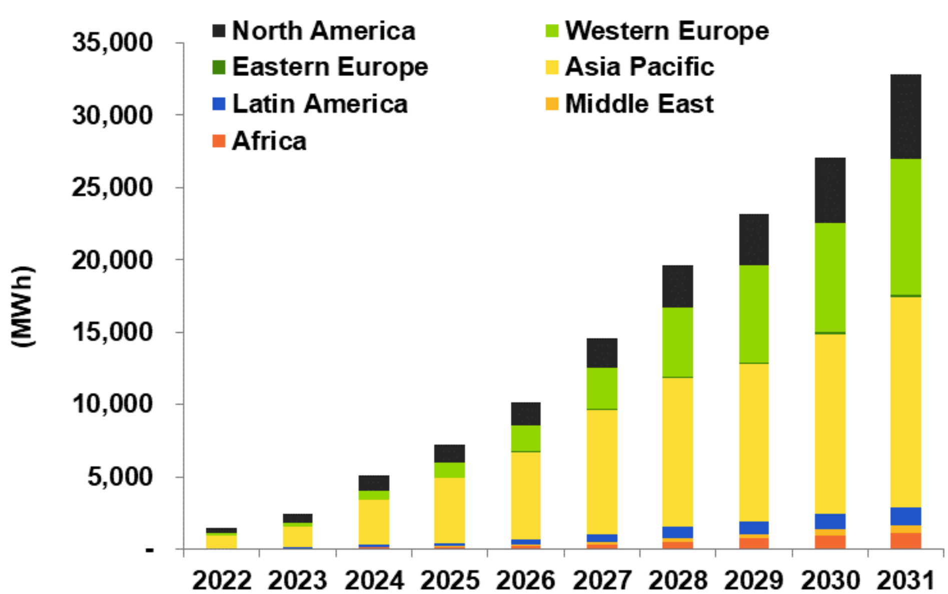


(Source: Guidehouse Insights)

Leading the VRFB market in revenue is Asia Pacific, North America, and Western Europe, respectively. These three regions also lead the flow battery market in general and are leaders for energy storage deployments globally. Asia Pacific leads significantly, with a compound annual growth rate (CAGR) of 25.7% for revenue and 37.4% for energy capacity. By 2031, it is estimated that Asia Pacific will reach around 14.5 GWh of annual VRFB energy capacity. North America is expected to reach 5.8 GWh and Western Europe is anticipated to reach 9.3 GWh.

China, a leader in renewable deployments, has ambitious climate goals to achieve carbon neutrality by 2060. This endeavor requires not only large generation capacities from wind and solar but also a large capacity of energy storage. In September 2021, Chinese titanium and vanadium producer Pangang Group Vanadium/Titanium Resources and the world's largest producer of high purity vanadium products and vanadium electrolytes, Dalian Bolong New Materials, signed an agreement that introduced Pangang to the energy storage market. It is notable that Pangang chose vanadium as an entry point, likely due to VRFBs' long-duration capabilities as well as the fact that China is a top mining producer of vanadium. Based on recent VRFB project pipelines in China, the country's share of VRFB capacity in Asia Pacific could be somewhere between 60%-80%. This range could shift based on 2025-2030 pipelines as well as VRFB market development from other countries such as South Korea.

Chart 2 Annual Installed VRFB Utility-Scale and Commercial and Industrial Battery Deployment Energy Capacity by Region, All Application Segments, World Markets: 2022-2031



(Source: Guidehouse Insights)

The VRFB market is poised for steeper growth in the coming years, especially as demand for long-duration storage capabilities increases. Hurdles still exist for this technology in the current market, either from the relatively lower energy density compared with Li-ion or due to market dynamics. Table 2-1 is a summary of these variables that could shape the future outlook for VRFBs.

Table 2-1. VRFB Solutions Strength, Weakness, Opportunity, and Threat Analysis

Strengths	Weaknesses
• Relative high efficiency compared with some other long-duration technologies • Safe, nonflammable electrolyte • Long lifecycle • Virtually unlimited cycles • 100% DoD • End of life reusability/recyclability • Salvage value at end of project life	• Lower energy density compared with Li-ion leading to larger and heavier systems • Vanadium electrolyte can account for 30%-50% of the total system cost, higher relative to other chemistries • Less mature supply chain than other battery technologies
Opportunities	**Threats**
• VRFBs can out-compete Li-ion batteries for long-duration applications, which are increasing in demand • Much of the future VRFB demand could be met by existing vanadium suppliers who have historically supplied it for steel alloy • Long-term offtakes with low cost producers allow for long-term price stability	• In the past, vanadium has faced fluctuating price volatility. If this continues, it could delay future growth for VRFBs • Production pace of VRFBs not propelled through EV applications

(Source: Guidehouse Insights)

Economies of Scale

As mentioned earlier, one barrier for flow batteries has been the limited number of deployments historically relative to Li-ion technologies. However, as demand for long-duration storage capability grows, flow batteries and especially VRFBs are poised to accelerate in deployment capacity. This is important not only to build confidence in the commercial performance of VRFBs but also to achieve economies of scale and become more cost-effective. In many cases, VRFBs become more cost-effective compared with Li-ion when scaling up capacity and duration. Still, the majority of deployments continue to come from Li-ion batteries. Li-ion suppliers have rolled out gigafactories capable of producing storage systems at a very large scale, many of which are to accommodate EV production. Recently, VRFB players have been following suit, and showcasing the added value of VRFBs that comes from a long lifecycle and increased safety rating. Even though VRFBs can be more economical over the lifetime of a project, reaching economies of scale is important for further lowering upfront costs and making this technology more attractive to investors and developers from the outset.

Supply Chain Dynamics

As the global battery storage market races to secure supplies, VRFB manufacturers are also looking to lock in a strong supply chain. For now, the bulk of vanadium material is owned by China, which could result in a strong reliance on the nation for future large-scale VRFB projects. In 2020, China, Russia, South Africa, and Brazil accounted for roughly 99.8% of global vanadium production. Companies such as Australian Vanadium Limited (AVL) are developing supplies in mineral-rich areas. AVL, with government support, has created the Australian Vanadium Project, which produces and processes VRFB materials in Western Australia that will then be supplied to VRFB manufacturers as either V_2O_5 or vanadium electrolyte.

To ramp up production, VRFB industry leaders have invested in gigafactories. A South Korean developer, KORID Energy Company, has signed a JV with a metals exploration company called Margaret Lake Diamonds (MLD). MLD is looking into potential sources of vanadium in the US and plans to take a role of constructing the batteries for KORID. Phase 1 of this project plans to output 50 MW annually at 200 MWh capacity. In the US, companies such as U.S. Vanadium Holding Company are producing high purity vanadium in Arkansas for different products, including batteries.

From the US market, the Biden administration is investing $20 million to advance the manufacturability of flow battery systems. This plan includes talks between the Department of Energy and industry leaders to understand and overcome significant barriers to market for flow batteries.

In addition to manufacturing capability, vanadium processing supplies are important. Traditionally, much of the global vanadium supply has been used to strengthen metal alloys such as steel. Because this vanadium application is still the leading driver for its production, it's possible that flow battery suppliers will also have to compete with metal alloy production to secure vanadium supply. However, increased demand, and deployments of VRFB systems, could alleviate the strain of lithium battery supply chains. As noted previously, Li-ion batteries are best suited for durations of 4 hours or less. Bolstering the market for flow batteries in long-duration storage applications could help deviate between supply needs and avoid diverting limited resources to too many applications.

Risk Mitigation and Partnerships

Given the barriers due to the lack of confidence from customers in this new technology, an emerging trend for flow battery vendors is to partner with third-party financiers to offer a form of warranty insurance that protects a customer's investment in the event the vendor is no longer in business. Flow battery vendors, such as Largo Clean Energy (formerly Vionx Energy), have implemented this type of value-added service product to reduce the perceived risk for its customers. In 2017, Vionx completed an 18-month underwriting process with New Energy Risk to obtain a Performance Warranty Insurance policy from the A-rated global insurer XL Catlin. This backstops the company's 20-year Performance Warranty Program for as many as 15 years, providing for the bankability of Largo Clean Energy's system.

Other vendors are offering solutions to reduce the risk to customers by shifting a portion of their upfront investment to an annual expense as part of their operations and maintenance (O&M) service and warranty. For example, flow battery vendors CellCube and Invinity offer their customers an optional electrolyte lease program. A flow battery's electrolyte represents a major cost component; however, when properly maintained, the electrolyte can be fully recycled at the end of a project's life. CellCube's offering allows customers to lease the battery's electrolyte, which reduces the upfront price of a system, ensures the company stays involved in O&M throughout a project's life, and allows CellCube to repurpose the electrolyte for future projects.

Largo Physical Vanadium (LPV) is using vanadium to back shares of the company purchased by investors in an effort to increase exposure to the metal. Its vanadium supply will then be used to produce electrolyte that can be provided to VRFB systems, essentially "erasing" the cost of vanadium from the total system cost. Because vanadium does not degrade after use in a VRFB, investors can maintain the value of their holdings. LPV also protects these assets with a safekeeping agreement with investors. While still in early stages of development, this financing model could reduce upfront costs by almost half, overcoming significant cost barriers associated with VRFBs.

VRFB Case Studies and Recent Projects

Sumitomo Electric – Grid-Scale VRFBs in Japan

Sumitomo Electric installed a 15 MW/60 MWh VRFB at the Minami-Hayakita substation owned by Hokkaido Electric Power Company in the town of Abira on the island of Hokkaido, Japan. The installation in 2015 was part of a demonstration project, supported by Japan's Ministry of Economy, Trade, and Industry, to determine how to best incorporate large-scale variable, renewable energy sources such as wind and solar into the electric grid. Long-duration energy storage can be useful in providing zero-carbon electricity to the grid during times of insufficient renewable output and can be used to save excess renewable energy during times of potential overgeneration. In addition to peak shifting, the battery enables frequency regulation. Power output from the wind and solar sources in the area was used along with weather forecasts and load information as inputs to the control system for the battery.

The battery was installed inside a dedicated two-story building because of the cold weather climate in the region and consists of 520 cell stacks and 5,200 cubic meters of electrolyte. It is one of the world's largest redox flow batteries in operation. The system underwent capacity testing at the time it was commissioned and in total the 13 banks showed a discharge capacity of roughly 75 MWh, higher than the 60 MWh that was specified. Additional initial performance testing was conducted including an efficiency test, a high power charge and discharge test, and a response time test to set baseline parameters for the system. It underwent more capacity testing after 1 year of operation and again after 2 years of operation. Each of the 13 banks tested showed minimal capacity degradation after 2 years when compared with the capacity at the time of commissioning.

Because of the success of the demonstration project over 3 years, Sumitomo Electric was selected again as the installer for another large VRFB system on the island of Hokkaido, Japan. Construction on this VRFB began at the end of July 2020 and is expected to be completed by March 2022. The system will be able to provide 17 MW for up to 3 hours or 51 MWh of energy capacity and will serve the grid from April 2022 to March 2043. The installation is part of the phase-one grid expansion plans for the northern region of Japan. The plan also includes more than 162 MW of new grid-scale wind generation, the output from which will be smoothed by the VRFB.

Invinity – VRFB in Energy Superhub Oxford

The Energy Superhub (ESO) project, led by Pivot Power, a part of EDF Renewables, combines energy storage technology with EV charging, low carbon heating, and smart energy management systems to reduce carbon emissions. Once fully operational, the government-backed project aims to save 10,000 metric tons of CO_2 each year, rising to 25,000 metric tons each year by 2032. The ESO is the site of the UK's largest flow battery, a VRFB manufactured by Invinity Energy Systems, with a power output of 2 MW and an energy capacity of 5 MWh, enough to serve the daily electricity needs of roughly 600 UK households. The VRFB, which was fully energized in December 2021, is combined with a 50 MW Wärtsilä Li-ion system to form a single hybrid energy storage asset, the largest vanadium flow and Li-ion hybrid system ever deployed. Through a JV with Bushveld Minerals, Invinity formed a special purpose vehicle called Vanadium Electrolyte Rental Limited (VERL) to lease the electrolyte used in the VRFB at the Superhub to the project developer, Pivot Power. By leasing the electrolyte for 10 years from VERL, Pivot Power lowered the upfront cost associated with getting the system deployed.

The VRFB system consists of 27 Invinity VS3 flow batteries installed between September and December 2021 at National Grid's substation in Cowley, Oxfordshire. Each VS3 battery is the size of a 20-foot shipping container and Invinity worked with trading optimizer Habitat Energy and power electronics supplier Gamesa Electric on the integration and commissioning of the system. The control system will determine the optimal charge and discharge schedule for the entire hybrid battery system based on grid conditions.

The hybrid battery system is the UK's first and largest grid-scale battery storage system connected directly to the transmission network allowing it to deliver large volumes of power to public and commercial EV charging locations across the city of Oxford without straining local electricity networks. The VRFB is the first resource activated when the system is called upon so that wear and tear on the Li-ion battery can be reduced. The Li-ion system is only called into service when the required response exceeds the capability of the VRFB thereby minimizing the required number of charge and discharge cycles for the Li-ion battery. Because Li-ion batteries experience significant degradation with each discharge cycle, a hybrid configuration making use of a VRFB extends the operational life of the asset. A hybrid ESS like this is a promising configuration as more variable, renewable energy sources are brought online this decade and longer, more frequent discharge cycles are required.

Conclusions and Key Takeaways

VRFBs are a promising energy storage technology because of their energy storage capacity scalability, full DoD, ability to cycle frequently and for long durations, nonflammable construction, and recyclable electrolyte. Guidehouse Insights expects global annual deployments of VRFBs to reach approximately 32.8 GWh in 2031, with Asia Pacific leading in deployments. This presents significant growth with a CAGR of 41% across the forecast period. As power grids around the world continue to replace fossil fuel power plants with large-scale solar PV arrays and wind farms, long-duration storage is critical to ensuring reliable grid operation. VRFBs can work as standalone, stationary ESSs or can be combined with Li-ion systems to form a hybrid solution. Hybrid systems offer the advantage of extending the lifetime of the Li-ion systems by using the VRFBs as the first resource, when possible, thereby minimizing the number of discharge cycles required for the Li-ion system. While the physical size of VRFBs may limit where the systems can be deployed, VRFB technology is suitable for numerous applications in addition to grid-scale storage for the smoothing of renewable generation output, including EV charging stations, microgrids and backup power for isolated or remote communities, and load shifting in the industrial sector.

Although the stationary energy storage market's focus on short-duration and infrequently cycled applications has limited the demand for VRFB systems to date, there are operational systems of various sizes on every continent except Antarctica. In fact, two systems are under construction in China with rated energy capacities in the hundreds of megawatt-hours. There are a few VRFB vendors that have managed to establish themselves as reliable and bankable given their project portfolios, however, many vendors are still viewed as high risk because of their limited experience delivering VRFB systems to customers. To mitigate these concerns, VRFB vendors can look to alternative financing models, such as electrolyte leasing programs where capital expenditures are shifted to annual expenses or LPV's model where investor shares are backed by vanadium stored in VRFB electrolyte. Partnering with third-party financiers or other established companies can also reduce risk by offering a version of warranty insurance to customers.

Decoupling power and energy capacity, as is the case with VRFB construction, allows the addition of more electrolyte solution at a comparatively low incremental cost, which can result in lower costs per kilowatt-hour. Nevertheless, the high capital cost of VRFB systems remains a significant barrier to their adoption. Vanadium makes up a significantly higher percentage of the overall system cost compared with any single metal in other battery technologies and in addition to large fluctuations in price historically, its supply chain is less developed and can be more constrained than that of materials used in other battery technologies. Vanadium mining companies and suppliers need to work with vanadium electrolyte producers to secure long-term, low cost deals to ensure vanadium supply for VRFB applications can keep pace with demand without driving up costs.

With proper funding, continued project development, and increased demand for long-duration storage or frequent discharge applications, the VRFB industry can grow and establish its products as a significant part of the large and growing energy storage field. Overcoming the barriers related to high capital costs, new supply chains, and limited deployments will allow VRFBs to increase their share in the energy storage market.

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Scope of Study

Guidehouse Insights has prepared this white paper, commissioned by Vanitec, to provide an overview of vanadium redox flow batteries (VRFBs) and their market drivers and barriers. It provides an overview of the key elements of VRFB technology and their value in supporting energy storage projects. Two examples selected from a diverse range of projects that are using the capabilities of VRFB solutions to provide grid balancing services and reduce greenhouse gas emissions by utilizing more renewable energy capacity are presented. The market forecasts for global annual installed VRFB energy capacity and revenue presented in this white paper were prepared solely by Guidehouse Insights without input or bias from Vanitec.

Sources and Methodology

Guidehouse Insights' industry analysts use a variety of research sources in preparing white papers. The key component of Guidehouse Insights' analysis is primary research gained from phone and in-person interviews with industry leaders including executives, engineers, and marketing professionals. Analysts are diligent in ensuring that they speak with representatives from every part of the value chain, including but not limited to technology companies, utilities and other service providers, industry associations, government agencies, and the investment community.

Additional analysis includes secondary research conducted by Guidehouse Insights' analysts and its staff of research assistants. Where applicable, all secondary research sources are appropriately cited within this report.

These primary and secondary research sources, combined with the analyst's industry expertise, are synthesized into the qualitative and quantitative analysis presented in Guidehouse Insights' reports. Great care is taken in making sure that all analysis is well-supported by facts, but where the facts are unknown and assumptions must be made, analysts document their assumptions and are prepared to explain their methodology, both within the body of a report and in direct conversations with clients.

Guidehouse Insights is a market research group whose goal is to present an objective, unbiased view of market opportunities within its coverage areas. Guidehouse Insights is not beholden to any special interests and is thus able to offer clear, actionable advice to help clients succeed in the industry, unfettered by technology hype, political agendas, or emotional factors that are inherent in cleantech markets.

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