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A forty-year history of the development, commercialisation and implementation of the UNSW Vanadium Flow Battery

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Abstract

Long-duration energy storage plays an important role in the energy transition as the deployment of renewable energy has been accelerating in recent years. Vanadium flow batteries invented 40 years ago at UNSW are regarded as one of the most favourable technologies for large-scale energy-storage applications because of their unique properties that allow energy and power to be decoupled. The development at UNSW from fundamental scientific studies of electrolytes, electrodes and membrane materials to stack design, sensors, modelling, simulation, system design and integration has formed an important foundation for the multi-GWh systems that have been installed and commissioned around the world particularly in China, Europe, North America and Australia to date. Many more GWh systems are in the pipeline to support the global energy transition to net zero, while on-going research efforts are continuing to further improve power density and to reduce cost.

Introduction

With the accelerating shift to renewable energy in recent years, the need for long-duration energy storage (LDES) is becoming increasingly apparent. While lithium-ion batteries are currently being deployed globally in large numbers, fires in multiple installations around the world are creating much concern about their safety (Chen Y et al. 2021). Despite the on-going reduction in lithium-ion battery costs in recent years, alternative battery technologies are being sought. Flow batteries are now emerging as a viable, cost-effective technology for LDES (Hou et al. 2024, Poli et al. 2024).

Flow batteries store energy in external electrolyte tanks, so energy storage capacity can be increased by simply adding more solution. As the electrolyte represents a fraction of the cost of the overall system, the cost per kWh of a flow battery decreases with increasing energy-storage capacity or energy-to-power ratios (E/P). Other attractive features are their very long cycle life and their inherent safety compared with lithium-ion batteries. In the case of Vanadium Flow Batteries (VFBs), a 20-year cycle life has already been demonstrated, while the indefinite life of the vanadium electrolyte gives it a significant residual value at the end of a project (Blume et al. 2024).

VFBs were invented more than 40 years ago by researchers at the University of New South Wales (UNSW) Sydney; while early commercial interest led to multiple field trials in the late 1990s and early 2000s, it is only in the last 5 years that the VFB technology has been experiencing a rapid growth in demand around the world. The use of vanadium in flow

batteries had been suggested earlier, but it was not until the first experiments conducted in 1984 by researchers at UNSW Sydney that vanadium redox couples were successfully employed in both halves of a working flow cell (Sum & Skyllas-Kazacos 1985, Sum, Rychcik & Skyllas-Kazacos et al. 1985). Earlier researchers had eliminated vanadium during their screening studies on the basis of cost, the relatively poor electrochemical reversibility of vanadium redox couples (NASA 1980), and the low solubility of pentavalent vanadium compounds in acidic solutions that would limit the practical energy density (Oei 1985). Despite these potential limitations, vanadium's multiple oxidation states made it a good candidate for a single element flow-cell that could overcome the problem of cross contamination observed with the NASA Fe/Cr battery (Thaller 1975; Hagedorn and Thaller 1982). It was therefore chosen as the starting point of the flow battery development program at UNSW.

In this review, we describe the early VFB research that was conducted at UNSW in the areas of electrochemical evaluation, electrolyte preparation, electrode screening and surface modification, membrane screening and modification, electrolyte thermal properties and stabilisation, modelling and simulation, sensors and battery management as well as battery design safety. The early licensing and field trials of the VFB are also described, together with the current commercialisation status around the world. Finally, we provide a future outlook on vanadium supply chain considerations, and important research and development areas for further performance improvements and cost reduction.

Early studies and first All-Vanadium Flow Cell

To evaluate the feasibility of an All-Vanadium Flow Battery, cyclic voltammetry was used to investigate the electrochemical reversibility of the V(II)/V(III) and V(IV)/V(V) couples in VCl_3 solutions in H_2SO_4 (Sum and Skyllas-Kazacos 1985; Sum, Rychcik and Skyllas-Kazacos 1985). Initial results showed poor reversibility for the V(II)/V(III) and V(IV)/V(V) couples, but, by roughening the glassy carbon electrode to produce surface defects, a dramatic improvement in the reversibility was observed. These results suggested that vanadium redox couples could demonstrate good reversibility for flow cell applications, but the low solubility of V(V) compounds still appeared to be a limitation.

With support from the Australian National Energy Research, Development and Demonstration Council (NERDDC), the UNSW research efforts were extended to explore the possibility of producing concentrated V(V) solutions by oxidising the much more soluble $VOSO_4$ compound in sulphuric acid. A 2 M vanadium electrolyte was successfully produced and tested, leading to the first "All-Vanadium Redox Flow Battery" patent being filed by UNSW in 1986 (Skyllas-Kazacos, Rychcik and Robins 1986).

Low-cost electrolyte process

Early work on the VFB involved the preparation of the vanadium sulphate electrolyte by dissolution of $VOSO_4$ in sulphuric acid[1], but the high cost of $VOSO_4$ ($300/kg at the time) was a major concern. While V_2O_5 (around $15/kg) could be sourced at a fraction of the price of $VOSO_4$, its very

1 $VOSO_4$ is vanadium exo sulphate, or vanadyl oxysulphate. [Ed.]

low solubility seemed prohibitive. A simple experiment led the way to the development of a number of vanadium compound dissolution processes that would provide the low-cost electrolyte production needed for commercial implementation of the VFB. Two graphite electrodes were immersed in a suspension of V_2O_5 powder in H_2SO_4 and a current was passed between them. After an hour or so, the powder was seen to be dissolving and a bright blue solution of V(IV) was being produced.

The simple beaker-based cell was then upgraded to a two-compartment cell that used a membrane to separate the two half-cells. The V_2O_5 suspension was placed in the negative half-cell while sulphuric acid was used in the positive half-cell. By adjusting the electrolysis time, the V_2O_5 powder could be electrochemically dissolved while further reducing the resultant solution to the 50:50 V(III):V(IV) mixture ($V^{3.5+}$) that forms the starting solution for the two half-cells of the all-vanadium redox flow cell. To avoid disintegration of the positive electrode during oxygen evolution in the positive half-cell, dimensionally stable anodes were considered, but were replaced by lead anodes to avoid the possibility of inert metal contamination of the vanadium electrolyte (Cao et al. 2018).

Several other chemical and electrochemical processes were subsequently developed, and a patent was filed in 1988 (Skyllas-Kazacos, McDermott and Kazacos 1988). This patent describes the process of dissolving and reducing an insoluble vanadium compound in an aqueous electrolyte using an electrochemical cell or by adding a chemical reductant such as oxalic acid. The use of the much cheaper V_2O_5 compound for electrolyte production was a major breakthrough that ensured the commercial viability of the VFB.

Later electrolyte process developments by the UNSW team included the reactive powder dissolution process where V_2O_3 and V_2O_5 powders are slowly mixed together in H_2SO_4 (or other supporting electrolyte) at around 80 ºC in the appropriate molar ratio to produce a $V^{3.5+}$ electrolyte (Skyllas-Kazacos 2004). The commercial viability of this process depends on the relative cost of V_2O_3 compared to V_2O_5. Furthermore, the tendency for V_2O_3 to oxidise in air means that it must be stored in airtight containers before processing to avoid oxidation to V_2O_4 that would lead to a final vanadium electrolyte oxidation state higher than the $V^{3.5+}$ required for direct use in the VFB. An additional processing step to produce $V^{3.5+}$ would then be needed.

To overcome the higher cost of V_2O_3, an alternative process was developed where V^{3+} is electrochemically generated in the negative compartment of an electrolysis cell and then used as a reductant to dissolve the V_2O_5 powder into solution to produce the $V^{3.5+}$ electrolyte product. A portion of the $V^{3.5+}$ solution is returned to the electrolysis cell to produce more V^{3+} reductant that is fed into the mixing tank to dissolve more V_2O_5 powder in a continuous process (Kazacos and Skyllas-Kazacos 1994; Skyllas-Kazacos 1998).

Each of these methods was further extended to evaporate most of the water to produce a vanadium electrolyte concentrate or slurry that would reduce transportation costs (Skyllas-Kazacos and Kazacos 2002). The concentrate or slurry can then be reconstituted on delivery by simply adding water.

With improvements in processing methods for vanadium compounds in recent

years, the cost of V_2O_3 has become comparable to that of V_2O_5, making the V_2O_3/V_2O_5 reactive powder dissolution method simple and cost effective. This method and the suspended powder electrolysis method described previously are currently being used by most vanadium electrolyte producers to supply $V^{3.5+}$ electrolyte to the VFB manufacturers around the world.

Early electrode screening and modification

Various electrode materials were screened by the UNSW group in the 1980s and '90s, and graphite and carbon felts were selected as the most suitable electrode materials for both the positive and negative half-cells in the VFB (Rychcik and Skyllas-Kazacos 1987). Provided that the cell is protected from excessive overcharge to avoid corrosion of the positive electrode under oxygen evolution conditions, sufficient chemical and mechanical stability can be achieved when combined with a suitable low cost and chemically resistant bipolar substrate material (Zhong et al. 1997).

A wide range of carbon and graphite felts was tested, and certain materials were found to give much higher voltage and energy efficiencies than others during charge/discharge cycling in the VFB (Zhong et al. 1993). X-ray photoelectron spectroscopy (XPS) demonstrated the role of surface oxide functional groups on the electrochemical behaviour of the electrode material. Thermal, chemical and electrochemical treatments of carbon and graphite felts were therefore evaluated for the purpose of enhancing the electrochemical activity of these materials as electrodes in the VFB (Sun and Skyllas-Kazacos 1991; Sun and Skyllas-Kazacos 1992a; Sun and Skyllas-Kazacos 1992b). XPS measurements showed that the amount of chemisorbed oxygen on the activated graphite felt surface increased dramatically after treatment. The improved performance of the treated graphite felts for the vanadium redox reactions was thus attributed to the increased surface concentration of the C–OH and C=O functional groups that were formed during activation. In another UNSW study, Mn, Te and In modified graphite fibre electrodes exhibited an improved performance compared to the untreated one (Sun and Skyllas-Kazacos 1992a).

The above studies also demonstrated that with appropriate thermal, chemical and electrochemical treatments, both the wettability and electrochemical activity of low-performance carbon and graphite felts can be substantially improved (Sun and Skyllas-Kazacos 1992b). This was a critical milestone in achieving cost reduction for commercial application of the VFB technology, since lower-cost carbon felts could be used in stack production. Thermal treatment is currently used by most carbon felt manufacturers to produce high-performance felt electrodes for VFB applications.

Early membrane screening and modification

During the early stages of the UNSW vanadium battery R&D program, low-cost, chemically stable commercial membranes were not readily available. Although Nafion membranes showed excellent chemical stability in the highly oxidising V(V) solutions, they were too expensive for practical application at the time. Various off-the-shelf membranes and separators were therefore initially tested in a laboratory-scale flow cell to determine coulombic, voltage and energy efficiencies at different current densities, but suitable characterisation methods were

needed to assess the suitability of different membranes for use in the VFB. The UNSW group therefore developed a range of methods to characterise each membrane in terms of its ionic conductivity, vanadium-ion selectivity, water-transfer properties and chemical stability in the highly oxidising V(V) positive half-cell solution (Chieng, Kazacos and Skyllas-Kazacos 1992; Mohammadi and Skyllas-Kazacos 1995; Mohammadi, Chieng and Kazacos 1997; Mohammadi and Kazacos 1997; Sukkar and Skyllas-Kazacos 2003a; Sukkar and Skyllas-Kazacos 2003b; Sukkar and Skyllas-Kazacos 2004).

Of all the membranes tested, perfluorinated membranes such as Nafion showed the best long-term stability, with negligible weight loss observed even after five years of immersion in V(V). Despite its high chemical stability, however, Nafion was not initially considered for use in the VFB because of its high cost at the time, which would limit its competitiveness in commercial systems (Mohammadi and Kazacos 1997).

Water transfer across the membrane was also found to be a significant issue during charge–discharge cycling of the VFB. Early water-transfer studies showed a net water transfer into the negative half-cell when using an anion-exchange membrane (AEM), and into the positive half-cell in the case of cation-exchange membranes (CEMs) (Mohammadi, Chieng and Kazacos 1997). To address the shortcomings of both AEM and CEM membranes, the amphoteric ion-exchange membrane (AIEM) was first proposed for the VFB (Mohammadi and Kazacos 1996). Sulphonation of the anion-exchange membrane was used to introduce cation-exchange groups in order to reduce water transfer and improve performance in the VFB. A range of anionic and cationic polyelectrolytes were subsequently incorporated into a Gore-Select cation-exchange membrane to successfully reduce water transfer in the VFB (Sukkar and Skyllas-Kazacos 2003c).

Electrolyte thermal stability

The composition of the vanadium electrolyte plays a critical role in determining the practical operating-temperature range of the VFB. While V(II), V(III) and V(IV) sulphates show increased solubility at higher temperatures and lower sulphuric-acid concentrations (due to the common-ion effect), V(V) undergoes thermal precipitation to V_2O_5, and this increases at higher temperatures and lower proton concentrations (Kazacos, Cheng and Skyllas-Kazacos 1990). A typical operating-temperature range of 10–40 °C was thus proposed for 2 M vanadium in 5 M total sulphate electrolytes, but to extend this range and minimise precipitation risks in extreme climates, lower vanadium concentrations (1.5–1.8 M) are usually employed (Kazacos, Cheng and Skyllas-Kazacos 1990; Skyllas-Kazacos et al. 2016). The sulphuric-acid concentration is also adjusted to maintain an approximately 2:5 vanadium-to-total-sulphate ratio, but this can be further modified to suit climate conditions. For example, in very hot climates, a higher sulphuric-acid concentration can reduce the rate of V_2O_5 precipitation (Kazacos, Cheng and Skyllas-Kazacos 1990; Skyllas-Kazacos et al. 2016).

The operating-temperature range can also be extended without lowering the total vanadium concentration. State-of-charge (SOC) control avoids precipitation of V(V) at high temperatures and V(II)/V(III) at low temperatures (Corcuera and Skyllas-Kazacos 2012), while precipitation inhibitors

extend the induction time for precipitation in supersaturated electrolytes (Cao et al. 2018; Mousa and Skyllas-Kazacos 2015; Kausar, Mousa and Skyllas-Kazacos 2016). While an extensive list of additives was shown to dramatically increase induction time for precipitation of one or more of the vanadium ions in the electrolyte, a range of phosphate and ammonium compounds was found to be effective inhibitors for both half-cell electrolytes (Skyllas-Kazacos 1998; Kazacos and Skyllas-Kazacos 1994; Skyllas-Kazacos and Kazacos 2002; Mousa and Skyllas-Kazacos 2015; Kausar, Mousa and Skyllas-Kazacos 2016).

In the case of state-of-charge control, a battery management system was used to continuously monitor SOC and electrolyte temperature. The controller varies the upper and lower SOC limits to stay within a safe operating range that would minimise the risk of precipitation at low or elevated temperatures (Corcuera and Skyllas-Kazacos 2012). For simplicity, emergency discharge could involve turning on the pumps during standby to increase the rate of self-discharge. This avoids the capital and maintenance costs associated with active cooling systems and allows the VFB to be effectively used in hot climates (Skyllas-Kazacos 1986).

While restricting the SOC range can avoid precipitation of the vanadium ion at temperature extremes, this will inevitably reduce the practical energy density of the flow battery and limit available capacity. A preferred solution is to stabilise the vanadium electrolyte by using precipitation inhibitors. Hundreds of potential additives were screened and a large number of chemicals were found to be effective precipitation inhibitors for the V(II), V(III), V(IV) ions at low temperatures, while others were shown to reduce the rate of thermal precipitation of V(V) at elevated temperatures (Cao et al. 2018; Mousa and Skyllas-Kazacos 2015; Kausar, Mousa and Skyllas-Kazacos 2016).

Although the exact mechanism of precipitation inhibition is not fully understood, it is believed that these additives affect the precipitation rate by being adsorbed on the crystal surface to form a monomolecular layer that changes the crystal habit and growth rate. It is possible that the additive molecules are adsorbed on certain edges or corners that play a special part in the crystal growth. A small amount of the additive could thus be enough to block most of these active sites, causing a significant decrease in the crystal growth rate.

From the additive screening studies, ammonium phosphate and ammonium sulphate were selected for their ability to stabilise both half-cell solutions, and these were used to prepare a 3 M vanadium electrolyte that was successfully tested in a laboratory cell and in the UNSW electric golf cart in the late 1990s (Roe, Menictas and Skyllas-Kazacos 2015). While the 3 M solution was stable during charge-discharge at room temperature, its use at temperature extremes over a broad SOC range requires further optimisation.

Other UNSW Vanadium Redox Flow Cell research highlights

With grant funding from the NERDDC (Skyllas-Kazacos 1986; Skyllas-Kazacos 1989; Skyllas-Kazacos and Kazacos 1992) and the NSW Office of Minerals and Energy (Skyllas-Kazacos 1989; Skyllas-Kazacos 1991), as well as industry funding from Agnew Clough Ltd, Mitsubishi Chemicals and Kashima Kita Power Corporation, the VFB was taken from the initial concept stage at

UNSW in 1983 through the development and demonstration of several 1–5 kW prototypes over a 40-year period at UNSW in both stationary and mobile field trials. As part of this program, a wide range of research projects was undertaken. In addition to the electrolyte production, electrode, membrane and additive studies described above, other areas of research at UNSW have included electrolyte characterisation, measurement of electrolyte density, viscosity and conductivity as a function of vanadium and acid concentration, temperature and state-of-charge (Kazacos, Cheng and Skyllas-Kazacos 1990; Skyllas-Kazacos et al. 2016). The variation in these electrolyte properties as a function of state-of-charge can be used for the individual state-of-charge monitoring of each of the two half-cell solutions to identify any state-of-charge imbalance that will lead to capacity loss during long-term charge-discharge cycling. This allows the battery management system to initiate an electrolyte remixing operation to restore capacity. A state-of-charge monitoring method based on solution absorbance was also developed using the distinct colours of the different vanadium ions and the varying spectroscopic properties of each half-cell solution at different states-of-charge (Skyllas-Kazacos et al. 1989; Corcuera and Skyllas-Kazacos 2012).

While simple remixing of the two half-cell solutions can restore capacity loss associated with the different rates of vanadium ion transfer across the ion exchange membranes, capacity loss caused by side reactions such as hydrogen evolution during charging or air oxidation of V(II), requires chemical or electrochemical rebalancing. The use of oxalic acid was proposed as a chemical reductant which is added to the V(V) solution in the positive half-cell to partially reduce it to V(IV) in order to match the state-of-charge of the negative half-cell electrolyte. Oxalic acid was selected since it is oxidised to carbon dioxide and water during reaction, leaving no residual biproducts in the electrolyte (Skyllas-Kazacos et al. 1989).

Another major activity in the 1990s was the development of low-cost bipolar electrodes to replace the heavy and expensive graphite plates used as substrates for the graphite felts in stack assembly. Novel conducting plastic bipolar plate formulations led to manufacturing trials of bipolar electrode assemblies that were used in the fabrication of several 1–5 kW prototype stacks for the first field trials of the VFB in the 1990s. By combining a thermoplastic polymer such as high-density polyethylene, an elastomeric polymer, and a conductive filler material, a flexible, conducting plastic electrode with good physical strength, chemical stability and electrical conductivity could be produced (Zhong et al. 1993). This material was used to produce multiple bipolar electrodes by heat bonding graphite felt onto each side of the conducting plastic plate as illustrated in Figure 1. These bipolar plates were employed in the fabrication of several 5 kW prototype stacks at UNSW during the 1990s.

Fig 1: Bipolar electrode fabricated by heat bonding graphite felt sheets onto each side of the conducting plastic sheets developed by UNSW.

In recent years, mathematical modelling has been a major focus area at UNSW and has been used to assist in stack design optimisation and battery performance prediction. Mathematical models were therefore developed to predict shunt currents and pumping energy losses in order to assist with optimal flow-frame and stack design (Tang et al. 2013; Tang, Bao and Skyllas-Kazacos 2014; Li, Skyllas-Kazacos and Bao 2016). Capacity losses associated with the differential transfer of vanadium ions across the membrane were also modelled for a range of different membranes (Tang, Bao and Skyllas-Kazacos 2011), allowing the development of automated remixing and other procedures to restore capacity.

Thermal modelling of VFBs under a range of operating conditions and environmental temperatures has been used to predict temperature gradients in cell stacks during standby using different types of membranes. When the pumps are turned off during standby, the transfer of vanadium ions across the membrane gives rise to self-discharge and heat generation within the stack that would normally be removed by electrolyte flow. This leads to an increase in the stack temperature, the rate of which depends on the membrane, stack design and ambient temperature. The shapes of the stack temperature gradient reflect the rate of heat generation caused by the self-discharge reactions during standby and the rate of heat dissipation to the environment. Thermal modelling and simulation studies were conducted for various climate conditions in both open and in containerised VFB systems to optimise insulation and design of passive and active cooling systems (Tang, Bao and Skyllas-Kazacos 2012; Yan, Skyllas-Kazacos and Bao 2017; Shu et al. 2023a; Shu et al. 2023b).

An electrical safety analysis of different VFB configurations during electrolyte leakage has also been undertaken to identify measures needed to avoid potential safety hazards in the event of an electrolyte leak (Shu et al. 2025). Simulation studies showed that battery voltage plays a critical role in determining the magnitude and safety hazard caused by current that would flow through the body if a person were to step into a pool of electrolyte in ionic contact with the battery stacks. A wide range of conditions were simulated and results showed that safety risks associated with low-voltage battery configurations were low, but safety hazards increased with high-voltage configurations on wet concrete in close proximity to the leak if the negative terminal of the battery stack was grounded. While the body current under low voltage configuration is expected to be within a safe range, protective shoes are highly recommended under high-voltage configurations.

To ensure a long operating life of any flow battery system, a sophisticated battery management system is essential. Using a range of sensors and monitoring systems, a battery management system is currently being developed to detect the condition of the battery in real-time and remotely implement all the necessary actions to prevent precipitation at extreme temperatures, restore capacity and optimise electrolyte flow rate for maximum overall efficiency (McCloy et al. 2022).

The vanadium-halide redox flow cell was proposed in 2002 in an effort to increase the energy density of the VFB. The higher solubility of vanadium ions in mixed halide solutions was the initial motivation, but the high cost of bromine complexing agents to prevent bromine vapours during

charging has been an obstacle to its commercial development (Skyllas-Kazacos 2002; Skyllas-Kazacos, Mousa and Kazacos 2003; Kazacos and Kazacos 2006; Skyllas-Kazacos et al. 2010).

The vanadium-oxygen fuel cell (VOFC) continues to be an attractive technology that has the potential to more than double the energy density of the VFB by replacing the positive half-cell electrolyte tank with an air electrode (Menictas and Skyllas-Kazacos 2011; Risbud et al. 2019). Since the VOFC only requires half of the vanadium raw material per kWh of energy produced, its cost could also be potentially halved compared with the VFB. While the negative vanadium half-cell functions well, however, an efficient non-noble metal gas diffusion electrode is still needed to reduce costs and increase energy efficiency. This is an on-going area of research at UNSW.

Early licensing and field trials

In 1987, an exclusive international licence to the VFB technology was granted by UNSW to the Australian vanadium mining company Agnew Clough Ltd., leading to 3 years of industrial funding that enabled UNSW to fabricate and test the first 1 kW VFB laboratory prototype which produced an overall energy efficiency of 90% at a current density of 20 mA/cm^2 (Skyllas-Kazacos et al. 1991). Unfortunately, due to financial difficulties, the company was forced to relinquish its licence in 1991, allowing the University to seek other licensees (Skyllas-Kazacos 2023).

A Thai-based construction company was granted a licence to the technology in 1993 for the South-East Asian region (Skyllas-Kazacos 2023). This led to the installation of a 5 kW/15 kWh VFB in a vanadium-powered solar demonstration house just outside Bangkok (Figure 2 left).

Around the same time, Kashima-Kita Electric Power Corporation, a subsidiary of Mitsubishi Chemical Corporation, became interested in the VFB technology as a way of using the vanadium waste extracted from the soot produced by the Orimulsion fuel derived from the vanadium-rich Venezuelan pitch employed at the power station. A 5-year R&D collaboration program between the UNSW research group and the Japanese companies led to further advances in solution chemistry, stack design, improved materials and control systems (Skyllas-Kazacos 2023).

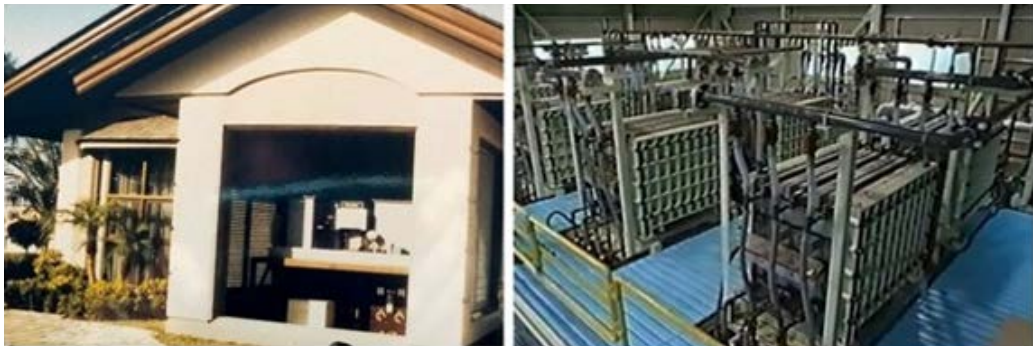

Fig 2: Early VFB Field Trials: (Left) VFB installation in Demonstration Solar House in Bangkok in mid-1990s; (Right) 200 kW/800 kWh VFB at Kashima-Kita Electric Power Station in Japan in 1996–97. Photos courtesy Rui Hong (left) and Chris Menictas (right).

By 1997, Kashima-Kita Electric Power Corporation had progressed to the design and installation of the first multi-kWh VFB in a load-levelling field trial at their power station in Japan (Figure 2 right). The system was a 200 kW/800 kWh battery that was tested over a wide range of conditions and an overall energy efficiency of 80% was achieved, demonstrating the excellent scalability of the VFB.

In the mid-1990s, the UNSW team installed a VFB in an electric golf cart (Figure 3). Using the UNSW ammonium phosphate-based proprietary stabilising agent, a 3 M vanadium electrolyte was produced by the UNSW team and installed in the electrolyte tanks that were located below the seats. In this and other prototype batteries and field trials at UNSW, the negative electrolyte was protected from air oxidation of the V^{2+} by the use of a thin (1 cm) layer of paraffin oil on the surface to act as a barrier to oxygen (Mousa and Skyllas-Kazacos 2015; Kausar, Mousa and Skyllas-Kazacos 2016). Paraffin oil is chemically stable in the negative half-cell solution, but its use requires greater care during the periodic remixing of the electrolytes to restore capacity. The golf cart was subjected to a large number of driving tests around the UNSW campus for several years before it was donated to the Powerhouse Museum in Sydney in 2005.

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Fig 3: VFB powered electric golf cart at UNSW in 1997 (Left). Compact stack and tanks with hidden plumbing designed for the golf cart (Right). Photos courtesy Maria Skyllas-Kazacos UNSW Sydney.

The UNSW VFB technology was sold to the Australian ASX-listed company Pinnacle VRB in 1997, and several demonstration systems were installed by Pinnacle in South Africa, King Island in Australia, and in the USA, using battery stacks acquired from Sumitomo Electric Industries, electrolyte supplied by Highveld, and balance of plant sourced from a range of local suppliers. In 1999, Pinnacle VRB entered into a new licence agreement with Sumitomo Electric Industries that had been evaluating the UNSW VFB technology for several years and had built a 450 kW/1 MWh vanadium redox battery load leveling demonstration system at the Kansai Electric Power Plant in Japan, as well as several other VFB systems for wind energy storage and other stationary applications.

Pinnacle also licensed the VFB technology to the Canadian-listed company Vanteck VRB for the African continent and a 250 kW VFB system was commissioned by Vanteck in conjunction with the South African utility, ESCOM. A 250 kW/2 MWh VFB system was supplied by Pinnacle to US-based PacifiCorp in the early 2000s. The system was used by PacifiCorp to supply peak power capacity (charging in the off-peak hours) and provide end of line voltage support (supplying up to 250 kVAR of reactive power) in a remote area in southeastern Utah.

Despite the successful field testing of the VFB in a wide range of applications by SEI and the substantial early investment and capital raising, however, Pinnacle was unable to fight off take-over attempts and the company and all the VFB patents were eventually taken over by a Canadian company that successfully completed a number of projects in South Africa and the USA in the early 2000s. A short-lived peak in vanadium prices in 2007 followed by the 2008 Global Financial Crisis, however, eventually led to its insolvency and its assets being acquired in a fire sale by a Chinese-based energy storage developer.

After the sale of the UNSW patents in 1997, the UNSW team continued to explore alternative redox couple combinations and the Vanadium Halide Flow Battery (often referred to as the Generation 2 Vanadium Halide Battery) was patented in the early 2000s (Skyllas-Kazacos 2002; Skyllas-Kazacos, Mousa and Kazacos 2003; Skyllas-Kazacos and Kazacos 2006; Skyllas-Kazacos et al. 2010). In 2005, a new start-up company V-Fuel, was established

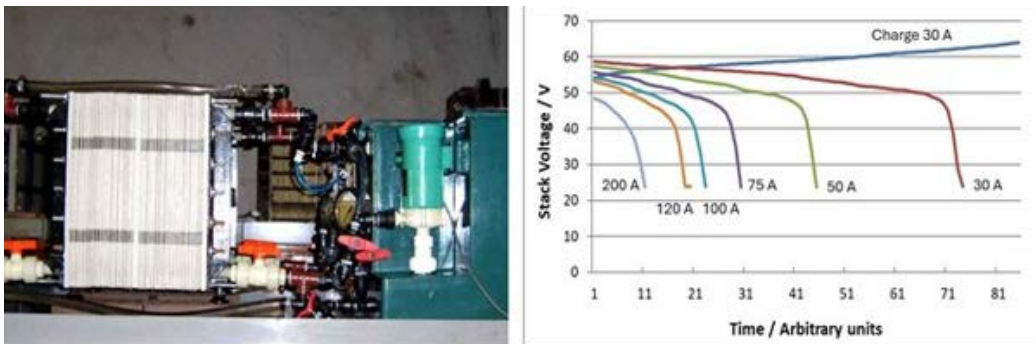

Fig 4: Left: L 5–10 kW V-Fuel stack using conducting plastic bipolar electrode with heat bonded graphite felt; Right: Discharge curves for V-Fuel stack at different currents after charging at 30 A. Photo courtesy Maria Skyllas-Kazacos.

with initial investment funding from the Victorian government-funded venture capital company, CEGT (Centre for Energy and Greenhouse Technologies) and a grant from the Australian government's Renewable Energy Development Initiative (REDI). The start-up successfully developed an improved perfluorinated membrane treatment process, identified suitable bromine complexing agents to bind the bromine produced at the positive electrode during charging (Kazacos and Kazacos 2012) and optimised a conducting plastic bipolar electrode assembly (Kazacos and Kazacos 2013). These electrodes were used in the fabrication of a 5–10 kW stack (Figure 4) that also included specially treated perfluorinated membranes. The company also designed a novel stack (Figure 5) that employed laser-welded bipolar electrode assemblies and could also be externally sealed by laser welding. However, the sudden jump in global vanadium price in 2007 combined with the effects of the Global Financial Crisis of 2008 prevented the company from attracting the necessary investment capital, so it was wound up and the patents transferred to UNSW's commercial arm New South Innovation.

When the basic UNSW All-Vanadium Flow Battery patent expired in 2006, groups around the world were free to develop and commercialise the VFB technology using the extensive research foundations provided by UNSW. One of the first companies to develop commercial systems using the UNSW technology outside of Japan was Cellstrom in Austria with its containerised 120 kWh CellCube system while multiple MW-scale field trials were conducted by Sumitomo Electric Industries in the early 2000s, verifying the efficiency and durability of the VFB in a wide range of applications.

Fig 5: V-Fuel integrated battery on a trolley, with pumps and piping incorporated inside tanks.

Current status

Since the expiration of the basic UNSW VFB patent in 2006, multiple companies have embarked on commercialisation of the VFB technology, with excellent performance demonstrated during long-term operation. More than 200,000 cycles were achieved in a 3-year VFB field trial by Sumitomo in the early 2000s, while a recent evaluation of a CellCube system has verified negligible capacity loss or performance deterioration after 10 years' operation (Li Y et al. 2024). These VFB companies continue to show a strong presence in the market, but others were forced to merge, restructure, or in some cases wind up, because of the slow growth of the energy storage market. Fortunately, this has changed dramatically over the last 5 years with the global push for net zero targets and increased renewable

energy uptake. While Li-ion batteries have attracted most of the attention to date due to their successful cost reduction in recent years, on-going safety issues and the growing need for longer duration energy storage are now starting to shift interest towards flow batteries.

At present, there are around 20 companies manufacturing VFBs around the world, with several of these being established in Australia to meet the rapidly growing demand for energy storage systems to achieve net zero targets. Since 2010, many new research groups around the world have been extending the original UNSW VFB research and have contributed significant improvements and cost reductions that are helping to enhance VFB performance and economic viability. The UNSW Vanadium Redox Battery technology is currently being successfully commercialised in a range of stationary applications such as wind, solar and load-leveling installations around the world and the demand for these systems is growing rapidly in China, North America, Japan, Europe and Australia.

Current R&D, commercialisation and implementation in China

Vanadium redox flow batteries have seen a fast development in China over the past decade, especially since 2020 when China announced its carbon neutrality strategy aiming to reach carbon peak in 2030 and carbon neutrality in 2060. With a skyrocketing deployment of renewable energy, China achieved a milestone in 2023 where clean energy generation (e.g., solar, wind, etc.) had for the first time broken through 50% of the newly installed power generation capacity. To sustain grid stability and security, therefore, long-duration energy storage technologies have been promoted to a high strategic level of national development, among which the VFB, with its high safety and flexibility in deployment, has been regarded as one of the most effective technologies for long-duration energy storage.

Fig 6: 200 MW/1000 MWh VFB in Xinjiang, China. Published with permission from Xingchen New Energy.

In 2024, over 440 MW/1.74 GWh of VFB systems were successfully installed and connected to the grid, where the capacity has been increased by 600% compared to 2023. Notably, this included the world's largest VFB installation of 250 MWh/1000 MWh system in Xinjiang Province. In addition, a 50 MW/200 MWh VFB system was recently installed in Gansu Province, while a 100 MW/400 MWh system has also been installed in Inner Mongolia. More recently, a 5-hour long-duration VFB project has been completed in Xinjiang, which achieves a total 200 MW/1000 MWh capacity as illustrated in Figure 6. This boom in VFB application is not only driven by the national strategies but is also attributed to the technical advances in VFB technology. Taking 4 hours storage capacity as an example, the average bid-winning price of a VFB system has significantly fallen to 2000 RMB/kWh in 2024. In the next few years, a further cost reduction to 1500 RMB/kWh is

expected, due to a well-developed material supply chain, enhanced battery efficiency and automated stack assembly (Figure 7), that has been dramatically reducing manufacturing costs.

Fig 7: Automated stack assembly at Rongke Power, China (reproduced with permission of Rongke Power).

Of all the VFB components, the vanadium electrolyte is still the most expensive part and may account for over 60% of capital expenditure. China owns ca. 37% of the total vanadium resources of the world. Currently, 80% of the vanadium electrolyte is produced by using vanadium from the by-product of the steel industry. Recent developments of short-processing vanadium electrolyte production technology (Zhang et al. 2022) have largely promoted the productivity, which has recently realised an electrolyte production capacity of over 60,000 m^3/year. With the shrinkage of the steel industry, however, other vanadium resources, such as stone coal, will be needed to meet the increased demand of vanadium electrolyte.

Apart from electrolyte, the power density of the VFB stack has been significantly increased in recent years. Large stacks such as 32 kW modules, can now deliver an energy efficiency over 80% at 200 mA/cm^2 constant charging-discharging mode, effectively reducing the material usage and lowering the power cost of the VFB.

Commercialisation and implementation in Europe and North America

The development activity of VFBs in Europe can be traced back to early 2000 (Mardilovich and Harrer 2023). In 2003, the first VFB system in Europe was installed, with 1 kW power and 50 kWh storage capacity. The system was operated in an off-grid configuration charged by solar and wind. The findings from the demonstration unit led to further research and development activities to improve the battery stack performance. A few years later, the concept of containerised VFBs started to emerge offering a standalone turnkey solution that fits all the necessary components, including tanks, power stacks, pumps and power electronics into a closed structure that has the same dimensions as a standard shipping container. Containerised units have gained interest because they simplify deployment on site, enable easy relocation and improve ingress protection. Early versions of containerised systems typically have power ratings ranging from 10 to 30 kW and capacity ranging from 40 to 130 kWh. One notable installation was the 10 kW/100 kWh system commissioned in Lichtenegg Energy Research Park, Austria, as part of a micro grid demonstration project in 2010. The Lichtenegg system has shown very little degradation after more than a decade of continuous operation according to a study in 2023 (Li et al. 2023).

Since 2010, research and development activities have continued to grow, with a strong focus on cost reduction while improving the system design and performance. More VFB manufacturers around the world have started to emerge, offering containerised VFB products based on a

modular concept. For example, some designs integrate multiple small VFB modules into a standard shipping container unit. The containerised units can be stacked in multiple levels to minimise the total footprint of large-scale installations. Studies have shown that the normalised footprint of a VFB installation can be less than a lithium battery installation of the same capacity due to the non-flammable nature of a VFB and the ability to be stacked (Reber, Jarvis and Marshak 2023). Some designs also are certified for road and sea transport with electrolyte filled in the tanks, which eliminates filling on site and simplifies the commissioning process (Cols 2025). Many MW scale installations in Europe and North America include:

- the 5 MWh Energy Superhub Oxford project in the UK (Cols 2024)
- the 1 MW/8 MWh project in Spain supported by the government energy research institute CIUDEN (Huh and Han 2025)
- a 2 MW/20 MWh system installation in Fraunhofer ICT as part of a European-funded project (Seiler et al. 2025)
- a 2 MW / 8 MWh system for G&W Electric in Illinois to use in a resilience micro-grid application (Whitehead et al. 2025)
- an 8.4 MWh Chappice Lake Solar Storage project in Canada for utility application (Cols 2024)
- a 2 MW/8 MWh system in San Diego California for grid stability application (Figure 8).

Fig 8: VFB projects in Europe and North America (top left: system in Lietenegg, top right: system in Spain, bottom left: system in Oxford Energy Superhub, bottom right: system in San Diego).

Besides offering DC VFB systems, several suppliers focus on the development and manufacture of the battery cell stack, the most important component in a VFB system. One important aspect includes optimising cell stack design to improve the stack performance, such as reducing the internal resistance by using a zero-gap reactor design with interdigitated flow field targeting high-power applications (Austing 2025). The stack manufacturing process has also been improved by utilising a fully automated stack assembling process to lower the cost (Seipp 2025). The overall stack performance has dramatically improved over the past decade. According to a study conducted in 2022, the average stack round trip efficiency is above 80% and some can reach as high as 88%, comparable with lithium-ion batteries (Li, Kienbaum and Lüth 2023).

While the development activities on the VFB stacks and containerised modules are expanding, with the increase in renewable energy penetration, the use of VFB is shifting towards longer duration (8–12 hours) due to better economics compared to lithium batteries. Several companies focus on system integration, including integrating containerised systems using a high voltage concept to ensure a seamless integration with existing proven power conversion systems (PCSs). The high-voltage concept offers better system efficiency by eliminating the need for DC-DC converters while still minimising shunt current losses in the common manifolds. Non-containerised solutions offering better flexibility to fit different applications and the ability for future expansion have gain interest, such as the 200 MW/800 MWh VFB system constructed in a building in Dalian China and the 15 MW/60 MWh system for the Hokkaido electric power network. In 2025, an AI data centre began construction in Laufenburg (Switzerland), which will include an 800 MW/1.6 GWh VFB in the basement of the building to support the grid. This is one of the largest flow battery projects in Europe and the world (Wyss 2025).

Activities in Australia

Australia's energy landscape is currently undergoing a rapid transition aiming to reach 82% renewable energy by 2030, according to The Department of Climate Change, Energy, the Environment and Water Australia (Edis 2025). Scalable and flexible long-duration energy storage solutions are critical to reach this ambitious goal. In 2024, the Australian Government released the National Battery Strategy as a key part of the government's Future Made in Australia agenda. The strategy outlines how the Australian Government will support domestic battery industry to:

- improve Australia's energy security
- ensure its place in global battery supply chains
- drive economic growth
- create positive social, economic and resilience outcomes for all Australians.

As of 2024, 35% of total electricity across the country is generated from renewable sources (DCCEEW 2025). VFBs are recognised as a favourable technology for large-scale energy storage systems to manage the intermittent supply and demand fluctuations of renewables. Vanadium, as an important critical mineral, plays a vital role in the VFB value chain and is a key enabler of VFB deployment. Australia has the world's best vanadium reserves, including: deposits in Meekatharra, West Australia;

Fig 9: Vanadium electrolyte manufacturing facilities in Western Australia (left) and Queensland (right).

in Julia Creek, Queensland; and Speewah, Western Australia. While the vanadium mining projects are being developed, several plants have been setup to produce vanadium electrolyte, including a 35 MWh annual production capacity plant in Western Australia commissioned in 2024 using the mixed oxide method (Skyllas-Kazacos 2004) and a 35 MWh annual production capacity plant in Queensland commissioned in 2023 using the V_2O_5 powder electrolysis method (Skyllas-Kazacos and Kazacos 2002). (Figure 9).

Besides electrolyte production, several important VFB pilot systems have been installed in Australia, including the 2 MW/8 MWh Yadlamalka Energy project in South Australia, the 250 kW/750 kWh Berrinba project in Queensland, and the 78 kW/230 kWh Horizon Power project in Kununurra, Western Australia (Noack et al. 2025). In early 2025, the WA Labor government announced the plan to build a 50 MW/500 MWh VFB in mining town Kalgoorlie by 2029 to support the electricity grid and is committing AUD$150 million funding towards the project.

Conclusion and outlook

Renewable energy generation has grown rapidly around the world and is expected to continue growing, as countries aim to reduce fossil fuel consumption and the associated greenhouse gas emissions. LDES plays an important role in balancing the power grid demand and supply associated with the inherent intermittent nature of renewable sources. VFBs, a 40-year-old technology invented at UNSW, are regarded as one of the most effective technologies for large-scale energy storage and long-duration applications. The early development of the VFB at UNSW focused on low-cost electrolyte manufacturing processes, electrolyte stabilisation, screening and modification of electrodes and membranes, novel bipolar stack design, fabrication and testing, modelling and simulation studies, as well as system monitoring and control. The fundamental research conducted at UNSW has been the key enabler for the commercialisation and deployment of the technology around the world, particularly in Japan, China, Europe, North America and Australia. To date, multi-GWh capacity VFBs have been installed and connected to grids around the world and many GWh projects are in the pipeline. The scale of VFB deployment is expected to continue its growth and form an important part of the global energy transition.

As MW- and GW-scale VFBs continue to be implemented around the world, the supply of vanadium will become a critical factor that is already being addressed, with

new vanadium mines expected in Australia and elsewhere in the coming years. The logistics of transporting thousands of cubic metres of electrolyte to remote locations will however require considerable research to reduce transportation costs. The production of an electrolyte concentrate or slurry, first proposed by Skyllas-Kazacos and co-workers in the 1990s (Kazacos and Skyllas-Kazacos 1994, Skyllas-Kazacos and Kazacos 2002), is currently being considered as a possible solution. By producing an electrolyte concentrate or slurry, the electrolyte weight and/or volume could be reduced by up to 50%, saving on costs of shipping and transportation over long distances. The concentrate or slurry can then be reconstituted by simply adding water prior to use. Further research on the storage, transportation, and reconstitution of the electrolyte concentrate is currently being undertaken, as is the effect of electrolyte impurities on battery performance and gassing side reactions. Electrolyte impurities are a critical issue which requires further research to determine whether lower purity vanadium raw materials could be used in the VFB to allow significant cost reduction.

Another important area of future research is the development of non-fluorinated membranes that can help to address increasing global concerns relating to "forever" chemicals. Many research groups and companies are developing such membrane materials (Huynh et al. 2025) but they still need to undergo long-term testing to verify their durability in the VFB for 20 years or more. The operation of VFBs in extreme hot or cold climates is also an area of further research and development. While such systems are already operating in many hot or cold regions of the world, the need to use active heating or cooling has been a drawback, since it reduces overall energy efficiency. New electrolyte formulations, including the mixed sulphuric acid/hydrochloric supporting electrolyte developed by Pacific Northwest National Laboratories (Li et al. 2011), are being considered, but the possible evolution of chlorine during charging requires special chlorine scrubbing equipment to minimise corrosion and prevent human exposure.

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