Discovery and invention: How the vanadium flow battery story began

Flow batteries | Andy Colthorpe speaks to Maria Skyllas-Kazacos, one of the original inventors of the vanadium redox flow battery, about the origins of the technology and its progression

Credit: CENELEST via Twitter.

Prof Skyllas-Kazacos with UNSW colleague Chris Menictas and Prof. Dr. Jens Tübke of Fraunhofer ICT, in 2018 at a 2MW / 20MWh VRFB site at Fraunhofer ICT in Germany.

In Volumes 21 and 23 of PV Tech Power, we brought you two exclusive, in-depth articles on 'Understanding vanadium flow batteries' and 'Redox flow batteries for renewable energy storage'.

The team at CENELEST, a joint research venture between the Fraunhofer Institute for Chemical Technology and the University of New South Wales, looked at everything from the principles behind how flow batteries work, to their applications and potential.

One of the authors, Maria Skyllas-Kazacos AM, is an emeritus professor at the UNSW Sydney Australia. Recognised as one of the original inventors of the vanadium redox flow battery (VRFB) and holder of more than 30 patents relating to the technology. We spoke to her about how some of those original discoveries came about — and why it's been a long road for VRFBs from lab to mainstream deployment ever since.

The first vanadium flow battery patent was filed in 1986 from the UNSW and the first large-scale implementation of the technology was by Mitsubishi Electric Industries and Kashima-Kita Electric Power Corporation in 1995, with a 200kW / 800kWh system installed to perform load-levelling at a power station in Japan. So what has taken so long?

It took a long time for our work to even be noticed. But we were lucky that very early on, even though the scientific community hadn't really picked up on it, industrial groups like Sumitomo and Mitsubishi Chemicals did. We also had a couple of people here in Australia and in Thailand who picked it up fairly early, because they were working on flow batteries and they had an interest in vanadium.

One of Mitsubishi Chemicals' subsidiaries, Kashima-Kita, was using orimulsion made from Venezuelan pitch in their power stations, which was very rich in vanadium. So they had this huge amount of waste product that they were extracting from this soot from the power station, and they were looking for ways to use it.

They had been working on iron-chromium batteries for a few years in Japan, under NEDO (the National New Energy and Industrial Technology Development Organisation). But when they saw the work that we did on vanadium, they became quite interested. We licensed our technology to Mitsubishi Chemicals and Kashima-Kita Electric Power Corporation and in the mid-1990s, they installed the first industrial-scale vanadium battery at their power station at Kashima-Kita.

So it was picked up by industry and implemented in quite a reasonably sized field trial very early. After that, within Japan were also quite a few other companies that were involved in iron-chromium battery development that picked it up as well, like Sumitomo. But it took a lot longer for it to be observed and even noticed elsewhere.

This obviously has changed in the last 10 years. Especially since 2006, when our first patent expired, a lot more companies and research groups were able to get involved. Especially in the US, there was no longer a problem with the freedom to operate, so researchers were able to get government funding to do work on vanadium flow batteries.

But the issue has been — or had been — about maybe 10 years ago, that the industry itself was still failing to acknowledge that you needed to store energy, that there was a market for energy storage.

It took quite a long time, but once they started observing huge issues with grid stability, they realised the grid isn't so good at stabilising all these renewable energies. People have realised that for the sort of energy storage we need for renewables, you really need long duration. And that's why flow batteries have been attracting a lot of attention.

Even before renewable energy came along, it seems a bit counterintuitive that electricity supply and demand should always have to be matched in real-time. It doesn't offer much margin for error, but I guess one of the main problems is that electricity markets have always been arranged around that?

A lot of the power industry has been extremely conservative, unfortunately. It didn't help that for many years, the renewable energy sector were preaching that you don't need storage, that the grid would be able to handle up to 30% renewables.

And that was not true. Overall, the whole system may be able to cope with distributed amounts, but you get local areas where you just can't cope, the distribution system just can't cope with too much renewable energy. We've started seeing major grid stability issues at much lower penetration levels than 30%.

Now that renewables are down in cost, we can address the issue of storage, and hopefully get the same sort of support from governments as well [that renewables had] to help get the volume up and bring the cost down.

I used to have a lot of contacts in the electricity sector, and they were scratching their heads and asking me, "Well, what can you do with batteries? And how can we use batteries?"

They couldn't work it out. That was a long time ago, but all they could see was renewable energy, off-grid applications. They couldn't see how they could use it in a grid-connected situation. That was very frustrating.

To get a little bit of a sense of what it was like for you and your colleagues to have actually kind of discovered this configuration of using vanadium electrolyte. Was it a kind of 'eureka!' moment? Or it was a more gradual process to come across that?

There wasn't really a single 'Eureka!'. Some parts of it, I suppose were, because people had suggested vanadium could be used as redox couples for a battery, but no one had. They were all discounting vanadium because all the literature was showing that the vanadium redox couples are not very reversible. That was a 'Eureka!' moment: we found that if we just roughly abrade our electrode rather than finely polishing and just roughly abrade it, we got good reversibility. That was very good and totally unexpected. We discovered something that no one had known before.

Another obstacle for vanadium which discouraged other people was because of the very low solubility of vanadium-five (vanadium pentoxide, V2O5) compounds. A lot of people thought, "Oh, well, you won't be able to dissolve it adequately to get the energy density you need".

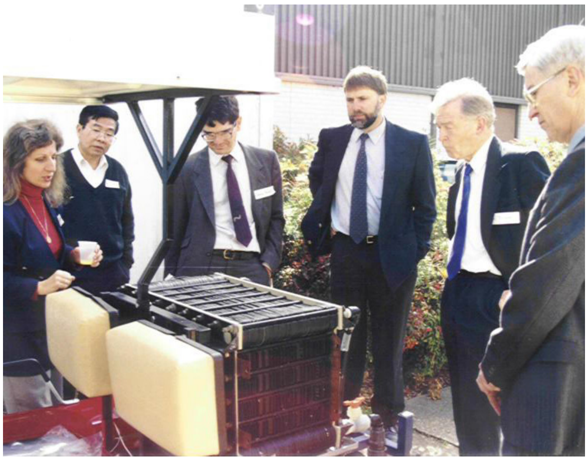
We thought we'd just try a few different ways of seeing if we can make vanadium-five solutions in different ways. We thought, if we did it a different way, we could get 2 moles per litre of vanadium whereas according to the litereature, 0.3 moles or something like that was the limit, which was not practical.

They were the two major discoveries that made us realise that this actually could work. We thought this would just be a few academic papers and that will be the end of it, but we just kept on realising that we can keep going with this, we can actually achieve a lot more than we had imagined at the beginning.

So we just kept on going. Before we knew it, 35 years had passed and more. We're still working on it. But it was also very fortunate, because very early on, somehow we attracted the interest of the media and that led to early licensing and collaboration with industry.

Right at the beginning, there was an article in the university magazine that got media interest and led to Sir Garrick Agnew [former Olympian and businessman] in Western Australia, whose company Agnew Clough had a vanadium mine. He got really excited about the vanadium battery.

He came to the university very early on and entered into a licence for the technology. At the time, we were still



Credit: Courtesy of Maria-Skyllas-Kazacos.

Maria Skyllas-Kazacos shows off a vanadium battery installed on a golf cart in the mid-1990s at UNSW. Standing next to Prof Skyllas-Kazacos is Dun Rui Hong, the project's mechanical engineer in charge of battery fabrication and installation.

making vanadium electrolyte from vanadyl sulphate — which is really expensive — because we worked out that we can get high concentrations if we started with that raw material.

The first thing he said to us was that unless you use vanadium pentoxide, the cheapest raw material, it's not going to be practical. Straightaway, he sent us a barrel of vanadium pentoxide and said, "I want you to develop a process for that".

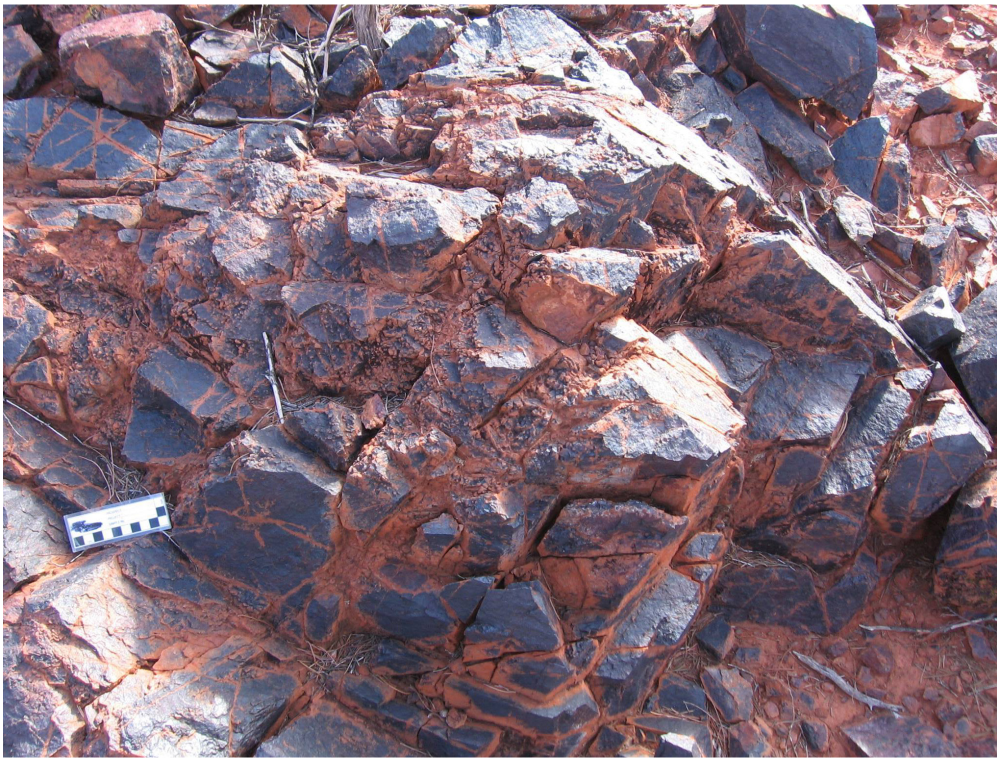
One of our colleagues, Rod McDermott — an absolutely amazing guy — got some of this vanadium pentoxide, stuck it in a beaker, started stirring it in sulfuric acid, put two electrodes in there and passed the current through it. Sure enough, it started dissolving. He came up to me one day and said, "Hey, Maria, I've got it, it's dissolving!" That was it, then I realised, well, it's going to work. And that was a major, major breakthrough.

That process itself would only take you as far as V4. But then, with that knowledge, that understanding that we can electrolytically dissolve it, we started developing more industrial-type processes that could be used to produce the electrolyte. They're the processes that people are using now.

I was so fortunate to be surrounded by a group of amazing, dedicated people who were just as passionate as I was about the technology and much of the success, I owe to them. From 1986 and up until 2010, my husband Michael Kazacos was always there beside me, sourcing materials and working with our subcontractors to manufacture components. He has since retired, but I am still working on it with colleagues at UNSW, Professor Jie Bao on battery control systems, and Professor Chris Menictas, on new materials and stack designs.

Primary vanadium producers' flow battery strategies

Flow batteries | Vanadium flow batteries are considered a leading light of the push towards technologies that can meet the need for long-duration energy storage. Not least of all by the companies that mine the metal from the ground. Andy Colthorpe learns how two primary vanadium producers increasingly view flow batteries as an exciting opportunity in the energy transition space.



Credit: Australian Vanadium.

Vanadium ore at a site in Western Australia.

The Valley of Death: the difficult gap between the tireless efforts of academics and entrepreneurs to bring their discoveries to life and establishing commercial products or services that meet true end-market demand.

It's likely you've already read many articles discussing the potential of vanadium redox flow batteries (VRFBs) to offer a long-duration, high energy counterpart to the high power, shorter duration capabilities of lithium on the power grid.

Flow batteries decouple the energy and power components of energy storage systems. That means you can scale up the amount of energy (kilowatt-hours, megawatt-hours) of a system with a set amount of power (kilowatts, megawatts), giving the opportunity to store several hours of energy.

The batteries, based on liquid electrolyte, are also almost entirely free of degradation even over many years and frequent cycles of charge and discharge. They also come without the risk of thermal runaway that lithium-ion batteries can suffer if faulty, mishandled or mismanaged.

Despite these advantages, non-technical factors — mainly economic ones — have held VRFBs back. When it comes to the economics of vanadium flow batteries, the dynamics of supply and demand for vanadium, the silvery-grey transition metal which when dissolved forms the electrolyte and therefore the key component of the battery, have long been the key talking point.

There are only three primary vanadium producers in the world today; Largo Resources, which has a mine in Brazil; Bushveld Minerals, which has mines in South Africa and mining giant Glencore (also South Africa). They account for roughly 20% of the world's vanadium supply, while about 70% comes from co-production — vanadium as a by-product of steel production. Secondary production, recycling of spent oil refining catalysts that contain vanadium, accounts for about 10%.

Two of those primary vanadium producers, Bushveld and Largo, are betting big on the success of VRFBs. Both have established subsidiaries which diversify their interests into the energy sector. So are these primary producers taking a serious gamble here? And what strategies do they have for entering this brave new world?

A sensible bet

According to Erik Sardain, a principal consultant at critical materials supply chain intelligence group Roskill, about 116,000MT of vanadium was produced globally in 2020. Adding small amounts of vanadium to steel creates much stronger alloys and more than 90% of vanadium consumption was accounted for by steel production last year. Smaller market shares were taken by aerospace, chemicals and other industries where it is also used.

Sardain says "a very, very, very small" percentage was used for flow batteries in 2020, with no major projects coming online. In 2017 and 2018, between about 1% and 1.5% of vanadium demand came from the VRFB sector. By about 2030, however, this figure could rise to 10% according to Roskill projections. Flow battery demand is a 'wild card' for vanadium, he says, largely dependent on how the technology is going to evolve.

"It's very difficult to put a number on because it is something which is very binary. But, I think one of the questions a lot of people have is: 'Yes, but if the demand for VRB is really high, will you have a shortage of vanadium?'

"I say no, because I believe that your supply and your demand are going to go in tandem, hand-in-hand. Because, if you have a new project of vanadium, you will not have the funding, banks are not willing to give the money unless you have some off-takers. Your demand is going to create your supply."

Bushveld Minerals and Largo Resources have customers in areas including steel and aerospace. In Sardain's view, they regard energy storage as a growth area with great potential, not an area into which they have to diversify or die.

"Let's take a worst-case scenario: Largo's production is going to be 6,500 tonnes of vanadium per annum. Even if the VRFB technology doesn't really take off, they will still have demand from aerospace, they still have demand from the chemicals industry. So they can probably live without it," Sardain says.

Fortune Mojapelo, Bushveld Minerals' CEO, says that steel is still the biggest driver of demand for his company and will remain the "main underwriter of demand," but flow batteries will become a serious opportunity.

US analysis and research group Guidehouse Insights has projected that 100GWh of new energy storage could be deployed in the next six years worldwide and Mojapelo says that even if VRFBs capture only 10% of that market, we're talking about 10GWh of storage systems.

"We would need about 55,000 tonnes of vanadium just to support that. VRFBs in time will contribute a significant amount of vanadium demand, way up from the single digits that it is today," Mojapelo says.

If the market does take off, the primary producers will have a competitive advantage over later entrants, smaller producers who Sardain says are unlikely to be able to come to market any time before 2024.

"They're taking a gamble, but a gamble in a position of strength."

The long road to long-duration

As we heard in our interview with University of New South Wales emeritus professor Maria Skyllas-Kazacos (see p.79), one of the original inventors of the vanadium flow battery, a gap of more than three decades passed from the first discovery of vanadium pentoxide as an effective electrolyte to today, where we are seeing commercially available VRFBs.

Fortune Mojapelo says it's an idea and a technology whose time has now come. Global energy consumption is increasingly taking the form of electricity, from about 10% in 1980 to 20% today. By 2050, it is projected to be 45%, not least of all because of the growing electrification of "just about everything, including mobility," Mojapelo says.

"With the move to clean energy, renewable energy is going to be a big part of new electricity generation capacity going forward, helped in large part by the cost-competitiveness of renewable energy. Today, we've got solar for example, which is comparable, if not cheaper, than fossil fuel-based electricity."

But with renewable energy from wind and solar intermittent — or variable — in its generation profile, energy storage will grow in importance, while the Bushveld CEO says the uptake of energy storage will also be driven by the need for utilities to become more efficient in how they use their capital.

"Energy storage can help a grid become a lot more efficient. It is not only for integrating renewable energy, but it helps, for example, with smoothing out your demand curve, load curve, away from a peak kind of construct shape to a flatter load curve. Storage helps, because you can basically load shift, you can you can store power during off-peak, which you can use to supplement during the peak hours."

"Within that, long-duration energy storage is going to be the biggest share of stationary energy storage, will account for more than 90%," Mojapelo says.

"That's great news for vanadium flow batteries, because they are really great and efficient for long-duration. Unlike lithium-ion, in a vanadium flow battery, the energy component where you store the electricity in the electrolyte is distinct from the power unit. If I want to store more energy, I don't have to replicate the entire system, I just need to extend my electrolyte tank content. Which is why the more energy I need to store, the more hours' duration, the more efficient it becomes."

For Bushveld, the question then became how the vanadium producer should support the rise and promotion of VRFBs. The answer, its CEO says, is around creating a vertical integration model between supply of vanadium and the production and deployment of battery storage using it.

Bushveld has established a subsidiary, Bushveld Energy, which is currently building an electrolyte processing plant in South Africa, near the parent company's vanadium mines. Bushveld Energy is also aiming to support VRFB deployments with project development, such as contracting Abengoa to build a system at Bushveld's own facilities. It has also invested in VRFB manufacturers, like Anglo-American company Invinity Energy Systems and Austria-headquartered Enerox-CellCube.

Changing a sceptical position on flow batteries

Largo Resources produces about three tonnes of vanadium pentoxide (V2O5) per month from its mine in Brazil. Largo is also bullish on the prospects for flow batteries and going even further into vertical-integration, launching subsidiary Largo Clean Energy, which will make its own VRFB systems.

Credit: Abengoa

Bushveld Energy contracted Abengoa to deploy a VRFB system for a solar microgrid at its Vametco production site.

"It's been a long time coming for this energy technology to develop and I have to admit, until a year or two ago, I was very sceptical. People were talking about how good it was, but we did not see any demand in the market," Largo Resources commercial VP Paul Vollant says.

However, there were a few different drivers that led Largo to rethink its position: "To the point that we are now completely transforming the whole company to focus on on integrating this battery business and essentially becoming a vertically integrated battery manufacturer," he says.

Vollant says Largo's position as a primary producer offers a head start, which it needs to capitalise upon. Largo needs to be "very dynamic," he says. The need for long-duration energy storage is "evident" and the company is "getting more enquiries than we can process".

The vanadium Largo has been producing for many years could be a key component in an earth-saving transition to renewable energy. Yet without an economic imperative the strategic transformation of the company would not be happening.

"We're very confident that we can make more money from batteries than from the traditional markets," Vollant says.

"We looked at the historical average price of vanadium pentoxide, which is about US$8 per pound and we translated that into a cost of storage for a vanadium redox battery, and at that particular point, we are much more competitive than lithium batteries, our main competitor right now, for…let's say six to eight hours duration."

In June, Largo Resources held a "Battery Day" to highlight its strategies for entering the global VRFB industry. While vanadium pentoxide (V2O5) as an additive for steel manufacturing is indeed around US$8 per pound, in the energy storage business that same V2O5 could be worth more than US$12.

Why leasing is so important

As mentioned previously, the upfront cost of flow batteries has been a major barrier to their market uptake. Although they actually come at a lower lifetime operational cost, Capex investment required has been an obstacle for many potential customers.

Granted, electricity market rules and design will have to change in the coming years to adapt to the need for long-duration storage. This is already happening in some parts of the world, like California which is preparing to launch its first gigawatt tender for long-duration in the next couple of years. The technology of VRFBs is gaining acceptance after several years of deployments around the world.

But even this being the case, how can a company like Largo seek to make higher margins from VRFBs than its other off-take industries without confronting the customer with costs that are too high? Largo, as well as Bushveld, see the answer in leasing the electrolyte, the flow battery's single most expensive component.

"The reality in a VRB is that the economics are very different from a lithium battery and lithium battery has a much lower capex, upfront cost, but much higher Opex. Long term, operation and maintenance cost. Lithium batteries are cheaper to make for the same capacity, but they degrade quite fast," Paul Vollant says.

"If you were paying for the full cost of a lithium battery, and for the full cost of a vanadium battery, you probably be ending up paying about US$6 to US$7 for lithium battery and probably US$10 for VRB upfront, but over 25 years, you probably need to replace your lithium battery two to three times.

So your lithium system will cost you much more at the end of the day, compared to a vanadium battery that does not degrade because of the intrinsic technical aspect of the electrolyte, the fact that it's vanadium on both the anode and the cathode side, there is no contamination and there is no degradation of the battery efficiency."

However, vanadium flow battery companies have to confront the fact that today's electricity market is largely focused on that Capex upfront cost. By leasing the electrolyte that uses vanadium coming straight from its parent company's mines to its customers, Largo Clean Energy will be able to effectively "subsidise" the battery initially.

"We're not getting the customer to pay for the full cost of the vanadium that is in it, but we are replicating the cash flows of lithium batteries."

UNSW's Maria Skyllas-Kazacos explains that there can be several key strategies for reducing the cost of VRFBs. Introducing automated manufacturing — the process is largely still manual in the small volumes of production that we see today — which can be located closer to demand centres would be one. Volume production, particularly of other key components like membranes, will further reduce costs.

Credit Fraunhofer ICT.

Electrolyte tanks at a 2MW / 20MWh flow battery demonstration project at Fraunhofer ICT, Germany. With VRFBs capable of many thousands of cycles without deteriorating, the electrolyte retains much of its capital value for many years.

The technology still holds room for improvement too, like increasing the electro-catalytic properties of the electrode to be able to run at a much higher current density without too much energy loss, increasing the output power capacity, or power density of the batteries. A lot of research effort has gone into those areas, Skyllas-Kazacos says, but it's still the electrolyte that remains key.

"When you look at long-duration storage, the cost of the electrolyte is more than half of the cost. I've done quite a lot of modelling on different costs and cost components and cost reduction and the effect of different… you can reduce the resistance of the stack by half and double the power density, but it has a tiny impact on the total system cost, depending on if the vanadium price is high, when you're looking at more than four hours of storage. So really, in the end, for long-duration, the big focus has to be on the cost of the vanadium."

What are the unknowns?

Leasing can bring down the upfront cost "dramatically," Maria Skyllas-Kazacos confirms, compared to cost reduction by other means. And for companies like Largo and Bushveld it helps establish a long-term customer relationship over many years rather than a series of one-off sales.

But what's in store for vanadium prices themselves? A few years ago, a spike in vanadium prices, driven by increased construction industry demand in China, led some people to consider using something else for flow battery electrolytes.

There are other options of course, like zinc-bromine or iron, but vanadium prices have since come down and stabilised and Largo Resources expressed a view at their Battery Day that spikes tend to last a year to 18 months at most. It remains likely, as Erik Sardain pointed out earlier, that since vanadium is an abundant but largely untapped resource, supply can scale with demand.

According to Maria Skyllas-Kazacos, that's been something of a 'chicken and egg' question for the vanadium industry. The vanadium industry has been waiting for years to see an increase in demand from the energy storage industry which is only just now starting to materialise. A vanadium processing plant in Windimurra, Australia, was built in the early 2000s, only to be shut down and reopen again before being forced to close after a fire in 2014. That plant has been acquired again and elsewhere in the country, Australian Vanadium Ltd is developing a processing plant to capitalise on a high-grade deposit in Western Australia.

"There's a lot of vanadium around the place, but everyone is sort of waiting for what's the right time to start investing and, and putting in a lot of capital to increase the supply of vanadium," Skyllas-Kazacos says.

"Once that happens, then the vanadium prices will come down dramatically and the prices will stabilise and that's the important thing."

Roskill's Erik Sardain reiterates that the world is not likely to be in short supply of vanadium, but it's a question of getting the economics right, of companies' ability of "getting the money to take it from the ground and make it economical".

It's interesting to note that beyond the primary producers, the majority of vanadium co-produced from steel slag currently comes from China. Bushveld CEO Fortune Mojapelo says that the energy storage market would be big enough to support both primary and co-producers supplying into it, but also notes that with co-producers already operating at "almost full capacity today," they will not be the big drivers of supply into the flow battery space.

Having said that, China's government has established a programme to develop several large VRFB projects of hundreds of megawatt-hours each in strategic locations around the country. As with the solar PV and lithium battery industries, China could be the leader that kickstarts a global wave of long-duration VRFBs, Roskill's analysts believe.

"I believe that the VRFB story is going to be driven by China, because it's not only based on economics, it's also based on politics. Because if the Chinese government says, "Let's go for it," then they will go for it," Erik Sardain says.

"If it's successful, China is going to show the way. And basically the rest of the world is going to follow after that."

That said, the US government is on record expressing a view that the future lies with flow batteries for large-scale grid energy storage, Fortune Mojapelo points out, and the question remains within the flow battery space as to which chemistries will be dominant. Other electrolyte chemistries like those mentioned above "don't have any meaningful deployments to talk about," compared with vanadium flow batteries, he says.

But nonetheless, the race to decarbonise needs to speed up and different flow battery types — and other types of long-duration storage — can work together in powering the global energy transition.

"Here's the thing: you can have multiple technologies," the Bushveld Minerals CEO says.

"We're fine with that, because vanadium flow batteries just won't have the capacity to capture all of that market growth. If vanadium flow batteries get to even 20% of that stationary market, we think it's a massive deal. It's a big, big deal and we're very pleased for that. It's not a case of one technology, winning over all the other technologies, I think you will see multiple technologies very active in that space."

Largo Resources takes a similar view, Paul Vollant says. It takes about 6,000 tonnes of vanadium to supply about one gigawatt-hour of storage. Today, only about 1,000 to 2,000 tonnes a year goes into VRFBs at most. With the "strong inflection point in the demand for long-duration storage" that Largo is seeing, there will be a supply chain shock coming that only an increase in the global supply of vanadium coupled with a diversification of long-duration solutions can solve.

"Vanadium redox batteries are not going to be the only solution for long-duration, you have geographies where pumped hydro storage is a better solution, you've got other applications where compressed air would be better. The ambition for Largo and for the VRFB industry is not to capture the whole market, the ambition is to capture the applications where VRFB makes more sense, and that are most profitable."

Meanwhile Largo, and others, have the ability to scale up production, but it is a question of time and money. Vollant says it costs in the region of about US$300 million to US$400 million and about three to four years to establish and ramp up a vanadium plant.

"It's a bit like oil: there's no global shortage of oil, but there is a shortage of cheap vanadium as there is a shortage of cheap oil from deposits that are high grade and low cost. If the world really needs a lot more vanadium as when the world needs a lot more oil, then the world would have to pay a higher price for vanadium. So you will find an equilibrium between supply and demand." ■

Credit: Largo Resources.

Largo's vanadium flakes. The company believes vanadium pentoxide can be worth more per pound in energy storage than in some of its traditional markets