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White Paper

Vanadium Redox Flow Batteries for Mass Scale Energy Storage

Solarin Solar Power Solutions Pvt Ltd.
Call Toll Free: 8010 469 469
404, Urbtech Matrix Tower, Sector 132,

1. What is the niche Vanadium redox flow battery offers in the energy storage solution space which is heavily dominated by Li-ion technology?

Vanadium Redox flow battery is a part of flow battery family which offers a distinct advantage in the stationary energy storage application space. Flow battery becomes very competitive in cost and performance for high energy to power applications (E/P>3). Figure 1 precisely show the applications where flow batteries dominates.

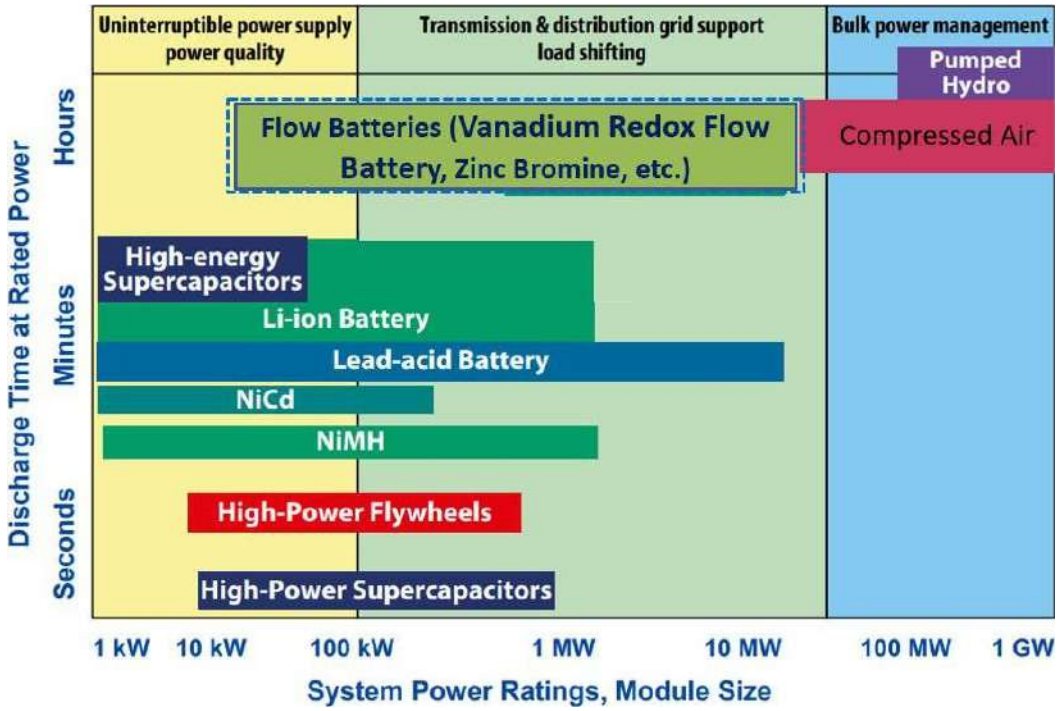

Fig 1: Positioning of diverse energy storage technology[1].

The specific applications where flow batteries offer better utilization and economics are Frequency restoration, energy shifting, load levelling, community storage and village electrification[1]. Bloomberg new energy finance highlights that there will be over $620 billion of new investment in energy storage sector by 2040 and **vanadium redox Flow battery will capture around 18% of stationary energy storage market[2]**. The recent unprecedented interest in Lithium ion technology in but natural from its suitability for portable and mobile application. Li-ion technology offers an unmatched performance for electric vehicle application and there is rarely any technology competition but it is not the most suitable solution for large storage energy storage application. Short life (requiring 3-5 time replacement), fire safety issues coupled with capacity degradation makes them expensive and unreliable for large scale stationary energy storage application. Huge infrastructure are cost often incurred to account for safety of li-ion battery in larger project.

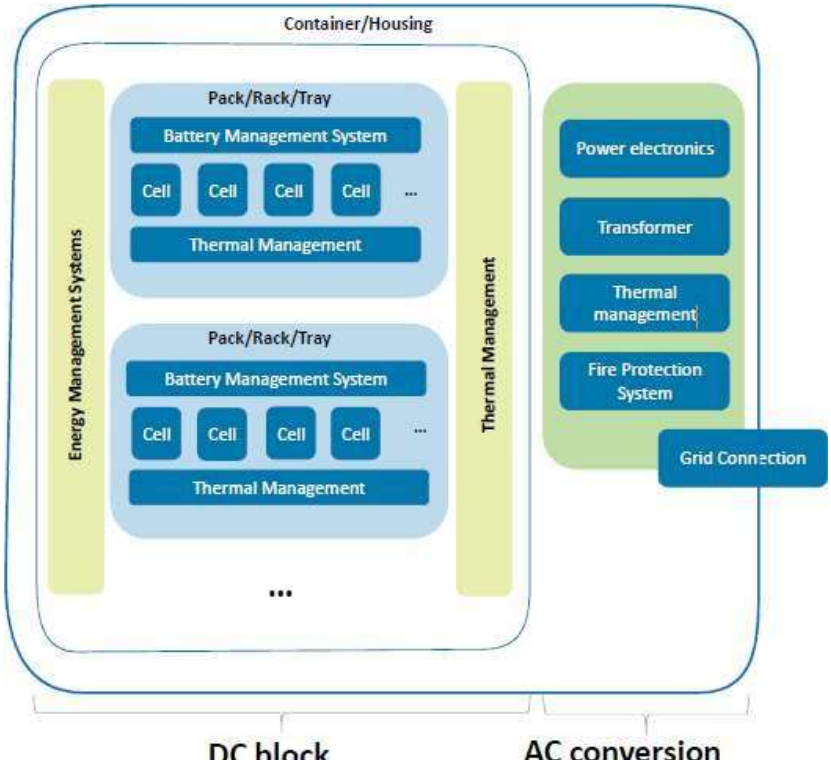

Fig 2: Components of a typical energy storage system[1].

The AC side of almost all ESS system is typically the same but differs significantly on the DC side. **A major advantage of Flow battery is that it doesn't need dedicated fire protection system and thermal management which make them simple in design with a scope of significant cost reduction**. Flow batteries also offers significant advantage over Li-ion technology in terms of design flexibility (as power and energy are decoupled), stability and life span when considering large scale ESS. Some of the advantage of the flow batteries over other technology in mitigating risk is explained in figure 3.[3]

Risk	lithium-ion	Flooded Cell	Sodium Sulfur	VRB Flow Battery
Voltage	X	X	X	
Arc-Flash/Blast	X	X	X	
Toxicity	X	X	X	X
Fire	X	X	X	
Deflagration	X	X		
Stranded Energy	X	X	X	

"VRFB along with lead acid is the only battery chemistry to receive a letter of no objection from the New York Fire Department."

- ESJ (Energy Storage Journal), 14.11.16

Fig 3: Risk analysis of different ESS technology[3].

Flow battery family consists of different chemistries and each of them has its own pros and cons. Vanadium (VRB), Zinc bromide (ZBR), Iron Flow (FeRB) and Iron chromium

(FeCr) are some of the prominent chemistries that has been commercialized. Off all the above chemistry, Vanadium is the most mature and proven technology. Globally, about 1 GWh of vanadium batteries have been deployed till date (details attached in Annex A). **V-Flow tech was setup on a fundamental to deliver a cost effective, reliable, safe and sustainable energy storage solution for renewables**. For the same reason, V-Flow tech selected Vanadium as a preferred chemistry for flow battery. Vanadium outperforms other flow chemistry in terms of stable performance (no capacity loss), safety and infinite life of electrolyte. Some of the key advantages of Vanadium redox flow battery compared to other technology are listed below:

- VRB uses same vanadium metal ions in both tanks, therefore there is no detrimental effect by the cross contamination. This results in stable capacity over lifetime. Other flow battery suffers a lot by cross contamination.
- Electrolyte does not degrade and is 100% reusable after the shelf life of battery. This has about 25% value of the battery.
- Stack components are made of graphite/carbon and do not consume and electrolyte during charge/discharge cycle which allows the stack performance to be stable for long time.
- There are no harmful gases released during operation compared to other chemistry ($ZnBr_2$ has risk of bromine gas release, mixed acid vanadium has risk of chlorine gas release, etc.)
- Round trip efficiency is relatively higher compared to other chemistry (all iron, zinc bromide, etc.)
- Minimum maintenance is required, and all materials used in battery are recyclable/reusable.

Traditionally, Vanadium redox flow batteries suffers from the precipitation of Vanadium (V^5) at higher temperature and low efficiency compared to semi-solid-state chemistry like Li-ion. V-Flow tech has precisely worked on these problems and resolved it. V-Flow tech has specific IPs which makes our VRB much superior to other competing technology (Detailed comparison attached in Annex B). Some of the key advantage of V-Flow tech are as listed below:

- Increased operating temperature -10 °C to 60 °C without active cooling. Usual operation range is -10°C to 40 °C.
- Highest stack efficiency > 85%, others are 75-80 %. This helps us to be cheaper and compact.
- Minimal parasitic losses (developed a method to reduce pump power to very low, automatic capacity rebalancing approach.
- No halide chemistry, environment friendly.
- Smart and Intuitive battery with efficient use of IOT and propriety algorithm.

2. Vanadium is a major component of VRB battery and a significant cost component of the battery. Vanadium metal is price sensitive and expensive. How do plan to negate the economic impact of the Vanadium metal price in the VRB?

It is true that vanadium is a major cost component of VRB battery. Vanadium metal is a commodity and its price fluctuate. However, Vanadium is also one of the most abundant elements in the earth crust and current known reserve is enough to meet vanadium demand for more than 150 years[4]. There are enough references that suggest that VRFB projects are viable for investment when the vanadium price is below $10/lb. At $8/lb, the LCOS of vanadium battery is still significantly cheaper than Li-ion battery technology due to it unlimited cycle life. Vanadium prices has been historically lower than that of $6/lb, baring few occasions of short spikes caused due to modified supply and demand. Figure 4 shows a price trend of vanadium over the last 40 years. The trend shows that the average price of vanadium metal has been quite stable with the median price below $6/lb. **So, the threat from unstable vanadium price is relatively low for VRBs development in the long run.**

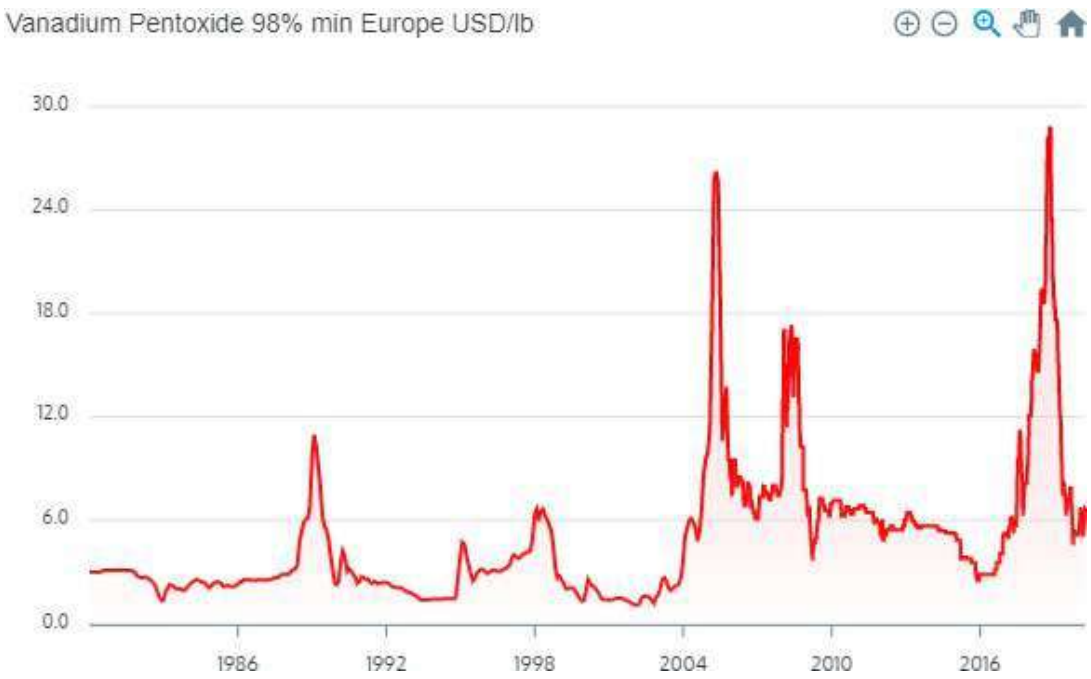

Fig 4: Vanadium metal price variation over four decades.[5]

Furthermore, the best part of VRB battery is that lifetime of vanadium electrolyte is infinite and 100% of vanadium is re-usable upon decommissioning of the system. This creates an unique opportunity for VRB developers to potentially remove Vanadium from the capital cost and negate the impact of vanadium metal. Bushveld minerals have already launched a vanadium leasing program where VRB developer pays a nominal upfront deposit for electrolyte and pay annual rental fee which can be clubbed as a part of annual O&M fees[3]. Figure 5 shows the electrolyte leasing model introduced by Bushveld. The vanadium leasing model has significant impact on the energy storage project economics. The project internal rate of return increases drastically while decreasing the direct capex burden on the project owner.

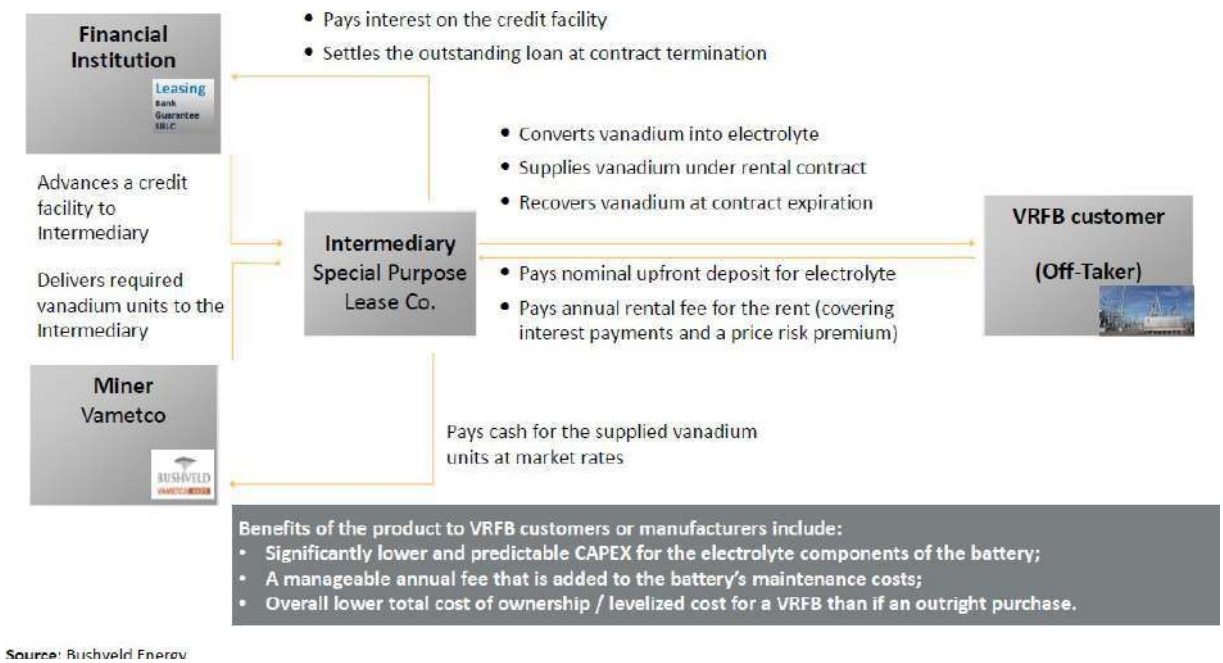

Fig 5: Bushveld Electrolyte rental model.[3]

There are many mining companies in the region specializing in Vanadium metal. V-Flow tech has strategic plans to partner with few Vanadium miners in the long run and develop leasing model to stabilizes the supply of vanadium and pass on the cost benefit to the customer. Furthermore, as a technology company, V-Flow tech has research plan/roadmap to gradually increase the energy density of VRB through development of new additives and electrolyte (Vanadium/Air) thereby, slowly reducing the dependence on pure vanadium electrolyte.

3. Scale at which Vanadium gets competitive.

VRB batteries are already cost competitive to any other storage technology on terms overall cost of ownership or levelized cost of storage (LCOS)[6]. The upfront capex cost is about 1.2-1.5 times the cost of Li-ion technology which is mainly due the relatively low scale of manufacturing and deployment of flow batteries. However, there is a tremendous potential of cost reduction with the VRFB battery technology. The cost reduction potential of li-ion technology is slowing whereas the cost reduction potential of flow batteries is increasing[3]. This can be well interpreted from the fact that Flow battery technology uses a much simpler power electronics and overall BOS as compared to li-ion technology (Figure 2). This offers a tremendous scope of cost reduction at scale. This is further supported by recent report published by Lazard that shows the cost of flow battery technology has reduced by 38% whereas Li-ion technology is slowing to 28%.[3,7] Figure 6 compares the 5 year cost decrease and CAGR of Li-ion with VRFB respectively.

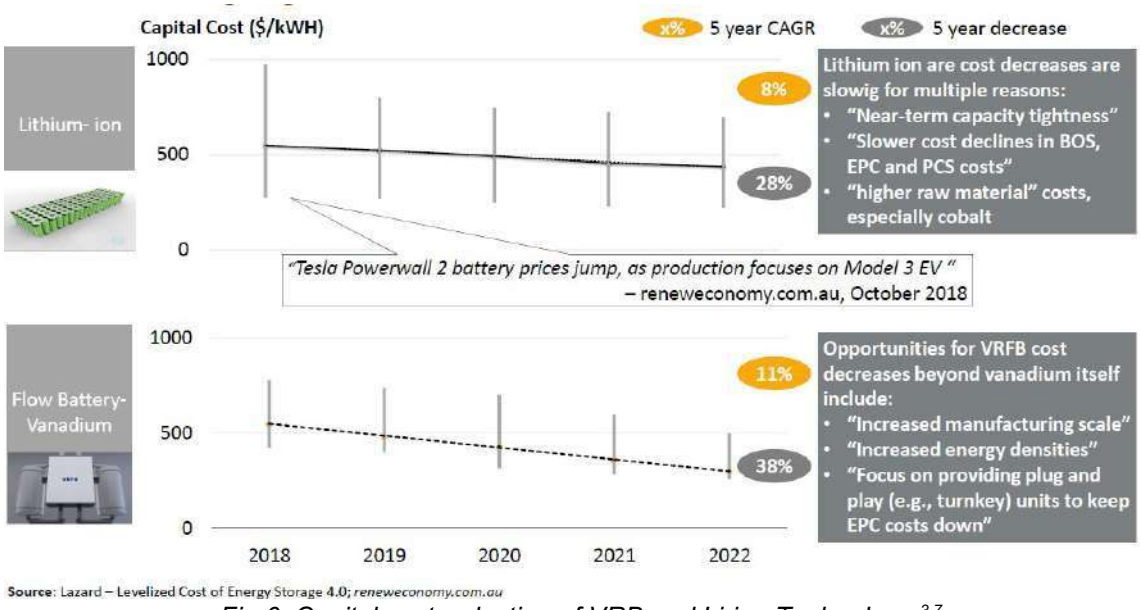

Fig 6: Capital cost reduction of VRB and Li-ion Technology.[3,7]

Furthermore, a recent report published in Nature energy by Imperial college London shows that economics of scale for Vanadium redox flow technologies is achieved at **7GWh of deployment at utility scale while the same for Li-ion is achieved at 33 GWHh.[8] The findings of this research paper is encouraging which clearly demonstrate that VRFB technology has potential to reach scale of economics at 1/5 of the required Li-ion technology.**

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7. https://www.lazard.com/media/450774/lazards-levelized-cost-of-storage-version-40-vfinal.pdf
8. https://www.nature.com/articles/nenergy2017110.

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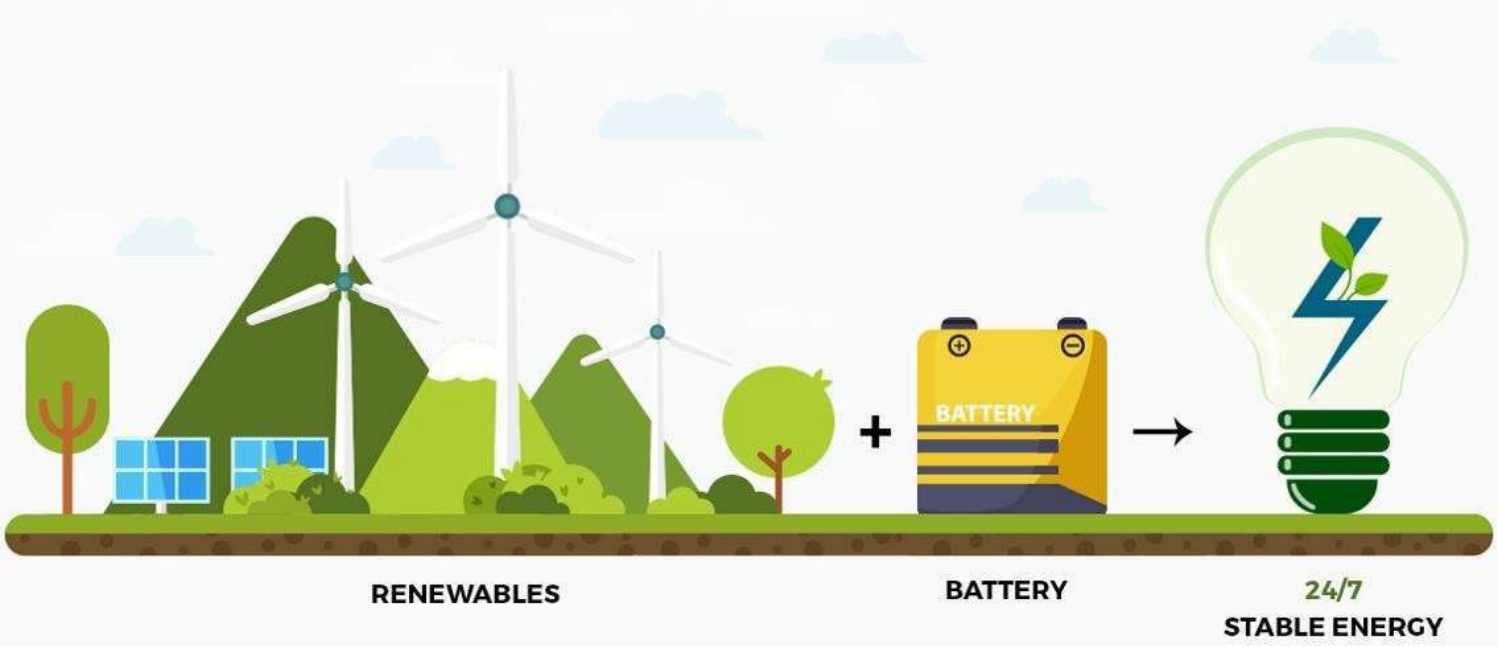
A long-lasting battery solution for your energy needs

Renewable Energy is the Future!



- Cost of renewable energy has dropped exponentially over the decade
- Urgent need for long duration energy storage to drive the renewable demand further

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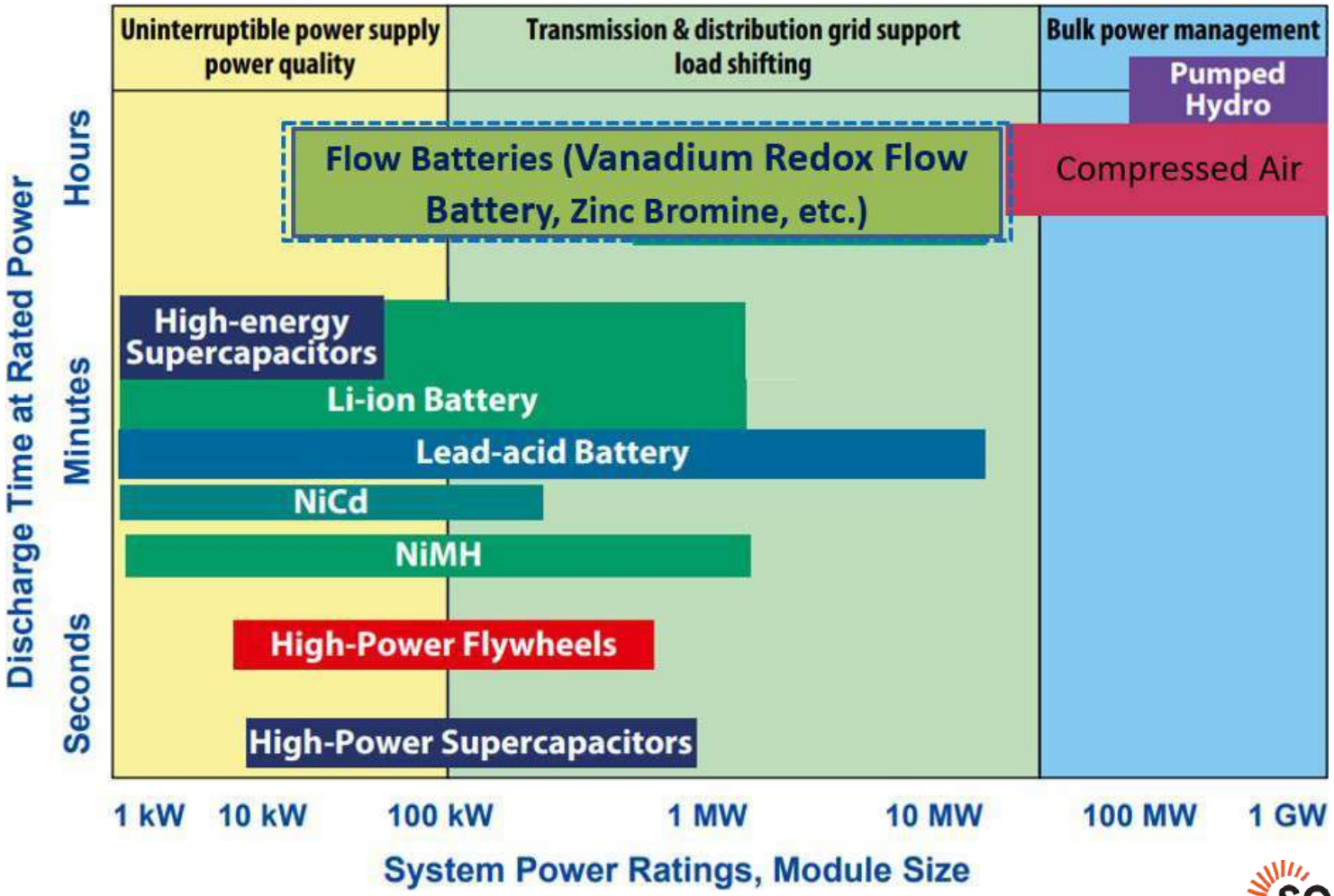
Not One ESS Technology fits all Applications!



- Li-ion and Lead Acidare good for short duration storage (minutes to 2 hours).
- Supercapacitors are good for high power for few seconds.
- Redox flow batteries are suitable for large scale energy storage (kW to MW) and backup time (hours to days)

Source: International Renewable Energy Agency

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Current Technologies Have Limitations

Explosions Threatening Lithium-Ion's Edge in a Battery Race

By Brian Eckhouse and Mark Chediak
April 24, 2019, 6:58 AM GMT+8 *Updated on April 24, 2019, 10:24 PM GMT+8*

- Battery exploded at plant in Arizona; two others were shut
- Arizona utility regulator calls for 'thorough investigation'

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BLOOMBERGNEF

Another lithium-ion battery has exploded, this time at an energy-storage complex in the U.S.

At least 21 fires had already occurred at battery projects in South Korea, according to BloombergNEF. But this latest one, erupting on Friday at a facility owned by a Pinnacle West Capital Corp. utility in Surprise, Arizona, marked the first time it has happened in America since batteries took off globally.

Local regulators are now demanding answers, companies are investigating the cause, and analysts are wondering: Could more blazes threaten the future of lithium-ion – the only technology that has proven capable of bringing battery storage into the mainstream?

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Burning concern: Energy storage industry battles battery fires

FM Global conducts fire research on a lithium-ion battery storage system at its research center in West Glocester, Rhode Island.

Source: © 2019 FM Global. Reprinted with permission. All rights reserved.

When a 2-MW battery array in Surprise, Ariz. caught fire and subsequently exploded on April 19, it highlighted a troubling reality for the nascent energy storage industry: the sector's momentum, marked by record numbers of deployments, falling prices and expanding state

Impacts of Improper Battery Disposal Lead Acid Contamination

Haina, Dominican Republic

- Toxic fumes produced were over the limits
- Improper decommissioning of recycling plant
- 91% of 147 children had lead poisoning

Regulator says lithium-ion batteries create "unacceptable risks"

Arizona regulator Sandra D. Kennedy has filed a review of lithium ion technology's drawbacks relative to other energy storage technologies, specifically noting hydrogen fluoride release and thermal runaway, in light of two Arizona energy storage battery fires.

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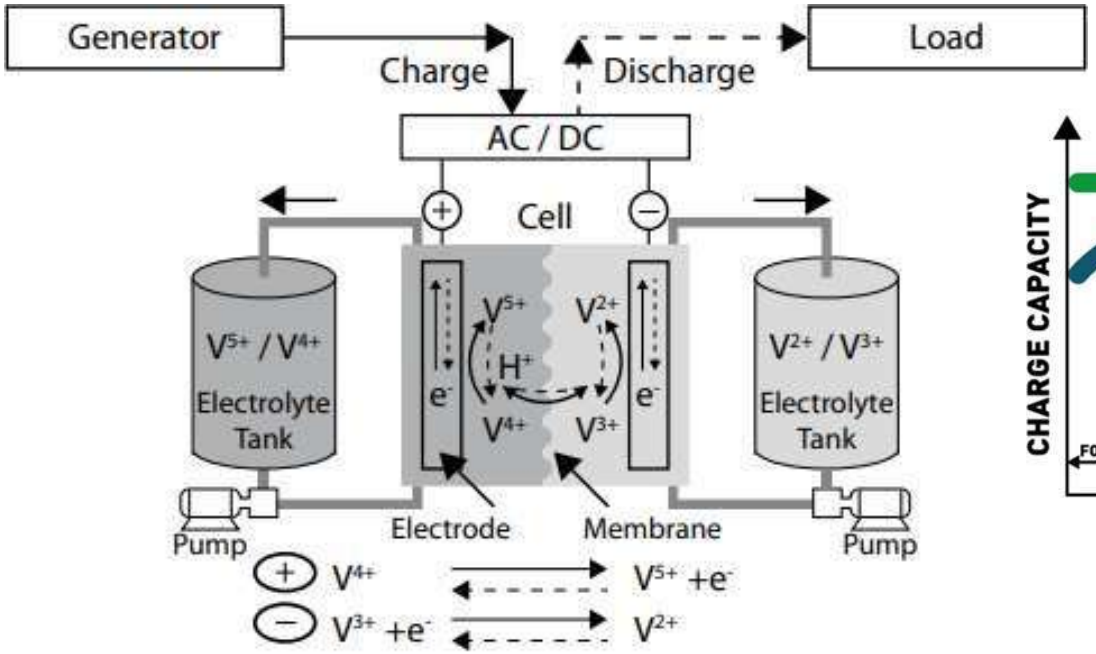
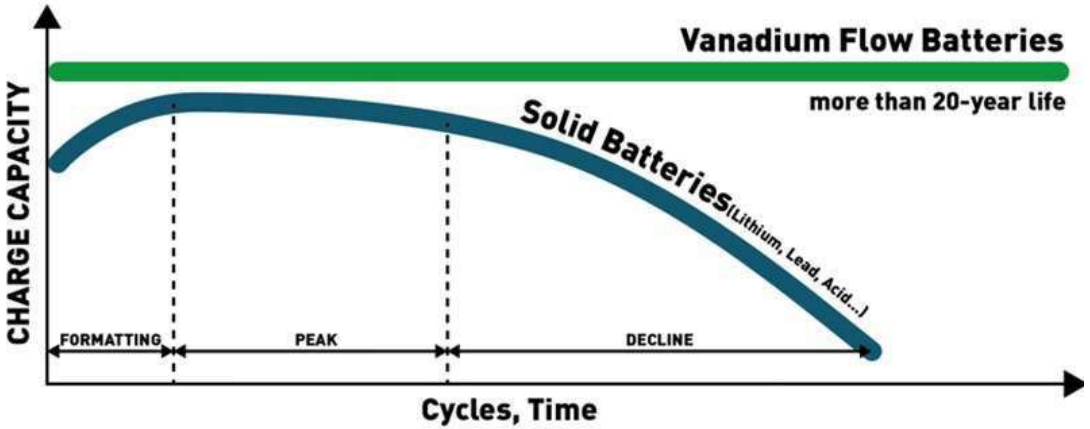
Vanadium Based Redox Flow Batteries



Working mechanism



No degradation

Safe to use

100% Recyclable

25-year Life

100% DOD

Long hour

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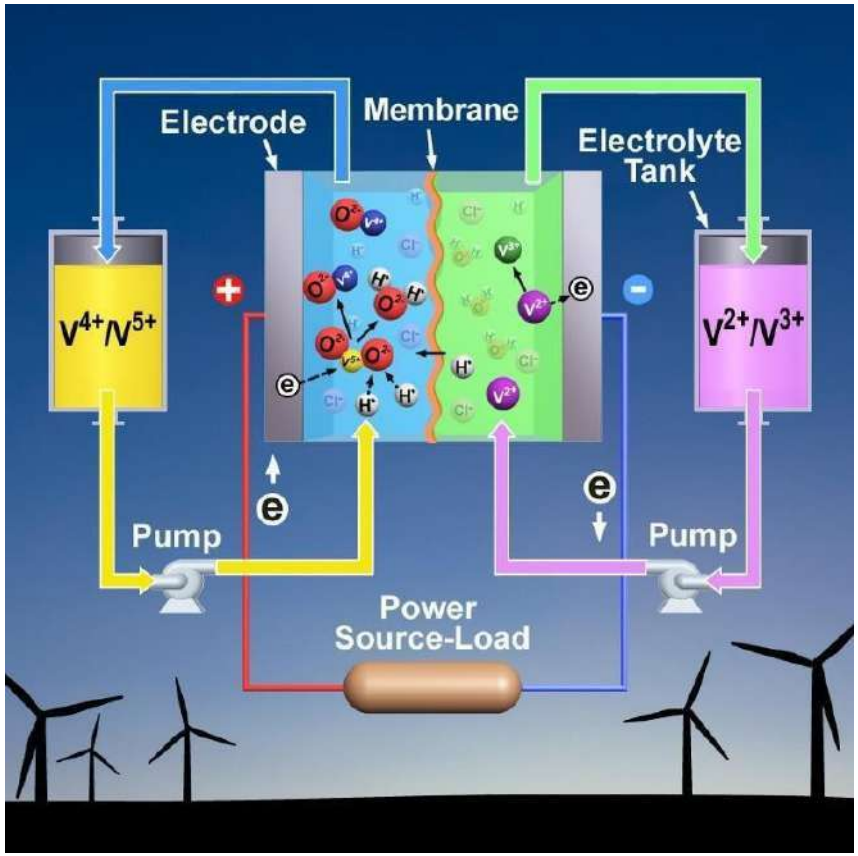
Challenges with Existing VRFB Technology

Issue with current vanadium flow batteries is stopping the mass adoption of thetechnology



- High parasitic losses (shunt current, pump loss, poor flow)
- Poor round trip efficiency <70%
- Precipitation of V^{+5} above 40°C (restrict high temperature operation in tropical conditions)
- Low energy density
- Chemical handling with potential leakage
- High upfront cost

At V-Flow Tech, we have resolved all the above key challenges

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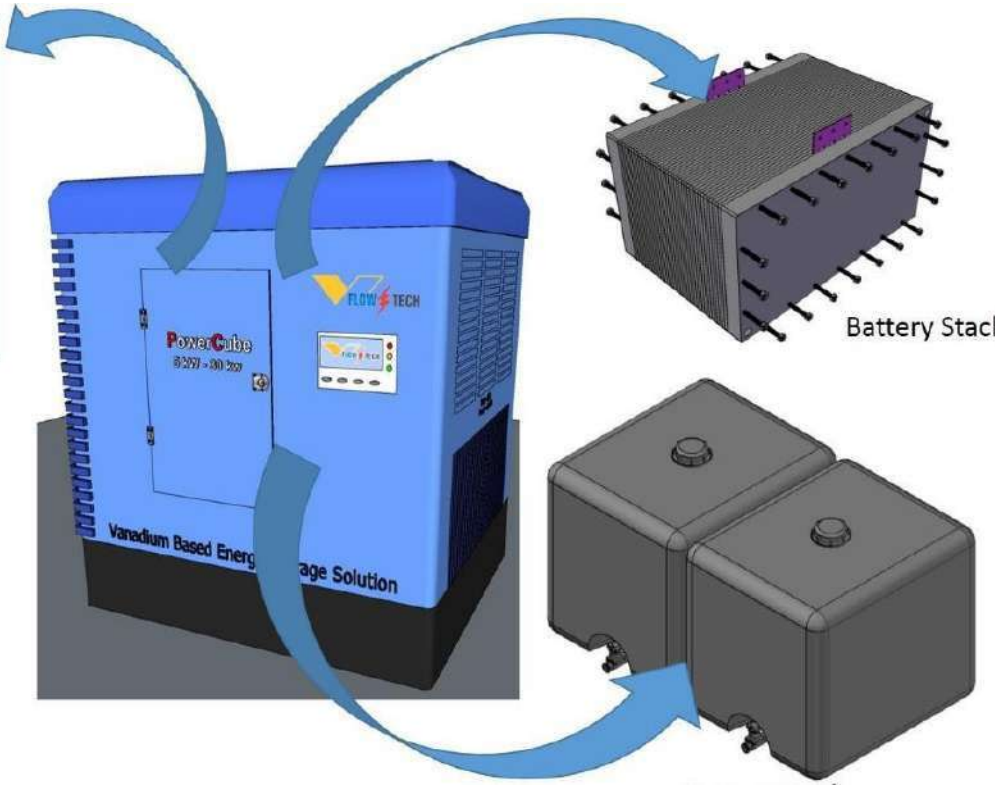
V-Flow-Technological Innovation

Electrical components



Battery Stack

Stack design
Compact and scalable design

Reduced parasitic losses
High and stable efficiency & capacity

Novel Chemistry
Allows better thermal window

Higher solubility of vanadium
25% Higher energy density

Proprietary BMS and EMS
>IOT and Load management capabilities

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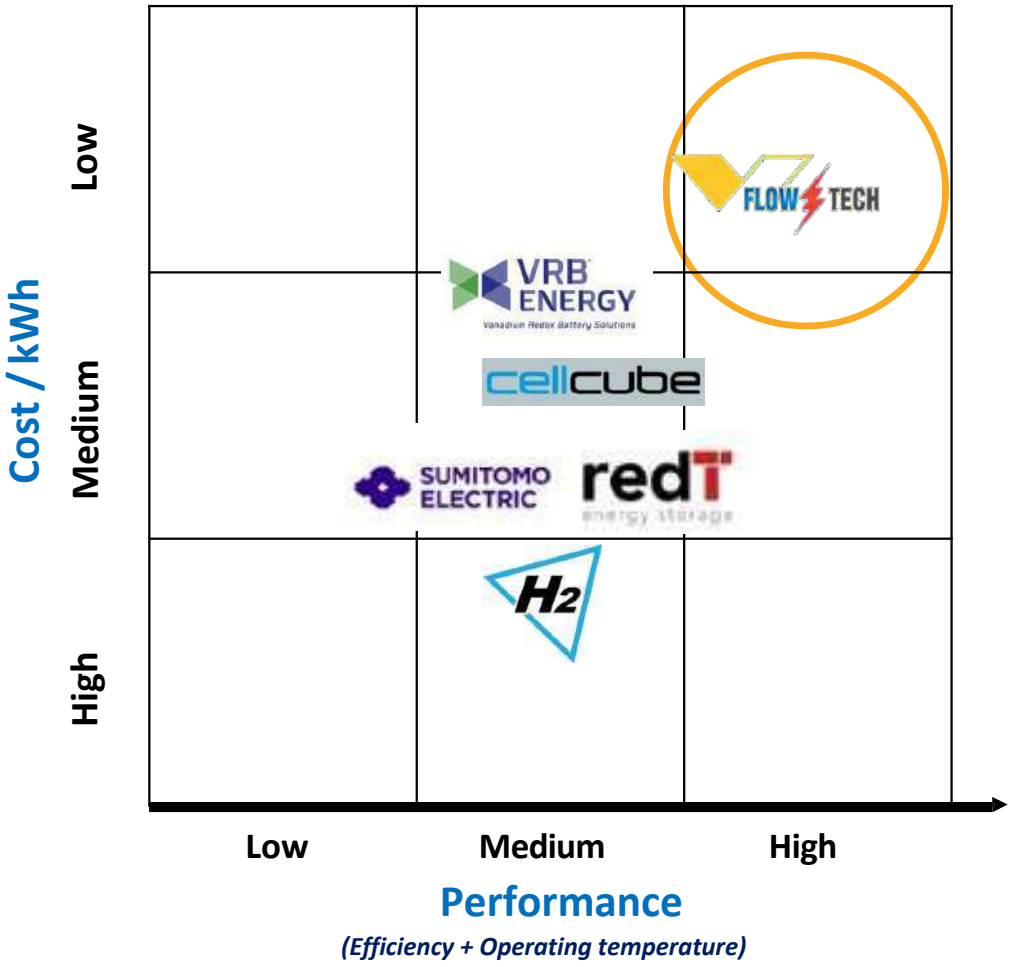
V-Flow Tech Outperforms VRFB Competitors



Higher efficiency
(10% higher than industry)

Lower cost
Provide affordable energy

Higher operating temperature
Save more energy

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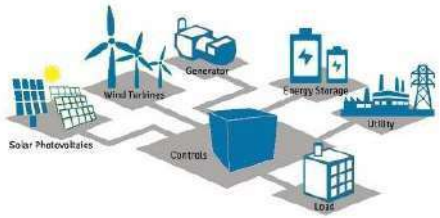
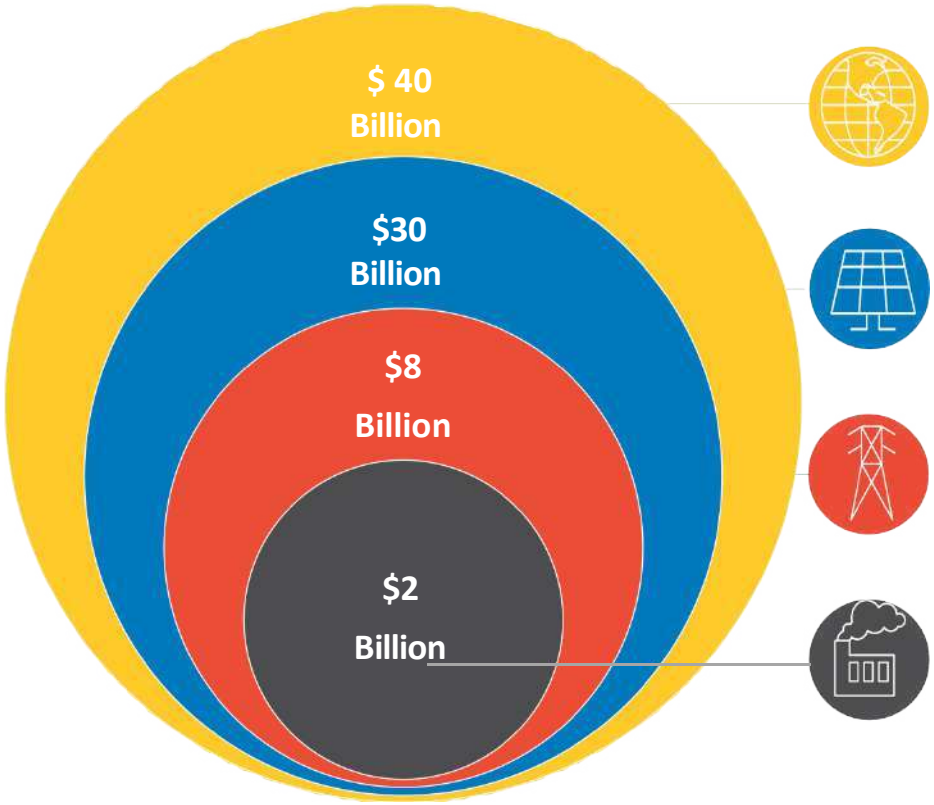
V-FLOW: Application & Target Market Size



Small and Micro grid application

Grid Stabilization
Integration with renewables

Solar tracker



Overall > $40 billion
Target market ~ $10 billion

Grid connect renewables
Cost of solar < 3 cents

Large grid & balancing
Renewable intermittency & variable cost of electricity

Off-grid and diesel gen
Cost of diesel generated electricity is $ 0.40 - 0.60 and cost of solar plus V-flow battery is ~ $0.15

1. https://www.power-technology.com/comment/global-diesel-generators-market-reach-value-115-11bn-coming-years/.
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V Flow Tech POC 1: Powering JTC building with Renewables

JTC office

250 kW Solar rooftop

Corridor lighting

Lift

System ready at workshop for deployment

10 kW/100 kWh V-Flow Battery

Carpark lighting load

Funding partner

TEMASEK FOUNDATION ecosperity

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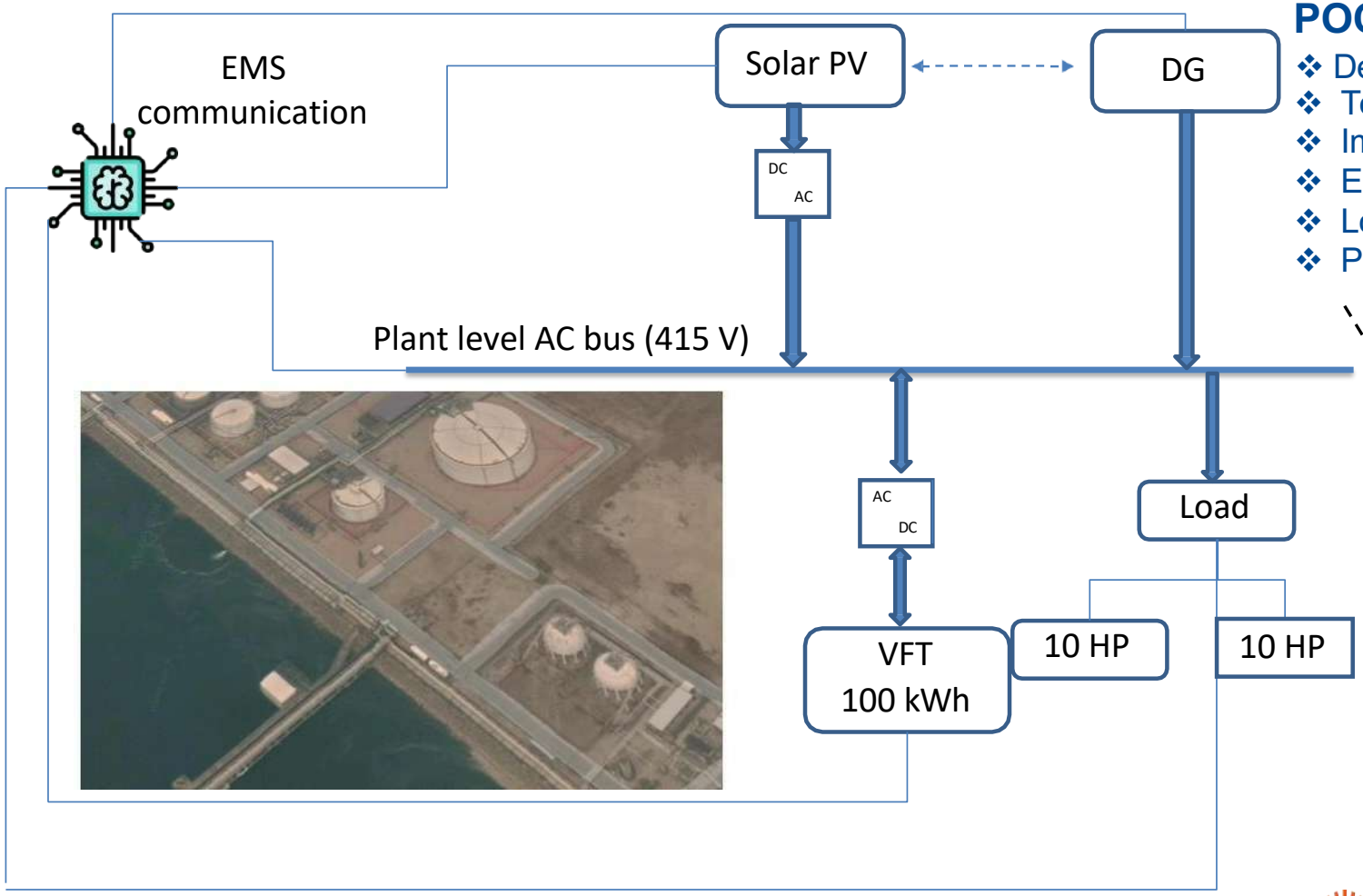
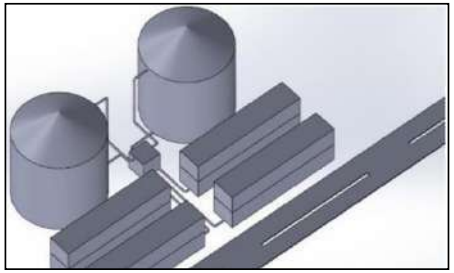
V Flow Tech POC 2: Smart Grid to test the Battery and Pump



POC Objective:

- Demonstration of the Smart Grid.
- Test VFT performance in harsh climate.
- Impact of solar on DG consumption.
- Energy synchronization.
- Load balancing.
- Prepare for full scale project at Island.



2 MWh full scale project

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V Flow Tech POC 3: Hybrid VRB/Li-ion Battery at Marina Barrage

50 kW/300 kWh Hybrid ESS System

175 kWp Solar System

EV Charging

Space and Lighting load

Case Study: V-Flow vs Li-ion Solution

	Lithium ion (250/700 kWh)	V-Flow Power Cube (100-500 kWh)
Cost [$]	259,000	290,000
$/kwh	370	580
Depth of Discharge	90%	100%
Maintenance	Frequent	Very low maintenance
Lifetime/Cycle	7 years/4000	25 years/>10,000
Environmental and safety issue	Highly flammable	No emission, not flammable
Performance degradation	Yes (Rate depend of external factor)	No degradation, stable performance guarantee
Container Solution	1X20” feet container	1X40” Feet container
COO – LCOS ($/cycle/Kwh)	0.21	**0.12**
Additional Information	• EMS allows application customized to support the special application of each customer. • Thermal and fire system management included • Yearly system optimising service • Long term tech support and services required during system operation	• Charge and discharge at the same time • No thermal and fire system management required • Minimum service requirement due to our IP • Able to operate at high temperature of tropical conditions up to 55 degree Celsius without active cooling

V-Flow batteries outperform in cost and performance

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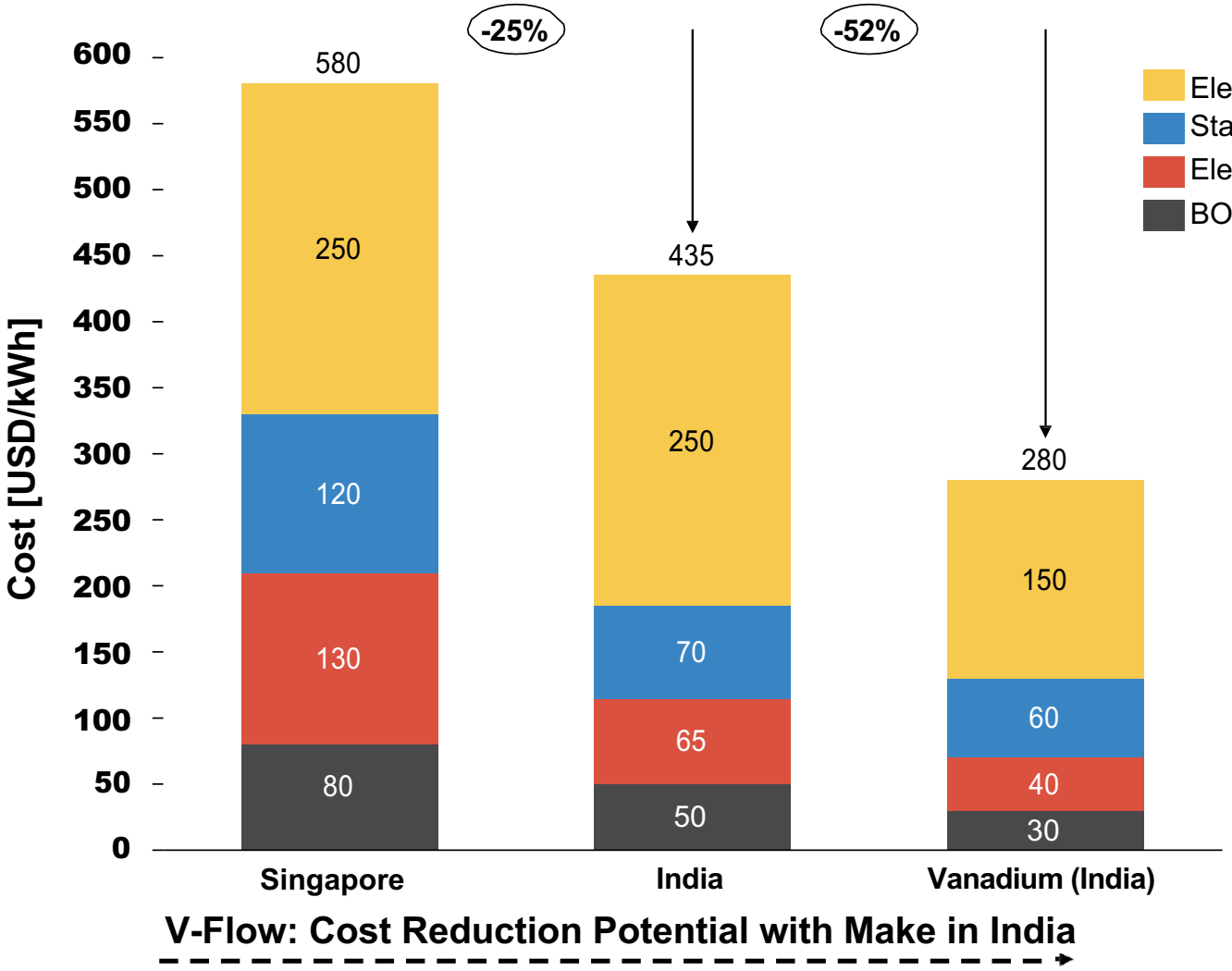
Cost Reduction with Make in India



V-Flow: Cost Reduction Potential with Make in India

- India has ~ 64,000 mT of V_2O_5
- 7 GWH of VRFB battery can be supported.
- Recyclable nature of VRFB battery will allow continuous operation of

GWh of Battery.

https://ibm.gov.in/writereaddata/files/05282015123416Vanadium_2013.pdf

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Pradeep Khanna CEO
ceo@solarinsolar.com
+91 98112 90832