An Industry Perspective on the State-of-the-Art RFBs

DOE OE Energy Storage Peer Review Meeting 2025

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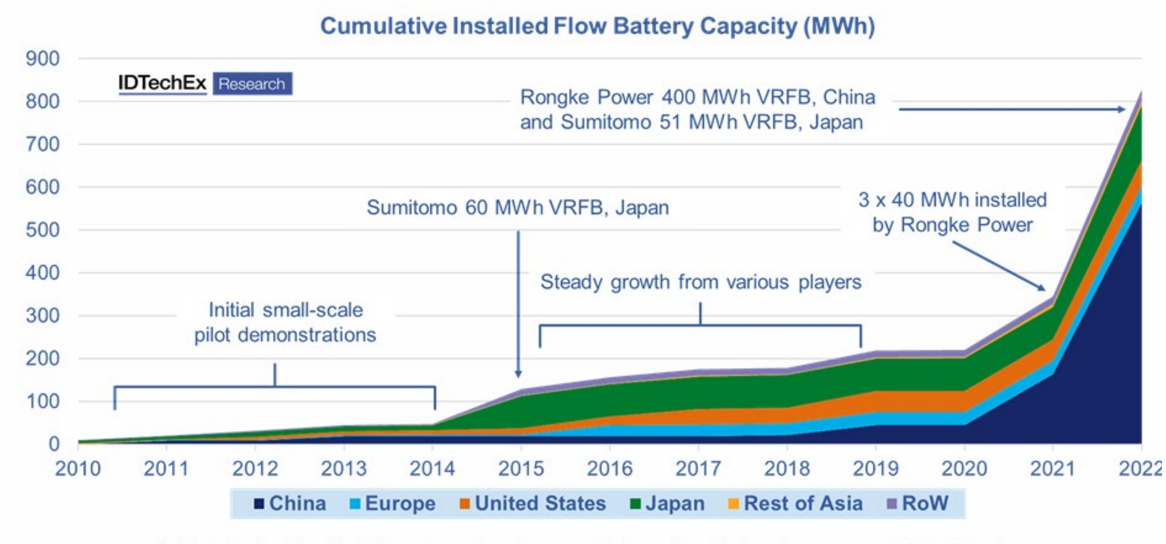
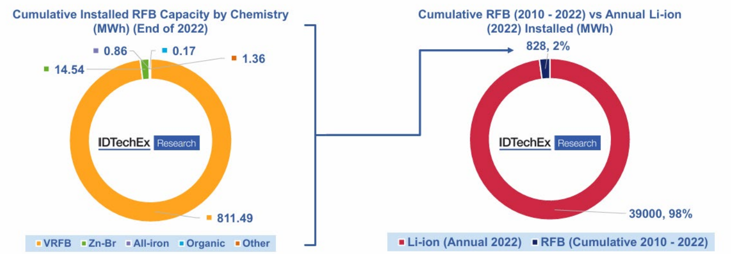
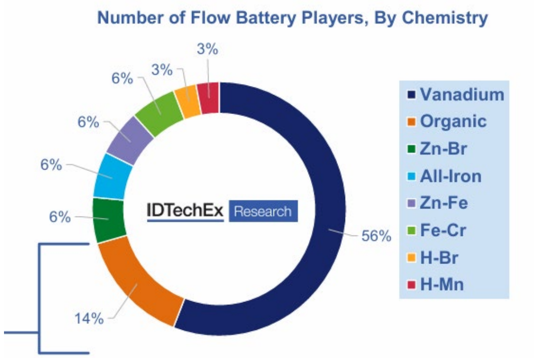
Trends in Flow Battery Markets

Data Presented by IdTechEx at 2025 International Flow Battery Forum, Vienna



(This includes identified FB project data, there are likely unidentified projects, especially in China).

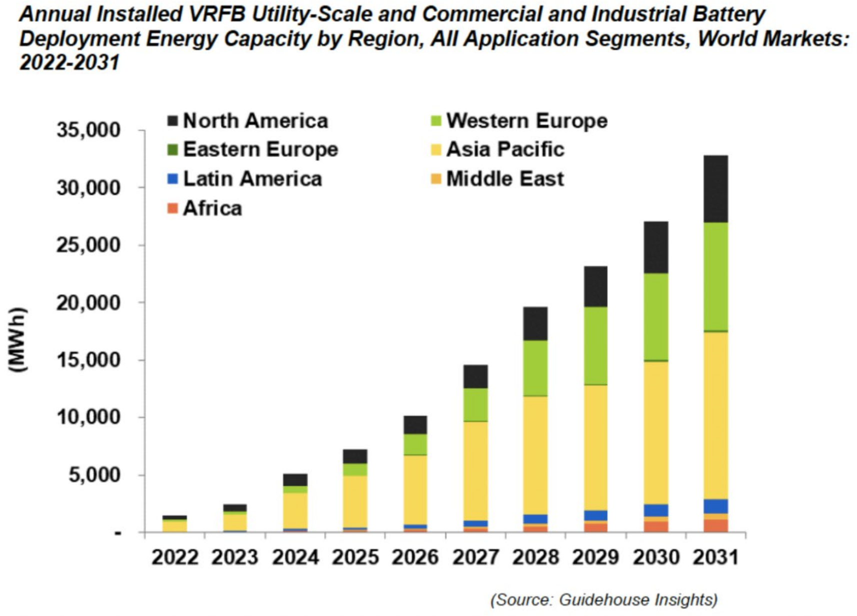




An Acceleration Trend for RFB?

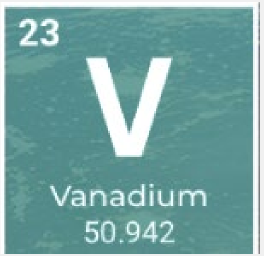
- In the United States
  - TerraFlow Energy Announces 9.6 MW / 5-Hour Vanadium Flow Battery Project in Bellville, Texas – TerraFlow Energy (10MW/50MWh)
  - SRP and CMBlu Energy: Long-Duration Energy Storage Project (5 MW/50 MWh)
- Worldwide
  - Dalian flow battery energy storage station is the largest and most powerful worldwide (200MW/800MWh)
  - Swiss developer breaks ground on 1.6 GWh redox flow storage project – pv magazine International (800MW/1.6GWh)

Guidehouse Research Projections Published on Vanitec Website (2022)



Vanadium is Uniquely Well-Suited for LDES

Earth-Abundant



- Fifth most abundant transition metal in the Earth's crust
- Vanadium reserve base to support > 10 TWh of VFB
- Similar deposit levels to Cu, Ni
  - With lower mining capacity

https://en.wikipedia.org/wiki/Abundance_of_elements_in_Earth%27s_crust
www.doi.org/10.1016/j.jpowsour.2010.08.056

VFBs are Real-World Proven

SUMITOMO ELECTRIC | cellcube | TERRAFLOW ENERGY | INVINITY ENERGY SYSTEMS | H2 | InoHub Energy | VRB ENERGY | RKP

- + 500MWhrs in single installations
- High Response Time
- Unparalleled Lifetime – 20+ Years
- Unmatched Cycling capability (100%DoD with >95% Capacity retention)
- > 99% Operability

www.doi.org/10.1016/j.est.2024.111790
https://pv-magazine-usa.com/2023/07/11/sumitomo-reveals-testing-results-of-redox-flow-battery-project-in-california/,
https://www.ess-news.com/2025/03/03/sumitomo-electric-launches-vanadium-redox-flow-battery-with-30-year-lifespan/

Highly Recyclable

Flexible Options at End of Life (EOL)

- Renew Lease
- Return Electrolyte for Recycling

99+% vanadium recovery at EOL = strong candidate for leasing.

Circular Economy of Lead Batteries - Battery Council International

Wide Ecosystem

Mining and Raw Materials → Components and Sub-Assemblies → VRFB System Manufacturing → Site Design and Integration → Project Development → Service, O&M

Bipolar Plates

Membrane Electrode Assemblies

Electrolyte

High Performance Cell Stacks

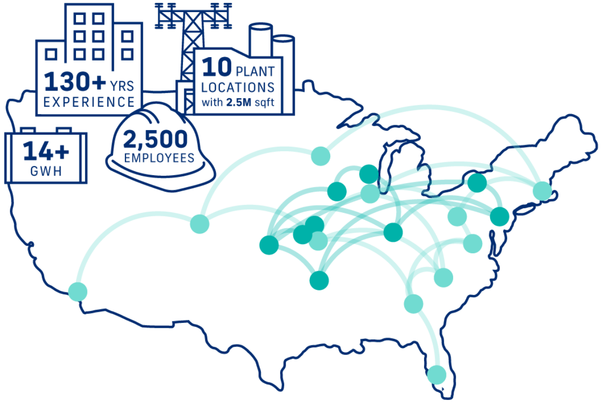
Aim to Copy Lithium BESS Model with Unique Companies Supporting Each Vertical

Who is Storion Energy

Stryten's scaled battery manufacturing expertise, complemented by Largo's direct vanadium supply chain & strong VRFB patent position combine to form Storion Energy

STRYTEN ENERGY

U.S.-Based Energy Storage Manufacturer



Technology agnostic, large-scale manufacturing of the right battery technology and the right cost for each application.

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STORION ENERGY

Established February 2025

LARGO

Vanadium (Critical Mineral) Sourcing, Patented Purification Technology

$160mm (CAD) Market Cap

20 Year Est. Total Mine Life

10,396 Tonnes V_2O_5 Sold in 2023

6.1MWh VRFB Deployment in 2023

Vanadium Electrolyte Production

Historical

70+ Million Liters/ Year of High Purity, Sulfuric Acid Based Electrolyte Produced for Lead Acid Battery Markets

2024

Proprietary Vanadium Electrolyte Manufacturing Developed

Pilot Line Commissioned

MAKEIT Prize Phase 2 Awarded to Scale Production

2025

Rapidly Scale Production Capacity

MAKEIT Prize Supports Production of 50 MWh/year

Scale to Market Demand

Roadmap

Large Scale Commercialization Exceeding Annual Capacity of 1GWhr

SECURING AMERICA'S VANADIUM ELECTROLYTE (SAVES)

AMERICAN MADE

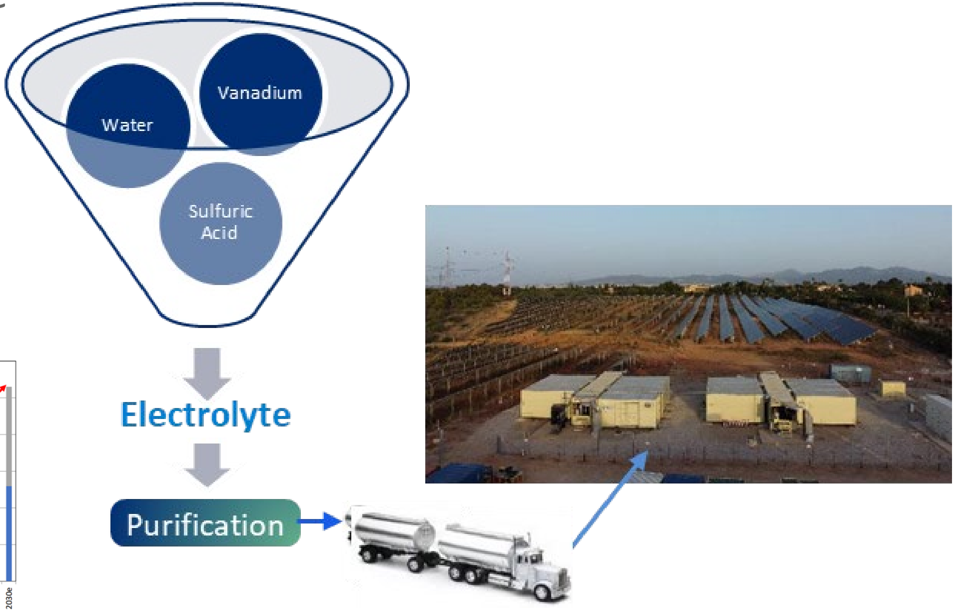
U.S. DEPARTMENT OF ENERGY

[TerraFlow Energy and Storion Energy Sign Agreement to Advance Vanadium Flow Battery Solutions]

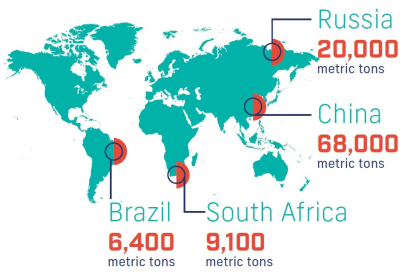
Electrolyte Purification Broadens Available Sources

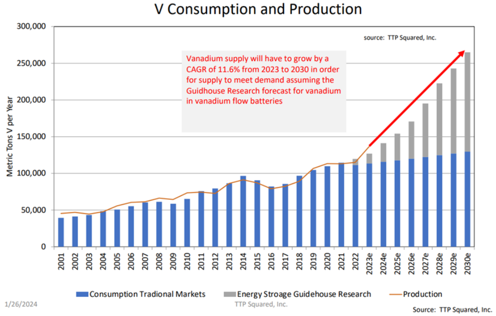
Storion produces some of the purest and most effective vanadium electrolyte

- Our patented purification process is simple and highly effective
  - Enables using lower-purity feedstocks
- Enables 20+ years of operation with no performance degradation



The world's leading vanadium producers include[1]:

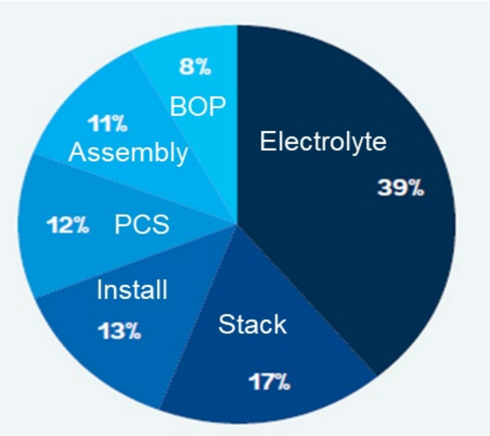




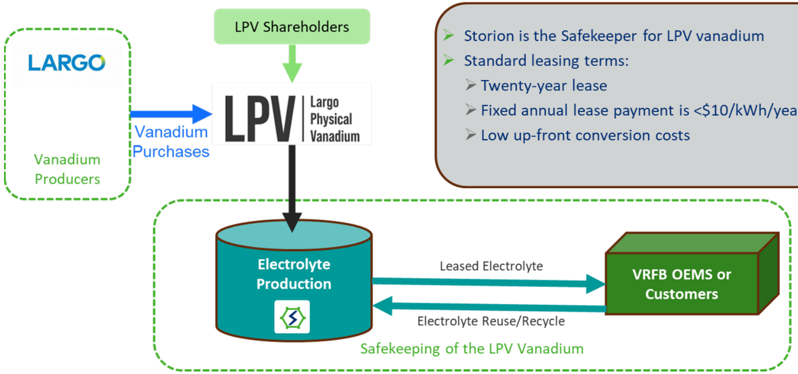
Storion Annotation:
100,000 metric tons V Supports >20 GWh of storage capacity

Leasing Model Solves VRFB Cost-Competitiveness

VRFB Cost Break Down for a 4- to 6-h battery*

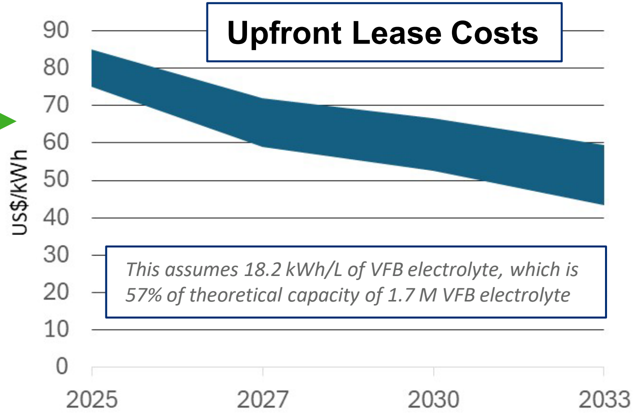


From: World Bank Group, "Vanadium battery storage report," (2024)
*Electrolyte costs can be 40-70% based on duration



- Storion is the Safekeeper for LPV vanadium
- Standard leasing terms:
  - Twenty-year lease
  - Fixed annual lease payment is <$10/kWh/year
  - Low up-front conversion costs

Vanadium Electrolyte Up-Front Costs	
Purchase	Lease
<$200/kWh	<$85/kWh



Key Attributes of VRFBs

Most mature RFB chemistry, due to multiple inherent attractive attributes:

- Single species enables simple crossover-mitigation strategies
- Excellent stability of active materials
  - No capacity losses due to V-species degradation within controlled temperature range
- Relatively facile redox kinetics on carbon electrodes
- OCV is ≈ 1.55 V (at conventional V concentrations)
  - Located in aqueous-stability window (minimal HER)
- Decent solubility (≈ 1.6 M)
  - Theoretical energy density of ≈ 30 Wh/L
- Unlimited electrolyte recyclability
  - Reuse in VRFBs, or convert back to commodity product (*e.g.*, V2O5)

VRFB SOA

- System
  - Proven technology
  - Capital Cost is the primary barrier
- Stacks
  - Large stacks w/ high power densities
    - ASR < 0.5 Ohm-cm^2
- Electrolyte
  - Continuous production processes are being scaled
  - Innovative leasing models available
    - Price ≤ $75/kWh
- BOP
  - Simplest known RFB system

Future Opportunities

- Systems
  - Building vs. containerized
- Stacks
  - Even higher power densities
  - Lower-cost membranes
- Electrolyte
  - Improved active-material utilization
  - Expanded operating temperature window
  - Densification for reduced shipping costs
- BOP
  - Improved SOC and [V] measurements
  - Improved shunt-mitigation options
- Durability
  - Demonstrate exceptional lifetimes
  - Advanced Diagnostics

Active Material Utilization in RFBs

- Utilization is poor relative to conventional batteries
  - Primarily due to low Energy Efficiency (EE)
- Improvement here can be very valuable
  - Assume Active Material Utilization may be improved by > 10%, then:
    - Reduce Electrolyte Capital Cost by > 10%
    - Reduce size of Electrolyte Tanks by > 10%
    - Improve operating costs (due to higher EE)

Parameter	SOA RFB *	Proposed RFB Targets	Li-Ion
EE (AC/AC)	65%	70 to 75%	85 to 90%
SOC Range	80%	90%	80%
Active Material Utilization	**52%**	**63 to 68%**	**68 to 72%**

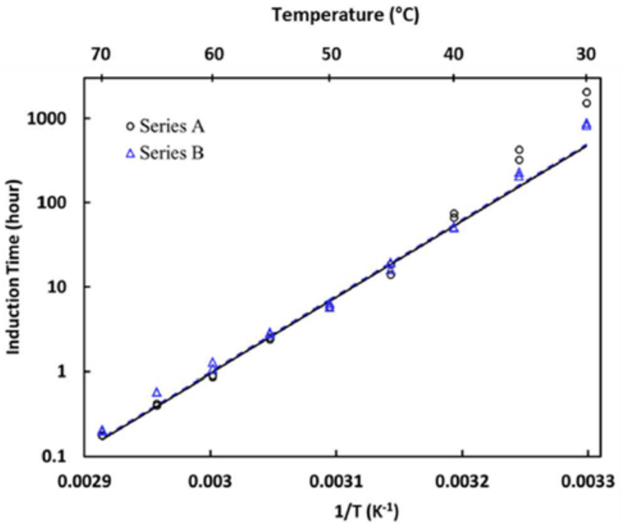
* Values from PNNL's: "Energy Storage Grand Challenge Cost and Performance Assessment 2022"

Limited VRFB operating temperature (typically ≤ 50 C)

- Due to "thermal precipitation" of V2O5 due to this equilibrium reaction:

  (VO2)2SO4 + H2O ↔ V2O5 + H2SO4

- Conventional [V] in VRFB electrolyte is 1.6 to 1.8 M
  - Maximum SOC is typically < 90%
    - Therefore, max [V(V)] ≈ 1.4 M to 1.6 M
  - Stability is ≈ 1,000 h at < 30 C
- This limited operating temperature adds cost to the VRFB thermal-management system (TMS)
  - And, adds substantial system complexity as well as reduced reliability, if active TMS is required



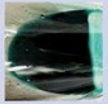
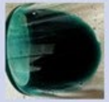
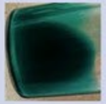
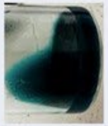
	Concentration (mol dm^{-3})	
Species	Series A	Series B
Vanadium	1.601	1.600
Sulphate	4.147	4.165

** Figures copied from: Andrea Bourke et al, "Review – Electrode Kinetics and Electrolyte Stability in VRFBs," J. Electrochem. Soc.* ***170*** *(2023).*

VRFB Electrolyte Densification (Demonstrated at lab-scale)

- VRFB electrolytes can be densified and precipitated into a solid form that can be quickly re-dissolved
  - Solids are low-crystallinity V salts
- The controlling variables are the densified or oversaturation level, the amount or density and type of the nucleation materials used, and the mixing time needed to allow the gel network to form
  - Nucleation material can be low-crystallinity V salts
- **This process can potentially enable substantial savings in electrolyte shipping cost**

Densification Level = 51.5% = (V of removed water) / (V of total electrolyte)

Nucleation Density (mg/mL)	1	1	1	10	10	10	10
Mixing Time (hr)	1	1.5	2	0.5	1	1.5	2
After Stirring							
Overnight Storage							

Y. Li, S. T. Mouron, M. L. Perry, and T. V. Nguyen (Kansas University), "Vanadium Electrolyte Densification and Gel Formation Process," *Ind. Eng. Chem. Res.*, **62** (2023). This work was part of ongoing AMMTO project.

DOE AMMTO Project

Focused on developing five new manufacturing processes for Stacks & Electrolyte

- Three new RFB Stack-assembly processes (both stack components & complete cell stacks)
- Two new RFB Electrolyte-production processes

	Process	Current SOA	Key Innovations	Major Benefits
Cell Stack	Unitized Electrode Assembly (UEA)	Manual lamination of discrete sheets	High-volume conversion process w/ more automation	Reduce UEA cost; improve quality
	Bipolar Plate & Frame Assembly (BPFA)	Manual integration of seal and plastic frame	Overmolding of seal onto the plastic picture frames	Reduce BPFA cost; improve integration
	Cell Stack Assembly (CSA)	Manual layering of UEAs and BPFAs	Automation of key stack assembly processes	Reduce cost and improve quality
Electrolyte	Electrolyte Purification Process (EPP)	Complex processes that are not effective	Novel and simple electro-chemical process	Reduce cost & waste; improve quality
	Electrolyte Densification for Shipping Process (EDSP)	Liquid electrolyte is shipped in totes	Novel processes to form gel and ship inside tanks	Reduce shipping costs & required onsite work

All of these improved processes could also potentially be used to produce non-V RFB Systems

Summary

- VRFBs are the most mature RFB systems
  - The simplest known RFB technology with many attractive attributes
  - Proven real-world lifetime (project system lifetimes of > 20-years)

- *Storion Energy* is focused on being an exceptional RFB-component supplier
  - Initially focus: *high-purity VRFB electrolyte* & *high-performance RFB stacks* at *unmatched prices*, enabled by:
    - Innovative business models (*e.g.*, leased electrolyte with V owned by LPV),
    - Manufacturing efficiency (*e.g.*, continuous electrolyte production with low-cost feedstock)
    - Advanced technology (*e.g.*, high-performance cell stacks, and simple electrolyte purification)
    - Continuous future improvements resulting from economies-of-scale and ongoing R&D

- Rich set of RFB improvements are possible, even with VRFBs
  - *Storion Energy* can provide DOE with guidance on potential topics & key metrics for future *competitive solicitations*

Questions?

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- DOE "Manufacture of Advanced Key Energy Infrastructure Technologies (MAKE IT) Prize