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Vanadium Redox Flow Batteries

Technology and Market Maturity

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Summary

- There are only a few real competitors in the VRFB space; the rest can be considered startups still working with prototypes
- The VRFB market in the U.S. is practically non-existent, with a few one-off demonstrations mostly funded by DOE
- Low costs of energy in much of the U.S. inhibits sales of energy storage in general
- VRFB technology has remained mostly static over the past 15 years
  - Shows that many parts of the technology may already be at their technological limits
  - Cost reduction opportunities reside mainly in the stack components and the electrolyte
- 25–30-year ROI doesn't seem to be a compelling selling point
- Consider alternative business models
  - Leasing systems/electrolyte
  - Partnership with an energy developer (e.g. Agilitas Energy)
  - Energy Savings Performance Contracting

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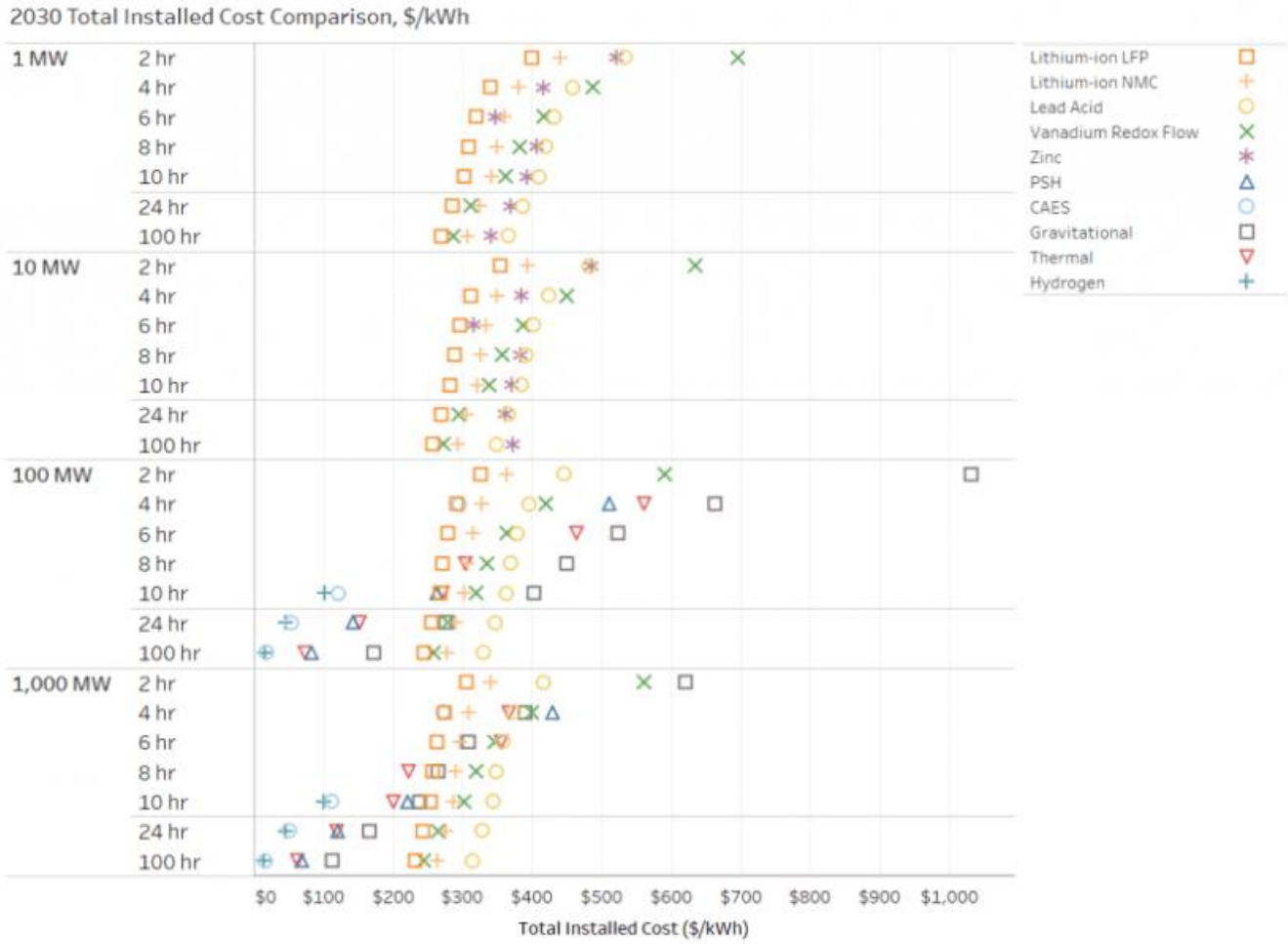
Grid Energy Storage Cost Assessment

- DOE assessment from the Energy Storage Grand Challenge program
- VRFB compares favorably with Li-ion on long duration storage; is much more expensive for short (<4hr) storage durations
- Most VRFBs are built in 1:2 up to 1:4 ratios of power to energy; this study suggests they should be 1:24 up to 1:100 to be cost comparable to Li-ion
- Lowest cost-to-energy ratios for all battery systems occurs at 10-hour capacity
  - At lower durations cycle life limitations necessitate frequent augmentation or replacement
  - At higher durations, the number of cycles per day is reduced

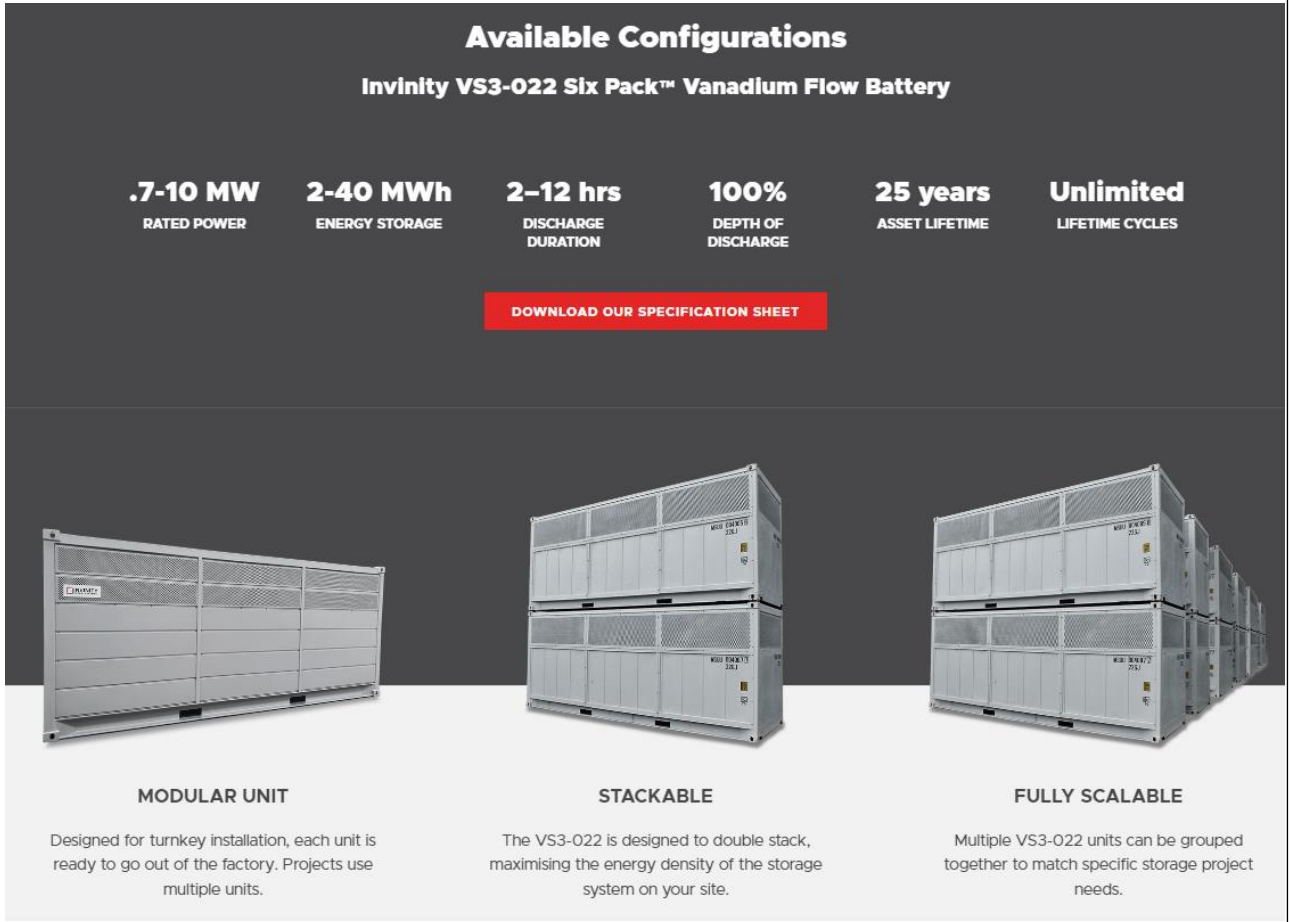


Cellcube (Enerox GMBH) -- Leader

- Enerox is an Austrian company that acquired the former assets of Gildemeister GMBH, which was the original acquirer of Cellstrom , co-founded by Martha Schreiber.
- Likely the most mature of all VRFB companies, has manufacturing and actual products, with 140+ deployments on six continents
- Manufactures three standard products of either 1:4 or 1:8 power to energy ratios, each scalable in blocks
  - 500kW – 2Mwh
  - 250kW – 1Mwh
  - 250kW – 2Mwh
- Acquired Pure Vanadium Corp in 2018 – Electrolyte producer
- Acquired EnerCube Switchgear Systems in 2018 – Power control systems manufacturer
- Partnered with Australian company in Dec 2022 to build manufacturing and assembly line in Australia
- Partnered in July 2022 with G&W Electric to support microgrid in Illinois within PJM for demand response and peak load reductions
- Partnered in Feb 2022 with U.S. Vanadium for electrolyte
- Offers 20-year performance guarantee backed by Munich Re
- Has a sales office in Denver
- American Vanadium of Canada is the master sales agent in North America

Invinity Energy Systems -- Leader

- Formerly redT Energy, completed merger with Avalon Battery in 2020 in rare VRFB industry consolidation
- Based in Windsor England, listed on the London Stock Exchange
- Currently the only head-to-head competitor to CellCube in the VRFB space
- Claims over 65MWh of installed capacity worldwide
- Utilizes Jabil as their manufacturer, assembly in Edinburgh Scotland
- Patent for "Means for maintaining desired liquid levels between inter-connected tanks"
- Marketing focus is for Utility-grade Energy Storage; secondary is a more cost efficient over 25+ years over LI-on
- Builds one base unit that is stackable and scalable
  - .78MW / 230kWh power/capacity
- DC round trip efficiency of 75%

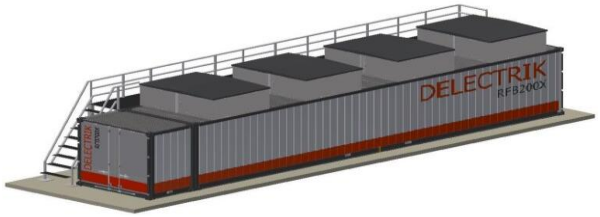


VRB Energy -- Contender

- Canadian company, formerly Pu Neng, formerly Prudent Energy who acquired patents from VRB Power Systems Inc, now a subsidiary of Ivanhoe Electric, part of the I-Pulse group
- VRB Power Systems did some of the initial commercialization patents in VRFB technology but was unable to find a market.
- Prudent Energy acquired the patents and only found success by moving to China to work with State Grid Corp of China
- VRB's most recent product announcements have been custom projects in China including a 100MW / 500 MWh VRFB integrated with a 100MW solar farm
- Marketing focus in large scale storage utilizing Chinese manufacturing and vanadium sourcing to reduce system costs
- Has 2 patent grants in last five years
- Integrated system for electrochemical energy storage system
- Systems and methods for assembling redox flow battery reactor cells
- Markets 250kw and 500kw containerized building blocks in 4-, 6-, and 8-hour configurations scaled from 1MWh to 200MWh
- Claims 40MWh deployed, 750MWh in projects under development, primarily focused in 8-hour duration systems

Delectrik Systems - Contender

- India-based company, founded in 2016 by former Imergy/Deeya Energy senior director
- Produces 10kW/40kWh system for small-scale stationary applications
- Announced start of commercial production of 40kW/200kWh containerized system in Jan 2023
  - Plans first deployments in U.S. and Australia
- Claims 70-75% DC-DC efficiency at -5° to 50° ambient temperatures
- Partnered with Tdafoq Energy in Saudi Arabia
  - Exclusive sales rights in GCC region
  - Building a factory for Delectrick manufacturing in GCC



RFB200X is a MWh scale system for use in medium to large scale Commercial and Industrial applications .

RFB200X System Specification						
Model	S1	S2	S3	S4	S5	S5N
No of RFB200 Units	1	2	3	4	5	N*5
Discharge Power (kW)	40	80	120	160	200	200*N
Output Capacity (kWh)	200	400	600	800	1000	1000*N
Voltage BOD to TOC (V)[a]	40-60	80-120	120-180	160-240	200-300	200-300
Charge Power (kW)	40	80	120	160	200	200*N
Charging Mode CC/CV	800/60	800/120	800/180	800/240	800/300	800*N/300
DOD	100%					
Cycle Life	Unlimited					
DC-DC Efficiency	70% - 75%					
Ambient Temperature	-5°C – 50°C					
Remote Monitoring	GPRS – RS232					
Remote Setting	SMS					
Programmable Relay	2					
Auto Restart	Auto-Start Feature for both AC/DC coupled system					
Integration with PV/Grid	Provision for both AC/DC coupled system					
Enclosure[b]	Outdoor Container, IP54					
Footprint[c]	8 m^2 x N					
Total Weight	15000 Kg x N					

CC – Constant Current CV – Constant Voltage
BOD – Bottom of Discharge TOC – Top of Charge

a – Higher DC Voltage (500 – 1000V) option available for direct integration to Solar DC. 400V/3Ph AC optional available with Bidirectional Inverter for AC coupling.
b – System assmebled in standard 10/20/40 feet shipping containers.
c – 40 m2 per MWh. Containers can be placed adjacent to each other for compact layout

StorEn Technologies -- Startup

- Early-stage startup out of Stony Brook University Clean Energy Business Incubator Program
  - Moved to Greenville S.C.
- Three full time employees as of end of 2021; more listed on website
- Currently crowdfunding via Start Engine @ $7.33 per share; raised $10M previously
- MOU with Multicom Resources, an Australian mining company, for Vanadium Pentoxide
- MOU with Freedom Energy PTY Limited, a subsidiary of Multicom to sell and distribute VRFB in Asia-Pacific region
  - Purchased 3 residential VRFBs for $500k total + 125k shares
  - One installed at National Battery Testing Centre in Brisbane
  - Multicom has completed concept design for full-scale manufacturing facility
- Has received an order for a battery to Canada
- Launched R&D program, TitanStackTM to develop larger battery stack
- Has four patent applications:
  - Multigrids™: stack fluid dynamic to improve electrical performance and deliver higher power density
  - Thermastable™: underground battery installation design
  - Equilevels™: electrolyte rebalancing method
  - Resafe™: leak control system
- Initial market focus is residential, telecoms, and microgrids
- CEO John Davis is a Clemson grad, likely explaining the Greenville move.
- Had 3 open engineering positions: mechanical, electrical, battery systems (applications are closed as of 3/29/23)

WattJoule - Startup

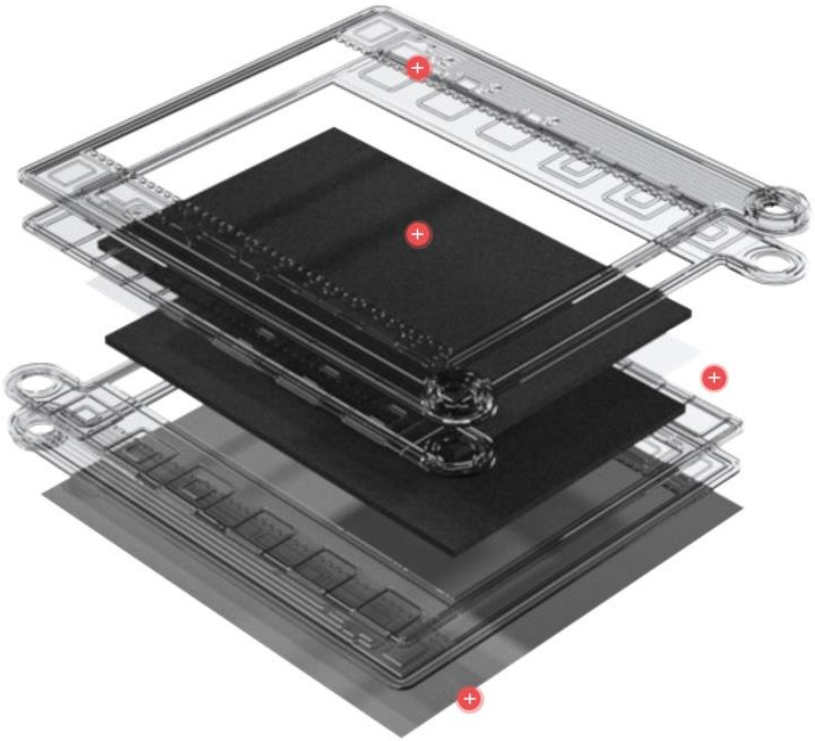
- Massachusetts – based company with Dr. Thomas Zawodzinski, famed fuel cell expert at ORNL, is a technical advisor
- Licensee of University of Tennessee Research Foundation IP for VRFB developed through DOE funding resources
- Claims include improved electrolyte density, and greater power density per cm2 than industry
- Makes sulfate and chloride-based electrolytes (using PNNL license)
- Last press release was in 2019

Cost & Performance Metrics	Competitive Vanadium Benchmark	WattJoule Gen 1 2020	WattJoule Gen 2 2025	WattJoule Gen 3 2030
Electrolyte Energy Density (Wh/l)	12	25	50	100
Stack Max Power Density (mW/cm^2)	300	1500	1900	2500
Electrolyte Temperature Range (°C)	+10 to +40	-40 to +70	-40 to +70	-40 to +80
DC Roundtrip Efficiency (%)	65-75	80-90	85-92	90-95
Vanadium Utilization (kWh/MT)	86	137	250	TBD
Vanadium Electrolyte Cost ($/kWh)[1]	170	105	70	TBD
DC System Capital Cost ($/kWh)	600	200	150	100

[1] Cost based on the historical average price of V205

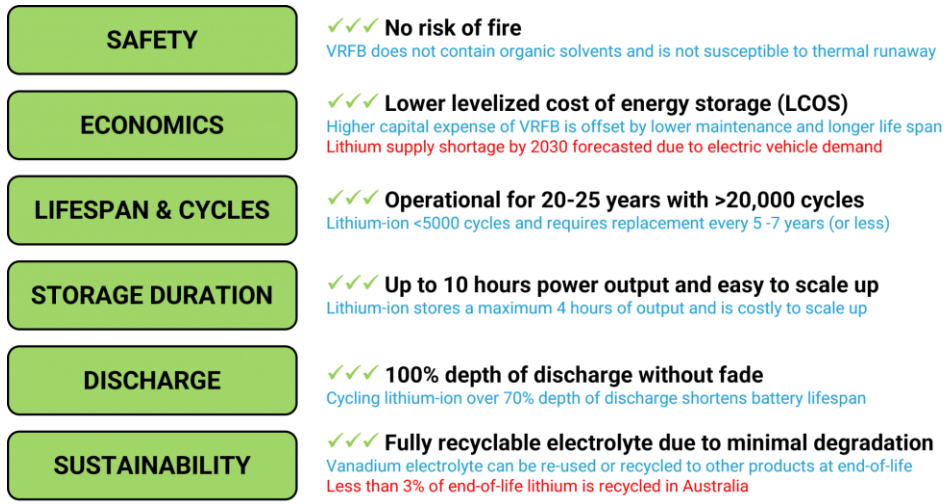
VoltStorage -- Startup

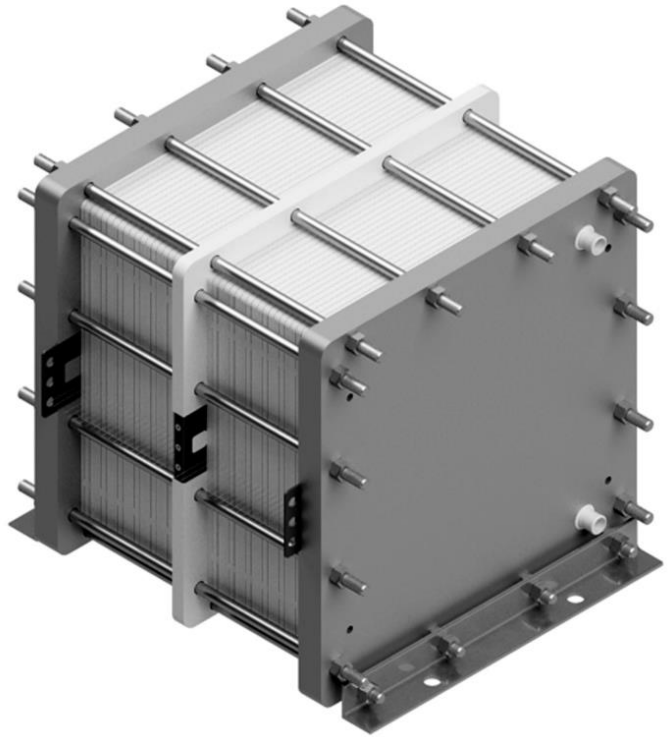
- German company, currently in Series C funding
- Latest funding round Series C of $24.29M from U.S.-based Cummins
- Focus is on lithium-free energy storage technologies including VRFB, and Iron-Salt redox flow
- Main market focus is peak load reduction
- Awarded licenses in early Jan 2023 to install 3 batteries in Greece of a total of 156MW of injection capacity
- Has 1 patent for cell and cell stack producing methods
  - They have a cell frame with electrolyte channels to provide uniform supply of electrolyte into the cell
  - Additionally, they over-mold the cell stack with liquid plastic to prevent leakage



AVESS and KORID Energy -- Startup

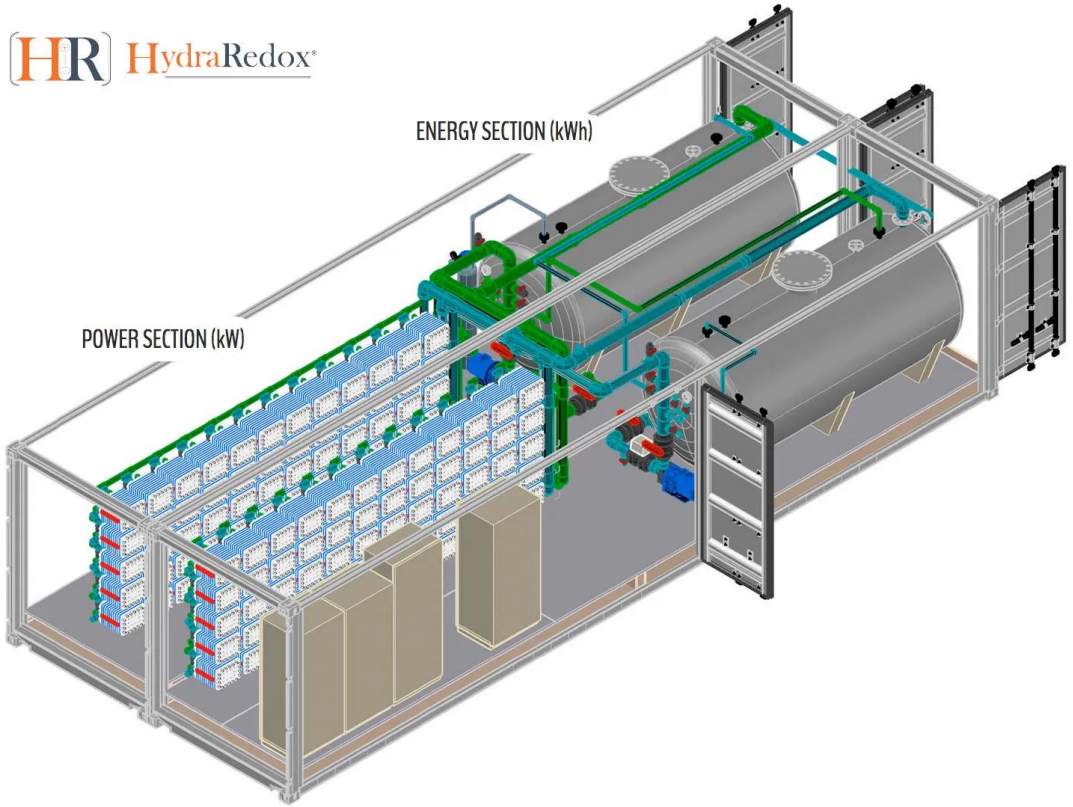
- Australian – Korean partnership with Maria Skyllas-Kazacos as a consultant
- In the prototype building stage
- KORID Energy makes battery cell stacks from 5kW to 50kW
- Produces cell frames using an injection molding process (however, they still bolt the stack together old school style)





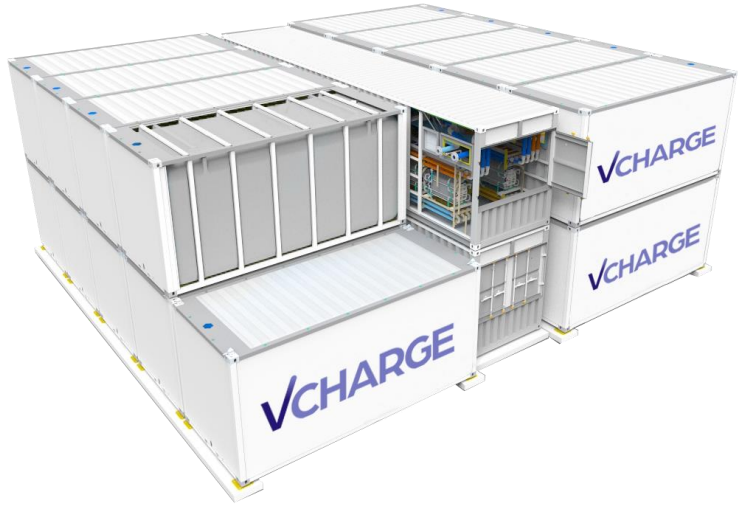
HydraRedox -- Startup

- Spanish company with a UK office
- Claim to have a proprietary "single cell" design where each cell operates independently
  - BMS monitors each cell
- Utilizing a vanadium concentration of 1.5 – 2.0 mol/L, which is a general limit without the use of additives
  - Higher mol/L concentrations lead to precipitate formation within the carbon felt cell layers, reducing flow rates and resulting in more frequent cell maintenance requirements
- Marketing focus is telecommunications and microgrids
- Received a previous 1.7M euro grant from the EU Horizon 2020 program



Largo Clean Energy -- Startup

- Canadian mining company, publicly traded
- Operates a large Vanadium mine in Brazil
- Volume manufacturer of Vanadium Pentoxide (V_2O_5) (base chemical in VRFB electrolytes) in flake and powder form
- Building Massachusetts factory to produce VRFB electrolyte and energy storage systems
- Has two VRFB installations
  - Solar panel integration project in Spain to deliver 6.1MWh for peak shifting of solar generation
  - Took over 3MWh VionX Energy VRFB at a solar site and completed grid interconnection with National Grid
- Claimed market differentiators
  - Proprietary and patented VRFB electrolyte processing technology
  - Utilization of industry-leading battery stack technology
  - Unrivaled supply of high-purity vanadium products (via Largo Physical Vanadium business)



VFlowTech -- Startup

- Singapore-based
- Recently raised $10M Series A funding
- Partnered with Sing Fuels to sell and distribute utility-scale VRFBs in Africa
- Peter Ridley, formerly of Red-T (now Invinity) is a technical advisor
- Has three products (unknown if they are all manufactured at this time):
  - 5kW / 30kWh for residential, solar, telecom
  - 10kW / 100kWh for EV charging, off-grid, corporate and industrial
  - 100kW/500kWh for grid balancing, EV charging, solar and wind farms
- Claims up to 80% roundtrip efficiency and operation up to 55°C without active cooling
  - Note: 55°C is well above standard industry limitations of 40°C top operating temperature environment
  - Using additives in increase operating temperature window
- Claims LCOS as low as $0.10 per kWh
- Claims 25% higher energy density due to higher solubility of vanadium in their electrolyte

Ashlawn Energy – Dormant?

- VanCharg™ battery system
- Based in Binghamton, NY; may be HQ in Springfield VA
- One reported funding round: incubator/accelerator (amount unknown)
- Marketing focus is on CO^2 emission reductions to help building owners in NYC comply with NYC Local Law 97
  - Creates carbon caps for buildings greater than 25ksf
  - Multi-family residential, commercial office, small industrial buildings
  - Also markets reduction to utility demand charges (charge off-peak, discharge during peak)
- One patent granted; 4 others abandoned
  - Granted: Storage tanks using super ellipse geometries
  - Abandoned: Gravity fee flow battery system and method
  - Abandoned: Polarity switching flow battery system and method
  - Abandoned: Pressure feed flow battery system and method
  - Abandoned: …sequencings for multiple electrolyte storage tanks in a redox flow battery
- One reported project: USAF Phase I SBIR for forward-deployed operations
- Part of DOE Smart Grid demonstration program in 2012
  - Painesville OH 8MWh redox flow battery at municipal electric plant to supplement steady state coal generation plant
- May be dormant

Vanadis / UniEnergy Technologies – Dormant?

- Partner companies founded by Dr. Z. Gary Yang, formerly of PNNL and Rick Winter, formerly of Imergy/Deeya Energy and Primus Power
  - Dr. Yang focused research on electrolyte chemistries to overcome temp operating ranges and to increase vanadium content in chemistry
  - UniEnergy Technologies was founded in Seattle
  - Vanadis was founded in Europe
- Vanadis is partnered with Rongke Power, who is/was their manufacturer
- Builds a single 10kW/40kWh 48V module block
  - Up to 25 can be connected in series to meet higher voltage requirements
  - Multiple series can be connected in parallel to provide higher power and/or capacity needs
- Also partnered with Bolong New Materials for electrolyte production
- Partnered with Chemours to produce Nafion™ membranes
- Vanidis ReFlex™ uses a chloride-based rather than a sulfate-based chemistry in an effort to increase temperature operating range and reduce precipitates formation
- Claims over 70 patents
- Marketing focus appears to be China, Australia, and South-East Asia
- UniEnergy Technologies went bankrupt in Oct 2021
- No news on Vanadis since 2020

Considerations for Go-To-Market on VRFB

- Target cost per kWh: manufactured price, sales price, profit margin
  - Active components (i.e. cell stack, BMS, Power management) are most likely targets for cost reductions through innovation
  - Passive components already commoditized so price reductions likely only for volume buying or partnerships
- Levelized cost of system per kWh
  - Current systems claim $0.10kWh but that's over 25-30 years
- DC-to-DC round trip efficiency needs to consistently reach 85%+
- AC balance-of-plant overhead must be considered in use cases
- ROI considerations
  - Most competitors market 25–30-year system lifespan to match solar/wind lifespans
  - Electrolyte has potential 25–30-year lifespan, assuming you don't burn it up through over-volted charging
  - Cell stack materials have5-10-year lifespan or sooner due to precipitate formations, carbon catalyst reductions
  - Pumps usually have a 5-year warranty
  - Electronics have 5–10-year lifespans
  - Most of the balance-of-plant would need to be replaced once or twice in a 25-year lifespan
- Where are the best use cases for a VRFB?
  - Renewables storage
  - Peak shaving / demand response (in very high-cost utility markets)
  - Frequency regulation
  - Demand charge / power factor correction

Technical Innovation Topics

- Separation of charged electrolyte from uncharged
- Differential flow vs. parallel flow rates – to reduce Vanadium ion membrane migration
- Stack flow vs. cell flow – increase charge and discharge rates
- Charging algorithms
- Increasing current per mm^2 of cell surface layer
- Increasing columbic efficiency
- Bipolar plate efficiency increases due to material selection
- Poured membranes vs. off-the-shelf membranes (methods to get greater permselectivity)
- Using nanoparticles to create carbon catalyst felts
- Capillary cell flow vs. free cell flow
- Increasing Vanadium concentrations without increasing precipitates formation
- Power electronics / BMS

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