New Generation VRFB for Electrical Grid and Utility Applications

Z. Gary Yang

Outlines

- Introduction of UET
- Discuss RFB and VRFB in particular
- Journey of commercialization: From molecules to MW
- Status and challenges
- RD&D needs
- Acknowledgements
Mission: Be a major global provider of bulk energy storage products through Innovation + Partnerships + Quality

We are accomplishing this by commercializing break-through vanadium redox flow batteries with:

- High performance electrolytes & electrode stacks
- Industrial engineering of fully integrated system products
- State-of-the-art controls & power electronics
- Value-added field services
NEW ELECTROLYTE
✓ 2X energy density
✓ -40°C to +50°C
✓ Improved reliability

ELECTROLYTE PRODUCTION
✓ 1,324,000 ft² production facilities
✓ Electrolyte production capacity > 1.5GWh/year
✓ ISO9001:2008 Certified

PRODUCT ENGINEERING AND MANUFACTURING
67,000ft² design, development & manufacturing facility in Seattle

STACK PRODUCTION
✓ 108,000 ft² manufacturing facility
✓ 100MW production capacity (scale up 300MW in 2016)
✓ ISO9000/14000, GB/T28001 Certified

FIELD EXPERIENCE
✓ 5MW/10MWh wind firming installation
✓ Numerous MW-class micro-grid sites

Vanadis Power GMBH
Field engineering, installation, service, marketing, sales in Europe

$250M Invested in UET’s DNA & Corporate Group
Broad Partnerships and Manufacturing Chain

Materials
- Vanadium
- Electrolyte
- Carbon felt
- Membranes
- Compatible Plastics
- Tanks
- Manifolds

Components
- Stacks
- Pumps
- Containers
- Manifolds

Development
- E’lyte Development
- Optimized Conditions
- Power Density & Efficiency
- Chemical Utilization
- Control Methodology

Engineering
- Engineering Prototypes
- Fluid & Thermo dynamics
- Thermo Dynamics
- Design for Manufacture
- Design for Serviceability

Control
- Power Electronics
- Battery Management
- Site Controller
- Application Algorithms
- Data Storage & Analysis

Manufacturing
- Business Process Software
- Quality Supply Chain
- Just in Time logistics
- Lean Manufacturing
- Quality Control & ISO9001
Delivering MW Scale Uni.System™

- Modular, highly integrated, containerized, plug & play

0.5MW; 2.0MWh

Ribbon-cutting with Governor Jay Inslee and Madam Secretary Pat Hoffman on July 8, 2014

Safe, Reliable, Flexible, Affordable
Performance Validation

- 180MWh Dispatched into local grid, analyzed with OSI Coresight™
- 3rd party validation testing from
  - Storage Industry Expert
  - Sandia National Labs

<table>
<thead>
<tr>
<th>2015 Uni.System.AC™</th>
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<tbody>
<tr>
<td>Peak Power</td>
<td>600 kW&lt;sub&gt;AC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Maximum Energy</td>
<td>2.2 MWh&lt;sub&gt;AC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Discharge time</td>
<td>2 h</td>
</tr>
<tr>
<td>Power</td>
<td>600 kW&lt;sub&gt;AC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Efficiency</td>
<td>DC &gt;80%; AC system 70%</td>
</tr>
<tr>
<td>Voltage</td>
<td>12.47kV +/- 10%</td>
</tr>
<tr>
<td>Current THD (IEEE 519)</td>
<td>&lt;5%THD</td>
</tr>
<tr>
<td>Response Time</td>
<td>&lt;100ms</td>
</tr>
<tr>
<td>Reactive Power</td>
<td>+/- 450kVAR</td>
</tr>
<tr>
<td>Humidity</td>
<td>95%RH noncondensing</td>
</tr>
<tr>
<td>Footprint</td>
<td>820 ft&lt;sup&gt;2&lt;/sup&gt;</td>
</tr>
<tr>
<td>Envelope</td>
<td>41’W x 20’D x 9.5’H</td>
</tr>
<tr>
<td>Total Weight</td>
<td>170,000 kg</td>
</tr>
<tr>
<td>Cycle and Design Life</td>
<td>Unlimited cycles over 20 year life</td>
</tr>
<tr>
<td>Ambient Temp.</td>
<td>-40ºC to 50ºC (-40ºF to 122ºF)</td>
</tr>
<tr>
<td>Self Discharge</td>
<td>Max capacity loss: &lt;2%</td>
</tr>
</tbody>
</table>
Deployment and Application Partners

1MW/3.2MWh, substation, Shifting, voltage control, islanding, grid flexibility

600kW/2 hour, demand shifting, load firming for a COGEN unit

2MW/6.4MWh, substation, flexible capacity, T&D support, etc.

250kW/1MWh, wind firming
Redox Flow Battery (RFB) – Reversible Fuel Cell

- **Decoupling of power (kW) and energy (kWh)**
  - power (kW) determined by cell stacks
  - energy (kWh) determined electrolytes

- **“Inert” electrodes** – no structural change, stress buildup or undesirable reactions with electrolytes, e.g., SEI layer in Li-ion
  - Potential long cycle life independent of SOC/DOD
  - High electrolyte utilization (0-100%SOC)

- **Storing large amounts of power (MW) for hours (MWh)** - significantly simpler in a RFB with large tanks than actively managing the SOCs of thousands of static batteries

<table>
<thead>
<tr>
<th>Devices</th>
<th>Sites of reactants/products</th>
<th>Electrolyte conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow battery</td>
<td>Liquid electrolytes in tanks</td>
<td>Liquids flowing through cells</td>
</tr>
<tr>
<td>Static battery</td>
<td>Active materials in electrodes</td>
<td>Static and held within cells</td>
</tr>
<tr>
<td>Fuel cell</td>
<td>Gaseous or liquid fuel plus air</td>
<td>Solid polymer/ceramics within cells</td>
</tr>
</tbody>
</table>

October 22, 2014
Vanadium RFB or VRFB of Best Electrochemical Activity

- Various redox couples have been developed
- Dominated by aqueous supporting electrolytes, $\text{SO}_4^{2-}$, $\text{Cl}^-$, $\text{Br}^-$, ...
- A few non-aqueous electro-chemistries explored

![Graph showing standard potential (V) of redox couples]
Traditional VRFB

- **Cathode:** $\text{V}^{5+}$, $\text{V}^{4+}$, $\text{V}^{3+}$, $\text{V}^{2+}$

- **Anode:** $\text{V}^{2+}$

- **Cell:** $\text{E}_0 = 1.26 \text{ V}$

- **Benefits:**
  - Same element (V) both sides, mitigating cross-contamination
  - Excellent reversibility - unlimited cycle life, (270,000 deep cycles demonstrated)
  - Unmatched safety – aqueous, fire extinguishing electrolytes; room temperature operation; no thermal run away
  - Fully recyclable of vanadium electrolytes

- **But:**
  - Low energy density, large foot print, etc.
  - Limited chemical stability to operate between 10-35°C
  - Engineering must be improved to lower maintenance

**Chemical Equations:**

- Cathode: $\text{VO}_2^+ + 2\text{H}^+ + \text{e}^- \overset{\text{Discharge}}{\longrightarrow} \text{VO}^{2+} + \text{H}_2\text{O}$
- Anode: $\text{V}^{2+} - \text{e}^- \overset{\text{Discharge}}{\longrightarrow} \text{V}^{3+}$
- Cell: $\text{VO}_2^+ + \text{V}^{2+} + 2\text{H}^+ \overset{\text{Discharge}}{\longrightarrow} \text{VO}^{2+} + \text{V}^{3+} + \text{H}_2\text{O}$ $E_0=1.26 \text{ V}$
Developed at and licensed from PNNL, world-wide covering

- Over 8 years RD&D, optimization and stack/system validation
- Won the US Government’s highest Award of Excellence in Technology Transfer to UET
- Extraordinary electrolyte stability, stable from -40°C to +50°C
- 2X energy density improvement → 5X product footprint reduction
- Improved reliability and performance and deployment flexibility through containerization and power electronics

Cathode: $\text{VO}_2\text{Cl} + 2H^+ + e^- \leftrightarrow \text{VO}^{2+} + \text{Cl}^- + H_2O$
Anode: $V^{2+} - e^- \leftrightarrow V^{3+}$
Cell: $\text{VO}_2\text{Cl} + V^{2+} + 2H^+ \leftrightarrow \text{VO}^{2+} + V^{3+} + \text{Cl}^- + H_2O \quad E_o=1.26 \text{ V}$
Production of High Quality Electrolytes

German-engineered

- 6 years of process optimization and quality control
- One of the world’s leading producers of vanadium products
- BNM produces 70% of the world’s vanadium electrolyte
- Vertically integrated with vanadium mining operations
- 10-year stable pricing visibility
- ISO9001:2008 Certified
- 1,324,000 ft² production facilities
- **1.5GWh** annual electrolyte capacity
**Proven Stacks:** 14 years in R&D and Production

9 years of field-driven stack development

- 1kW Stack in 2006
- 2kW Stack in 2008
- 5kW Stack in 2008
- 10kW Stack in 2010
- 22kW Stack in 2011
- 25kW Stack in 2012

**Over 6 yrs testing!**

- **Energy Efficiency**
- 0~100%SOC cycling

- **31.5 kW Stack in 2014**
  - Mature, powerful stack
  - ISO9000/14000, GB/T28001 Certified
  - Individual cell voltage data
  - 108,000 ft² facility
  - 100MW annual stack capacity, scale up to 300MW in 2016
Fully Integrated, Modular, Containerized Design

- **Factory Integration**
  - System level quality and performance testing
  - Factory integrated for rapid field deployment
  - On-site assembly versus on-site engineering

- **Modular Subassemblies and System Architecture**
  - Efficient and cost-effective production
  - Compact and flexible site arrangements
  - Scales to meet the application: up to 50MW
  - Incremental field capacity upgrades

- **Containerized Plug & Play Deployment**
  - Built-in secondary containment
  - Engineered with seismic strength and anchoring
  - More rapid permitting
  - Transportable
  - Possible lease financing as non-fixed asset

20’ standard container
Advanced Power Electronics and Control

- **Optimized Software Architecture**
  - Designed for scalability and pre-configured for deployment
  - Stand-alone control for multiple use cases
  - Software tools for third party integration and control

- **Optimized Control Architecture**
  - Siemens hardware and software platforms
  - UET proprietary embedded software puts focus on energy delivery
  - Single customer point of control

- **Communications and Control**
  - Industry standard command protocols
  - Multiple options for secure communications and data transfer

- **Proprietary Self-Balancing and Battery Management**
  - Simplified design
  - Reduced maintenance
Sophisticated Value-Added Data Analysis and Reporting

- **OSI PI**
  - Industry standard data historian
  - Custom analysis tools and templates
  - Event notifications
  - Real-time monitoring
  - System cloning for rapid deployment

- **Maintenance Management System**
  - Warranty and work order tracking
  - Service procedures and costs

- **Value-Added Services**
  - Optimized asset utilization
  - Stand-alone use-case economic analyses

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Monitoring and Decisionmaking

- Performance analysis
- Predictive analysis
- Reports
- Monitoring
- Notifications

Service Management

- Call Center Management
- Service Procedures
- Spare Parts Inventory Management
- Work Order Management
- Preventive Maintenance/Regular Service Management
- Dispatch

Field Service

CMMS Interface

Live Monitoring

OSI PI
Uni.System™ stores hours of energy that can be released for a duration of hours or even days, with very limited self-discharge loss, while simultaneously supporting short duration power functions.

Energy (long duration) + Power (short duration) Functions

Frequency regulation + Energy Arbitrage
## Deliver Multi-Applications & Benefits for Maximized Value

<table>
<thead>
<tr>
<th>Use Case</th>
<th>Primary Benefit</th>
<th>Conventional Technology</th>
<th>Value Basis</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>T-Connected Bulk Storage</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peaker Alternative</td>
<td>Capacity, Energy, A/S</td>
<td>CT</td>
<td>PPA, Mkt Rev, Avoided cost savings</td>
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<tr>
<td><strong>T&amp;D Support</strong></td>
<td></td>
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<tr>
<td>Deferral, Added Capacity,</td>
<td></td>
<td>Line &amp; Substation Expansion</td>
<td>Avoided cost savings, FTR revenue</td>
</tr>
<tr>
<td>Reliability</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Distribution Energy Storage</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distributed Peaker</td>
<td>Resource Services, Resiliency, Microgrids</td>
<td>Circuit &amp; Sub Expansion, CT, DG</td>
<td>PPA, Mkt Rev, Avoided cost savings</td>
</tr>
<tr>
<td><strong>Substation-Sited Storage</strong></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Deferral, Resiliency, Microgrids</td>
<td></td>
<td>Circuit and Substation Expansion, DG</td>
<td>Avoided cost savings</td>
</tr>
<tr>
<td><strong>Renewable Integration</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Renewable Curtailment Reduction</td>
<td></td>
<td>none</td>
<td>PPA, Energy arbitrage w/ ‘0’ cost</td>
</tr>
<tr>
<td><strong>Behind-the-Meter Energy Storage</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Behind the Meter</td>
<td>Bill Reduction, Power Quality</td>
<td>DR, DG</td>
<td>Customer bill shared savings</td>
</tr>
<tr>
<td>Behind the Meter Utility</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Controlled</td>
<td>Bill Reduction, Avoid Cost, Market $, Grid Rel</td>
<td>Circuit Upgrade, DR, DG</td>
<td>Bill savings, Avoided Cost</td>
</tr>
</tbody>
</table>
Competitiveness in Performance and Value

- Unmatched safety, aqueous electrolytes, no thermal runaway
- Full rated capacity access (0~100% SOC), no cycling limitations
- No capacity fading over life time (targeting 20 yrs)
- Acceptable efficiency, DC 80-85%; AC-AC system 70%
- Fairly competitive capital costs
- Lower deployment cost (20~25% of battery, compared to 50~100% others)
- Highly competitive in LCOC or LCOE
- Capable of a long duration, while covering short-time power functions
- Flexible to deliver multiple benefits for maximized value
Molecules to Megawatts through Valley of Death

http://www.energy.ca.gov/research/buildings/demonstrations.html
Status and Challenges

☑ There is strong customer interest in energy storage products

☑ Technology maturity
  • While most emerging chemistries are still in their experimental phase, some very high performance and reliable technologies are available today

☐ Product maturity
  • We are beginning to see products with the required seamless integration of chemical, mechanical, thermal, electrical, and controls engineering to deliver affordable, reliable & safe systems
  • Product maturity also requires tremendous investment of engineering and manufacturing resources into field demonstrations to prove out reliability and value propositions

☐ Bankability
  • More full-scale, profitable field deployments are needed to establish low financial risk
  • Regulations are slowly facilitating utilities to capture the value of grid storage assets
RD&D Needs

RFB or VRFB has existed over 3 decades, but never been as widely invested as Li-ion, fuel cells, etc.

- Further improve battery stack performance capability, durability and reliability – 1,000 mA/cm$^2$ of fuel cell vs 100 mA/cm$^2$ of RFB
- Extend electrolyte energy capacity and improve utilization
- Optimize power electronics and control, and battery management
- Lack of mature integration tools and energy management
- Need of standardization
- Government and industry collaboration on demonstration
Acknowledgements

- DOE-OE Energy Storage Program, Dr. Imre Gyuk
- Pacific Northwest National Laboratory
- RKP, BNM, Vanadis, all other partners
- UET employee, contractors