A NOVEL ALL IRON FLOW BATTERY FOR GRID STORAGE

June 2015

Ronen Badichi
President, Arotech Power Systems Division
badichi@electric-fuel.com

Jonathan Sassen
Chief Technology Officer, Electric Fuel
sassen@electric-fuel.com
BATTERY EXPERTISE SINCE 1989

1. Lithium Battery Pack Design, Assembly, BMS and Charging Systems. One-Stop-Shop for Custom Power from Concept to Field

2. Magnesium-Copper Chloride Water Activated Batteries for Life Jacket Lights

3. Zinc-Air Cells and Batteries

4. Comprehensive Battery Testing Services
A NOVEL ALL IRON FLOW BATTERY FOR GRID STORAGE
The Need

Storage of billions of Watt-hours from renewables

Load shifting to peak demand

Efficient utilization of production

UPS for large users and long times
STORAGE MARKET SIZE ACCORDING TO MULTIPLE STUDIES

MARKET WILL BE WORTH TENS OF BILLIONS OF DOLLARS WITHIN 10 YEARS.
STORAGE METHODS AND MARKETS

System Power Rating, Module Size

<table>
<thead>
<tr>
<th>UPS Power Quality</th>
<th>T&amp;D Grid Support</th>
<th>Load Shifting</th>
<th>Bulk Power Mgt</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hours</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High - Energy Supercapacitors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minutes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Li - Ion Battery</td>
<td></td>
<td></td>
<td>Pumped Hydro</td>
</tr>
<tr>
<td>Lead - Acid Battery</td>
<td></td>
<td></td>
<td>CAES</td>
</tr>
<tr>
<td>NiCd</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NiMH</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seconds</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HIGH - POWER FLYWHEELS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HIGH - POWER SUPERCAPACITORS</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Flow Batteries:
VRB | PSB | Zn - Br | New Chemistries

CAES
Pumped Hydro

System Power Rating:
1 kW 10 kW 100 kW 1 MW 10 MW 100 MW 1 GW
## THE COMPETITION: COMMERCIALLY AVAILABLE

<table>
<thead>
<tr>
<th>NAME</th>
<th>PRODUCT</th>
<th>TECHNOLOGY</th>
<th>CAPEX ($/KWH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prudent Energy, Sumitomo</td>
<td>Flow Battery</td>
<td>Vanadium Redox</td>
<td>600-700</td>
</tr>
<tr>
<td>Primus Power, ZBB, Redflow</td>
<td>Flow Battery</td>
<td>Zinc Bromine</td>
<td>400-500</td>
</tr>
<tr>
<td>A123, AltairNano, Samsung, Tesla</td>
<td>Standard Battery</td>
<td>Various Lithium ion</td>
<td>300-900</td>
</tr>
<tr>
<td>Xtreme Power, Silent Power</td>
<td>Standard Battery</td>
<td>Advanced Lead-Acid</td>
<td>700-3000</td>
</tr>
<tr>
<td>NGK Insulators, GE (Durathon)</td>
<td>High Temperature Standard Battery</td>
<td>Sodium Sulphur and Sodium Nickel Chloride</td>
<td>500-700</td>
</tr>
</tbody>
</table>
## THE COMPETITION: R&D

### All claim they can meet the “magic” goal of $200/kWh in mass production

<table>
<thead>
<tr>
<th>NAME</th>
<th>PRODUCT</th>
<th>TECHNOLOGY</th>
<th>STATUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enervault</td>
<td>Flow Battery</td>
<td>Iron-Chromium</td>
<td>Closing down?</td>
</tr>
<tr>
<td>EnStorage</td>
<td>Flow Battery</td>
<td>Hydrogen-Bromine</td>
<td>100 kWh pilot</td>
</tr>
<tr>
<td>ViZn</td>
<td>Flow Battery</td>
<td>Zinc-Iron Complex</td>
<td>160 kWh pilot</td>
</tr>
<tr>
<td>EOS</td>
<td>Standard Battery</td>
<td>Zinc Hybrid</td>
<td>Pilots announced</td>
</tr>
<tr>
<td>Aquion</td>
<td>Standard Battery</td>
<td>Sodium Ion</td>
<td>60 kWh pilot</td>
</tr>
<tr>
<td>CUNY</td>
<td>Standard Battery</td>
<td>Zinc-Nickel Oxide</td>
<td>200 kWh pilot</td>
</tr>
</tbody>
</table>
WHAT IS A FLOW BATTERY?

Liquid reactants are stored in external containers.

They react in the cell to generate electricity.

Extra capacity is added by adding liquid.
OUR PATENTED IRON / IRON COMPLEX HYBRID FLOW BATTERY

ANODE
\[
Fe(s) + 2OH^-_{(aq)} \rightleftharpoons Fe(OH)_2(s) + 2e
\]

CATHODE
\[
Fe(CN)_6^{3-}_{(aq)} + e \rightleftharpoons Fe(CN)_6^{4-}_{(aq)}
\]
The Challenge: Power and Capacity of Iron Anodes are too low!

**The Electrochemical Couple**

**Iron Anode**
- Commercial for more than 50 years
- Demonstrated 1000s of cycles for decades
- Very safe
- Very robust against abuse. Can withstand over-charge and over-discharge.

**Iron Complex Cathode**
- Well characterized electrochemical couple
- Reasonable energy density
- Very safe, unregulated food additive
- Developed by Lockheed for a zinc flow battery in the 80s
- Recently under development again for flow batteries by ViZn, Sun Catalytix (now part of Lockheed Martin), PNNL
ANODE CYCLING RESULTS AT HIGH POWER

Capacity (mAh/cm²) at 50 mA/cm² and 40-60°C

- **Target:** 300 mAh cm⁻²
- **Reported State of the Art**

- **Electrical Fuel Method 1**
- **Electrical Fuel Method 2**
STATUS

- Funding: Partially funded by the Israel Office of the Chief Scientist
- Team: 3 Ph.D.s, 5 M.Sc.s and growing fast
- Subject matter experts: top global consultants

Patents:
- Patent pending on the chemical couple
- Patent pending on high performance anode

Demonstration Milestones:
- 2016 – 10kW pilot
- 2017 – 100kW field demonstration
- 2020 – commercial with MW plants
**Low CAPEX** $<190$/kWh

*Assuming 20MW, 120MWh per year.
Includes labour, grid connection and mark-up

- Non-toxic materials, safe
- Low cost, readily available commercial materials, including separator and bipolar plate
- Modular and scalable
- Abuse tolerant – simple balancing and BMS
- Geographically flexible

**Low OPEX**

- Long cycle life
- Simple operation
- Environmentally friendly
- Low cost disposal
Electric Fuel’s flow battery answers the huge market opportunity for low cost grid storage batteries.

**CONCLUSION**

- **LOW COST**
- **SAFE**
- **PROVEN TECHNOLOGY**
Clean Horizon Assessment of Market Size in 2020 as a Function of Storage Prices of 3 Countries/Applications show that storage CAPEX will be key.

These 3 cases alone show a cumulative market for storage of around 300M$ if the 250 $/kWh price level is reached.
The analysis assumed 20 units per year of 1MW/6MWh flow batteries. Bottom line median cost: 188€/kWh.