OPEN FRAMEWORK MATERIALS ENABLE LOW-COST, LONG-LIFE BATTERIES

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PROJECT TITLE: Prussian Blue Open Framework Electrode Batteries
PROGRAM: Open 2012
AWARD: $4,599,935
PROJECT TEAM: Alveo Energy
PROJECT TERM: February 2013 to March 2016
PRINCIPAL INVESTIGATOR (PI): Dr. Colin Wessells

TECHNICAL CHALLENGE

Advanced energy storage promises to play a key role in the modernization of our nation's electricity grid by enabling the integration of increasing amounts of renewables, improving the grid's operating capabilities, enhancing reliability, allowing deferral of infrastructure investments and providing backup power during emergencies. The primary barrier to widespread adoption of electrical energy storage is lifecycle cost. Overcoming this barrier requires a combination of capital costs that are significantly lower than incumbent Lithium-ion (Li-ion) and extremely long cycle life.

TECHNICAL OPPORTUNITY

An important class of electrochemical energy storage materials – intercalation compounds – has many positive attributes and widespread adoption, but also has limited cycle life because mechanical expansion/contraction during charge/discharge ultimately leads to material failure. Just prior to the award of this project, it was established that open framework crystalline materials, which readily transport ions, such as Prussian Blue, do not suffer this failure mode and may therefore provide both long cycle life and high power.[1] This is one of the few significant new energy storage materials advances in the last fifty years. This new novel class of materials has presented several barriers to implementation, such as aqueous instability, lack of matching anode material, and cost effective production of battery quality material. Solving these barriers was required in order to provide a path towards a commercially significant and sustainable storage solution.

INNOVATION DEMONSTRATION

Alveo's primary goal was to develop a practical, low-cost, high performance battery based on chemical analogues of Prussian Blue dye. The cell performance goals included power capability up to 20C rate, projected cycle life >10,000 cycles, and projected calendar life >10 years.

Alveo began with a development of an open framework cathode material based on Prussian Blue dye and developed an anode based on a similar crystal structure. The anode-cathode combination was designed and demonstrated to have an average cell voltage of 1.6 V, high enough for practical commercial packs and systems. The company implemented this couple in a substantially aqueous cell, to provide intrinsic safety and thus reduce the balance of system costs. In doing so, Alveo was awarded five patents (listed below) on the composition of matter of its electrodes and electrolyte.

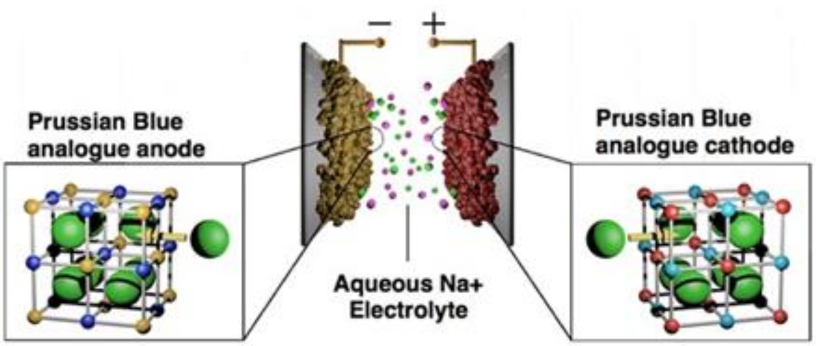

Figure 1. New Na^+ battery chemistry based on Prussian Blue analogue anodes and cathodes in aqueous Na^+ electrodes. The electrodes have near-zero strain during cycling.

Alveo carried out extensive charge/discharge testing of the system components at 20C rate, and demonstrated that the cells have a high power capability equivalent to >1000 W/L for large form factor production cells – higher than present commercial Li-ion power cells at a fraction of the cost. The company also developed a novel nonflammable aqueous-organic electrolyte, solving the problem of active material dissolution and instability in purely aqueous

[1] Wessells, C.D., et al. Nat. Commun. 2:550 (2011).

electrolytes, in order to achieve industry leading calendar and cycle life. Furthermore, they demonstrated that an extremely long cell lifetime (over 30,000 cycles) at full charge/discharge is possible, based on over 7 months and 10,000 measured cycles at 100% depth of discharge.

After successfully demonstrating cell chemistry and design, Alveo scaled up active material synthesis and commercially viable manufacturing processes based on roll-to-roll electrode processing compatible with existing manufacturing lines, with a focus on low capital cost. The team has built and tested demonstration batteries of up to 2Ah capacity for third-party testing, including the University of California, San Diego Cycling Hardware to Analyze and Ready Grid-Scale Electricity Storage (CHARGES) program, and for customer engagement.

Alveo has demonstrated a useful combination of attributes, extremely long cycle life (projecting to > 30,000 cycles), high power, low capital cost and fundamental safety (substantially aqueous). The trade-off for this is a moderate energy density (50 Wh/L) which makes this technology most suitable for grid-scale energy storage and back-up power.

PATHWAY TO ECONOMIC IMPACT

Alveo was established primarily on the basis of PhD work[2] of one of the co-founders – Dr. Colin Wessells – conducted while he attended Stanford University. Khosla Ventures provided initial funding. In March 2016, Alveo closed a B round with Prelude Ventures as the lead and contributions from Khosla Ventures, NanoDimension and Fluxus Ventures.

The company is still in the development phase for its first commercial cells and has potential customers with high interest in back-up power; other markets in which the break-through low cost cycle life makes the product compelling are nearly all renewables intgration scenarios and start/stop for electrified transportation.

LONG-TERM IMPACTS

The successful implementation of open framework active materials into a battery with breakthrough life cycle will potentially impact both the technical community and the battery storage markets. In the technical community, the results may lead to new directions of investigation in materials science for energy storage materials, with potential for further improvements in storage properties. For instance, it may potentially drive forward the rapidly growing field of sodium-ion batteries, which includes several promising chemistries that could achieve a much lower cost/energy floor than incumbent technologies such as Li-ion and lead acid.

For markets, such breakthroughs in low cost cycle life open realistic opportunities for battery storage to improve grid stability and enable expanded grid integration of renewables. The anticipated life cycle costs would be sufficient to enable renewables to compete with existing fossil fuel base load generation, provided that related system level cost reductions continue – for example in power conversion.

INTELLECTUAL PROPERTY AND PUBLICATIONS

As of March 2016, the Alveo project has resulted in 14 U.S. Patent and Trademark Office (PTO) patent applications and 5 patents issued by the U.S. PTO. The team has also collaborated with researchers at Lawrence Berkeley Lab and NYU to explore the scientific underpinnings of this technology, and their first publications in the scientific literature are expected in mid-2016.

"*Stabilization of battery electrodes*," (9/8/2015), Patent No 9,130,234, Washington, DC: U.S. Patent and Trademark Office.

"*Stabilization of battery electrodes using prussian blue analogue coatings*," (9/1/2015), Patent No 9,123,966, Washington, DC: U.S. Patent and Trademark Office.

"*Homometallic cyanide-containing inorganic polymers and related compounds*," (8/4/2015), Patent No 9,099,740, Washington, DC: U.S. Patent and Trademark Office.

"*Cosolvent electrolytes for electrochemical devices*," (3/15/16), Patent No 9,287,589, Washington, DC: U.S. Patent and Trademark Office.

"*Surface-modified cyanide-based transition metal compounds*," (3/29/2016), Patent No 9,299,981, Washington, DC: U.S. Patent and Trademark Office.

[2] Wessells, C.D. *New Materials Systems for Aqueous Batteries*. Diss. Stanford University, 2012.