Cultivating Cross Sector Partnerships in Energy Storage for Smart Grid Applications

J.F. Whitacre, *> 150 amazing people*

Carnegie Mellon University, Department of Materials Science and Engineering, Department of Engineering and Public Policy, 5000 Forbes Ave, Pittsburgh PA 15213

Aquion Energy 32 39th Street, Pittsburgh PA 15201

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Target Markets: Stationary, Daily Deep Cycling Applications

Market Segments	 Off-grid and Microgrids	 Energy Management	 Grid Services
Applications	+ Diesel Reduction + Islanding with Renewable Generation + Critical Power	+ Demand Response + Power Quality + Peak Shaving	+ Load Shifting + Renewables Integration

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Initial Goal: low cost and sufficient enough energy density

- Identify the “sweet spot” between specific cost, energy density, and cycle life

- Significant testing yielded a finding:

  - Aqueous electrolyte sodium ion functional materials and battery structures
  - If you set aside energy density at requirement, using neutral pH electrolyte allow for very substantial cost savings, and benign electrode reactions

The Economic Reality of energy storage

- Another key - cycle life:
  - Issue: typically energy density and cycle life are inversely correlated

$$LCOSE(\$/kWh) = \frac{Cost}{\#cycles \times efficiency} = \frac{(\$/kWh)}{\# \times \eta}$$

- Assuming we must have a have a LCOSE of < $0.1/kWh
- Then we need > 5000 cycles
- Price point of under $300/(usable kWh installed)

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The Economic Reality of energy storage

Must use:

cheap materials (<$4/kg),

Simple manufacturing approach ("borrowed technologies")

From the lab to Early stage spin out

- Founded in spring 2008
  - Venture funded, KPCB, incubation at Carnegie Mellon, $1.6 M (two tranches)
  - Promising concept, minimal proof of concept
- Spun out in Fall 2009
  - DoE ARRA grant won; $5 M, Series B Venture funding (KPCB)
  - Functional cell level prototype, no processes scaled
- 1.5 years of early development
  - Electrode production, large format prototype,
  - Hired full time CEO in 2011, raised 25 M (venture)

History of Support: >$120 Million

Round				
A/B	Carnegie Mellon University	KPCB Kleiner Perkins Caufield Byers	U.S. Department of Energy	ARRA Recovery act "grid Demo Program"
C	Foundation Capital	ATV Advanced Technology Ventures	(State of PA after C round)	(other unnamed family investors in D/E)
D/E	 Bill Gates	Bright Capital	YUNG'S ENTERPRISE	tao capital partners
D/E	Shell Technology Ventures	Prelude Ventures	Constellation. An Exelon Company	Total Committed to Better Energy

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Innovating to scale. . . .

Materials Readiness Level or "MRL"

Level	Proven Phase	Indicator	Metric	Time for Proof	Cost	Required Precision
0	idea	thought/written only	is it physically possible	N/A	Lowest	none/boolean
1	Materials Function	cheapest fixture that shows function	does it work	8 weeks	low	none/boolean
2	Materials Performance	cheapest fixture that shows performance	within specified precision	16 weeks	low	+/-100%
3	Device Performance	cheapest, fastest device that maps to a product	within specified precision	1 year	med	+/-25%
4	Prototype Performance	device proves product manufacturability	within specified precision	1 year	high	+/-5% + yield loss tolerance
5	Product Performance	revenue producing units sold; clear path to scale	within specified precision	3 years	extremely high	+/- 0.5% (yield loss tolerance)
6	Unit Economics	minimum efficient scale reached	within specified precision	3 years	extremely high	+/- 0.5% (yield loss tolerance)

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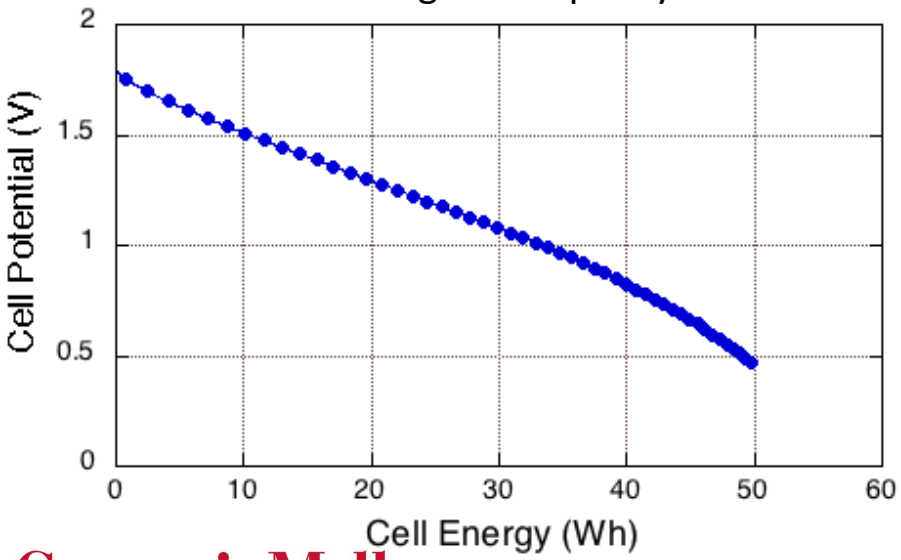
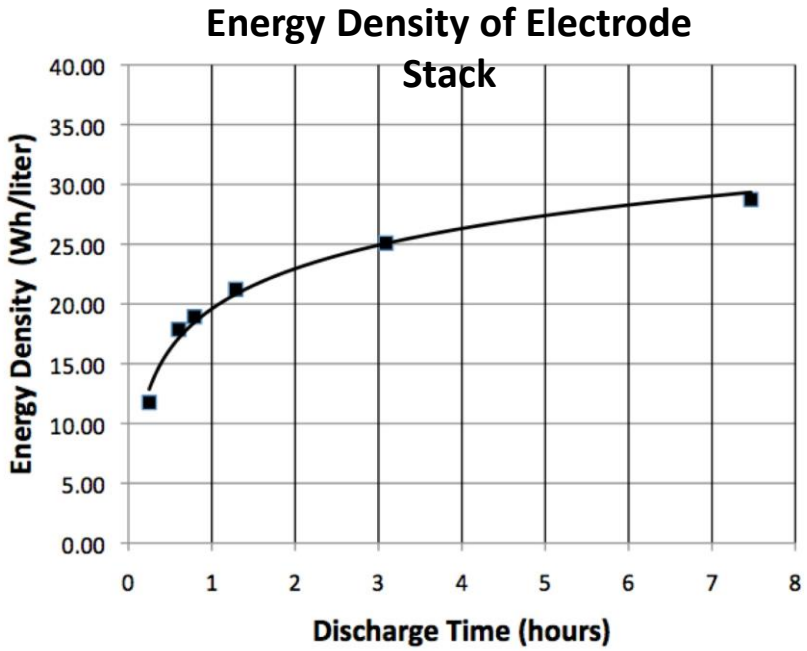
Engineering Prototype Performance:

"Battery 0"

- About 1.5 internal electrode volume
- 50 Wh prototype demonstrated
  - Over 30 Wh/liter at electrode stack level
- Industry-proven polypropylene casing and sealing technologies
- Poor terminal pass through approach used

Voltage vs. Capacity





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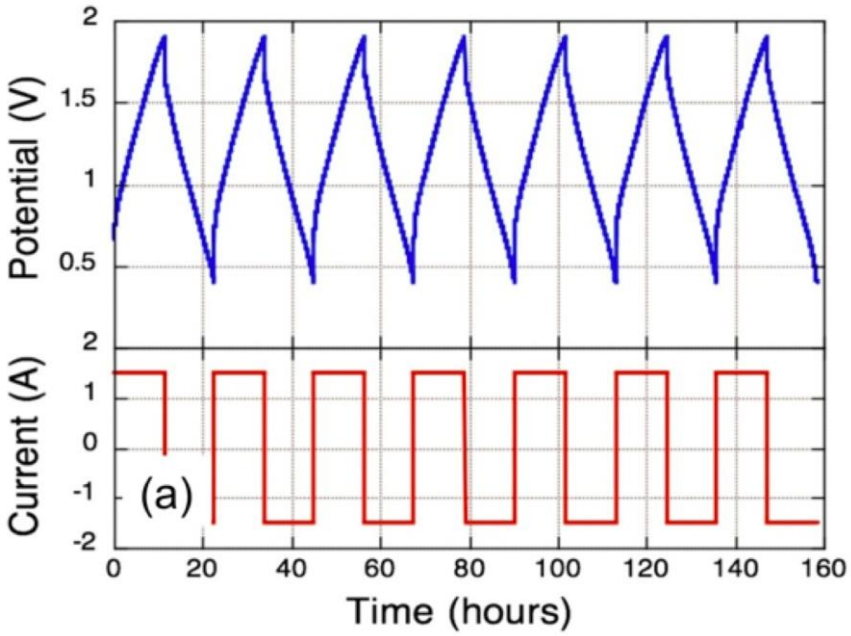
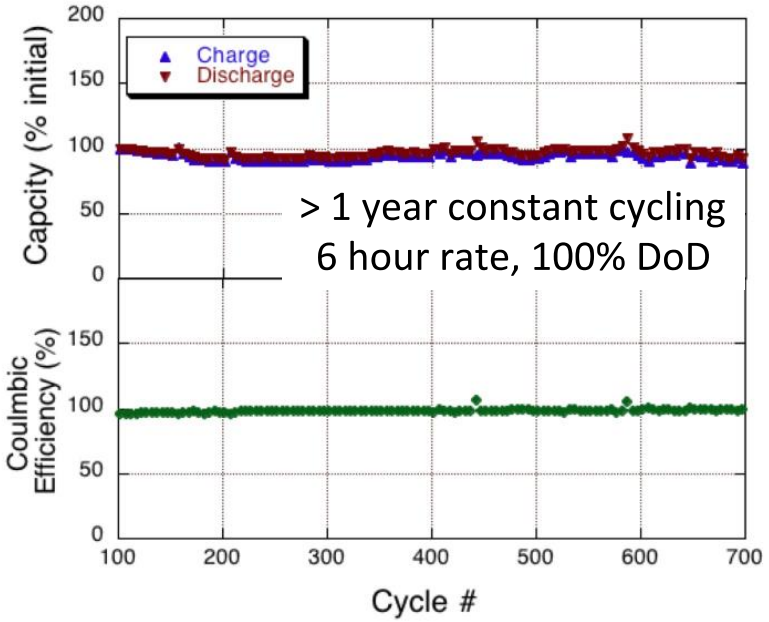
Promising Thick format cell level results





- Early single cell results indicate that it is possible for the thick format electrodes to be stable
- > 12 months continuous deep cycling with little loss in capacity
- ~99% columbic efficiency

J.F. Whitacre, et al, Journal of Power Sources, Volume 213, 1 September 2012, Pages 255-264

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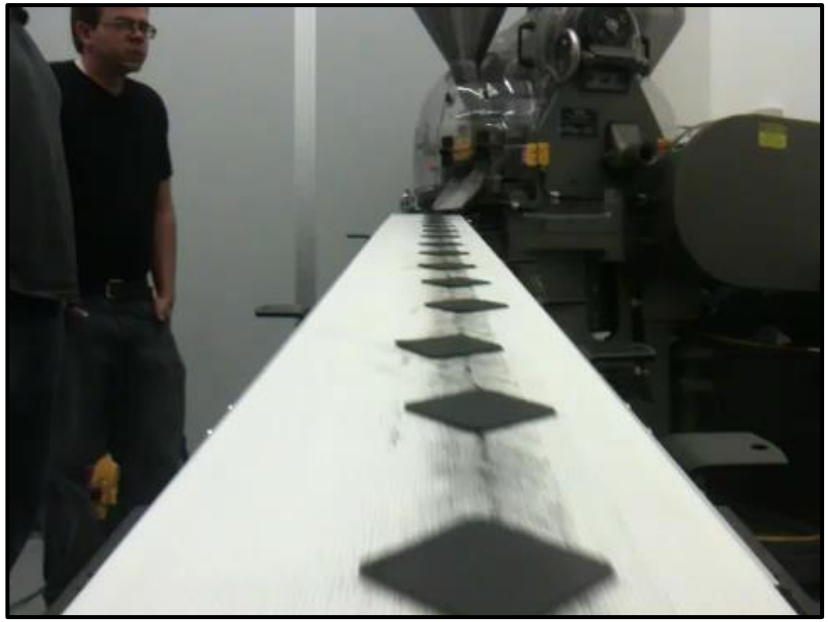
Battery Assembly: Engineering Prototype

Electrode Production



Battery Assembly

SEMI-AUTOMATED MANUFACTURING IN PLACE; FULLY AUTOMATED IS DESIGNED

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1000 Volt System

540 batteries connected in a single string

NO BMS used. Reliance on anodic hydrogen reaction for self balancing to occur

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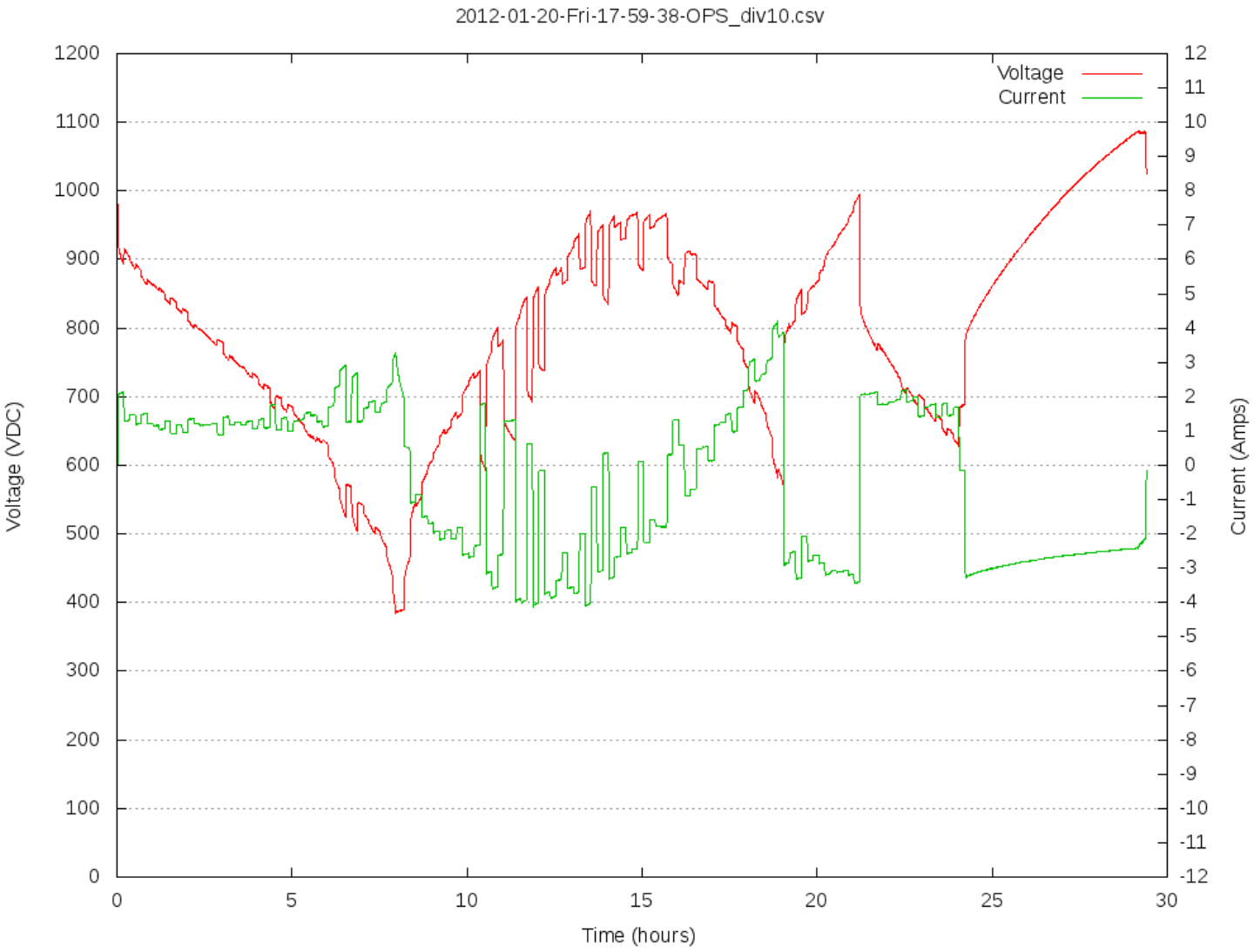
1000 volt system: Data



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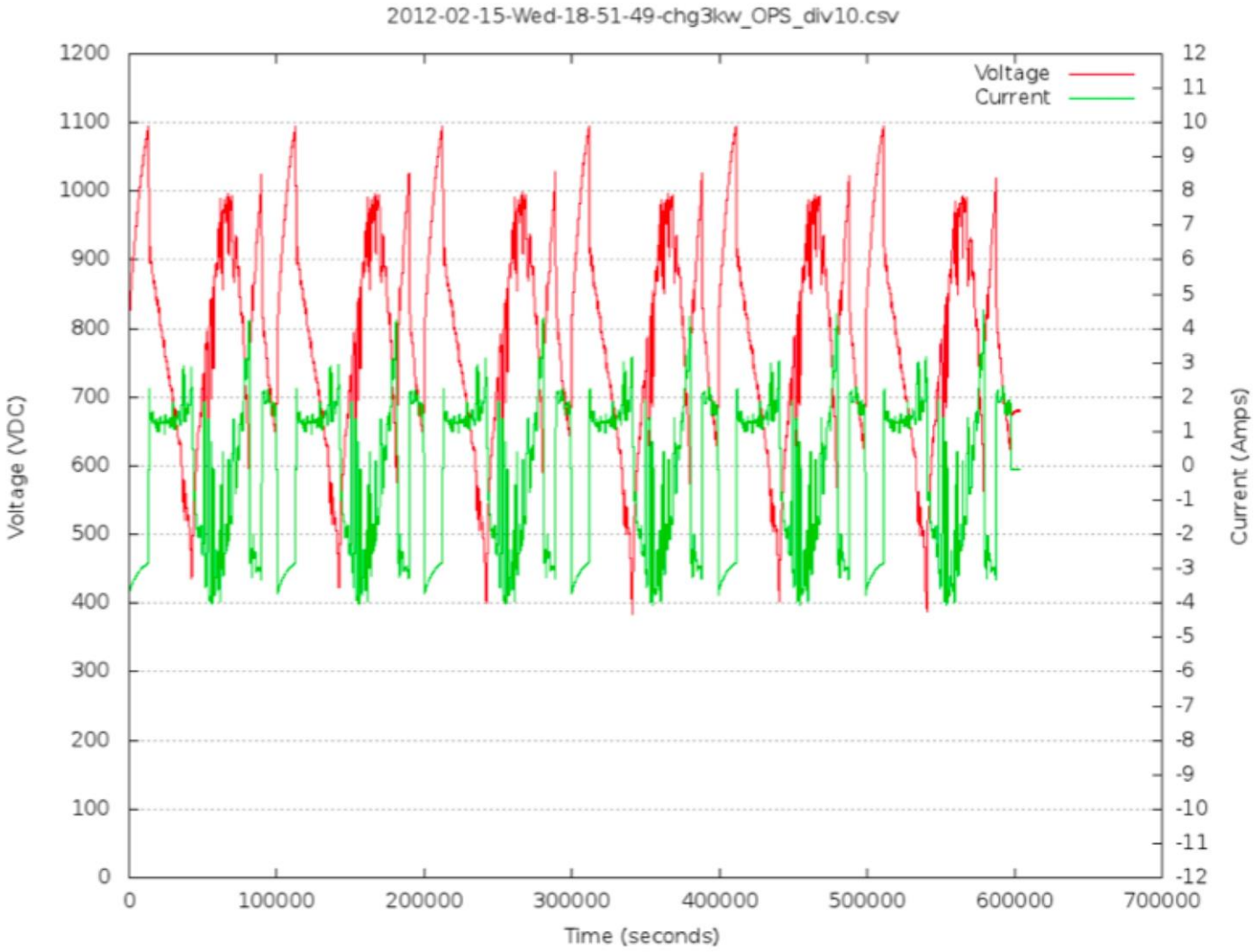
1000 volt system: Data



- Off-grid diesel hybrid support cycle run on 1000 V system after 2 months of testing/break-in.

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Early Stage Spin Out through Full Manufacturing

- 2011/12: Factory space in PA identified, construction starts
- 2012: pilot line at R&D headquarters fully opertional
  - first high voltage “battery stacks” are built and tested
  - Significant customer demos start
  - ~50 employee mark reached
- 2013:
  - First assembly line in factory finished
  - Series D fund raising started (~$50 M in total)
  - New anode materials system introduced
- 2014:
  - First official product launch, rapid improvement in performance
  - Series E funding closed (~$38 M)
  - Multiple MWh of batteries produced and sold

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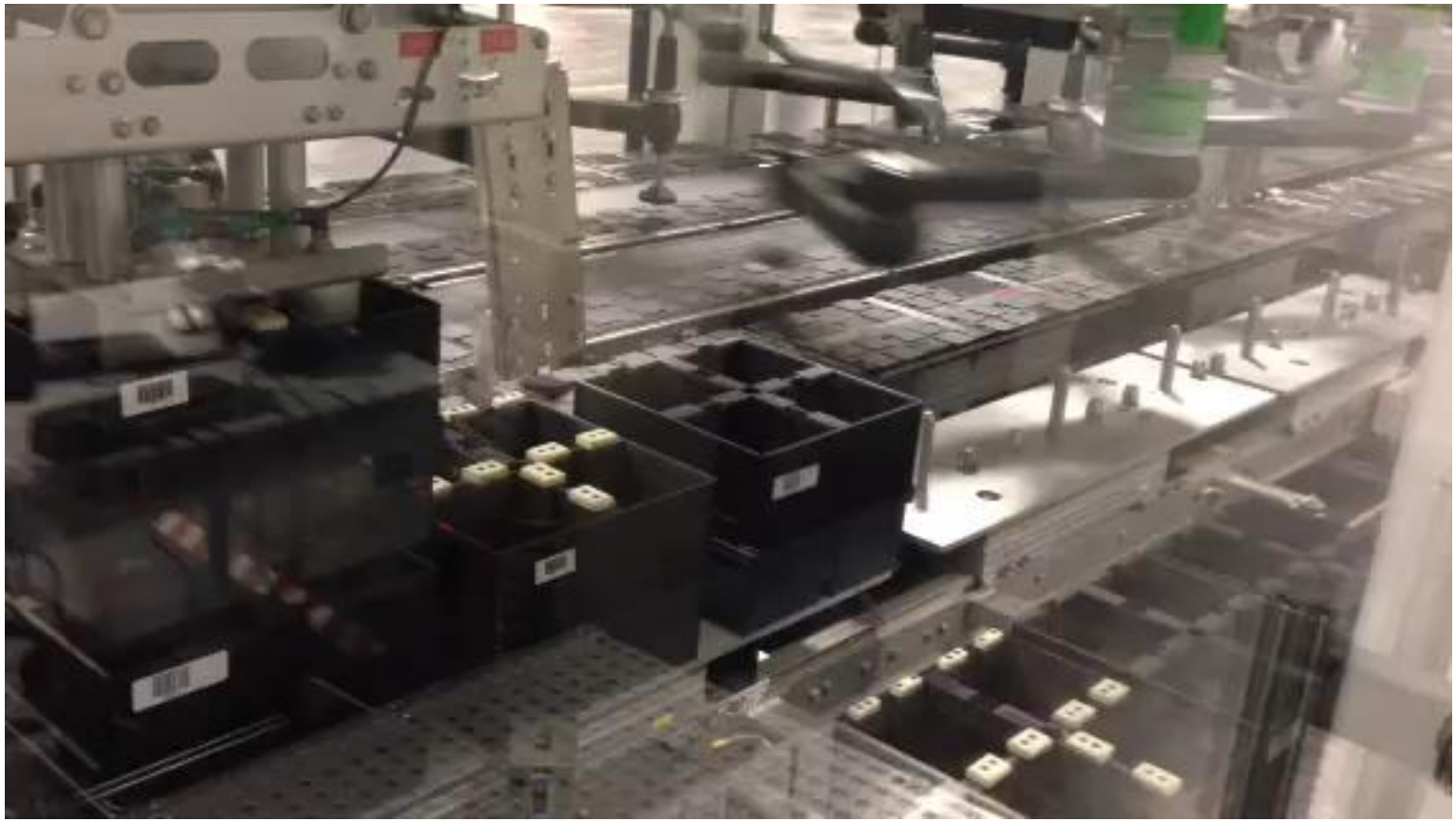
In-Situ Technical Pivot: A new Anode material

- Feedback from market:
  - Energy density and voltage swing not ideal – ruled out from some applications because of this
- Feedback from long term testing:
  - Mechanical stability of the system an engineering challenge.
- Pure carbon anode identified as target for replacement
- Meanwhile, low-level R&D on alternative anode materials pays off with the finding that $NaTi_2(PO_4)_3$ (STP) can be long-term stabilized.
  - Work done first at CMU and then rapidly transitioned into scaled effort
  - Extremely fast; under 1 year between lab finding to product demo
  - HIGH RISK/high payoff

Production Intent Units: “Battery 1”

Manufacturing at the plant. . .



Manufacturing at the plant. . .

Product Specification: “S20”

S20-008F Battery Stack

For models S20-008F and S20-0080

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PRODUCT SPECIFICATION SHEET

Aquion Energy's 2.4 kilowatt-hour S20-008F Battery Stack is the first cost-effective energy storage solution that is high-performance, safe and sustainable. Based on Aquion's patented Aqueous Hybrid Ion (AHI™) technology, the S20-008F is designed for stationary, long-duration cycling applications.

PRODUCT INFORMATION

Time (h) (30 to 59 Vdc)	4	8	12	20
Current (A)	10.4	5.6	3.9	2.5
Capacity (Ah)	41.6	45.3	47.8	51.0
Energy (Wh)	1,635	1,955	2,150	2,395

Constant Current Discharge, 30°C

Time (h) (40 to 59 Vdc)	4	8	12	20
Current (A)	7.7	5.4	3.9	2.5
Capacity (Ah)	30.8	43.7	47.7	50.2
Energy (Wh)	1,335	1,780	2,040	2,360

Constant Current Discharge, 30°C

Voltage Range	30 to 59 Vdc
Nominal Capacity	51.0 Ah at 20 hour discharge, 30°C, to 30 Vdc
Nominal Energy	2,395 Wh at 20 hour discharge, 30°C, to 30 Vdc
Nominal Voltage	48 V
Continuous Power	450 W
Maximum Current	15 A

OPERATION & PERFORMANCE

Cycle Life	>3,000 cycles, 100% depth of discharge*
Operating Temperature Range	-5 to 40°C ambient
Round Trip DC Efficiency	>85% at at 20 hour discharge, 30°C
Charge / Discharge Modes	CC, CP, CV, AC ripple tolerant
IP Rating	IP22 Rated
Shipping Testing	Tested to ISTA 6B

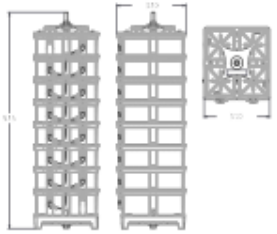
* Cycle life to 80% retained capacity

PHYSICAL CHARACTERISTICS

Height	935 mm (36.8")
Width	330 mm (13.0")
Depth	310 mm (12.2")
Weight	113 kg (249 lbs)
Certifications	UL Recognition Targeted
In-Line Fusing	15 A (Unfused Model Available)

CONNECTORS

Female	Amphenol H4
Male	Amphenol H4



S20-008F Battery Stack

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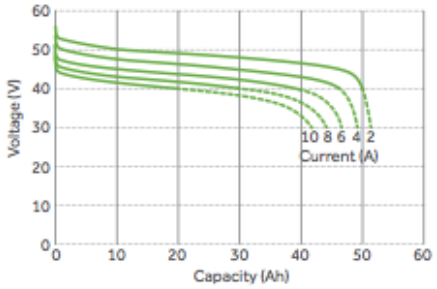
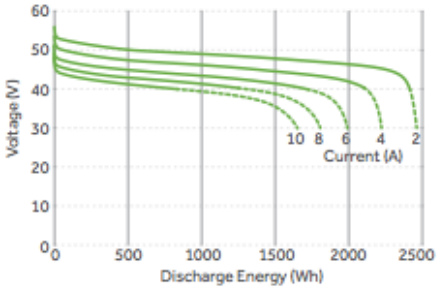
PERFORMANCE DATA AT CONSTANT CURRENT DISCHARGE

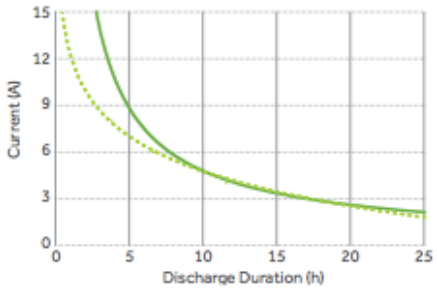
Voltage vs. Capacity



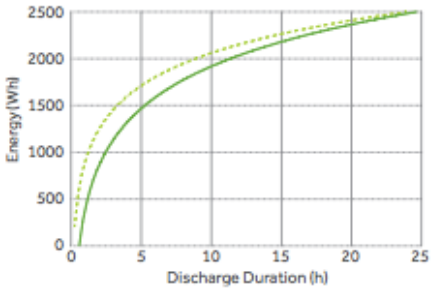
Voltage vs. Energy



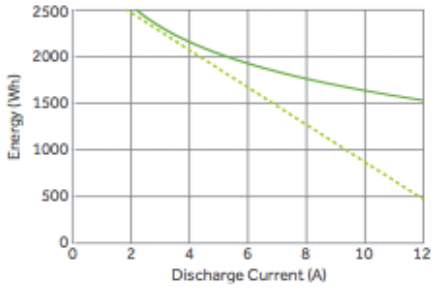
Current vs. Discharge Duration



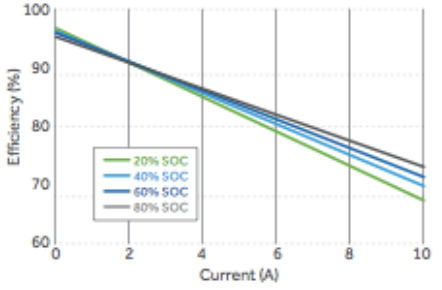
Energy vs. Discharge Duration



Energy vs. Discharge Current



Round Trip Efficiency vs. Current



* Solid lines indicate battery performance at a 30 V cutoff. Dotted lines indicate battery performance at a 40 V cutoff.
Performance characteristics based on testing conducted by Aquion Energy. Performance may vary depending on use, conditions, and application.
For the most up-to-date specification, visit our website: http://info.aquionenergy.com/customer-portal

Form factors

AHI PRODUCTS

S20 Battery Stack

+ >2 kWh
+ Nominal 48V output
+ Smallest product increment

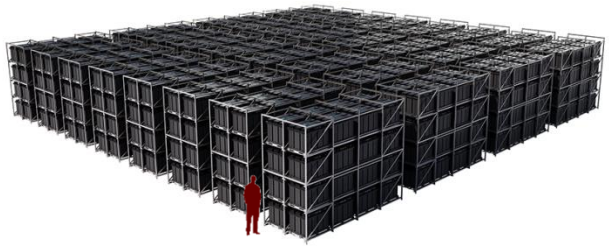
M100 Battery Module

+ > 24 kWh
+ 48V or 600V
+ Designed for industry-standard racking
+ Forklift-ready

SYSTEM CONFIGURATIONS

Stack-Based Systems

Racked Module-Based Systems



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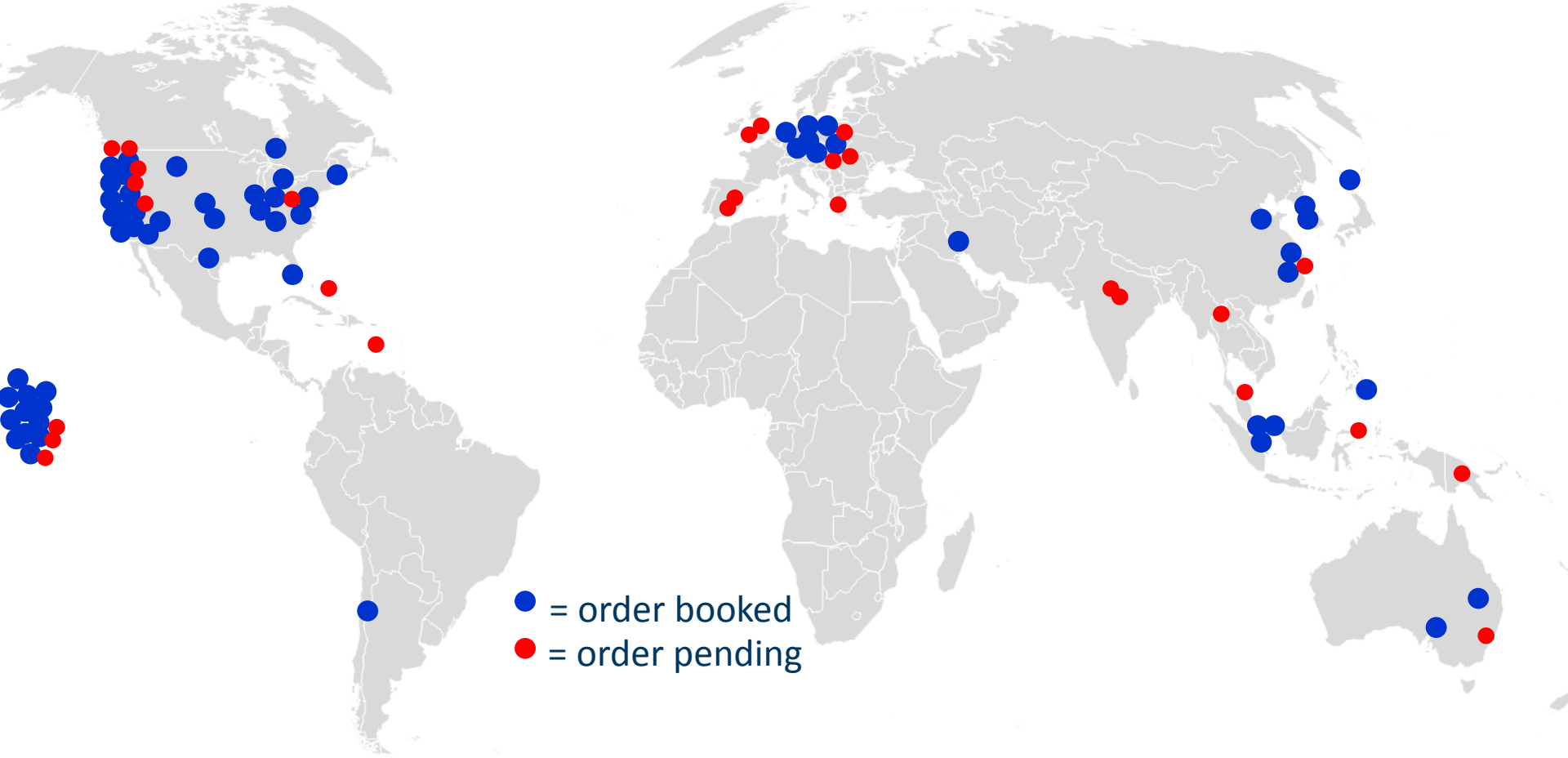
Aquion systems sold/shipped by end of 2014



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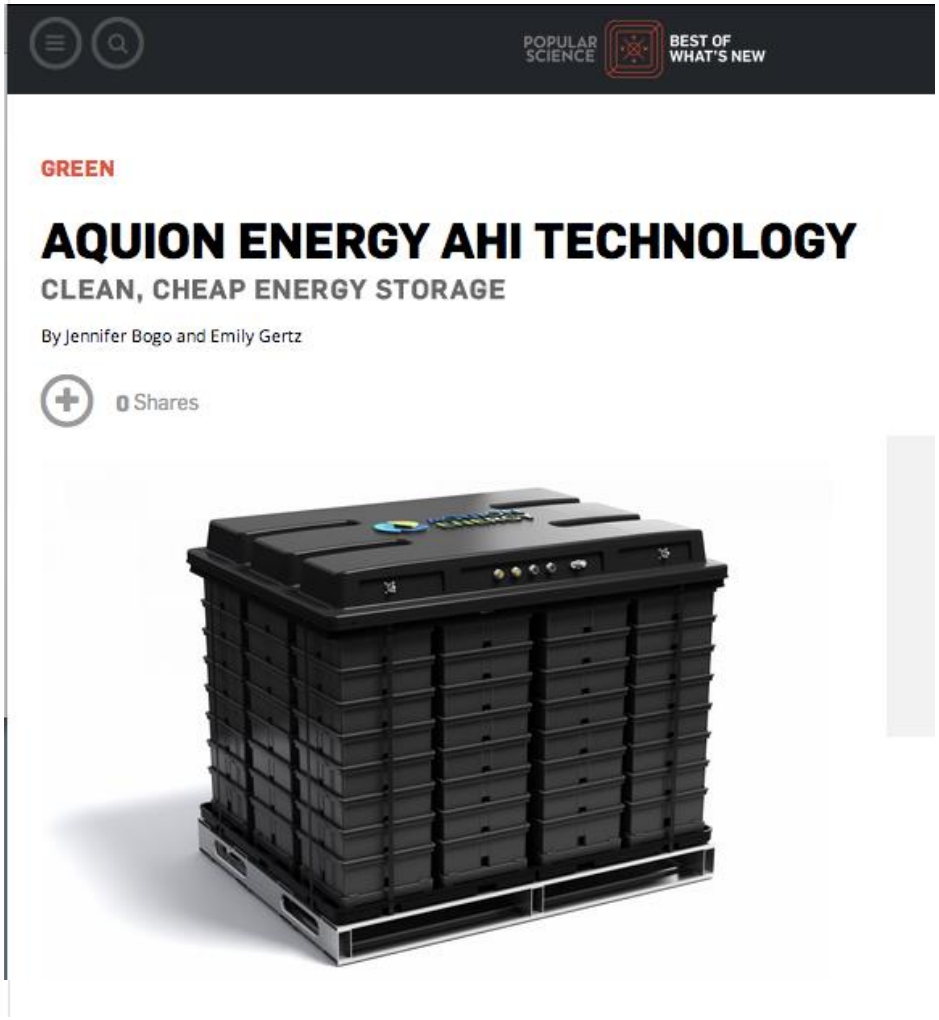
Going Forward. . .

Timeframe	Bussines Stage	Nameplate Storage Price (at wired 60V stack level)
H2'14 - 2015	Initial Projects & Credibility Building	$350 - $450 per kWh
2016	Initial Scaling of Business, Grid-Scale Projects Starting	$250 - $350 per kWh
2017/2018	Major Expansion, Grid-Scale Projects Become Significant	High $100's per kWh
2019 +	Storage Goes Mainstream in all Target Apps	Mid to Low $100's per

Breaking News: Popular Science “Innovations of the Year”



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