SAND2013-8850C

# High Performance Flow Battery Design for Grid Scale Energy Storage

**Primus Power**
Jonathan Hall

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# Primus Power gratefully acknowledges the support of: DOE, ARPA-E, DOD, and CEC

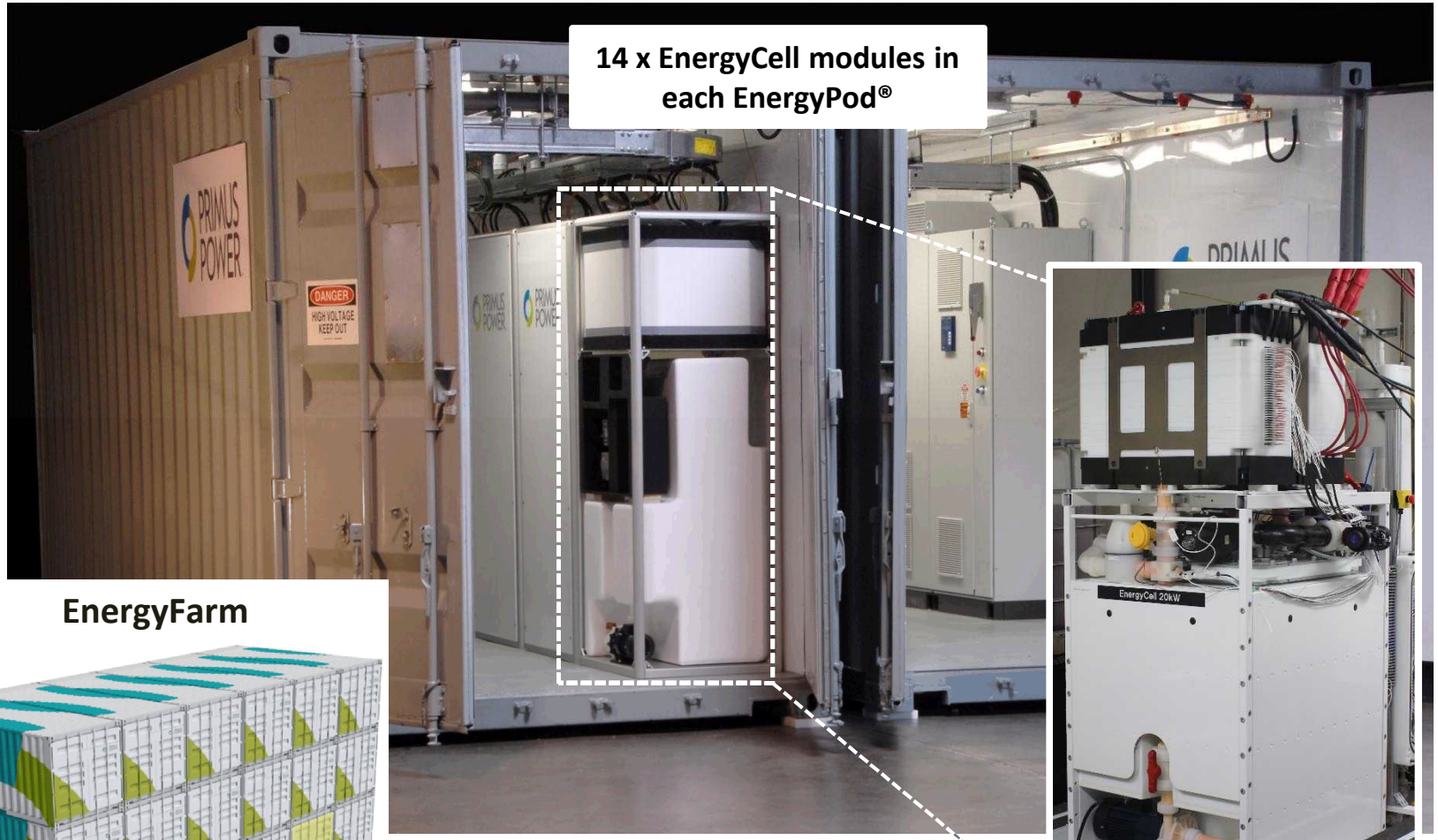
Independent performance verification testing by Sandia:

Sandia National Laboratories

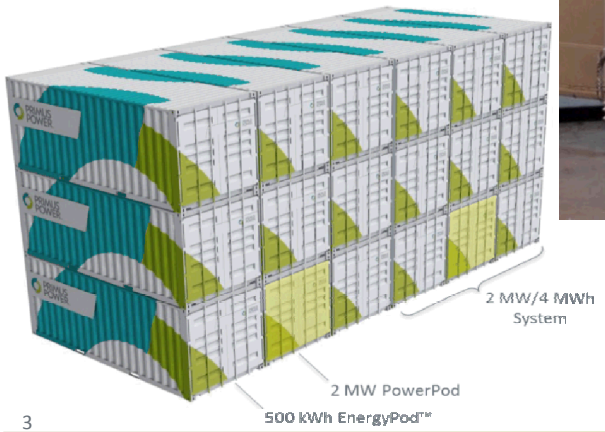
Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

# EnergyCell modules are the core technology in the EnergyPod®, a modular and easily deployable storage product

14 x EnergyCell modules in each EnergyPod®



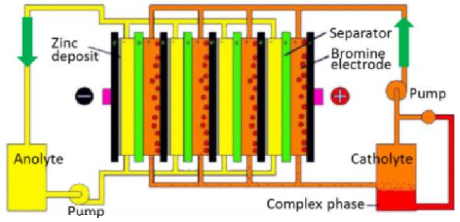

EnergyFarm




EnergyPod®

EnergyCell

# Primus Power's EnergyCell is a superior flow battery design

| | Legacy flow batteries | Primus Power EnergyCell |
|---|---|---|
| |  |  Metal electrode<br>No separator<br>Single flow loop<br>Compact and integrated design |
| Separator / membrane based | Membrane is inherent to design:<br>• Hi resistance<br>• Life-limiting<br>• Catastrophic failure modes | Clean sheet design, no membrane<br>• Low resistance = high power density<br>• Long stack life = low cost<br>• Reduced failure modes |
| Electrodes | Plastic + graphite, felt | Metallic |
| Current density ($mA/cm^2$) | $ZnBr_2$ 20 – 50<br>Vanadium 30 – 40<br>$Fe_2Cr_3$ 20 – 40 | 200 |
| Electrochemical couple (VDC) | $ZnBr_2$ 1.8<br>Vanadium 1.4<br>$Fe_2Cr_3$ 1.2 | 1.8 |
| Tanks / Flow loops / pumps | 2 / 2 / 2 | 1 / 1 / 1 |
| Stack integration | Separated from balance of plant | Integrated with balance of plant |

High conductivity

5x current density

Need to work on comments

Fewer parts, **low cost, high reliability**

Factory built & tested, **rapid installation**

4 Legacy flow battery diagram from ZBB website



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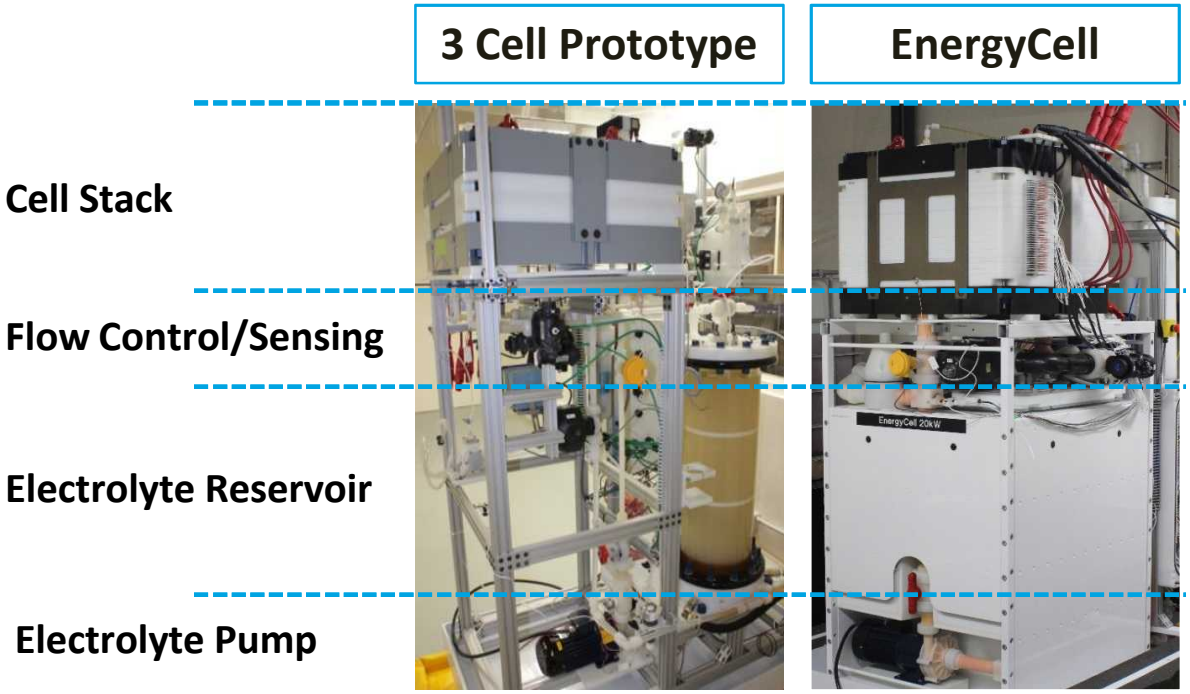
# EnergyCell systems tested by Sandia

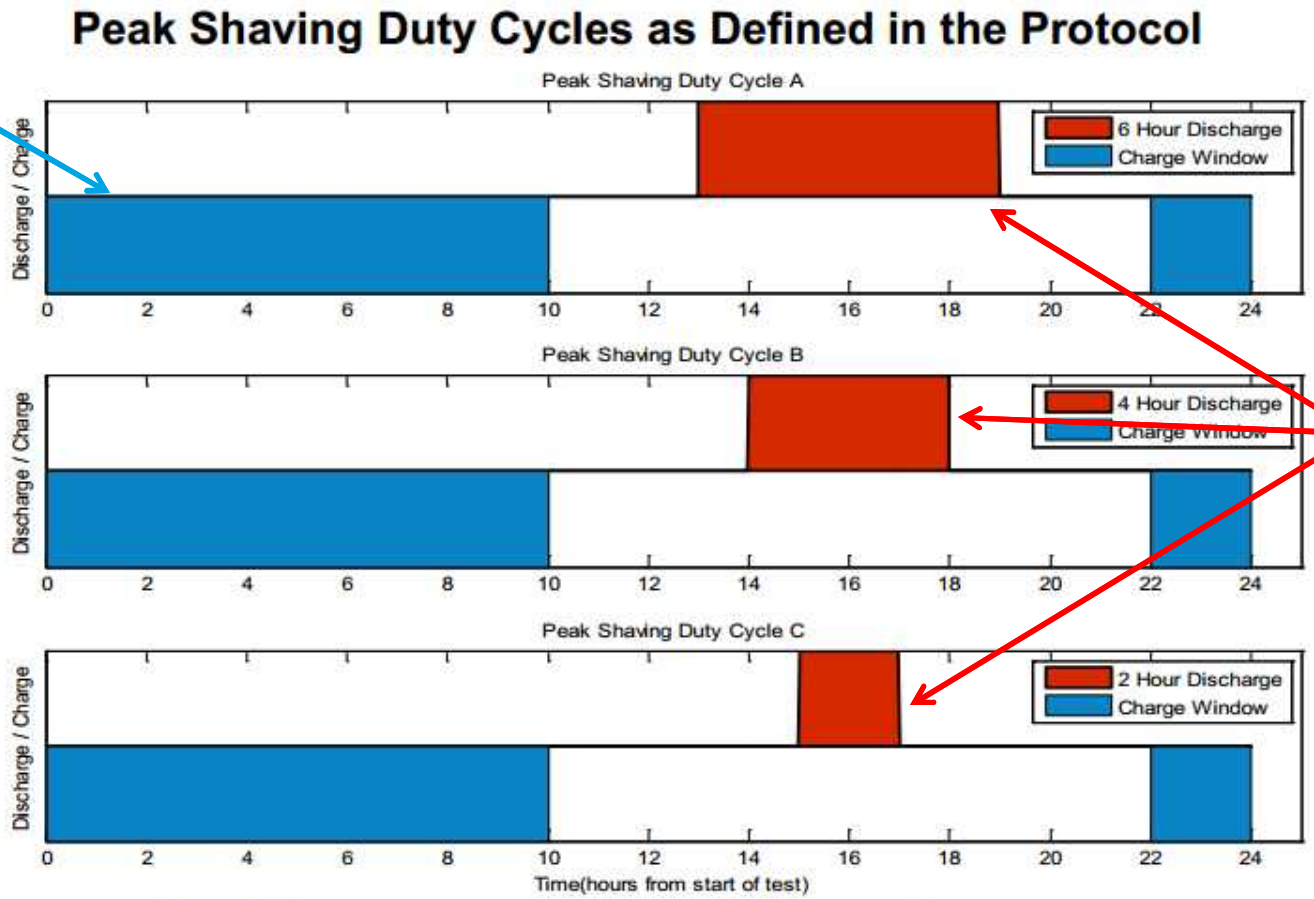



| | 3 Cell Prototype | EnergyCell | Comments |
|---|---|---|---|
| Single Cell Active Area | 2,693 $cm^2$ | 2,693 $cm^2$ | Identical cell design |
| Cells in stack | 3 | 39 | |
| Open circuit stack potential | 5.2 V | 68 V | |
| Discharge Power, continuous | 30 kW* | 30 kW | Steady state |
| Energy Capacity | 43 kWh* | 25 kWh | To date, active development |

* Equivalent power and energy for 3 cells is based on the ratio of cells in the stacks of these two systems: 39/3

# Key features of the DOE/SNL/PNNL ESS test protocol

Charging window: 12 hours




3 different discharge durations: 2,4,6 hours

**Discharge duration is primary differentiator between peak shaving applications**

Sandia National Laboratories

Pacific Northwest NATIONAL LABORATORY

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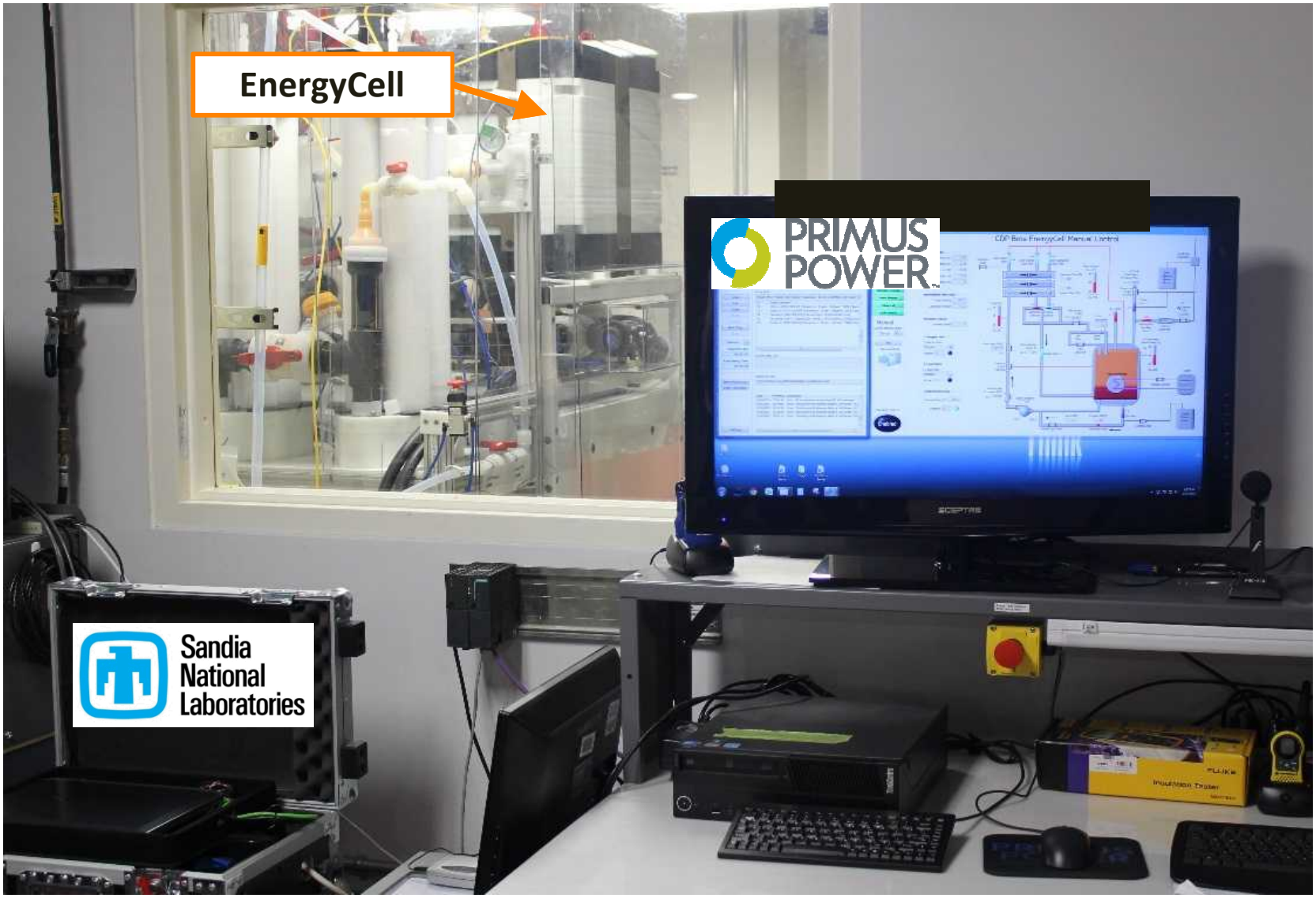
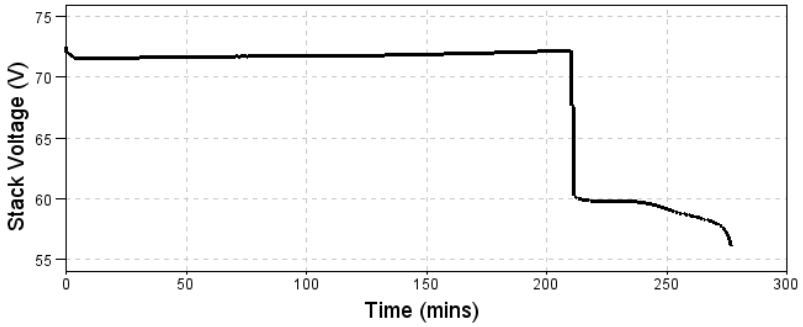
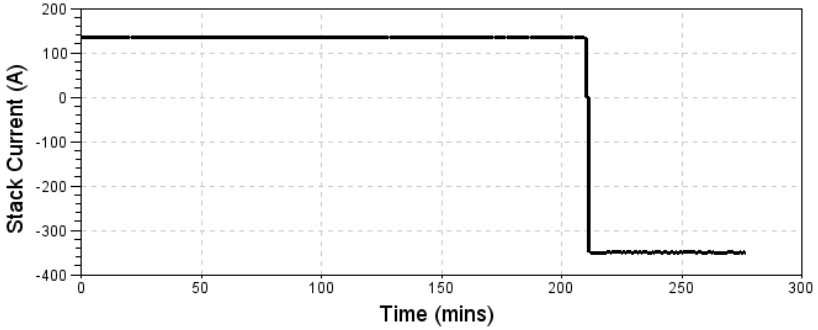
# Configuration of Sandia Testing of EnergyCell

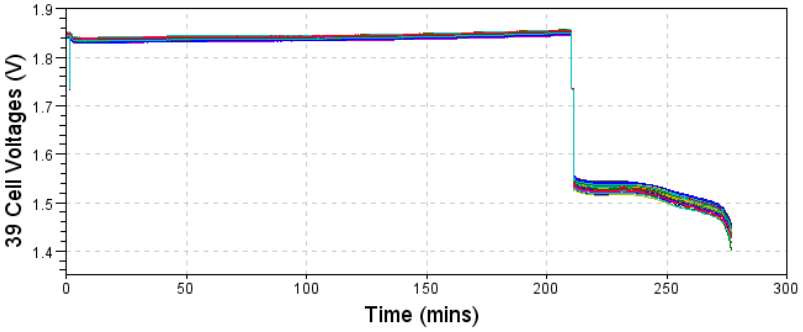


# Typical EnergyCell Stack Performance

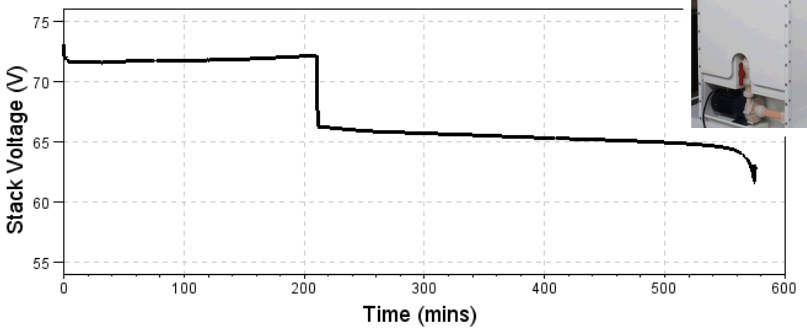
EnergyCell Beta Test: 20 kW, 23.8 kWh

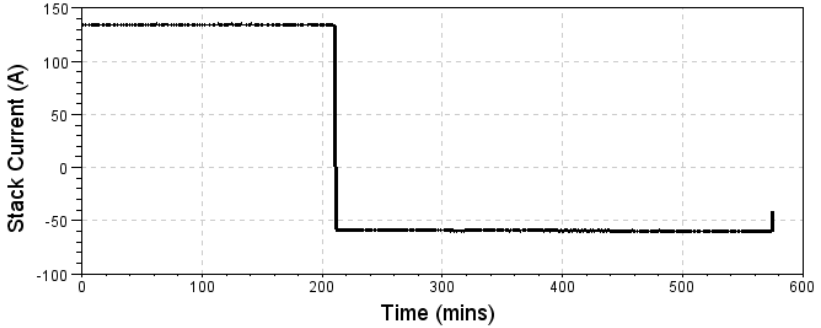


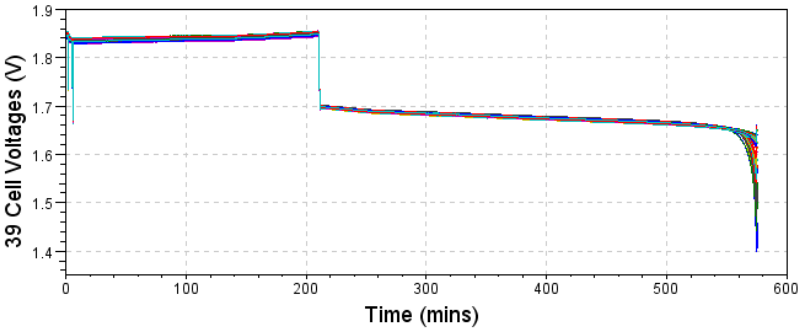




EnergyCell Beta Test: 4 kW, 23.5 kWh





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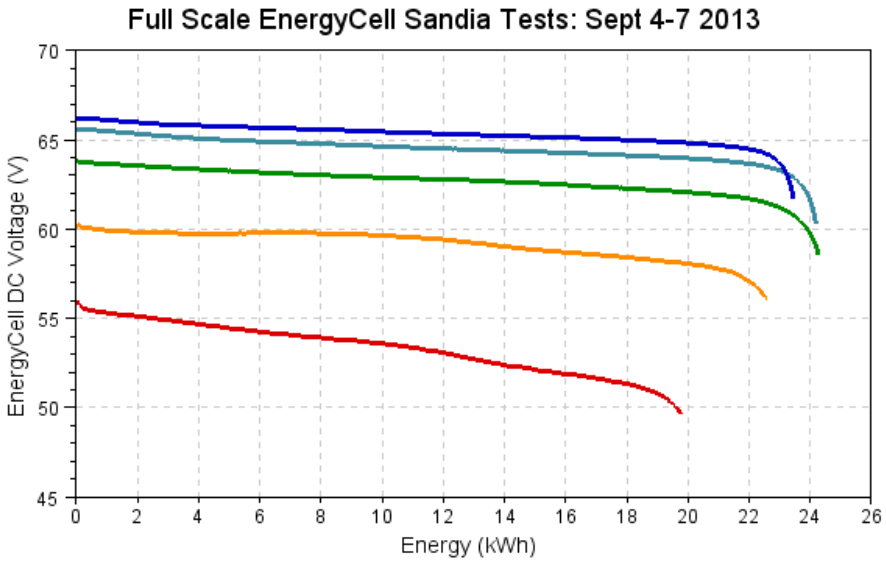
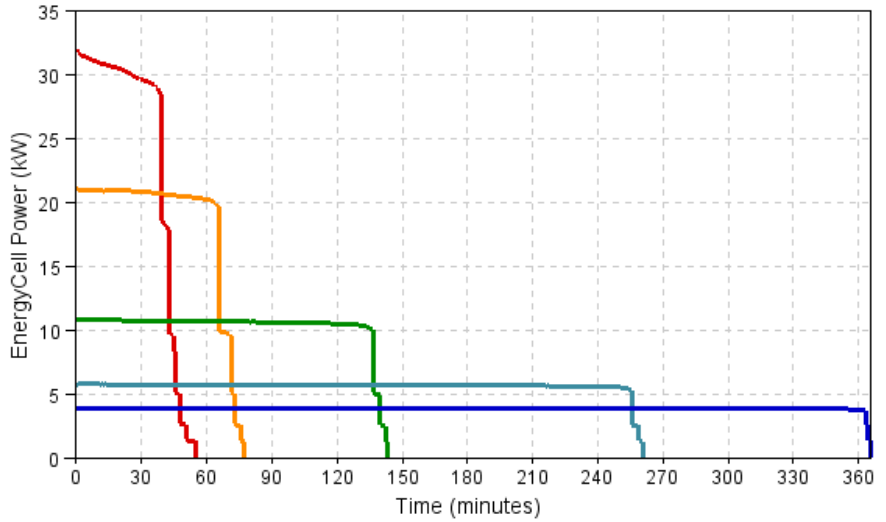
# EnergyCell operates over a wide range of output power/duration



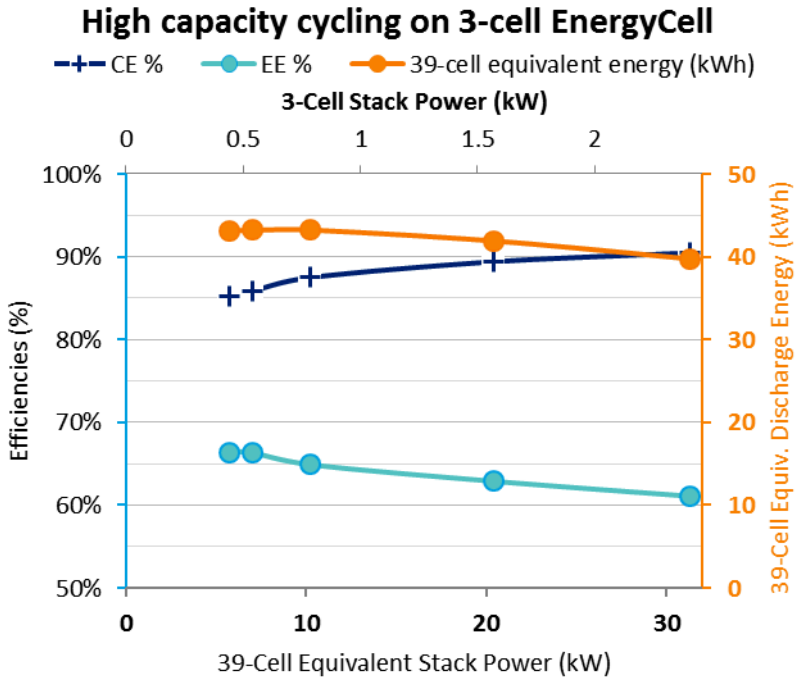

- 6 hour discharge/peak shave A
- 4 hour discharge/peak shave B
- 2 hour discharge/peak shave C
- 1 hour discharge
- High power test

# 3-Cell Prototype Cell test Results

## Highlights

- 3-cell Beta system demonstrates equivalent of 43 kWh energy capacity at scale
- High efficiency performance (61% to 67%) across a wide range of power outputs

| | Power (scaled) | Energy (scaled) | Efficiency |
|---|---|---|---|
| **High capacity tests** | (kW) | (kWh) | (stack, DC) |
| 7.5 hour discharge* | 5.8 | 43.2 | 66.4% |
| 6 hour discharge* | 7.0 | 43.2 | 66.3% |
| 4 hour discharge | 10.2 | 43.2 | 64.9% |
| 2 hour discharge | 20.4 | 41.9 | 62.9% |
| High Power* | 31.3 | 39.7 | 61.1% |



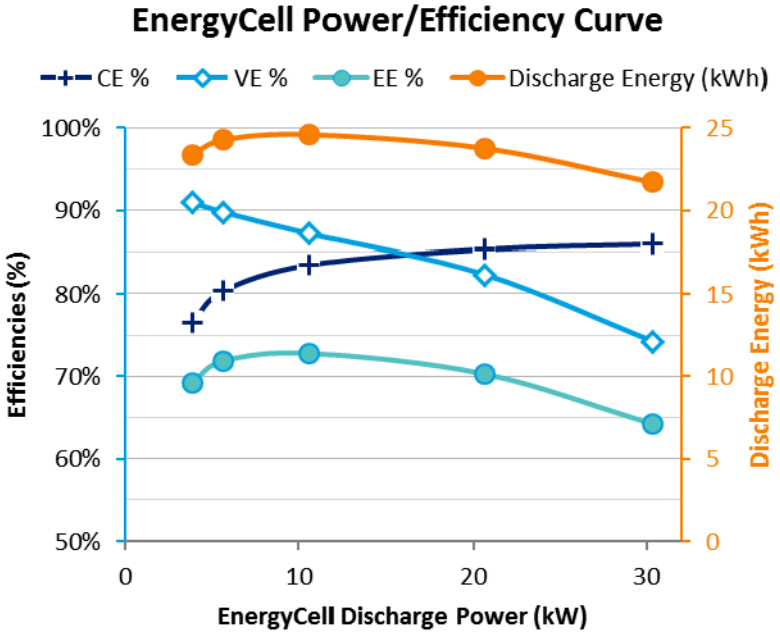

* Primus DAQ data, At press time, these data points had not yet been incorporated into the final Sandia report

# EnergyCell test results

## Highlights

- Production representative module performance validated at scale
- High efficiency performance (64% to 73%) across a wide range of power outputs (4 to 30 kW)

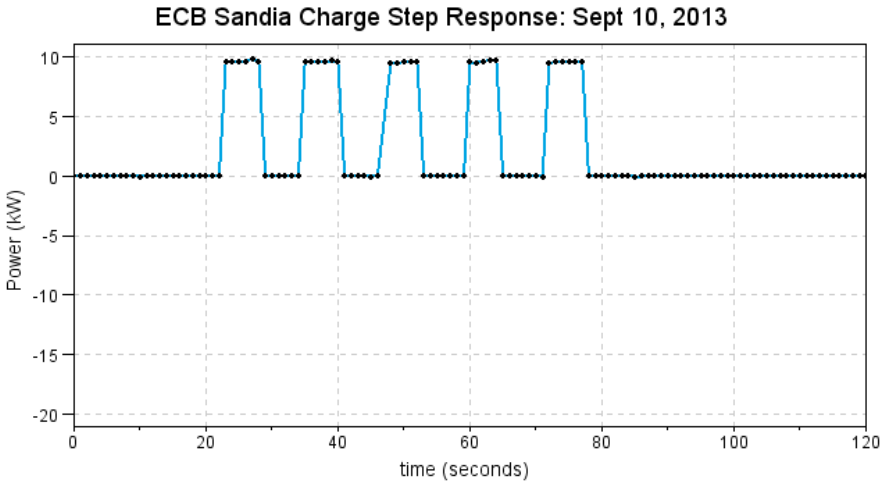
| High capacity tests | Power (kW) | Energy (kWh) | Efficiency (stack, DC) |
|---|---|---|---|
| 6 hour discharge | 3.9 | 23.4 | 69.3% |
| 4 hour discharge | 5.7 | 24.3 | 71.9% |
| 2 hour discharge | 10.6 | 24.6 | 72.8% |
| 1 hour discharge | 20.6 | 23.8 | 70.3% |
| High power | 30.3 | 21.7 | 64.2% |



# EnergyCell step response tests

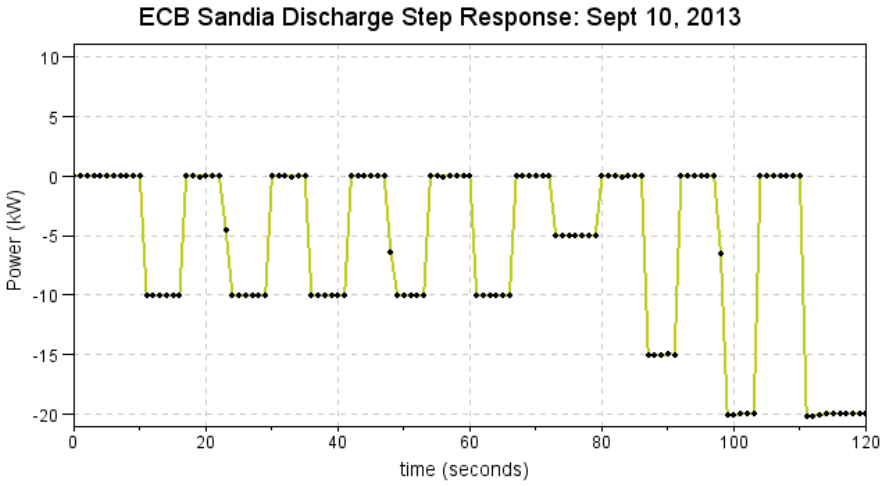
## Charge Step Response

- Command: idle to +10 kW
- Results: response ~1 sec




## Discharge Step Response

- Command: idle to -5, -10, -15 and -20 kW
- Results: response ~1 sec




## Step Response test results

- Data demonstrates that the system is capable of high response rate energy storage applications

Note: 43 kW power supply and 30 kW load bank used for testing

# EnergyCell testing summary and takeaways

| | Current Performance | Applicability to real world |
|---|---|---|
| EnergyCell scale up validated | • Discharge power of > 30kW<br>• Discharge energy of > 40kWh | Large format, grid scale suitable battery design enables EnergyPods® with 280 – 420 kW DC power rating |
| Flexible discharge rate | • Discharge at any power between 4 – 30 kW with small efficiency sensitivity<br>• Translates to 0.75, 1, 2, 4, 6, 7.5 hour long discharge durations | Critical capability to serve applications:<br>• Peak shaving<br>• Distribution deferral applications |
| Rapid response to dispatch commands | • Can respond to full scale step change power commands in 1 second or less | Critical capability to serve applications:<br>• Frequency regulation<br>• Spinning reserve<br>• Renewables firming |

Next steps:

- Additional Sandia EnergyCell testing in the near future
- EnergyPod® completion and testing

# In 2014 Primus will ship EnergyPods to three customers

| Application | Primus demonstration deployment | Value streams | Partners |
|---|---|---|---|
| **Military and Microgrids** | **Marine Base at Miramar**<br>EnergyPods® + PV<br>  <br>**100's kW** | • Energy security w/out generators<br>• Demand charge avoidance | Raytheon<br>Department of Defense<br>ESTCP |
| **T&D deferral** | **Puget Sound Energy**<br>Power dense arrays<br>  <br>**2-5 MW** | • Avoided cost and asset deferral<br>• Capacity value<br>• Balancing services<br>• Outage mitigation<br>• Arbitrage | Department of Energy<br>Bonneville Power Administration<br>Pacific Northwest National Laboratory |
| **Renewable integration** | **Modesto Irrigation District**<br>Multi-MW arrays<br>  <br>**10+ MW** | • Avoided cost and asset deferral<br>• Capacity value<br>• Balancing services<br>• Arbitrage | State of California Energy Commission<br>Department of Energy<br>BOSCH |





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# Smart Grid Storage™