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Cooperative Agreement

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Renewable Firming EnergyFarm®

Final Report

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The early testing performed by Sandia National Laboratory was informative and encouraging. For their support and willingness to share information, we would like to thank Mick Wasco from MCAS Miramar and the Raytheon Integrated Defense Systems - Advanced Technology Programs team, especially Ryan Faries and David Altman.

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1 Introduction

The American Recovery and Reinvestment Act (ARRA) of 2009 (Recovery Act) provided the U.S. Department of Energy (DOE) with funds to modernize the electric power grid. One program under this initiative is the Smart Grid Demonstration program (SGDP). The SGDP mandate is to demonstrate how a suite of existing and emerging smart grid technologies can be innovatively applied and integrated to prove technical, operational, and business-model feasibility. The aim is to demonstrate new and more cost-effective smart grid technologies, tools, techniques, and system configurations that significantly improve on those commonly used today. Primus Power's project was selected through a merit-based solicitation in which DOE provides financial assistance through a cooperative agreement.

Primus Power is a provider of low cost, long life and long duration energy storage systems. The Company's flow batteries are shipping to US and international microgrid, utility, military, commercial and industrial customers.

Founded in 2009, Primus is privately held, located in Silicon Valley and has a subsidiary in Asia. The Company has received 32 patents in 8 countries, and has 37 additional patents pending. Primus has R&D and commercial partnerships with several of the world's leading electrical component, chemical and power companies.

Flow batteries offer a unique advantage for grid storage. As Bill Gates remarked in launching the Breakthrough Energy Coalition "unlike lithium-ion batteries, a flow battery could last for decades and the rechargeable electrolyte liquid could last indefinitely."

Primus Power's EnergyPod® is a modular battery system for grid scale applications available in configurations ranging from 25 kW to more than 25 MW. The EnergyPod provides nameplate power for 5 hours. This long duration unlocks economic benefits on both sides of the electric meter. It allows commercial and industrial customers to shift low cost electricity purchased at night to offset afternoon electrical peaks to reduce utility demand charges. It also allows utilities to economically reduce power peaks and defer costly upgrades to distribution infrastructure.

An EnergyPod contains one or more EnergyCells - a highly engineered flow battery core made from low cost, readily available materials. An EnergyCell includes a membrane-free stack of titanium electrodes located above a novel liquid electrolyte management system. This patented design enables reliable, low maintenance operation for decades. It is safe and robust, featuring non-flammable aqueous electrolyte, sophisticated fault detection and built-in secondary containment. Unlike Li Ion batteries, the EnergyCell is not susceptible to thermal runaway.

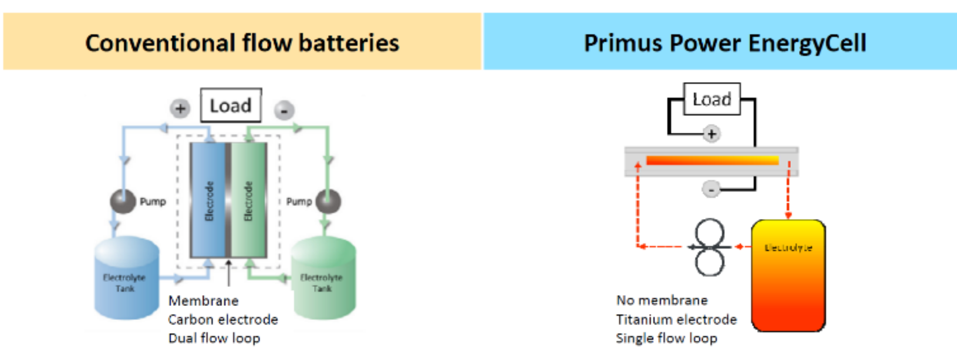

Figure 1: Comparison of Primus Power to conventional flow batteries

2 Project Objectives

The objectives of the project are:

1. Trigger rapid adoption of grid storage systems in the US by demonstrating a low cost, robust and flexible EnergyFarm®.
2. Accelerate adoption of renewable energy and enhance grid stability by firming the output of wind & solar farms.
3. Demonstrate improved grid asset utilization by storing energy during off-peak periods for dispatch during local load peaks.
4. Establish an advanced battery manufacturing industry in the U.S.
5. Reduce CO_2 emissions from utilities.

The project was originally described as Wind Firming EnergyFarm® with an installation at Modesto Irrigation District (MID) as the demonstration of performance. This title and installation site were chosen very early in the process. When Primus Power first applied for the ARRA grant, the first prototype had not yet been built. During the project, MID ultimately decided to not install any storage systems within this time period. However, an EnergyPod® installation at Marine Corps Air Station (MCAS) Miramar was a good platform for demonstrating the objectives. The MCAS Miramar system is a microgrid with photovoltaic panels, building loads and an EnergyPod® ESS. It can be operated either connected to the grid or in an island mode. This enables demonstrations of renewable generation smoothing, peak shaving, resiliency to grid outages and net load time shifting. This microgrid project was built by Raytheon Integrated Defense Systems.

3 Key Milestones

To support the project objectives, several key milestones were established to measure progress.

Milestone	Original Plan Date	Actual Completion	Comment
Beta EnergyCell testing	Sep 2013	July 2013	
EnergyPods® 3rd Party Validation	Jun 2014	Sep 2013 & Jul 2014	Sandia Nat'l Lab test 2013 NREL Controls test 2014
First production EnergyPods® built	Apr 2014	May 2015	
Field commission first EnergyPod®	Aug 2014	May 2015	Factory acceptance test at Primus
Field commission final EnergyPod®	Jul 2016	Nov 2015	Commissioned at MCAS Miramar

Figure 2: Key project milestone summary

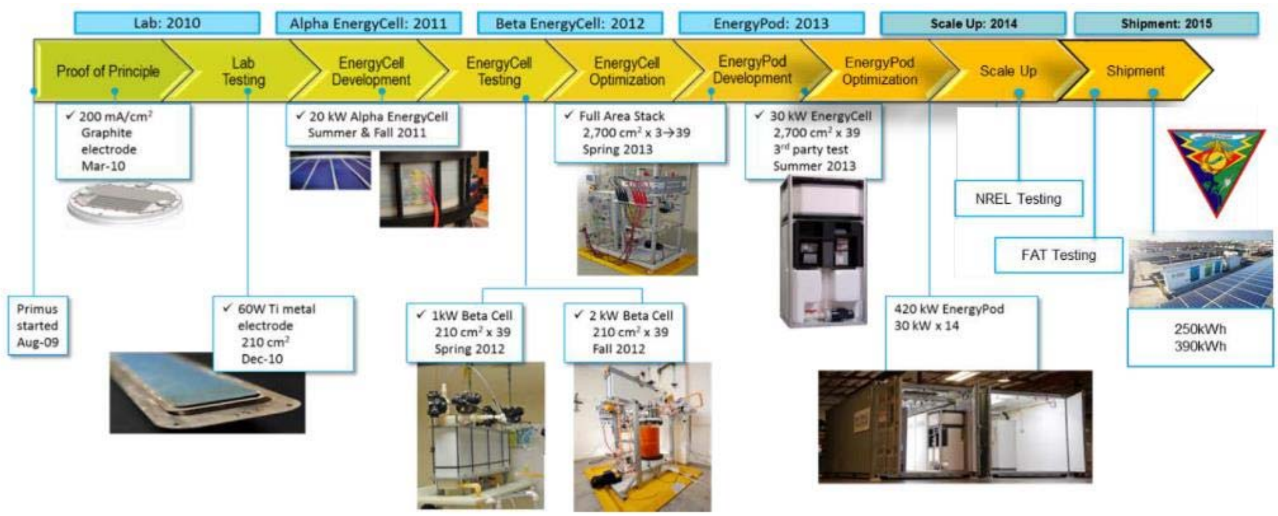

Figure 3: Key project milestones

4 Results and Data

4.1 Beta EnergyCell testing results

A hybrid flow battery is defined by one or more electroactive species being deposited as a solid. In the zinc-bromide battery, the capacity is determined both by electrolyte volume and by the electrode area on which solid zinc is deposited. Therefore, the tank and battery stack must be sized together to dictate capacity.

Primus Power technology is a novel approach to battery energy storage systems. An EnergyCell includes a membrane-free stack of titanium electrodes located above a unique liquid electrolyte management system. This patented design enables reliable, low maintenance operation for decades. It is safe and robust, featuring non-flammable aqueous electrolyte, sophisticated fault detection and built-in secondary containment.

During the period 2010-2013 Primus Power developed the basic process and built progressively larger systems to scale the electrolyte tank capacity and electrode area. By July 2013, Primus Power had developed a full-scale electrode system designated as a Beta EnergyCell. Internal testing confirmed that the results were scaling as expected. Testing by a third party was then scheduled to validate these results.

4.2 3rd Party Validation

4.2.1 Beta Energy Cell Testing by Sandia National Laboratory

The Sandia National Laboratories (SNL) performed independent validation of the electrical performance of the Primus Power EnergyCell. In September 2013, testing was performed at Primus Power's headquarters in Hayward California. An engineer from SNL installed a remote Data Acquisition System (rDAS) to independently collect data and validate the electrical performance of the EnergyCell.

Figure 4: Beta EnergyCell Test Setup

The high capacity test protocol mirrored the emerging DOE protocol with discharge durations of 2, 4 and 6 hours.

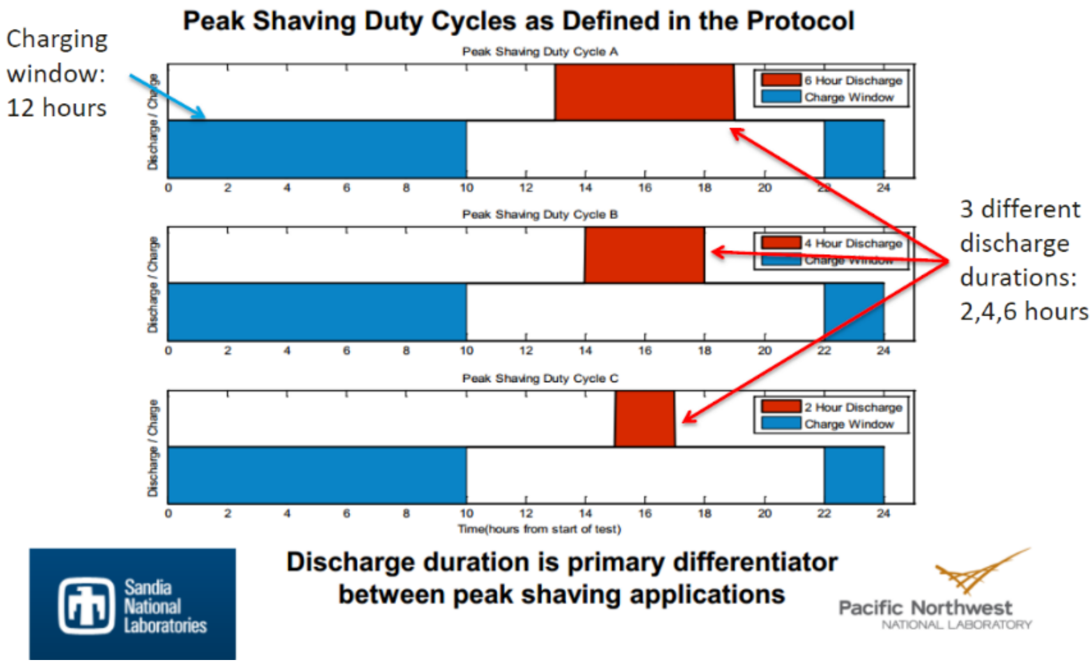

Figure 5: High Capacity Test Protocol

The testing showed strong performance and storage application versatility.

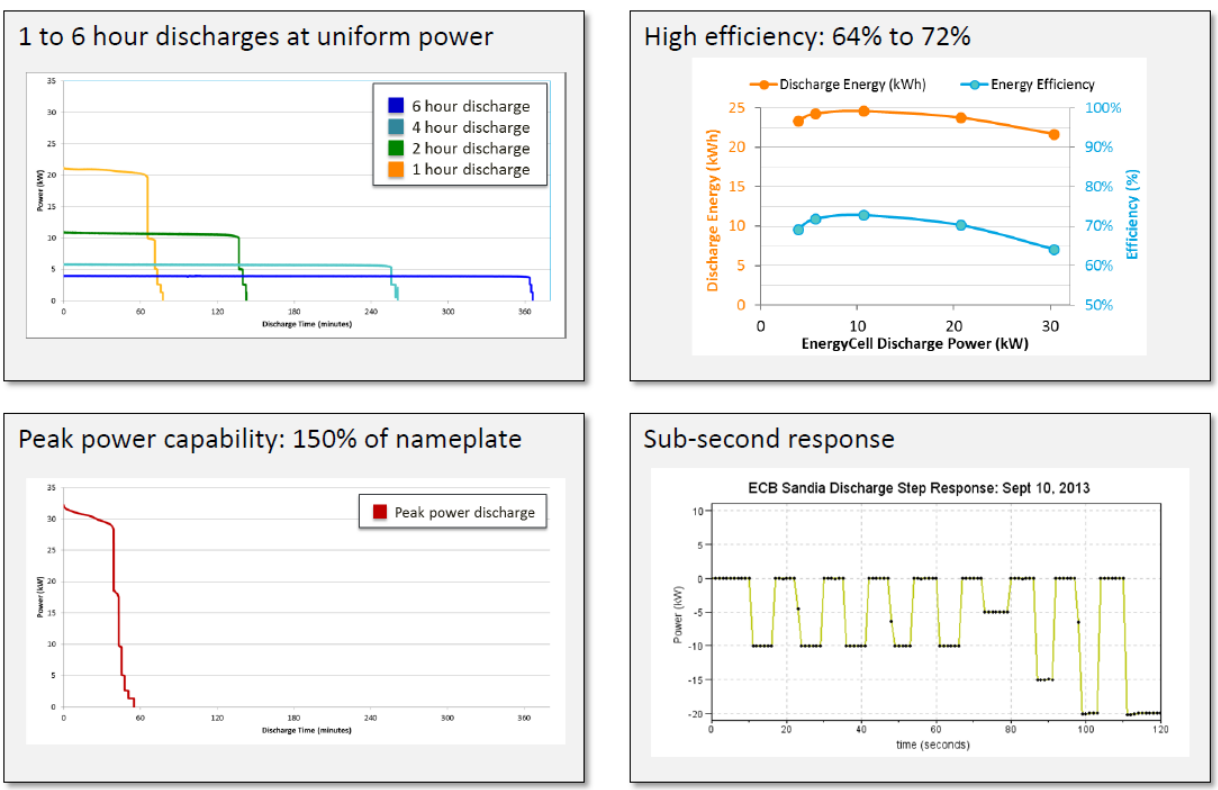

Figure 6: Summary of Beta EnergyCell Testing by Sandia National Laboratory

In *Test Report: Primus Power EnergyCell (SAND2013-9034)* SDL summarized the results as:

> *The EnergyCell represents the full-scale module that will be replicated 14x in order to build an EnergyPod®. It has allowed engineers to rapidly implement changes in design to a full scale module. The EnergyCell performed as expected during testing, successfully completing the discharge rate sensitivity test, the pulse impedance test, and the capacity test on the 3-cell module. The EnergyCell was measured to have energy efficiency between 64.2% and 72.8%. The highest energy efficiency of 72.8% was observed at a 10kW discharge rate.*
>
> *The data show that the system can rapidly respond to fluctuations in current, and therefore to system power setpoints, despite the need to actively supply reactants to the cell. These data are consistent this design being capable of high response rate application.*

	EnergyCell Performance	Energy Storage Applications
Flexible discharge rate and duration	• Discharge at any power between 4 – 30 kW with small efficiency sensitivity • Translates to 0.75, 1, 2, 4, 6, 7.5 hour long discharge durations	Critical capability to serve applications: • Peak shaving • Distribution deferral applications
High power capability	• Discharge power at 150% of nameplate	Ability to have superior economics by capturing/releasing power at economically optimal times
Rapid response to dispatch commands	• Can respond to full scale step change power commands in 1 second or less	Critical capability to serve applications: • Frequency regulation • Spinning reserve • Renewables firming

Figure 7: Test Results and Storage Application Relevance

4.2.2 Controls Testing at National Renewable Energy Laboratory

Raytheon Integrated Defense Systems was contracted to demonstrate the energy security and cost benefits of implementing a Zinc Bromide (Zn/Br) Flow Battery-based Energy Storage System (ESS) at the MCAS Miramar. The effort integrated Primus Power's Zn/Br Flow Battery Energy Storage System and Raytheon's Intelligent Power and Energy Management (IPEM) technologies with the existing MCAS infrastructure including photovoltaic panels and building loads. The project demonstrates energy security and islanding capability, while reducing costs.

While Primus was building their large scale EnergyPod® in 2014, Raytheon orchestrated integrated controls testing of the MCAS Miramar microgrid utilizing the National Renewable Energy Laboratory (NREL) Energy System Integration Facility (ESIF). The testing was designed to provide high-fidelity evaluation of the MCAS Miramar microgrid in a simulated operational environment with real hardware in the loop and full scale/full power simulated sources and loads. The system testing reduced a lot of risk on integrating the IPEM controller to manage the existing Advanced Energy PV inverters at MCAS Miramar, the Primus ESS, and the various metering and control logic of the microgrid. The testing at NREL was designed to re-create the designed Miramar microgrid at as high a fidelity as possible.

The NREL test system utilized the same PV inverters that exist at MCAS Miramar, a similar main breaker point of common coupling, and the same inverter & BMS utilized by Primus Power's ESS.

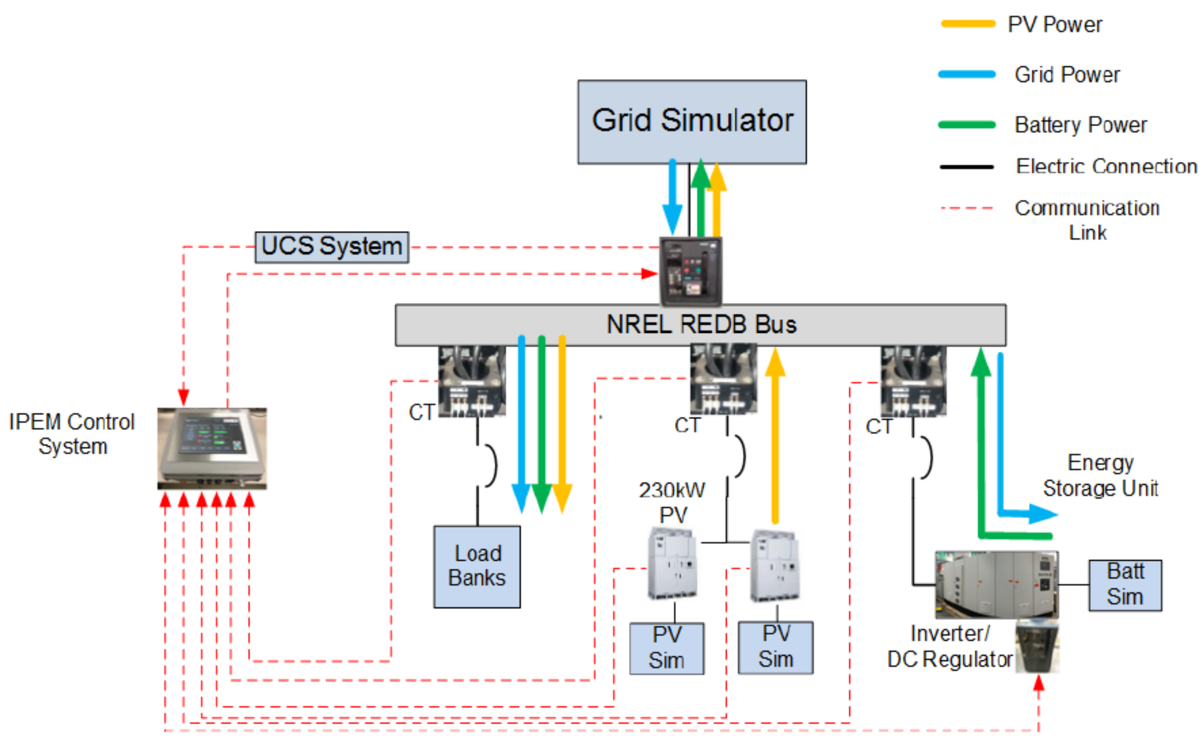

Figure 8: Single Line Drawing of Raytheon Controls Test at NREL

During the course of testing, Raytheon hosted a demonstration with Primus Power, MCAS Miramar stakeholders and a representative from the US Marine Corps Headquarters (Randy Monohan). Randy was the MCAS Miramar station energy manager when this project was originally proposed and one of the earliest advocates in the project.

The results of the NREL testing are summarized below:

Goal	Result
The black start sequence and transition to islanding work as anticipated within the 1hr time requirement	Demonstrated automated back start sequencing
The ESS inverter and PV inverters power share properly in islanding mode	Verified load sharing across operating range (0-200kW, 0.1-1.0PF)
The UL1741 anti-islanding algorithms do not destabilize the ESS inverter in voltage control mode	No issues observed
The PV penetration be pushed to >50% without de-stabilizing the ESS inverter in voltage control mode	Successfully run up to 100% PV penetration (w/bi-directional power flow to ESS)
The system does not destabilize due to dynamic PV curtailment and the system can handle load step requirements for Miramar's load	Characterized PV curtailment response timelines in response to increasing and decreasing load changes
The system meets IEEE1547.4 requirements for power quality.	No issues staying within trip points

Figure 9: Raytheon Controls Test Results at NREL

4.3 First production EnergyPod® built

The EnergyPod® for MCAS Miramar consisted of 14 EnergyCells integrated into a 40' containerized enclosure with thermal management, fire suppression and DC power management systems. There is an adjacent Power Box that houses the storage inverter, transformers, protection devices and AC/DC distribution equipment. This was the first EnergyPod® built by Primus Power and required overcoming numerous challenges and setbacks. The effort applied to developing a supply chain, procedures and systems helped to establish an advanced battery manufacturing industry in the U.S.

Figure 10: EnergyCell Being Tested in Pilot Manufacturing

Figure 11: EnergyCells Installed in the EnergyPod®

4.4 Factory Acceptance Test of EnergyPod®

Prior to shipping the EnergyPod®, Raytheon and MCAS Miramar participated in a Factory Acceptance Test (FAT) at Primus Power's facilities in Hayward, CA. These tests were conducted in May 2015.

Peak Shaving test: The objective of the Peak Shaving test was to demonstrate that EnergyPod® is capable of storing energy during off peak hours and push 250kW back to the grid during peak hours. It is important to note that the power output of battery is the net output power of the entire Energy Storage System. This means the battery output power minus the auxiliary power to the battery which includes: the control power to all the pumps, power electronics, inverter, chiller and the heaters. It is important to mention this as various energy storage systems have a separate auxiliary power requirements in their systems and don't subtract it from their output power when providing ratings.

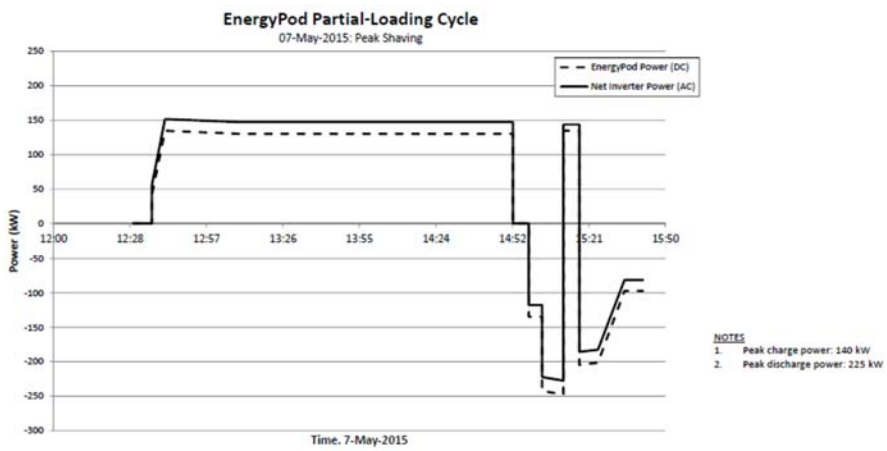

Figure 12: FAT 250 kW Discharge During Peak Shaving Test

Energy Storage Capacity: The objective for the Energy Storage Capacity test was to demonstrate the Energy storage capacity capability in grid tie mode. The energy capacity capability of the ESS was determine to be 390kWh during the FAT

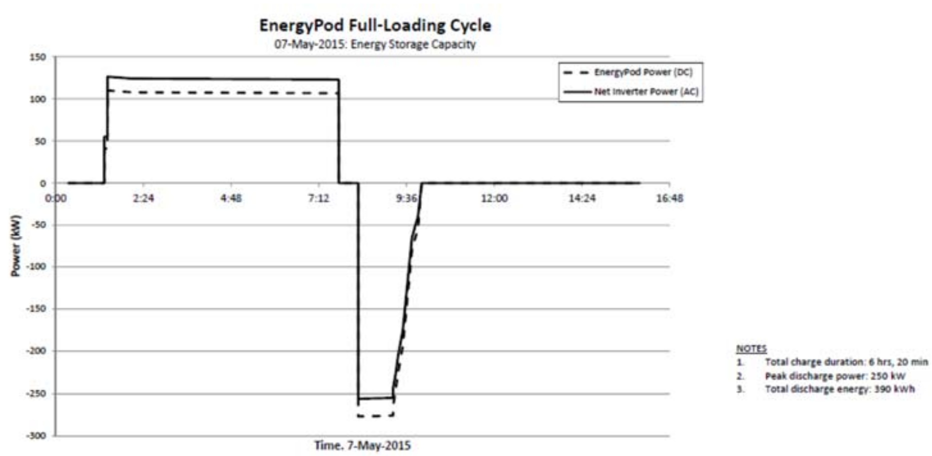

Figure 13: FAT Energy Storage Capacity Test

Islanding Capability test: The objective of the Islanding Capability test is to demonstrate that in islanding mode the Central Regulator (CR) can regulate the bus voltage while the inverter creates the grid to supply power to any load connected to the island. This test has two important aspects. The system needs to be able to start the EnergyCells and boost the bus voltage in order to enable the inverter to create the island by putting out 480vac 3ph output. Test Procedure:

1. Open the main disconnect switch to the Grid and lock out tag out the disconnect switch
2. From the EnergyBlock GUI select Islanding operation
3. The system shall:
4. Turn the Aux. power to the EnergyPod and inverter
5. Send the EnergyCells into the discharge mode
6. Charge the bus voltage to 750vdc
7. Start the inverter

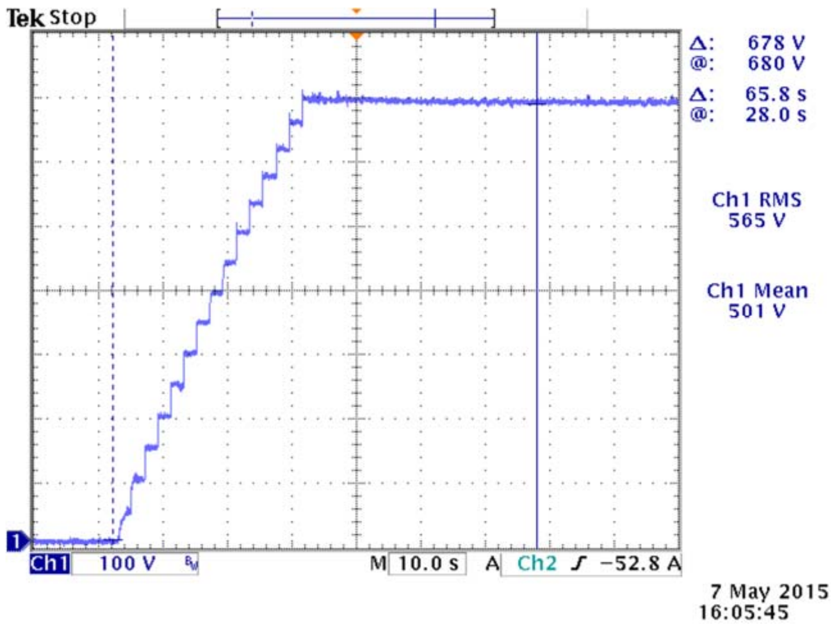

Figure 14: FAT Islanding Capability Test

At the conclusion of the FAT testing, the ESS was demonstrated to be functionally operational however still lacking in the desired Energy Capacity performance. At this point, Primus Power's team had made tremendous amount of progress and investment to get the system to function as required. Primus presented solutions that provided better electrolyte flow across the electrode reducing the non-uniformity allow more zing to be plated across the electrode surfaces improving the energy capacity. The new design of the cell frames were still in their test phase and would require retrofits of all 14 EnergyCells that were ready to be deployed, delaying the program. As the program did not have enough time or resources to continue developing the ability to increase the energy capacity any further the system was accepted by Raytheon with agreement and understanding from MCAS Miramar to deliver the system at the end of May 2015.

4.5 Field Commission and Objectives of EnergyPod®

The site civil and electrical work were completed at MCAS Miramar in the summer of 2015. The EnergyPod® was installed below car port photovoltaic panels adjacent to the photovoltaic inverters and a building.

Figure 15: EnergyPod® Rigging and Placement at MCAS Miramar

Figure 16: EnergyPod® Installed at MCAS Miramar

There are four performance objectives for demonstration at MCAS Miramar. The performance objectives were established based on early discussion with MCAS Miramar personnel and to meet particular mission scenarios for improved energy security and operational cost reductions.

1. Islanded Duration
2. Building Load Reduction
3. Switchover Time
4. Peak Shaving
5. Energy Storage Capacity

4.5.1 Islanded Duration

Islanding is defined as being able to intentional isolate local facility circuit from the local electric power system as defined in IEEE 1547.4. The circuit is then power by the operation of the ESS, and RE. The Islanded duration will be the time that the system is commanded into islanded mode to the time that the system can no longer sustain the loads of the circuit.

The purpose of the Islanding objective is to demonstrate the applicability of an isolated utility circuit going off-grid. This is useful in the case of an extreme event that could disrupt commercial utility power supply. Emergency back-up operations can be maintained by operating off of RE and an ESS if the load required is maintained within acceptable operation levels of the PV system and ESS.

4.5.2 Building Load Reduction

The building load reduction Performance Objective is defined as the percentage of load that has been reduced during an islanded event as compared to the previous year's average for that given month during normal grid connection.

The purpose of this Performance Objective is to characterize the amount of building load reduction during an islanded event required in order to meet the 72hr islanded objective.

4.5.3 Switchover Time

The Switchover Time defined as the time required to switch the system from its grid transition mode (i.e. standby during grid outage) into islanded mode.

The purpose is to characterize the timeline for islanded operations.

4.5.4 Energy Storage Capacity

This Performance Objective (PO) measures the energy storage capacity of the ESS when operating in grid connected operations. The purpose of this Performance Objective is to show that the energy capacity of the energy storage system meets its rated 1 MWh capacity.

4.5.5 Peak Shaving

Peak Shaving is defined as being able to arbitrage power stored from off-peak to on-peak periods. This allows a facility to load shift in order to reduce the facilities demand charges. The ESS is charged and discharged in order to change its demand load profile seen by the utility company as shown in Figure below. This is useful for facilities that are on a tiered pricing scheme and/or are hit with high charges of energy use during hours of peak operation. The ESS can charge during off peak times at a lower cost and discharge during peak hours reducing the peak loads required by a facility.

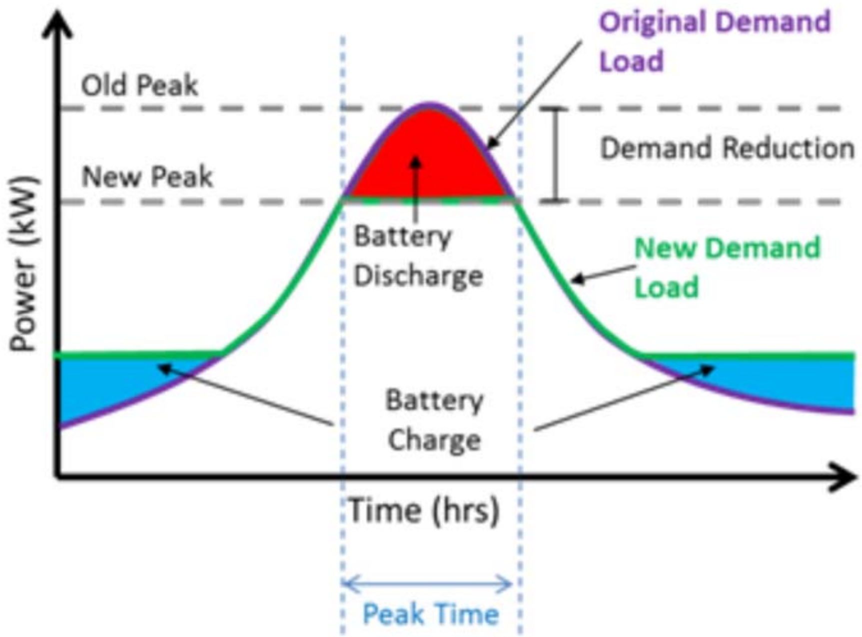

Figure 17: Simplified Representation of Peak Shaving

For many commercial and industrial facilities the cost of electricity can be heavily determined by the amount of peak power that a facility uses during a billing period. The largest peak power demand, typically for a minimum of 15 minutes, will dictate how much the facility is charged for that billing period. Different utility companies have different demand charge rate structures. Some utilities are so congested during peak times that they have a defined peak time period during the day where they charge a higher demand rate then off-peak periods. Utilities that have this type of rate structure also usually have incentive programs or mandatory demand response programs where the facility can volunteer to participate or be directed to participate in load shedding during seasonal peak times. Some utilities have a blanket demand charge that is based on the highest 15 min peak demand for a given billing month regardless of peak times. Controllable peak shaving can provide a facility with flexibility to reduce its peak demand depending on its rate structure.

4.6 EnergyPod® Test Results at MCAS Miramar

In conjunction with Raytheon and MCAS Miramar various tests were performed to evaluate the performance of the battery against these objectives.

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives				
Energy Security Performance Objectives				
Islanded Duration	Islanded Duration (hours)	Meter readings from RE system, ESS, and grid power feed	Building loads are met by ESS and PV for 72hrs under controlled load conditions meeting power quality standards of IEE1547.4	Building loads were met by ESS and PV for 5 hours 10 minutes meeting power quality standards of IEE1547.4. ESS is capable of 7 hrs 10 min.
Building Load Reductions	Delta Average kWh/day usage	Meter readings from building 6311.	Building loads can be reduced by 50% through manual changing of thermostats and lighting when compared to its previous year's average for that given month.	Building loads were able to manually increased and decreased increased by 68% when compared to baseload during islanding test
Switchover Time	Time (minutes and seconds)	Clock timing from command to go into islanded mode to ESS discharging power	Time is less than hour	Switchover from Grid to Islanding was 4 minutes
Operational Cost Reduction Performance Objectives				
ESS Energy Storage Capacity	Energy Discharged in kWh	Meter reading of energy discharged by ESS	ESS is able to discharge 1MWh of energy during peak shaving cycle.	ESS was able to discharge 390kWh in the lab and 290kWh in the field
Peak Shaving	Peak Demand Reduction (kW)	Meter readings from RE system, ESS, and grid power feed	ESS is able to store energy during off peak time and discharge 250 kW during peak time to reduce peak load relative to historical data over similar time period.	ESS was able to store energy during off peak time and discharge 100kW during peak time for 2 hrs and 45 min
Qualitative Performance Objectives				
Ease of Operation	Degree of ease of use	Survey	Satisfactory rating from survey results.	Survey to be issued before final report

Figure 18: Summary of Performance Objectives and Results

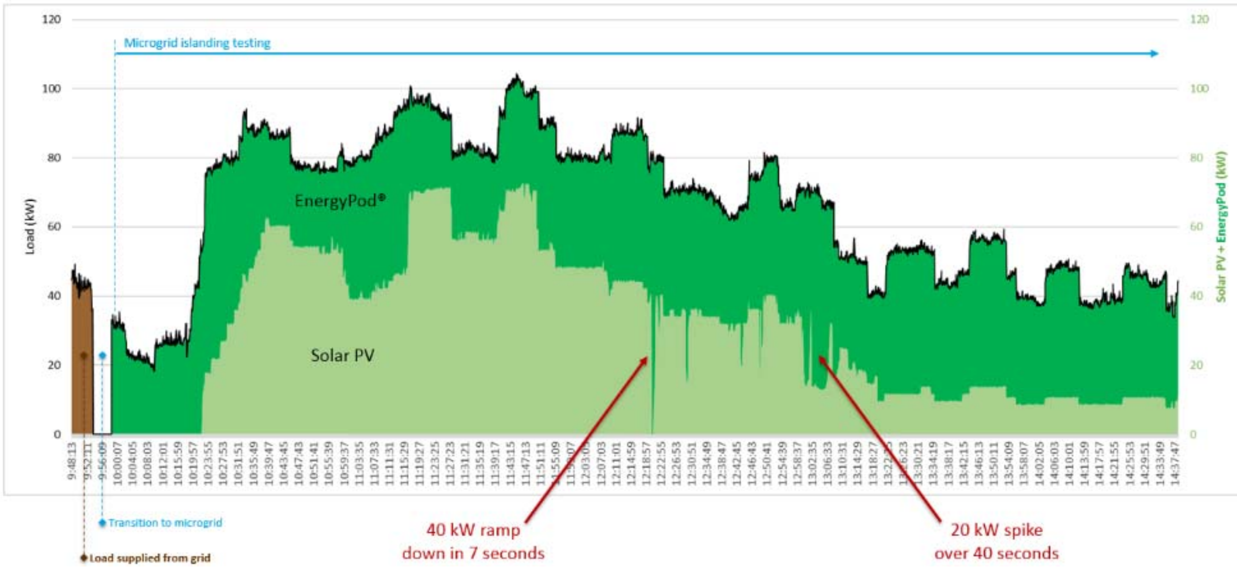

Figure 19: Renewable Smoothing by EnergyPod® at MCAS Miramar

5 Summary and Lessons Learned

The desired goals and benefits of the cooperative agreement with the DOE have all been achieved. The project has contributed to reducing power costs, accelerating adoption of renewable energy resources, reducing greenhouse gas emissions and establishing advanced battery manufacturing in the U.S.

The Recovery Act funds provided thru the DOE have been leveraged multiple times by additional private equity investment. Primus Power continues to ship low cost, long life and long duration EnergyPods® flow battery systems to utilities, commercial/industrial, microgrid and data center customers.

The ARRA investments categorically kick-started the energy storage industry. There is a large ecosystem that did not exist at the start of the project with companies currently becoming highly advanced. In order to move the energy storage industry forward, Primus believes that the next round of government funded projects should focus on reference projects that get storage to a tipping point. For Primus, the next tier would be a 2 MW reference project. It would also be helpful if the DOE loan guarantee program could encompass projects of this size.

After the conclusion of this project, Primus Power has modified the EnergyCell and EnergyPod® design to optimize around energy performance. Primus Power has moved to a prefabricated enclosure instead of multiple EnergyCells in a container. This lowers capital and maintenance costs and can optimize site design. Utilities are starting to adopt energy storage for a variety of functions. The market will grow as the technology is proven and profitable applications expand.

State level incentives and mandate have greatly increased the deployment of energy storage systems. This has spurred competition, led to a maturation of various technologies and a significant decrease in market costs across the industry. Similar federal programs could have an even larger effect; improve the electrical grid infrastructure and further spur investments in U.S. based manufacturing.