Project Overview

• Supporting the industry investigation into vehicle battery secondary-use through testing, demonstration, and modeling.
  – Potentially a cost competitive energy storage technology
  – Validate reliability and safety – working with industry to troubleshoot and test systems under operational conditions
  – Examining regulatory environment – investigating hurdles that are institutional
  – Industry acceptance – build confidence in this technology.
Secondary Use of EV Batteries

• Potentially significant electric vehicle market.
  – Projections from different studies show significant growth.
  – June 2014, Tesla is releasing all patents to encourage electric car production

• What can we do with the on-board battery technologies?

  Repackage/Reuse: Could provide a low-cost grid storage solution (if design of repackaged system does not require significant modifications and added expense.)
Already Available in USA

- Over 150,000 plug-in electric vehicles (PEVs) currently in USA (study by UCLA Luskin Center for Innovation – December 2013)
  - ~55% of PEVs are PHEV and 45% are BEV
  - Near 70% of these vehicles are Nissan Leaf, Chevy Volt, or Tesla

  - Nissan Leaf
    - Nearing 40,000 Vehicles
    - 24 kWh per pack
    - ~960MWh

  - Chevy Volt
    - Exceeding 50,000 Vehicles
    - 16.5 kWh per pack
    - ~825MWh

  - Tesla
    - Nearing 20,000 Vehicles
    - 85 kWh per pack
    - ~1700MWh

- Leads to an estimated 3.485GWh of existing battery storage.

- Estimates on capacity of the batteries. Detailed analysis will need to consider operational constraints, BMS level limits, and other aspects.
Demonstration Sites: Repurposing of Batteries

- Utilizes BMW mini-E batteries and BMS/Princeton Power Systems interface hardware.
- 108 kW/180kWh with DC coupling to PV.

- Utilizes General Motors Volt batteries and BMS/ABB interface hardware.
- 25kW/50kWh system connected to ORNL test-bed, PV smoothing and shifting.
Current Activities

An effective partnership that merges equipment, technical know-how, and infrastructure:

- Energy Storage – Used EV Batteries
- Energy Management System
- Electric Grid

ORNL is testing and demonstrating the technology as a third party.
The Technology

GM Chevy Volt Battery

Automotive Application
- Capacity for 10 Years in Automotive Application
- Power 111kW
- Liquid Cooled / Heated

Grid Application (25kW/50kWhr)
- Expected capacity for 10 Years of Operation
- 5 Volt Battery Packs
- 5 kW per Volt Battery
- Air Cooled/Heated

ABB Enclosure

Re-Packaged
Zone 1: The system has a single-phase connection with the grid, PV Array, AC breakers, islanding contactor, and voltage sensing.
Zone 2: Inverter measures and senses inputs to control charging and discharging needs (4 quadrant)
Zone 3: Batteries connected on DC link and controlled by BMS. BMS uses voltage, current, and temperature information to relay control information to inverter.
Zone 4: Safety interlocks to prevent unsafe access
Zone 5: Thermal management with fans, heaters, and HVAC.

Multi-tiered layers of security are present in the system to ensure a safe operation.
System Benefits: CES

Local benefits:
Real and Reactive Power Support
• demonstrate that load factor and power factor can be maintained.

Service reliability
• during outage, CES unit can still supply load for a period of time.

Phase balancing
• if three units are installed (each on separate phases) additional energy can be used to balance phases.

Grid benefits:
Firming and shifting Renewables and Load leveling / T&D Deferral
• battery can charge/discharge depending on control and load behavior.

Ancillary Services
• regulation/spinning

Similar benefits can be realized by distributed energy storage for commercial applications.
Testing Setup at ORNL

- ORNL objective for testing: Provide **real world** examination **systems integration** and **applications** with the flexibility to capture many different case scenarios.
Hard/Soft: Communication and Control

Communications and control done through Serial, Modbus over Serial, and TCP/IP

- All integrated through Matlab/Labview

- Load Bank utilized for Emulation.

DECC Facility
ORNL/Distribution
GRID

Communications Cable, RS232/RS485
over Modbus

Communications Cable, RS232
over Modbus

LabVIEW

CT/VT

LOAD

M&V

CONTROL/COMPUTING

CES

ROOFTOP PV
Hardware: Equipment Inside DECC

- 480V/240V (split-phase) Transformer
- Emergency Disconnect
- Programmable Load Bank
- Islanding Contactor/Relay
Battery
Enclosure
Inverter
PV Array
Emergency Disconnects
Interface

Manual Control

Set of pre-programmed controls

CES Alarms

State display
Controls and Programs

- Auto-runs at 12:00AM
- Controls depend on selected settings.

• MATLAB
  - Load Bank Temp
    - Temperature (C)
  - Emergency Monitoring
    - text message
    - email
  - Main Control
    - STOP
  - Data Processing
    - Data
  - Historian
    - Data
  - Storage
    - Cloud Cover
      - % Cloud Cover
  - Solar Irradiance/PV output
    - kW PV
  - Residential Model Consumption
    - kW load
  - GA Optimization
    - Control Mode, P, Q
    - SOC Estimate
    - Load Factor Control Points
    - PV Forecast
  - Load Bank Temp
    - Temperature (C)
  - Data Acquisition
    - Measured Data
Measurements and Simulation Additions

- Load Bank is controlled to follow residential load profiles through macros.
- Residential profiles are developed through modeling and historical data collection.
Residential Modeling

- Residential data has been sub-metered and collected for several years. Used to develop and validate load models.
- Markov Chains are used to drive residential loads such as washer/dryer/water heaters...

Markov Chains

<table>
<thead>
<tr>
<th>Activity</th>
<th>09:00</th>
<th>10:00</th>
<th>11:00</th>
<th>12:00</th>
<th>01:00</th>
<th>02:00</th>
<th>03:00</th>
<th>04:00</th>
<th>05:00</th>
<th>06:00</th>
<th>07:00</th>
<th>08:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleeping (6:59 pm)</td>
<td>99.55%</td>
<td>0.08%</td>
<td>0.06%</td>
<td>0.05%</td>
<td>0.04%</td>
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<td>0.00%</td>
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<tr>
<td>Grooming (6:59 pm)</td>
<td>0.26%</td>
<td>96.43%</td>
<td>0.05%</td>
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<tr>
<td>Laundry (6:59 pm)</td>
<td>0.07%</td>
<td>0.09%</td>
<td>98.23%</td>
<td>0.01%</td>
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<tr>
<td>Food Preparation (6:59 pm)</td>
<td>0.01%</td>
<td>0.03%</td>
<td>0.01%</td>
<td>0.02%</td>
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<tr>
<td>Dishwashing (6:59 pm)</td>
<td>0.06%</td>
<td>0.15%</td>
<td>0.10%</td>
<td>0.12%</td>
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<td>Watching TV (6:59 pm)</td>
<td>0.05%</td>
<td>0.03%</td>
<td>0.01%</td>
<td>0.04%</td>
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<td>Computer Usage (6:59 pm)</td>
<td>0.03%</td>
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<td>Non-Power Activity (6:59 pm)</td>
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<td>Away (6:59 pm)</td>
<td>0.00%</td>
<td>0.01%</td>
<td>0.00%</td>
<td>0.04%</td>
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<td>Away, Traveling (6:59 pm)</td>
<td>0.04%</td>
<td>0.19%</td>
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PV Forecasting for Optimization

Collect Cloud Forecast

Neural Networks (Irradiance Forecast)

Weather Underground

Solar Irradiance

Ambient Temp

Solar Panel/Model

Module Temp

Solar Thermal Model

PV Curves

Maximum Value

MMPT (Power)

FEMP
Federal Energy Management Program

TVA
Testing Procedure (Systems Tests)

• Objectives:
  – Obtain standard metrics (round-trip efficiency/ensure within bounds of standards)
  – Demonstrate application examples

• Standard Metrics:
  – Round-trip efficiency
  – Harmonics, etc.

• Applications
  – Load factor,
  – Power factor,
  – Renewable Integration,
  – Islanding
Multiple Value Streams: Stacking Benefits (Load Factor/Power Factor, Renewable Integration)

- Power (W)
- Grid (nearly flat)
- SOC (%)
- Histogram power factor

Target Set to 0.97
SOC target to return to 50%

Power (Var)
Target Set to 0.97
TE: PV Smoothing/Capacity Firming

Objectives:
Integrate PV by removing oscillations and error in forecast.

Benefits:
1) Removing oscillations in PV output can impact local voltage.
2) In some cases these oscillations lead to significant tap changes in transformers. Smoothing this behavior with storage can extend transformer life.
**TE: Islanding Mode**

**Objectives:**
Utilize storage for emergency backup power

**Benefits:**
1) Provides power during an outage
2) Can be used to support contingency type events as well to reduce load consumption.
Initial Economic Approach

- Battery Model
- Grid Services
- Data
- (Mixed Integer) Linear Optimization
- Optimal Battery Dispatch
- Cost/Savings
Initial Economic Results

- Arizona Public Service Company residential rate structures
- Year-long simulated load for 3 homes
- Dispatch the battery to minimize the homeowners’ cost
- Utilized efficiencies of real system, 10year/3000 cycle battery
Initial Economic Results

Arizona PSC E-12 (Tiered) (10yrs/3000cycles)

- Cost with battery
- Cost without battery

Arizona PSC ECT-2 (Demand Charge) (10yrs/3000cycles)

- Cost with battery
- Cost without battery

Arizona PSC ET-2 (Time-of-Use) (10yrs/3000cycles)

- Cost with battery
- Cost without battery

Arizona PSC ET-SP (Time-of-Use SuperPeak) (10yrs/3000cycles)

- Cost with battery
- Cost without battery
Future Tasks

- Modeling and economics assessment for DES.
- Development of refurbished secondary use ES.