Proceedings of

NIST/DOD Workshop on

Power Conditioning System Architectures for Plug-in Vehicle Fleet as Grid Storage

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List of Abbreviations

AC	Alternating Current
AFCI	Arc Fault Circuit Interrupter
A/S	Ancillary Systems
DC	Direct Current
DOD	Department of Defense
DER	Distributed Energy Resource
DRG	Distributed Resource Generator
EPRI	Electric Power Research Institute
ES	Electrical Systems
ETESS-DC	Energy Tank Electricity Storage System-Direct Current
EV	Electric Vehicles
FREG	Frequency Regulation
FY	Fiscal Year
GFCI	Ground Fault Circuit Interrupters
GIV	Grid Integrated Vehicle
GWh	Giga Watt-hour
ICE	Internal Combustion Engines
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineers
ISO	Independent System Operator
kVA	kilo Volt Ampere
kW	kilo Watt
kWh	kilo Watt-hour
Li	Lithium
MAGICC	Mid-Atlantic Grid Interactive Car Consortium
NEC	National Electric Code
NFPA	National Fire Protection Association
NIST	National Institute of Standards and Technology
OEM	Original Equipment Manufacturer
PCS	Power Conditioning System
PV	Photovoltaic
PEV	Plug-in Electric Vehicles
PHEV	Plug-in Hybrid Electric Vehicles
SMUD	Sacramento Municipal Utility District
SOC	State of Charge
T&D	Transmission and Distribution
TSO	Transmission System Operator
UL	Underwriter Laboratories
UPS	Uninterruptible Power Supply
V2G	Vehicle to Grid
VAC	Volts AC

1. Summary

On June 13, 2011, 43 invited participants convened in a Workshop held at The Pentagon in Arlington, VA. The objective of this Workshop, sponsored by NIST and DOD, was to discuss the characteristics of system architectures that will be required for power conditioning systems in vehicle batteries that can be periodically used to feed electricity to the grid to meet demands for increased power. This approach has been designated as Vehicle to Grid (V2G).

The Workshop began with an introduction by the Workshop Chairman and a Department of Defense (DOD) presentation on their perspective on Ancillary Services (AS) that could be provided by Electric Vehicles (EV). Seventeen additional presentations were then given by selected speakers in seven panel sessions that addressed the following questions:

Panel A	What are existing ancillary service markets where a Plug-in Electric/Hybrid-Electronic Vehicle (PEV) Fleet might participate?
Panel B	What additional grid storage requirements and markets might emerge that could utilize a PEV Fleet?
Panel C	How might a PEV Fleet aid in integration of distributed variable renewable generators? How might a PEV Fleet aid in integration of resilient micro-grids?
Panel D	PEV Battery as Grid Storage - Impact of dual-use on Battery Life Degradation?
Panel E	What PEV charging and bi-directional charging units are available today? How might onboard vehicle propulsion inverters and converters be utilized for PEV grid interconnection?
Panel F	How might large grid inverters be used to integrate multiple vehicles and other generator/storage devices? How might DC circuits and DC micro-grids be utilized within a PEV Fleet Power Conditioning System (PCS) architecture?
Panel G	In addition to DOD, what other potential large PEV Fleets might emerge?

When the panel sessions were completed, the Workshop participants were asked to summarize and submit their responses to the following questions:

- How might the value proposition of different PEV Fleet PCS approaches be categorized by vehicle type, fleet usage type, and local grid type?
- What are PCS gaps and next steps required to enable Vehicle Fleet as storage?

The key conclusions of the Workshop were that:

- The number of PEV vehicles and fleets are expected to increase in size as federal government energy goals for reductions in liquid transportation fuel consumption and carbon emissions are pursued.
- The potential for storage of electricity in vehicle batteries is large. Attractive opportunities exist with vehicles and fleets that have a low service factor including

delivery vans, rental car lots, used car lots, taxi fleets, bus fleets, school bus fleets, etc.
- The present cost of vehicle batteries is high. Dual use helps spread the cost burden. The cost impact of the addition of electricity storage capability must be factored in.
- Ancillary Services have the potential to provide income to battery owners.
- Injection of relatively small amounts of stored energy into local T&D networks smoothes out grid operation, provides renewable ramp-rate smoothing, and provides fast response power during transition to islanded mode during start up of diesel generators.

Additional conclusions specific to DOD were that:

- DOD has specific targets for reducing liquid fossil fuel (gasoline and diesel) consumption.
- Several DOD bases have specific objectives for security purposes of becoming grid independent islanded operations. In support of that objective, plans are in place to increase the amount of on-base renewable power production.
- A market exists for electricity that can be delivered to the grid for ancillary services from vehicle batteries at DOD facilities.
- Utilities look at the power quality at the connection point of DOD bases. Therefore, DOD bases may have a unique opportunity to accrue monetary value by improving power quality prior to electricity export.

2. Introduction

On June 13, 2011, 43 invited participants convened in a Workshop held at The Pentagon in Arlington, VA to discuss architectures and technologies for grid connected power conditioning systems used as bidirectional chargers of electric vehicle batteries that also provide grid storage functions. The following description of the workshop was provided to each invited participant.

> *Transportation electrification has become a US national priority emphasized in legislation (such as the Energy Independence and Security Act) and Administration Policy recognizing that it will bring about substantial reductions in petroleum consumption and harmful emissions through increased efficiency and fuel diversity advantages. Plug-in Electric/Hybrid-Electric Vehicles have advanced in recent years to become economically competitive with conventional vehicles, especially when considering the prospect of utilizing the vehicle batteries to also provide certain grid supportive electricity storage functions. In the near term, the economic advantages of vehicles providing grid storage functions might be more readily realized by Fleet Vehicles; such as the US DOD Fleet of non-tactical vehicles.*
>
> *The vehicle charging infrastructure is a key enabler in bringing about the transition to electric transportation. The purpose of this workshop is to identify gaps and opportunities in Power Conditioning System (PCS) architectures and technologies necessary to support the use of a Plug-in Vehicle Fleet as grid storage. The workshop will begin by reviewing the grid storage functions that might increase the value proposition of a Plug-in Vehicle Fleet as well as the impact of these storage functions on vehicle battery life. The grid storage use cases considered to potentially provide economic value for implementation with Plug-in Vehicle batteries will be used to define the functional requirements for the vehicle-to-grid PCS architecture discussions that follow.*
>
> *The status of existing and planned vehicle-to-grid charger/inverter systems will be reviewed during the workshop, and innovative approaches for increasing the value proposition of the vehicle-to-grid PCS will be discussed. For example, advanced vehicle charger/inverter PCS architectures might include: 1) using the on-board propulsion inverters and/or on-board DC-DC converters as part of the grid charger/inverter PCS, 2) using a large inverter for grid interconnection of multiple vehicles and Photovoltaic Solar (PV) arrays, and 3) using DC circuits and micro-grid approaches to reduce the number of required power conversion functions. The readiness of technology and safety codes to implement the advanced architectures will also be highlighted.*
>
> *The workshop concludes with discussions of possible transition strategies for electrification of large Vehicle Fleets including their use for grid storage functions. Vehicle Fleets that might be good candidates for electrification including grid storage functions will be identified and categorized by vehicle type, usage type, and local grid type. For representative Plug-in Vehicle Fleet types, the advantages and disadvantages of various PCS architectures will be discussed and contrasted. The outcome of the workshop is a report defining the PCS approaches, gaps and next steps required to enable electrification of Vehicle Fleets including grid storage functions.*

Introductory remarks reviewing US Policy and Programs for Electric Transportation were made by Camron Gorguinpour, U.S. Air Force – Office of the Assistant Secretary, who provided “A DOD Perspective on EV Ancillary Services”. The objectives of the DOD Electric Vehicle program are:

- Reduce petroleum consumption,
- Reduce greenhouse gas emissions,
- Increase use of Alternative Fuel Vehicles,
- Develop an optimal strategy to maximize use of Electric Vehicles in DOD’s non-tactical ground fleet, while minimizing lifecycle investment,
- Achieve lifecycle cost parity (or better) between EV and comparable ICE vehicles,
- Begin large-scale integration of EV within FY2012 to last over a period of 3-5 years.

Al Hefner of NIST, the Workshop organizer, then provided an introduction and workshop goals. The workshop objectives were summarized as follows:

- Focus on PEV Fleet deployment options within the next 1-5 years.
- Evaluate options to increase value proposition for V2G:
    - identify inverter and storage functions that provide value,
    - consider impact of these functions on battery/inverter life,
    - identify PCS architectures that might be low cost and suitable for near term deployment including grid integration requirements.
- Define fleet types (public and private) that might participate.
- For each Storage/Inverter function, PCS architecture, and PEV Fleet type; what are:
    - advantages and disadvantages,
    - technology and utility readiness for 1-5 year timeframe, and
    - appropriate approaches for different fleet types.

Seventeen presentations were then given by selected speakers in seven panel sessions, which included a question and answer period that followed each presentation. The individual panels of selected speakers were charged with responding to the following questions:

Panel A What are existing Ancillary Service markets where a Plug-in Electric/Hybrid-Electronic Vehicle (PEV) Fleet might participate?

- Scott Baker (PJM) - ISO/RTO Markets – Frequency regulation, Spinning reserve, Peak shaving and VARs
- Willett Kempton (MAGICC) Demonstration Project – Plug-in EVs for Frequency Regulation

Panel B What additional grid storage requirements and markets might emerge that could utilize a PEV Fleet?

- Tom Weaver (AEP) - Current Utility Needs for Storage and Ability to Integrate
- Kevin Schneider (PNNL) - Potential Value of Storage for Distribution Systems

Panel C How might a PEV Fleet aid in integration of distributed variable renewable generators?

- Glenn Skutt (PowerHub) - Inverter/Storage functions to support Renewable Integration

How might a PEV Fleet aid in integration of resilient micro-grids?

- William Siddall (next energy) - Storage functions to support Resilient Microgrids

Panel D PEV Battery as Grid Storage - Impact of Dual-use on Battery Life Degradation.

- Dave Nichols (Altairnano) - Impact of grid storage functions on battery degradation
- Cyrus Ashtiani (Saft) - Dual-use Energy Storage - Grid and Auto
- Eric Hsieh (A123) - Regulatory, Business and Policy Issues for PEV as Storage

Panel E What PEV charging and bi-directional charging units are available today? How might onboard vehicle propulsion inverters and converters be utilized for PEV grid interconnection?

- Kathryn Miles (Eetrex) - Vehicle to grid charging/inverter systems
- Ron Lacobelli (Azure Dynamics) - Hybrid Electric Truck Power Electronics
- Bill Alexander (Ideal Power Converters) - Multi-port converter: Grid, Battery, and Propulsion

Panel F What are existing ancillary service markets where a Plug-in Electric/Hybrid-Electronic Vehicle (PEV) Fleet might participate?

- Leo Casey (Satcon) - Large Grid-Supportive Inverters for Solar, Storage, and V2G

How might DC circuits and DC microgrids be utilized within a PEV Fleet Power Conditioning System (PCS) architecture?

- Paul Savage (Emerge Alliance) - DC Microgrids and Applications
- Mark Earley (National Electrical Code)- Safety Considerations - Grid Inverters and DC circuits

Panel G In addition to DOD what other potential large PEV Fleets might emerge?

- Bruce Gruenewald (NSI) - Bus Fleet Vehicle-to-Grid Storage
- John Bryan (Fleet Energy Company) - Business Development of Vehicle Fleets as Storage

These presentations are currently available for review and/or download at:

www.nist.gov/pml/high_megawatt/jun2011_workshop.cfm

When the panel sessions were completed, the workshop participants were asked to summarize and submit their responses to the following questions:

- How might the value proposition of different PEV Fleet PCS approaches be categorized by vehicle type, fleet usage type, and local grid type?
- What are PCS gaps and next steps required to enable Vehicle Fleet as storage?

3. Integrated Overview of Presentations

A) US Policy and Programs for Electric Transportation

Key Points

- US federal policy is supporting the electrification of the US vehicle fleet to accomplish the following objectives:
  - reducing fossil fuel consumption,
  - reducing air pollution (including CO_2),
  - increasing use of alternate fuel vehicles. (Hefner)
- Achieve lifecycle cost parity (or better) between EV and comparable ICE vehicles. (Gorguinpour)
- Begin large-scale integration of PEV within FY2012 to last over a period of 3-5 years (Gorguinpour)
- Typical vehicle usage in the US currently averages about one hour per day, leaving the other 23 hours per day potentially available for V2G applications. (Bryan)
- At a projected level of 1,000,000 plug-in vehicles (<1% of registered passenger vehicles on the US roads), each carrying a ~15 kWh store of energy, a sizable 15 GWh distributed storage system could become available. (Ashtiani)

Additional Information Specific to DOD

- DOD is considering an optimal strategy to maximize use of electric vehicles in DOD's non-tactical ground fleet, while minimizing lifecycle investment (Gorguinpour)
- Large, under-utilized non-tactical vehicle fleet is ideal for EV ancillary services
  - The majority of DOD trucks average about 6000 miles per year of use, compared to less than 20,000 miles per year for DOD passenger vehicles, which are both low use factors. (Gorguinpour)
  - Hardware and software exist to integrate EV with micro- and macro-grids. (Gorguinpour)
  - OEM support is necessary for implementation. (Gorguinpour)
  - Revenue estimates range from ~$2,000-$6,000/vehicle, depending on vehicle type. (Gorguinpour)
  - Cost savings estimates from peak shaving are ~$1,200-$1,800/vehicle. (Gorguinpour)
- Financial propositions remain unclear.
  - Revenues/Cost-Savings must be more clearly defined. (Gorguinpour)
  - Bi-directional charging infrastructure costs unclear. (Gorguinpour)
- Operational requirements for DOD fleet must be met. (Gorguinpour)
- Controlled environment on DOD bases enables relatively low-risk technology deployment. (Gorguinpour)
- Continental U.S. military bases are ideally suited as a prototype for green community micro grids (Ashtiani)

- There is an opportunity for DOD to take a leadership role in addressing the nation's looming energy security problem and dependence on foreign oil (Ashtiani)
- Hybrid Intelligent Power for Forward Operating Bases reduces diesel fuel requirements by up to 40% (Alexander)

B) Use of EV as Grid Storage

Key Points (Hefner)

- Economic drivers for off-grid electricity storage include:
    - supplying cost-effective ancillary services,
    - peak load shaving/leveling,
    - more efficient energy arbitrage,
    - premium power for islanding,
    - smoothing rapid ramp rates of solar, wind, and large loads.
- Several demonstration projects have shown that it is technically feasible to provide grid storage functions with PEVs
- Currently, battery and vehicle manufacturers believe fast charging and deep Depth-of-Discharge cycles will negatively impact the life of batteries:
- Value proposition for PEV depends on vehicle transportation and grid storage usage and is uncertain for the typical consumer.
    - Fleet Vehicles with well defined use conditions present a unique opportunity to assure a positive value proposition from V2G
    - Grid storage/inverter functions can have positive and/or negative affects on local and regional grids; e.g., participation in regional markets can impact local distribution system power quality.
- Distributed Energy Resources (DER) including generators and storage devices must comply with interconnection regulations of the local Public Utility Commission (in most states this is based on IEEE 1547 with local exceptions).
- DER installations must also meet the local legal requirements for compliance with the NFPA, National Electrical Code including UL 1741 conformity testing of installed devices.
- Photovoltaic solar generators have spearheaded the development and utility acceptance of grid inverter functions.
- The Smart Grid Interoperability Panel - Priority Action Plan 7, and the EPRI PV-Storage Communication Project defined requirements for storage functions in IEEE 1547.8 and IEC 61850-7-420.

Other Detailed Information (Weaver, Ashtiani, Kempton, Schneider)

General Benefits to the Grid of Electricity Storage

- Economic drivers for storage include:
    - Ancillary Services
        - Frequency regulation

        - Spinning reserve
    - Peak load shaving/leveling
        - T&D infrastructure project deferrals
        - Increased utilization of existing generation
        - Load Leveling at substation
    - Premium power for islanding
        - Islanding of Load Area
        - Power Quality
    - Integrating Solar / Wind Generation
        - Smoothing variability
        - Time shifting
    - Network decongestion by time-shifting load or generation
    - More Efficient Energy Arbitrage
        - Charge at lower cost / Discharge at higher value
    - Power Factor Correction
    - Ability to form micro-grids

- **Other Local Benefits of Storage**
    - Backup power (Weaver)
    - Flicker Mitigation (Weaver)
    - Microgrid communities can embody multiple synergistic concepts: distributed renewable generation (DRG), stationary distributed storage resources (community type ES, as well as larger scale for backup power & regulation), EV and PEV, and charging stations within the microgrid (Ashtiani)
    - EV and PEVs within that green community prototype can then become an integral part of the grid, and serve as a last resort rather than day to day functions of the grid (Ashtiani)

- **EV Storage Demonstration Projects**
    - Several demonstration projects have shown that it is technically feasible to provide grid storage functions with PEVs
    - University of Delaware Project (Kempton)
        - Create the Grid Integrated Vehicle (GIV), then operate, permit, and test it
        - Design of Aggregator
            - Provides a single, large, stable and reliable power source
            - Transmission System Operator (TSO) does not see details of single cars, only sees aggregate
            - Aggregator bids capacity in TSO market
            - Dispatches requests to vehicles
            - Reports actual power dispatched
        - Demonstration
            - Seven vehicles in Delaware
            - Each capable of up to 19.2 kW to or from power electronics (versus most OEMs at 3-4 kW charge only)
            - When plugged in, registers with server and offers capacity

    - Battery performance
        - Power response is very close to command signal
        - Far higher fidelity than any rotating equipment
  - Potential contribution of stored EV power to grid
    - US generation capacity ~1000 GW, average load ~450 GW
    - US light vehicles: 200 million
    - At 15 kW/vehicle: 3,000 GW
    - Vehicle batteries: 3x generation, 6x average load
  - Storage at the low-voltage end of the distribution system has value
    - 15 kW & 30 kWh means ~1 hr discharge thus capacity markets, not energy
    - Second use of customer equipment, thus capital costs are controls
    - Need to aggregate many small storage units to get utility-scale power for TSO
  - Capital cost is on-board intelligence plus communications is now ~$400
    - For example, an EV with 15 kW, 30 kWh
    - Capacity cost: $27/kW
    - Storage cost: $13/kWh
  - Recommendations for Power Plug
    - Should be 12 - 20 kW, not 2-6 kW
    - Should be 208 or 240 VAC, not 110 V
    - User convenience: last minute charge or roadside recharge at a mile-a-minute

- Mid-Atlantic Grid Interactive Car Consortium (MAGICC) (Baker)
  - Providing regulation from 5 aggregated vehicles
  - Vehicles primarily used during 7-9 AM, 12-1 PM, and 5-7 PM
  - Vehicles tested in non-use periods for regulation service at 50 ms charge/discharge
  - Over three years experience
  - Also demonstrated minimization of cost by responding to the PJM wholesale price signal (LMP) and the PJM frequency regulation signal in a 105-gallon, 4.5 kW electric water heater

- **Integration of the PEV Fleet with distributed variable renewable generators**
  - Integration of stationary storage with the intermittent load of rapid charging PEVs (Skutt)
    - Proposed 2-3 MW capacity ETESS-DC (Energy Tank Electricity Supply System – Direct Current) to act as dynamic buffer between renewable DC generation (PV, wind, and microturbines) and DC EV charging requirements
    - Requires storage system inverter control and integration with PEV activities
      - Emerging standards for inverter control

                - Inverters are generally underutilized relative to the functionality they can provide
            - Sacramento High Penetration Solar Demonstration Project
                - Control group of 25 homes with PV
                    - Residential Group – 15 units
                    - UL listed units
                - Community Energy System Group – 3 units
                    - Connected to secondary of 50 kVA pad mounted transformers serving 9-12 homes
                - Utility/Customer portals monitor PV, storage, customer load
                - Sending price signals to affect changes in customer usage
                - Quantifying costs and benefits of this storage deployment to gain insights to broader application for SMUD
                - Quantifying costs and benefits of this storage deployment to gain insights to broader application for SMUD

- **Microgrids**
    - The size of the microgrid, the amount of generation and load, matters to the effectiveness of individual and aggregated Plug-in Electric Vehicles (PEVs)
    - Examples include 60-200 kW Forward Operating Base Microgrid Simulation at Fort Irwin, CA and 20-80 MW Wright-Patterson AFB, Dayton, OH
    - PEV Fleet Characteristics are defined by
        - Vehicle Specification: PEV Balance of Parts' Design as presented by Original Equipment Manufacturer (OEM)
        - Vehicle Location: Operational requirements when PEV is not a micro-grid storage device
        - Vehicle Service Time: Operational duty cycle compatibility with micro-grid duty cycle. (Siddall)

- **Battery Performance Degradation**
    - Grid applications are diverse with very different duty cycles:
        - The backup power (UPS) {Uninterruptable Power Supply}, e.g., keeps the storage at high state of charge (SOC) and only occasionally taps into the battery with deep Depth-of-Discharge) at near constant rate (Ashtiani)
        - The frequency regulation (FREG), keeps the battery engaged fully when dispatched with random sharp pulses of a few seconds bi-directionally (charge & discharge). Many shallow cycles superimposed on a usually deep daily Depth-of-Discharge cycle (Ashtiani)
    - Time shifting involves charging and discharging the battery at constant rates intercepted by periods of alternately staying at high and low SOC (Ashtiani)

- Different duty cycles and loads call for very different system engineering especially from thermal management perspective (Ashtiani)
- Grid stability is maintained through the balancing of load and supply. Regulation is near zero-energy service compensation for minute-to-minute fluctuations in total system load and uncontrolled generation (Nichols)
- Incremental additions of "fast" energy storage increasingly stabilizes system frequency (Nichols)

- Battery technologies have different life characteristics dependent on Depth-of-Discharge and number of cycles
  - With Li-ion batteries,
    - At 100% Depth-of-Discharge, one technology provides 3-6 times more cycle life than others
    - At low Depth-of-Discharge cycles, over 1 million cycles and up to 100X more life than others (Nichols)
  - Grid Stabilization and hybrid applications that require many cycles per day result in an expected life of 20 years
  - Peak Shifting at a rate of 1 cycle per day results in an expected life of 50 years
  - Operating at 35 °C compared to 25 °C reduces cycle life by a factor of 1.5 to 2
- In two years of operation in PJM ISO
  - Performed over 250,000 small cycles and charged or discharged over 3,300 MW-hr
  - Less than two percent (<2 %) energy capacity degradation and no significant power capacity degradation
  - Expected to maintain rated power and energy capacity for over twenty years without battery replacements or upgrades (Nichols)
- Field data - 4 MW Battery smoothes ramp rate of 18 MW wind farm to 0.5 MW/min (Nichols)
- Variable charging provides ancillary market revenues without consuming life cycles and has the potential to add end-of-life revenue from remaining battery capacity (Hsieh)
- Full V2G (with bidirectional charging) may not be necessary (Hsieh)
  - Ancillary Services (AS) provide sufficient revenue to spur commercial standalone storage projects
    - Frequency regulation (example of actual revenues)
    - Spinning reserves
    - Renewable ramp management
  - Charge-only operation maximizes useful driving range
  - EVs with variable charging can access Ancillary Service markets within existing policy and market rules (EV acts like DR)
  - Variable-rate charging likely to optimize vehicle performance and cost

C) PCS Architectures for PEV as Storage, Alexander Savage

Key Points (Hefner)

- Value of V2G storage/inverter functions are offset by the additional lifecycle cost of PCS and degradation of the battery.
- Bi-directional charger options include on-board or off-board, integrated with drive-train power electronics, and integration with renewable generators and stationary storage.
- PCS architectures have different cost, functionality, communication and control requirements, and ability to integrate multiple devices.
- Two-stage architectures: DC-DC converter and DC-AC inverter/ rectifier can optimize cost and enable devices to share inverter.
- Modular bi-directional DC-DC converters are reported to be significantly cheaper than Level 3 AC chargers.
- Integrated architectures deliver power to both mobile and stationary systems to enhance operation and alleviate solar ramp-rate induced power quality problems at the source.

Other Detailed Information

- PHEV and EV Characteristics
    - Hybrid electric and electric powertrain products in the commercial vehicle segment PHEV and EVs are already cost and weight challenged – V2G must provide economic return if it is to be utilized in the future
    - Azure's PHEV product has the following performance characteristics
        - 14 kWh Li-Ion battery (nominal = 346 V)
        - electric drive motor continuous power ~50 kW
        - 20 mile electric range (blended)
        - Charge time (240 V) ~ 4 hours
    - Azure's Transit Connect Electric has the following performance characteristics
        - 28 kWh Li-Ion battery (nominal =346 V)
        - Electric drive motor cont. power ~ 57 kW
        - 80 mile electric range UDDS
        - Charge time (240 V/30 A) ~ 8 hours
        - Electric pack design life 10 Years - 120,000 Miles
    - What is the best way to integrate – standalone or with drive inverter and motor? Some level of integration is preferred for lower cost, weight and robustness (Lacobelli)
- Vehicle Charging Energy Storage Design Tradeoffs
    - Concentrated/Centralized vs. Distributed Architectures
    - Energy storage: Mobile storage only vs. stationary + mobile storage
        - Maintaining localized power quality, aggregating/managing energy storage, and meeting demand using only mobile resources presents a formidable challenge at high penetration. Limited by existing infrastructure.

        - Stationary storage could act as a buffer to mitigate these issues, and provide rapid charge capability
    - Integration with PV: Significant advantages compared to standalone energy storage architectures
    - Microgrid**:** PV + battery can provide the basis for a high reliability microgrid (Casey)
- Enhanced Inverter Capabilities Enabled by Energy Storage
    - Improved capacity factor: Small amounts of stored energy can mitigate intermittency of renewables
        - Stationary batteries act as a buffer to absorb rapid variations in plant output power
        - Grid Stabilization: Sub-cycle real and reactive power control
    - Reliability: Enables extended ride through and provides voltage and frequency support for both plant AND grid induced disturbances
    - Utility or PV plant
    - Simplified Integration: Capacity factor and reliability enhancements can be implemented on a *fully localized basis,* (Casey)
- Concentrated Inverters enjoy large cost advantages
    - Two-stage inverter architecture coupled with existing grid-smart inverter capabilities provide a natural platform for integration with stationary or mobile energy storage, mitigate problems and provide synergies
    - Enhances the EV value proposition: Low-cost, fully renewable Level 3 recharge capability, low round trip losses,
    - Simplified integration: PV/EV synergies may be realized with localized, autonomous control (no utility involvement); inverter's point of common coupling and site controller provide a natural gateway for managing V2G services
    - Microgrid: Potential to realize a robust, high reliability AC/DC microgrid (Casey)

Bi-directional EV Components

- Inverger (Miles)
    - Bi-directional battery charger/inverter
    - Intelligent charger uses wind/solar to charge
    - Turn vehicle into clean and quiet generator, powering "critical" home/work components for 2+ days
    - 56 PHEV Conversions to date - over 650,000 miles
    - AC Connection
        - 6.6 kW, Voltage Range: 110 – 240 VAC, Current Range: 12 – 30 A
    - DC Connection
        - Voltage Range: 100 – 400 V, Current Set by AC Connection

- Ideal Power Corporation Bi-directional Battery Inverter/Charger
    - Applications
        - Stationary Batteries
            - 30 kW, 480 VAC, three phase, 60 A
            - 0 to 700 V DC

            - Bi-directional, power-to-grid
        - Vehicle Batteries
            - Bidirectional Level 3 DC charger
            - Power-to-grid
            - Common mode isolated or full isolation
- 3-port PV & Battery Inverter
    - Single-Stage Conversion
        - Higher efficiency
        - Operates during faults
        - Grid faults
    - Communications faults
        - DC charging of EV during peaks
        - Reduce peak load/transmission
    - DC charging of EV during peaks
        - Reduce peak load/transmission
- Ideal Power Corporation PHEV Architecture
    - Multi-port, multi-directional converter
    - Superior efficiency, weight/size, cost
    - Simplified cooling systems
    - Supports inductor generator/motor
    - No Permanent Magnets or rare earths

DC Microgrids (Savage)

- Microgrid applications
    - 24 VDC - Lighting, Computers, Sensors, Fans
    - 380 VDC - Battery Storage, Server Gear, Variable Speed Motor Drives, Vehicle Chargers
- Installations for various applications in offices are increasing

Electrical Code Compliance (Earley)

- Applicable Codes
    - Electrical installation requirements--NEC®
    - Product standards -UL, NEMA, etc
        - Product testing to standards
    - Electrical inspection (ensures compliance with the installation rules of the NEC, along with any product installation requirements
- DC Requirements
    - Have been in every edition since the first NEC edition in 1897.
    - There are specific AC and DC requirements
    - Where not specified, requirements apply to AC and DC
- Higher power DC may present new challenges
    - Over-current protection
    - Ground Fault Circuit Interrupter (GFCI) protection
    - Arc Fault Circuit Interrupter (AFCI) protection
    - Switching
    - Circuit protection

- Arc flash evaluation
- Circuit separation

D) Transition to PEV Fleet as Storage

Key Points

- Typical vehicle usage in the US currently averages about one hour per day, leaving the other 23 hours per day potentially available for V2G applications.
- The majority of DOD trucks average about 6000 miles per year of use, compared to less than 20,000 miles per year for DOD passenger vehicles, which are both low use factors.
- Other attractive V2G opportunities exist with batteries in vehicles and fleets that have a low service factor including delivery vans, rental car lots, used car lots, taxi fleets, bus fleets, school bus fleets, etc.

Other Detailed Information

- School Bus Fleets (Gruenewal)
    - Grid operators and utilities have identified PEV V2G capable school buses as an ideal grid storage device for supplying frequency regulation services
    - Predictable usage pattern resulting in availability to the grid of > 75%
    - 77 % of school districts have at least 25 buses
    - Buses are stored in one of three locations: a depot, a school, or a driver's home
    - Average range (with 30 to 50 % margin) can be achieved with a battery of between 100 kWh and 130 kWh
    - 25 PEV V2G buses = 1 MW
- Third Party Ownership of Batteries (Bryan)
    - Fleet Opportunities
        - Transit and school buses
        - Delivery, insurance, utility and waste management company
        - Religious organizations
        - Rail and material transport
    - Fleet Energy owns batteries in commercial vehicles
        - Revenue Stream 1: end user pays "by the mile"
        - Revenue Stream 2: local utility pays "by the hour" for the use of the batteries
    - Fleet Energy operations are highly competitive in regulation and spinning services

4. Issues, Gaps, and Possible Approaches to Issue and Gap Closure

Issues

Technical Issues

- Lower cost, more efficient converters and inverters are being developed for this market. What is the timing of commercial availability and cost of these devices?
- Can small sources of battery-stored electricity be aggregated into marketable bundles that can be bid for ancillary service functions and what is the communication/control requirement?
- Who develops the software and communication and cyber security to control and measure operation?
- Is galvanic isolation of V2G systems required?
- Inverter systems may need to be remotely upgradable to take advantages of future advanced inverter/storage functions.
- Electric Vehicle Charging (Casey)
  - EV charging, especially during peak periods, stresses utility infrastructure
  - New charging infrastructure is required for ubiquitous charging capability
- Renewables Intermittency (Casey)
  - Large, sudden changes in solar and wind plant output power can result in power quality degradation (e.g., flicker)
  - Existing grid infrastructure has much slower reaction times than renewable intermittencies

Commercial Issues

- Energy storage costs remain too high for single benefit value streams although they are coming down. Traditional "cost / benefit" analysis sub-optimizes application (Weaver)
- At today's EV battery and inverter prices, EV have limited commercial competiveness relative to ICE vehicles
- What types of contractual options can be used to provide an economic return to battery owners for V2G functions?
- Who owns the batteries -- fleet owner, individual vehicle owner, leasing company, government unit (DOD), or other?
- How can individual battery owners be compensated for supplying electricity?
- Will there be penalties for failure to deliver?
- Currently, battery and vehicle manufacturers believe fast charging and deep Depth-of-Discharge cycles will negatively impact the life of batteries (Hefner)
  - Value proposition for PEV depends on vehicle transportation and grid storage usage and is uncertain for typical consumer.
  - Fleet Vehicles with well defined use conditions present a unique opportunity to assure value proposition from V2G

Regulatory Issues

- How does the V2G system operate in normal operation and during the need for critical resource operation during a reliability compromise?

- When will advanced storage/inverter interconnection practices (IEEE 1547.8) and object model standards (IEC 61850-7-420 normative revision and associated informative update documents) be available?
- What is the acceptable level of power quality delivered by the V2G operator to meet distribution and transmission requirements?

Gaps

Technical Gaps

- Standardized test protocols for EV batteries have not been established (Nichols)
- Bidirectional applications face technical constraints (Hsieh)
- Energy Storage should be "visible and controllable" to distribution operators via SCADA (Weaver)
- Energy storage should have "configurable" control algorithms to allow dynamic changes to meet economic / reliability benefit opportunities (Weaver)
- Integrated inverters (discharge) are not utility scale (MW are required, not kW) (Bryan)
- Lack of "vehicle to utility" standard communication protocols (Bryan)

Commercial Gaps

- Utility contracts are needed and are not simple "demand" programs (Bryan)
- Financial institutions are "wary" of utility market pricing (Bryan)
- Energy storage system warranties are difficult to describe (Bryan)

Regulatory Gaps

- Current IEEE 1547 Guidelines conflict with some benefits (Weaver)

Possible Approaches to Issue and Gap Closure

- Reduce cost and weight of EV batteries and inverters (Lacobelli)
    - There is no single answer => focus on all of the following areas will improve EV adoption:
        - Battery advancements
        - Vehicle and electric drive efficiency gains
        - Fast charging infrastructure => mitigate need of on-board energy
        - V2G and Smart charging => improve cost of ownership
        - Range extender and PHEV options
- Additional Field Test Data (Casey)
    - Real world experience is needed to assess appropriate blend of stationary and mobile energy storage resources

5. Conclusions

- The number of PEV vehicles and fleets are expected to increase in size as federal government energy goals are pursued.
- Potential for storage of electricity in vehicle batteries is large. Attractive opportunities exist with vehicles and fleets that have a low service factor including delivery vans, rental car lots, used car lots, taxi fleets, bus fleets, school bus fleets, etc.
- Cost of vehicle batteries is high. Dual use helps to spread the cost burden. The cost impact of the addition of electricity storage capability must be factored in.
- Each vehicle battery requires a control center for prices for buying and selling electricity. Criteria need to be established for rate of charging or discharging, limits on allowable Depth-of-Discharge, and allowable periods for charge and discharge
- Ancillary services have the potential to provide income to battery owners
- Dual use is most valuable where liquid fuel costs are very high.
- Dual use allows capture of additional high value renewable energy where transmission access is limited
- Injection of relatively small amounts of stored energy into local T&D networks smooth out grid operation, provide renewable ramp-rate smoothing, and provide fast response power during transition to islanded mode during start up of diesel generators.

Conclusions Specific to DOD

- DOD has specific targets for reducing liquid fossil fuel (gasoline and diesel) consumption.
- Several DOD bases have specific objectives of becoming grid independent islanded operations for security purposes. In support of that objective, plans are in place to increase the amount of on-base renewable power production.
- Utilization of the power stored in the batteries of idle base vehicles could allow elimination of high-priced peak-power purchases
- A market exists for electricity that can be delivered to the grid from vehicle batteries at DOD facilities for ancillary services.
- A business model needs to be developed to accrue benefit for providing smoothing renewables and island mode operation.
- Smoothing is an interconnection requirement for European high penetration solar regions
- A study at Fort Carson, CO showed that the highest cost for peak energy was when a cloud covered the PV array and it dropped offline
- Fort Irwin, CA and Wright Patterson AFB, OH are being directed that they need to be self-sufficient at times.
- Utilities look at the power quality at the connection point of DOD bases. Therefore, DOD bases may have a unique opportunity to accrue monetary value by improving power quality prior to export.

6. Appendices

A. Final Agenda

NIST Workshop on
Power Conditioning System Architectures
for Plugin-Vehicle Fleets as Grid Storage
(Invitation Only)

Location: **The Pentagon, Arlington VA**
Date: **June 13, 2011**
Time: **8am - 5pm**

7:30 - 8am: Guests Arrive at Pentagon Station Metrorail stop (see security and travel email).

Upon arriving at the Pentagon Station Metrorail stop, exit through the escalators on the left. At the top of escalators, there will be a Pentagon Visitor Security Line immediately to your left (You will need 2 government-issued IDs as described in the security email to get into the building). Once in the building, you should proceed left to the Visitor Lobby. We will have someone there holding a "NIST" sign who will help you get badged and taken to the conference center.

8:00 - 8:30am: Guests arrive in conference room (escorted in groups).

If guests arrive at the Metrorail stop before 7:30 they will proceed to the visitor lobby as described above and wait until for the first group. If they arrive after 8am they will be late for the meeting but will still be able to attend the remainder of the meeting by calling (703.697.4936).

The agenda will consist of brief presentations and discussions in a Panel Format to address the following areas:

8:30am <u>Workshop Begins</u>

<u>1) US Policy and Programs for Electric Transportation</u>

1.1) Camron Gorguinpour (U.S. Air Force – Office of the Assistant Secretary)
A DOD Perspective on EV Ancillary Services

1.2) Allen Hefner (NIST) - Introduction and Workshop Goals

9:10am

2) Use of EV as Grid Storage

Panel A:

2.1) What are existing ancillary service markets where a Plugin Electric/Hybrid-Electronic Vehicle (PEV) Fleet might participate?

Scott Baker (PJM)	ISO/RTO Markets – Freq. reg., Spin res., Peak shave and VARs
Willett Kempton (MAGICC)	Demonstration Project - Plugin EVs for Frequency Regulation

9:45am

Panel B:

2.2) What additional grid storage requirements and markets might emerge that could utilize a PEV Fleet?

Tom Weaver (AEP)	Current Utility Needs for Storage and Ability to Integrate
Kevin Schneider (PNNL)	Potential Value of Storage for Distribution System

10:20am Break

10:35am

Panel C:

2.3) How might a PEV Fleet aid in integration of distributed variable renewable generators?

Glenn Skutt (PowerHub)	Inverter/Storage functions to support Renewable Integration

2.4) How might a PEV Fleet aid in integration of resilient micro-grids?

William Siddall (next energy)	Storage functions to support Resilient Microgrids

11:10am

Panel D:

2.5) PEV Battery as Grid Storage - Impact of dual-use on Battery Life Degradation.

Dave Nichols (Altairnano) Impact of grid storage functions on battery degradation

Cyrus Ashtiani (Saft) Duel use Energy Storage - Grid and Auto

Eric Hsieh (A123) Regulatory, Business and Policy issues for PEV as Storage

12:00 <u>Lunch</u>

12:50pm

<u>3) PCS Architectures for PEV as Storage</u>

Panel E:

3.1) What PEV charging and bi-directional charging units are available today?
3.2) How might onboard vehicle propulsion inverters and converters be utilized for PEV grid interconnection?

Kathryn Miles (Eetrex) Vehicle to grid charging/inverter systems

Ron Lacobelli (Azure Dynamics) Hybrid Electric Truck Power Electronics

Bill Alexander (Ideal Power Converters) Multi-port converter: Grid, Battery, and Propulsion

1:40pm:

Panel F

3.3) How might large grid inverters be used to integrate multiple vehicles and other generator/storage devices?

Leo Casey (Satcon) Large Grid-Supportive Inverters for Solar, Storage, and V2G

3.4) How might DC circuits and DC micro-grids be utilized within a PEV Fleet Power Conditioning System (PCS) architecture?

Paul Savage (Emerge Alliance) — DC Microgrids and Applications

Mark Earley (National Electrical Code) — Safety Considerations - Grid Inverters and DC circuits

2:30pm <u>Break</u>

2:45pm

<u>4) Transition to PEV Fleet as Storage</u>

Panel G:

4.1) In addition to DOD what other potential large PEV Fleets might emerge?

Bruce Gruenewald (NSI) — Bus Fleet Vehicle-to-Grid Storage

John Bryan (Fleet Energy Company) — Business Development of Vehicle Fleets as Storage

3:20pm

Each Table Completes Information Charts for:

4.2) How might the value proposition of different PEV Fleet PCS approaches be categorized by vehicle type, fleet usage type, and local grid type?

4.3) What are PCS gaps and next steps required to enable Vehicle Fleet as storage?

4:00pm *<u>Wrap Up:</u>*

Each Table Presents Information Charts and All Attendees Comment and Merge

5:00pm <u>Escort to Metrorail</u>

B. List of Attendees

Name	Email Address	Affiliation
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C. List of Workshop Presentations

Bill Alexander, Ideal Power Converters
Current-Modulation Electronic Power Converters

Cyrus Ashtiani SAFT
Dual Use of PEV Batteries: V2G Storage and Propulsion

Scott Baker, PJM Interconnection
Electric Vehicles and Wholesale Markets

John Bryan, Fleet Energy
A Utility's Energy Storage and Fleet's Mileage Service Provider

Leo Casey, Satcon
Large Grid-Supportive Inverters for Solar, Storage, and V2G

Mark W. Earley, National Fire Protection Association
Infrastructure Codes and Standards - the National Electrical Code® - Electric Vehicles and DC Power

Camron Gorguinpour, Office of the Assistant Secretary of the Air Force
A DOD Perspective on EV Ancillary Services

Bruce Gruenewald, National Strategies
Bus Fleet Vehicle-to-Grid (V2G) Storage

Allen Hefner, NIST
Introduction to the NIST Workshop on Power Conditioning System Architectures for Plugin-Vehicle Fleets as Grid Storage

Eric Hsieh, A123 Systems
Business and Policy for Plug-In Vehicle Grid Uses

Willett Kempton, University of Delaware
Demonstration: Plugin EVs for Frequency Regulation

Ron Lacobelli, Azure Dynamics
AZD Power Electronics for Hybrid Vehicles

Kathryn Miles, Eetrex Incorporated
Inverger Technology

Dave Nichols, Altairnano
Impact of Grid Storage Functions on Battery Degradation

Paul Savage, Emerge Alliance
DC Microgrids and Applications

Kevin Schneider, PNNL
Potential Value of Storage for Distribution Systems

Bill Siddall, Next Energy
How Might A PEV Fleet Aid In Integration Of Resilient Micro-Grids? (Storage Functions To Support Resilient Micro-Grids)

Glen Skutt, powerhub SYSTEMS
Inverter/Storage Functions to Support Renewable Integration

Tom Weaver, AEP
Energy Storage at AEP