Advanced Vehicle Testing Activity at Idaho National Laboratory:

Evaluation of Vehicles and the Grid together as a System

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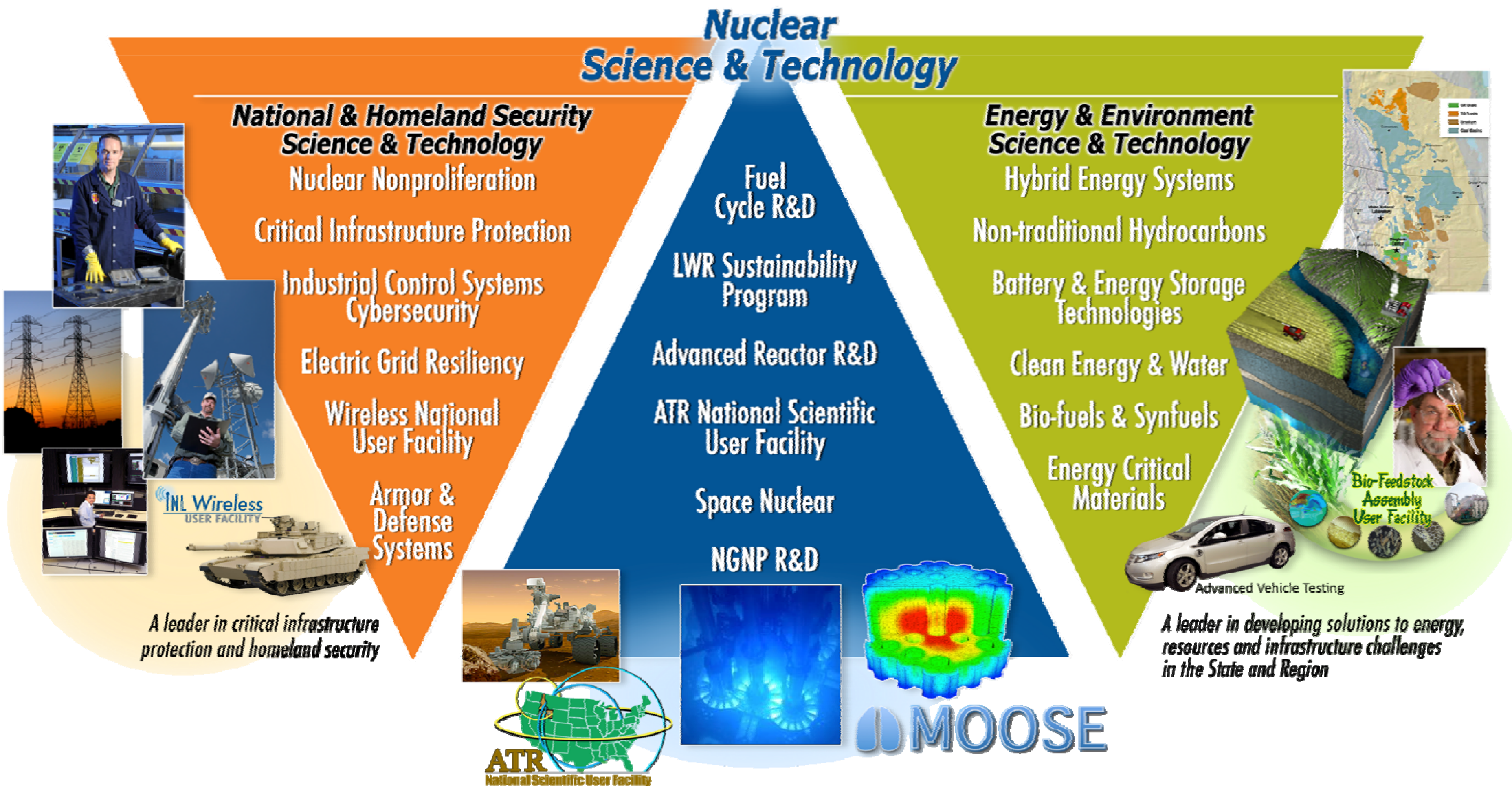
Presented to the IEA Task 17 meeting April 16, 2015

INL/MIS-15-34697

Idaho National Laboratory

INL Programs of National Importance



Research – Development – Demonstration – Deployment

The Idaho National Laboratory Site

We Maintain –

- *890 square miles*
- *111 miles of electrical transmission and distribution lines*
- *579 buildings*
- *177 miles of paved roads*
- *14 miles of railroad lines*
- *3 reactors*
- *2 spent fuel pools*
- *Mass transit system*
- *Security*
- *Museum*
- *“Landfills”*
- *300 metric tons of used fuel*
- *Educational and research partnerships – CAES*

…the National Nuclear Laboratory

Technical Challenges & Objectives

Advance Vehicle Testing and Analysis' objective is to support DOE's mission to reduce foreign imports by 50% by 2020, reduce green house gas emissions by 15% by 2020 & achieve 54.5 MPG CAFE mandate by 2025

- **Identify real-world potential of technologies to displace petroleum**
- **Verify / maximize return on investment of DOE-funded technology development, primarily on:**
  - **Advanced energy storage (i.e., batteries) technologies and chemistries**
  - **Plug-in electric whole-vehicle technologies**
  - **Fueling system technologies**
    - **conductive and wireless grid-connected electric drive vehicle fueling infrastructure**
  - **Advanced climate control, power electronic, and other ancillary and accessory systems technologies**
  - **Advanced internal combustion engines (CNG/Turbocharged Direct Injection Diesel)**

Feedback to DOE, OEMs, SAE, fleet managers, policy makers and other key stakeholders

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Vehicles and Electric Grid: Together as a System

- Areas of research at INL to improve Vehicle and Grid as a system
  - Renewable energy and non-fossil fuel energy sources
    - Wind, solar, hydro-electric
    - Waste heat (nuclear, other processes)
  - Vehicle Charging Infrastructure Evaluation
    - Utilization of home, workplace, and public charging
    - Wireless and Conductive Charging Evaluation
      - Efficiency
      - Power Quality impact to Grid
    - Test Procedure development
  - Advanced technology vehicles (BEV, PHEV, EREV, Adv. ICE)
    - On-road testing and data collection
      - Captured test fleet (195,000 miles per vehicle (313,800 km))
      - Data collection from privately owned vehicle
  - Energy Storage R&D, testing, and evaluation
    - Performance Assessment
    - Procedures and Protocols

Vehicles and Electric Grid: Together as a System

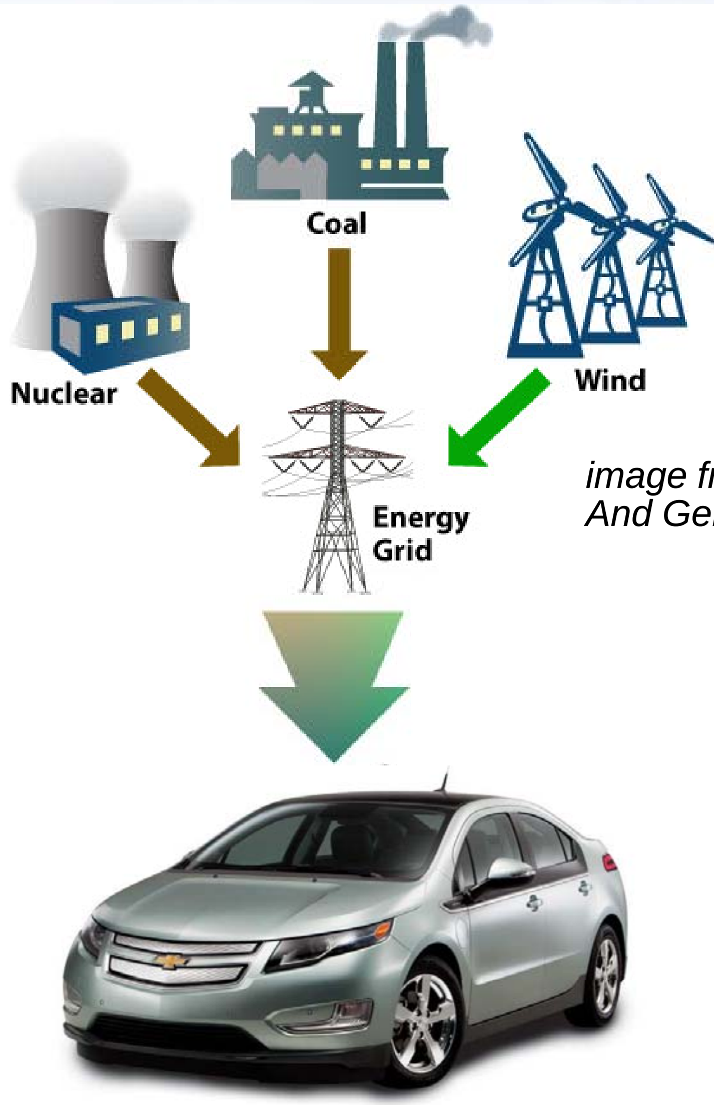
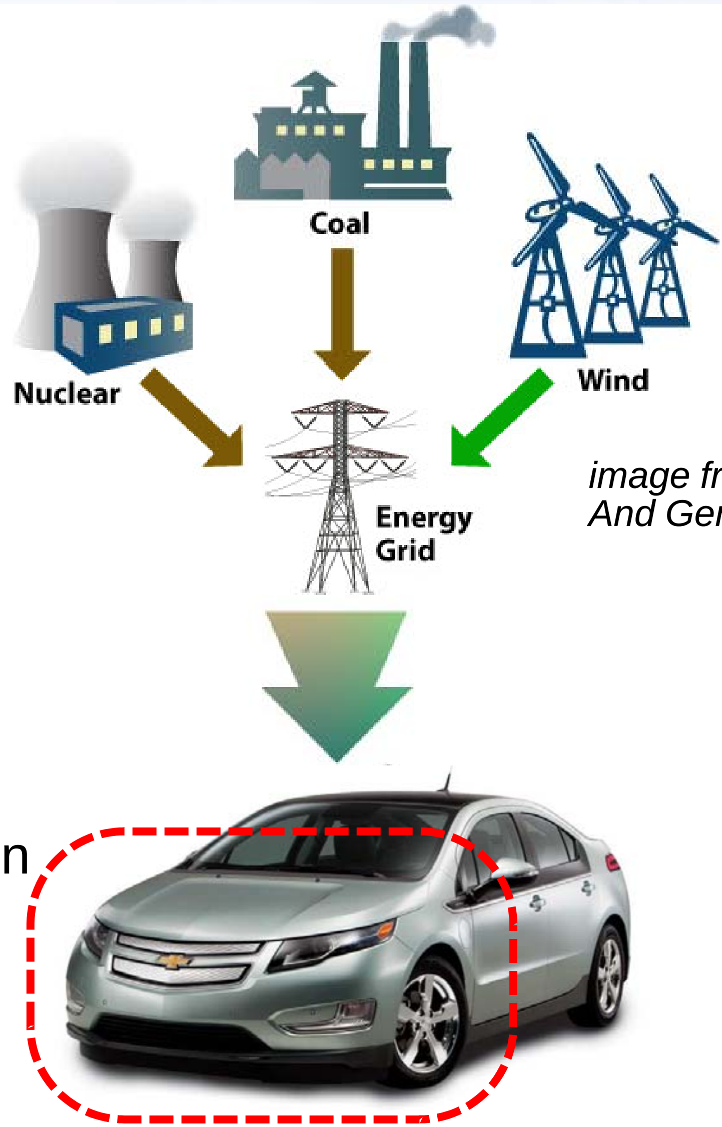


image from: Montgomery County, MD
And General Motors

Vehicles and Electric Grid: Together as a System



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- Vehicle Optimization

Vehicles and Electric Grid: Together as a System

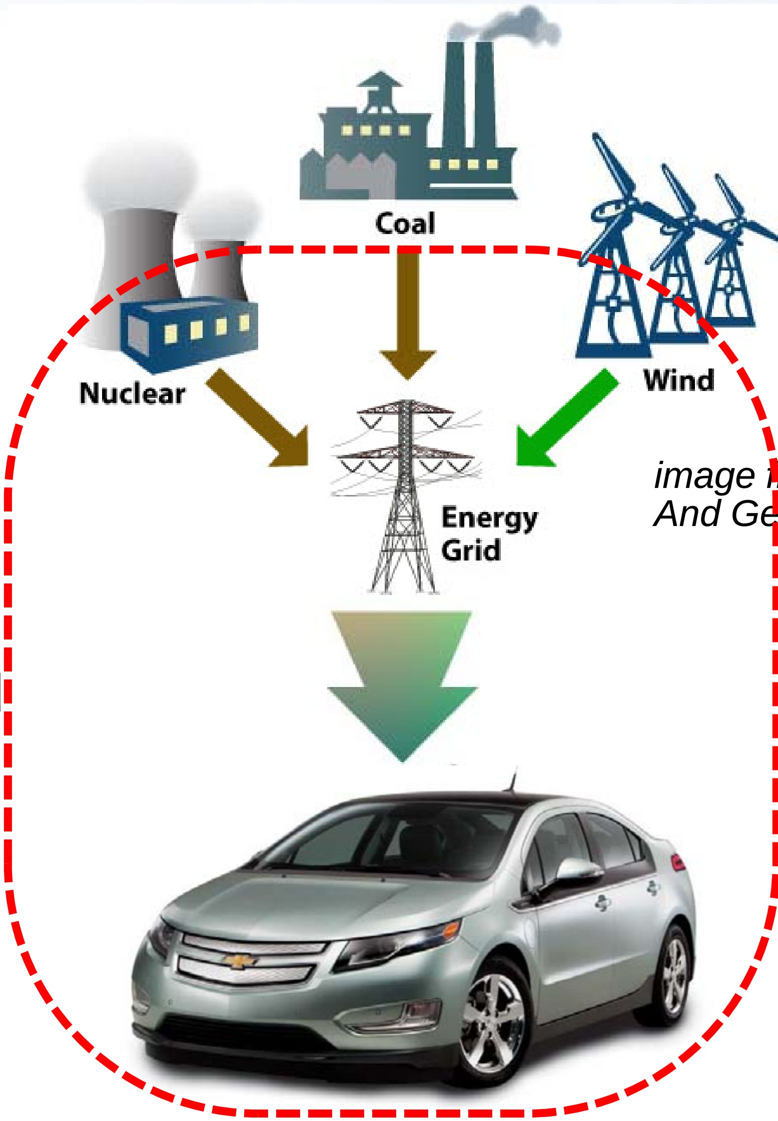


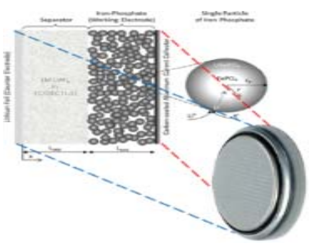
image from: Montgomery County, MD And General Motors

- Vehicle and Grid interaction and Optimization

INL – Battery Test Center and Advanced Vehicles Evaluation

Development of Next-Generation Low Cost / Reliable Batteries:

- ***INL capabilities to lead Performance Science***
- ***Battery Testing Center & Advanced Vehicle Testing***
- ***Strong partnerships with:***
  - ***DOE-EERE (USABC)***
  - ***OEMs***
  - ***Battery Developers***
- ***Enabling / accelerating next gen-batteries***



Half-Cell / Coin

Pouch / Cell

Pack

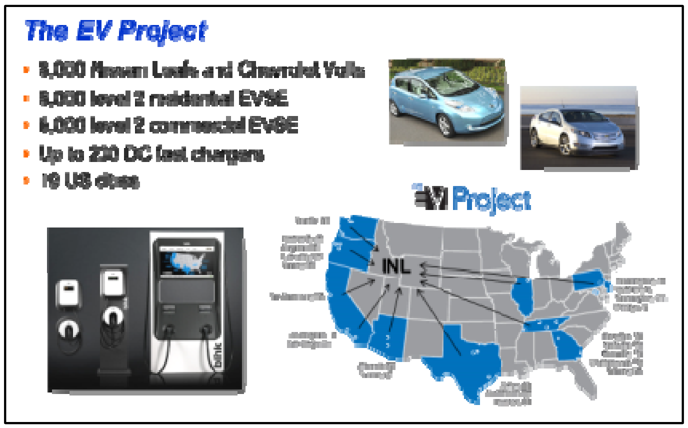
Vehicle

Expansion of Performance Science Life-Time Modeling

INL – Advanced Vehicles & Infrastructure

Enhance Consumer Experience with Advanced Technology Vehicles:

- ***Big Data Analysis***
- ***Advanced Vehicle Testing & EV Infrastructure Laboratory***
- ***Steward to DOE-EERE, OEMs, SAE & CARB***
- ***Impact: Increasing ROI (Return of Investment) on alt-fuel infrastructure development / deployment***



Big-Data Analysis

Heat Maps of EV Chargers

Global Standardization of wireless charging with SAE & automotive manufacturers

Alf-Fuel Corridor Analysis

Idaho National Laboratory

Vehicle Charging Levels

- On-board charger (AC power delivered to vehicle)
  - Level 1 (120 VAC)
    - SAE J1772 (~1.4 kW)
  - Level 2 (208 – 240 VAC)
    - SAE J1772 (up to 19.2 kW but typically 3.3 or 6.6 kW)

- Off-board charger (DC power delivered to vehicle)
  - DC Fast Charge (~50 kW)
    - CHAdeMO
    - SAE J1772 CCS (Combo Connector)

Vehicle Charge Connection International Standards

Level 1 & Level 2

	Type 1/USA	Type 2/Europa	GB/China
Alternating current (AC)	 SAE J1772/IEC 62196-2	 IEC 62196-2	 GB Part 2
Direct current (DC)	 IEC 62196-3	 IEC 62196-3	 GB Part 3/IEC 62196-3

DC Fast Charge

	System A CHAdeMO (Japan)	System B CATARC (PRC)	System C COMBO1 (US)	System C COMBO2
Connector				
Vehicle Inlet				
Communication Protocol	CAN		PLC	

Vehicle Charge Connection - Tesla

Tesla Roadster

Tesla Model S

Advanced Vehicle Testing Activity at Idaho National Lab

On-Road Vehicle Driving and Charging Analysis

Advance Vehicle Testing Experience

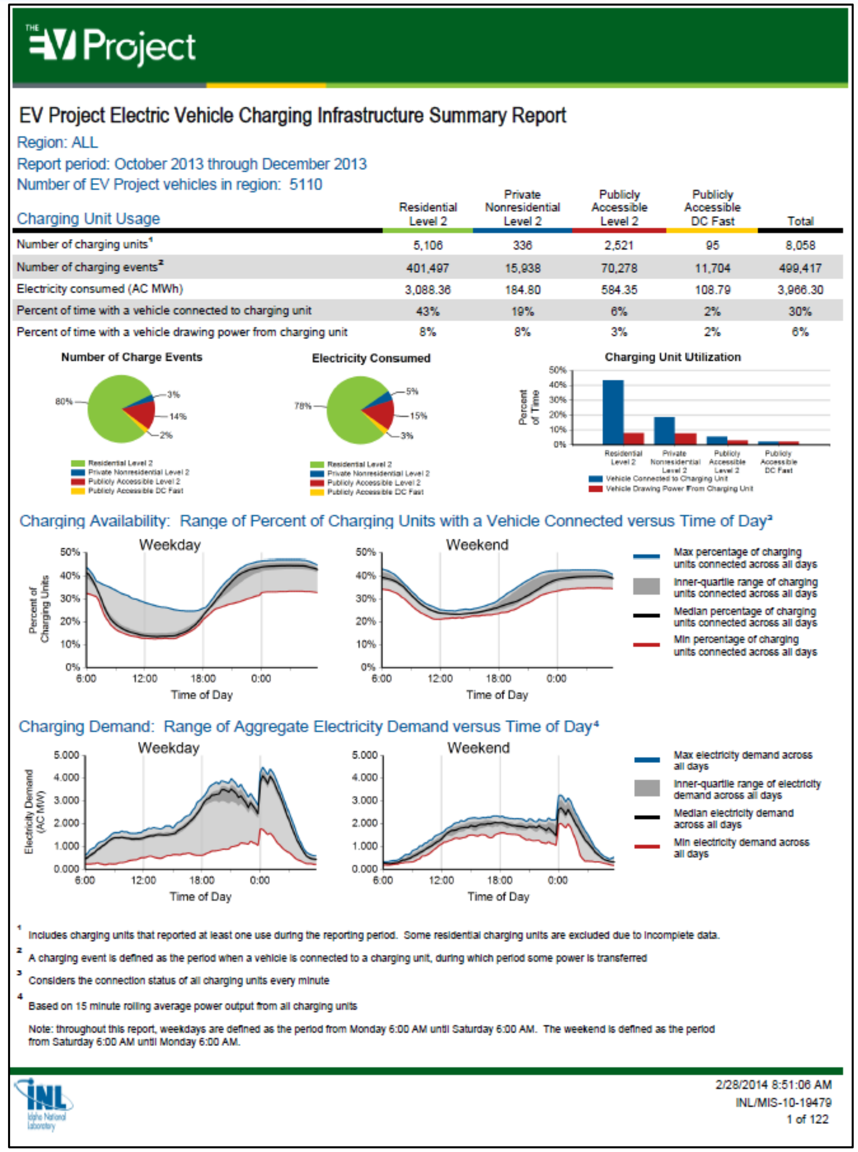
- **Since 1994, INL staff have benchmarked PEVs in field operations (via data loggers), closed test tracks and dynamometers**
  - **INL has accumulated 232 million miles (373 million km) and 44,300 AC MWh from 27,400 electric drive vehicles and 17,000 charging units**

Example: EV Project

- ***8,228 Leafs, Volts and Smarts,***
  - ***124 million test miles.***
  - ***At one point, 1 million test miles every 5 days***
- ***12,363 EVSE and DCFC***
  - ***4.2 million charge events***

Driving and Charging patterns

- Analysis of Driving Patterns
  - Energy consumption
  - Usage patterns
  - Common parking location
    - (i.e. should EVSE / chargers be located here)
- Analysis of Charging Patterns
  - Time of Day utilization
    - Home
    - Away from Home
    - DC Fast Charge
  - Power draw
  - Impact of variable time of day electricity pricing



THE EV Project

EV Project Electric Vehicle Charging Infrastructure Summary Report

Region: ALL

Report period: October 2013 through December 2013

Number of EV Project vehicles in region: 5110

Charging Unit Usage	Residential Level 2	Private Nonresidential Level 2	Publicly Accessible Level 2	Publicly Accessible DC Fast	Total
Number of charging units[1]	5,106	336	2,521	95	8,058
Number of charging events[2]	401,497	15,938	70,278	11,704	499,417
Electricity consumed (AC MWh)	3,088.36	184.80	584.35	108.79	3,966.30
Percent of time with a vehicle connected to charging unit	43%	19%	6%	2%	30%
Percent of time with a vehicle drawing power from charging unit	8%	8%	3%	2%	6%

[1] Includes charging units that reported at least one use during the reporting period. Some residential charging units are excluded due to incomplete data.

[2] A charging event is defined as the period when a vehicle is connected to a charging unit, during which period some power is transferred

[3] Considers the connection status of all charging units every minute

[4] Based on 15 minute rolling average power output from all charging units

Note: throughout this report, weekdays are defined as the period from Monday 6:00 AM until Saturday 6:00 AM. The weekend is defined as the period from Saturday 6:00 AM until Monday 6:00 AM.

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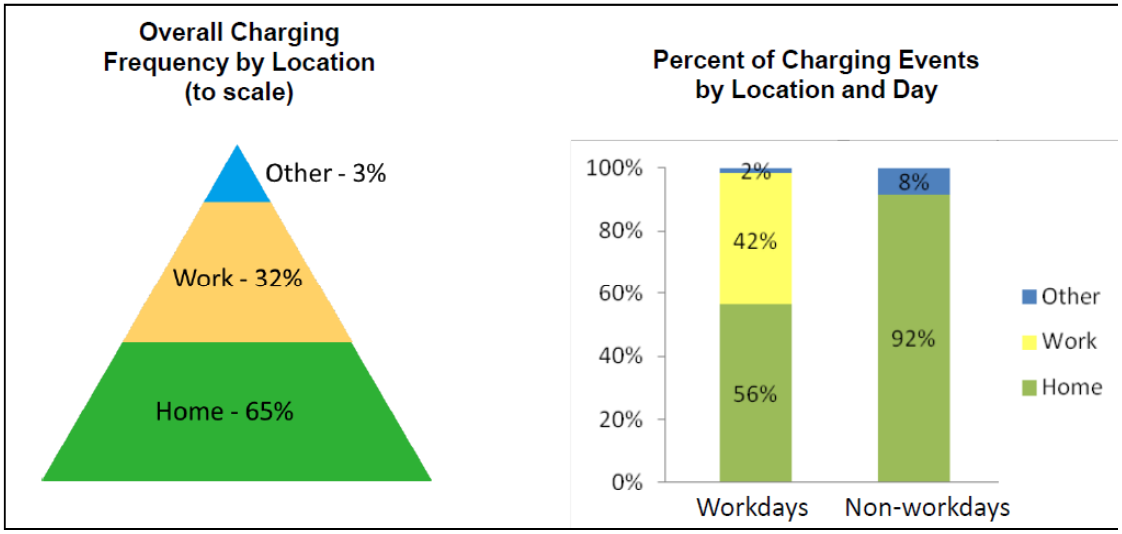
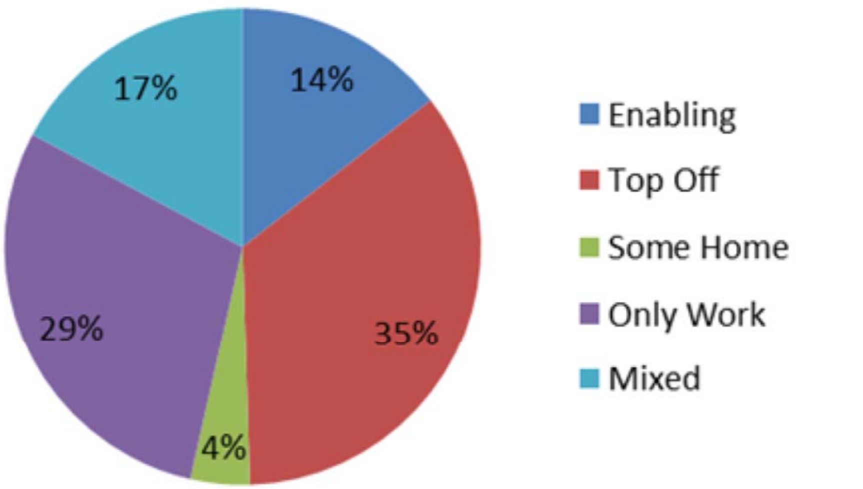
Workplace Charging Impact

- Most charging occurs at Home and Work
- But "Other" charging may be critical to a few drivers
- Workplace Charging:
  - Enabled 14% of commutes to work in a Leaf
  - 12% more EV miles on average than not charging at work
  - 15 mile range increase on average due to charging at work

Nissan Leafs





EV Miles Traveled (eVMT) Analysis Results

- **EREV (red) shows comparable eVMT as pure EV (green)**

	Nissan LEAF *	Chevrolet Volt *	Ford Focus Electric	Ford C-Max Energi	Ford Fusion Energi	Honda Fit EV	Honda Accord PHEV	Toyota Prius PHEV
Number of Vehicles	4,039	1,867	2,193	5,368	5,803	645	189	1,523
Number of Vehicle Months	35,294	20,545	12,622	38,096	32,022	6,090	1,437	15,676
Total Vehicle Miles Traveled *VMT* (miles)	28,520,792	20,950,967	10,043,000	39,376,000	33,098,000	4,912,920	1,794,494	19,772,530
Total Calculated Electric Vehicle Miles Traveled *eVMT* (miles)	28,520,792	15,599,508	10,043,000	12,918,000	11,572,000	4,912,920	399,412	3,224,981
Avg. Monthly VMT	808.1	1,019.8	795.7	1,033.6	1,033.6	806.7	1,248.8	1,261.3
Avg. Monthly eVMT	808.1	759.3	795.7	339.1	361.4	806.7	278	207.0
estimated Annual VMT	9,697	12,238	9,548	12,403	12,403	9,680	14,986	15,136
estimated Annual eVMT	9,697	9,112	9,548	4,069	4,337	9,680	3,336	2,484
Annual eVMT (km)	15,606	14,664	15,366	6,548	6980	15,578	5,369	3998
Data Format Description	Key-On / Key-Off	Key-On / Key-Off	Enhanced Key-On / Key-Off			Trip Summary		Trip Summary
Geographic Characterization	CA, OR, WA, AZ, TX, TN, GA, D.C., PA, IL	CA, OR, WA, AZ, TX, TN, GA, D.C., PA, IL	Nationwide			CA, OR, NJ, MD, CT, MA, RI, NY	CA, NY	ZEV States and other states



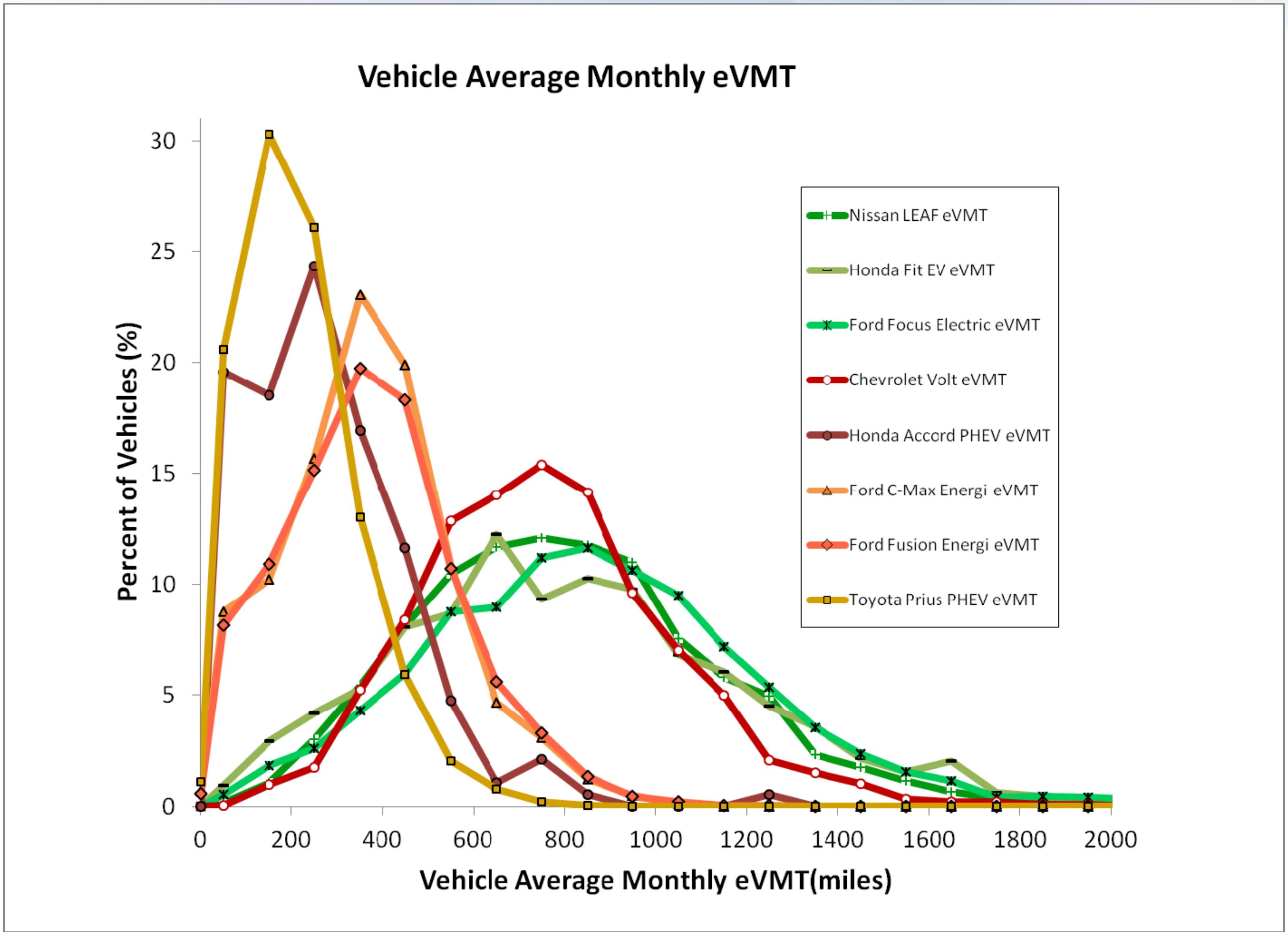





*** http://avt.inel.gov/pdf/EVProj/eVMTMay2014.pdf**

Minimally Charged Vehicles are Not Excluded from analysis. These data include 14% of Accord PHEVs that achieve between 0-50 monthly eVMT

eVMT Histogram



Distance Bins: =0, >0 to 100, >100 to 200, >300 to 400, >400 to 500, etc.

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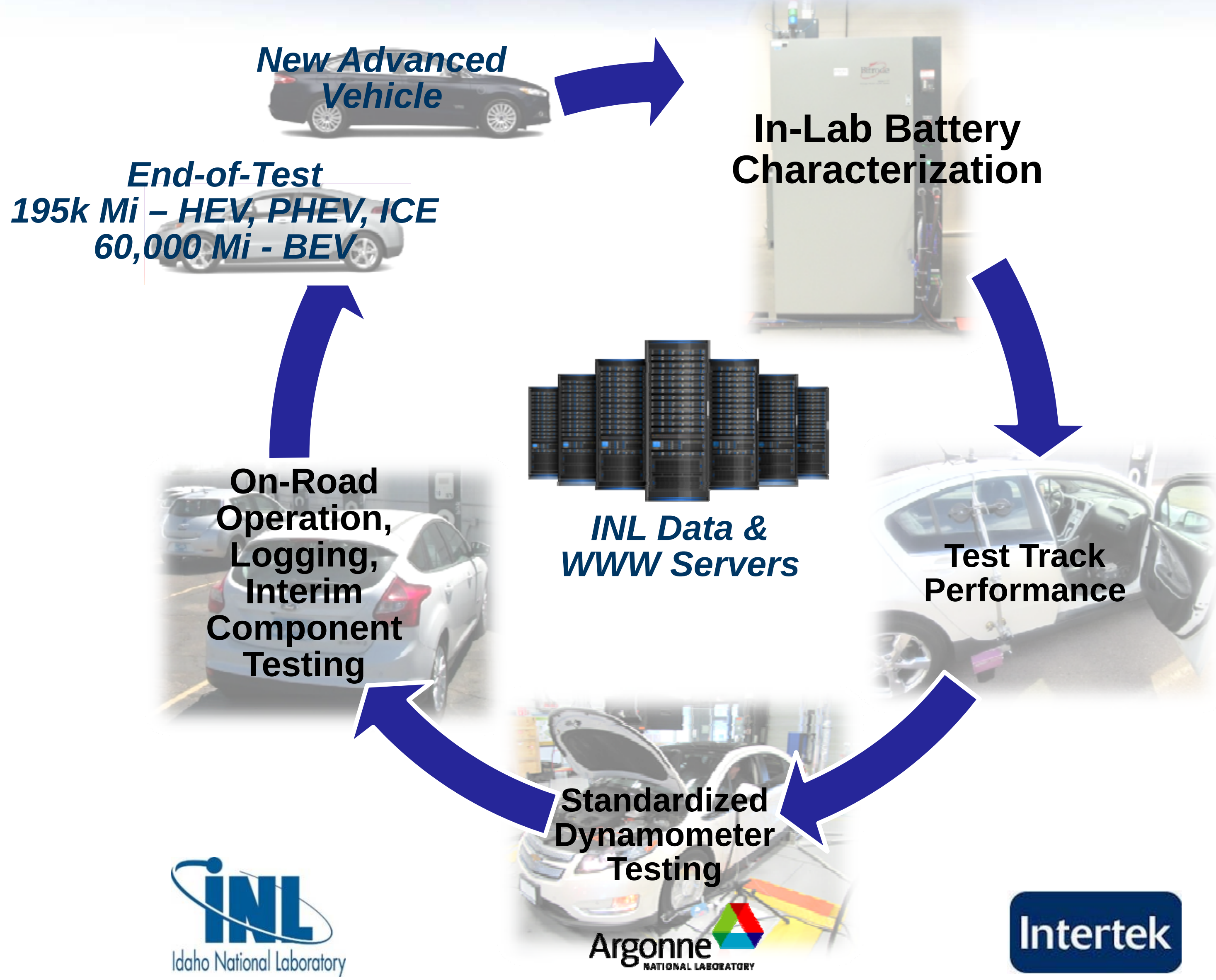
Advanced Vehicle Testing Activity at Idaho National Lab

On-Road and Laboratory Testing and Evaluation

Advanced Vehicle Testing Process



On-Road Vehicle Fleet Test Results

- Information and Results Published to AVTA website
  - Baseline Performance Testing
    - Specifications
    - Acceleration / Braking
    - Test Track energy consumption
  - Battery Test Results
    - Capacity
    - Power Capability
  - Fleet Fuel Economy results
    - Operation over vehicle life
  - Operating Costs Fact Sheet
  - Maintenance History

http://avt.inel.gov/phev.shtml

Advanced Vehicle Testing Activity

Idaho National Laboratory

Plug-In Hybrid Electric Vehicle Operation Data Summary for 2013 Chevrolet Volt VIN 1078

Reporting Period: November 2012 through September 2014

All Trips[1]

Overall gasoline fuel economy (mpg)[5]	41
Overall DC electrical energy consumption (DC Wh/mi)	59
Total distance driven (mi)	45,238
Average trip distance (mi)	7
Percent of miles city | highway	63% | 37%
Average ambient temperature (deg F)	94.9
Percent of miles driven with air conditioning selected	96%

EV Trips[2]

Overall gasoline fuel economy (mpg)[5]	N/A
Overall DC electrical energy consumption (DC Wh/mi)	295
Total distance driven (mi)	7,348
Average trip distance (mi)	5.0
Percent of miles city | highway	74% | 26%
Average ambient temperature (deg F)	82.0
Percent of miles driven with air conditioning selected	94%
Percent of total distance traveled	16%

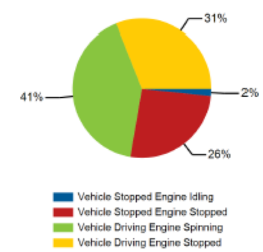
Mixed-Mode Trips[3]

Overall gasoline fuel economy (mpg)[5]	39
Overall DC electrical energy consumption (DC Wh/mi)	73
Total distance driven (mi)	12,135
Average trip distance (mi)	5.7
Percent of miles city | highway	62% | 38%
Average ambient temperature (deg F)	96.9
Percent of miles driven with air conditioning selected	96%
Percent of total distance traveled	27%

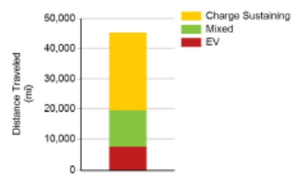
Charge Sustaining Trips[4]

Overall gasoline fuel economy (mpg)[5]	32
Overall DC electrical energy consumption (DC Wh/mi)	-15
Total distance driven (mi)	25,754
Average trip distance (mi)	8.7
Percent of miles city | highway	60% | 40%
Average ambient temperature (deg F)	96.9
Percent of miles driven with air conditioning selected	96%
Percent of total distance traveled	57%

Percent of Drive Time by Operating Mode



Distance Traveled By Trip Type



1. Calculated from on-board electronic data logged over 45,238 miles, which may be a subset of total lifetime miles driven.
2. Trips where the vehicle was propelled by battery energy only, using no gasoline.
3. Trips where gasoline was consumed by the engine, and net electrical energy was consumed from the battery to propel the vehicle.
4. Trips where gasoline was consumed by the engine to propel the vehicle, while the net electrical energy consumed from the battery was less than 1% of the gasoline energy consumed.
5. Gasoline consumption calculated using Mass Air Flow and Commanded or Measured Air-Fuel Ratio read from OBD2 messages assuming AFR_{stoich} = 14.7 and $\rho_{gasoline}$ = 2819 g/gal.

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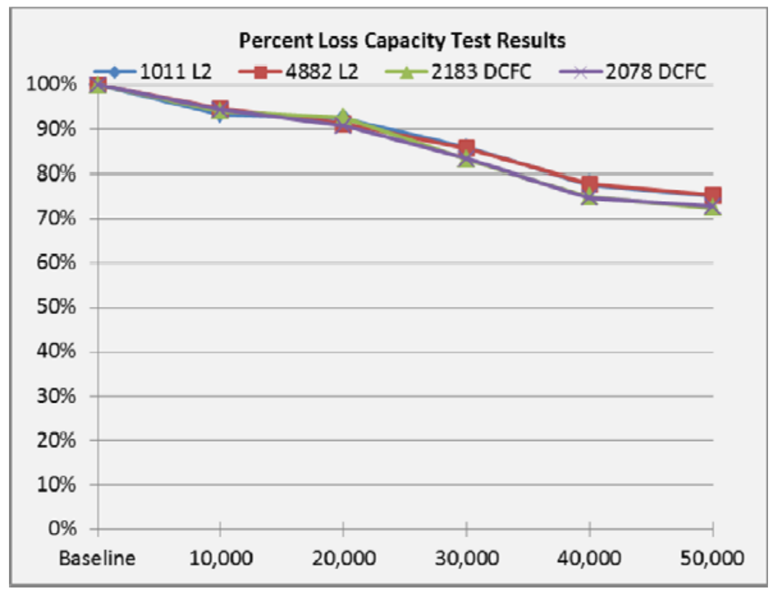
DC Fast Charging Impact Study on 2012 Leafs

After 50,000 miles (80,000 km):

- ***NO appreciable difference in capacity loss (~2%) between Level II and DC Fast Charging***



- **All Leafs were the same color – avoid unequal solar loading**
- **Leafs' climate control is set at 23ºC year round**

http://avt.inel.gov/pdf/energystorage/DCFC_Study_FactSheet_50k.pdf

Electric Vehicle Infrastructure (EVI) *Laboratory*

- **Evaluate Conductive and Wireless Charging Systems**
  - **Efficiency and energy consumption**
  - **EM field emissions (wireless charging only)**
  - **Power Quality (static and dynamic)**
    - **Total Harmonic Distortion**
    - **Power Factor**
  - **Cyber Security Assessment**

- **Wide range of power**
  - **Level 1, 120 VAC**
  - **Level 2, 208 / 240 VAC**
  - **DCFC, 480 VAC 3ϕ**
  - **Variable voltage source**
    - **Grid Emulator**

Electric Vehicle Infrastructure (EVI) *Laboratory Support of SAE J2954*

- Support SAE J2954 Wireless Charging standards
  - providing test results
  - test procedure development
  - document refinement

- INL conducted independent testing using draft J2954 test procedures for:
  - System Efficiency and EM-field across a range of misalignment, coil gap, and output power
    - Off-board vehicle (bench test)
    - On-board vehicle
  - Debris tolerance and response
  - Mock floor-pan characterization

- INL is the only DOE lab to publish wireless charging benchmarking results

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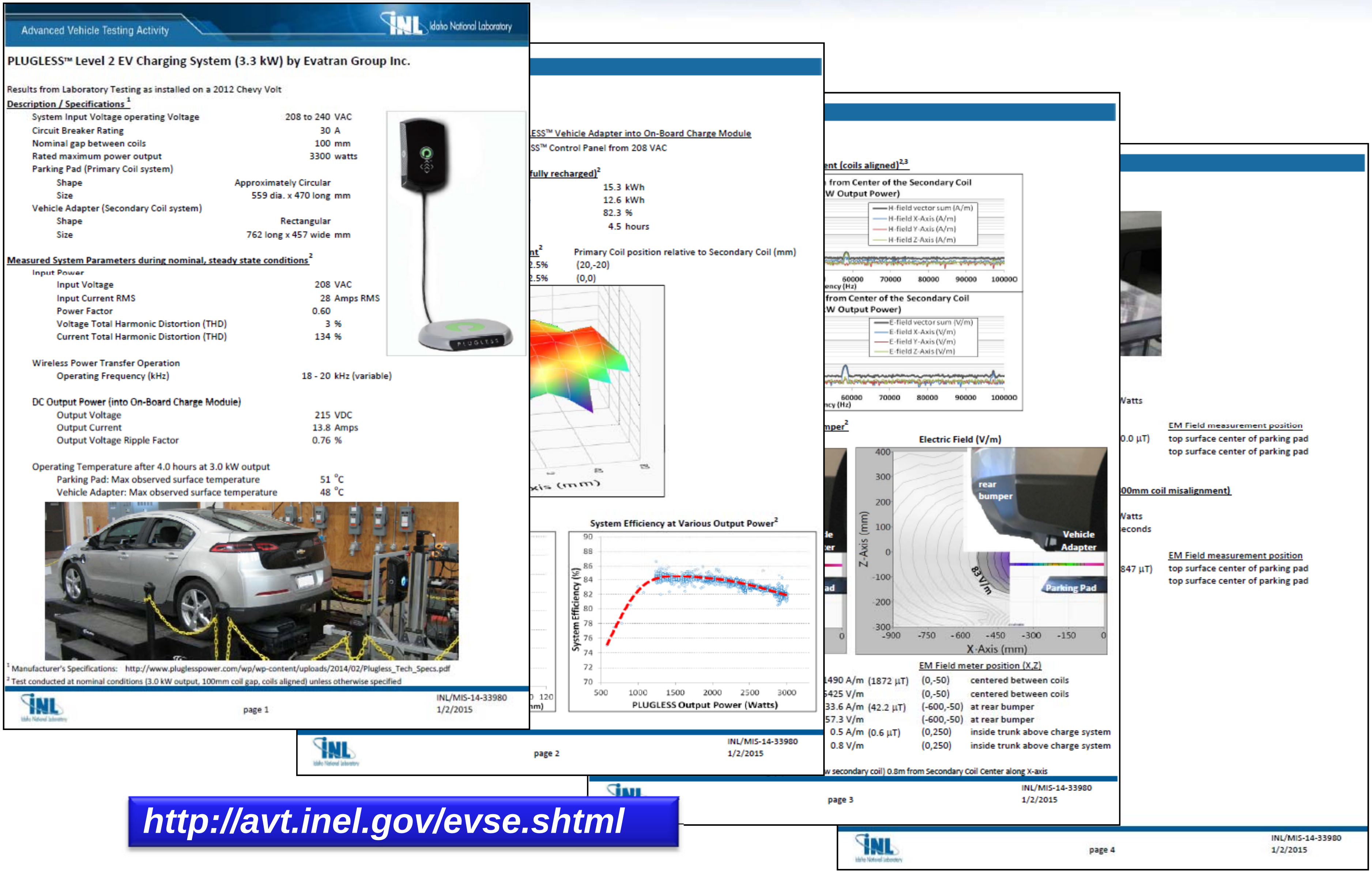
Fact Sheet: Wireless Charger Vehicle Test Results


Advanced Vehicle Testing Activity

Idaho National Laboratory

PLUGLESS™ Level 2 EV Charging System (3.3 kW) by Evatran Group Inc.

Results from Laboratory Testing as installed on a 2012 Chevy Volt

Description / Specifications [1]

System Input Voltage operating Voltage	208 to 240	VAC
Circuit Breaker Rating	30	A
Nominal gap between coils	100	mm
Rated maximum power output	3300	watts
Parking Pad (Primary Coil system)		
Shape	Approximately Circular	
Size	559 dia. x 470 long	mm
Vehicle Adapter (Secondary Coil system)		
Shape	Rectangular	
Size	762 long x 457 wide	mm

Measured System Parameters during nominal, steady state conditions [2]

Input Power		
Input Voltage	208	VAC
Input Current RMS	28	Amps RMS
Power Factor	0.60	
Voltage Total Harmonic Distortion (THD)	3	%
Current Total Harmonic Distortion (THD)	134	%
Wireless Power Transfer Operation		
Operating Frequency (kHz)	18 - 20	kHz (variable)
DC Output Power (into On-Board Charge Module)		
Output Voltage	215	VDC
Output Current	13.8	Amps
Output Voltage Ripple Factor	0.76	%
Operating Temperature after 4.0 hours at 3.0 kW output		
Parking Pad: Max observed surface temperature	51	°C
Vehicle Adapter: Max observed surface temperature	48	°C

[1] Manufacturer's Specifications: http://www.pluglesspower.com/wp/wp-content/uploads/2014/02/Plugless_Tech_Specs.pdf

[2] Test conducted at nominal conditions (3.0 kW output, 100mm coil gap, coils aligned) unless otherwise specified

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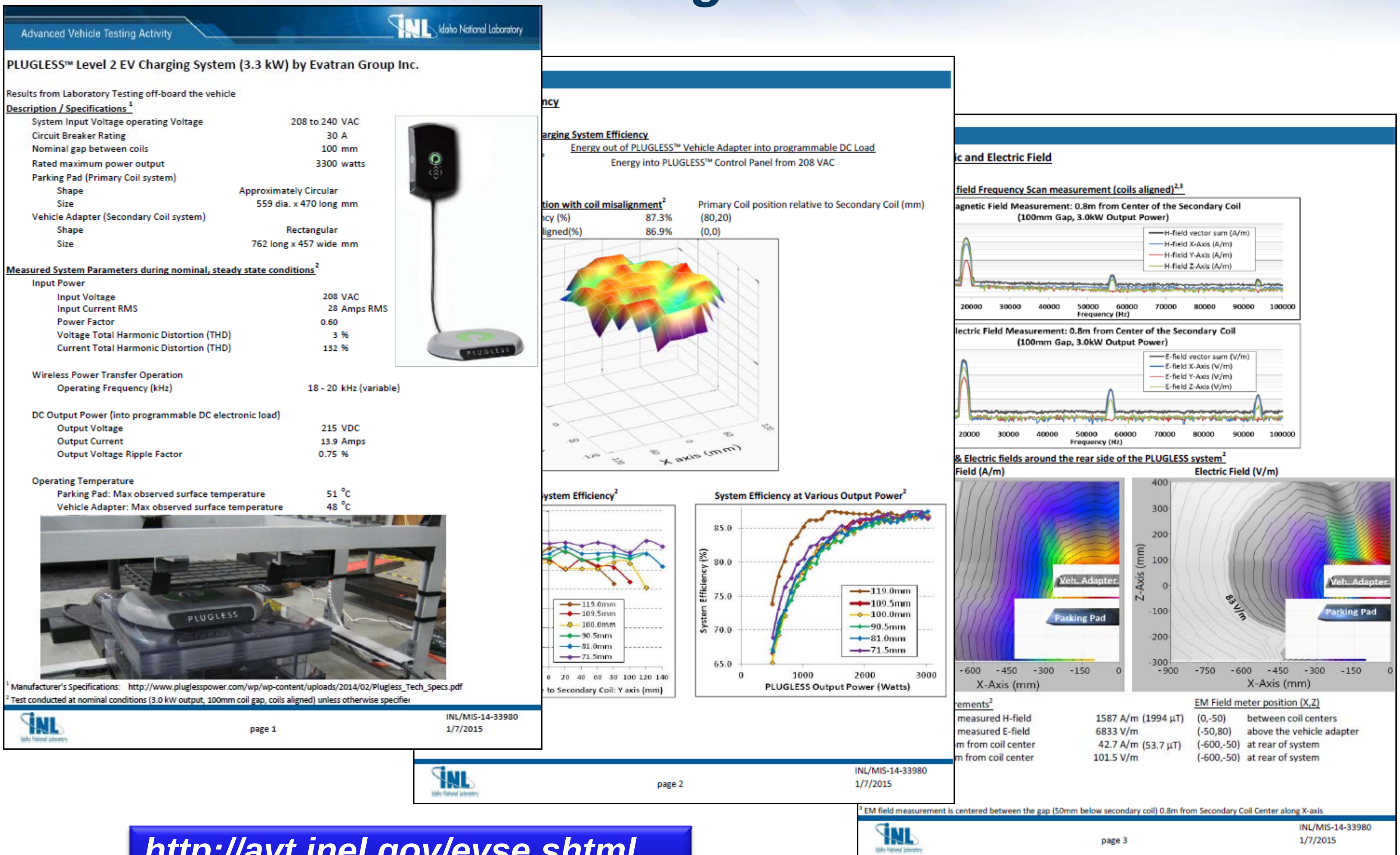
http://avt.inel.gov/evse.shtml

Fact Sheet: Wireless Charger Bench Test Results



Advanced Vehicle Testing Activity

Idaho National Laboratory

PLUGLESS™ Level 2 EV Charging System (3.3 kW) by Evatran Group Inc.

Results from Laboratory Testing off-board the vehicle

Description / Specifications [1]

System Input Voltage operating Voltage	208 to 240 VAC
Circuit Breaker Rating	30 A
Nominal gap between coils	100 mm
Rated maximum power output	3300 watts
Parking Pad (Primary Coil system)	
Shape	Approximately Circular
Size	559 dia. x 470 long mm
Vehicle Adapter (Secondary Coil system)	
Shape	Rectangular
Size	762 long x 457 wide mm

Measured System Parameters during nominal, steady state conditions [2]

Input Power	
Input Voltage	208 VAC
Input Current RMS	28 Amps RMS
Power Factor	0.60
Voltage Total Harmonic Distortion (THD)	3 %
Current Total Harmonic Distortion (THD)	132 %
Wireless Power Transfer Operation	
Operating Frequency (kHz)	18 - 20 kHz (variable)
DC Output Power (into programmable DC electronic load)	
Output Voltage	215 VDC
Output Current	13.9 Amps
Output Voltage Ripple Factor	0.75 %
Operating Temperature	
Parking Pad: Max observed surface temperature	51 °C
Vehicle Adapter: Max observed surface temperature	48 °C

[1] Manufacturer's Specifications: http://www.pluglesspower.com/wp/wp-content/uploads/2014/02/Plugless_Tech_Specs.pdf

[2] Test conducted at nominal conditions (3.0 kW output, 100mm coil gap, coils aligned) unless otherwise specified

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ncy

arging System Efficiency

Energy out of PLUGLESS™ Vehicle Adapter into programmable DC Load

Energy into PLUGLESS™ Control Panel from 208 VAC

tion with coil misalignment[2] — Primary Coil position relative to Secondary Coil (mm)

ncy (%)	87.3%	(80,20)
ligned(%)	86.9%	(0,0)

ystem Efficiency[2]

System Efficiency at Various Output Power[2]

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ic and Electric Field

field Frequency Scan measurement (coils aligned)[2,3]

agnetic Field Measurement: 0.8m from Center of the Secondary Coil (100mm Gap, 3.0kW Output Power)

lectric Field Measurement: 0.8m from Center of the Secondary Coil (100mm Gap, 3.0kW Output Power)

& Electric fields around the rear side of the PLUGLESS system[2]

Field (A/m) — Electric Field (V/m)

ements[2]		EM Field meter position (X,Z)	
measured H-field	1587 A/m (1994 µT)	(0,-50)	between coil centers
measured E-field	6833 V/m	(-50,80)	above the vehicle adapter
m from coil center	42.7 A/m (53.7 µT)	(-600,-50)	at rear of system
m from coil center	101.5 V/m	(-600,-50)	at rear of system

[3] EM field measurement is centered between the gap (50mm below secondary coil) 0.8m from Secondary Coil Center along X-axis

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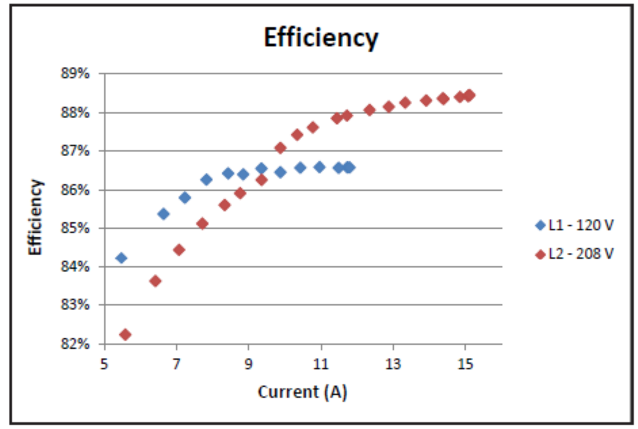
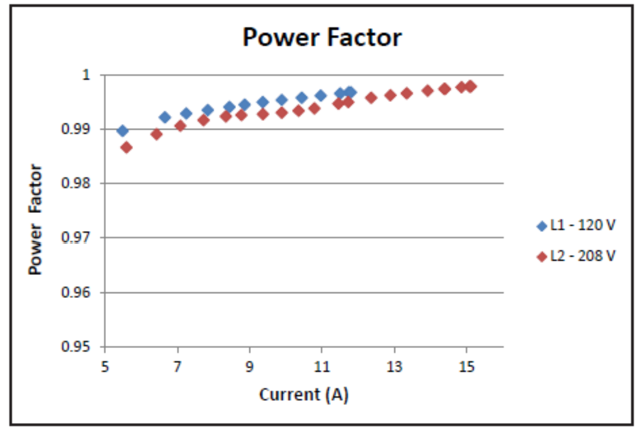
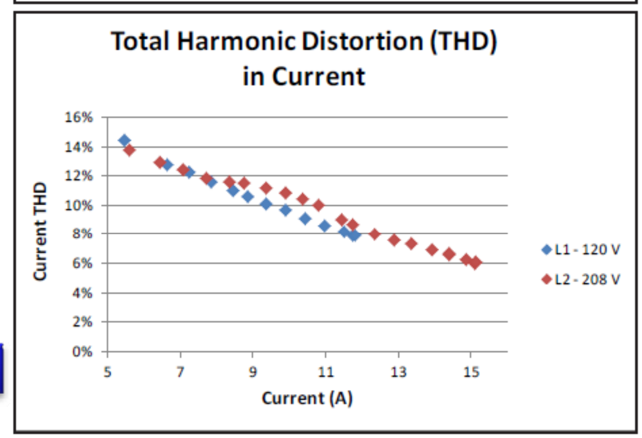
http://avt.inel.gov/evse.shtml

Charger Power Quality

- Power Quality evaluated across range of charge current for Level 1 and Level 2
  - Efficiency
  - Power Factor
  - Total Harmonic Distortion
- This negatively impacts the grid during a demand response curtailment
  - Efficiency decreases
  - Power Factor decreases
  - Distortion on Current increases
- Figures on right are results from
  - 2012 Chevy Volt





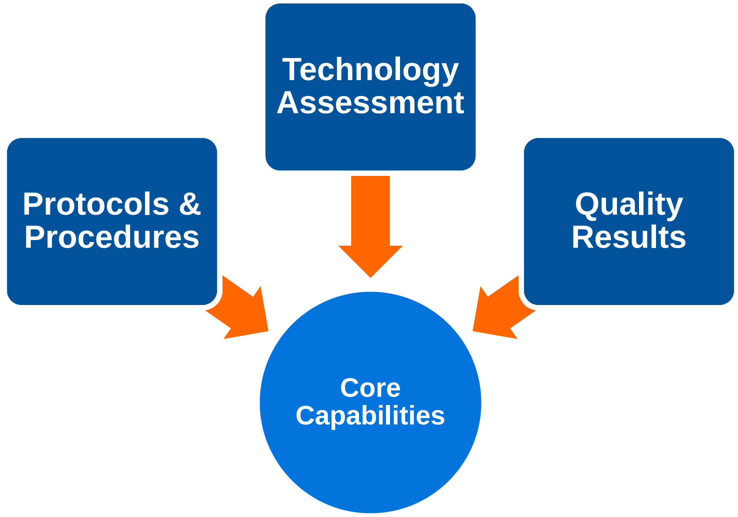


http://avt.inel.gov/pdf/EREV/SteadyStateVehicleChargingFactSheet2012Volt.pdf

Battery Test Center at Idaho National Lab

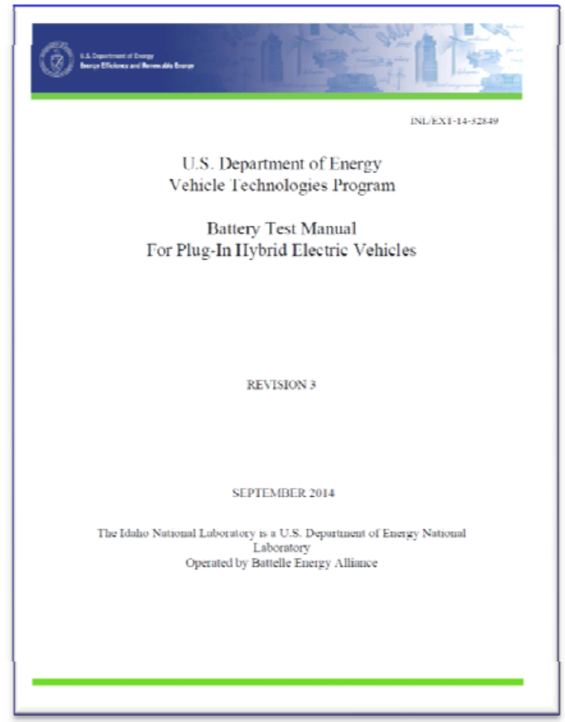
Battery Assessment at INL

- **Independent, science-based performance assessment of energy storage devices**
  - **Environmental control**
  - **Software analysis tools for data analysis and reporting.**
  - **Standards developed for data acquisition, analysis, quality, and management.**
- **Protocols & Procedures**
  - **Internationally accepted manuals for performance assessment of energy storage systems.**
- **Quality Results**
  - **Flexible state-of-the-art energy storage test facility capable of supporting current and future development activities.**
  - **Rigorous NIST traceable calibration procedures for in depth uncertainty analysis**
  - **Temperature controlled testing for reliable and repeatable results.**



Battery Test Manuals

- **Recently Published Manuals:**
  - **Battery Test Manual for Plug-In Hybrid Electric Vehicles (Sept. 2014)**
  - **Battery Test Manual for 12V Start/Stop Vehicles (Nov. 2013)**
  - **Battery Test Manual for Low-Energy Energy Storage Systems for Power-Assist Hybrid Electric Vehicles (Apr. 2013)**
  - **Battery Calendar Life Estimator Manual, Rev. 1: Modeling and Simulation (Oct. 2012)**
  - **Battery Technology Life Verification Test Manual Rev. 1 (Dec. 2012)**


INL/EXT-14-32849

U.S. Department of Energy
Vehicle Technologies Program

Battery Test Manual
For Plug-In Hybrid Electric Vehicles

REVISION 3

SEPTEMBER 2014

The Idaho National Laboratory is a U.S. Department of Energy National Laboratory
Operated by Battelle Energy Alliance

- **Manual Revisions ongoing:**
  - **EV Manual, Revision 3**

http://www.uscar.org/guest/article_view.php?articles_id=86

Idaho National Laboratory

INL Battery Test Center Facilities and Equipment

- Over 500 items tested per year
- ~20,000ft^2 lab space
- 671 cell test channels
- 27 module test channels
- 7 pack test channels
- ~100 controllable thermal chambers
- Vibration test system

Industry Partnerships

Lithium Ion

A123 SYSTEMS, SAFT, Leyden energy, altairnano, Hydro-Québec, ENVIA SYSTEMS, QUALLION, Johnson Controls, ActaCell, SK energy, COBASYS, K2 Energy, NIPPON CHEMI-CON CORPORATION, LG Chem, MILTEC, ENERDEL, Panasonic, VARTA

Lead Acid

OPTIMA BATTERIES, EXIDE, AXION POWER INTERNATIONAL INC., Deka EAST PENN manufacturing co. inc.

Ultracapicitor

enerG2, EPCOS, Maxwell TECHNOLOGIES, TDK, NESSCAP ULTRACAPACITORS

http://www.caesonline.org/ESL/Battery%20Lab.html

Summary

- ***INL Advanced Vehicle Testing & Analysis is a DOE Core Capability for advanced automotive technologies***
  - ***INL has accumulated 232 million miles (373 million km) and 44,300 AC MWh from 27,400 electric drive vehicles and 17,000 charging units***
- ***Advanced energy storage***
  - ***Performance Science analysis of Li-ion Batteries from half-cell to vehicle and back***
- ***Plug-in electric vehicles***
  - ***Continued testing and analysis of plug-in vehicles***
  - ***Big-Data analysis of vehicle usage***
  - ***Connected Automated Vehicles***
- ***Infrastructure***
  - ***Wireless Charging & Level I, II, III – standardization, energy & efficiency***
  - ***Big-Data analysis of infrastructure usage***
  - ***Cyber security***
- ***Additional Vehicle Testing***
  - ***Advanced climate control, power electronic, and other ancillary and accessory systems technologies***
  - ***Advanced internal combustion engines (CNG/Turbocharged Direct Injection Diesel)***

Tech to Market Workshop at INL

t2m Workshop


INL
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