U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Batteries and Electrification R&D Overview

Steven Boyd, Program Manager

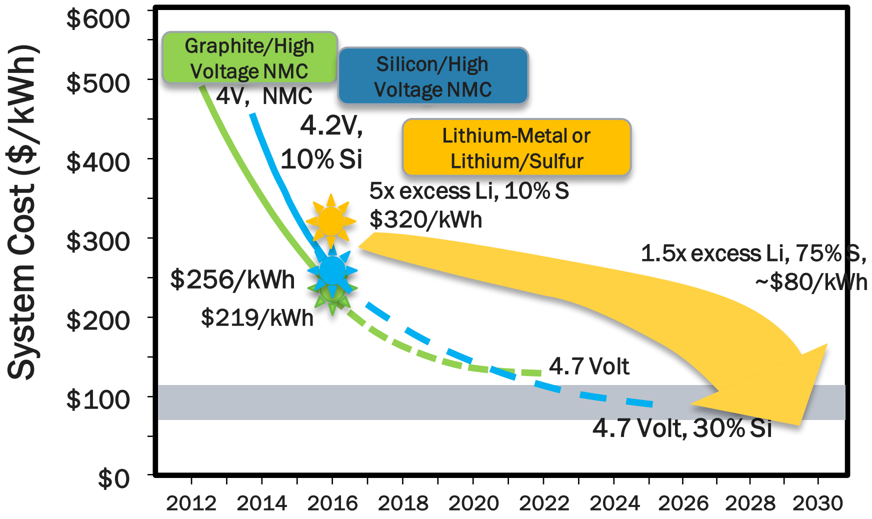
June 18, 2018

Batteries and Electrification

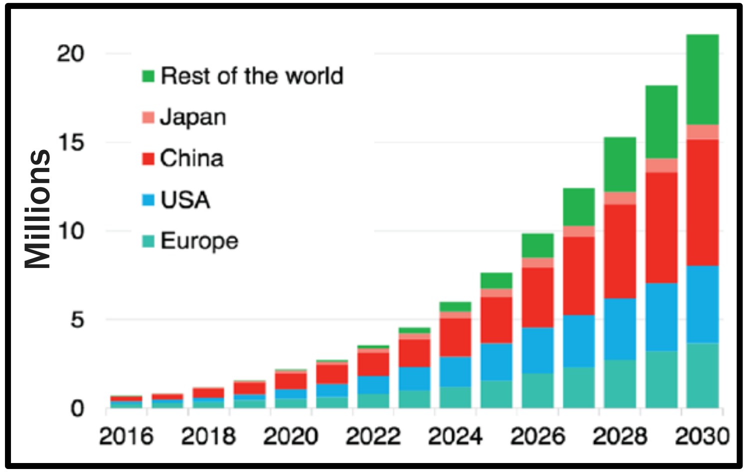
Enable a large market penetration of electric drive vehicles through innovative research and development:

- Reduce the cost of electric vehicle batteries to less than $100/kWh and decrease charge time to 15 minutes or less, with the ultimate goal of $80/kWh.
- Address the charging infrastructure and electricity grid challenges to enable a 15-minute or less charge
- An electric traction drive system at a cost of $6/kW for a 100 kW peak system

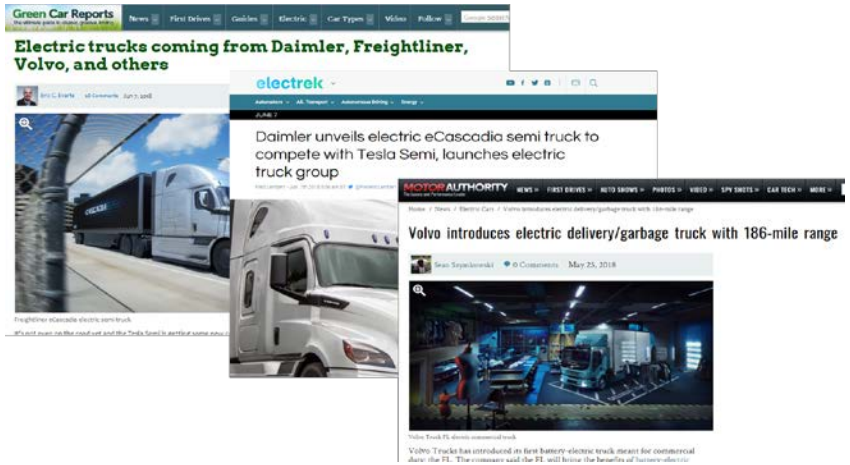
Cost Trends for Lithium-based EV Batteries



Global EV Forecast



Source: Bloomberg New Energy Finance



Green Car Reports

Electric trucks coming from Daimler, Freightliner, Volvo, and others

electrek

Daimler unveils electric eCascadia semi truck to compete with Tesla Semi, launches electric truck group

MOTOR AUTHORITY

Volvo introduces electric delivery/garbage truck with 186-mile range

Batteries Team and Focus Areas


Tien Duong


Peter Faguy


Samm Gillard

- ❑ **Beyond Lithium Ion Technology**
  - – Battery500 Consortium
  - – BMR (exploratory Battery Materials Research)
- ❑ **Next Generation Lithium Ion Materials Research**
  - – Low or “No” Cobalt Cathode Emphasis
  - – Intermetallic Alloy Composite Anode
  - – Materials Scale Up
  - – Processing Science
- ❑ **Advanced Cell development**
  - ❑ USABC
  - ❑ High Fidelity Performance , Life, and Safety Testing
  - ❑ Extreme Fast Charging R&D (Lab and FOA)
  - ❑ Recycling and Recovery R&D


Brian Cunningham


David Howell


Will James

Electrification Team and Focus Areas

- ☐ **Electric Drive Technologies**
  - Focus on power density and cost reduction
  - Higher voltages, larger and more diverse vehicle electrification

Susan Rogers

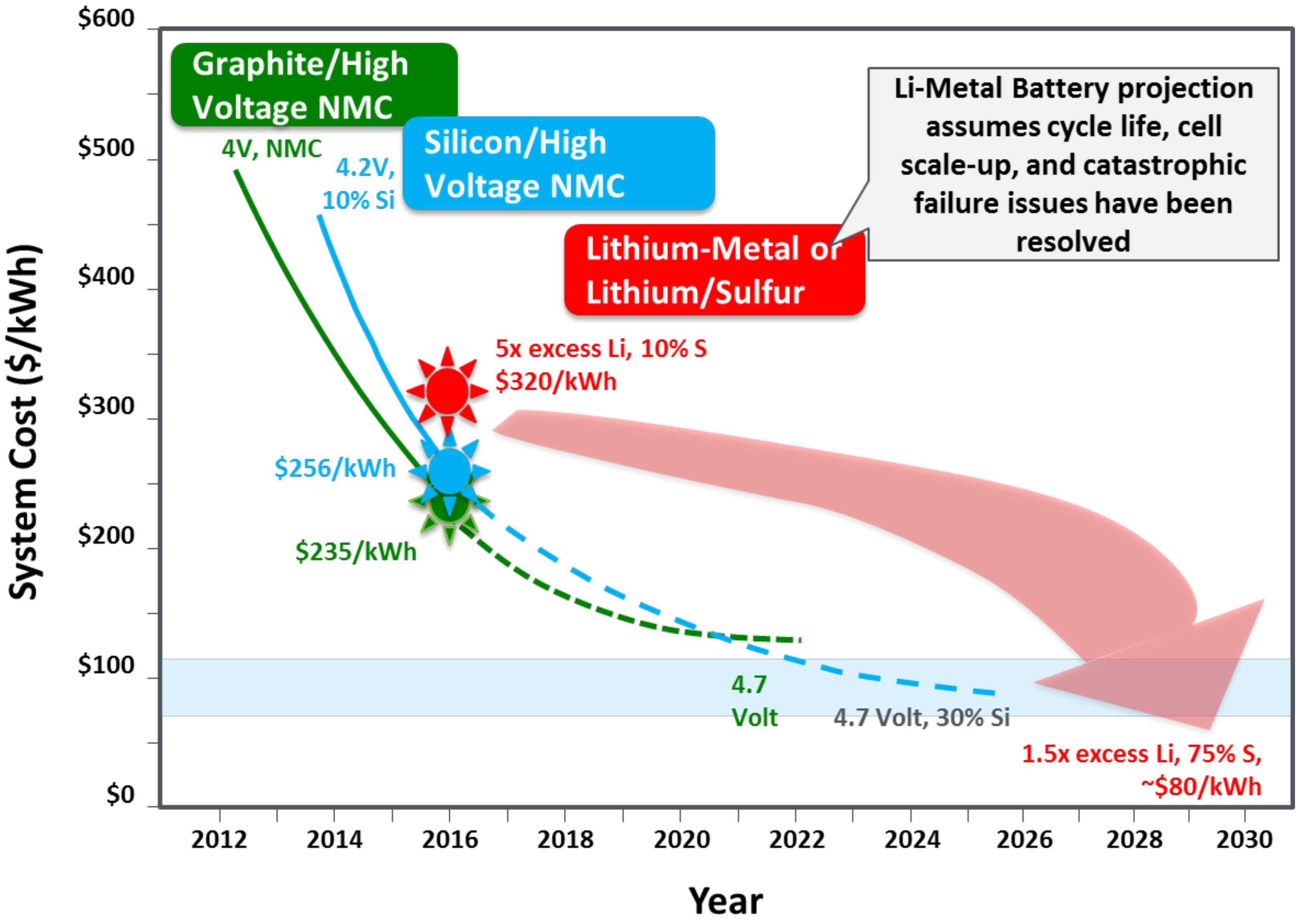
- ☐ **Grid and Charging**
  - EV Grid Integration and Services
  - High Power Static / Dynamic Wireless
  - EV / EVSE / Grid Interoperability & Control
  - Extreme Fast Charging (XFC)
  - Cyber Security

Lee Slezak

VTO Budget

VTO Program Area	FY17 Enacted	FY18 Enacted
Batteries and Electrification (Batteries, Electric Drive, Grid/Infrastructure)	$140,530,000	$160,000,000
Energy Efficient Mobility Systems (including Vehicle Systems)	$24,385,000	$41,000,000
Advanced Combustion Engine and Fuels R&D	$71,440,000	$65,200,000
Materials (Lightweight and Propulsion)	$28,100,000	$25,000,000
Technology Integration (Data and Systems Research and Advanced Vehicle Technology Competitions)	$37,400,000	$41,300,000
Analysis	$5,100,000	$5,000,000
VTO TOTAL	$306,955,000	$337,500,000

Battery Cost Reduction Pathways



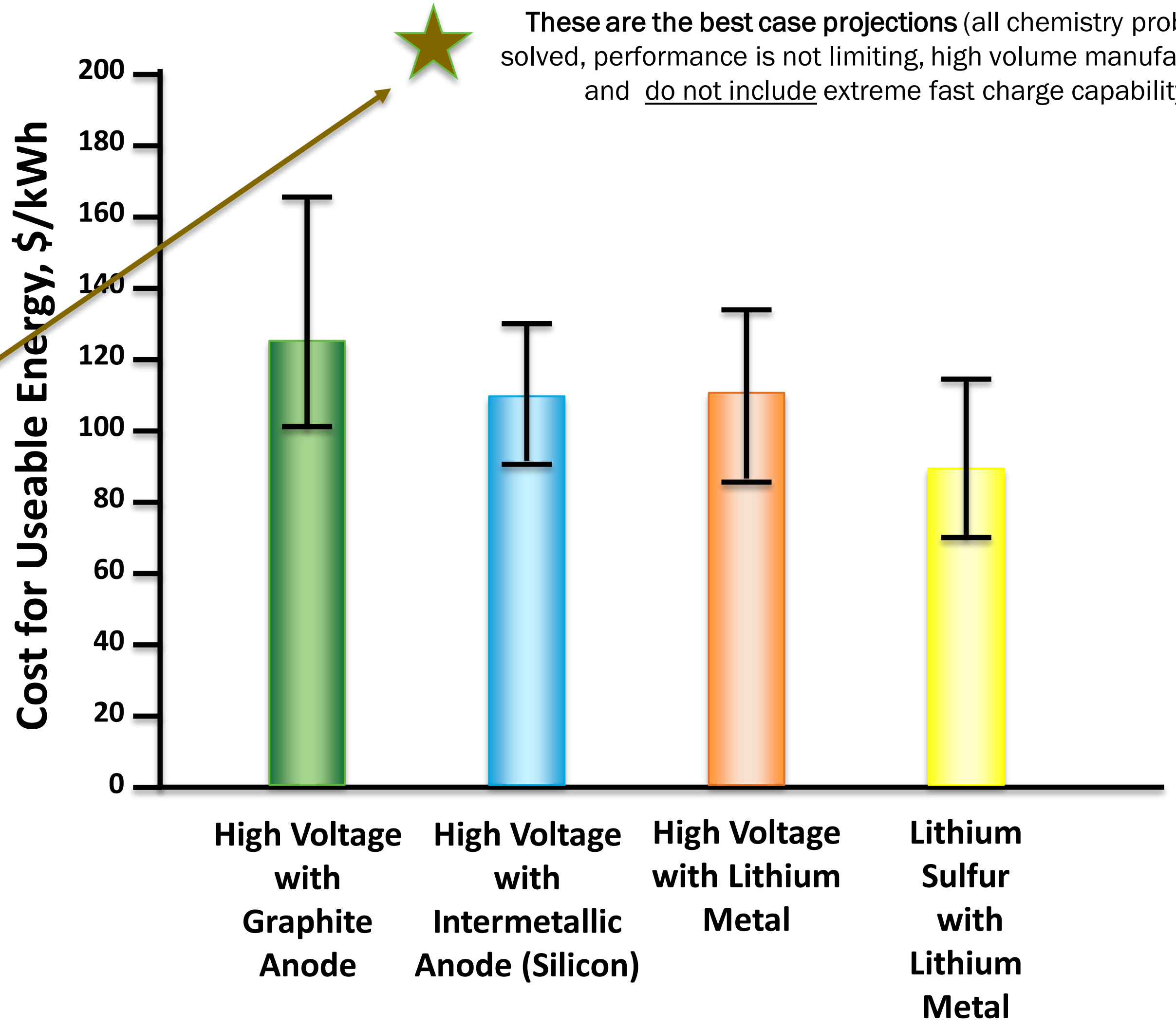
Li-Metal Battery projection assumes cycle life, cell scale-up, and catastrophic failure issues have been resolved

Potential for Future Battery Cost Reduction

Status

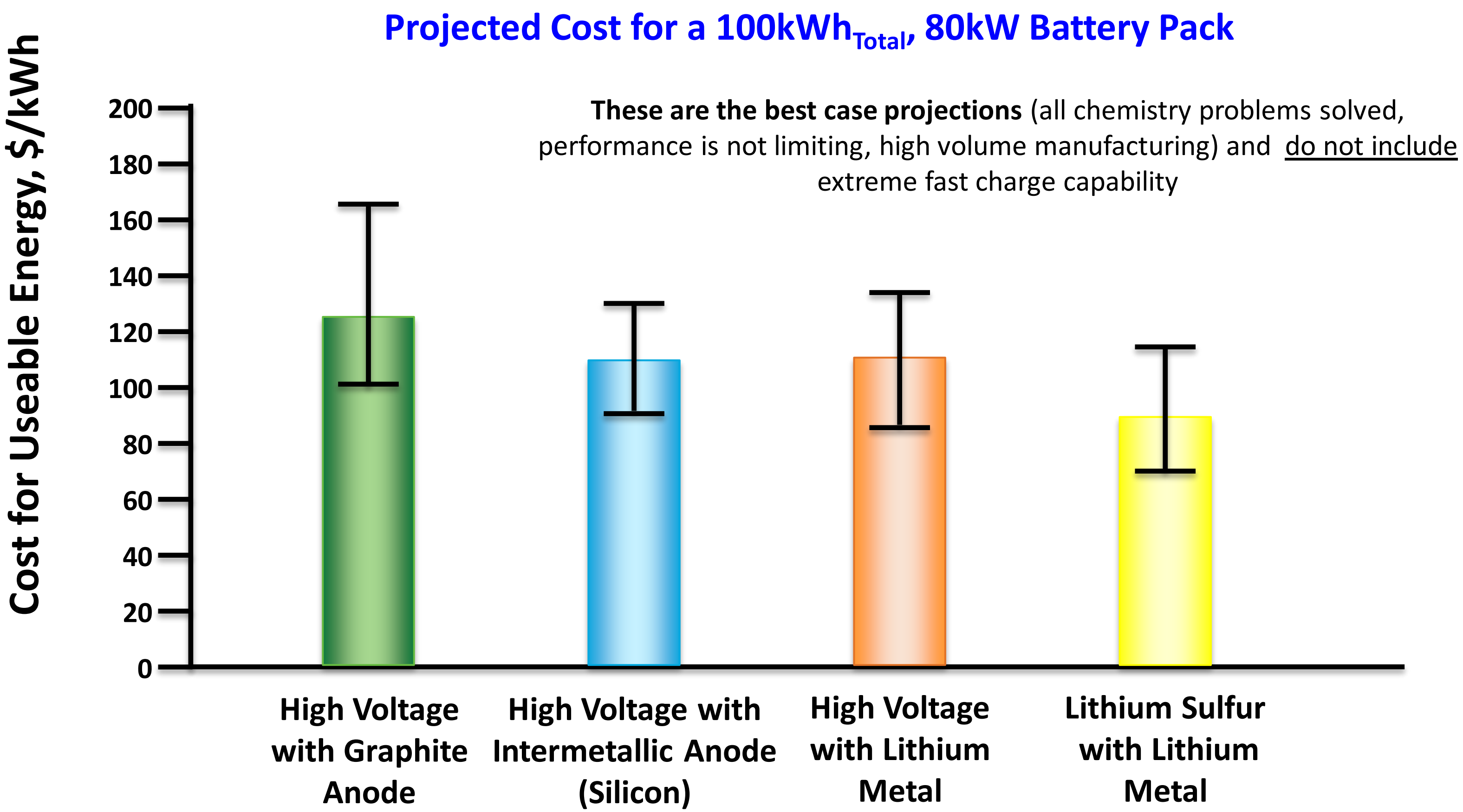
DOE R&D has lowered the cost of EV battery packs to \$219/kWh; ~80% reduction since 2008

Projected Cost for a $100kWh_{Total}$, 80kW Battery Pack



These are the best case projections (all chemistry problems solved, performance is not limiting, high volume manufacturing) and do not include extreme fast charge capability

Future Battery Technology Impact on Critical Materials

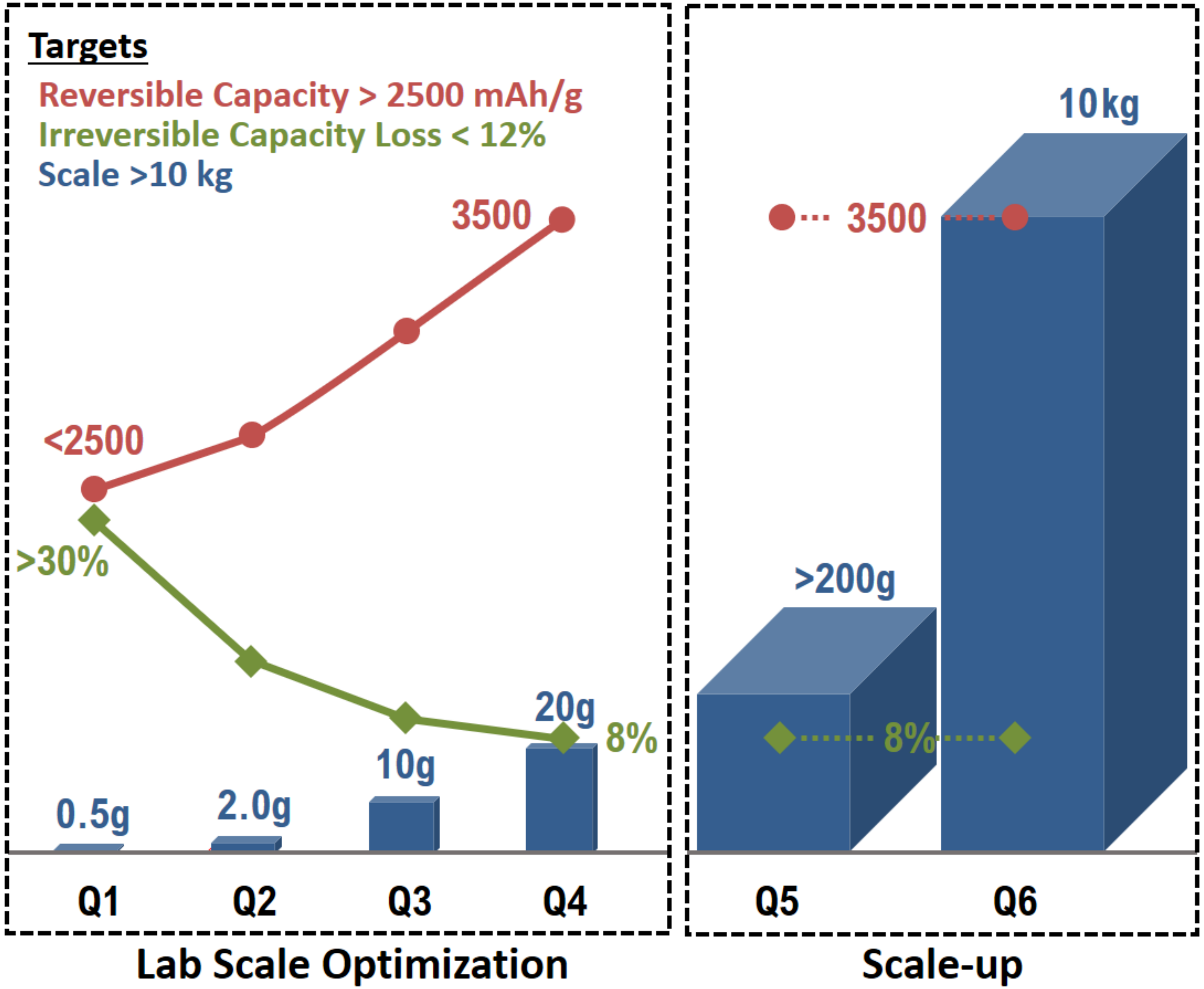


These are the best case projections (all chemistry problems solved, performance is not limiting, high volume manufacturing) and do not include extreme fast charge capability

Critical Materials Content (kg) *per Battery Pack*		High Voltage with Graphite Anode	High Voltage with Intermetallic Anode (Silicon)	High Voltage with Lithium Metal	Lithium Sulfur with Lithium Metal
	Lithium	13	13.7	19.4	24.3
	Cobalt	19	20.6	18.5	0
	Nickel	60	63.3	58.5	0

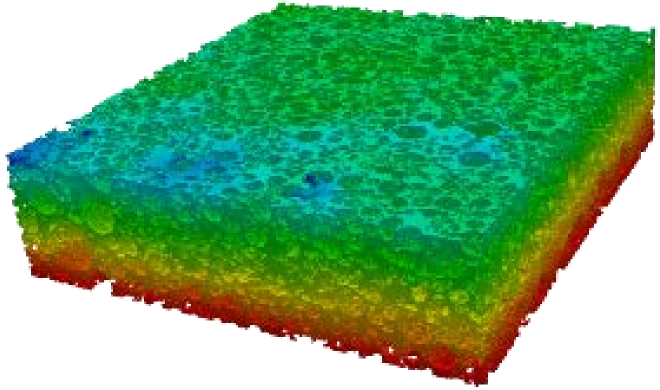
Microporous Silicon Anodes

- Navitas Systems has demonstrated a novel, commercially scalable approach to produce microporous silicon (μpSi) with a large reduction in the cost and environmental impact.
- DOE's EV battery cost goal of $100/kWh can be met by pairing Si-based high capacity anodes with NMC cathodes, but the Si cost must be <$25/kg. The Navitas material is able to meet the 1300 mAh/g and $25/kg targets.



X-CEL: eXtreme fast charge Cell Evaluation of Li-Ion batteries

- **Problem:** Lithium plating at high charge rates on high energy density graphitic anode cells have an affinity for lithium plating on the electrode surface. Understanding which factor limits the kinetics is critical to enabling fast charging.
- **Potential Impact:** Understanding the fundamental limits of what conditions cause this plating to occur will allow for optimized design to reduce or eliminate plating behavior at high rates (>6C)
- **Approach:** A multi-lab effort including modeling, cell fabrication, performance testing and post-testing characterization
- **Goal** (Year 1): Understand rate limiting step that is most responsible for lithium plating and limits on loading at high rates

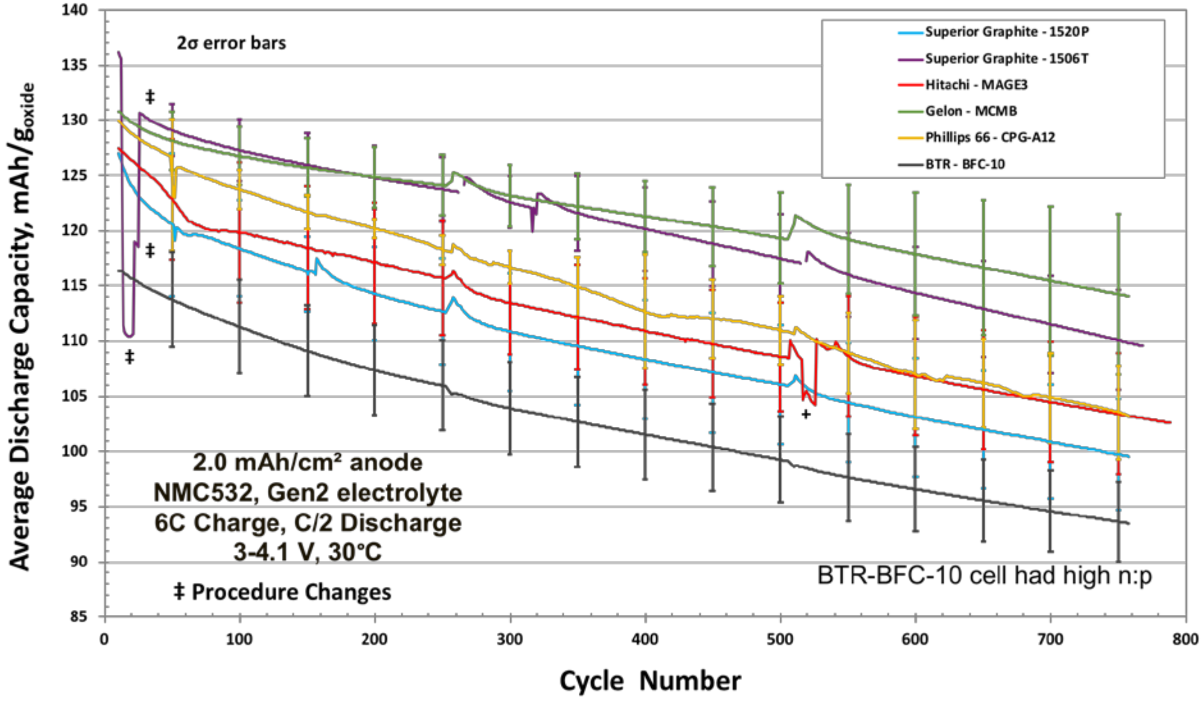


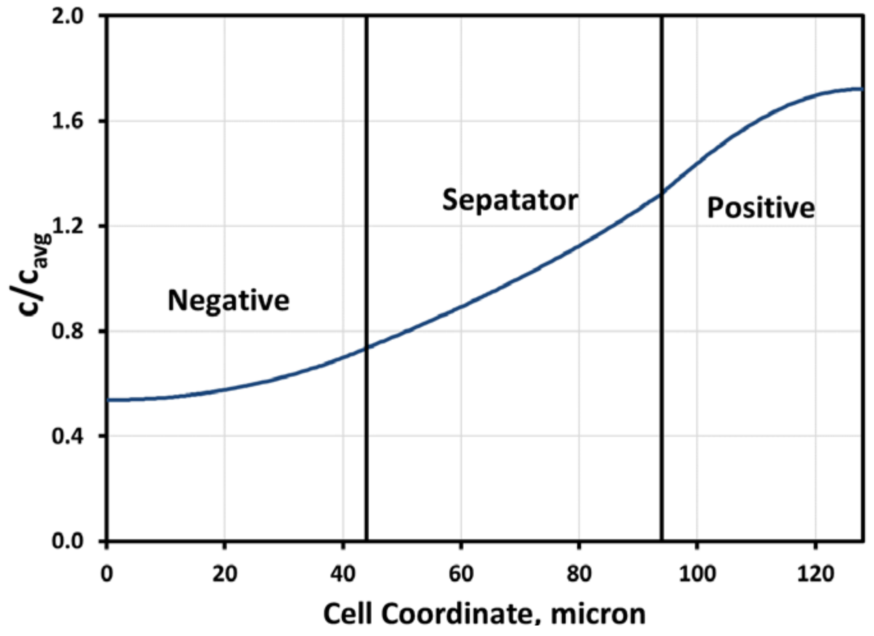
NREL NATIONAL RENEWABLE ENERGY LABORATORY INL Idaho National Laboratory Argonne NATIONAL LABORATORY

X-CEL: eXtreme fast charge Cell Evaluation of Li-Ion batteries

Key Findings

- 6 different compositions had similar fading behavior – indicated graphite intercalation is not the rate limiting step in charging
- Thin electrodes cycles well under fast charge conditions. But thicker electrodes show significant fade.
  - This suggests that Li plating driven by transport limitations in the porous anode.





Critical Materials for Li-based Batteries

Cobalt

- Cobalt is considered the highest material supply risk in the short and medium term
- Example: Cobalt is up to 20% of the weight of the cathode in lithium ion EV batteries
  - For the same cell (18650):
    - Consumer electronics batteries have ~9.5g of Cobalt
    - EV batteries have ~1.5g Co (NCA cathode)
- Cobalt is mined as a secondary material from mixed nickel and copper ore
  - The majority of the global supply mined in the Democratic Republic of Congo
- Current battery recycling practices profitably recover cobalt

Material	Availability (MT)	Cumulative US Demand	%	Basis
Cobalt	13	1.1	9	World reserve base
Nickel	150	6	4	World reserve base

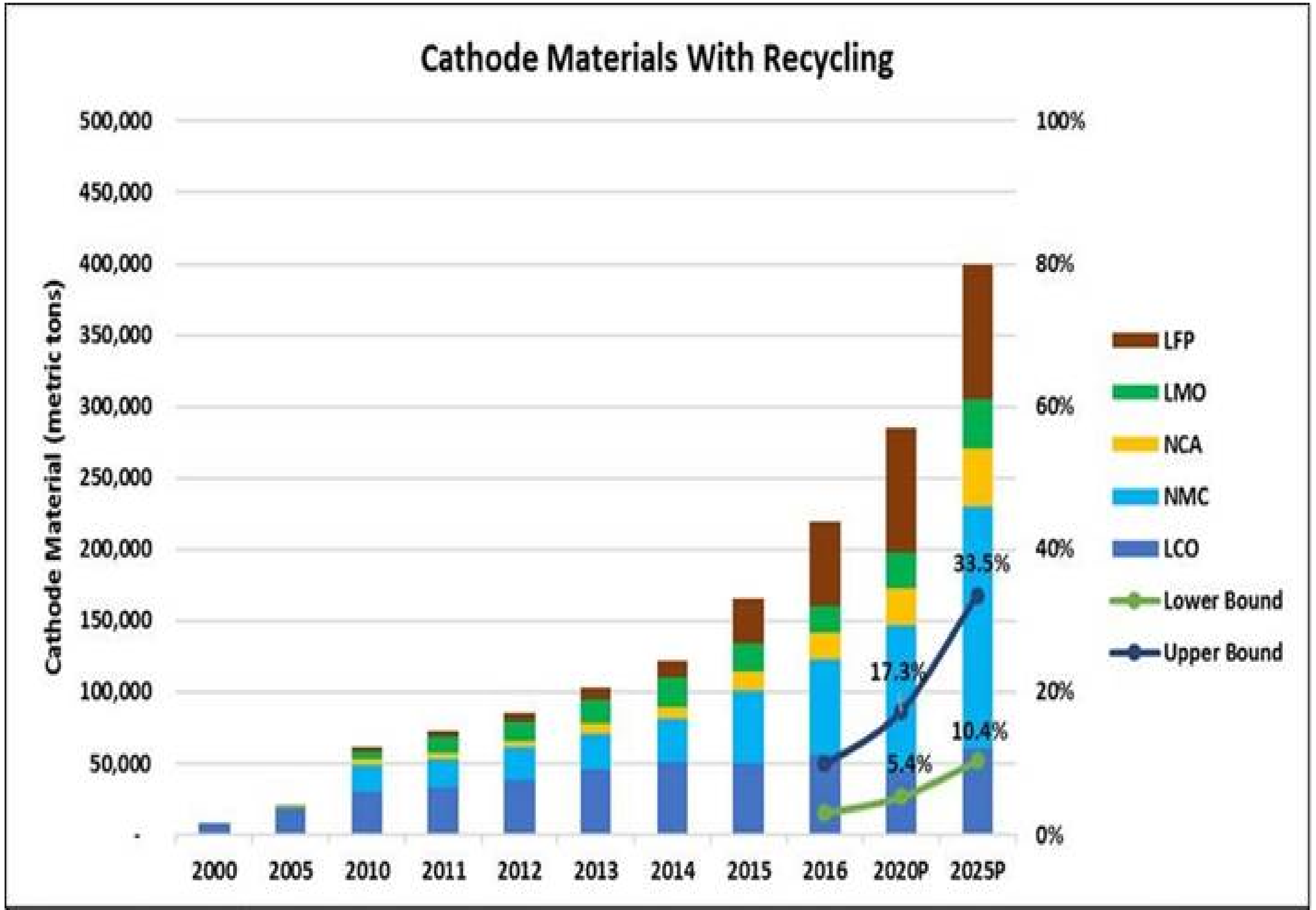
Table from: L. Gaines and P. Nelson, *Lithium-Ion Batteries: "Examining Material Demand and Recycling Issues*, TMS Annual Meeting (2009)

Cobalt mining in the Democratic Republic of Congo

Recycling Focus

Recycling Can Affect Material

- Virgin Demands
- Costs
- Availability

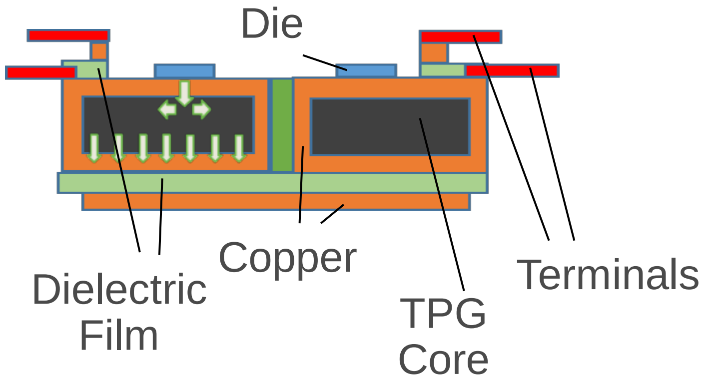


- Lower bound: 50% collection rate of the end-of-life batteries and 50% recovery rate
- Upper bound: 90% collection rate of the end-of-life batteries and 90% recovery rate
- Percentages represent potential of cathode materials demand filled by recycled materials

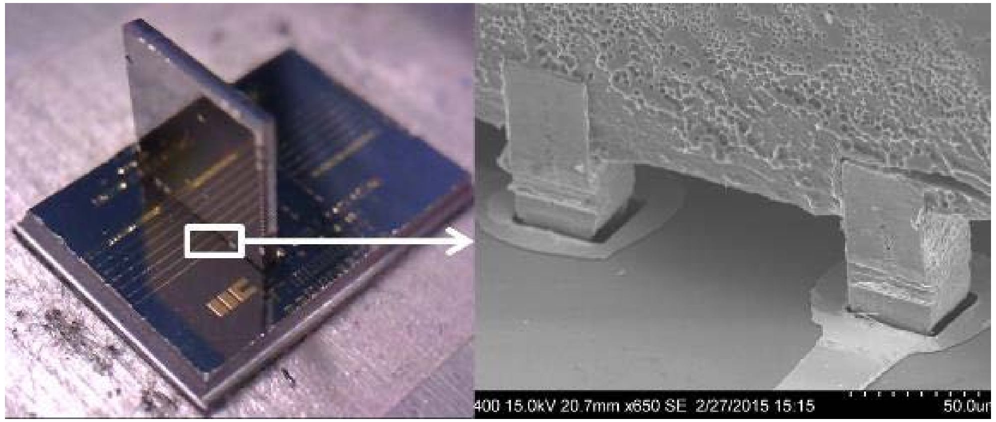
Electric Drive Research Highlights

Advanced Multiphysics Integration Technologies

New substrates and interconnects for high power density

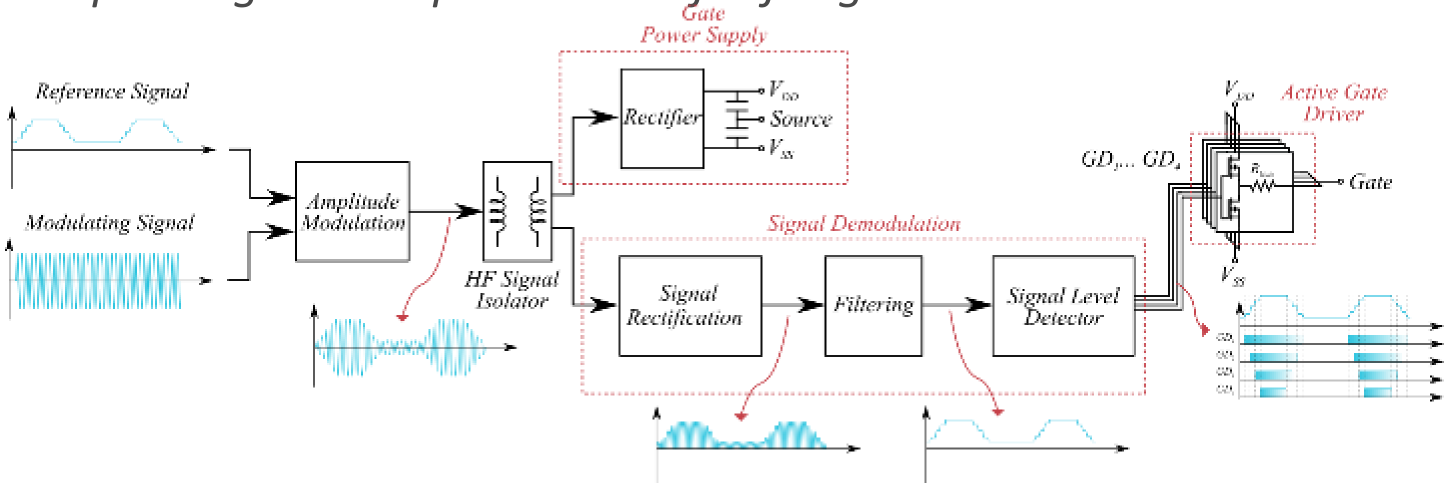


Source: Momentive



Source: Indiana IC

Compact signal and power transfer for gate drivers



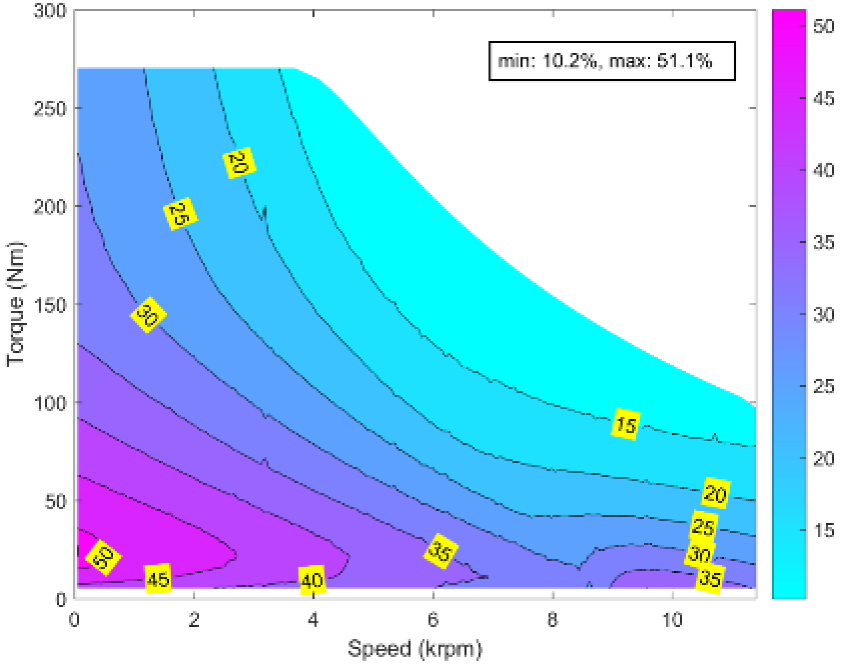
RF gate driver power supply circuit diagram

Source: ORNL

Electric Drive Research Highlights

Drivetrain Performance Improvement Techniques

Improve efficiencies in the low efficiency regions of operation by varying the modulation schemes

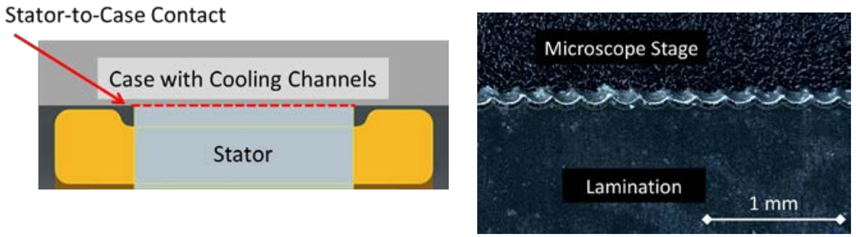


Source: ORNL

BMW i3 efficiency improvement

Increased Knowledge and Accuracy of Motor Material Parameters

- Produced data and physics-based model for stator-to-case thermal resistance.
- Collaboration to improve accuracy and prediction of electric motor performance with less product development time and cost.
- Published results improve access to data and tools for motor designs with increased power density without having to resort to overly conservative estimates.



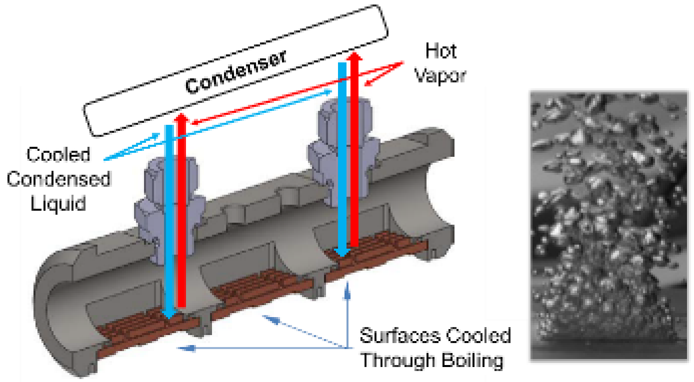
Source: NREL and UQM Technologies

Cross-section view highlighting a stator-to-case interface and edge view of one sample lamination showing a serrated edge

Electric Drive Research Highlights

Research for Power-Dense Two-Phase-Cooled Inverter Design

- Self-contained passive two-phase system enables high power density without conventional water-ethylene glycol (WEG) liquid cooling. Eliminates hoses, pumps and WEG coolant leaks.
- Research focuses on technologies for compact passive boiling below critical heat flux and compact modular condenser technologies.

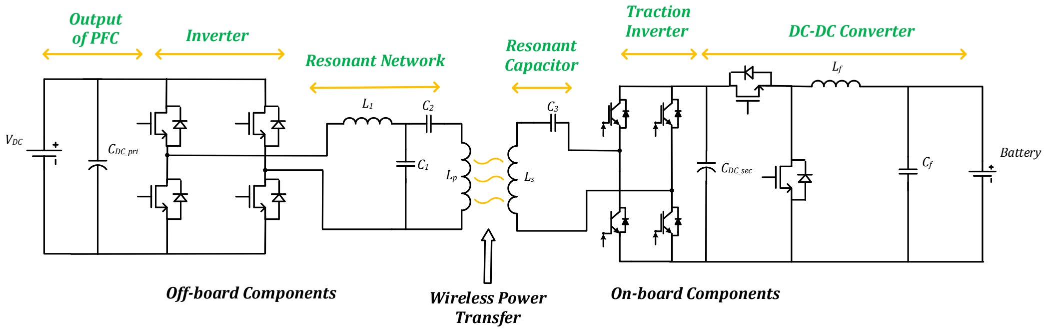


Source: NREL and John Deere

Illustration of example cross-sectional view of the evaporator vessel showing flow of two-phase fluid

Innovative Chargers and Converters

Integrated wireless charger; wireless charging capability with the addition of just a coil and a resonant network, utilizing the traction inverter.



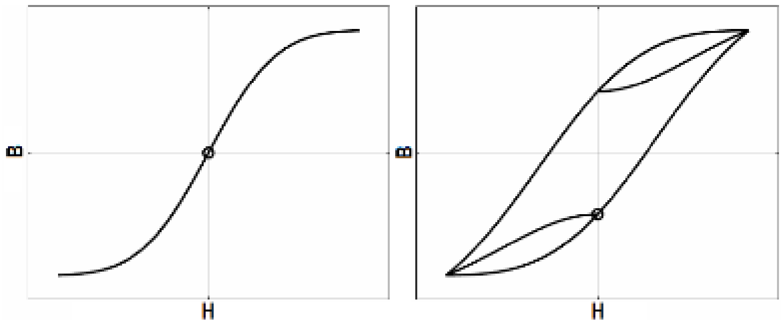
Source: ORNL

Integrated wireless charger circuit diagram

Electric Drive Research Highlights

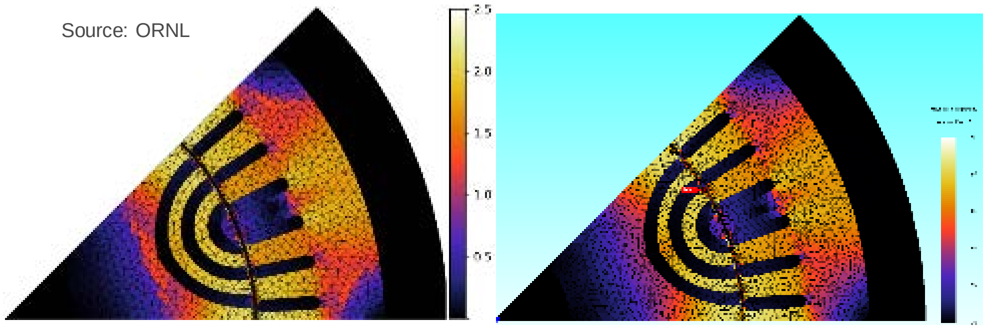
Advanced HPC Modeling of Motors and Materials

Improve motor modeling fidelity and facilitate optimization on HPC systems



Standard magnetic material (left) & improved model (right)

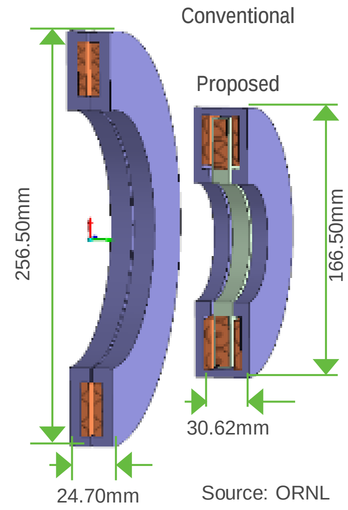
Source: ORNL



Magnetic flux density of a synchronous reluctance motor simulated using OeRSTED (left) and commercially available software (right)

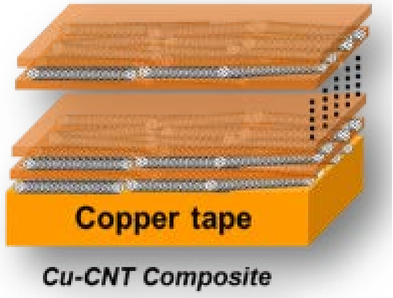
Non-Rare Earth Electric Motors and Ultra Conducting Copper (UCC)

- **Rotary transformers for wound rotor synchronous motors**
- **Reduction in mass and volume with UCC**



Source: ORNL

Rotary Transformer Concept



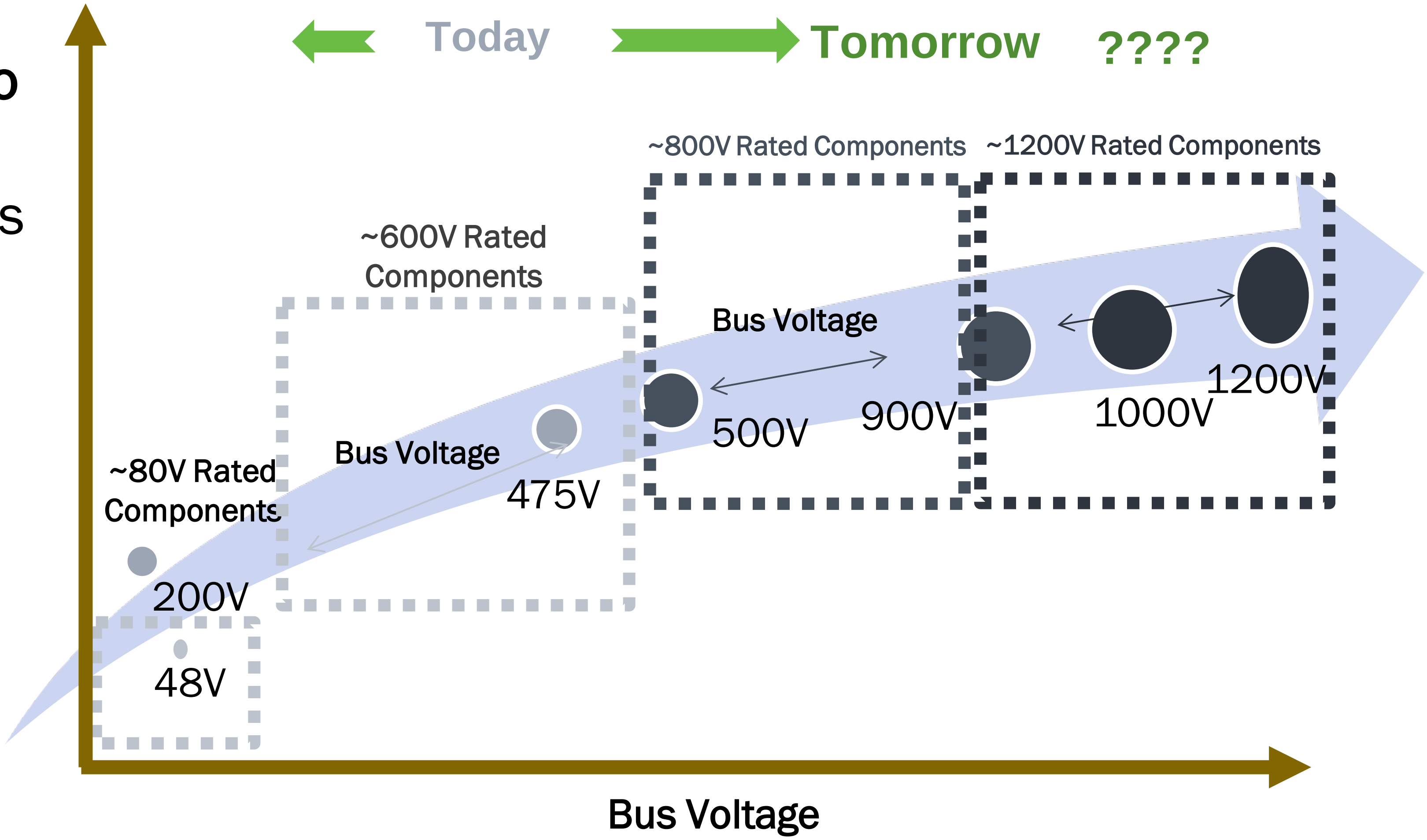
UCC composite

	Cu	CNT
Electrical Conductivity (MS/m)	59.6	100
Thermal Conductivity (W/m-K)	400	4000 W/m-K
Current Density (A/cm^2)	10^6	10^8

Electric Drive Highlight – Wide Bandgap Developments

Wide Bandgap Semiconductors are moving to Traction Drive Inverters

- Targeting higher DC link bus voltage systems (e.g. 600-1200Vdc)
- Similarly high phase currents of 300-600A and above peaks
- Can easily provide over 500kW of power in a compact package

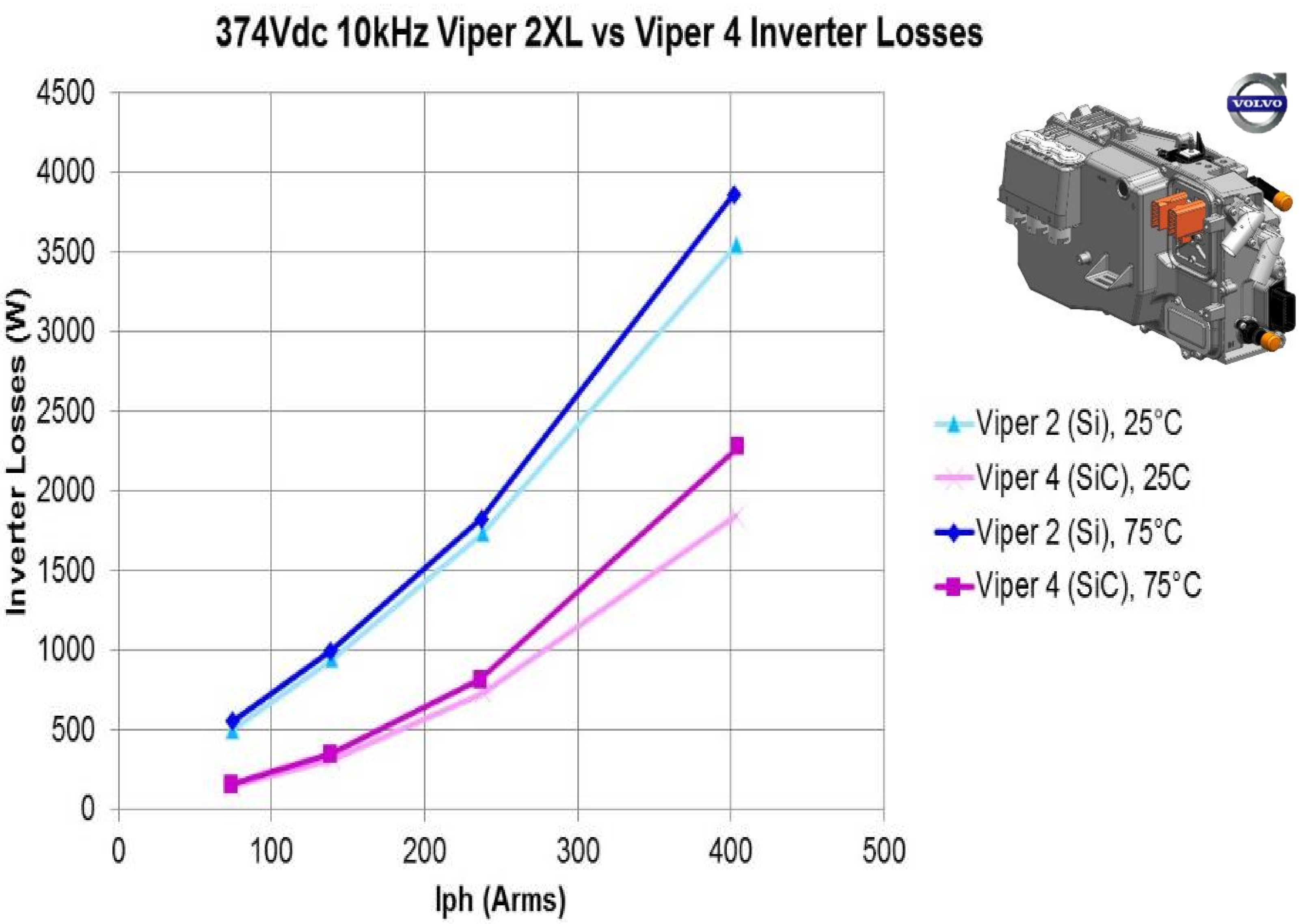


Higher Power for Premium/Performance drives Bus Voltages

Electric Drive Highlight – WBG Inverter Efficiency Improvements

The electrical characteristics should allow up to 80% conduction loss reduction in the inverters during normal drive cycles.

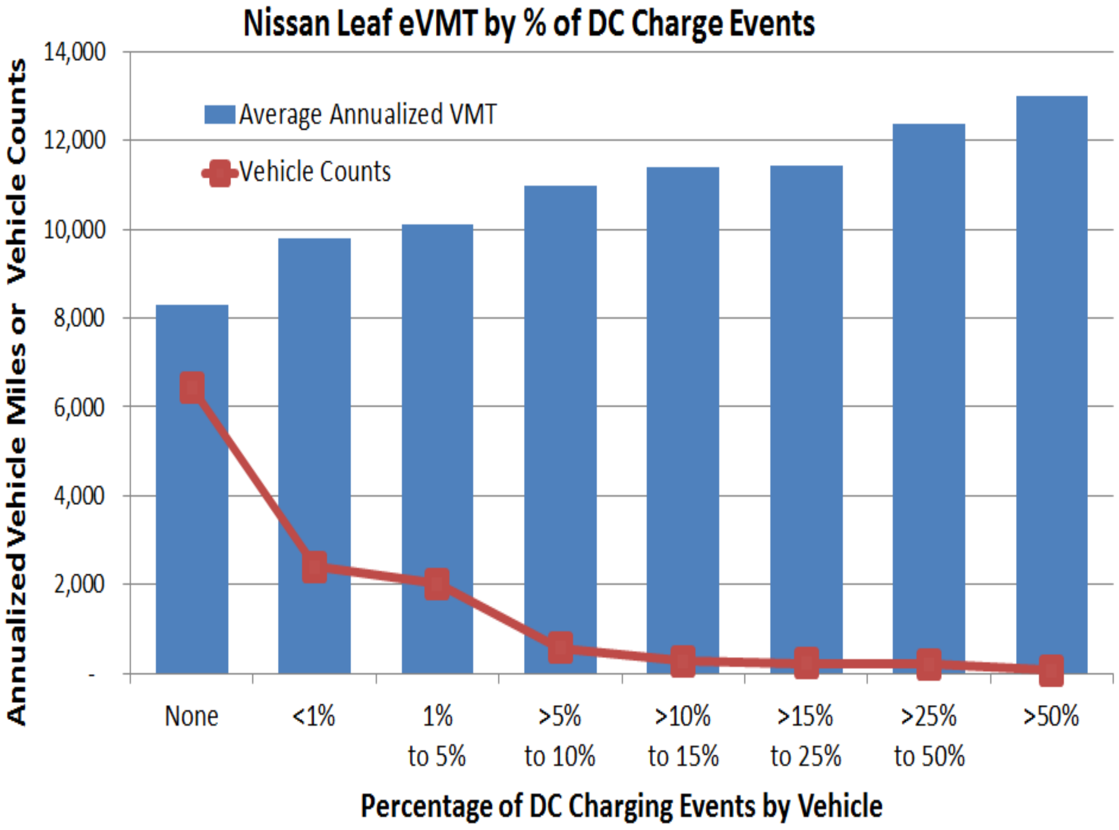
Implication: more vehicle range from a given battery pack capacity



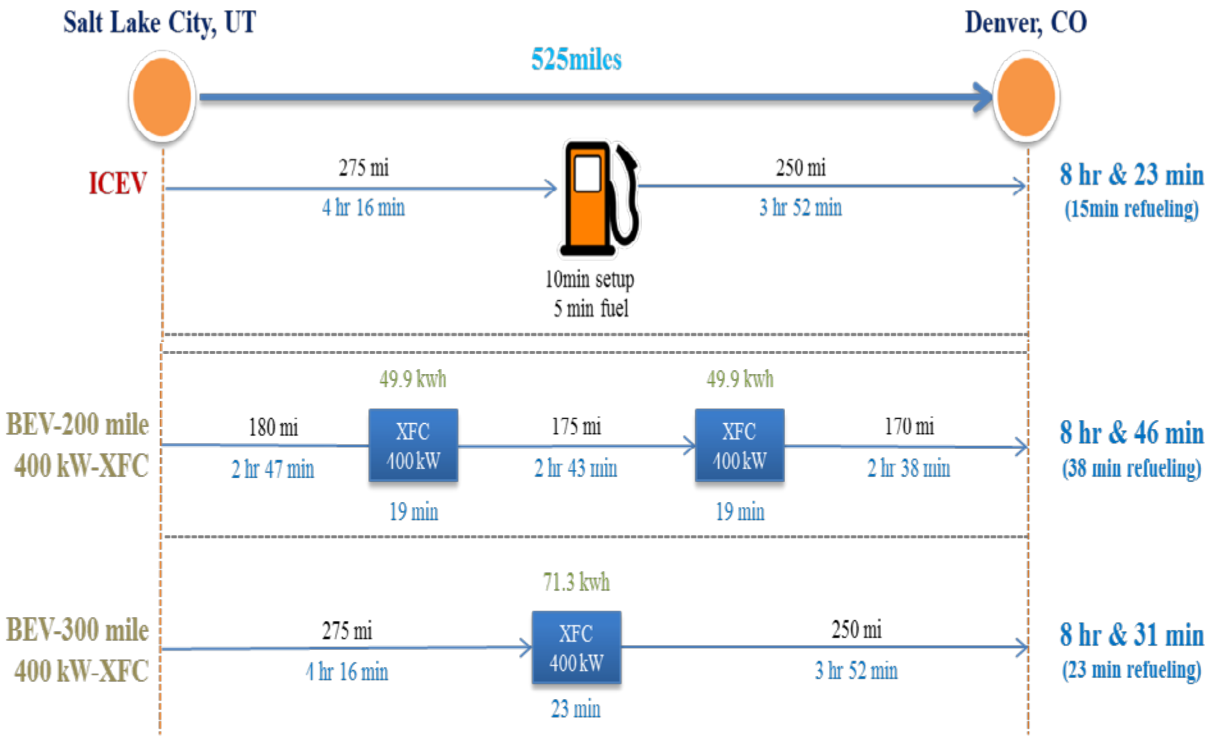
Focus Area: Extreme Fast Charging

Combination of fast charge batteries and a network of high capacity chargers can minimize range anxiety, promote the market penetration of BEVs, and increase total electric miles driven.

Type of Charging Station	Level 2 220V (~7.2kW)	DC Fast Charger (50kW)	Tesla Super Charger (140 kW)	Extreme Fast-Charging (400kW)
Time to charge (for 200 miles)	8 hours	2 hours	25 mins	10-15 mins



Source: Analysis Results from the California Air Resource Board (CARB)



Sources: Enabling Fast Charging, A Technical Gap Assessment, U.S. Department of Energy, Energy Efficiency and Renewable Energy, October 2017

Extreme Fast Charging Gap Assessment

FY 2017 VTO-funded Study

Enabling Fast Charging

A Technology Gap Assessment

- Assess the knowledge base of the fast charging capability of Electric Vehicles
- Identify technical gaps for fast charging
- Identify R&D opportunities

- Study focused on
  - Battery Technology
  - Vehicle Power Electronics
  - EV Charging Systems
  - Economics

U.S. DEPARTMENT OF ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Enabling Fast Charging:

A Technology Gap Assessment

October 2017

https://www.energy.gov/sites/prod/files/2017/10/f38/XFC%20Technology%20Gap%20Assessment%20Report_FINAL_10202017.pdf

XFC Considerations for Batteries

- Cost, life, and performance for xFC cells pose significant **technical challenges**
- Research into new materials and electrode designs are needed to mitigate Li plating and thermal management constraints

xFC Battery R&D Needs

Material & Cell Level R&D

- Study effects of xFC on state-of-the-art materials to gauge suitability and explore degradation mechanisms
- Understand/detect/prevent Li plating in operation to remedy safety and performance issues
- New anode materials to prevent or mitigate Li plating
- New electrode designs to allow fast diffusion in and out of reaction sites
- Abuse response of the cell due to xFC conditions may change and raise safety concerns

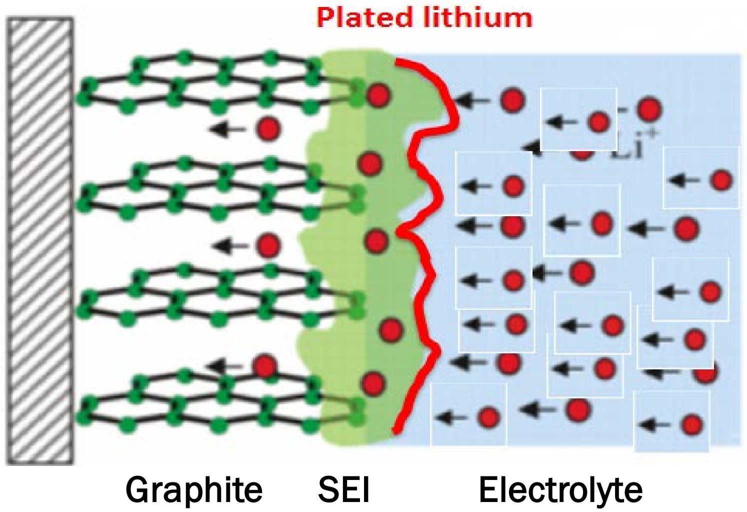
Pack Level R&D

- Improve thermal management
- Higher pack voltages (up to 1000 V) may be needed to reduce cost and weight of battery – more series connections will require more sensors for monitoring and robust BMS systems for control/management
- Advanced BMS to ensure cell balance after repeated xFC charges in order to minimize non-uniform aging and reductions in performance
- Charging algorithms to decrease charge time w/out impacting life

Lithium Plating

Charging Rate

At high charge rates, greater numbers of Li ions move to intercalate into graphite, but time and space constraints limit intercalations, so lithium ions may start plating as metal onto the surface of graphite



Challenges for Rechargeable Li Batteries, John B. Goodenough and Youngsik Kim, Chemistry of Materials 2010 22 (3), 587-603 DOI: 10.1021/cm901452z

Lithium Plating

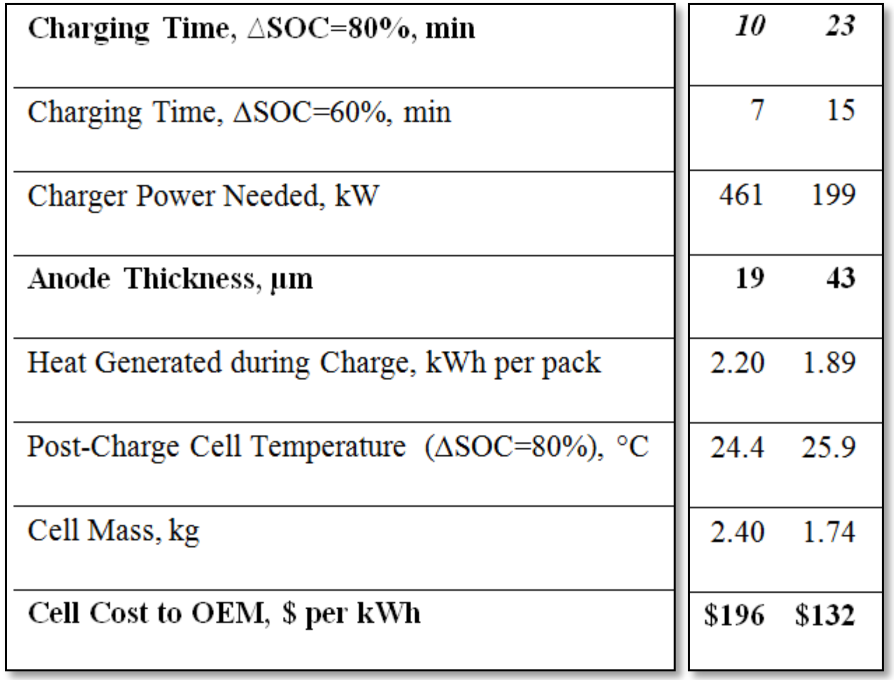
Higher areal capacity (mA/cm^2) can increase the likelihood of plating

K. Gallagher, et al., J. Electrochem. Soc. 163 (2016) A138eA149

xFC can induce lithium plating and impact performance, life, and safety of a cell

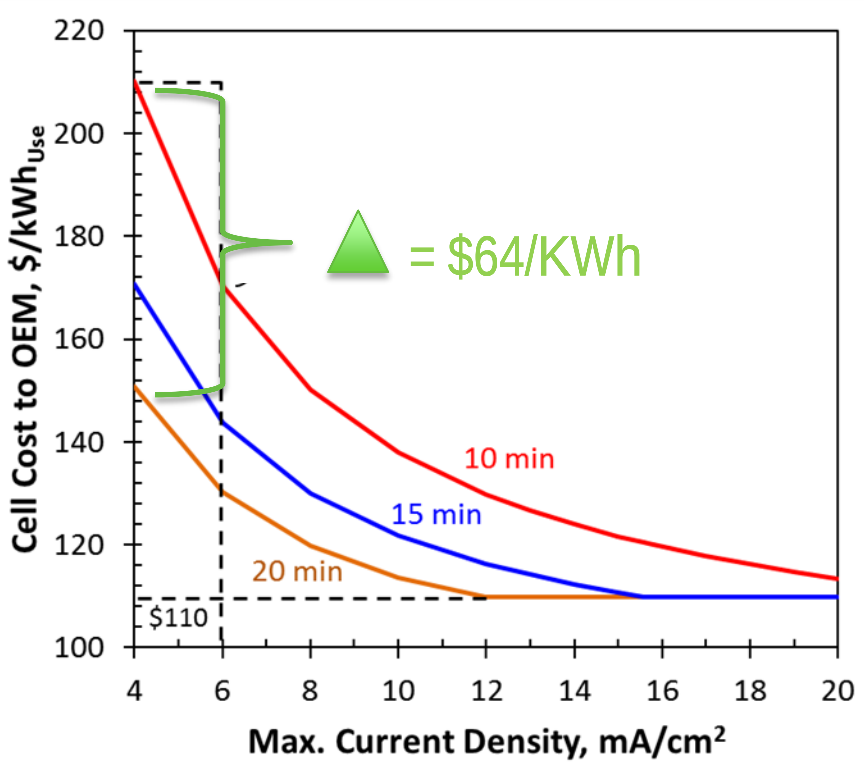
Impact of XFC on Cell Cost

xFC Cost: BatPaC simulation comparing the effects of charging time on the required anode thickness, the heat generation in the pack and the resulting temperature rise, the pack cost, and the incremental cost of charging faster than 1-C (60 minutes) rate



Charging Time, ΔSOC=80%, min	***10***	***23***
Charging Time, ΔSOC=60%, min	7	15
Charger Power Needed, kW	461	199
Anode Thickness, µm	**19**	**43**
Heat Generated during Charge, kWh per pack	2.20	1.89
Post-Charge Cell Temperature (ΔSOC=80%), °C	24.4	25.9
Cell Mass, kg	2.40	1.74
Cell Cost to OEM, $ per kWh	**$196**	**$132**

Cell Chemistry: NMC 622-Graphite; Pack Energy: 85 kWh; Rated Power (10 sec burst): 300 kW ; MACD (Maximum Allowable Current Density): 4 mA/cm^2; Number of cells per pack: 240

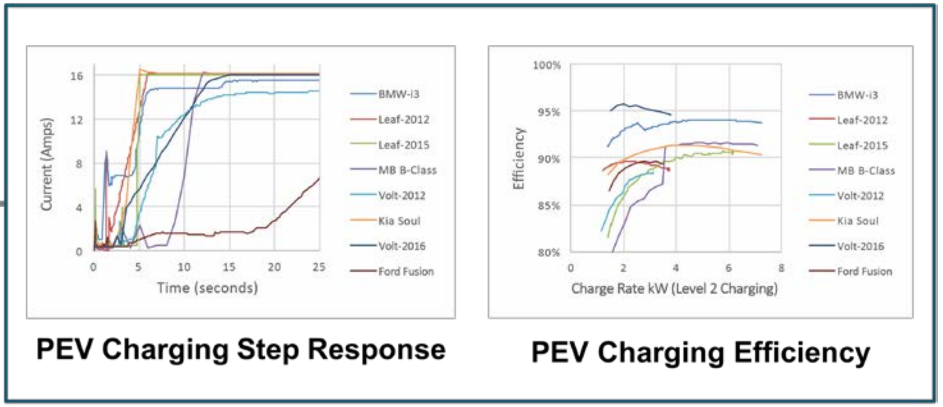


Thinner electrodes can facilitate high rate charging but increase cell cost

EV Charging Grid Impacts

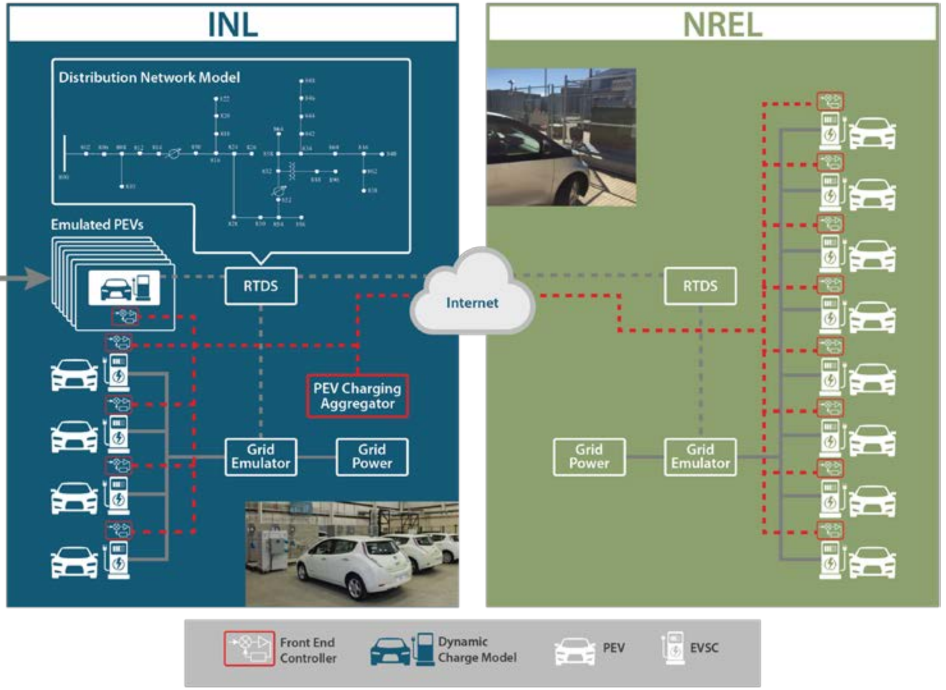
Can PEVs provide grid services and improve grid stability?

- Quantify impact of widespread uncontrolled charging
- Develop an open source control strategy to manage PEV charging that can provide grid services
- Understand cybersecurity risks
- Demonstrate uncontrolled and control of vehicle charging



PEV Charging Step Response

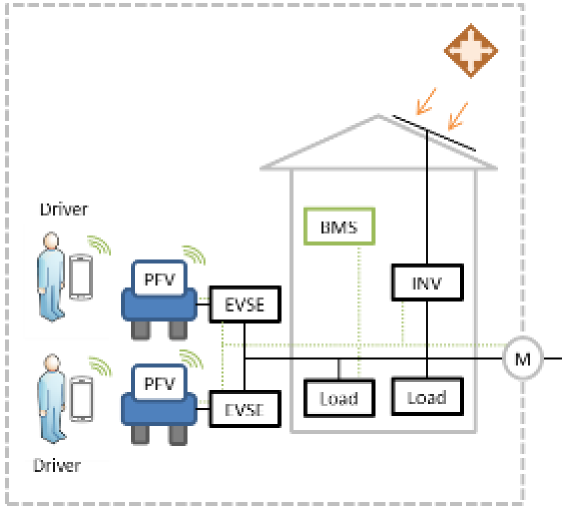
PEV Charging Efficiency



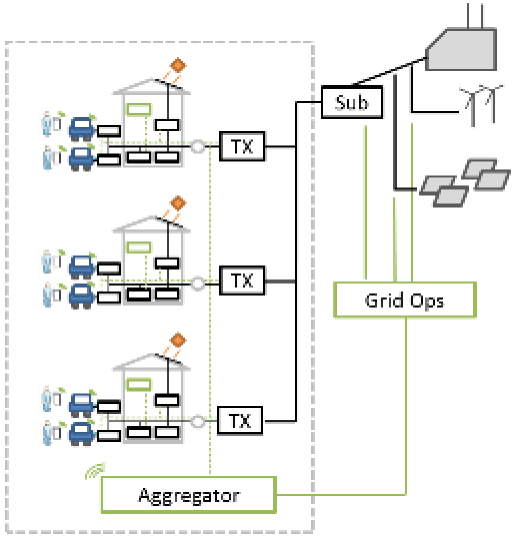
Hardware in the Loop Platform

Grid Modernization Lab Consortium Projects

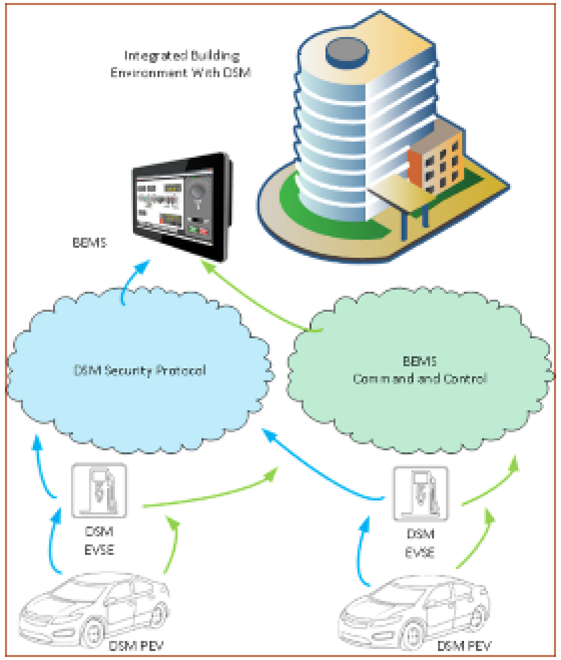
DOE’s Vehicle Technologies Office is funding three vehicle/grid integration projects for FY16 – FY18. The projects cross multiple domains:



GM0062 – Vehicle to Building



GM0085 - Distribution Network Level



GM0163 – Diagnostic Security Modules

Argonne NATIONAL LABORATORY

BERKELEY LAB

INL Idaho National Laboratory

Multi-Lab EV Smart Grid Working Group

OAK RIDGE National Laboratory

Pacific Northwest NATIONAL LABORATORY

NREL NATIONAL RENEWABLE ENERGY LABORATORY

Publications and Partnerships

Annual Progress Reports (2017 for Batteries and Electrification)
https://www.energy.gov/eere/vehicles/annual-progress-reports

USCAR Technical Teams http://www.uscar.org/guest/tlc.php

- Electrochemical Energy Storage Tech Team
- Electrical & Electronics Tech Team
- Grid Interaction Tech Team

U.S. Advanced Battery Consortium
http://www.uscar.org/guest/teams/12/U-S-Advanced-Battery-Consortium-LLC

Thank you

EERE VTO team members receive the EERE Outstanding Impact Award for their world-class leadership in furthering the mission at EERE with the successful development of the ground-breaking electric vehicle Extreme Fast Charging R&D Gap Assessment Research Roadmap