Argonne Mobility Research Impending Electrification

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Argonne National Laboratory
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U.S. DEPARTMENT OF ENERGY

Argonne: DOE’s Largest Transportation Research Program

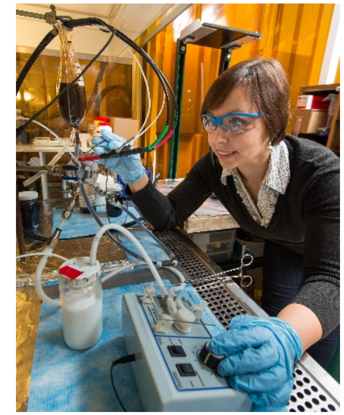
http://www.anl.gov/

- Located 25 miles from the Chicago Loop, Argonne was the first national laboratory, chartered in 1946
- Operated by the University of Chicago for the U.S. Department of Energy
- Major research missions include basic science, environmental management, and advanced energy technologies
- About 3,500 employees, including 178 joint faculty, 1000 visiting scientists and 6500 facility users
- Annual operating budget of about $750 million (≈80% from DOE)
- Research collaboration and partnerships are highly valued

Argonne's Center for Transportation Research
Unique Facilities and Depth of Expertise

Basic & Applied Combustion Research
- Fuels and After treatment

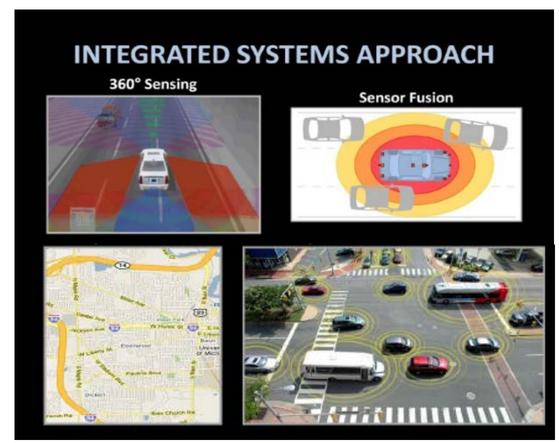
Modeling and Simulation
- CFD Engine Combustion
- Vehicle PT Energy & Controls



Materials Research
- Tribology
- Thermal Mechanical

Advanced Powertrain Research Facility

EV-Smart Grid Interoperability

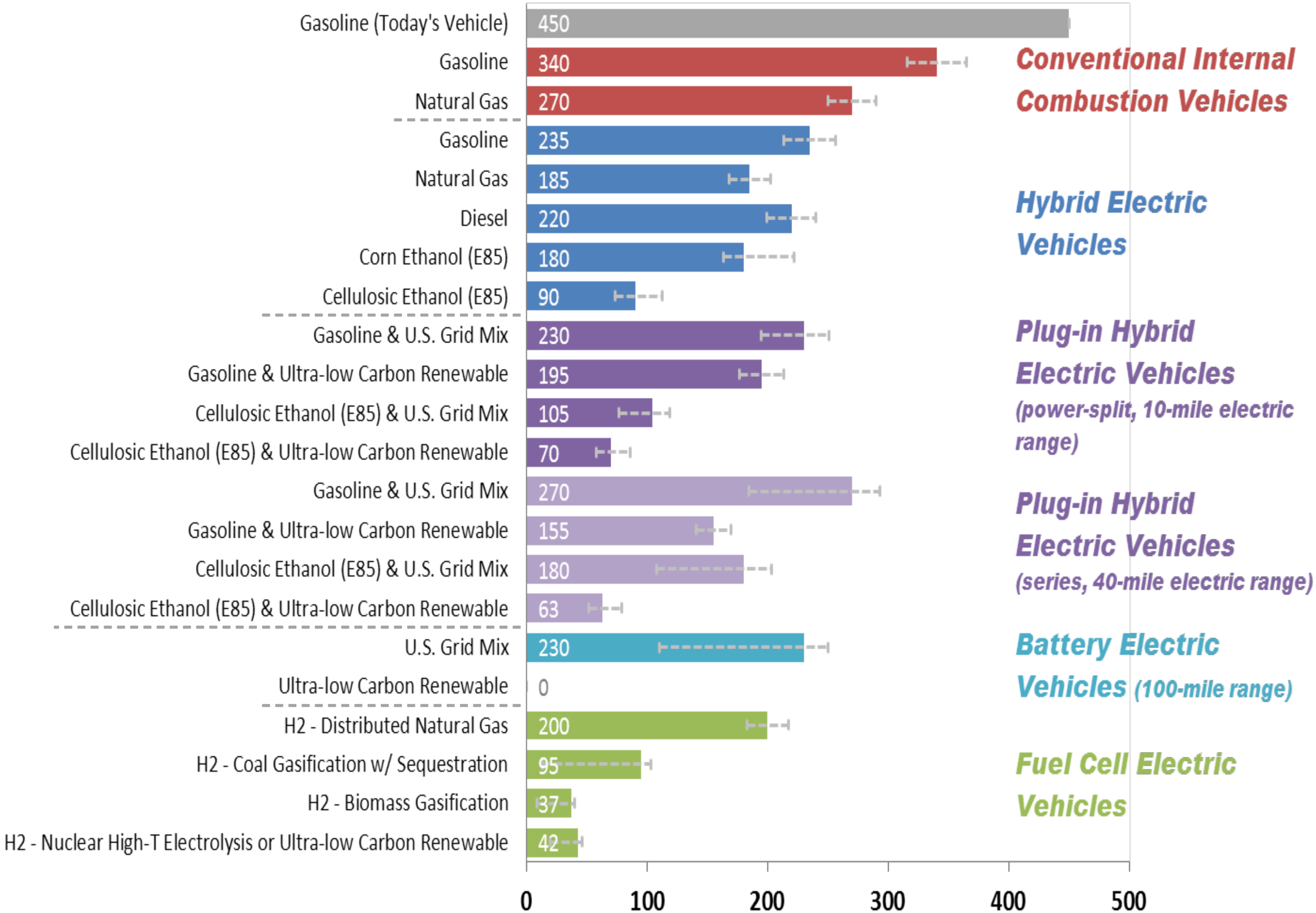


Smart Mobility

Argonne Develops Advanced Battery Technologies for Electric-Drive Vehicles

- Advancing electrochemical storage beyond lithium-ion batteries to other systems with new material discoveries
- Developing and demonstrating energy storage prototype, manufacturing, and recycling processes and technologies
- Developing large energy storage and power management systems that improve grid reliability
- Optimizing efficiency, performance, and emissions of electric-drive powertrains

WTW Results: GHG Emissions of a Mid-Size Car (g/mile)

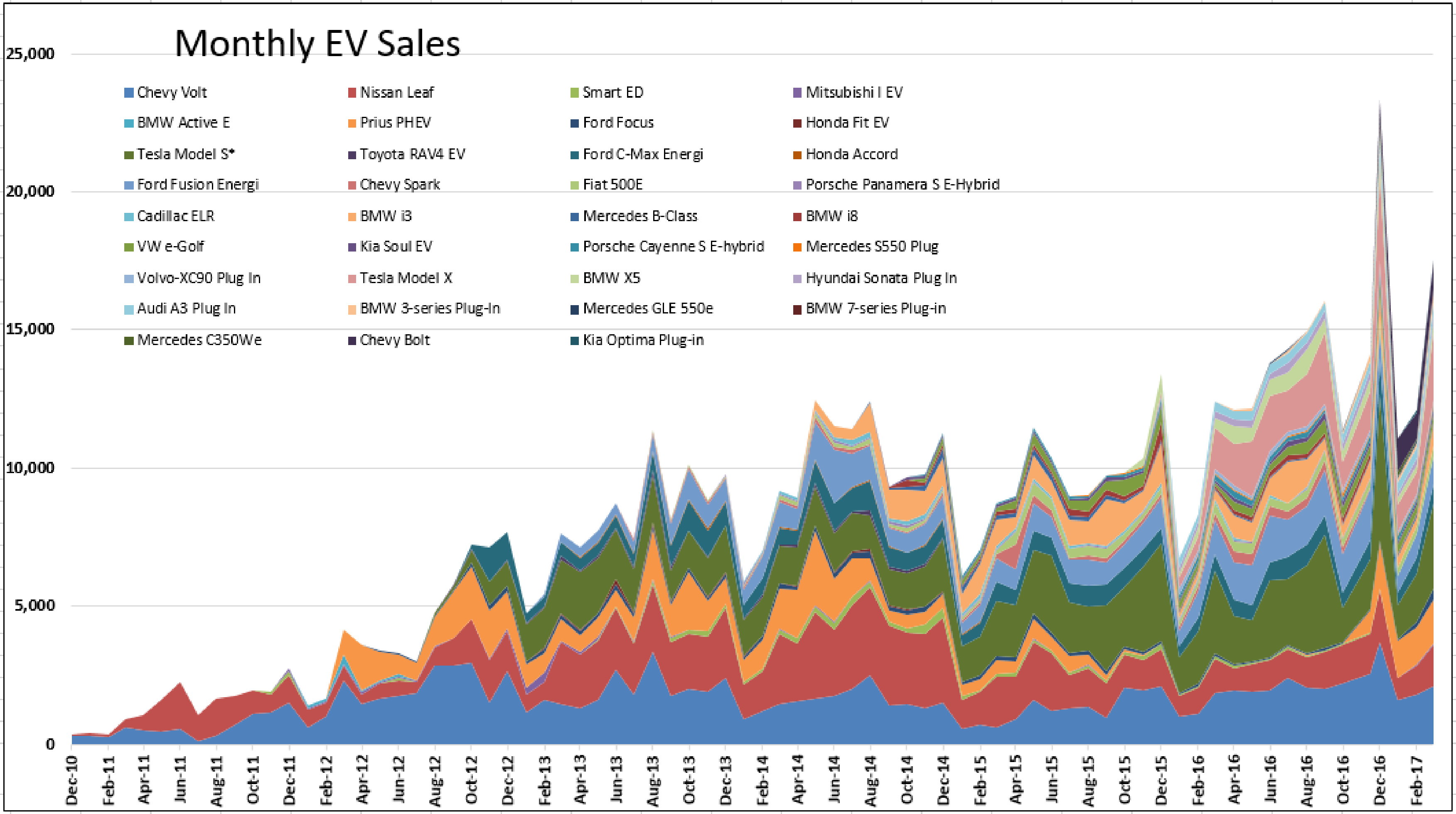


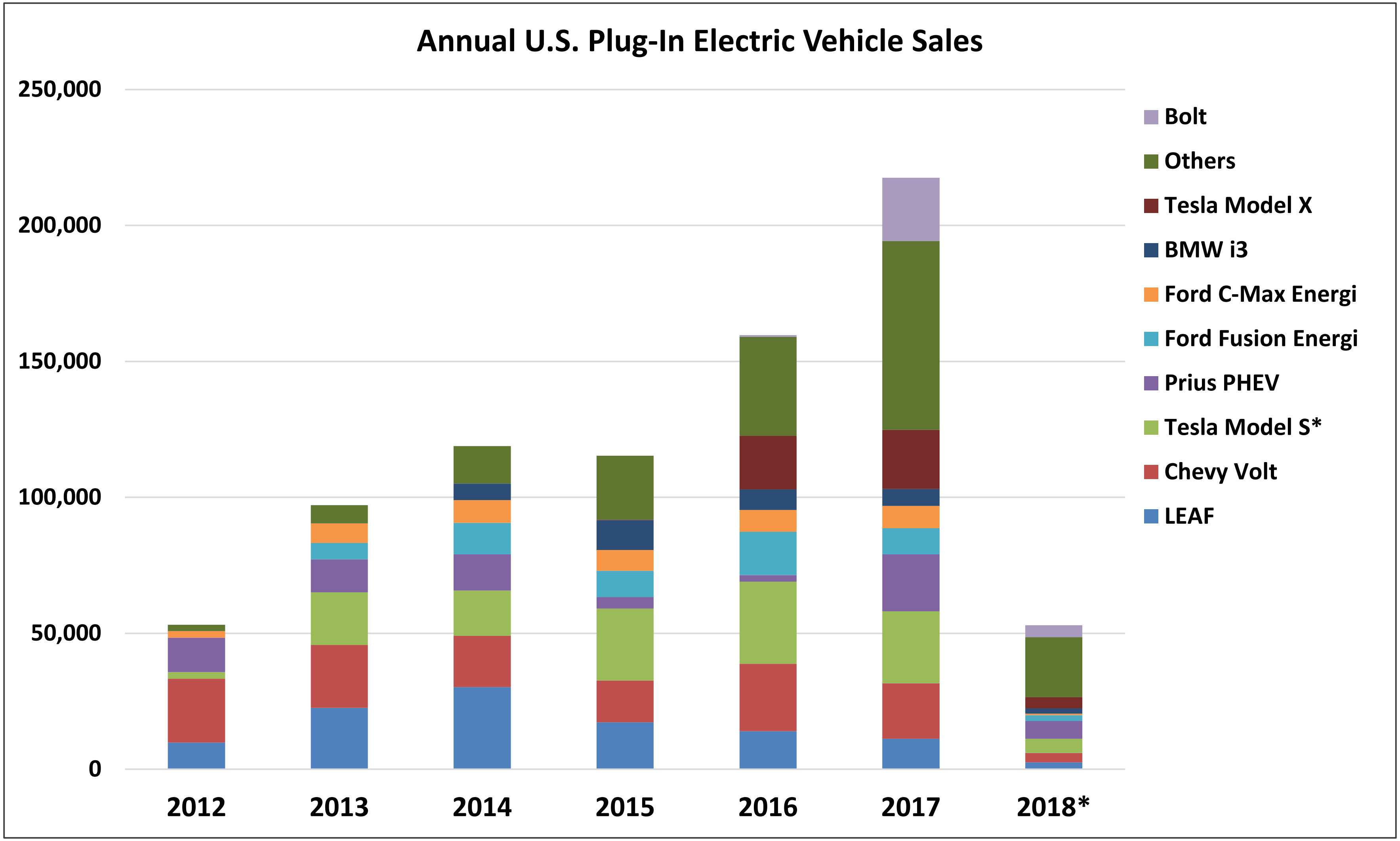
Low/high band: sensitivity to uncertainties associated with projection of fuel economy and fuel pathways

(DOE EERE 2010, Record 10001)

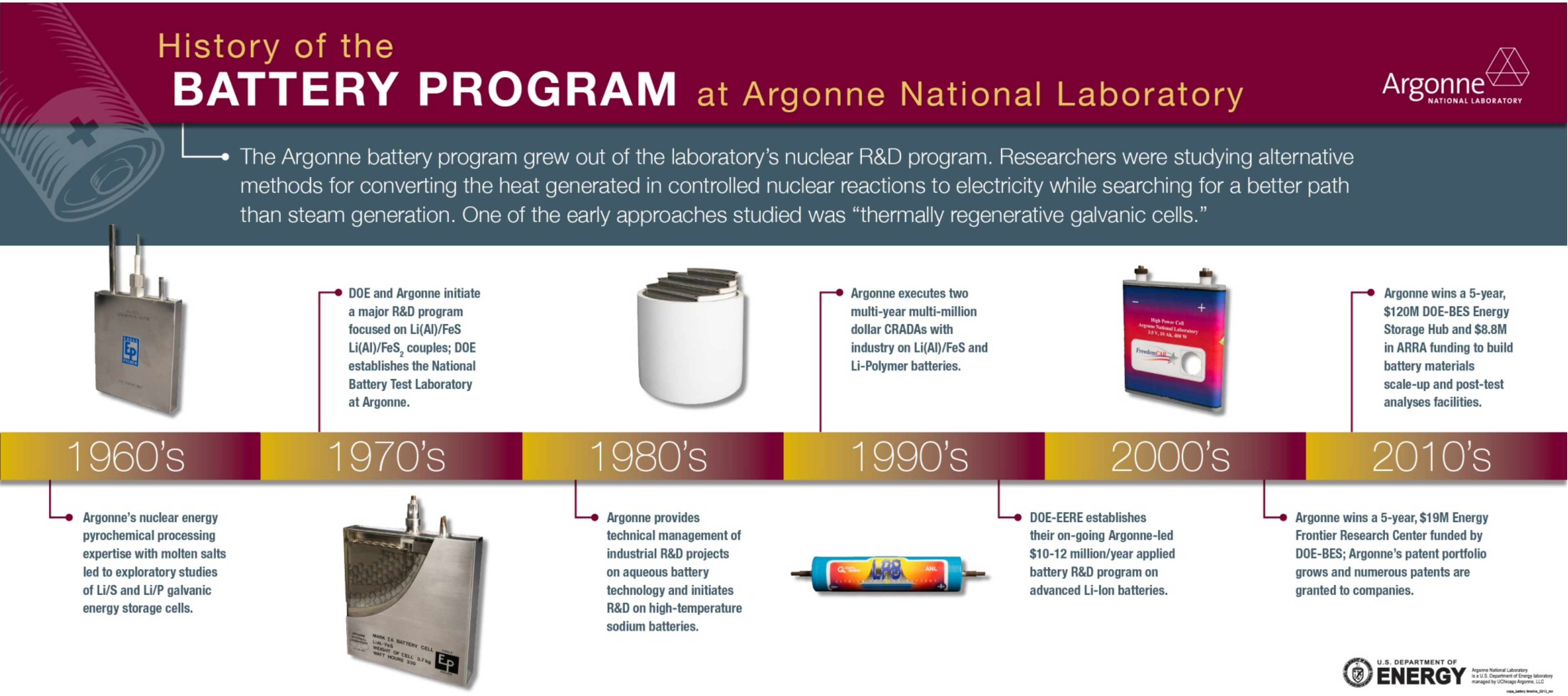
PEV Market

PEV monthly sales volumes are flat and growing slowly




Annual U.S. Plug-In Electric Vehicle Sales
250,000
200,000
150,000
100,000
50,000
0
2012
2013
2014
2015
2016
2017
2018*
Bolt
Others
Tesla Model X
BMW i3
Ford C-Max Energi
Ford Fusion Energi
Prius PHEV
Tesla Model S*
Chevy Volt
LEAF

Argonne's 50-year of Battery R&D Timeline



Prime R&D focus:

1964 → 1998	**High/Moderate temperature Li batteries**
1998 →	**Room-temperature Li-ion batteries**

Argonne Works
Across the Value Chain

Material Discovery
Models, Synthesis

Material Characterization
In Situ, Operando

System-level Analysis
Vehicle, Grid, Techno-Economic

Electrode and Cells
Modeling, Characterization

Recycling
Life Cycle, Processing

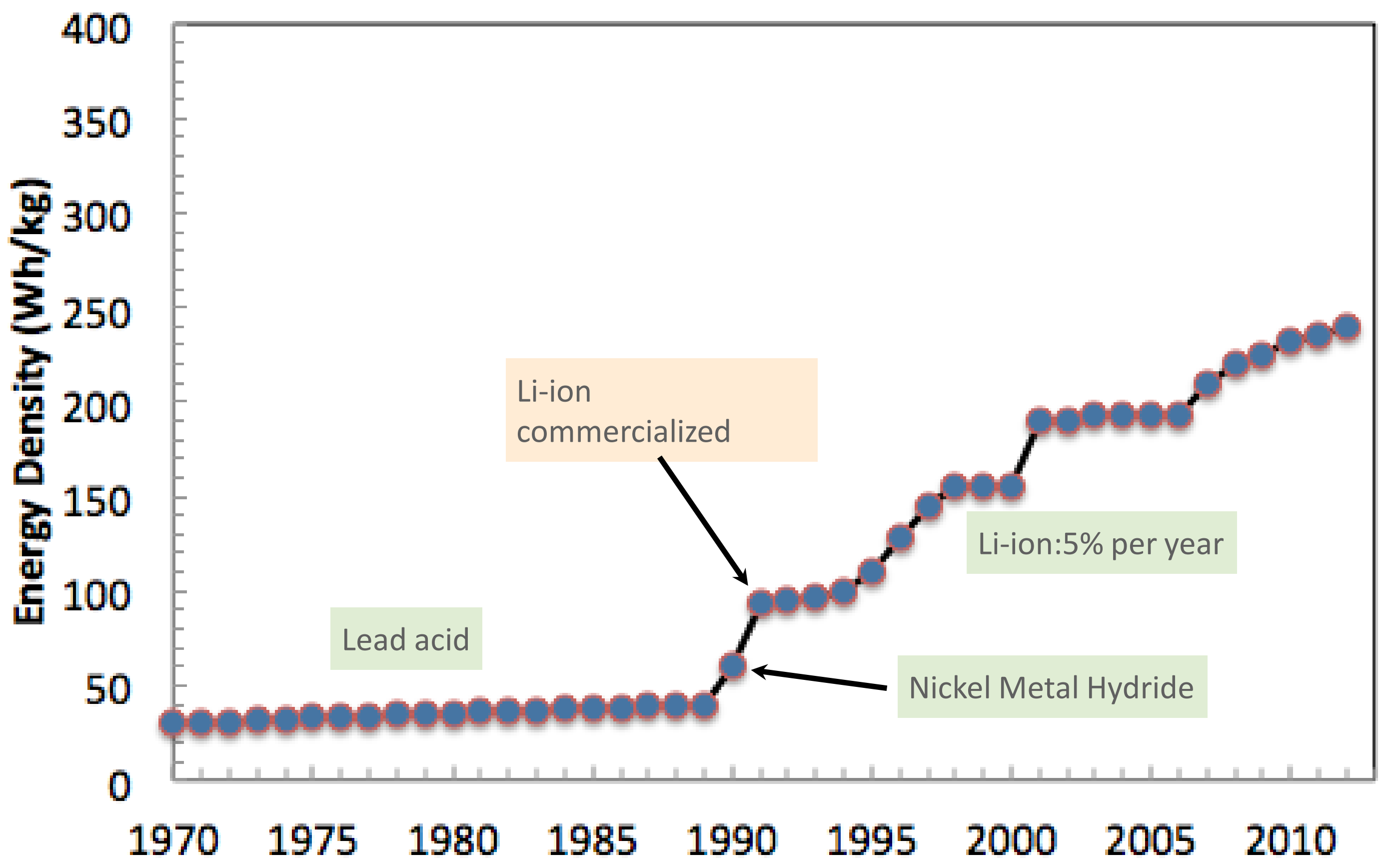
Material Process R&D and Scale Up
Organic, Inorganic

Cell Diagnostics and Modeling
Performance, Degradation

Large Format Devices
Pouch, 18650

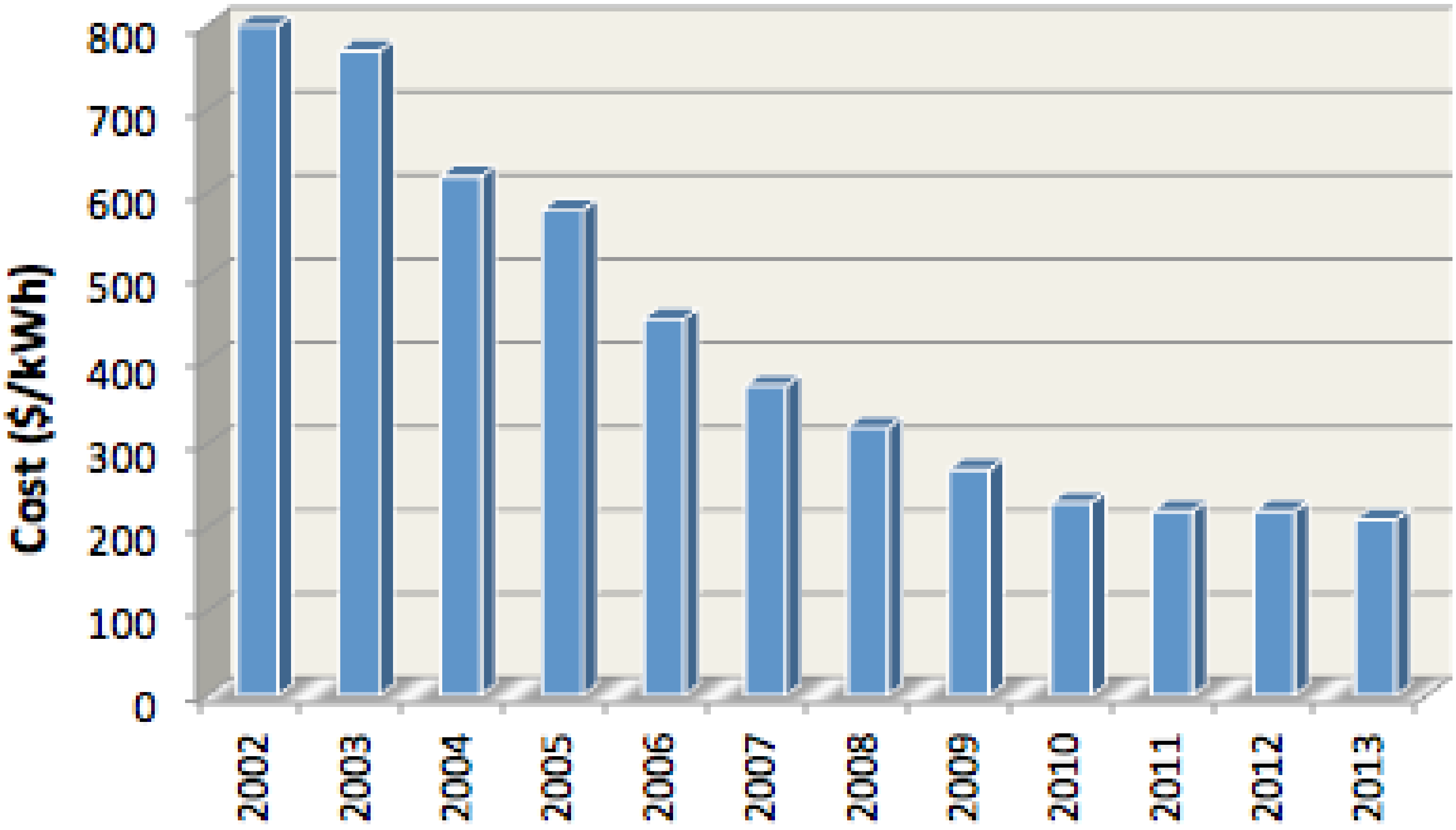
Standardized Testing
Vehicle, Grid

“Moore’s law” for batteries: 5% per year

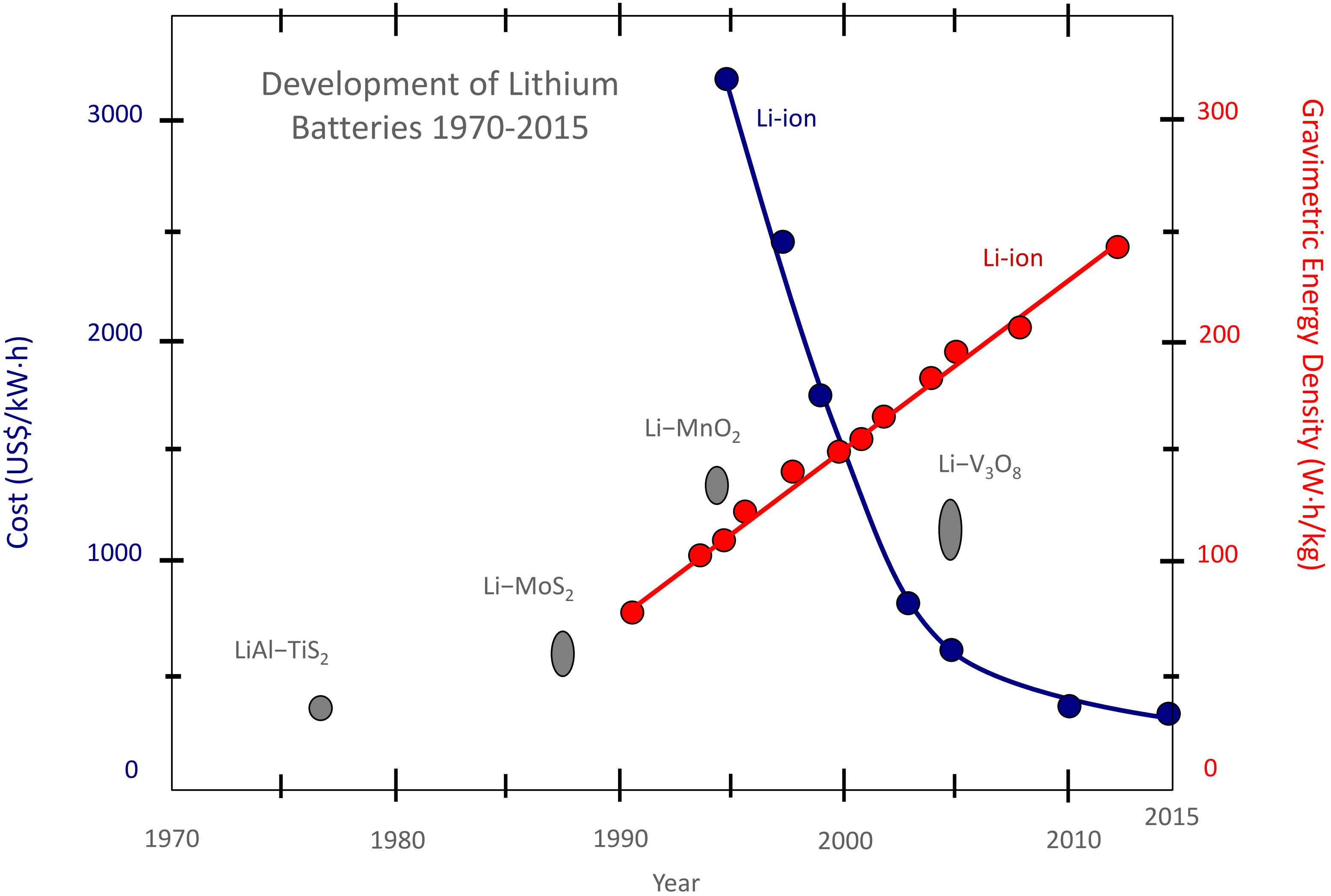


Batteries are improving steadily; but at a slow pace

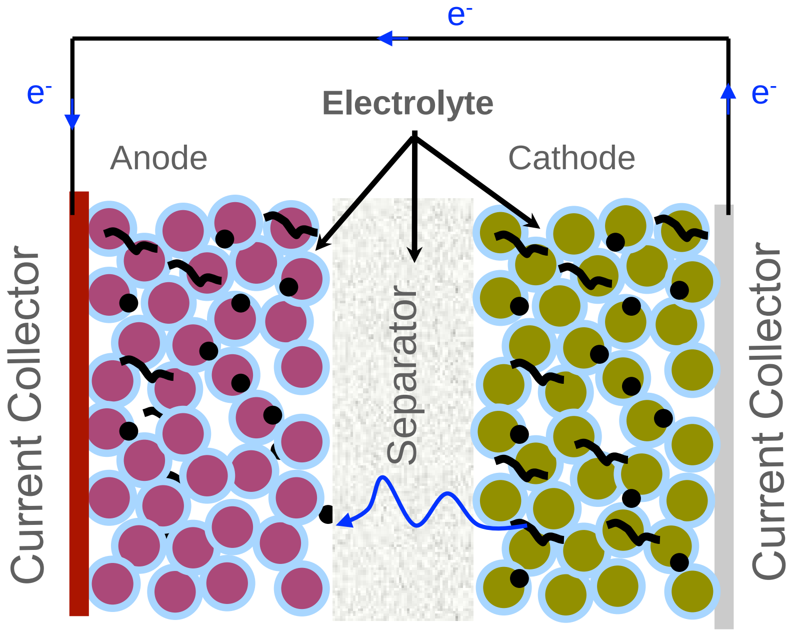
Costs are Decreasing – Enabling a Range of Possibilities



Lessons from Lithium-ion



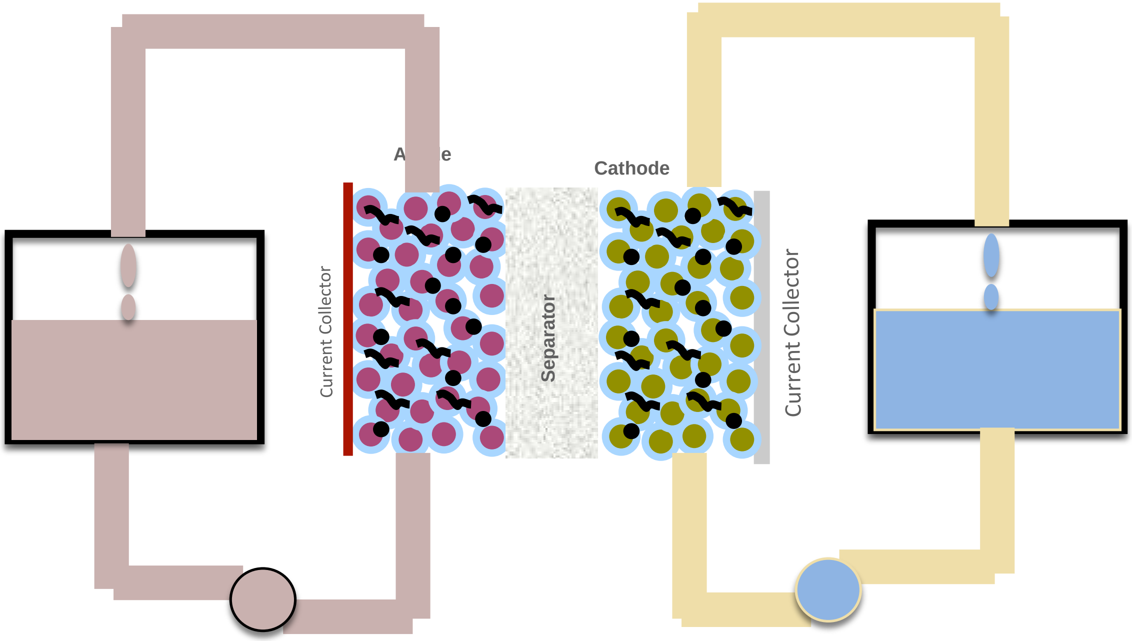
Areas of Research in Container Batteries



Lead	Sulfuric acid	Lead oxide
Graphite	Liquid electrolyte	Metal oxide
Silicon	High voltage electrolyte	High voltage cathode
Li metal	Solid conductor	Sulfur, oxygen
Mg, Ca, Zn	Liquid electrolytes	Intercalant cathode
Na-ion	Liquid electrolyte	Intercalant cathode

Focus on chemistries of the future. And from the past

New Materials for Flow Batteries



- Vanadium, iron
- Zinc
- Hydrogen

- liquid aqueous electrolytes
- Proton exchange membranes

- Vanadium
- Halogens(chlorine, bromine)
- chromium

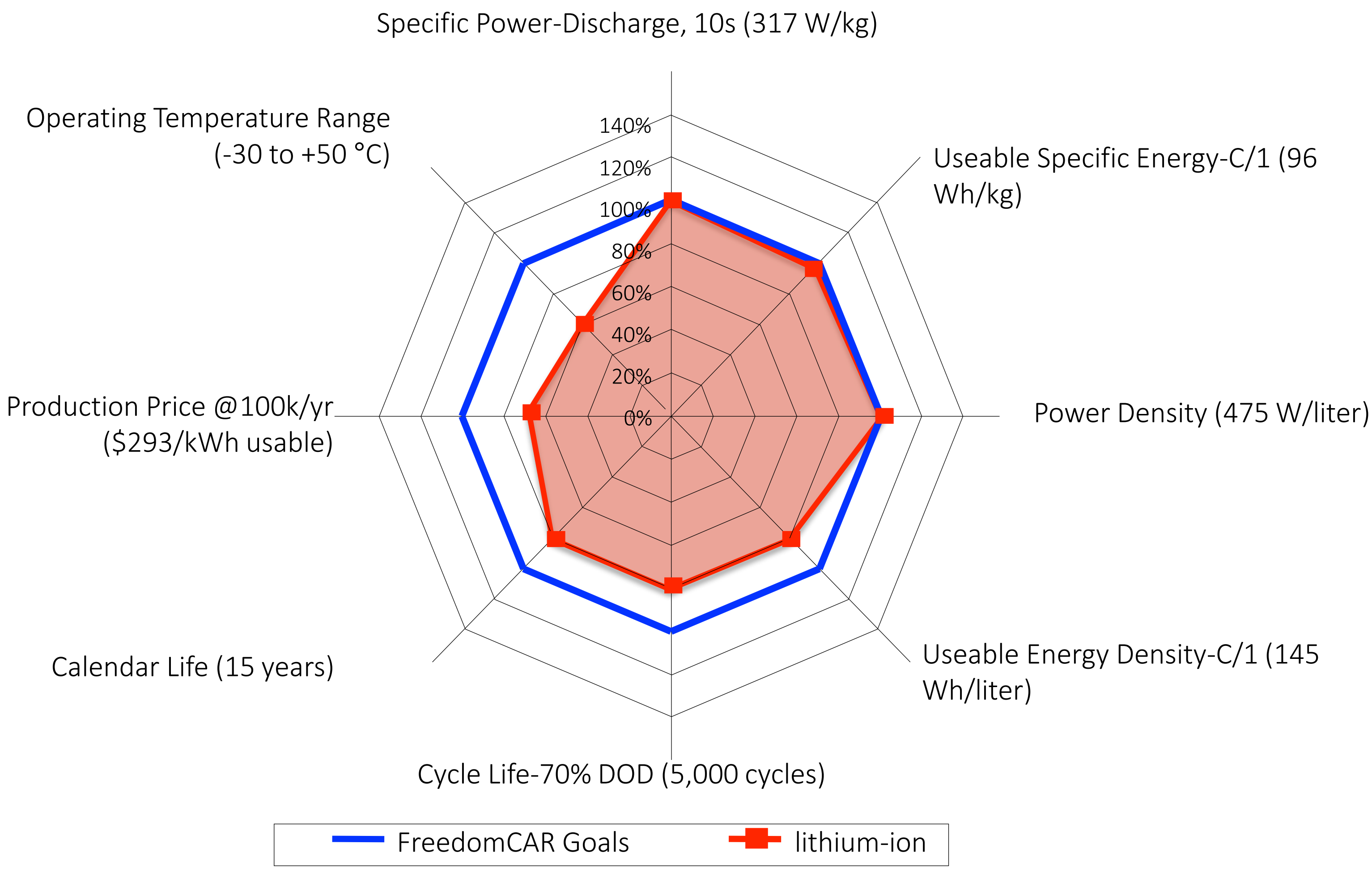
High Voltage systems
- Redox Organic Molecules
- Redox active polymers
- Tuned aqueous molecules

Separation membranes:
- Size selective
- ion exchange

High Voltage systems
- Redox Organic Molecules
- Redox active polymers
- Tuned aqueous molecules

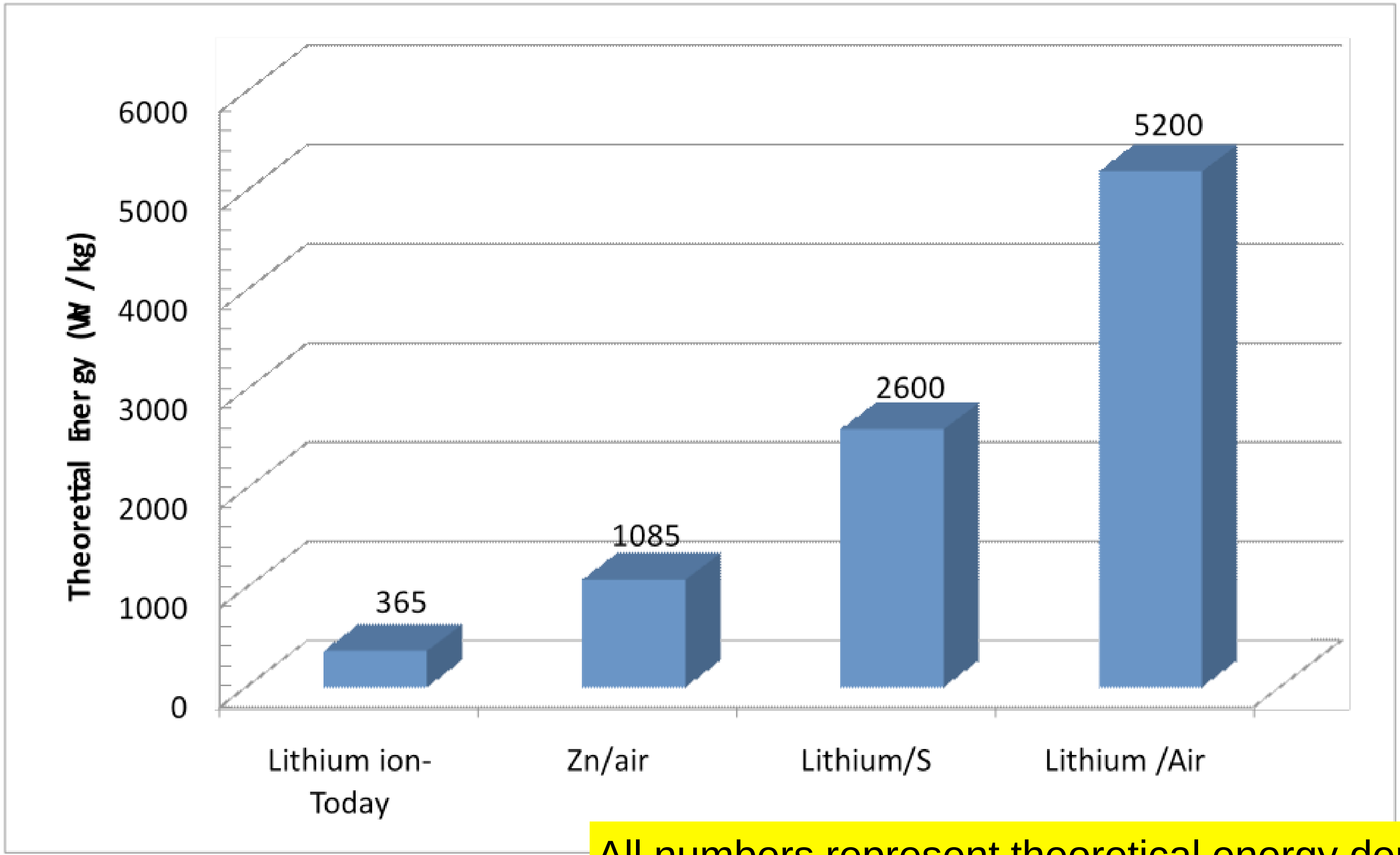
Next generation redox molecules can help decrease cost

Comparison of Present-day Li-ion Batteries vs. Plug-in vehicle Goals



Over the next 5 years, PHEVs will become cost effective

The next material on the roadmap: Li metal



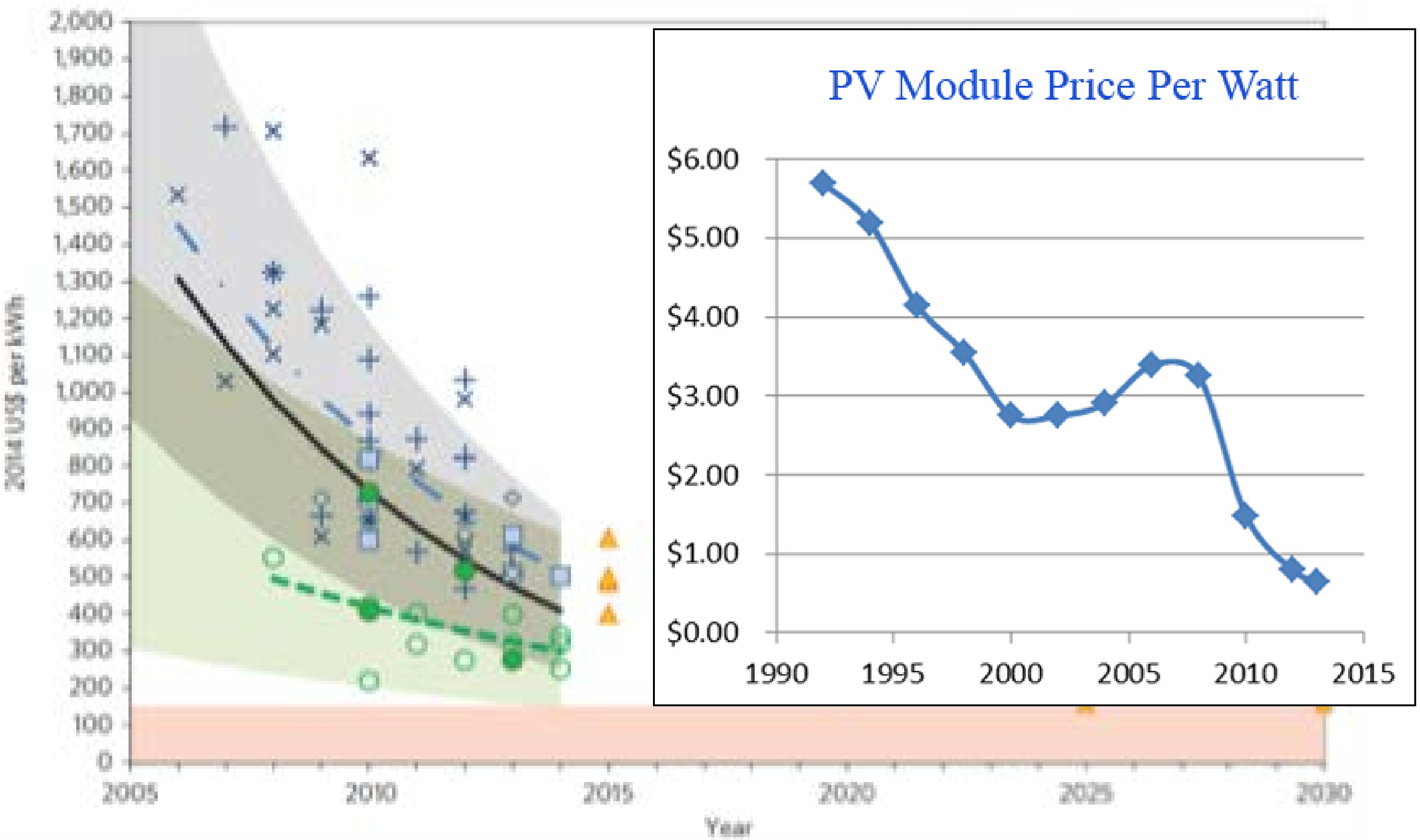
All numbers represent theoretical energy densities

- Systems exist that promise very high theoretical energy
- However challenges are significant

Are we seeing a “solar effect” in storage?

nature climate change
LETTERS
PUBLISHED ONLINE: 23 MARCH 2015 | DOI: 10.1038/NCLIMATE2564

Rapidly falling costs of battery packs for electric vehicles



Argonne: longer-range BEVs may be almost as powertrain energy dense as gasoline vehicles by 2045

9 May 2016

An analysis by a team at Argonne National Laboratory (ANL) has found that by 2045, some configurations of battery electric vehicles (BEV) could become almost as energy dense as a conventional vehicle. The team presented their paper at the recent 2016 SAE World Congress.

Hydrocarbon fuels (either fossil- or bio-derived) have high energy densities that are at least 100 times greater than that of a present day lithium-ion battery. Despite projected improvements in battery technology, this form of energy storage is still expected to be significantly less energy dense than gasoline even by 2045. However, the Argonne team argues, the energy density of storage medium (fuel or battery) should not be used as the sole criterion to compare conventional vehicles and BEVs. Rather, powertrain-level energy and power density will be better criteria to compare the propulsion technology used for BEVs and conventional vehicles, they suggest.

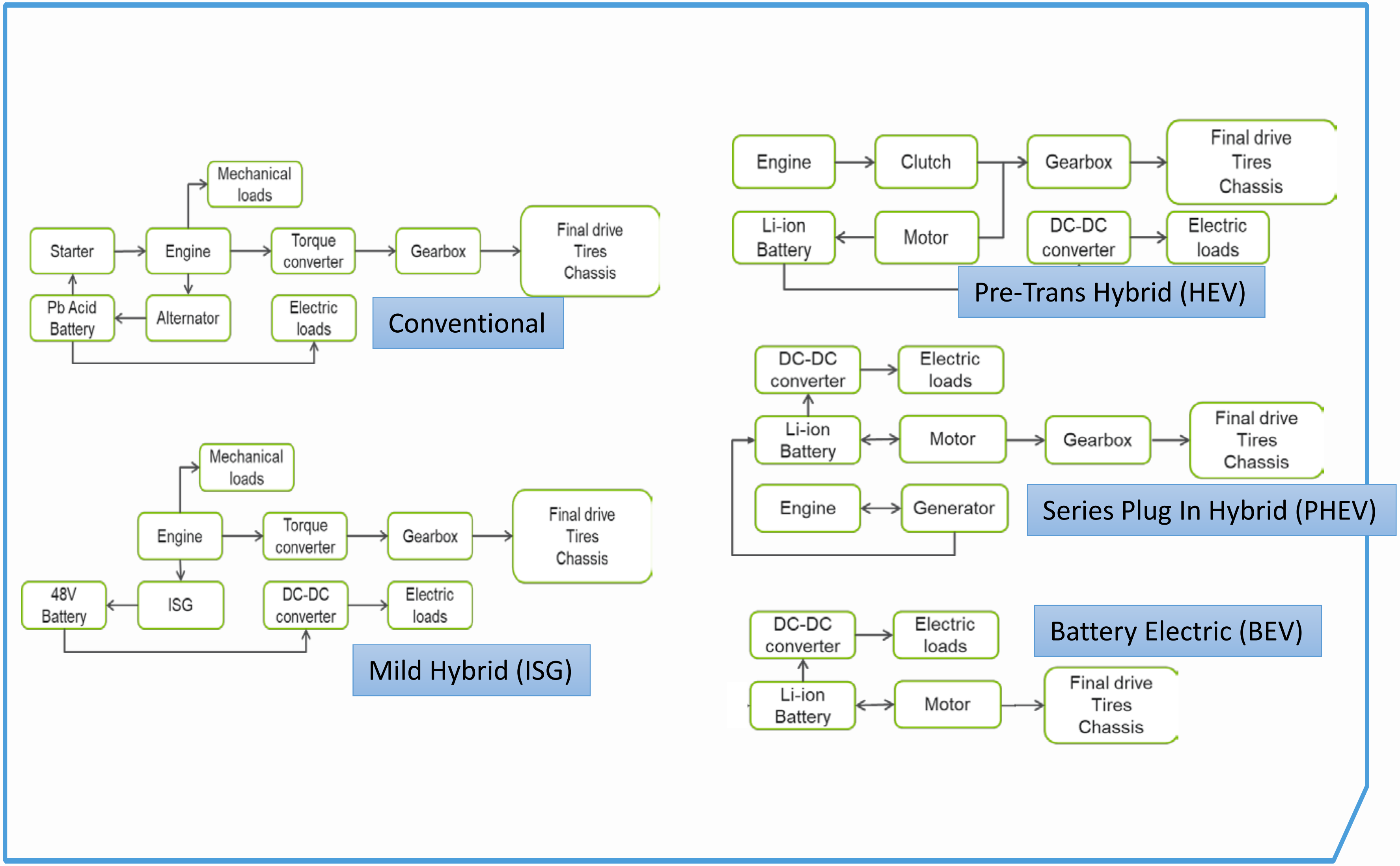
This requires assessing the efficiency of the conversion of the stored energy to useful mechanical energy to propel the vehicle.

Comparison of Truck Powertrains

- Argonne performed a study using a performance based sizing process for various powertrain architectures.
- The process was extended to quantify the fuel savings attributable to the powertrain electrification.
- Transit Bus is taken as the example for analysis

Baseline Vehicle	Nova LFS
Engine	209 kW, 9L, Diesel
Transmission	6 speed, Automatic
Auxiliary loads	10 kW
Test weight	15382 kg
Cargo/passenger	4000 kg
Tires	305/70/22.5
Final drive ratio	5.13
Starter	8 kW
Alternator	11 kW

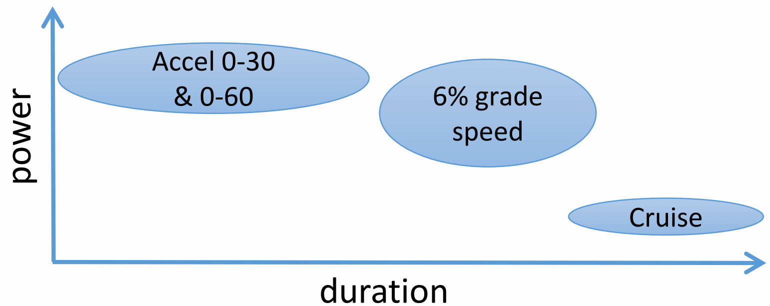
Architectures considered in this study

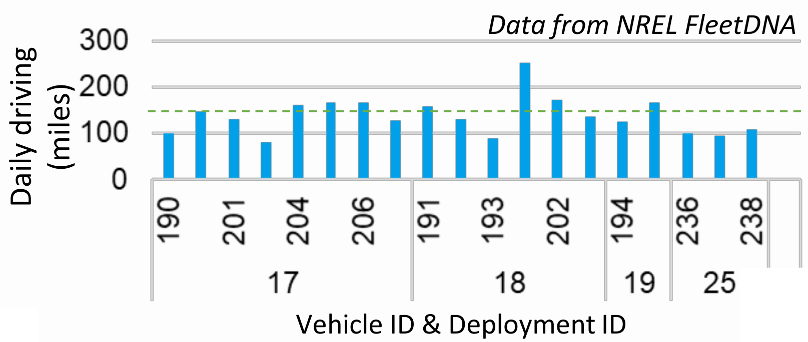


Performance Based Sizing Ensures Fair Comparison

Sizing assumptions

- No trade off on payload or performance
  - Fixed payload across all powertrains
  - Match or better the conventional vehicle in performance
- BEVs range will depend on the application. (150 miles assumed in this study)
- PHEVs will have 50 % all electric range as the BEV.





As performance parameters are not widely published for heavy vehicles, the baseline values can be estimated through simulations.

Simulation can predict performance accurately

- Simulated performance estimates were verified against test data from 'Altoona Bus Research and Testing Center'
- Acceleration and Grade performance matched with test data
- Based on test data and cruising speed observed in similar vehicles, the target performance was set at 60mph.

Performance Criteria	Test	Simulation	Target
Cruising Speed (mph)	50*	72	60
6% Grade Speed (mph)	30	29	29
0–30 mph Acceleration Time (s)	14.5	14.3	14.3
0–60 mph Acceleration Time (s)	NA*	66	66

- A new vehicle, with an electrified powertrain architecture, that matches this performance can be expected to perform the same functions as the baseline vehicle

Performance Based Sizing Logic

- Component power requirements vary with powertrain architecture
- Goal of sizing
  - To find minimum component sizes needed to meet performance targets
  - To reduce fuel consumption (not optimization).
  - Fully utilize the components available in architecture

<table>
<tr><th>Powertrain</th><th>Engine</th><th>Motor</th><th>Battery</th></tr>
<tr><td>Conventional</td><td rowspan="3">Acceleration
Grade &
Cruise</td><td></td><td></td></tr>
<tr><td>ISG</td><td>Size based on
Starter & Alternator</td><td>Energy: Sustain electric loads
for at least 1 minute*</td></tr>
<tr><td>HEV</td><td>Maximize regen
in ARB Transient</td><td>Power: to sustain peak motor
output</td></tr>
<tr><td>PHEV</td><td>Grade & Cruise</td><td rowspan="2">Acceleration
Grade & Cruise</td><td rowspan="2">Energy: Electric Range
Driving Range in EPA 65.
Power: Sufficient power to
support motor & aux loads</td></tr>
<tr><td>BEV</td><td></td></tr>
</table>

* Based on EPA off-cycle credit system in LDV. Transit buses could use longer stop time for sizing

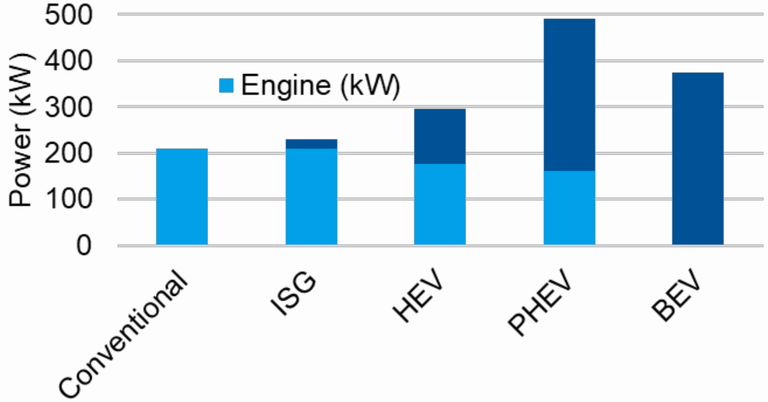
Performance Based Sizing Results

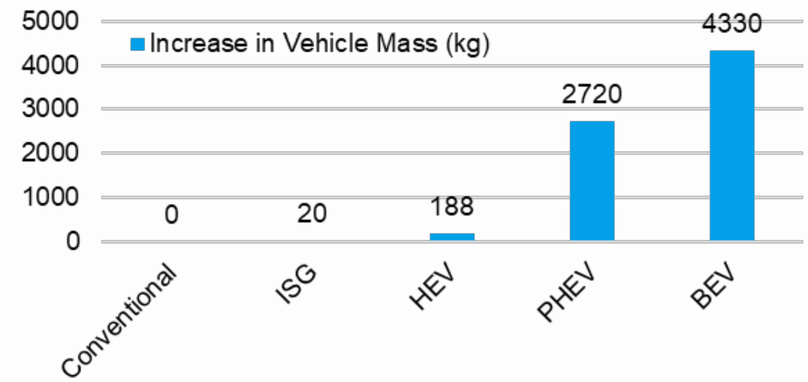
- ISG
  - Engine: same as the baseline, 209kW
  - Motor sized for 11kW continuous load
    - Based on Delco Remy alternators (10.8kW) and starter motors (8kW) used in transit bus applications
  - Battery needs 200Wh usable energy to meet 11kW load for a minute
- HEV
  - Engine is sized at 176kW (much smaller than a 9L engine)
  - 120kW Motor and Battery pack. Based on commercially available cells, such a HEV pack would also have ~5kWh total energy. (Eg. BAE Hybridrive buses)
- PHEV
  - Engine is sized at 160kW
  - 330kW Motor. 230kWh battery pack. It can meet motor power requirements
- BEV
  - 374kW Motor. 440kWh battery pack. It can meet motor power requirements

* Based on EPA off-cycle credit system in LDV. Transit buses could use longer stop time for sizing

Approaches: Retrofit vs. New Design

- New Design: new body, lighter chassis, efficient auxiliary systems.
- Retrofit: Vehicles share the same chassis, body, wheels etc.
    - Adding the mass of the new and replaced components will give the net difference in test weight.

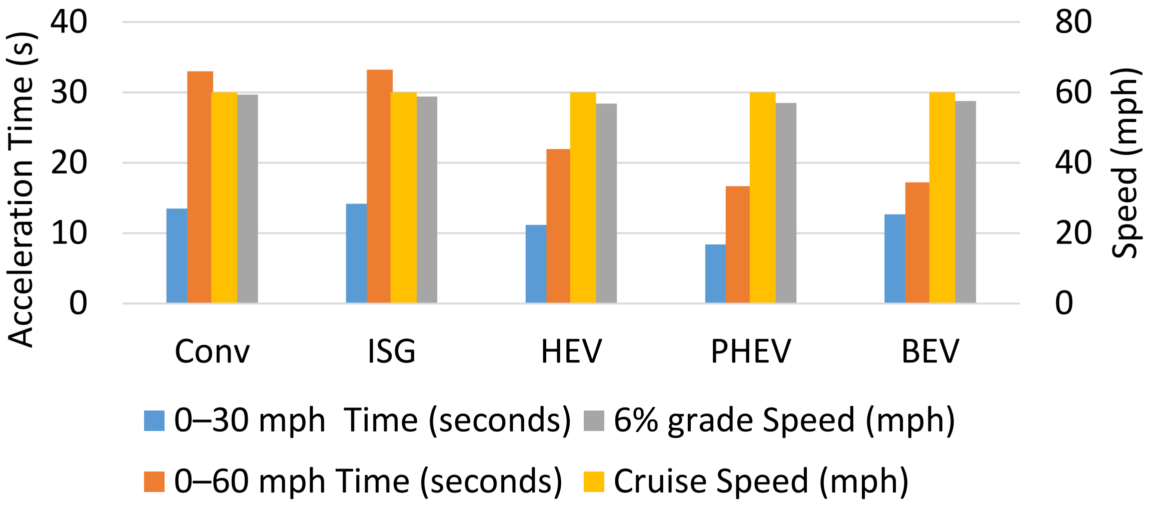




Note: Autonomie class 8 truck weights correlate well with results from electric drive implementation on class 8 trucks by TransPower.

Results: No Tradeoff in Performance

- In many aspects the performance of the electrified powertrains are better than that of the conventional baseline.
- The increases in weight of the powertrain is offset by the additional power available from the motor

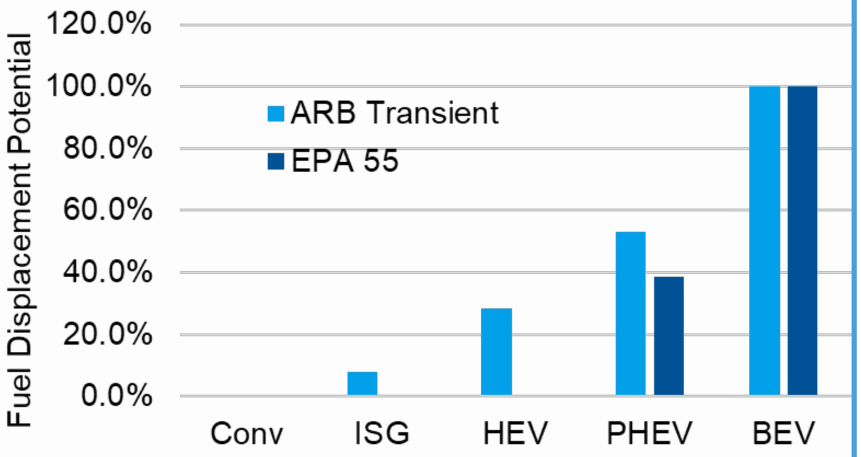


Difference in grade speed is within the 2% tolerance allowed in the sizing process.

Fuel savings depends on type of driving

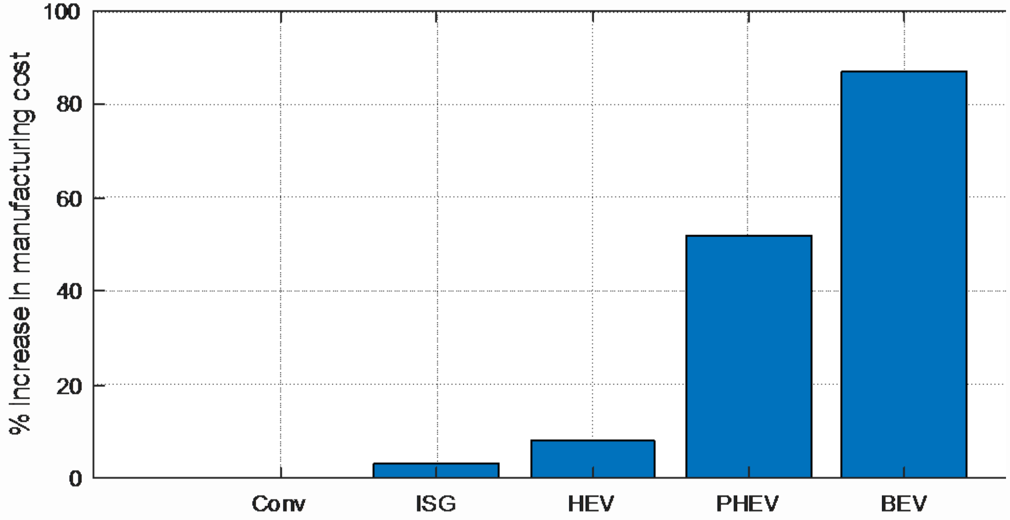
- Vehicles are evaluated over 150 mile drive in 2 drive cycles.
- ISG benefits attributable to
  - High efficiency electric machine replacing the alternator & Idle reduction
- HEVs offer 28% fuel savings in transient driving conditions.
  - Smaller engine & Higher average engine efficiency
- PHEVs and BEVs are necessary to achieve petroleum displacement in highway driving

Powertrain	ARB Transient		EPA 55	
	Diesel (gal)	Electricity (kWh)	Diesel (gal)	Electricity (kWh)
Conv	31.2	0	18.4	0
ISG	28.7	0.02	18.5	0.06
HEV	22.3	0.02	18.5	0.2
PHEV	14.6	167	11.3	174
BEV	0	357	0	332



Preliminary results on cost impact of electrified powertrains

- At 87% cost increase, full petroleum displacement is achieved for transit bus.
- PHEV bus achieves 53% fuel displacement at 52% increase in cost
- Hybrid bus achieves 30% fuel displacement at 10% increase in cost.



In this study cost implies estimated manufacturing cost based on component cost targets set by DOE. It is typically much lower than the selling price.

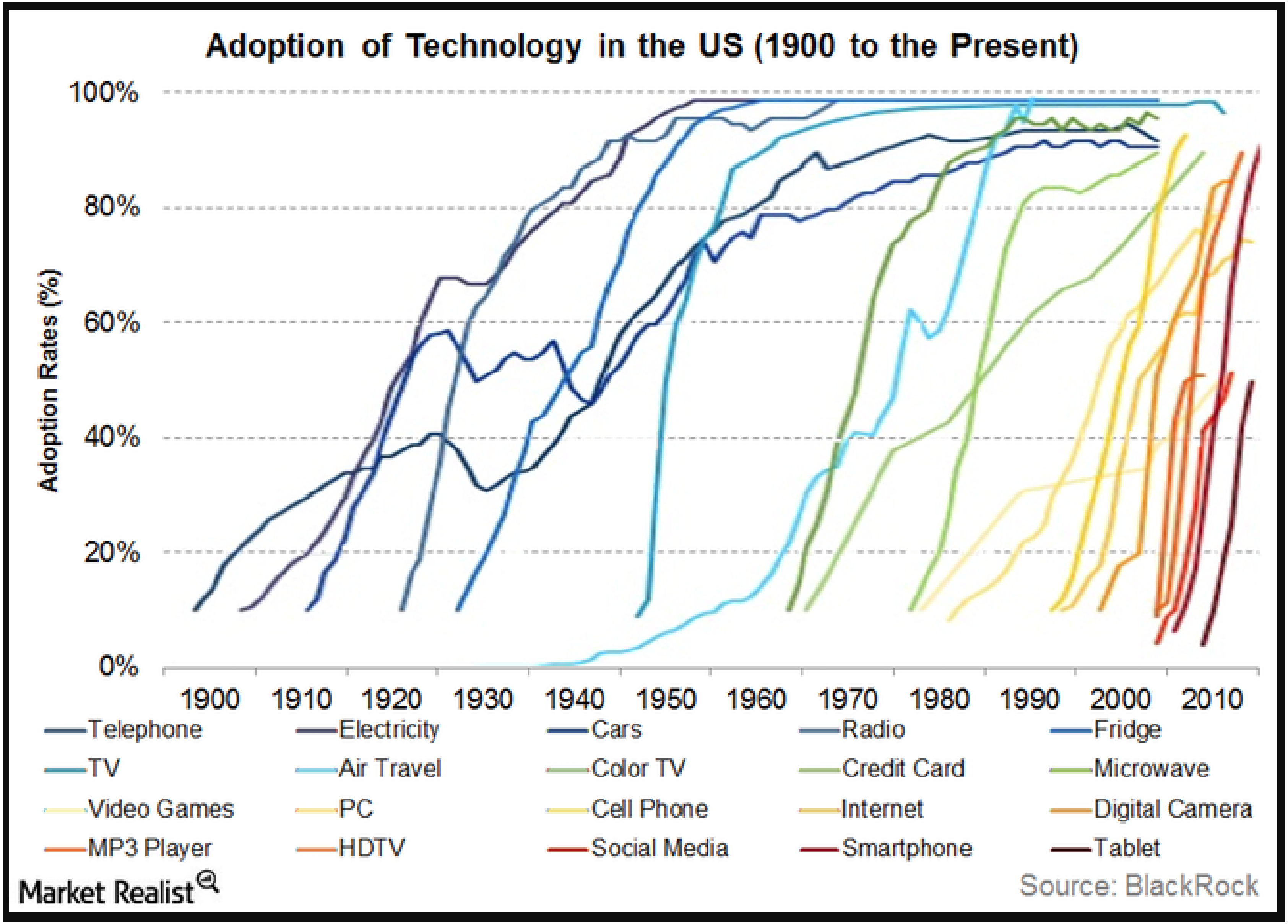
Summary

- A sizing logic is proposed for medium & heavy duty vehicles, without any tradeoff on cargo or performance.
- Fuel saving potential of various hybrid powertrains in evaluated in case of transit bus application. When sized for similar performance, 8% - 100% fuel savings can be achieved based on extent of electrification.

- Next Steps
  - Consider real world driving, fuel costs and optimization of ownership costs for component sizing.
  - Consider minimizing cost impact with other design choices
    - Current Estimate: Manufacturing cost increase w.r.t conventional transit bus BEVs (+87%), PHEV(+52%), HEV(+10%)
    - Evaluate a short range BEV option which can charge multiple times during the day. It could cost ~15% higher than conventional bus and still achieve 100% of petroleum displacement.

Concerns

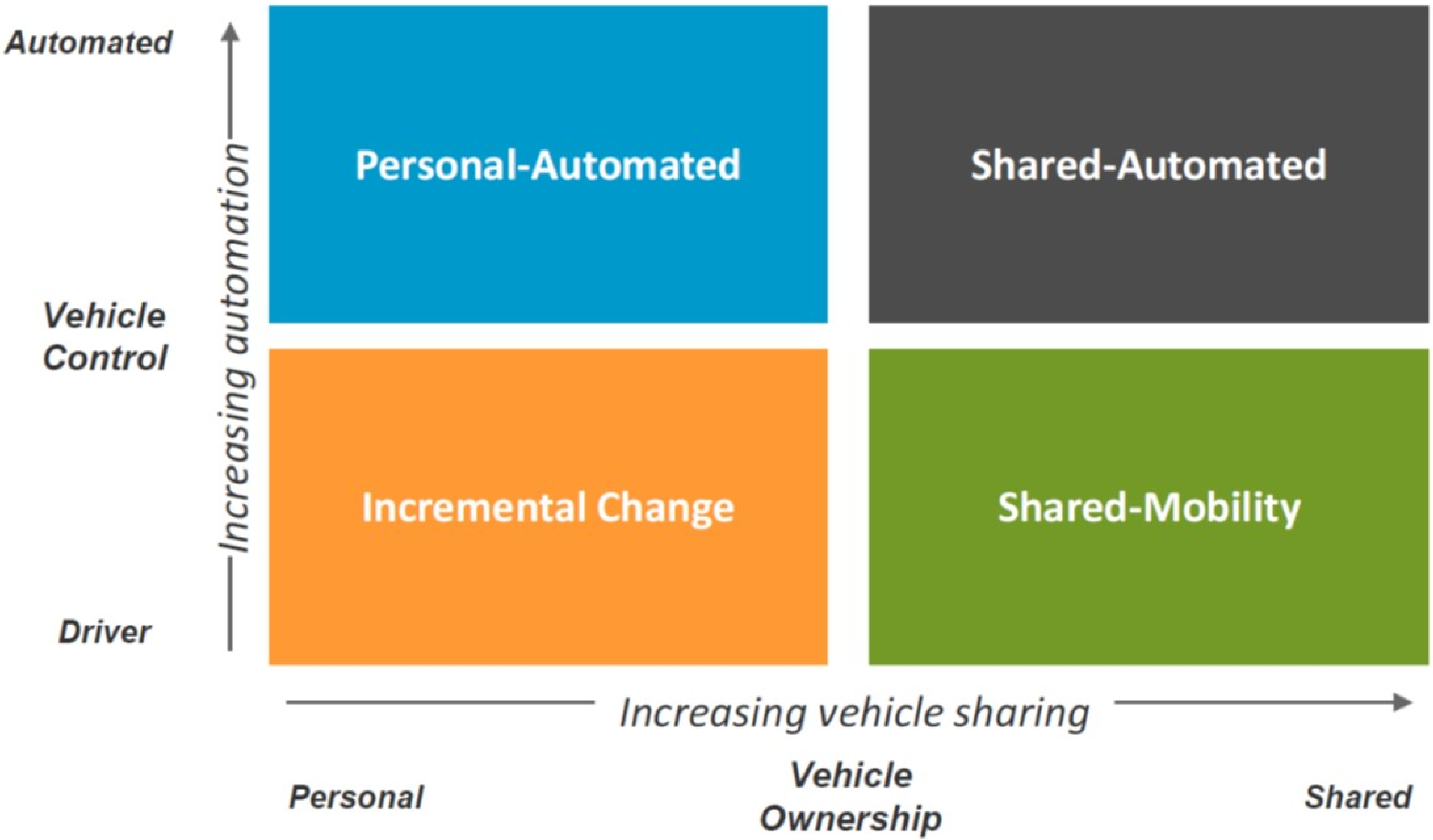
- Infrastructure
  - Grid
  - Wireless Charging
  - Fast Charging


Adoption of Technology in the US (1900 to the Present)
100%
80%
60%
40%
20%
0%
Adoption Rates (%)
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
2010
Telephone
Electricity
Cars
Radio
Fridge
TV
Air Travel
Color TV
Credit Card
Microwave
Video Games
PC
Cell Phone
Internet
Digital Camera
MP3 Player
HDTV
Social Media
Smartphone
Tablet
Market Realist
Source: BlackRock

THE FUTURE OF MOBILITY

Don Hillebrand
Energy Systems Division

Future R&D Opportunities in Mobility. Travelling 3 Trillion miles per year and moving 11 Billion Tons of Goods.



Source: 'The Transforming Mobility Ecosystem: Enabling an Energy-Efficient Future'. DOE/Reuben Sarkar. 2017