Challenges in Batteries for Electric Vehicles

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Agenda

- Introduction to Robert Bosch
- Importance of EV-battery research
- Current challenges & exciting milestones
- Exciting frontiers over the next 5-10 years

- Summary
  - Battery models can help reach cost and performance goals for EVs
  - New technology is required to reach the cost target for batteries. There are several candidates, each relies on a lithium-metal anode.

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Robert Bosch GmbH - 2013 key figures[1]

Bosch Group	→ 46,4 billion euros in sales (62.5 billion dollars) → 281,000 associates		
Automotive Technology	→ World's largest supplier of cutting-edge automotive technology	66 % share of sales	
Industrial Technology	→ Leading in drive and control technology, packaging, and process technology		
Energy and Building Technology	→ Leading manufacturer of thermo- and building security technology → World's largest supplier of heat pumps	34 % share of sales	
Consumer Goods	→ World's largest power tool manufacturer → Leading the field in household appliances		

1 Preliminary figures 01/ 2014

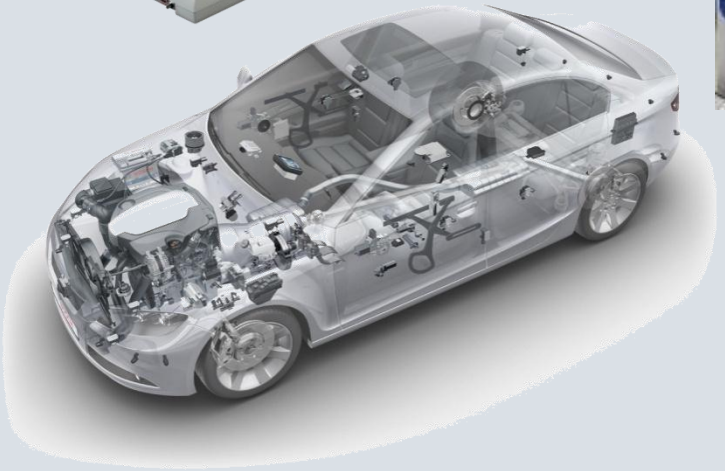
Electrification Activities of Robert Bosch GmbH

Drives for e-bikes

Electrical drives for passenger cars Hybrids, Plug-in & EV

Hydraulic hybrid system & electrical drives for commercial vehicles

Battery systems



Starters and generators for Start/Stop Systems

Aftermarket

Recuperative braking systems

Navigation systems

Chargers for EV / PHEV

Charging stations for electric vehicles

Software for infra-structure integration

Research and pre-development for future electrical vehicle concepts

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Some Bosch Series Projects

Peugeot PSA 3800

Chrysler F500

Volkswagen Touareg

BMW Active Hybrid 5er

BMW Active Hybrid 7er

SAIC IP24

SAIC EP11

Porsche Panamera

Porsche Cayenne

Volvo V60

Smart

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Lithium-ion Battery Systems - Product Range

- Bosch Battery Systems covers all types of applications including lithium-ion battery technology for automotive powertrain applications.

	Low-Volt Recuperation Systems	Mild Hybrid	Strong Hybrid	Plug-In Hybrid	Electric Vehicle
Power	9.5* – 12 kW	5 – 15 kW	20 – 60 kW	40 – 80 kW	40 – 150 kW
Energy	0.06 kWh – 0.5 kWh	0.6 kWh – 1.8 kWh		5 kWh – 15 kWh	>15 kWh

Battery systems for each vehicle segment

- Bosch Battery Systems belongs to the world's leading automotive supplier and is a proven specialist in electronics.

- The Bosch Group currently makes an annual investment of 400 million Euros ($537 million dollars) in the field of electric mobility and employs more than 1,100 associates throughout the world.

* 9.5 kW Peak Power Value

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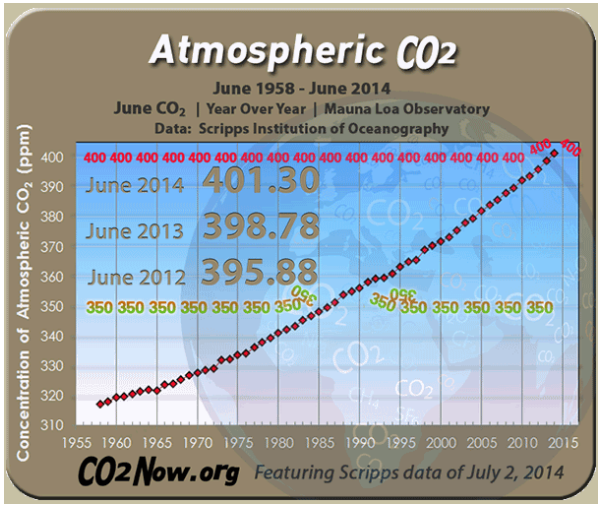
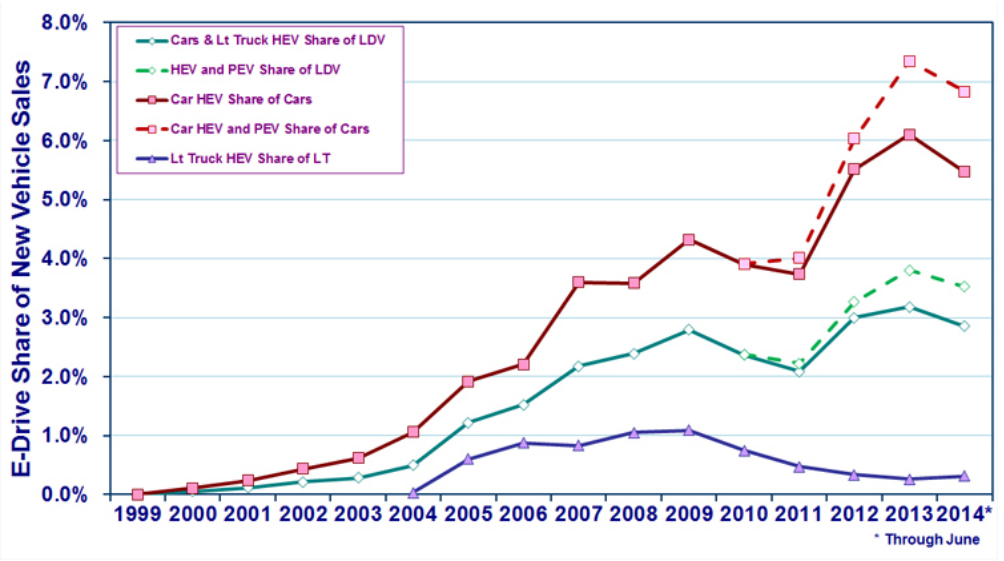
Why are EV Batteries Important?

- Reduction in greenhouse gases
- Decrease dependence on oil
- Lithium-ion batteries are replacing ICEs
- "If the United States is to compete in the future auto industry, it will need to be a major player in lithium-ion batteries."



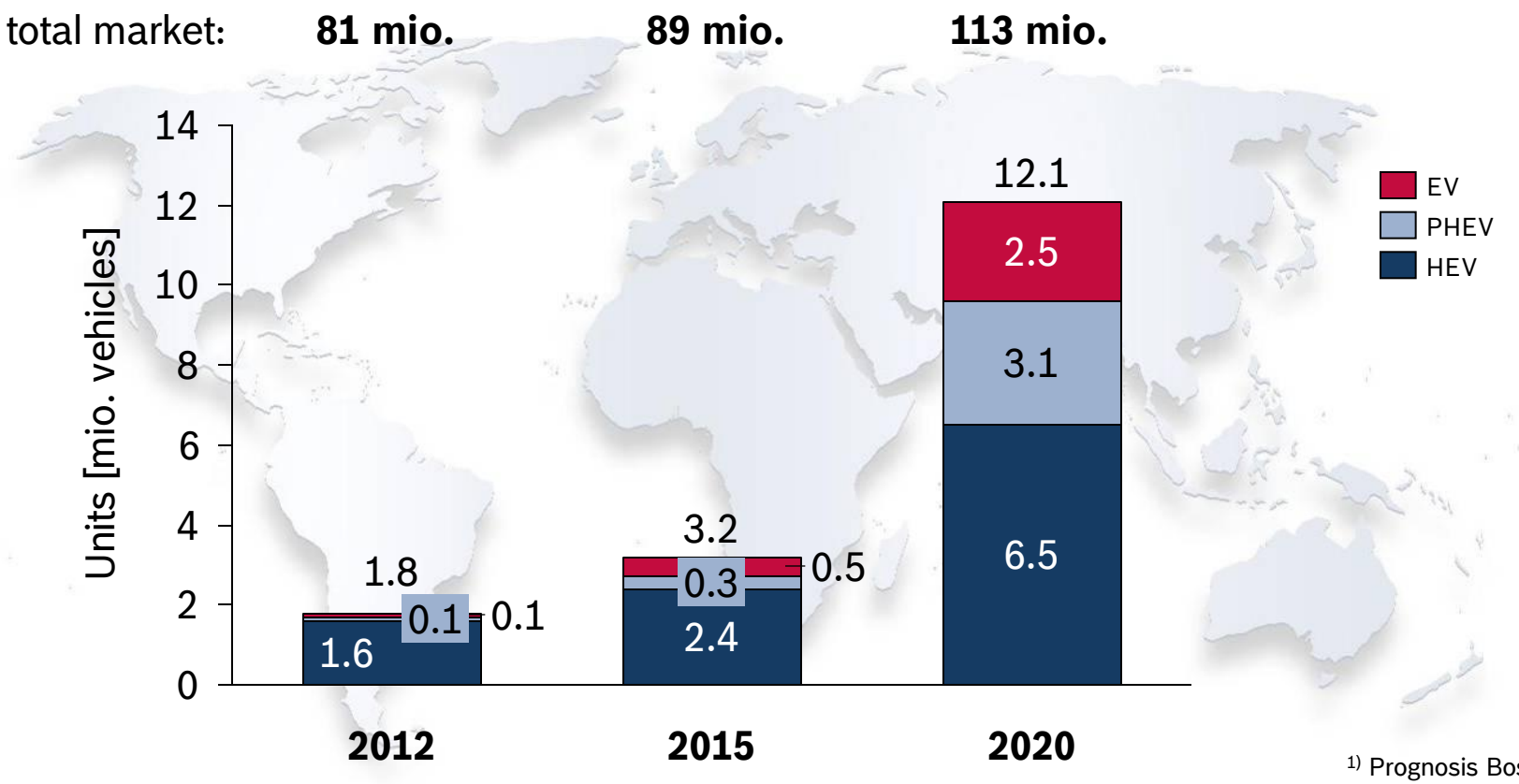


*Marcy Lowe et al., "Lithium-ion Batteries for Electric Vehicles"
**http://www.transportation.anl.gov/technology_analysis/edrive_vehicle_monthly_sales.html

EV Battery Challenges

xEV Market is Growing Rapidly
PHEV will exceed EV by 2020, HEV with highest volume

Sales PC & LCV<6t [1)]



[1)] Prognosis Bosch

EV electric vehicle
PHEV plug-in hybrid electric vehicle
HEV hybrid electric vehicle (strong / mild)

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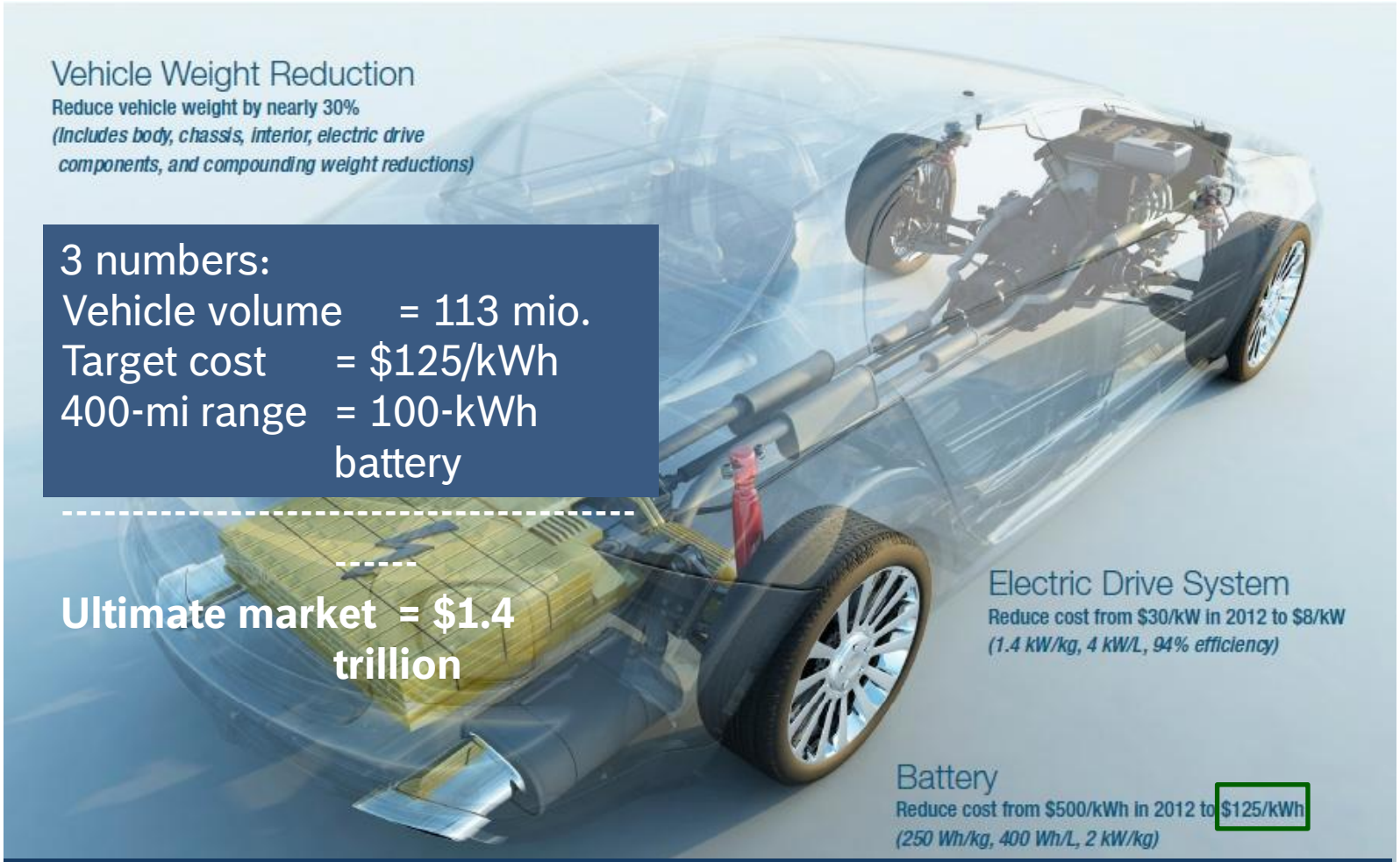
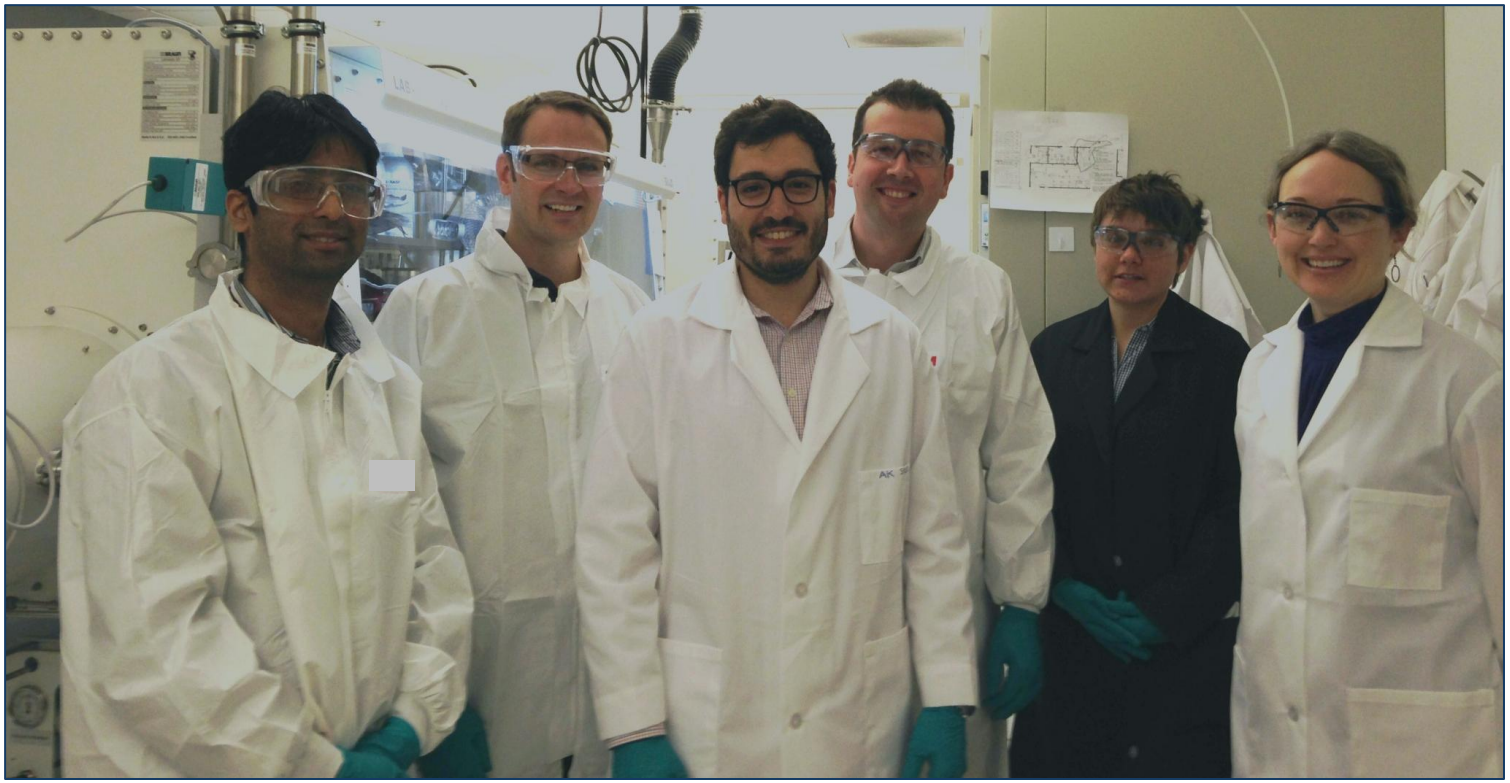
EV Battery Challenges



US DOE 2022 targets for 5-year cost of ownership parity ICE and EV

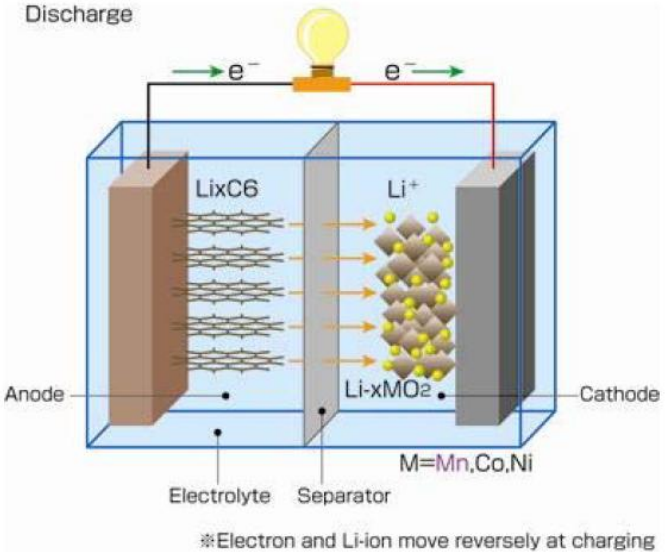
Our work on EV batteries

- Our team is working on developing more sophisticated battery models for EVs. We are improving the understanding of what limits cell performance & partnering with controls engineers to create optimal battery management systems.



Why is MODELING of EV Batteries Important?

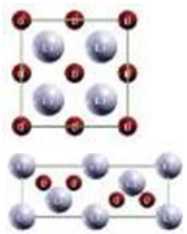
- Save money on testing
- Improve battery control
  - More efficient utilization
- Optimize design
  - Cell & pack
- Improve understanding of limitations & avoid failure modes
- Quickly understand the possible impact of new chemistries

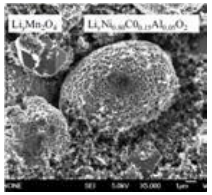


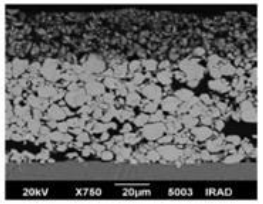
Source: (Automotive Energy Supply Corporation, 2007)

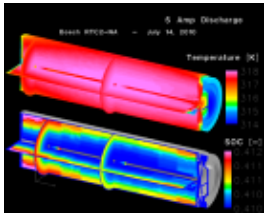
Models are essential to improving battery performance

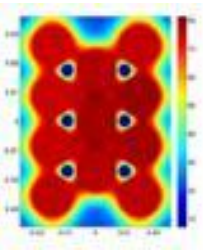
	ATOM LEVEL	CELL LEVEL	CELL LEVEL	MODULE/PACK	SYSTEM LEVEL
Palo Alto	Atomic scale models	1D electrochemical cell model (*e.g.*, Dualfoil)	3D thermoelectro-chemical cell model	Simplified thermal/electrical	System SW design
Other CR	Mesoscale microstructure		1+1D electrochemo-mechanical cell model	Detailed thermo-mechanical	System HW design











Aging, lifetime prediction

BMS

µstructure opt.

Cell design and optimization

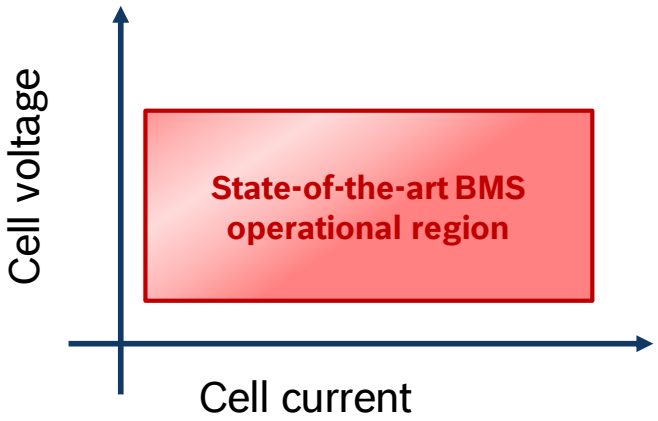
Module/pack design

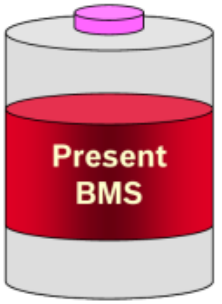
Safety evaluation and optimization

Thermal management strategies

Advanced Battery Management Software

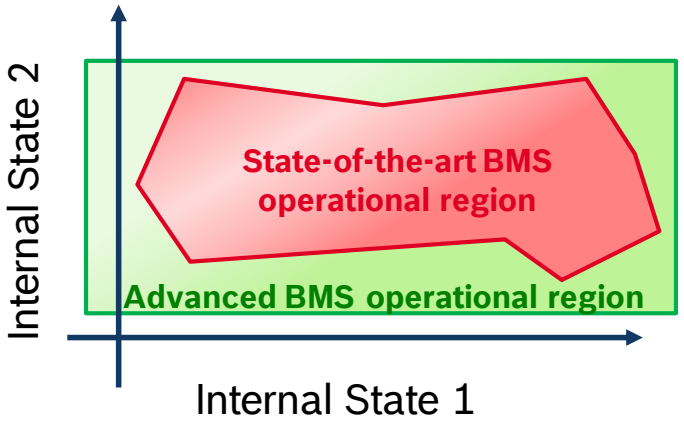
State-of-the-art

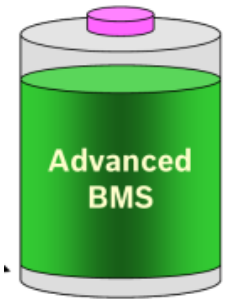




70% usage

Bosch innovation





100% usage

Current Challenges in EV batteries

- Where are batteries now?
  - Expensive
  - Limited range
  - Long charge times

VEHICLES	MSRP	RANGE	ANNUAL FUEL COST	MPGe	FULL CHARGE*
2013 Tesla Model S (60 kwh)	$69,900	208 mi.	$650	95 mi.	1/2 charge in 20 mins. with Tesla Super-charger.
BMW i3	$41,350	80-100 mi.	Est. $500-600	Not yet announced	30 mins.
2013 Chevrolet Volt Plug-In Hybrid	$39,145	38 mi. EV, 380 total	$950	98 mi.	4 hrs.
2013 Nissan Leaf	$28,800	75 mi.	$500	115 mi.	4 hrs.
2013 Toyota Prius Plug-In Hybrid	$32,000	11 mi. EV, 540 total	$950	95 mi.	1.5 hrs.

- Models can help!
  - Utilize more of the battery
  - Reduce charge time

Ford Focus Electric	$39,200	76 mi.	$600	105 mi.	4 hrs.
Honda Fit EV	$36,625	82 mi.	$500	118 mi.	3 hrs.
Smart ForTwo Electric	$28,800	68 mi.	$600	107 mi.	6 hrs.
Chevrolet Spark EV	$27,495	82 mi.	$500	119 mi.	7 hrs.

The Most Impressive Stats

* Charge times vary based on state of battery and equipment.

MSRP, Range, Annual Fuel Cost, and MPGe provided by FuelEconomy.gov. Charge times from au

* http://www.businessinsider.com/electric-car-comparison-chart-2013-8

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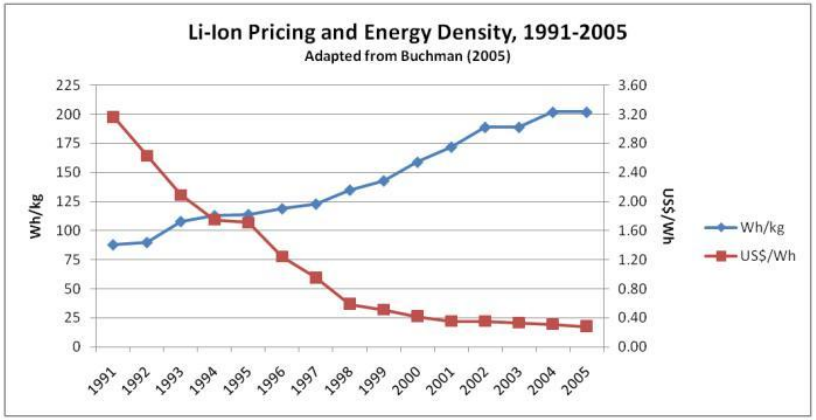
Current Challenges in EV batteries

- Where are batteries now?
  - Cost: $300-500/kWh
    - According to recent news, Tesla estimates pack costs of $300/kWh now & hopes to reduce below $200/kWh w/ the gigafactory*
  - Life:
    - Nissan:**
      - 8 years; 100K miles
      - >9 bars of capacity on the gauge for 60mos.
    - Tesla (from their website):
      - 8 years; either 125K or unlimited miles
      - Unclear minimum capacity

- Where do we want to be?
  - Cost: $125-200/kWh (~59% reduction)
    - USDOE goal is $125/kWh
    - "Sanford C. Bernstein, a research firm, reckons that when costs drop below $200 a kWh, battery-powered cars start to become competitive with conventional ones without subsidies."*
  - Life:
    - USDOE goal is 15 years, 1000 cycles >80% initial capacity



*http://www.businessinsider.com/elon-musks-assault-on-batteries-2014-6#ixzz35UtwoBNy
**http://www.nissanusa.com/electric-cars/leaf/charging-range/battery/
***http://money.cnn.com/2013/04/26/autos/tesla-service-gaurantee/
**** http://www.washingtonpost.com/blogs/wonkblog/files/2013/04/lithium-ion.jpg

Mass-Market EVs require cell technology breakthroughs

	Energy per mass (Wh/kg)	Cost per energy ($/kWh)
Today's values:	75 to 130 (battery system)	~300 to 500 (battery system)
Nissan Leaf (small passenger car)	24 kWh, 84 mi range	$15k pack
Tesla Model S (family sedan)	85 kWh, 265 mi range	~$26k pack

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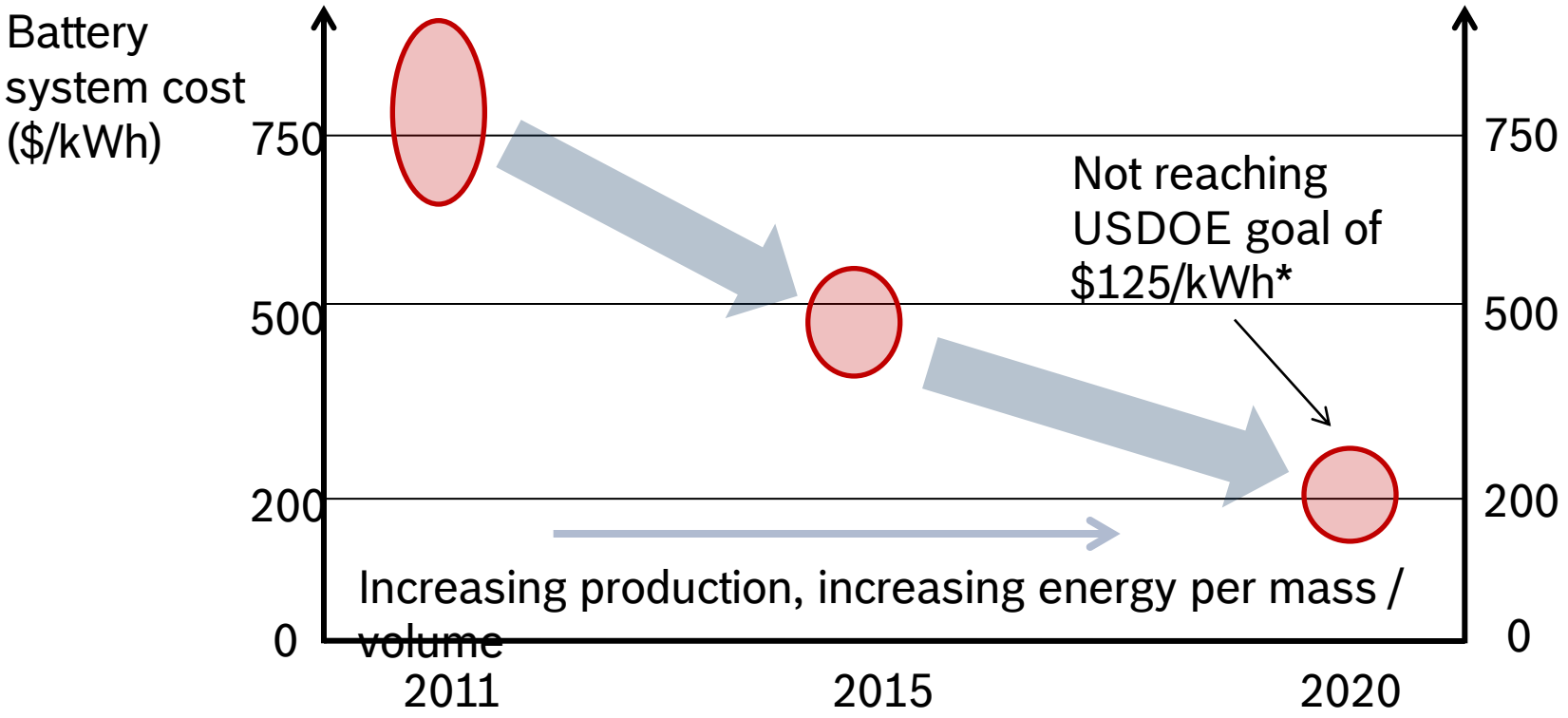
The Li-ion cost trajectory is not sufficient



Sources: Tiax, Institute of Information Technology, SB Limotive

* http://www.uscar.org/guest/article_view.php?articles_id=85

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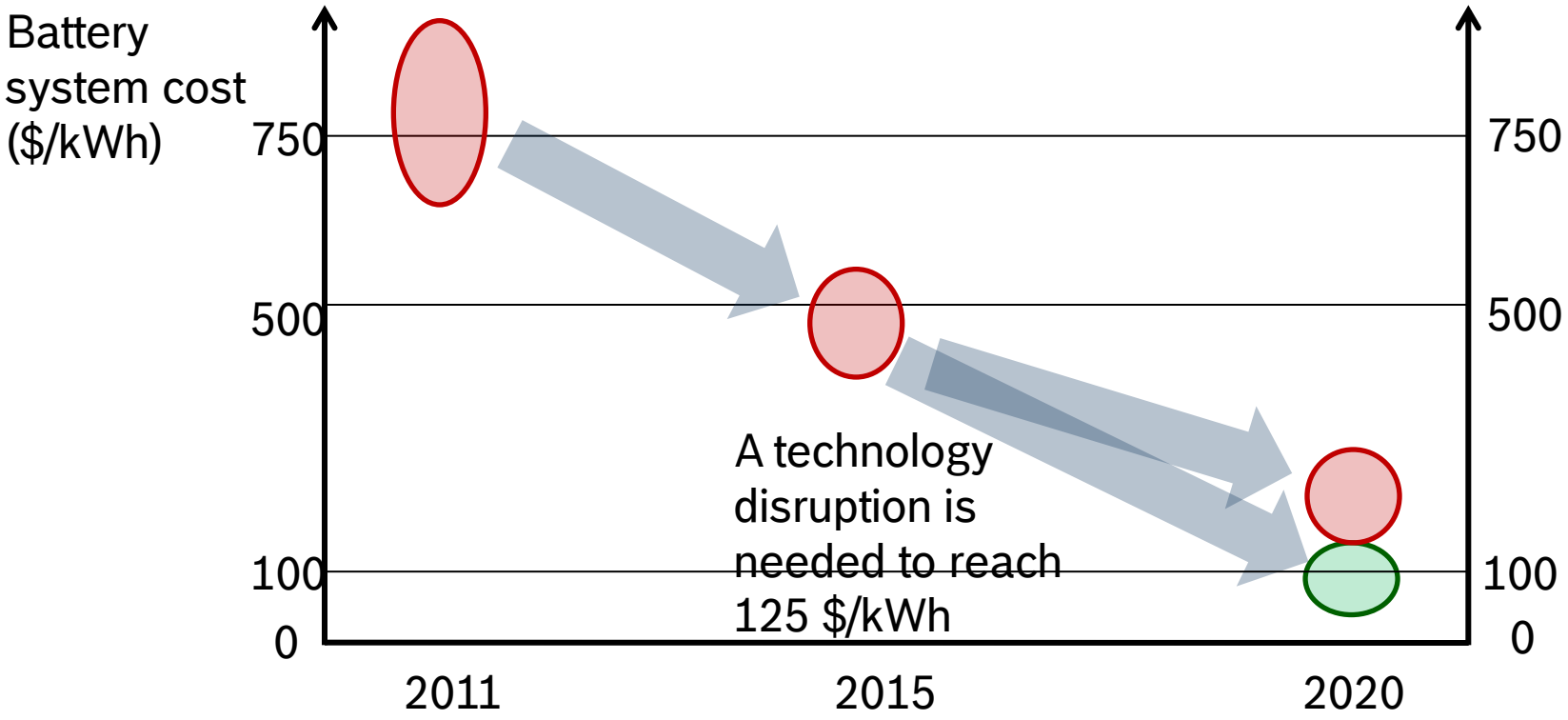
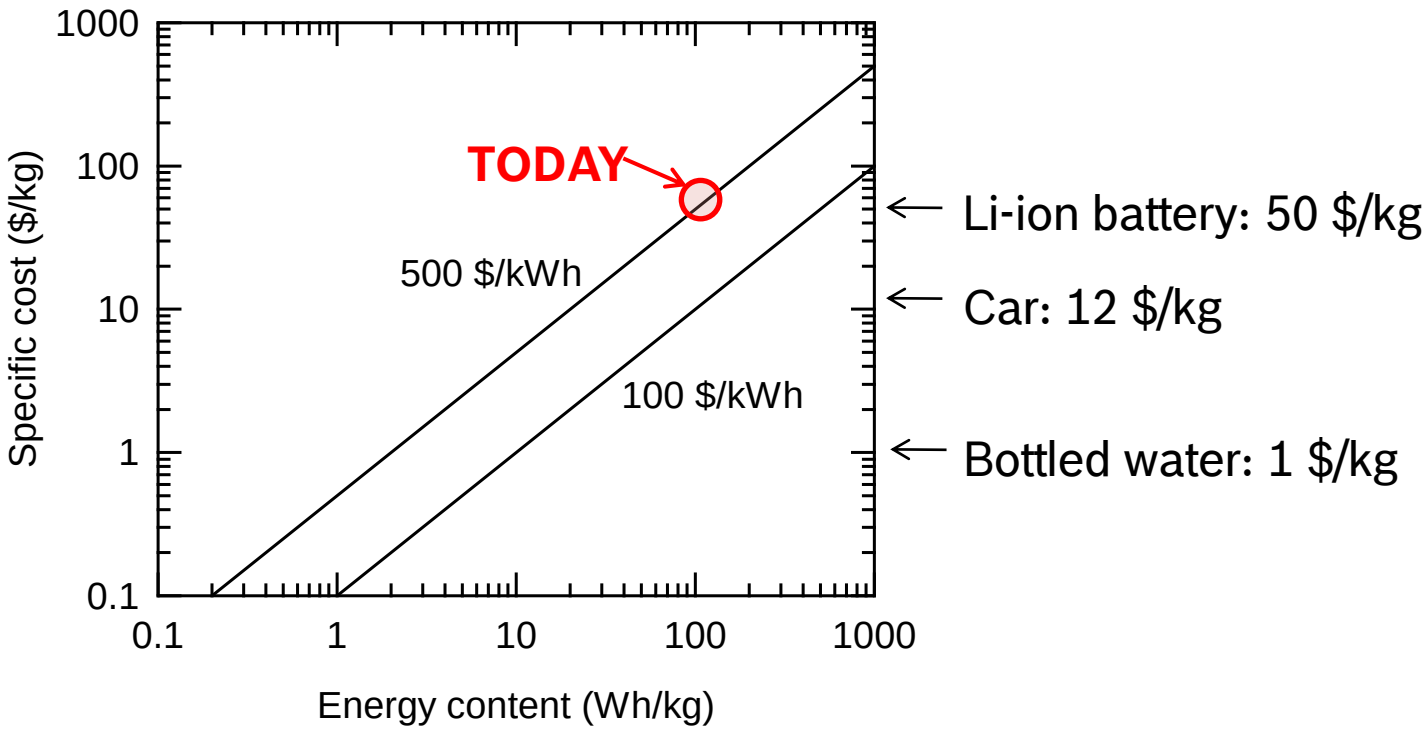


Sources: Tiax, Institute of Information Technology, SB Limotive

Costs can be lowered if the energy rises



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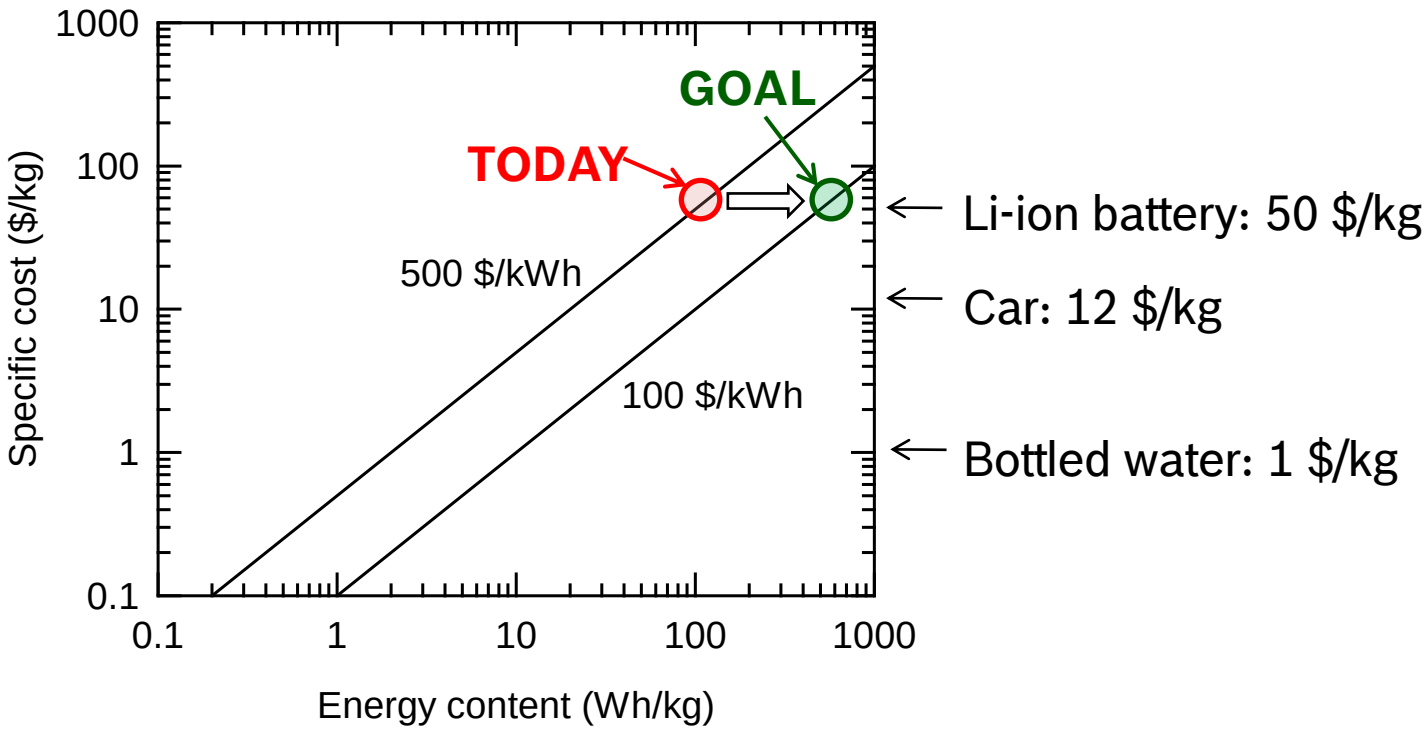
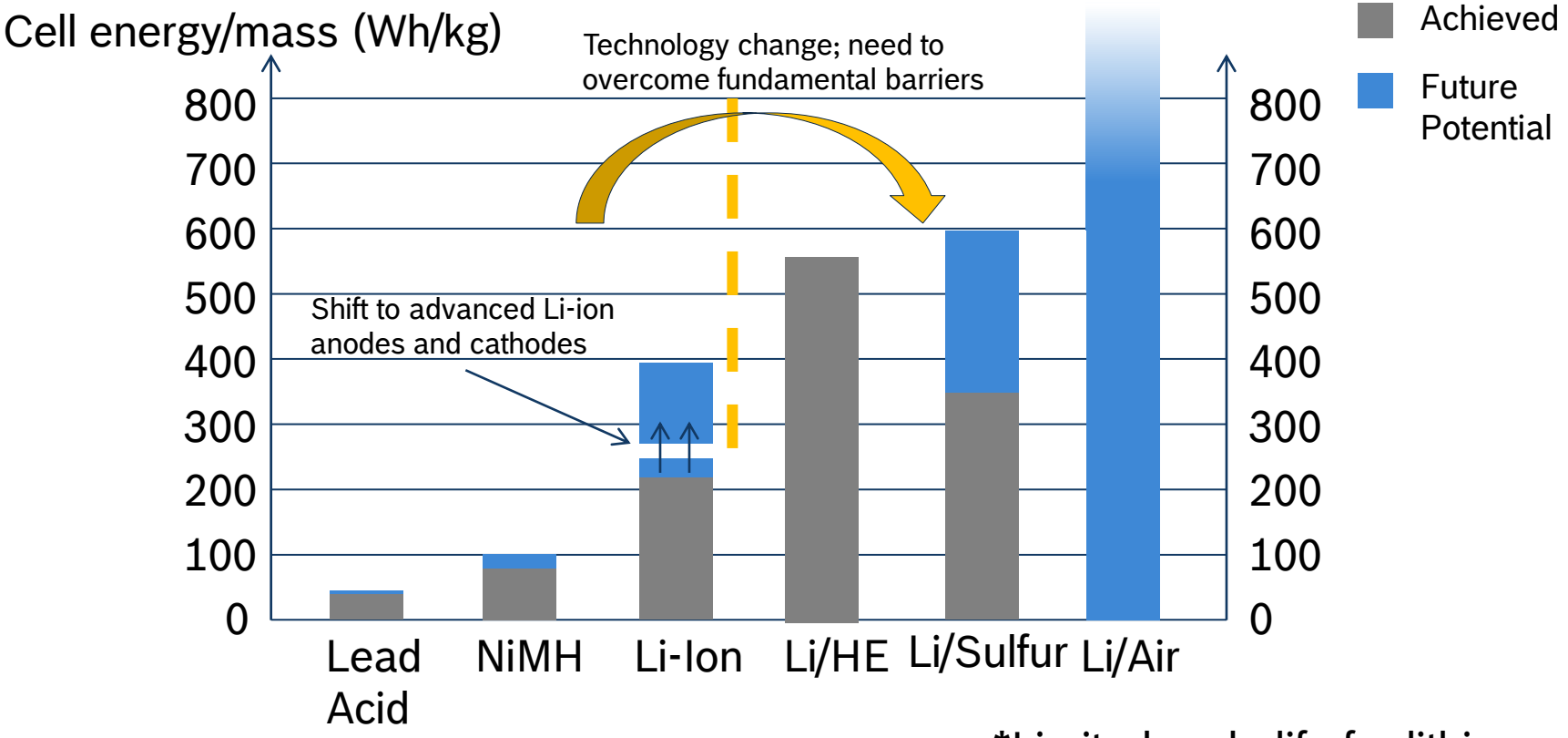


Goal: maintain cost of today's Li-ion batteries ($/kg) and increase energy/mass by 5x to reach 100 $/kWh.

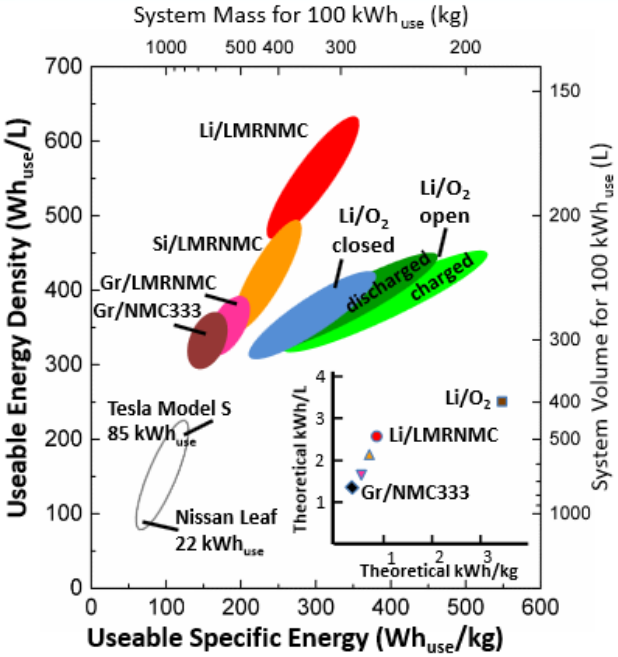
Chemistries exist with much higher energy/mass



*Limited cycle life for lithium

Frontiers in EV batteries: Future Materials

- Dramatic gains in energy density are possible, however significant challenges remain.
- Risk vs. Reward should be considered.
  - Example lower risk path:
    - Replace graphite anode with silicon
    - Replace cathode with NMC333
    - Replace cathode with advanced metal oxide (LMRNMC)
  - Disruptive technology capable of meeting $125/kWh target probably requires lithium anode.



Comparison of materials-to-systems analysis (main panel) and "active materials only" analysis (inset) of Li-O_2 batteries for electric vehicles

Source: Gallagher et al. "Quantifying the Promise of Lithium–Air Batteries for Electric Vehicles" Energy & Environmental Science, 2014, DOI:10.1039/C3EE43870H

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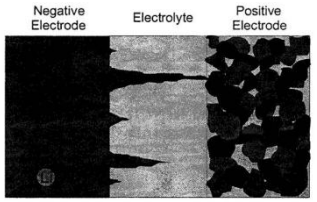
Frontiers in EV batteries: Li-Metal



- Anode: Lithium Metal
  - Primary challenges:
    - Low potential→Electrolyte decomposition
    - Morphology changes→unstable passivation, solvent dryout
    - Dendrite formation→electrical shorting risk
  - Current strategies to promote stable cycling have challenges
    - Polymer or ceramic solid electrolytes
      - Room-temperature Li^+ transport
      - Chemical and mechanical stability
    - Novel liquid electrolytes (solvents & salts & additives)
      - Coulombic efficiency
    - Alloying (e.g. Al/Li or Mg/Li)
  - Many approaches work well < 1mA/cm^2, but not higher current densities

*http://www.npc.org/FTF_Topic_papers/17-Advanced_Batteries.pdf
** http://www.solarnenergy.com/contents_img/259787.jpg

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