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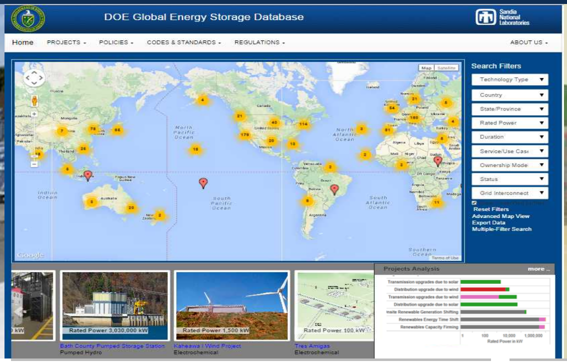

Grid Energy Storage: Materials, Manufacturing and Systems Engineering

Babu Chalamala

25th International Materials Congress, Cancun, August 16, 2016

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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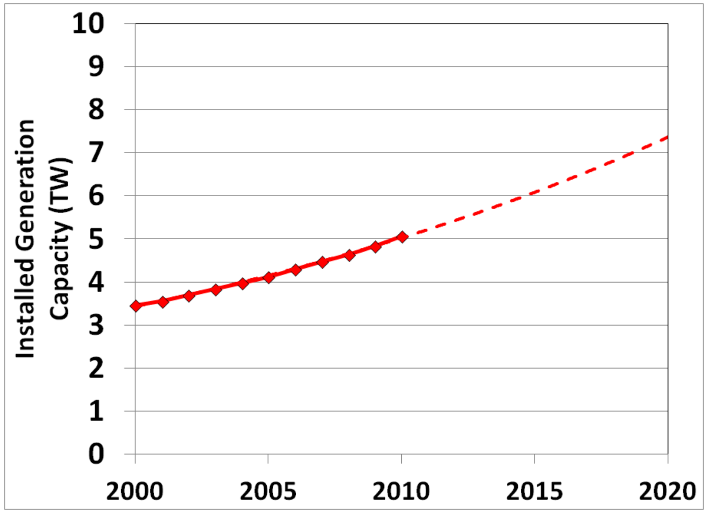
Global Trends in Energy

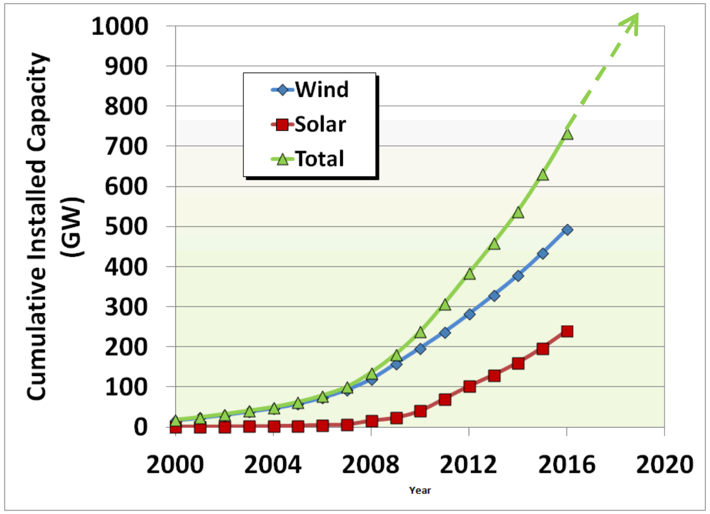
- Transition Towards a Renewable Electricity Regime
  - Distributed energy sources, improve resiliency, rapid adaption to climate and demographics change
- Electricity Infrastructure
  - Grid modernization needs major investments
  - Transition to a distributed generation model and technology needs for this transformation
- Smart Grids and High Level Systems Integration
  - Optimization distributed energy systems across multiple platforms and use regimes (residential, commercial and utility scale
  - Grid security and resiliency

- Energy Storage plays a key role in the future grid

Growth of Renewables is the Big Story

- Rapid transition towards a distributed generation model.
- Of the 6 TW of worldwide generation capacity, wind and solar are reaching the 5-10% range in many areas.
- By 2020, worldwide installed RE capacity will be ~ 1 TW, penetration levels may approach 30-40% in some markets.
- Are we really prepared to handle high levels of RE and the associated intermittency?
- Is the current grid ready for large amounts of renewables?
- Handling intermittency is a key challenge
- Can we provide electricity to the 1.6B people who are have connected to the grid?



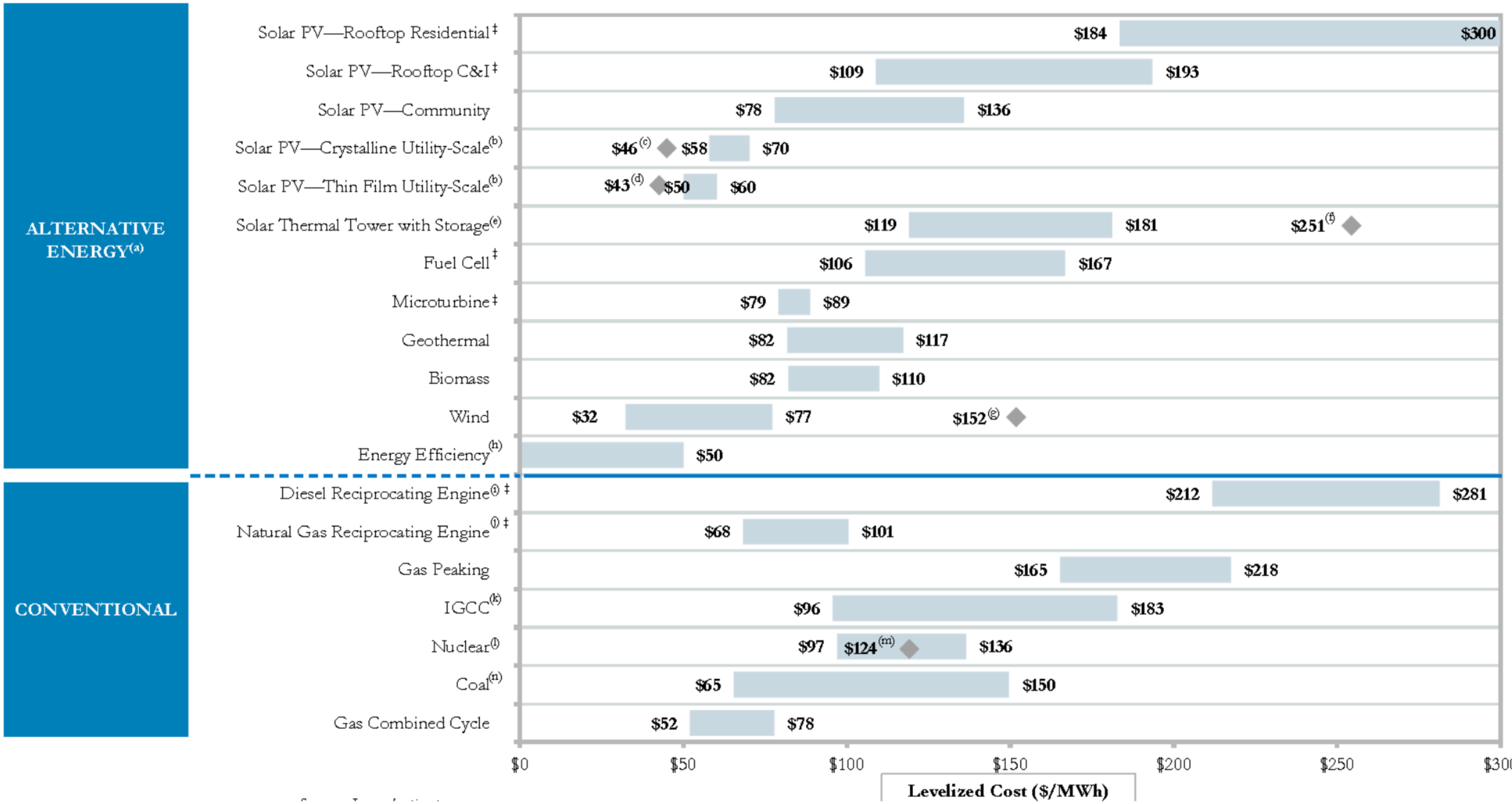


Data Sources: IEA, EPIA, Global Wind Energy Council, Earth Policy Institute, 2013

Application Drivers for Energy Storage

- Renewable integration
- Transmission and Distribution upgrade deferral
- Power quality, e.g., UPS application, microgrids, etc.
- Improved efficiency of nonrenewable sources (e.g., coal, nuclear)
- Off-grid applications

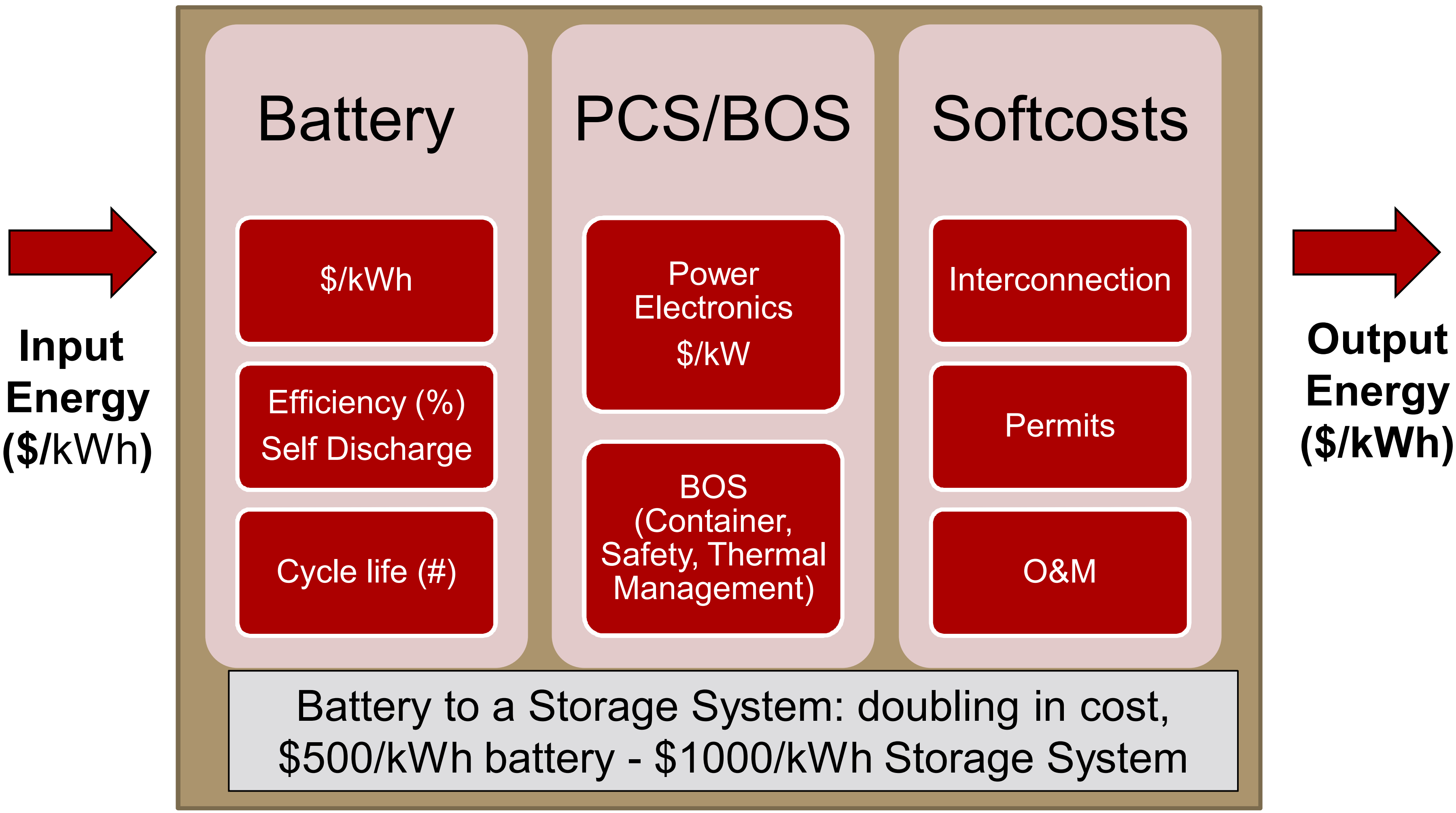
Unsubsidized Levelized Cost of Energy Comparison



Data Source: Lazard, 2016

Wind and solar PV have become increasingly cost-competitive with conventional generation technologies on an unsubsidized basis.

LCOE for Energy Storage Systems



Levelized Cost of Energy Stored LCOES: Energy Storage System + Cost of Capital

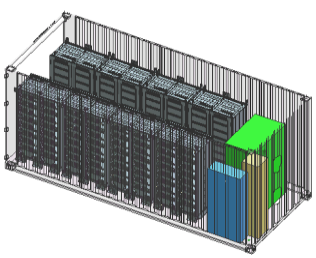
For Energy Storage to Become Ubiquitous

- LCOE on a $/KWh-cycle (energy delivered) needs to come down to <$0.05/KWh-cycle
- Got to look beyond bundling multiple benefit streams
- Better cost metrics – usable energy capacity in KWh-cycles.
- Greater attention to safety

Elements of an Energy Storage System

Storage

- Cell
- Battery Management & Protection
- Racking



Integration

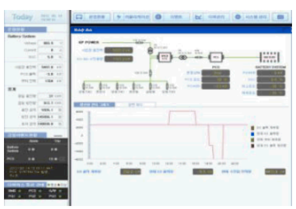
- Container / Housing
- Wiring
- Climate control

PCS

- Bi-directional Inverter
- Switchgear
- Transformer
- Skid

EMS

- Charge / Discharge
- Load Management
- Ramp rate control
- Grid Stability

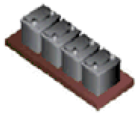


We need cost reductions across all areas, not just batteries

Energy Storage: SOA is where PV was 10-15 yrs back

- Needs major improvements in cycle life, reliability and safety of energy storage systems (batteries)
- Significant improvements needed in cost and efficiency in energy storage
  - Lead acid market is mature with ~ 2% CAGR
  - Lithium ion battery market is seeing a 3X drop in price and a 2x increase in energy capacity per decade
  - Insufficient commercial data for flow battery systems but cost and performance improvement potential is high
- Need for basic materials science
  - Electrochemistry, materials discovery, redox chemistries
  - Development of safe electrolyte solutions
  - Methods to augment cycle life
- Low cost starting materials, Low capex manufacturing
- Reducing the need for thermal management

Cost Structure of Storage System in 2016



Storage Racks+BMS

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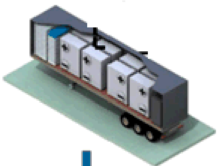

Product Integration

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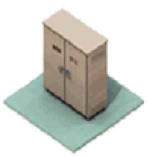

Power Conditioning (PCS)

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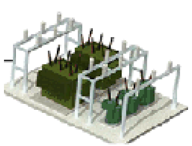
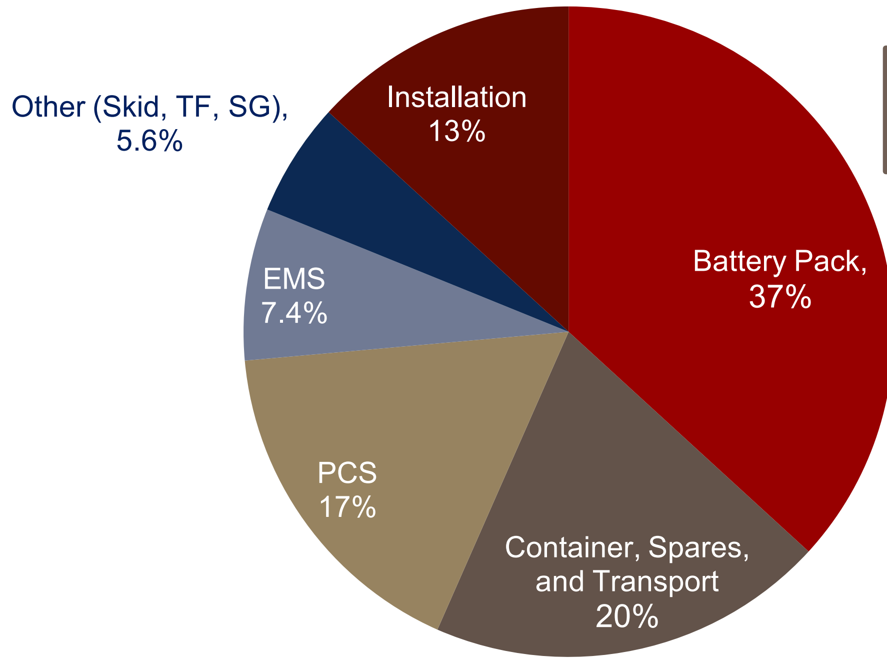


Field EPC Grid Integration



1MW/1MWh
LIB ESS

Projected cost line items for a 1MW/1MWh Li-ion energy storage system ($600/kWh and above depending on the system configuration)

Almost 60% of storage system cost is outside the Battery Pack

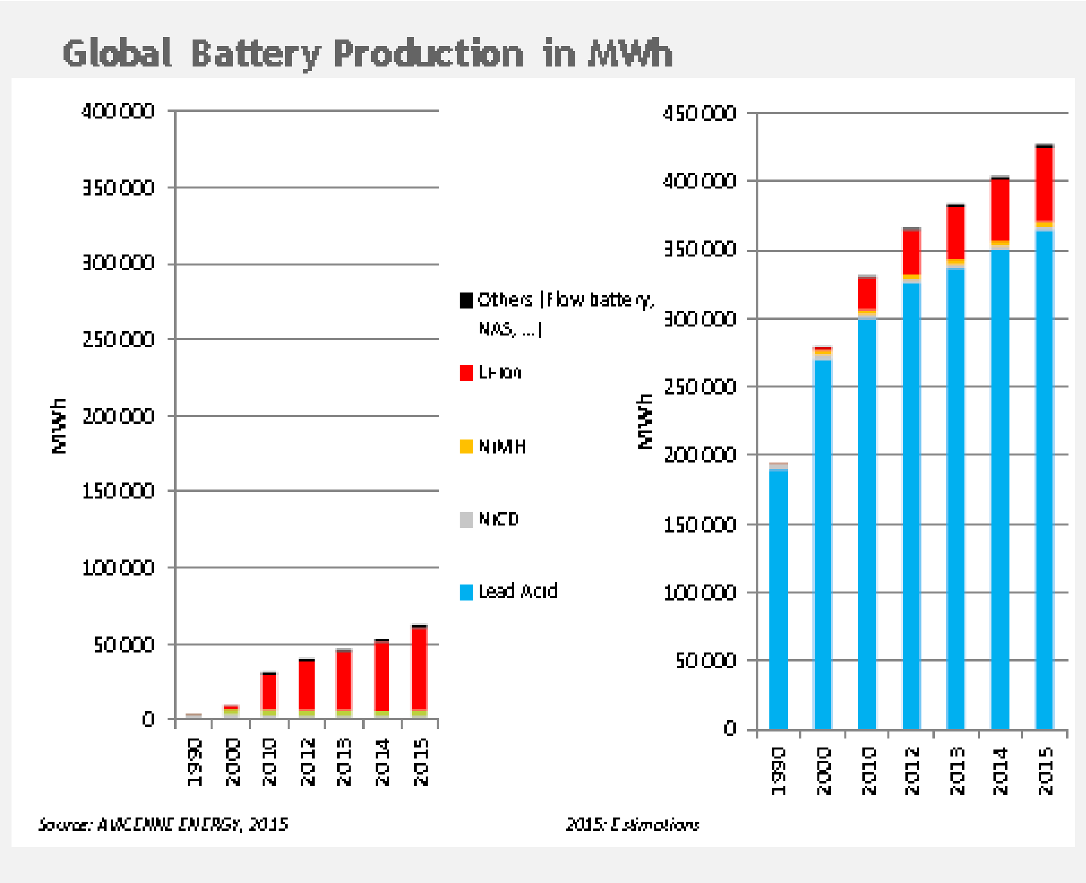
Data: Multiple industry sources

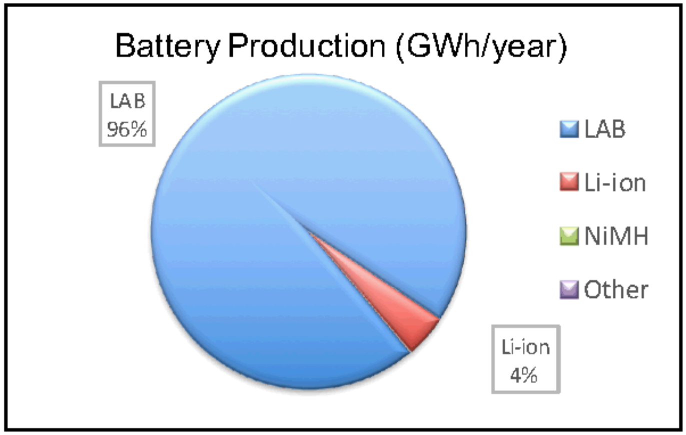
Battery Technologies

Mature Technologies				
	World Wide Capacity (GWh/y)	**Cost and Performance Improvements**	**Key Challenges for Energy Storage**	**Major Suppliers**
Lead Acid Batteries (LAB)	300	2%/year ((30 year data). $150/kWh	Cycle life. Advanced lead acid cycle life on par with EV grade LIB	JCI, GS Yuesa, EastPenn, EnerSys, Exide, Hagen
Lithium Ion Batteries (LIB)	50	8%/year (20 year data). Cell level price reaching $200/kWh	Cycle life for deep discharge. Safety. Thermal management	Panasonic, Samsung, LG Chem, BYD, GS Yuesa (Nissan, Honda JVS), Lishen, JCI, A123, Toshiba. EV Batteries: Converging to NMC chemistry
Emerging Technologies				
NaS and NaNiCl	300 MWh	No economies of scale	High temperature chemistry. Safely, Cost	NGK, GE
Flow Batteries	<200 MWh	Not fully mature. Potential for lower cost. $400/kWh. Reach $270/kWh	Not mature. Has not reached manufacturing scale.	Sumitomo, UET, Rongke Power, ZBB, Imergy, Gildenmeister. Only Sumitomo provides 18 yr. warranty
Alkaline chemistries (Na, Zn-MnO2,..)	<100 MWh	Not fully mature. Lowest cost BOM	Has not reached manufacturing scale.	Aquion (Na), UEP (Zn-MnO2), Fluidic Energy (Zn-air)

Lead acid and Lithium ion: Only two battery technologies with manufacturing capacity and scale to serve MWh - GWh ES markets

Global Production Volumes





Source: Avicenne (2015), DOE

Lead Acid Battery business continues to be highly profitable
Li-ion struggling with low factory utilization rates of ~10-20%

Battery Storage – How do they stack up in cost?

Battery system (complete system without charger)	2012	2015	2020
Li-ion (includes sophisticated BMS & cooling)	600-750	400-500	250-300
NiMH (includes simple BMS & cooling for HEV only)	500-700	400-500	350-400
NiCd (includes simple controller)	400-600	350-450	300-350
Lead-acid (includes simple controller)	220-250	200-220	180-200

- Market data does not give a true indication of the true cost of energy storage.
- How many total kWh of energy can be cycled during the lifecycle?
- What is the true normalized cost per kWh of storage?

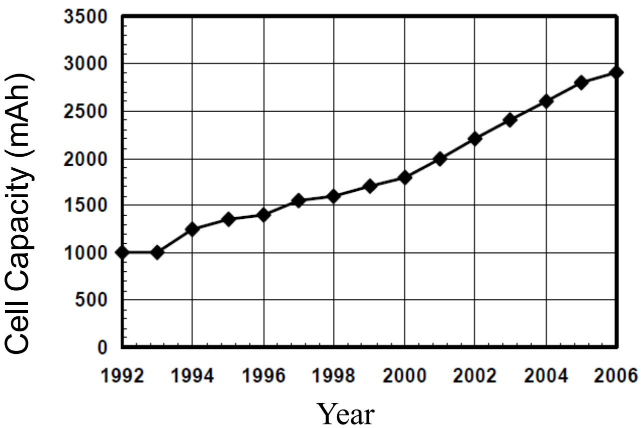
Roland Berger Consultants, Presentation at Batteries 2012

Cost of Energy Storage

- Costs have to reflect cycle life, efficiency, depth of depth and other long term performance metrics.
- For large scale deployment, other metrics become significantly more important
  - Product life: Most utility asset have 20+ year product cycles. PV system warrants are 20-25 years. Can storage provide similar product warranties?
  - Can storage be operated safely and reliably under all conditions?
  - Can storage compete with NG peaker plants?

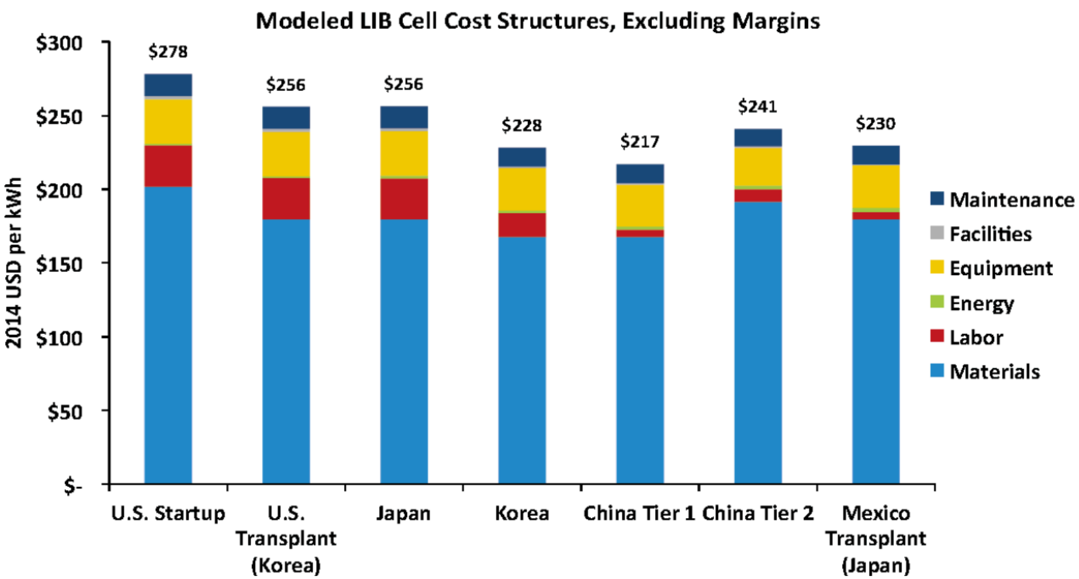
Li-ion Batteries: SOA

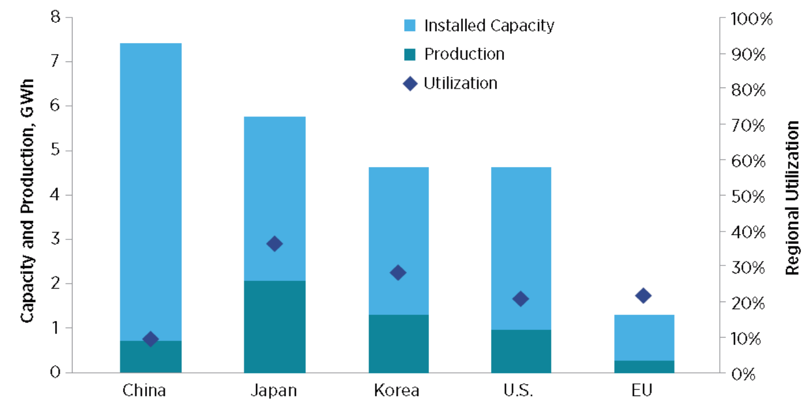
- Capacity improvements are incremental
  - Average 8% improvement in cell capacity per year (1992-2007)
- Continued reduction in cost/performance
  - Materials cost can not be scaled down much lower, BOM is 80-85% of cell costs
  - Need significant improvement in electrolytes, membranes, anode and cathode materials
  - Engineering larger cells (>100 Ah) is not still economical
- For MWh applications
  - Improve safety and control electronics
  - Thermal management is a bigger issue



18650 cell capacity improvement of 8% per year
Source: Proc. IEEE, vol. 95, pp. 2106 – 2107, 2007

Large Format LIB Manufacturing





Source: D. Chang, et al, Automotive Li-ion Battery (LIB) Supply Chain and U.S. Competitive Considerations, NREL/PR--6A50--63354, June 2015

Capex intensive $300-400M /GWh capacity addition
Continued consolidation in the Automotive Li Battery business
Excess capacity driving the need for applications beyond EVs

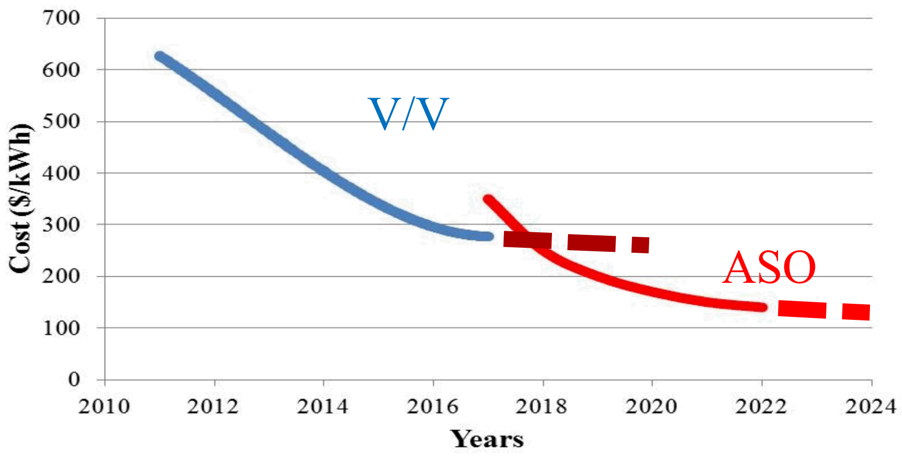
Lead Acid Batteries: SOA

- Lead acid batteries continue to be the lowest cost, high volume solution for energy storage
  - Variations of high carbon Pb acid
  - Cycle life and thermal management continue to present challenges
- High carbon batteries most promising for grid scale applications
  - Ultrabatteries
    - Long cycle life, 100k cycles under PSOC
      - 1.5x cost of conventional lead acid
  - Carbon foam anodes – reduces sulfation, low cell resistance

Flow Batteries: SOA

- Does not have the capacity limitations of LIB and LA, and scale is more and more economical
- No major IP issues, significant opportunity to scale up
- State of the Technology
  - Low energy densities (15-30 Wh/L)
  - Limited voltage window of aqueous electrolyte solutions (< 1.5 V)
  - Low solubility of redox species, needs further improvements in temperature range
  - Stack life and reliability concerns
- Potential opportunities to reduce materials cost
  - New redox chemistries, new electrolytes under development
  - Increased current density and lower cost stack design

Flow Battery Cost Projections

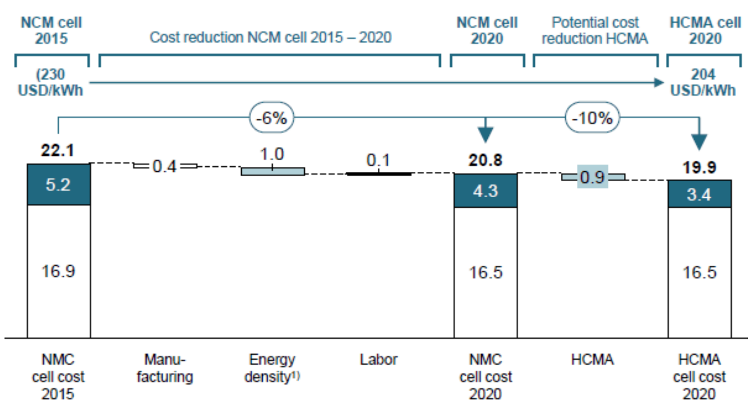


Source: PNNL, 2016

- Utility scale Vanadium flow battery systems approaching \$350/kWh. Further reductions in cost requires improved chemistry, lower stack costs.

Capex and Bill of Materials (BOM)

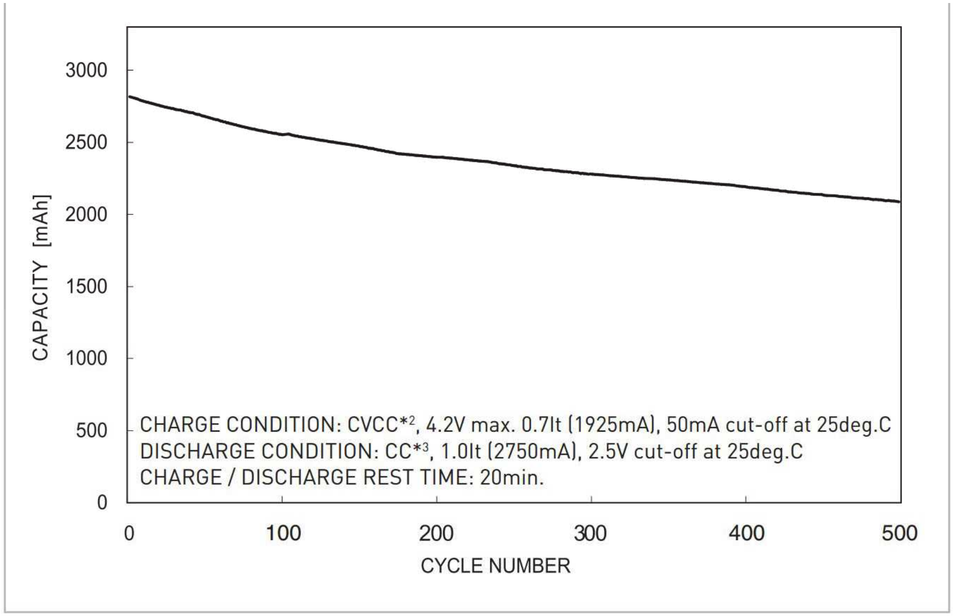
- Capex for GWh/yr production capacity
  - Lead acid: $50-60M
  - LIB: $300-400M
- For lead acid and Li-ion, BOM is 80-85% of the cell cost
  - Large format LIB: BOM $180-200/KWh
- For flow batteries, electrolyte cost ~30-40% overall cost
- For comparison, primary alkaline batteries: $18-20/KWh



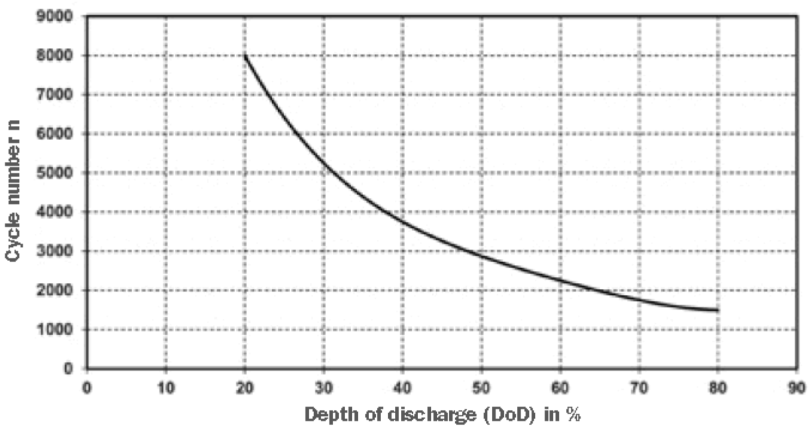
Manufacturing

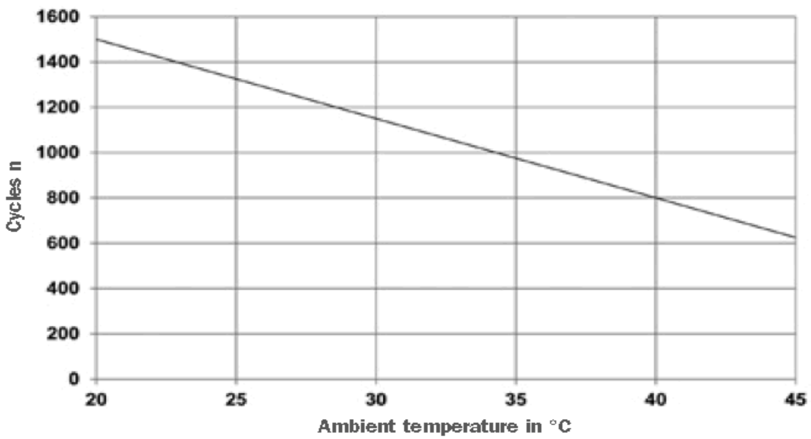
- Low manufacturing capex is critical
- 5-10x < Li ion batteries (currently $300-500M/1GWh capex)
- Closer to lead acid manufacturing costs ($50-60M / 1GWh)
- Low cost materials (BOM), established supply chain
  - Storage is volumetric, GWh needs lot of raw materials
  - BOM of $50/KWh and fullly manufactured cost of <$100/kWh (cell)
- Scalable to large format cells, and simpler BMS
- Scalable for large volume manufacturing in GWh

Cycle Life is a Major Challenge



Panasonic NCR18650 cell – cycle life





Hoppecke Lead Acid Batteries
Cycle life with DOD and Temperature

Materials and Manufacturing Challenge

- Critical challenges for energy storage are high system cost and cycle life
  - Existing storage solutions are too expensive
  - Deep discharge and longer cycle life
  - Safe and reliable chemistry
  - Scalable technology to cover all markets
- To make storage cost competitive, we need advances across all major areas:
  - Batteries, power electronics, PCS
  - BOS and Integration
  - Engineered safety of large systems
  - Codes and Standards
  - Optimal use of storage resources across the entire electricity infrastructure