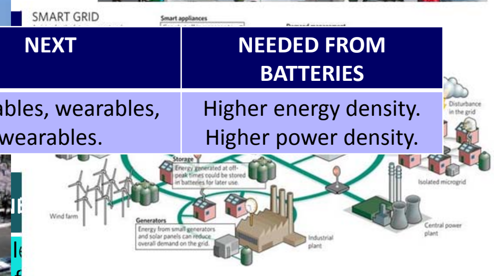
Solid State Energy Storage: Game-Changing Technology for the 21st Century

Dr. Ann Marie Sastry
CEO and Co-Founder
SAKTI3

Batteries enable important things.

BY SECTOR

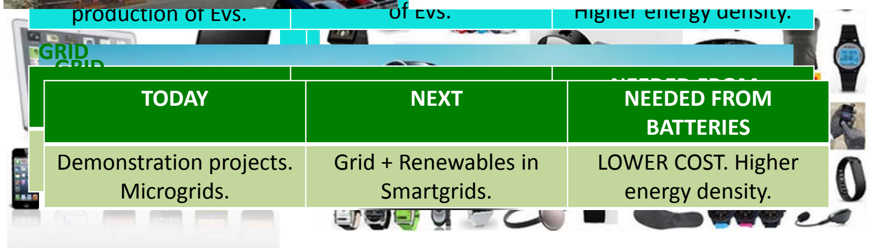


CONSUMER ELECTRONICS

TODAY	NEXT	NEEDED FROM BATTERIES
Smartphones. Laptops.	Wearables, wearables, wearables.	Higher energy density. Higher power density.

AUTOMOTIVE

production of EVs. | of EVs. | Higher energy density.



GRID

TODAY	NEXT	NEEDED FROM BATTERIES
Demonstration projects. Microgrids.	Grid + Renewables in Smartgrids.	LOWER COST. Higher energy density.

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How they work.

How they're made.

Where they're made.

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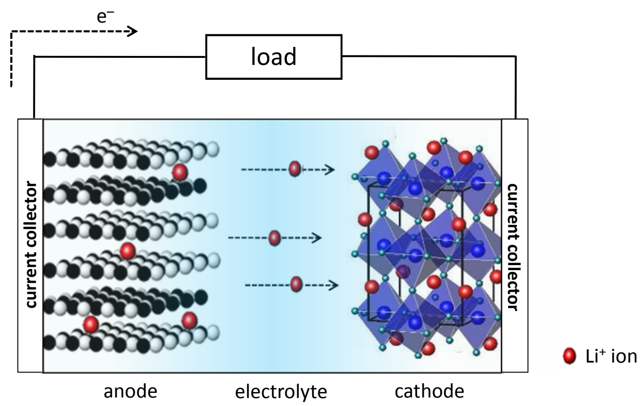
DISCHARGE



at negative electrode, loss of electrons (oxidation, anodic)

$$Li_xC \rightarrow C + xLi^+ + xe^-$$

at positive electrode, gain of electrons (reduction, cathodic)

$$Li_{1-x}MO_2 + xLi^+ + xe^- \rightarrow LiMO_2$$

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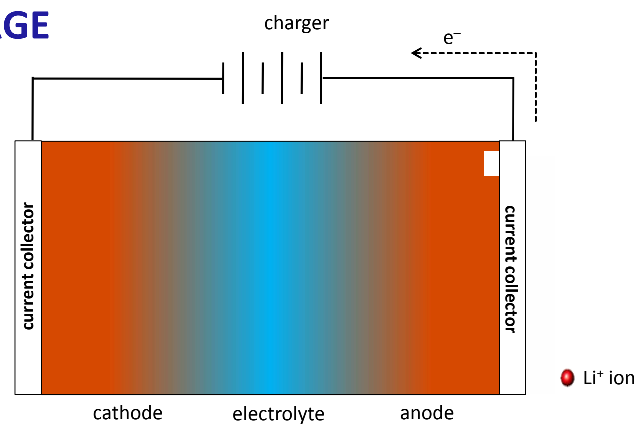
CHARGE



gain of electrons, reduction, cathodic

$$C + xLi^+ + xe^- \rightarrow Li_xC$$

loss of electrons, oxidation, anodic

$$LiMO_2 \rightarrow Li_{1-x}MO_2 + xLi^+ + xe^-$$

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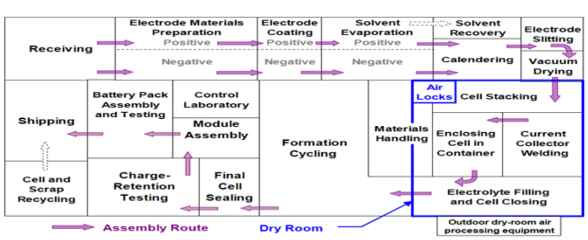
COMMON CATHODES

electrochemical system	Wh/L	Wh/Kg	mAh/g	x
$Li_xMn_2O_4$	2060	490	123	0.2≤x<1
Li_xFePO_4	2070	580	170	0≤x<1
$Li_xV_2O_5$	2920	870	357	0≤x<2.42
Li_xCoO_2	3000	600	151	0.45≤x<1
$Li_x(Ni_{1/3}Mn_{1/3}Co_{1/3})O_2$	3680	770	200	0≤x<0.7
$Li_x(Ni_{0.8}Co_{0.15}Al_{0.05})O_2$	3780	740	195	0.27≤x<1

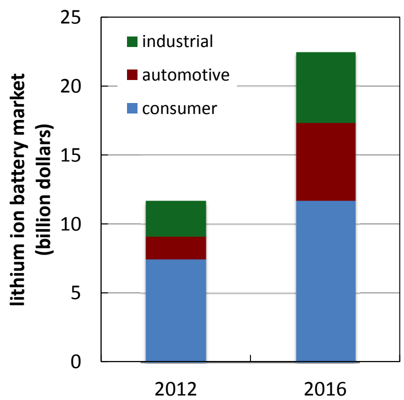
INCUMBENT: LAMINATION

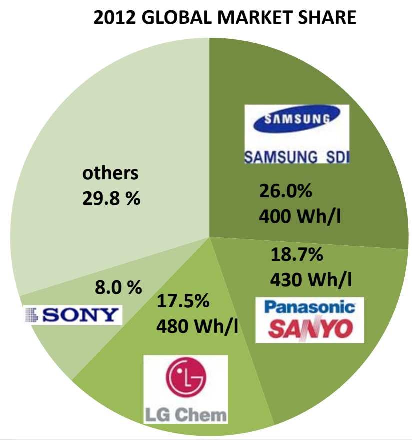
powder mixing → coating → pressing → stacking or winding → packaging



- **18+** steps for porous laminated electrode battery
- **60 DAYS** in formation and aging ($$$ and WIP, and errors in formation destroy cells)
- Depreciation/KWh: $98/KWh/year
- Battery Cost: $300-800 /kWh

>$12B BATTERY TAM: INCUMBENT TECHNOLOGIES ARE ALL LAMINATION





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Limitations: cost and performance.

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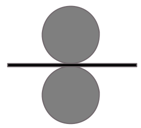
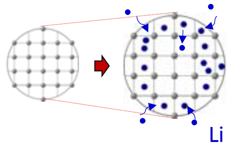
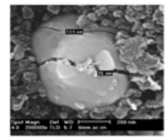
Mechanical Failure

compression during manufacturing

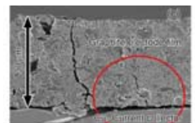


tension/compression/shear due to intercalation

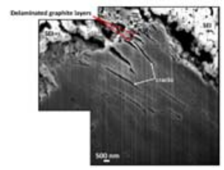




active material fracture



delamination from the current collector



SEI layer damage

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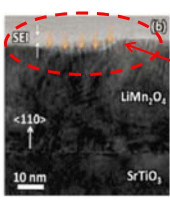
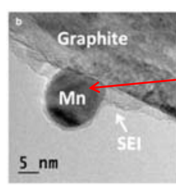
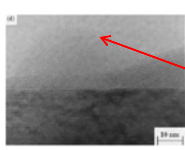
Chemical Degradation



Dissolution of metal ions in the cathode material

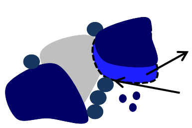


Deposition of the dissolved ions into anode

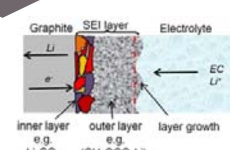


SEI layer becomes unstable at high temp.

Swelling due to off-gassing



material loss
contact loss



cyclable lithium loss
impedance rise

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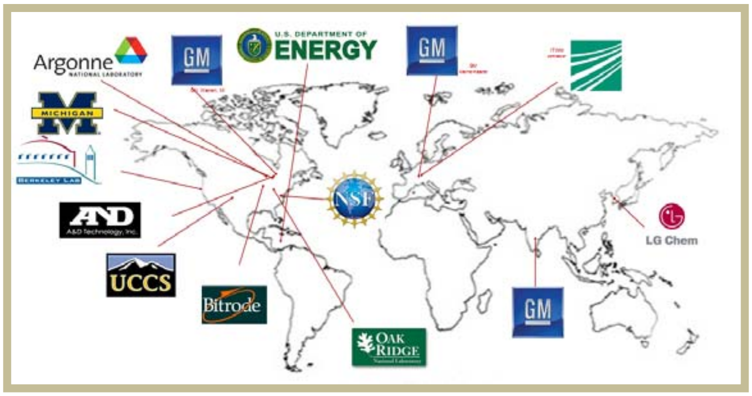
COLLABORATORS



- **Sakti3 Team**
- Select Laboratories / Industrial Partners
  - **Prof. Wei Lu**
  - **Prof. Wei Shyy**
  - **Prof. Christian Lastoskie**
  - **Dr. Jonghyun Park**
  - U.S. Department of Energy
  - General Motors
  - UCB / Lawrence Berkeley Laboratory
  - Oak Ridge National Laboratory
  - Argonne National Laboratory

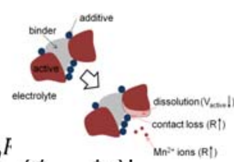
LIMITATIONS IN PERFORMANCE: KEY EFFORTS

Dissolution/Deposition

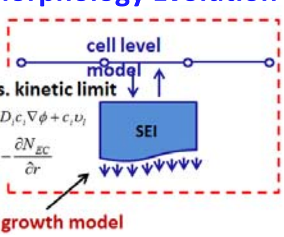
$$\frac{\partial \varepsilon_{1,pos}}{\partial t} = -a_{s,pos} k_{dissolution} \bar{V}$$

$$\frac{\partial r_{pos}}{\partial t} = -[a_{s,pos} k_{dissolution} \bar{V}]^{1/3}$$

$$i_{deposiiton} = -F k_{reduction} c_{Mn^{2+}} \exp\left[-\frac{\alpha_{c,Mn\_dep} F}{RT}(\phi_1 - \phi_2)\right]$$



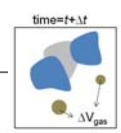
SEI layer Morphology Evolution



$$N_i = -D_i \nabla c_i - z_i \frac{F}{RT} D_i c_i \nabla \phi + c_i \upsilon_i$$

$$\frac{\partial c_{EC}}{\partial t} = -\frac{\partial N_{EC}}{\partial r}$$

Gas Generation

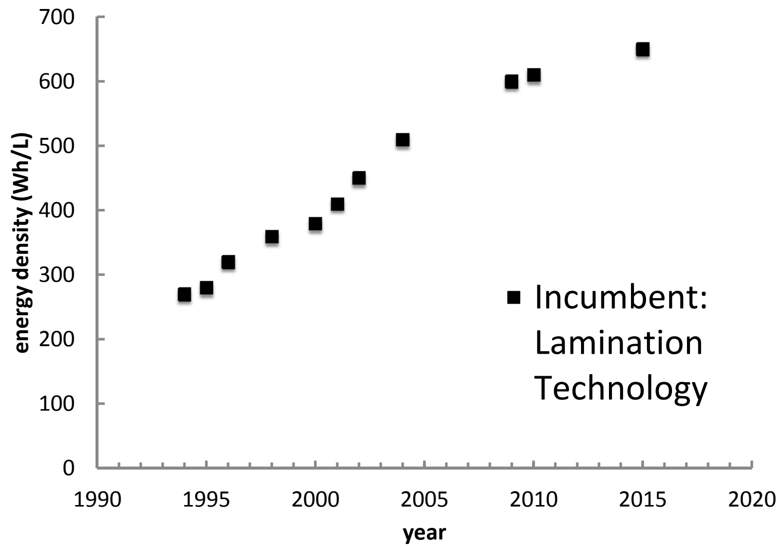


$$\varepsilon_{gas}(x, t + \Delta t) = \varepsilon_{gas}(x, t) + \int_t^{t+\Delta t} \Delta \varepsilon_{gas} dt$$

$$\varepsilon_e(x, t + \Delta t) = \varepsilon_e(x, t) - \Delta \varepsilon_{gas}(x, t)$$

$$\varepsilon_{inert}(x, t + \Delta t) = \varepsilon_{inert}(x, t) + \Delta \varepsilon_{gas}(x, t)$$

STATUS / PROJECTIONS



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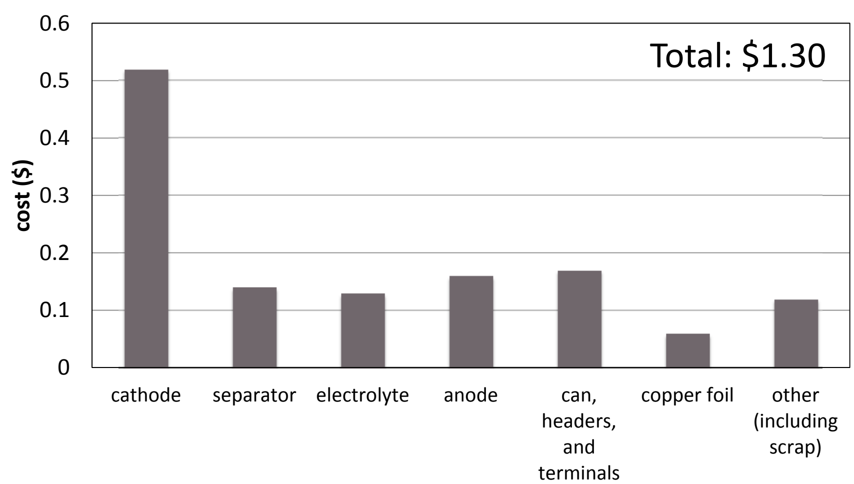
BOM: 18650 CELL



R.J. Brodd, C. Helou / Journal of Power Sources 231 (2013) 293-300

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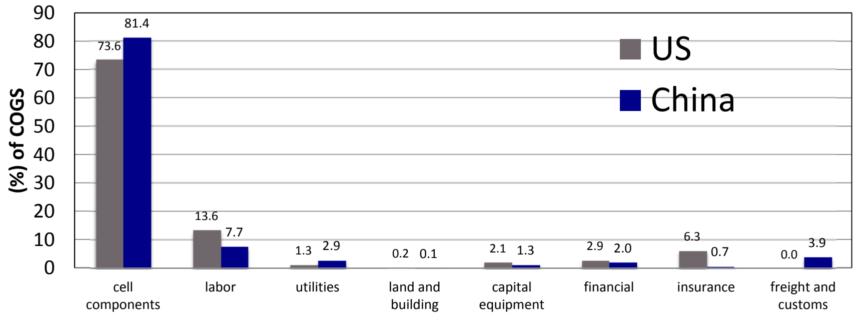
COGS: US AND CHINA, 35MM CELLS / y

10 lines
winder speed 30 cells/min
3 winders per line

3 shifts per day, 400min per shift
360 production days per year
yield 90%



BOM/COGS
74% in US; 81% in China

R.J. Brodd, C. Helou / Journal of Power Sources 231 (2013) 293-300

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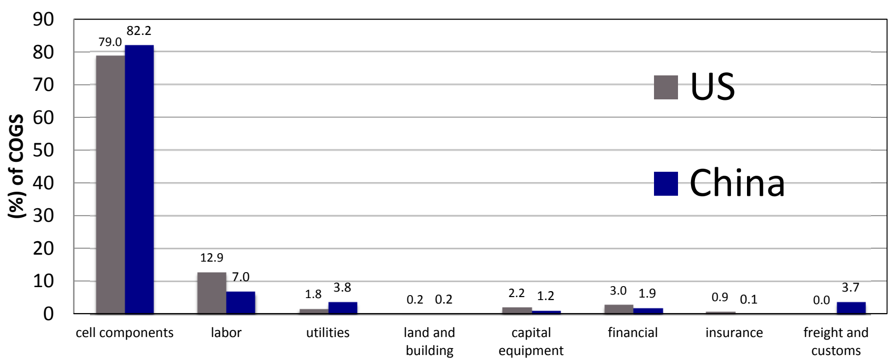
COGS: US AND CHINA, 350MM CELLS / y



BOM/COGS
79% in US; 82% in China

R.J. Brodd, C. Helou / Journal of Power Sources 231 (2013) 293-300

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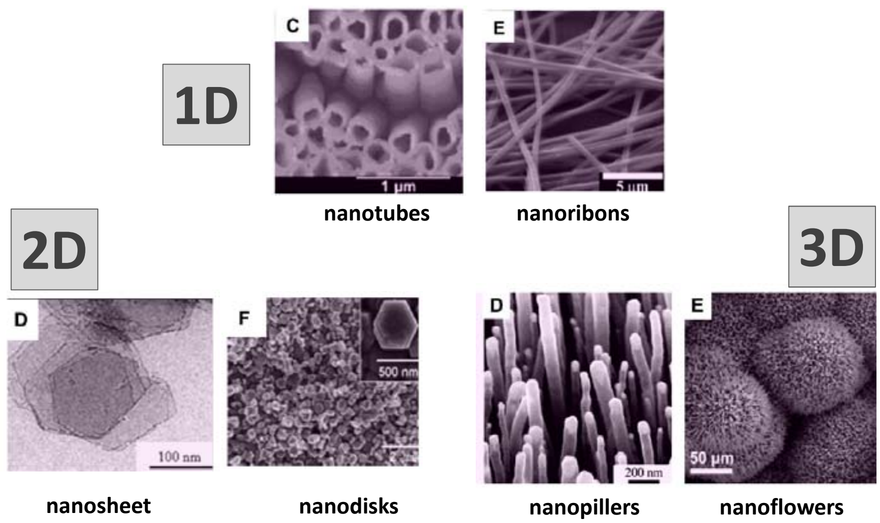
TECHNOLOGY / CAPACITY

- SUPPLY SIDE: stimulI, anticipated markets produced overcapacity in lamination technology
- DEMAND SIDE: EV markets unrealized as yet; smaller CE cells dominate
- LIMITATIONS: safety issues necessitate complex systems. BOM / COGS is high for lamination
- UPSHOT: New development path needed for significant improvement in batteries.

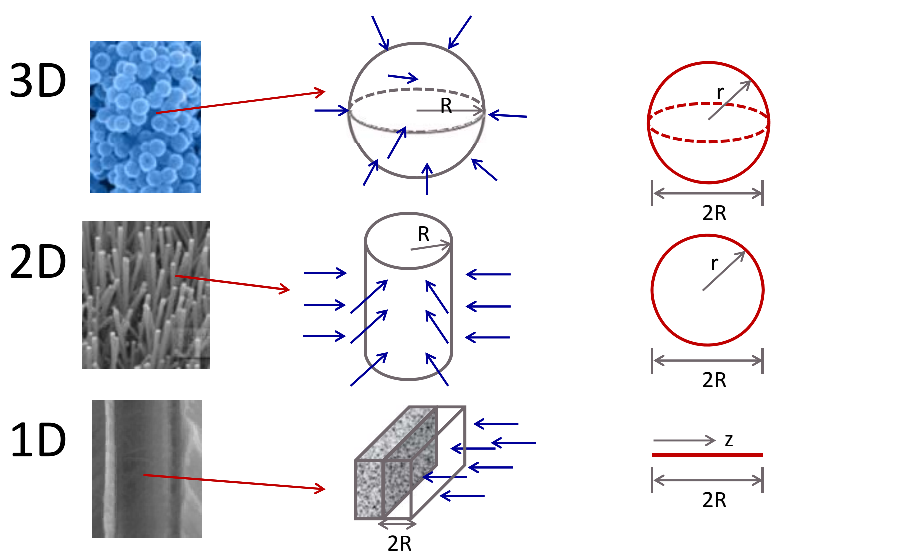
The best way to build a battery (if you could do it at low cost).

CHOICES!

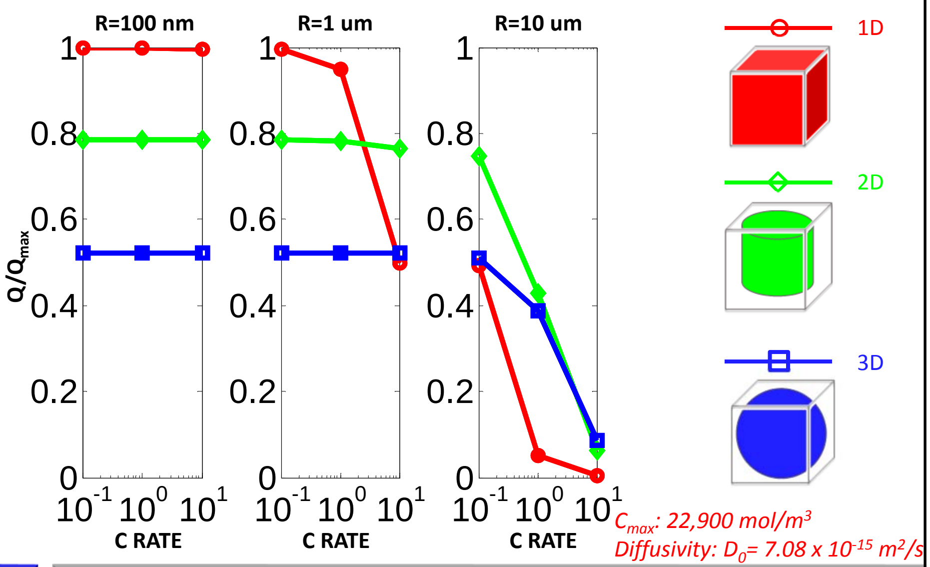


Jitendra N. Tiwari et al, Progress in Materials Science 57 (2012) 724–803

THOUGHT EXPERIMENT.



DIMENSION-DEPENDENT CAPACITY PER CUBE



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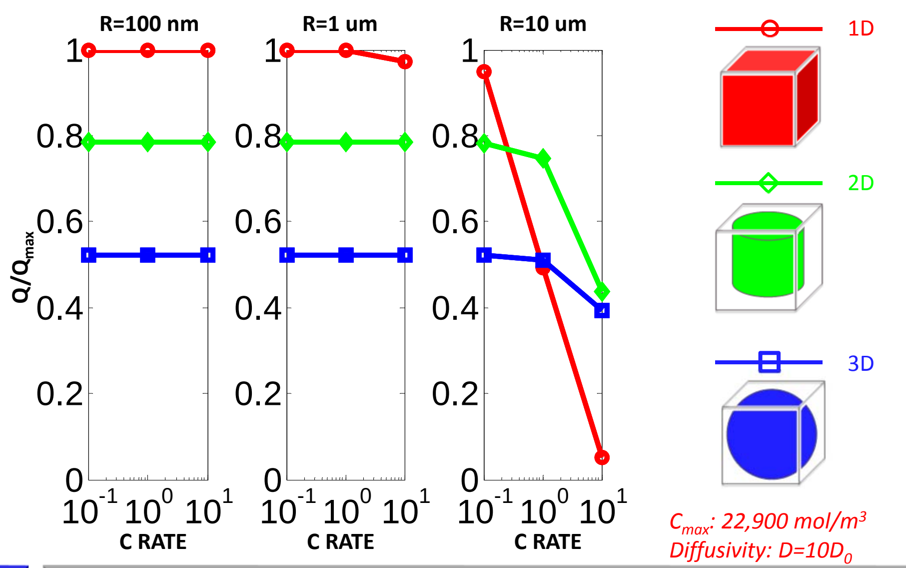
DIMENSION-DEPENDENT CAPACITY PER CUBE



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Today’s thin film.

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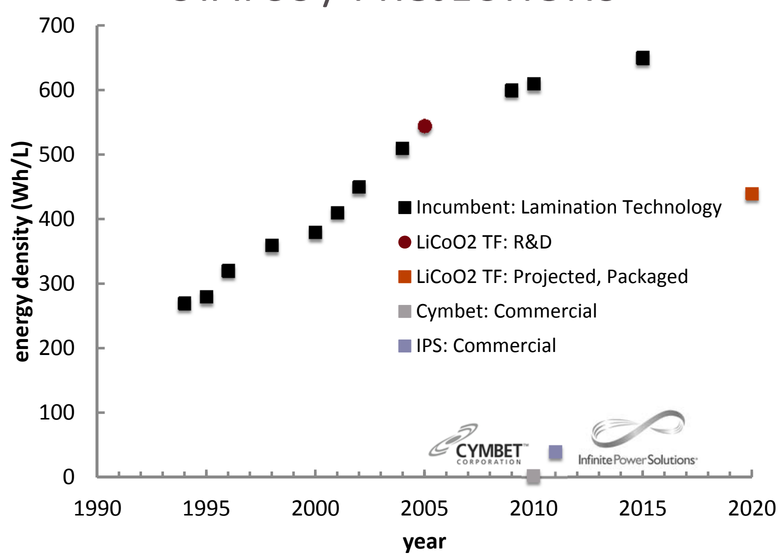
STATUS / PROJECTIONS



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Sakti3's approach: computationally-driven design.

INVESTORS

khosla ventures

III

BERINGEA

GM VENTURES

ITOCHU

SAKTI3 BUILT A NEW SUITE OF COMPUTATIONAL TOOLS

Function	R&D	COMMERCIAL	SAKTI
Multiphysics Modeling: Cell Performance	available	available	available
Cell Optimization: Materials Selection	partially available	not generally available	available
Battery Optimization: S-P Configurations, Charge Protocols	not generally available	partially available	available
Battery SOC Estimators: Use of Multiphysics	partially available	partially available	available
Battery Production Modeling: Plant Optimization	not generally available	not generally available	available
Financial Modeling: Manufacturing Model Incorporating Plant Design	not generally available	not generally available	available
Life Cycle Analysis Modeling for Battery Products: Solid State	not generally available	not generally available	available PARTNERED WITH UM

available — partially available — not generally available

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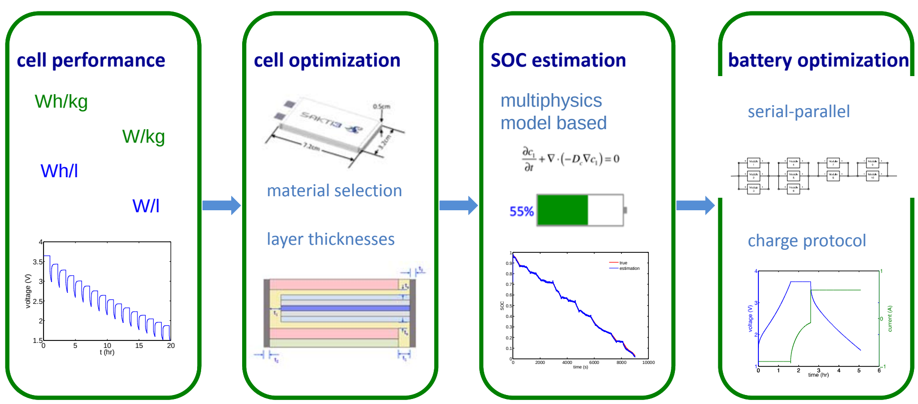
SAKTI DESIGN CODES



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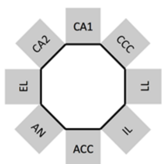
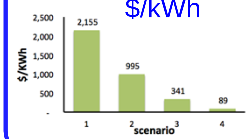
SAKTI DESIGN CODES

plant optimization



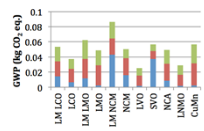
battery cost forecast

$/kWh

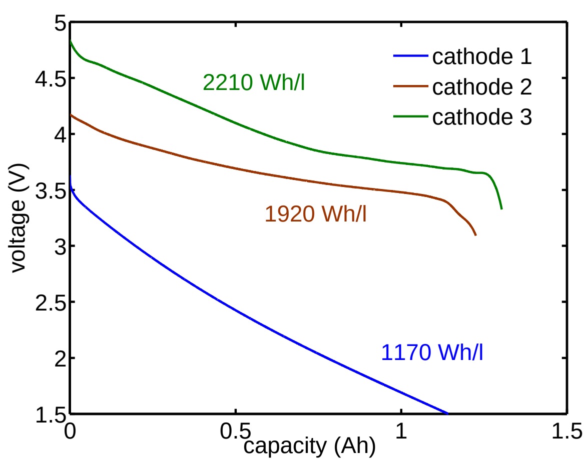


life cycle analysis

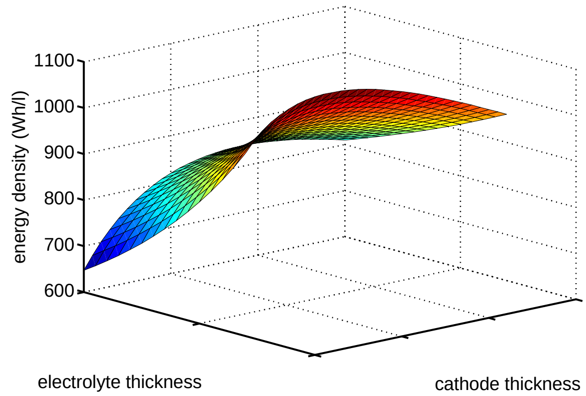
cumulative energy demand index
global warming potential index



SAKTI CELL-LEVEL PROJECTIONS: SOLID STATE

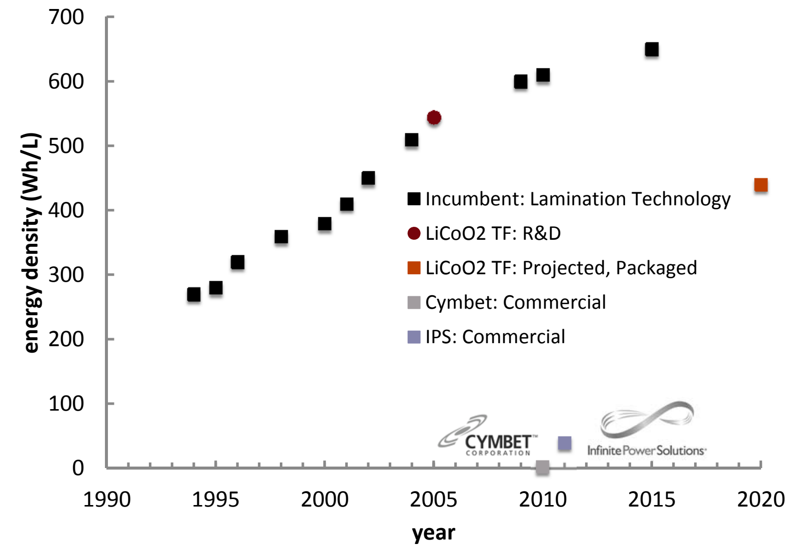


SAKTI CELL OPTIMIZATION



Capabilities.

STATUS / PROJECTIONS



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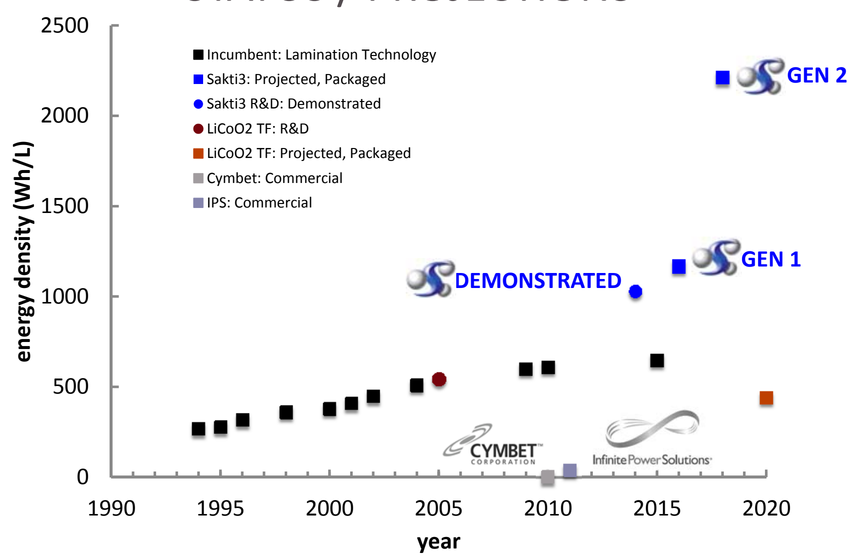
STATUS / PROJECTIONS



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PERFORMANCE

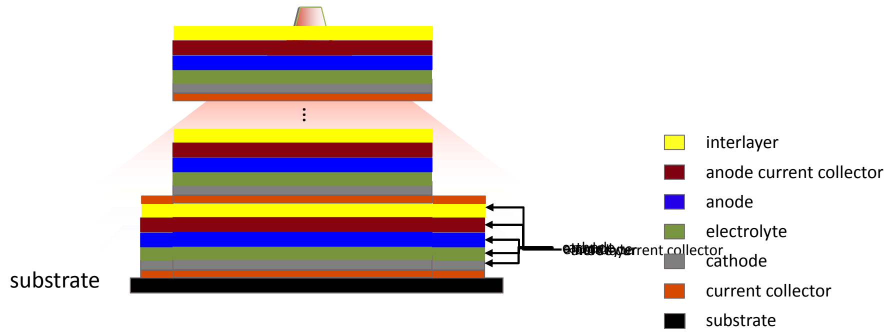
	CE commercial	AUTO commercial	GRID commercial	SAKTI3 CHAMPIONS
energy density (Wh/L)	570	310	250	1030
specific energy (Wh/Kg)	380	160	130	440
power density (W/L)	790***	2700*	4600**	1800***
gravimetric capacity (mAh/g)	60	41	39	180
cell capacity (typical) (Ah)	3.3	33	20	0.00012

* pulse power at 80% DOD
** unknown test protocol: assumed to be pulse
*** averaged power density of constant current discharge

To have real impact – we need to make them more cheaply.

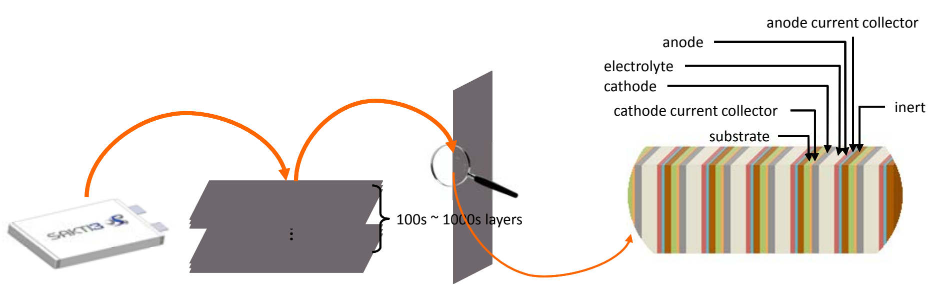
SAKTI PROCESS METHODOLOGY

- continuous, vacuum process
- cell are stacked to make higher capacity batteries



SAKTI DEVICE METHODOLOGY

- Thin electrodes (micron range) compared to conventional laminated battery cells (hundreds micron range)
- No additives are required to achieve high energy and high power



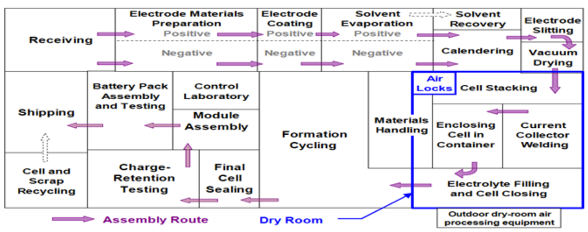
SAKTI3: MANUFACTURING ADVANTAGE

physical vapor deposition: all processes in one line

- 9 steps for sakti3 solid-state battery
- O DAYS in formation and aging – cells manufactured fully charged and ready to use
- Depreciation/KWh: $48/KWh/year [3]
- Battery Cost: $ 390/kWh [3]

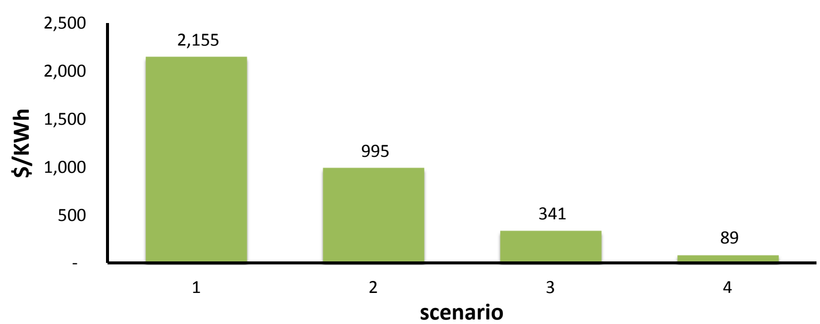
ALL LiB INCUMBENTS: LAMINATION

powder mixing → coating → pressing → stacking or winding → packaging



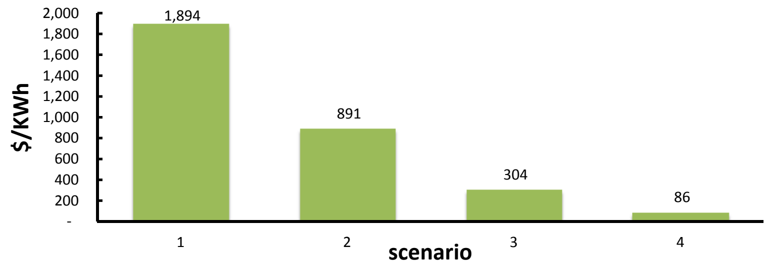
- 18+ steps for porous laminated electrode battery
- 60 DAYS in formation and aging ($$$ and WIP, and errors in formation destroy cells)
- Depreciation/KWh: $98/KWh/year [1]
- Battery Cost: $1080 /kWh[2]

COST REDUCTION ROADMAP: CONSUMER ELECTRONICS



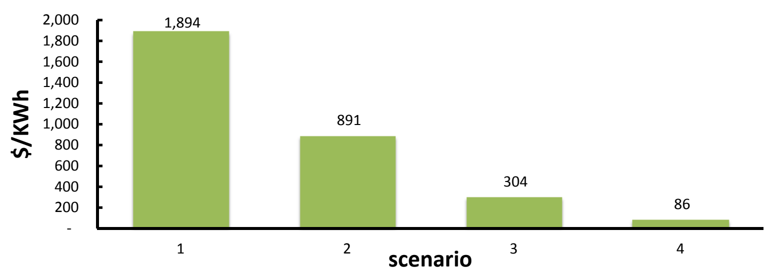
- CAPEX: capped at $20MM.
- Production volume, scenario 4: 9MM/y.
- Sakti COGS ~$0.90. Present pricing (iSuppli) at $5/per cell.

COST REDUCTION ROADMAP: AUTOMOTIVE



- CAPEX: capped at $60MM.
- Production volume, scenario 4: 2.8MM/y.
- Sakti COGS ~$8.

COST REDUCTION ROADMAP: GRID STORAGE

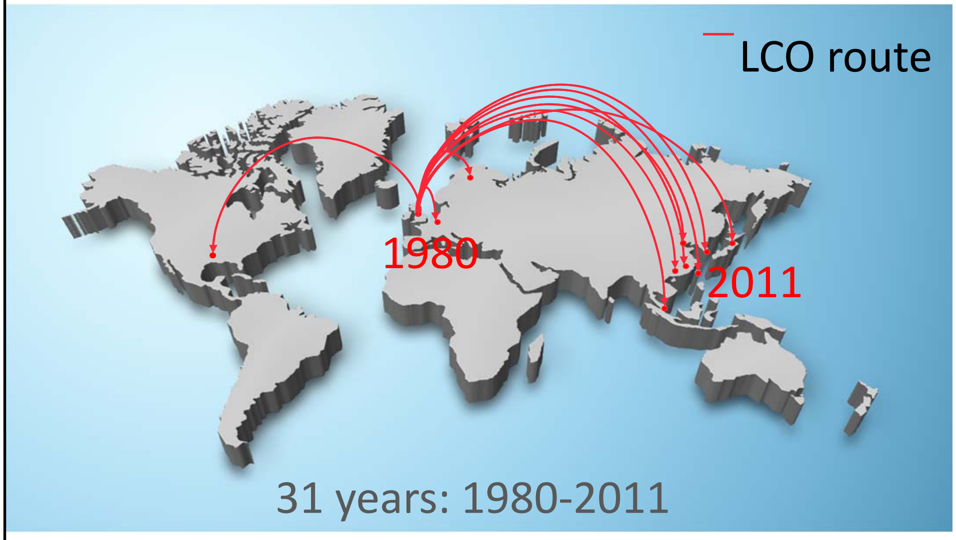


- CAPEX: capped at $60MM.
- Production volume, scenario 4: 2.8MM/y.
- Sakti COGS ~$8.

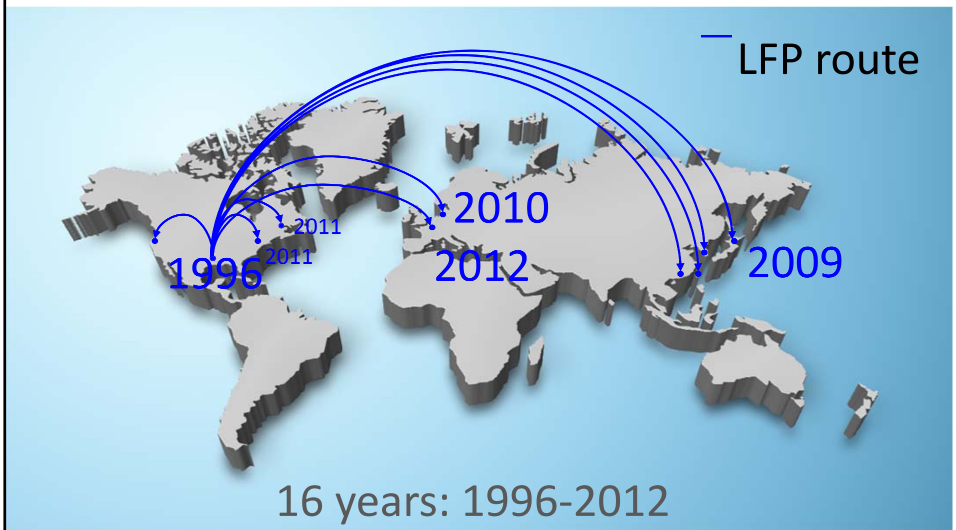
How fast can new technology scale in batteries?

Pretty fast if the manufacturing platform is similar.

TECHNOLOGY PATH

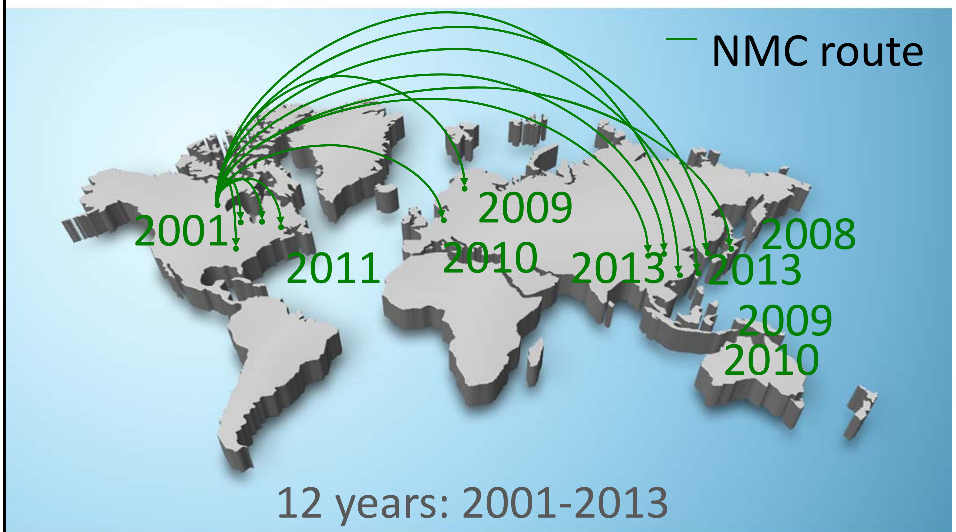


TECHNOLOGY PATH



TECHNOLOGY PATH

TECHNOLOGY PATH



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Integration.

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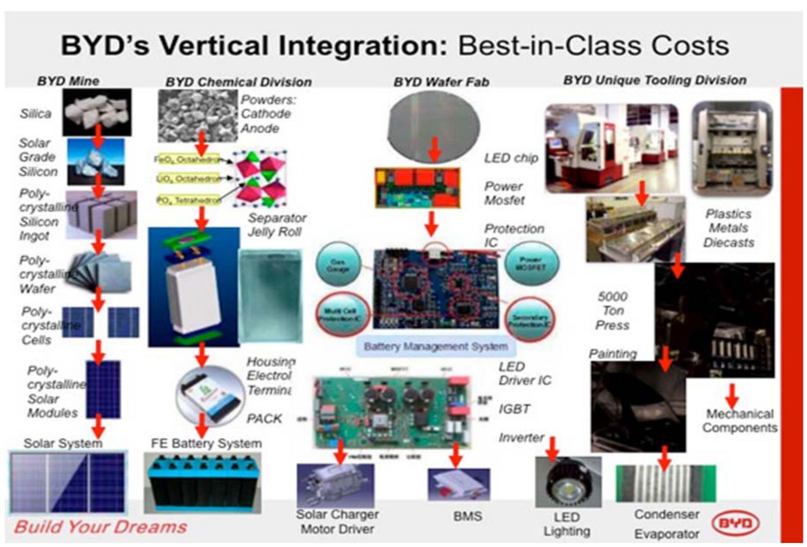
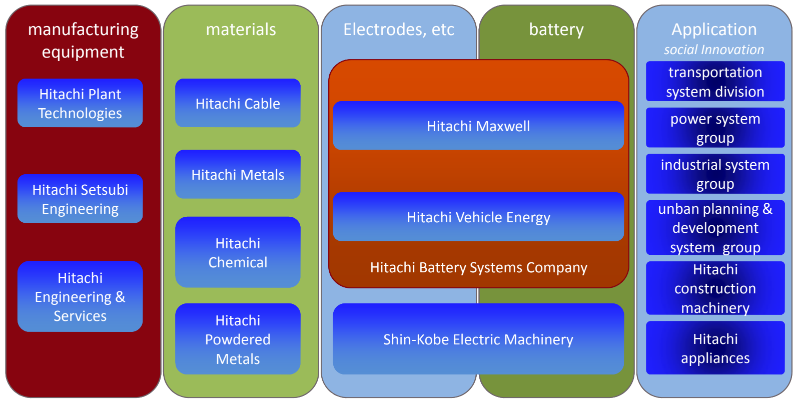
BATTERY INDUSTRY: VERTICALS AND HORIZONTALS

Applications	wearable device	smartphone	laptop	car
Pack				
Module				
Batteries				
Packaging Technology				
Electronic Technology				
Batteries Control				
Battery Manufacturing				
Materials				
Electrochemistry/Technology				
Mining				

BYD: VERTICAL



HITACHI: VERTICAL AND HORIZONTAL



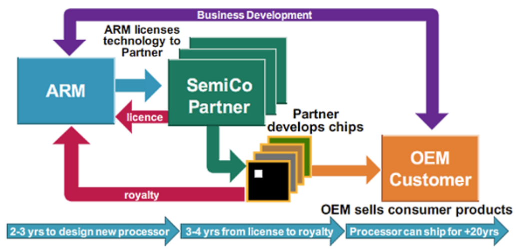
based on Hitachi's Chart presented at April 2009

adopted from https://www.semiconportal.com/en/archive/news/main-news/100618-hitachi-lithium-ion-battery-business.html

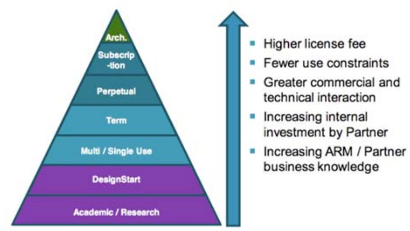
CHOICES – if foundries are available.

CHIPS: ARM

- ARM licenses its designs – $500,000 - $10 million per design.
- ARM has 20 to 30 key mobile licencees, and each chip they ship brings in a royalty.
- ARM relies on the spontaneous order of global markets rather than speculating on future demand.



ARM business model



ARM's license option

http://www.anandtech.com/show/7112/the-arm-diaries-part-1-how-arms-business-model-works

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MODELS

design	manufacture	sale
Intel	Intel	Intel
AMD Nvidia	TSMC Global Foundries	AMD NVIDIA
ARM	TSMC Global Foundries	Qualcomm MediaTek

http://www.anandtech.com/show/7112/the-arm-diaries-part-1-how-arms-business-model-works

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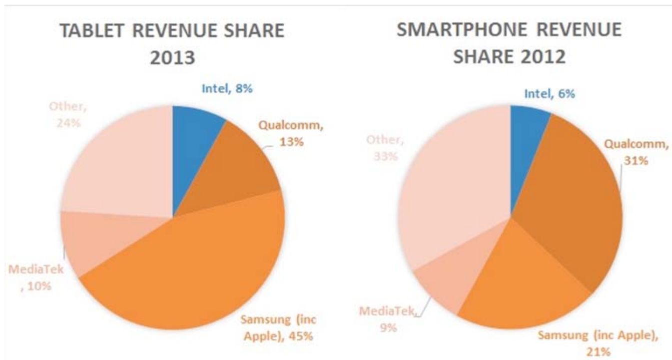
MARKETS

Qualcomm, Samsung, MediaTek, and Nvidia dominate – their CPU hardware is based on ARM's Cortex-A series of processors.



comparison of the share of revenue generated by Intel and ARM based manufacturers

http://blogs.marketwatch.com/thetell/2014/01/16/why-arm-has-the-upper-hand-over-intel-analysts/
http://www.androidauthority.com/intel-vs-arm-future-mobile-technology-338340/

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SOLID STATE BATTERY PRODUCTION

- Fast scaling is possible: thin film manufacturing base established across several industries.

FOR THE FIRST TIME – FOUNDRIES EXIST.

- Mass customization is possible: use of low cost substrates enables multiple SKUs on each line.
- Optimization of manufacturing will yield improvements for years to come: low BOM / COGS and improved simulation tools in manufacturing.

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Challenges

Today: consumer electronics (primarily)

- 6800 million mobile cellular subscriptions + 460 million laptop computers
- 90 TWh/year in energy use

U.S. Vehicle Fleet

- 254 million vehicles
- 7600 TWh/year in energy use

World Vehicle Fleet

- 800 million vehicles
- 29300 TWh/year in energy use

SAKTI3 Tenets

Continuously develop new technologies that will become products that improve people's lives.

Select worthy technology problems that merit the efforts of outstanding workers.

Create profitable products that offer world-leading capabilities.

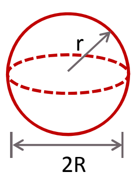
Respect and value our team and our investors, using transparent, logical rules and processes.

Exhibit interpersonal excellence in interactions within and outside the Company.

THANKS!

DIFFUSION EQUATIONS AND BOUNDARY CONDITIONS

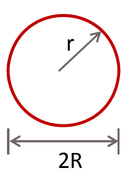
3D



$$\frac{\partial c}{\partial t} = \frac{D}{r^2}\frac{\partial}{\partial r}\left(r^2 \frac{\partial c}{\partial r}\right)$$

$$\left.\frac{\partial c}{\partial r}\right|_{r=0} = 0, \quad \left.\frac{\partial c}{\partial r}\right|_{r=R} = -\frac{j_{Li}}{FD}$$

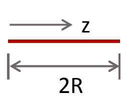
2D



$$\frac{\partial c}{\partial t} = \frac{D}{r}\frac{\partial}{\partial r}\left(r \frac{\partial c}{\partial r}\right)$$

$$\left.\frac{\partial c}{\partial r}\right|_{r=0} = 0, \quad \left.\frac{\partial c}{\partial r}\right|_{r=R} = -\frac{j_{Li}}{FD}$$

1D

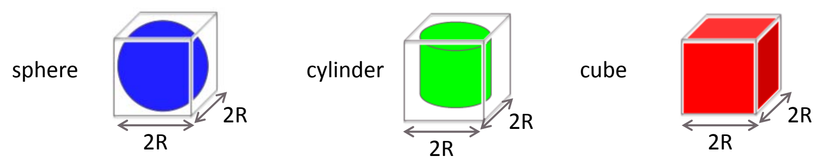


$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial z^2}$$

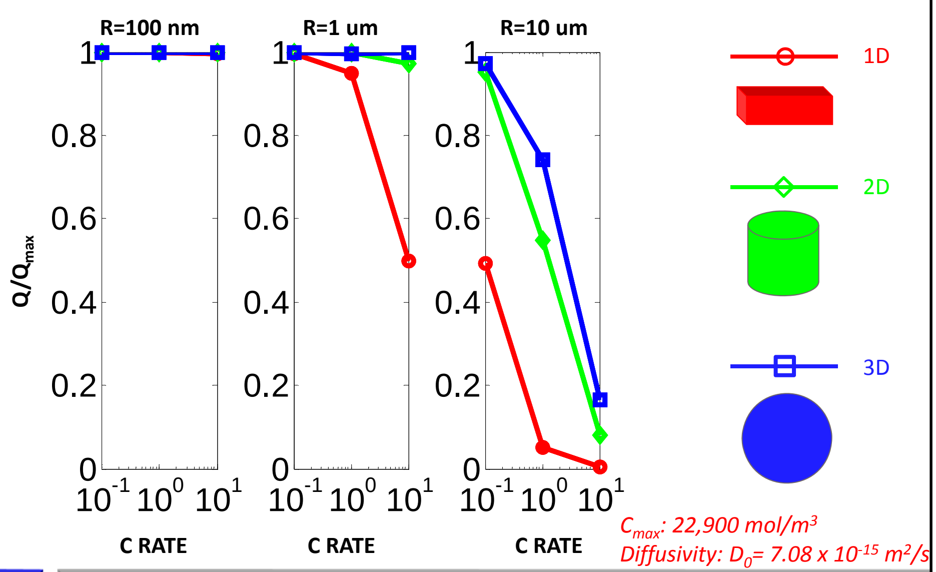
$$\left.\frac{\partial c}{\partial z}\right|_{z=0} = 0, \quad \left.\frac{\partial c}{\partial z}\right|_{z=R} = -\frac{j_{Li}}{FD}$$

VOLUMETRIC CAPACITY

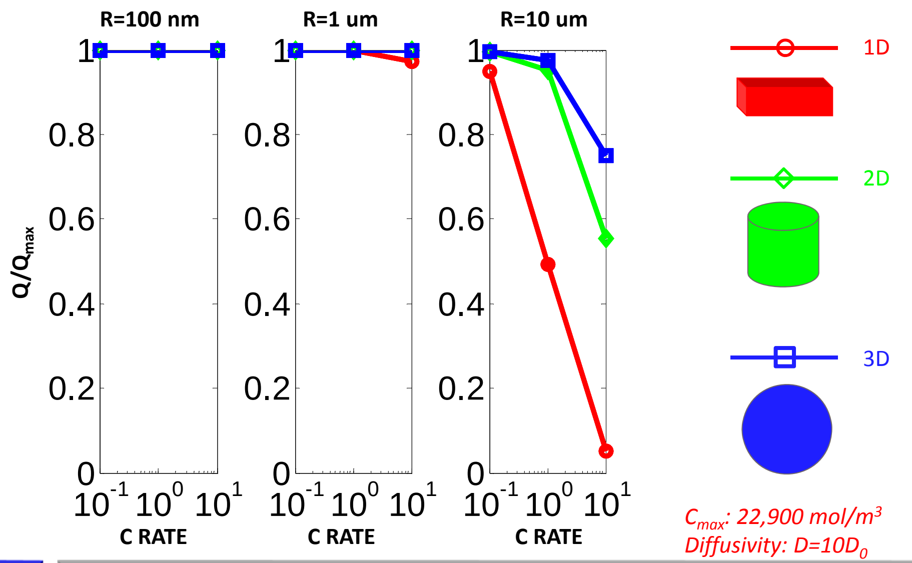
	variables	note
Particle Size (R)	0.1, 1, 10 (µm)	see below
C rate	0.1, 1, 10	based on maximum concentration
Diffusivity	D_{LMO} $10\times D_{LMO}$	• Baseline value, D_{LMO}: 7.08×10^{-15} (m^2/s) • Diffusivity varies depending on SOC • D_{NMC}: 10^{-14} ~ 10^{-16} (m^2/s)
C_{max}	22,900 mol/m^3	• LMO material (density: 4,140 m^3/kg)



DIFFUSION-LIMITED CAPACITY



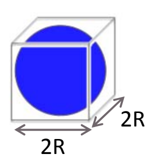
DIFFUSION-LIMITED CAPACITY



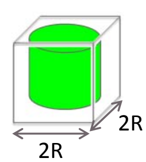
C_{max}: 22,900 mol/m^3
Diffusivity: $D=10D_0$

PACKING FRACTIONS

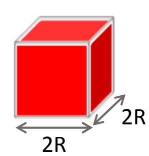
sphere



cylinder



cube



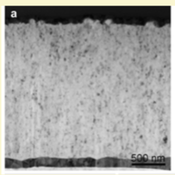
$$\frac{\frac{4}{3}\pi R^3}{8R^3} = \frac{\pi}{6} \approx 0.523$$

$$\frac{2\pi R^3}{8R^3} = \frac{\pi}{4} \approx 0.785$$

$$\frac{8R^3}{8R^3} = 1$$

STATUS

ORNL



TEM image of $LiMn_{1.5}Ni_{0.5}O_4$ cathode film

electrochemistries:

- anode: Li
- electrolyte: LiPON
- cathodes: V_2O_5, $LiMnO_4$, $LiCoO_2$, $LiMn_{1.5}Ni_{0.5}O_4$

published since: 1991

entity: R&D

Cymbet

CYMBET CBC3105 solid state battery

electrochemistries:

- anode: Li
- electrolyte: LiPON
- cathode: $LiCoO_2$

founded: 2000

entity: commercial

price (calculated): $\$3x10^8$/KWh

Front Edge Technology

Front Edge Technology demo cell

electrochemistries:

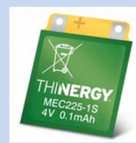
- anode: Li
- electrolyte: LiPON
- cathode: $LiCoO_2$

found: 1994

entity: commercial

price: not in production

Infinite Power Solutions



Infinite Power Solutions solid state battery

electrochemistries:

- anode: Li
- electrolyte: LiPON
- cathode: $LiCoO_2$

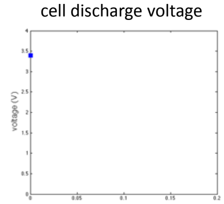
founded: 2001

entity: commercial

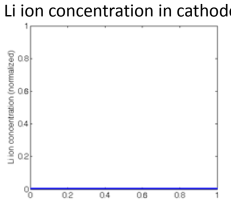
price (calculated): $\$1.1x10^8$/KWh

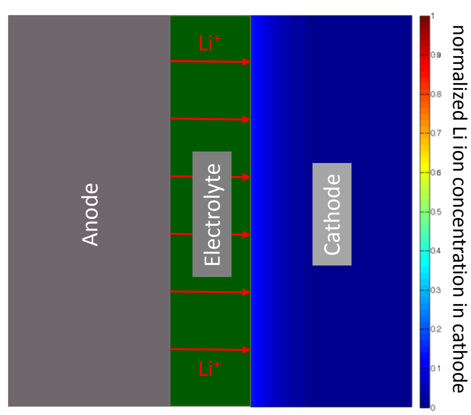
CELL DISCHARGE: THICK CATHODE, HIGH RATE

cell discharge voltage



Li ion concentration in cathode

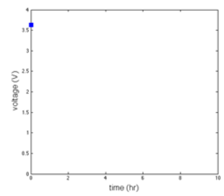




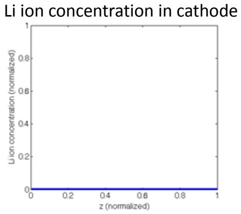
During higher rate discharge, cathode is less utilized.

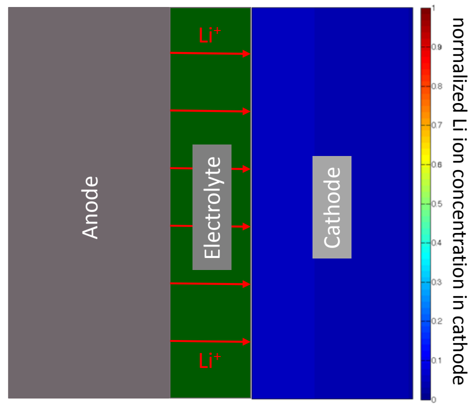
CELL DISCHARGE: THICK CATHODE, LOW RATE

cell discharge voltage



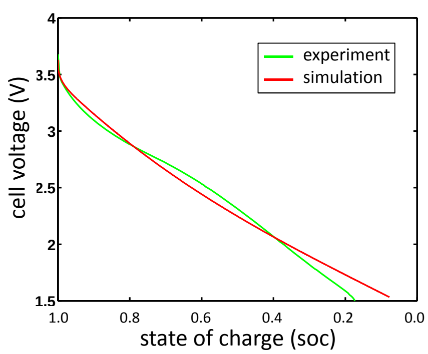
Li ion concentration in cathode

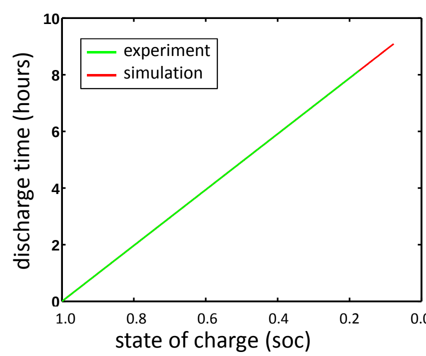




During lower rate discharge, cathode is more utilized.

Room temperature @ C/10—champion cell





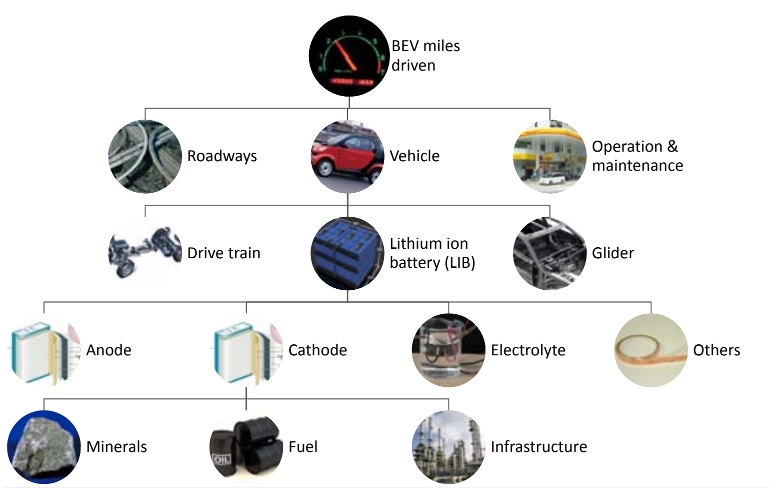
- Cell cycling at C/10 rate (**C is the theoretical value, not the nominal value**) at room temperature
- Discharge cutoff: 1.5V
- Maximum discharge energy: 1028 Wh/L
- Simulated energy density: 1107 Wh/L

Replacing all the batteries on the planet with improved versions – that's a lot of batteries.

LCA is important.

LIFE CYCLE ANALYSIS: BEV MOBILITY

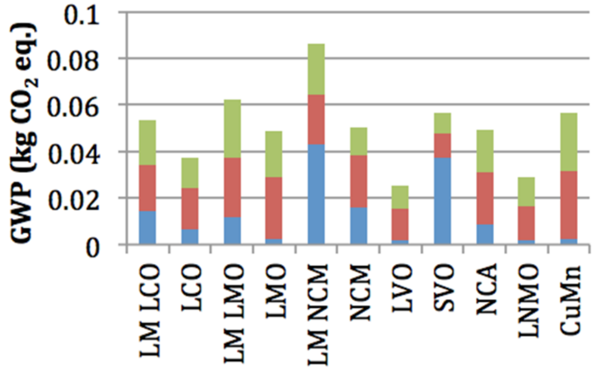
Prof. Christian Lastoskie, University of Michigan



LIFE CYCLE ANALYSIS

Prof. Christian Lastoskie, University of Michigan

cumulative energy demand index global warming potential index – SOLID STATE VERSIONS VERSUS LAMINATED VERSIONS



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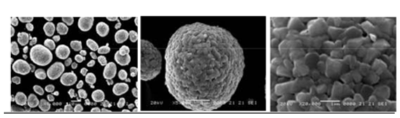
COST REDUCTION: CATHODE EXAMPLE

conventional laminated cells

- cobalt and nickel are expensive metals
- cost associated with processing could be high
  - materials made from precursors need to be annealed and crystallized
  - all active materials need to be milled to particles of desirable sizes
  - LiFePO4 requires carbon coating



solid state cells

- Avoid expensive metals
- cost associated with processing is low
  - PVD targets / source materials are cheaper
  - no milling or coating needed
  - low temperature processing

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