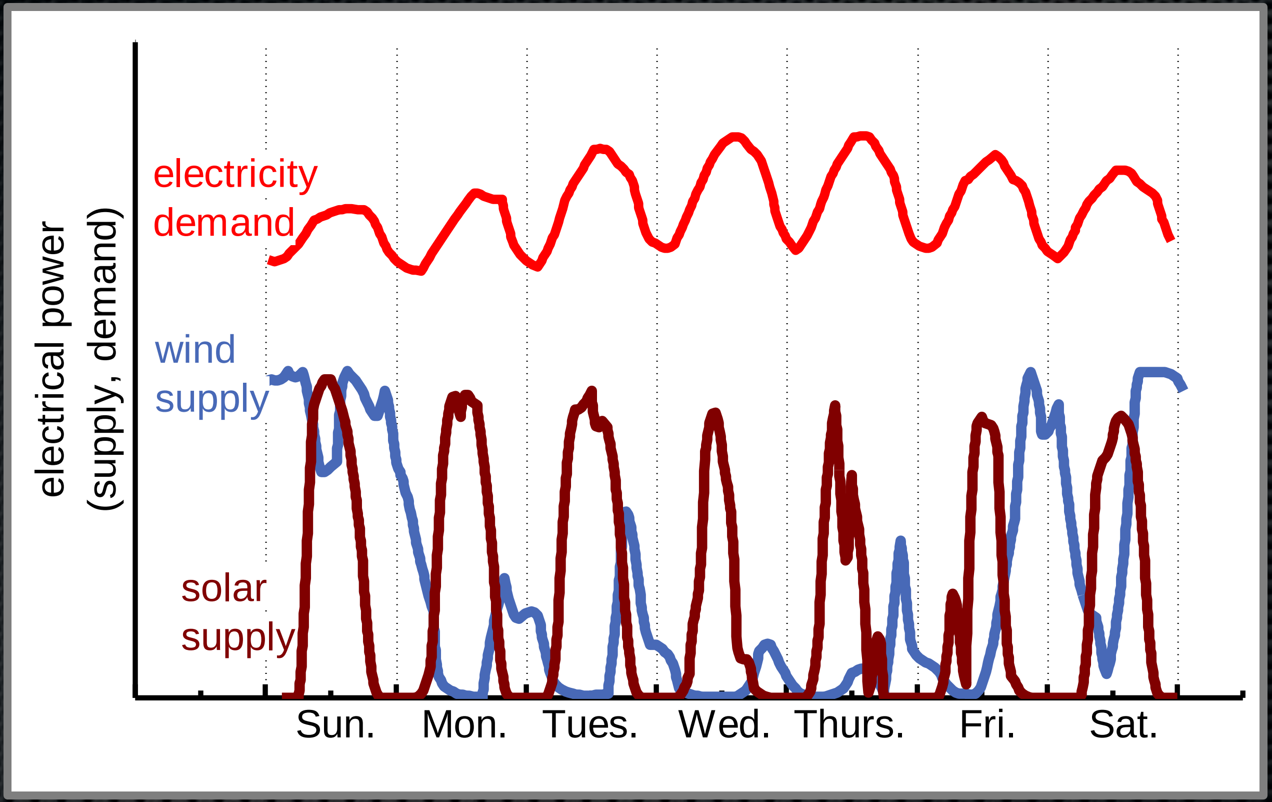
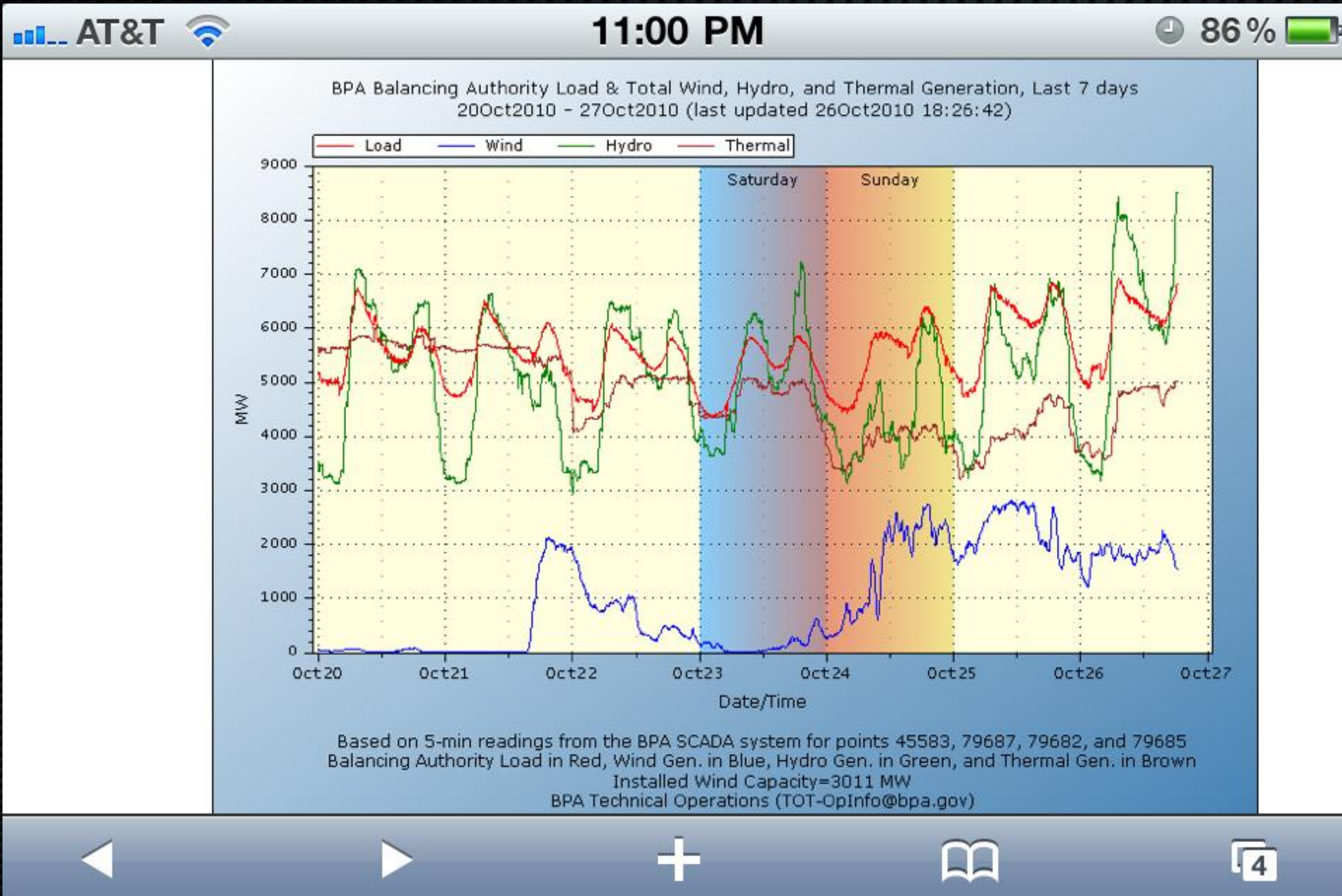
An Electrometallurgical Approach to Cheap, Grid-Scale Energy Storage Systems

Luis A. Ortiz

motivation



storage is a key enabler for
wind and solar renewable energy sources


AT&T
11:00 PM
86%
BPA Balancing Authority Load & Total Wind, Hydro, and Thermal Generation, Last 7 days
20Oct2010 - 27Oct2010 (last updated 26Oct2010 18:26:42)
Load
Wind
Hydro
Thermal
Saturday
Sunday
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
MW
Oct20
Oct21
Oct22
Oct23
Oct24
Oct25
Oct26
Oct27
Date/Time
Based on 5-min readings from the BPA SCADA system for points 45583, 79687, 79682, and 79685
Balancing Authority Load in Red, Wind Gen. in Blue, Hydro Gen. in Green, and Thermal Gen. in Brown
Installed Wind Capacity=3011 MW
BPA Technical Operations (TOT-OpInfo@bpa.gov)
4

cost as a driver of innovation

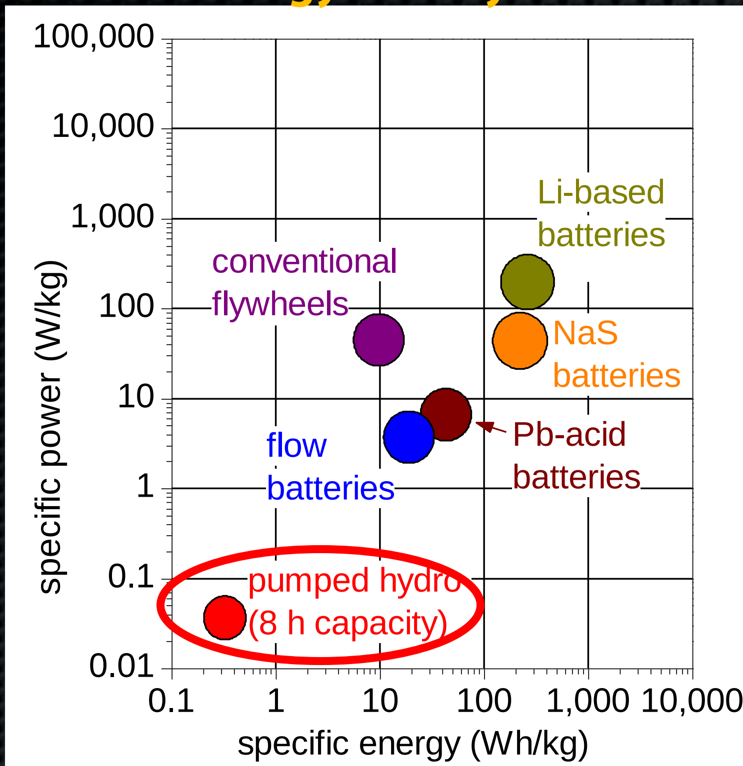
- grid-scale applications very attractive

- installed capital cost is a premium
  - ☞ best technical alternative is fossil fuel generation

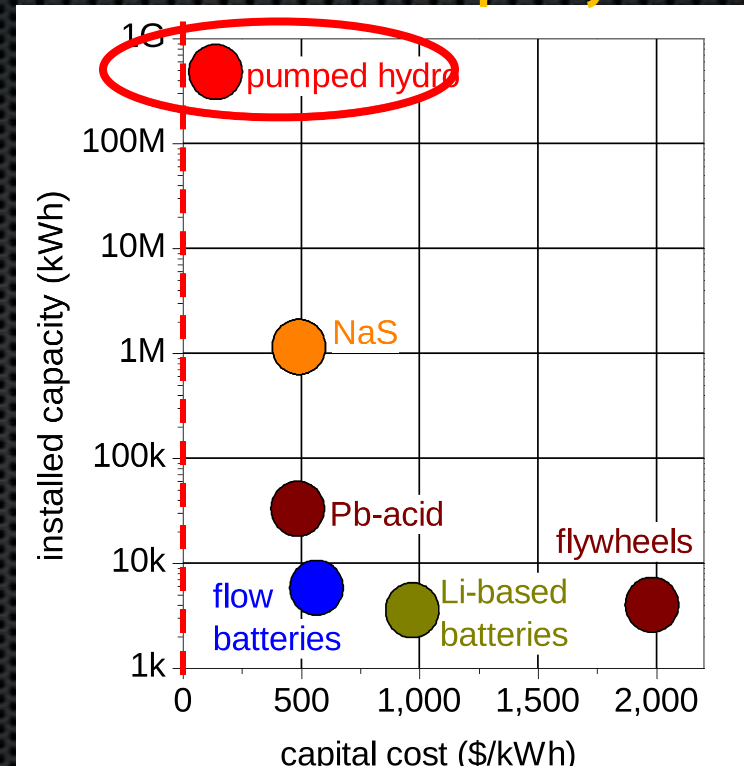
- different requirements than portable energy storage

key requirements

energy density



installed capacity



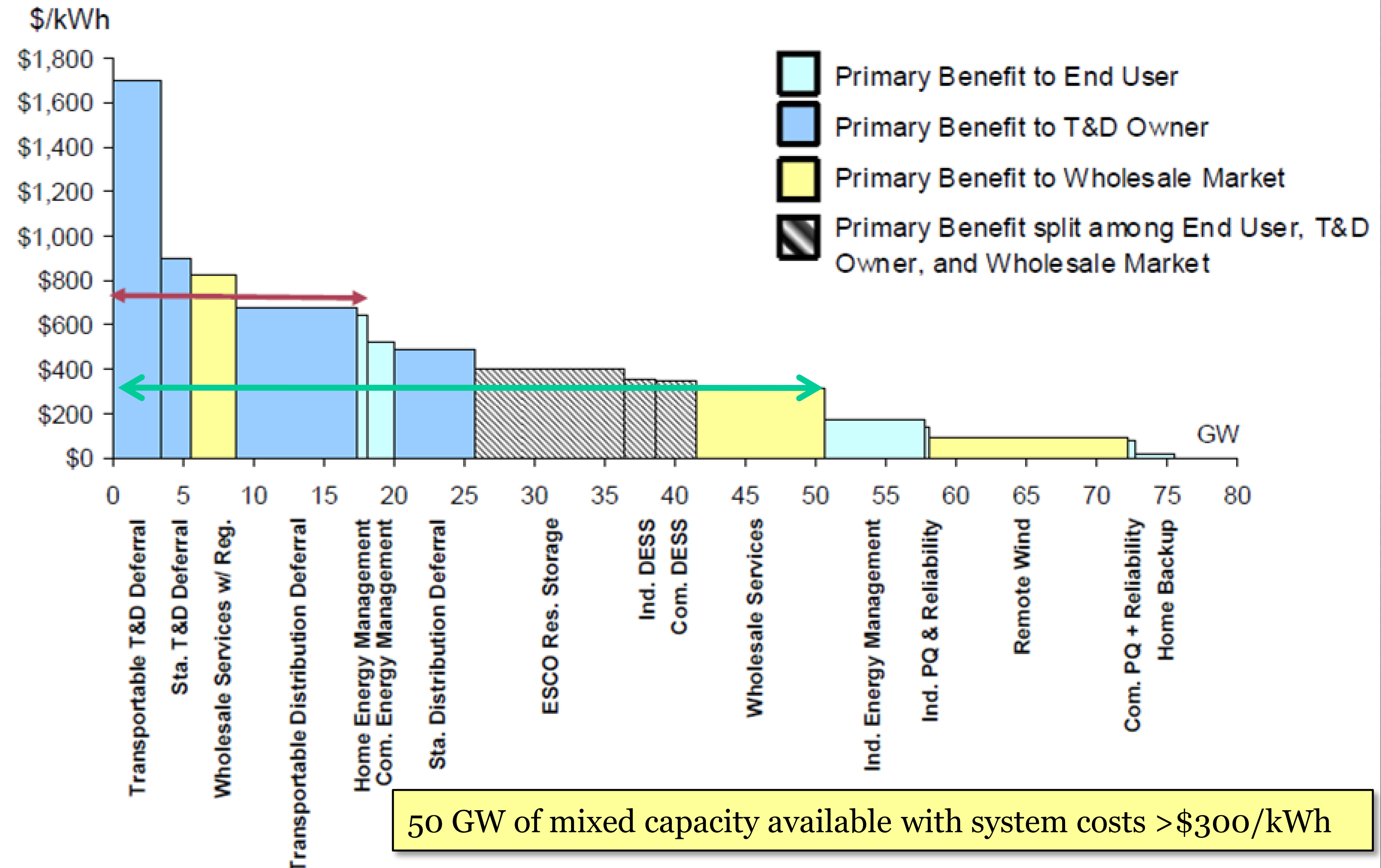
conventional metrics:

1. power density
2. energy density

metrics for grid-scale storage:

1. **cost** (< $150/kWh)
2. **lifespan** (> 10 years)
3. **energy efficiency** (> 80 %)

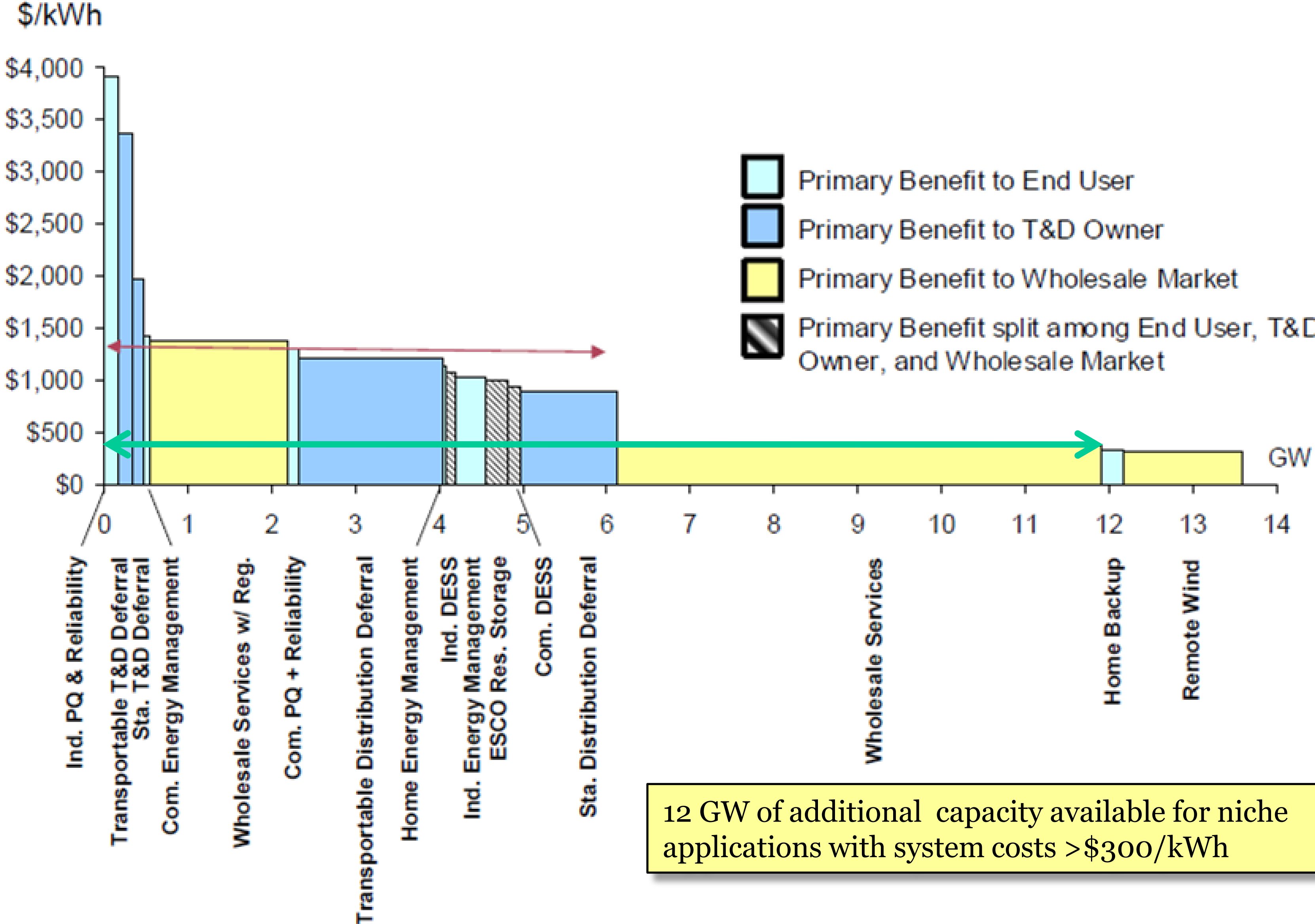
grid-level markets



50 GW of mixed capacity available with system costs >$300/kWh

ELECTRIC POWER RESEARCH INSTITUTE

niche markets



12 GW of additional capacity available for niche applications with system costs >$300/kWh

EPRI ELECTRIC POWER RESEARCH INSTITUTE

thought experiment

auto @ 45 mph
electric motor ~ 10A

C/2 for PHEV
C/12 for EV

auto accelerates to 70mph
electric motor ~ 100A

4C for PHEV
0.8C for EV

auto @ 70mph climbs hill
electric motor ~ 300A

12C for PHEV
2.5C for EV

PHEV	BEV
40 mile range 1.6 kWh → 8 mi	200 mile range 5x energy
8kWh battery 25 Ah @ 300V	40kWh battery 125Ah @ 300V

high rate discharge critical for PHEV

not as critical for EV

thought experiment

auto @ 45 mph
electric motor ~ 10A

C/2 for PHEV
C/12 for EV

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PHEV	BEV
40 mile range 1.6 kWh → 8 mi	200 mile range 5x energy
8kWh battery 25 Ah @ 300V	40kWh battery 125Ah @ 300V

high rate discharge
critical for ~~PHEV~~
regulation
not as critical for ~~EV~~
bulk

liquid metal battery

Donald R. Sadoway

David J. Bradwell

a modern aluminium smelter

1886

Charles Martin Hall, USA
Paul L.T. Héroult, France

$15\ \text{m} \times 3\ \text{m} \times 1\ \text{km} \times 0.8\ \text{A·cm}^{-2}$

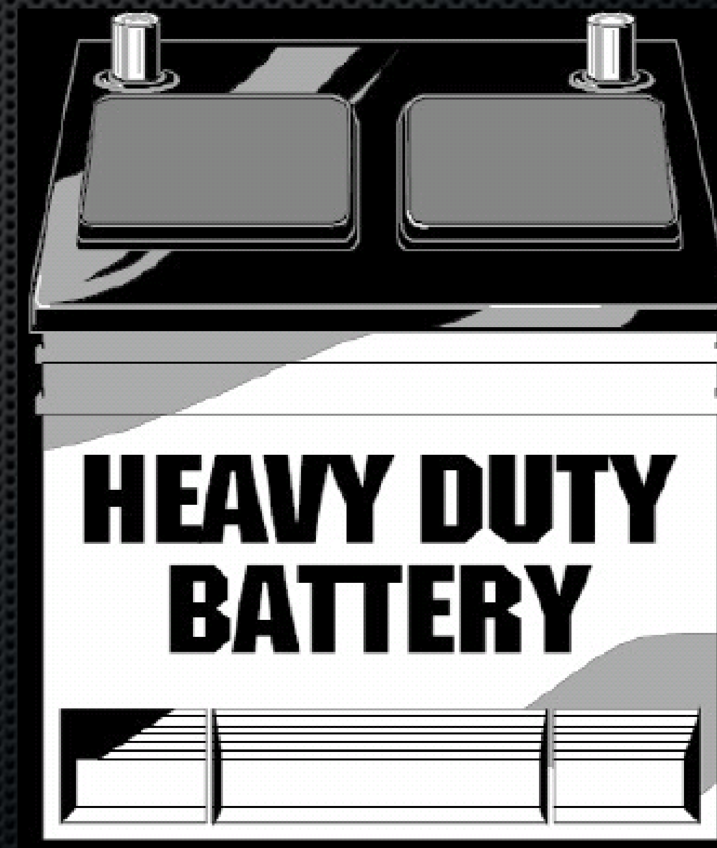
key to finding the answer: pose the right question

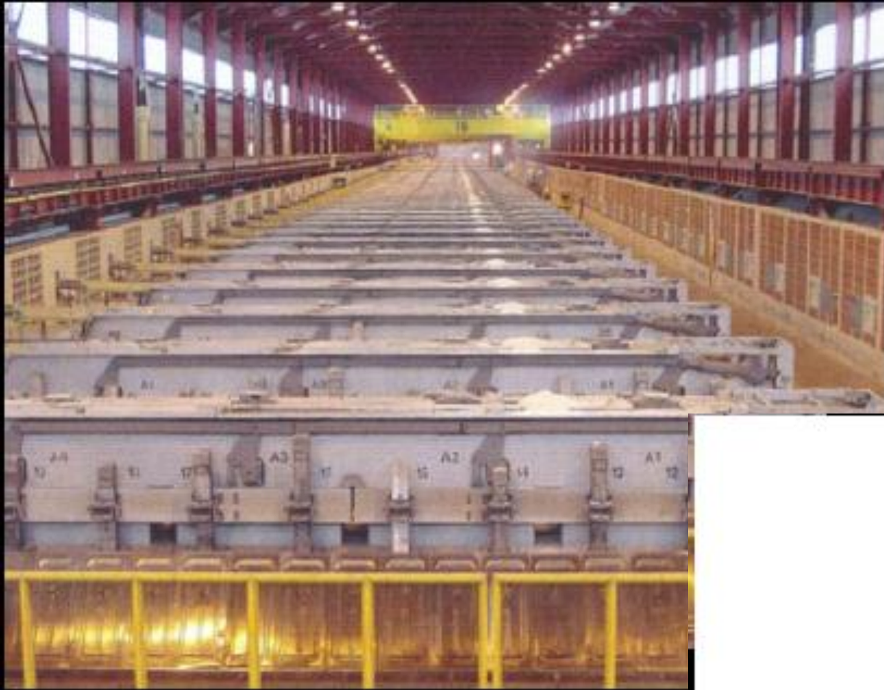
different approach: find a giant current sink

convert this...

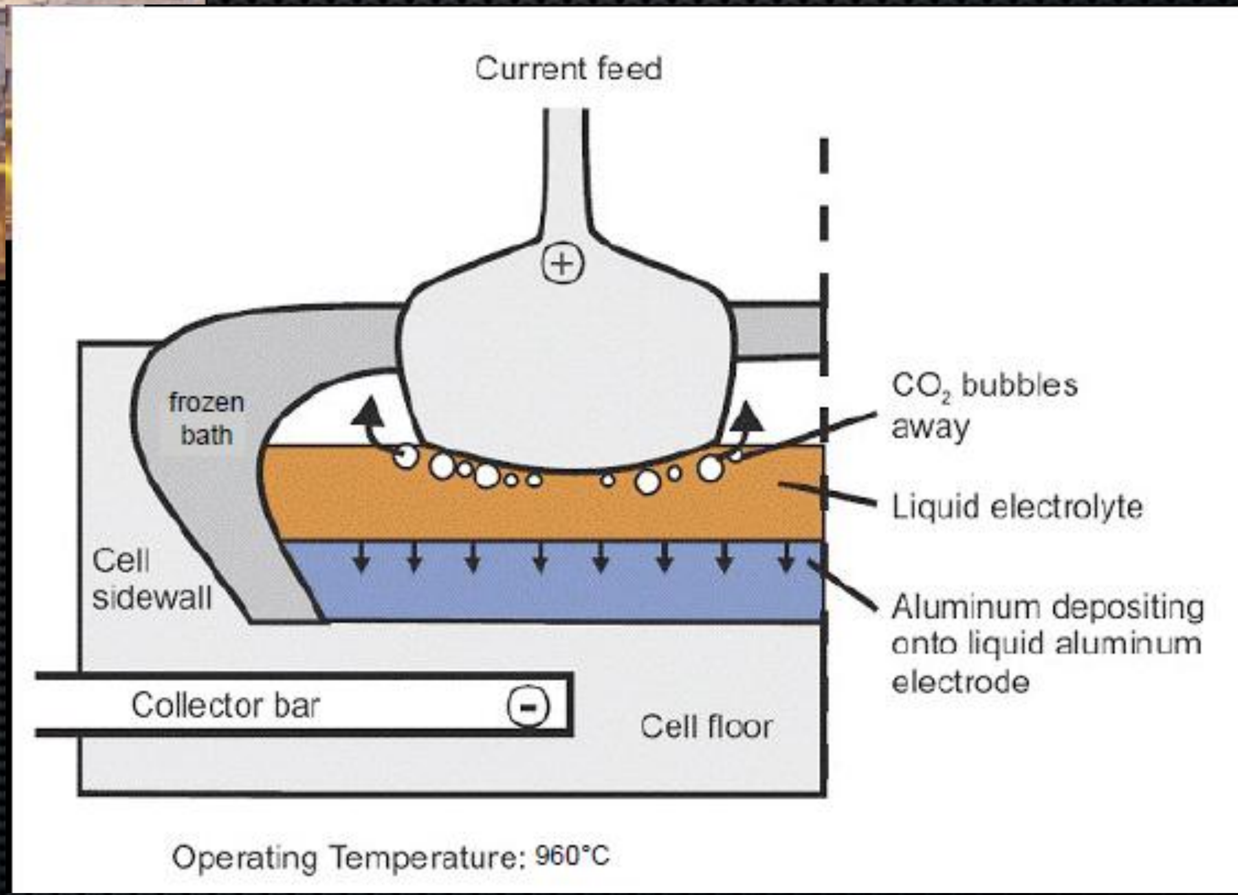
aluminum potline
350,000A ; 4V
multiple MW per cell

... into this



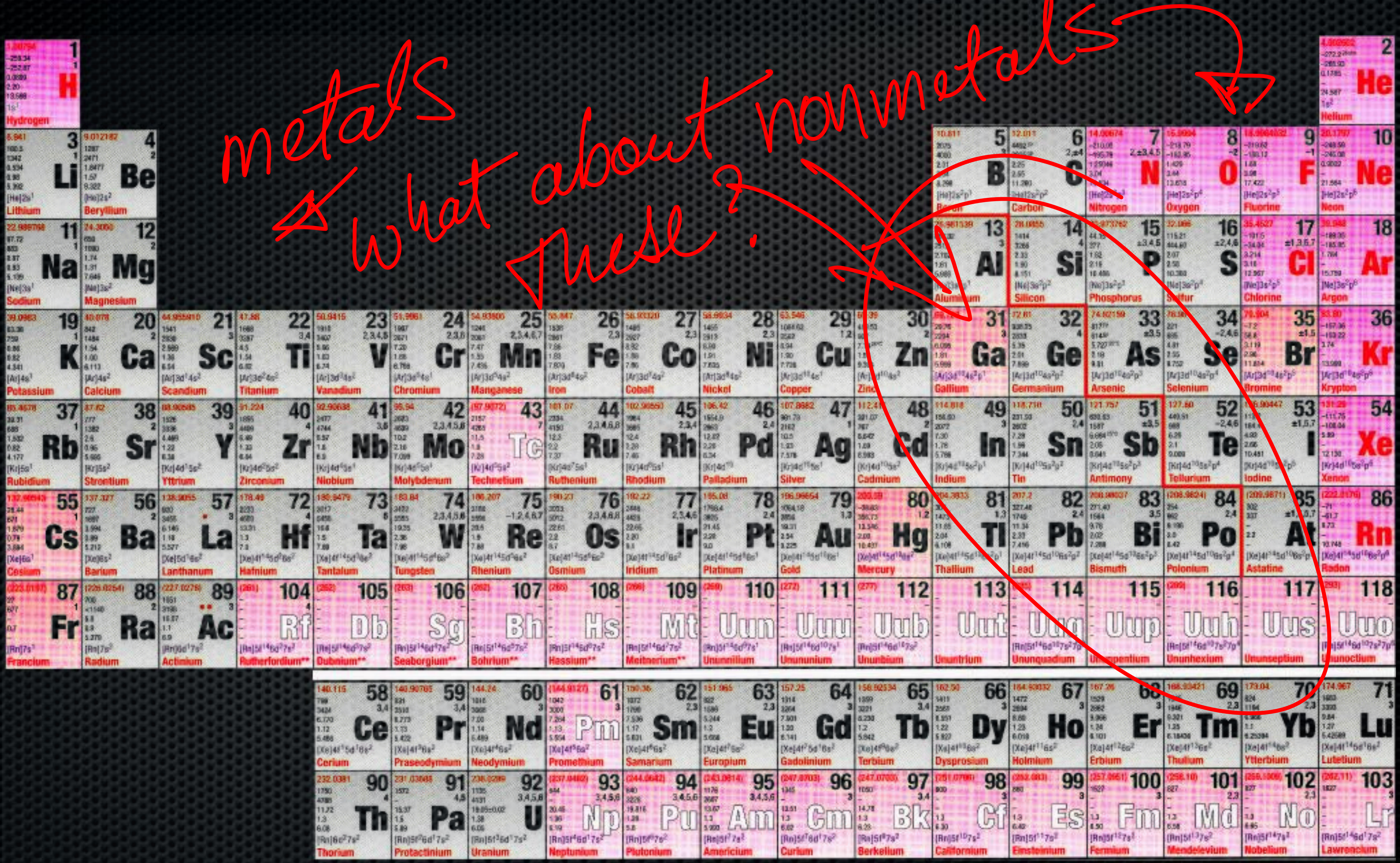


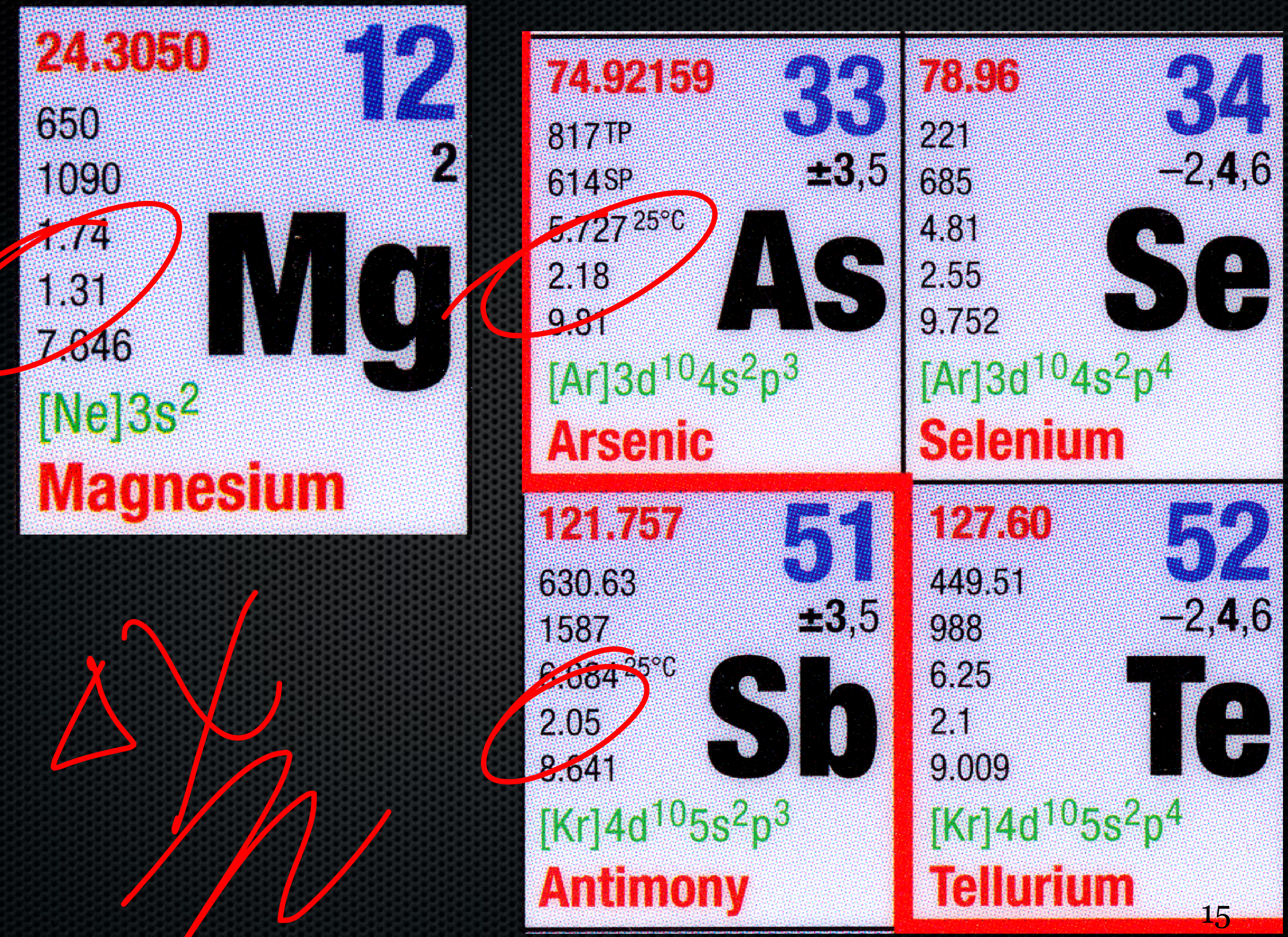
why is an aluminum cell not a battery?



☞ **produce liquid metals at BOTH electrodes**

The Periodic Table of the Elements



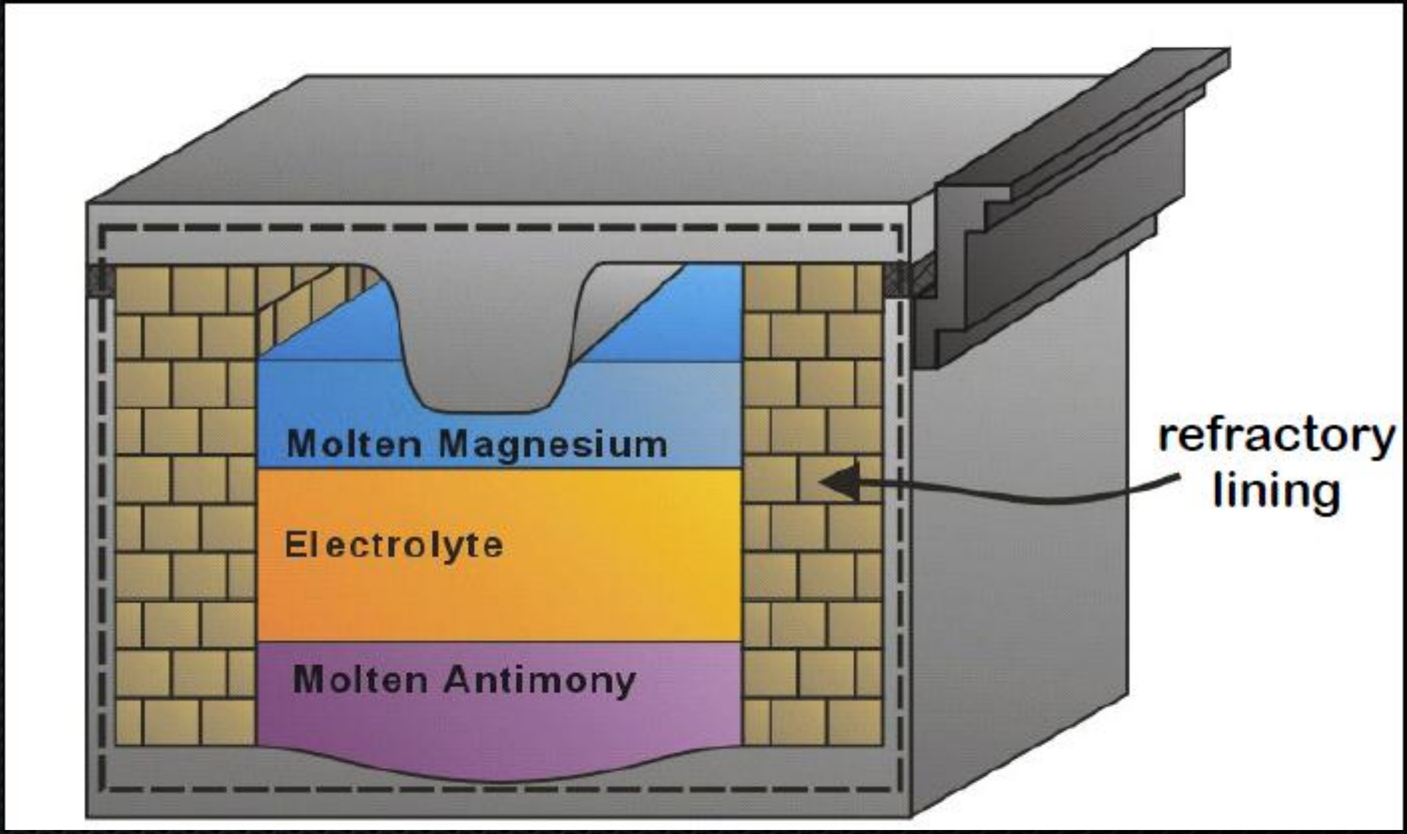

24.3050
12
650
1090
1.74
1.31
7.646
2
Mg
[Ne]3s2
Magnesium
74.92159
33
817 TP
614 SP
5.727 25°C
2.18
9.81
±3,5
As
[Ar]3d104s2p3
Arsenic
78.96
34
221
685
4.81
2.55
9.752
−2,4,6
Se
[Ar]3d104s2p4
Selenium
121.757
51
630.63
1587
6.684 25°C
2.05
8.641
±3,5
Sb
[Kr]4d105s2p3
Antimony
127.60
52
449.51
988
6.25
2.1
9.009
−2,4,6
Te
[Kr]4d105s2p4
Tellurium

ambipolar electrolysis

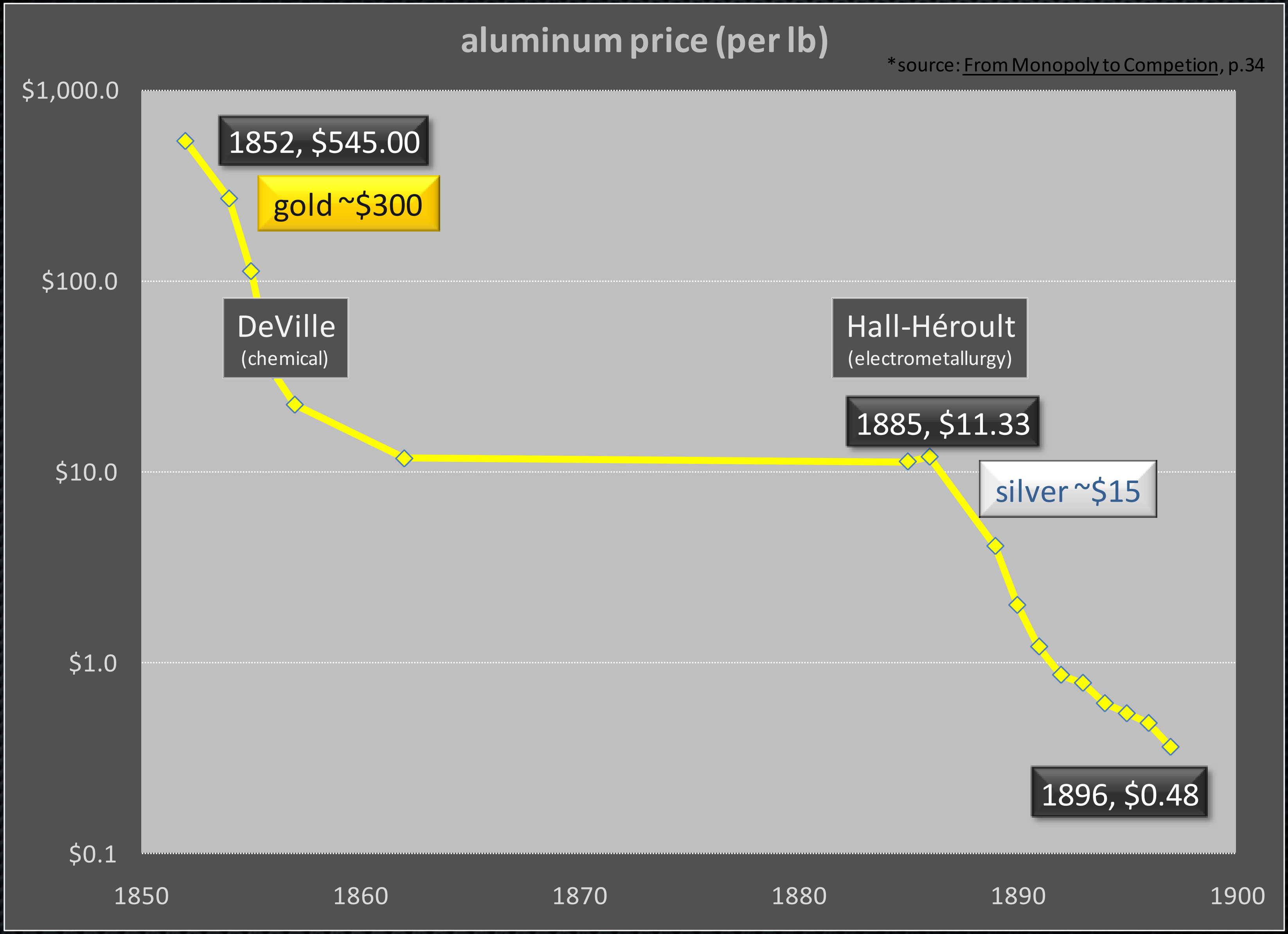
on discharge

$$Mg_{(liquid)} \rightarrow Mg^{2+} + 2e^-$$

$$Sb_{(liquid)} + 3e^- \rightarrow Sb^{3-}$$



economies of scale in electrometallurgy

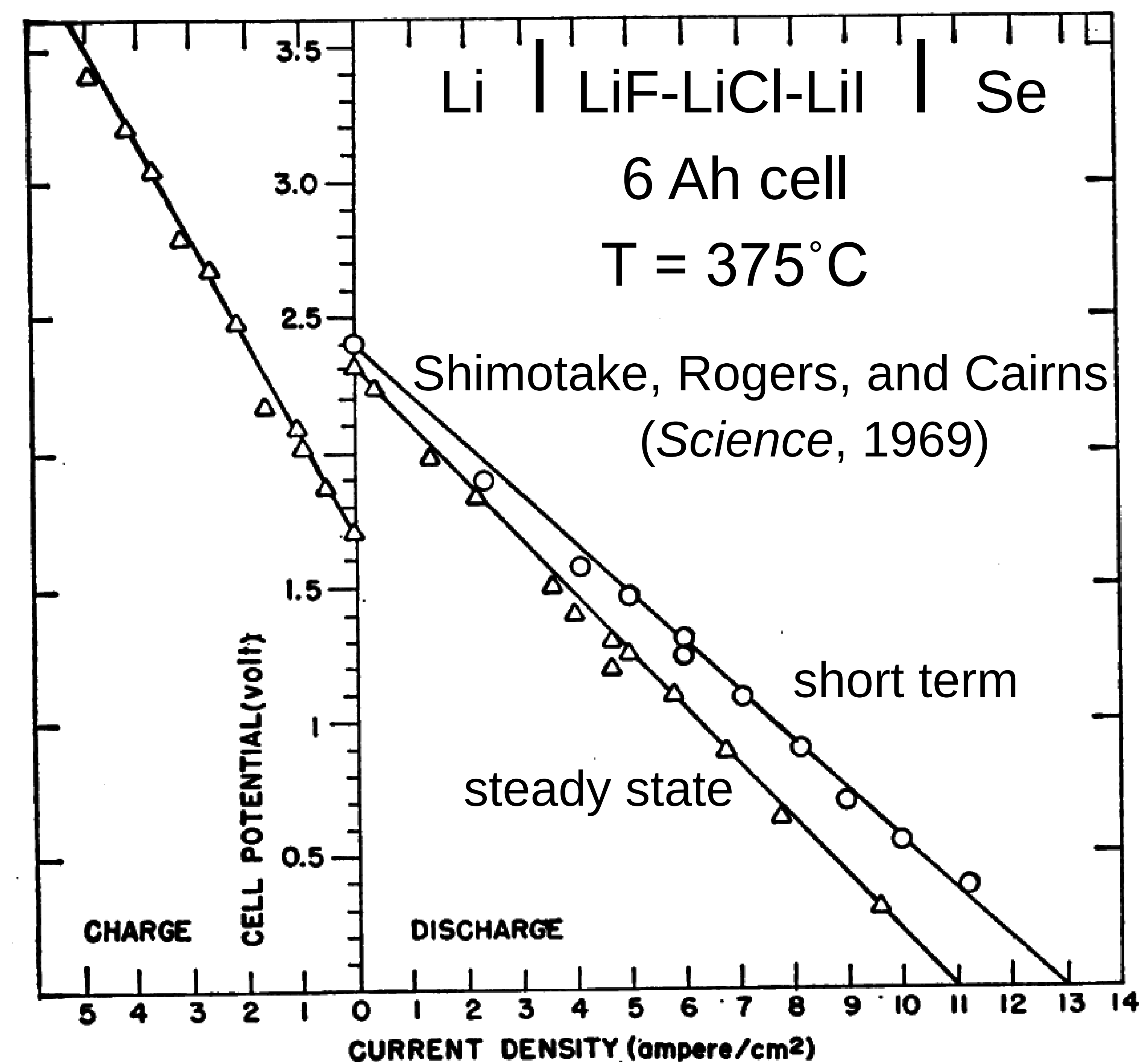


attributes of a liquid state battery

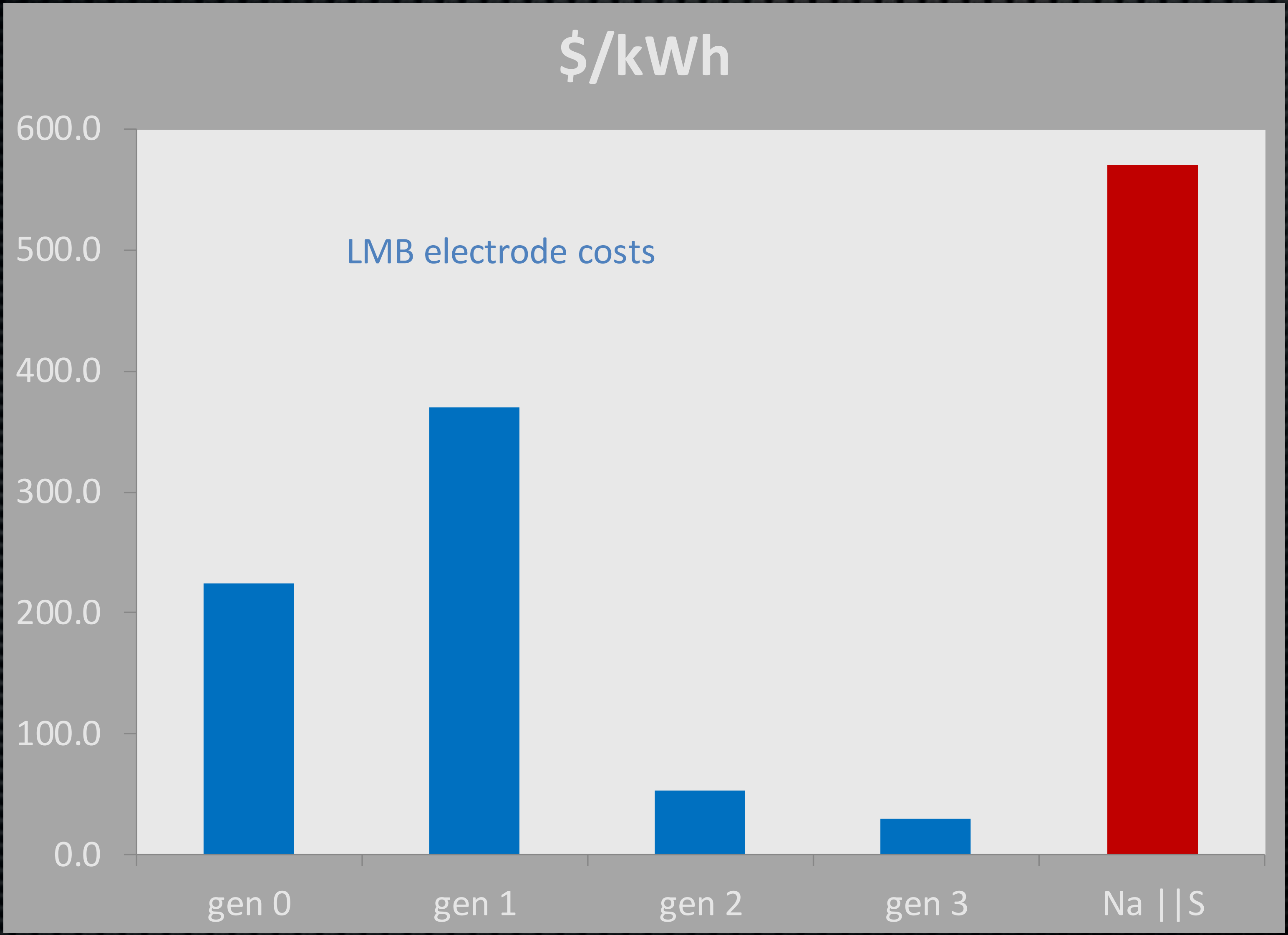
- liquid-liquid interfaces are kinetically the fastest in all of electrochemistry
  - ☞ low activation overvoltage

- all-liquid construction eliminates any reliance on solid-state diffusion
  - ☞ long service life

- all-liquid configuration is self-assembling
  - ☞ scalable at low cost

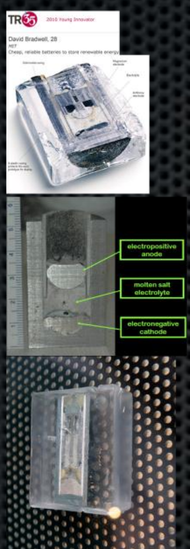

Li | LiF-LiCl-LiI | Se
6 Ah cell
T = 375˚C
Shimotake, Rogers, and Cairns
(*Science*, 1969)
short term
steady state
CHARGE
DISCHARGE
CELL POTENTIAL (volt)
CURRENT DENSITY (ampere/cm2)
3.5
3.0
2.5
1.5
1
0.5
5
4
3
2
1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14

ARPA-e project

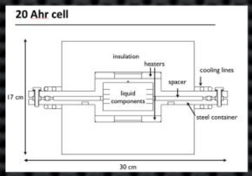


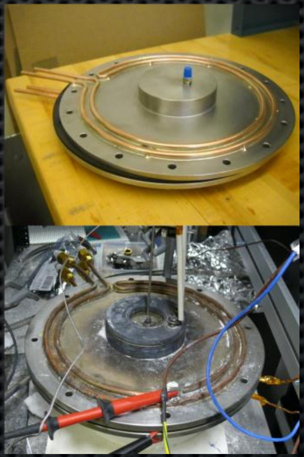
ARPA-e development plan

1 Ah

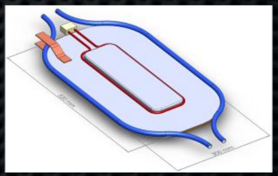


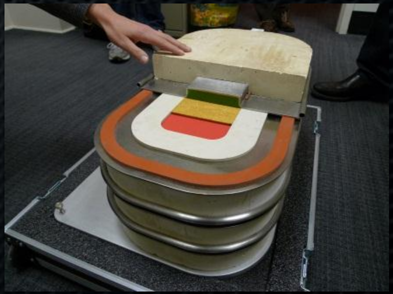
20 Ah



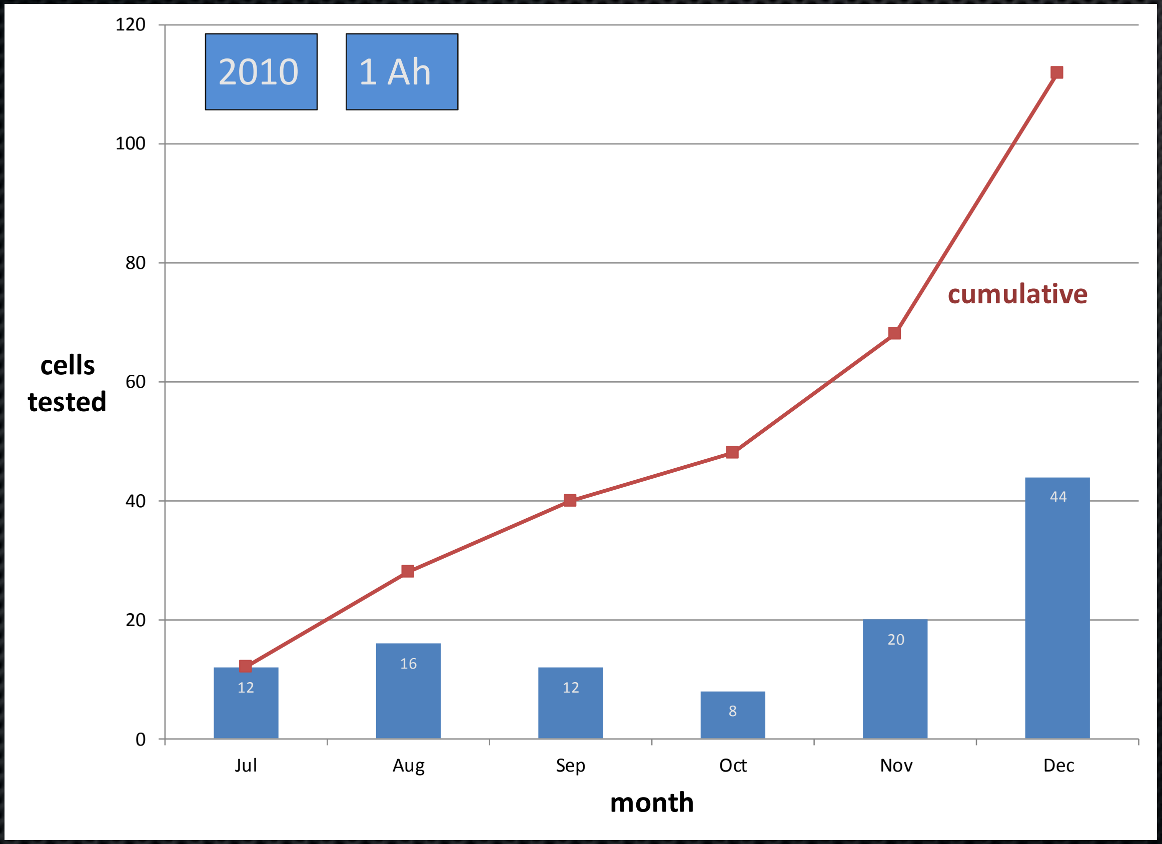


200 Ah





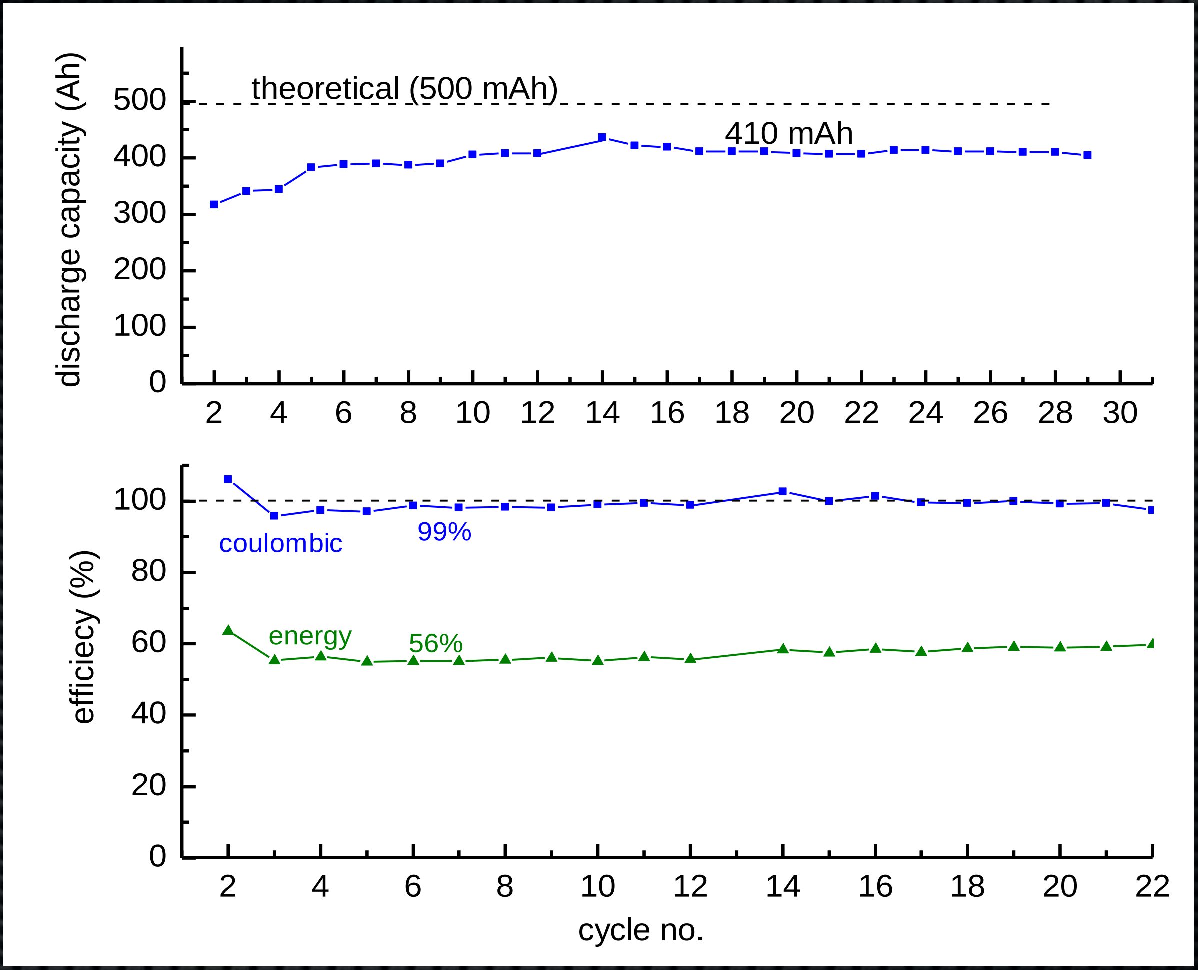
technology maturity



1 Ah cell performance

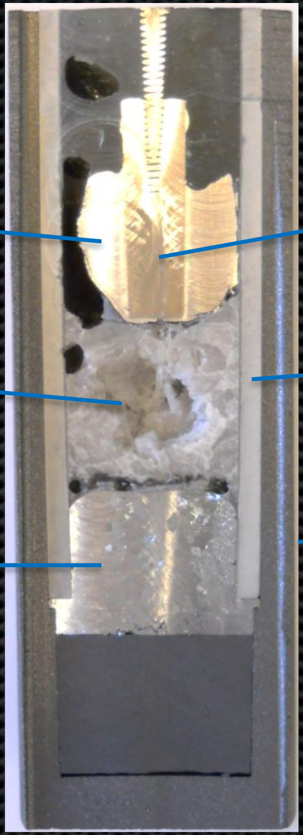
Metric	'Best of' cell results
1. Discharge capacity	650 mAh/cm^2
2. Nominal discharge voltage	0.68 V @ 250 mA/cm^2
3. Capacity fade	0 %/cycle
4. Round-trip energy efficiency	65 %
5. Electrode cost	$ 81 /kWh; $ 210 /kW

1 Ah cell performance

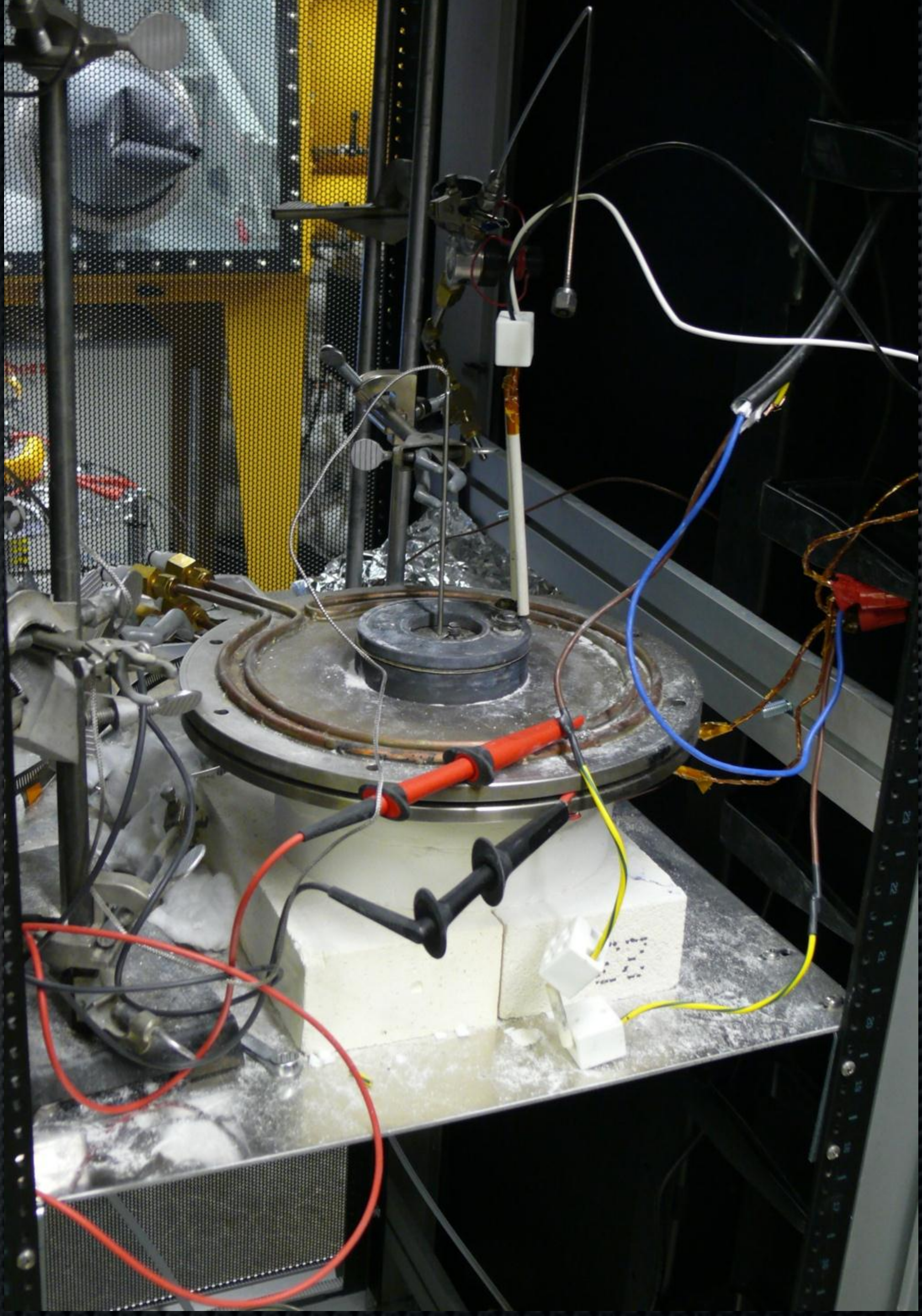


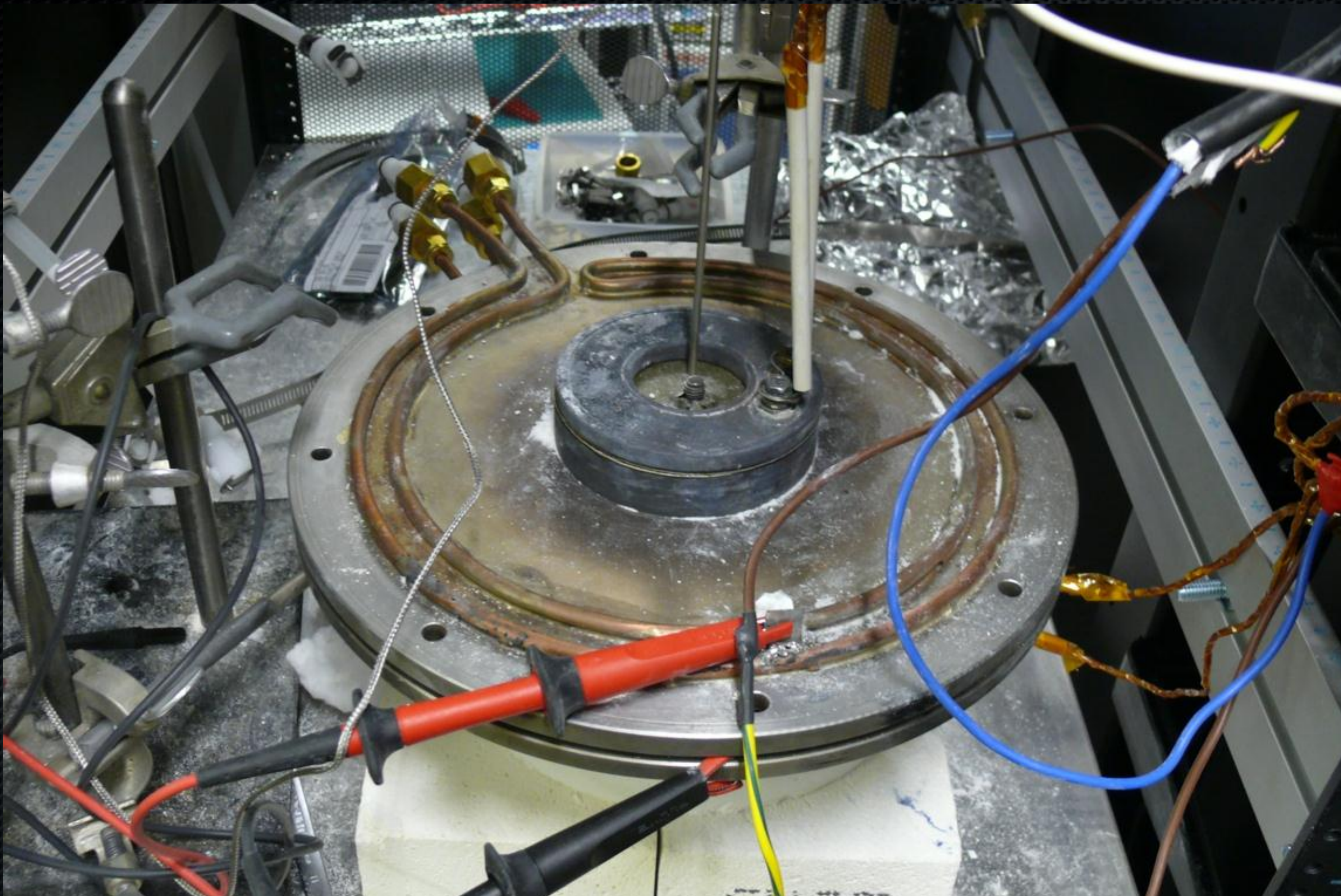
Capacity and efficiency performance data as a function of cycle number.
Note: energy efficiency can be improved by electrolyte optimization. Energy efficiency values of > 70 % have been achieved in other cells.

1 Ah cell cross section

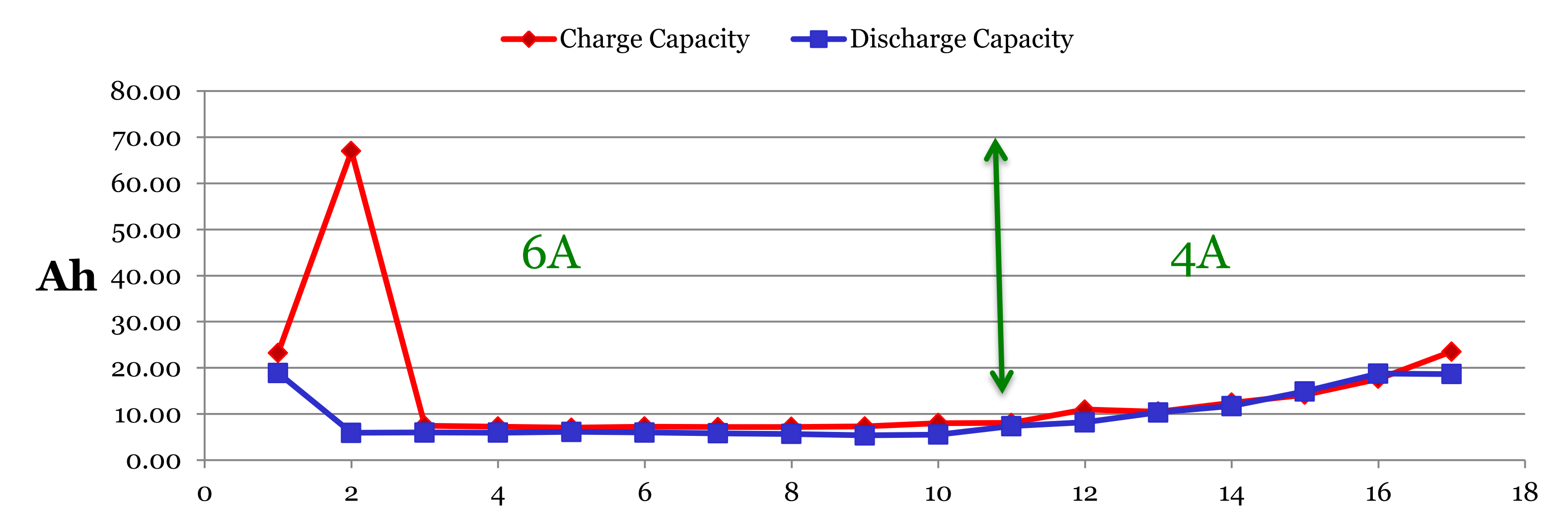


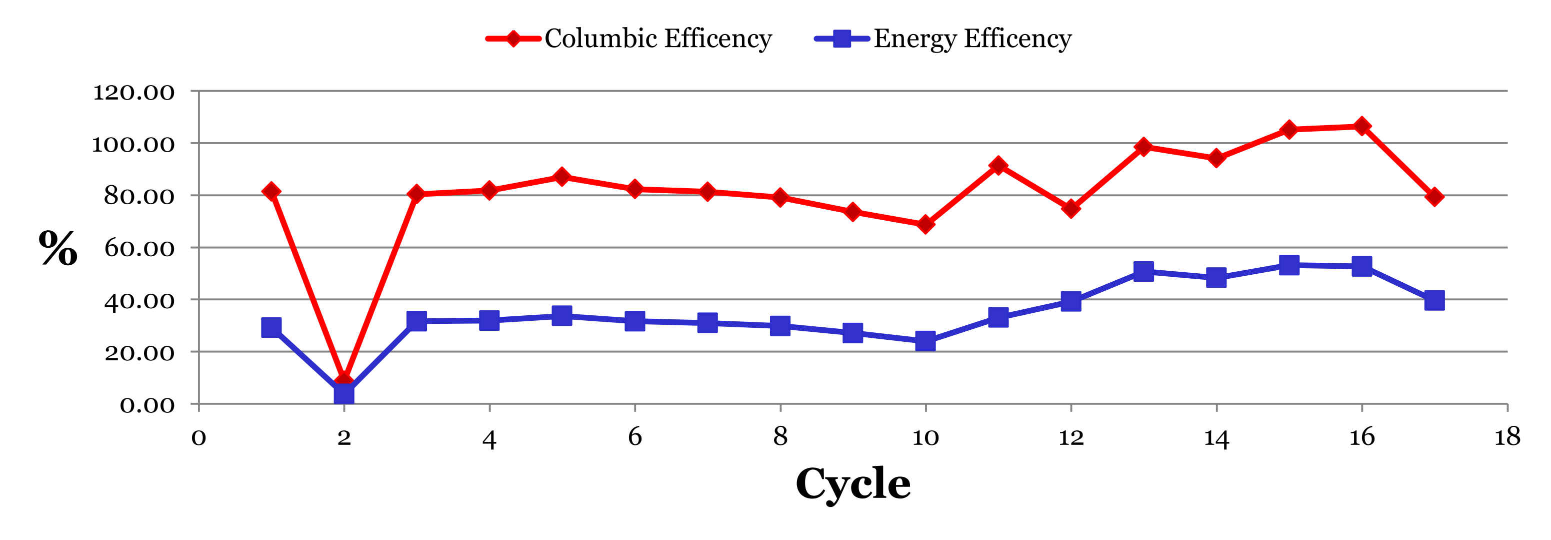
This is an example of a cross sectioned liquid metal battery. Although the component are liquid at room temperature, the two metal electrodes and electrolyte layers are all liquid during operation.



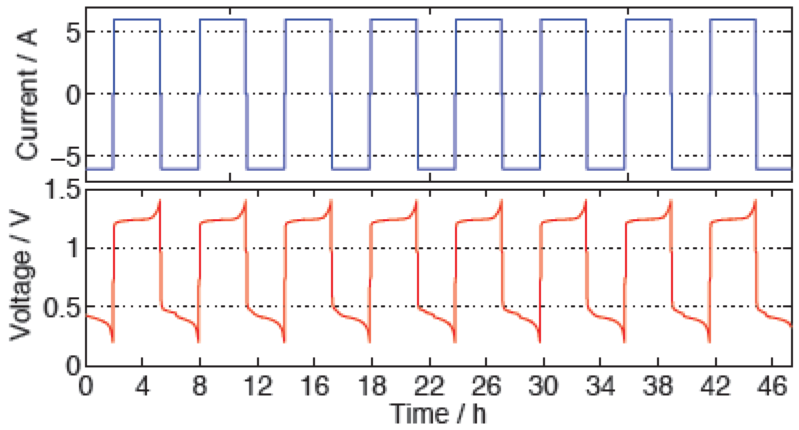


20 Ah cell cycling





20 Ah summary



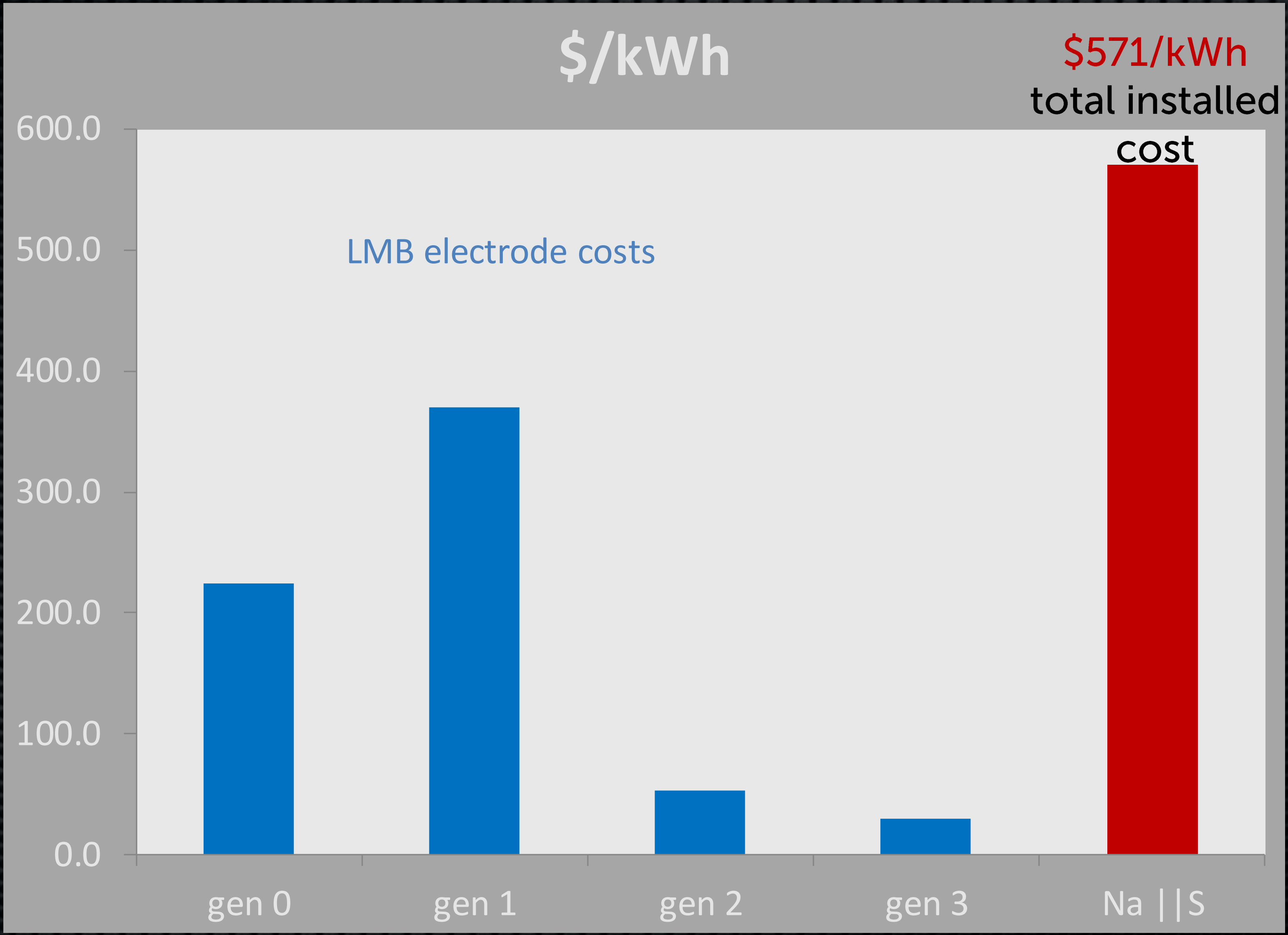
- Operated on first attempt
- 30 cycles (ongoing)
- 16 Ah discharge capacity
- 80% coulombic efficiency
- 80W heating power

- 3 weeks continuous cycling (on going)
- 70 cycles
- comparable to ANL performance (17 months continuous no fade or degradation)
- electrolyte not optimized → practical system will have improved efficiency

"The storage battery is, in my opinion, a catchpenny, a sensation, a mechanism for swindling the public by stock companies. The storage battery is one of those peculiar things which appeals to the imagination, and no more perfect thing could be desired by stock swindlers than that very selfsame thing. ... Just as soon as a man gets working on the secondary battery it brings out his latent capacity for lying. ... Scientifically, storage is all right, but, commercially, as absolute a failure as one can imagine."

THOMAS EDISON in The Electrician (London) February 17, 1883, pp. 329-331 as quoted in Bottled Energy: Electrical Engineering and the Evolution of Chemical Energy Storage by Richard H. Schallenberg

costs



$/kWh
$571/kWh
total installed cost
LMB electrode costs
600.0
500.0
400.0
300.0
200.0
100.0
0.0
gen 0
gen 1
gen 2
gen 3
Na ||S

cost estimation

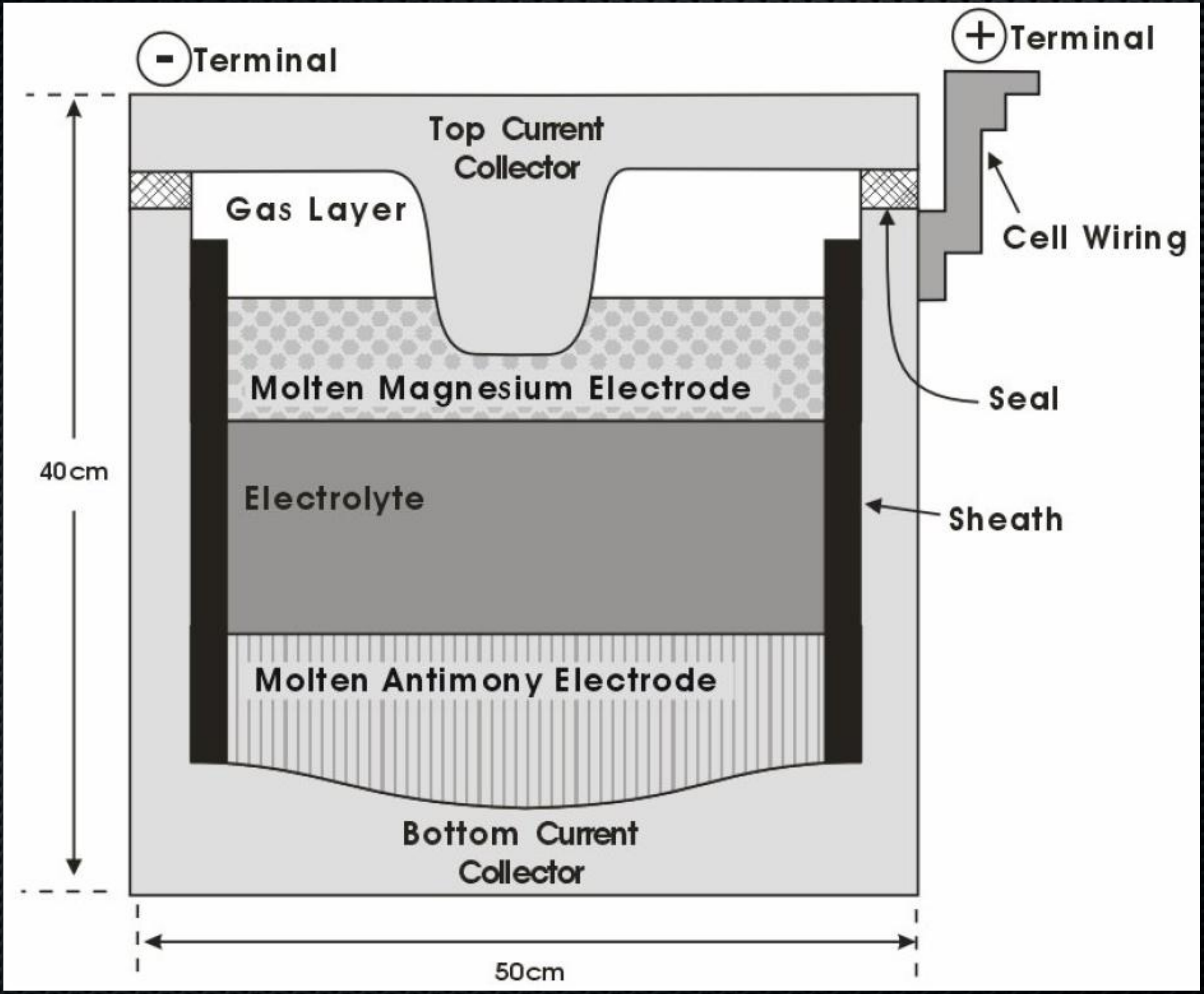
- LMB is believed not only to have low materials costs, but also economies of scale upon commercialization
- basis: intuition & analysis
- four (4) MIT masters theses
  - ☞ original analysis justifying initial research
  - ☞ NPV based analysis indicating need for multiple applications even when costs are low
  - ☞ top down 'retrofit' analysis of new build AL smelters which identified power electronics costs
  - ☞ recent analysis identifying electrolyte cost sensitivity

masters thesis #1

David J. Bradwell

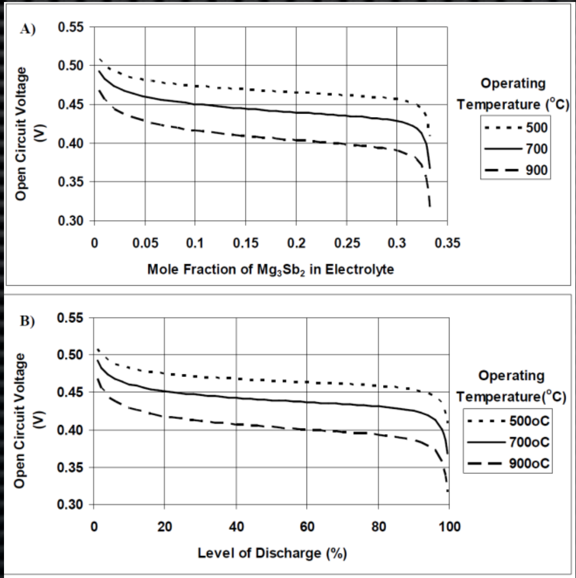
- bottom up analysis
- $100/kWh as critical price metric for pure arbitrage application
- key information point for Deshpande Center funding

cell concept

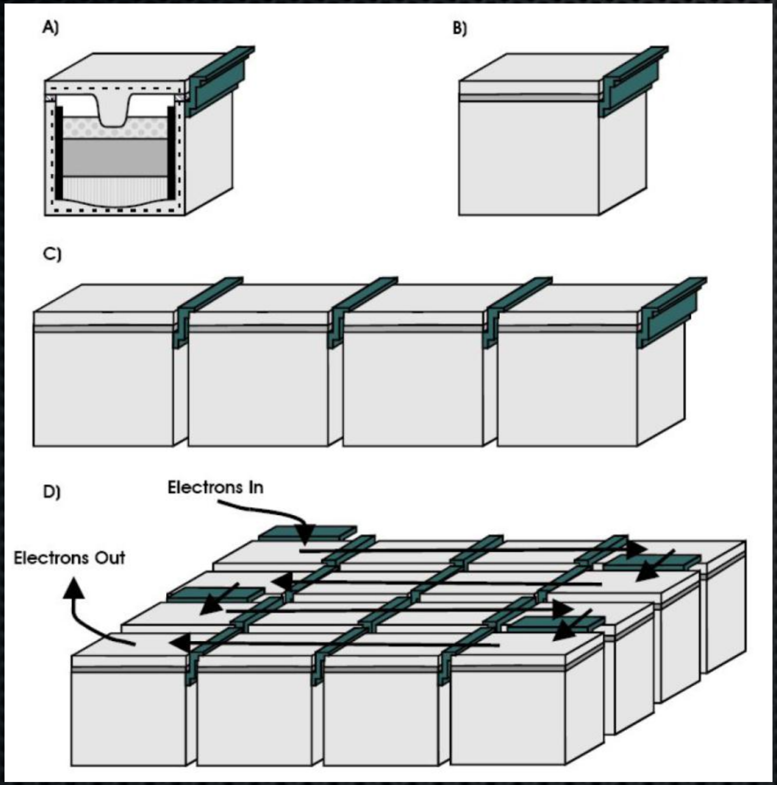


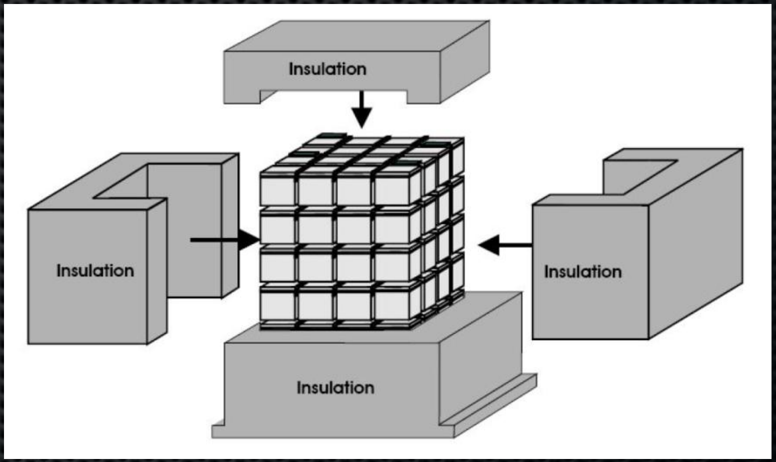
battery performance estimates

Compound	Dissociation Potential, 700°C (V)	Compound	Dissociation Potential, 700°C (V)
Na_2S	1.60	Li_2S	1.97
Na_2Te	1.35	Li_2Se	1.87
Na_2Se	1.20	Li_2Te	1.60
Na_3Sb	0.54 (?)	Li_3Sb	0.9 (?)
Na_3As	0.3 (?)	K_2S	1.60
MgS	1.66	K_3Sb	0.9 (?)
MgSe	1.30	K_2Te	0.75 (?)
MgTe	1.00	CaS	2.30
Mg_3Sb_2	**0.42**	CaSe	1.80
		CaTe	1.40
		Ca_3Sb_2	1.08 (?)

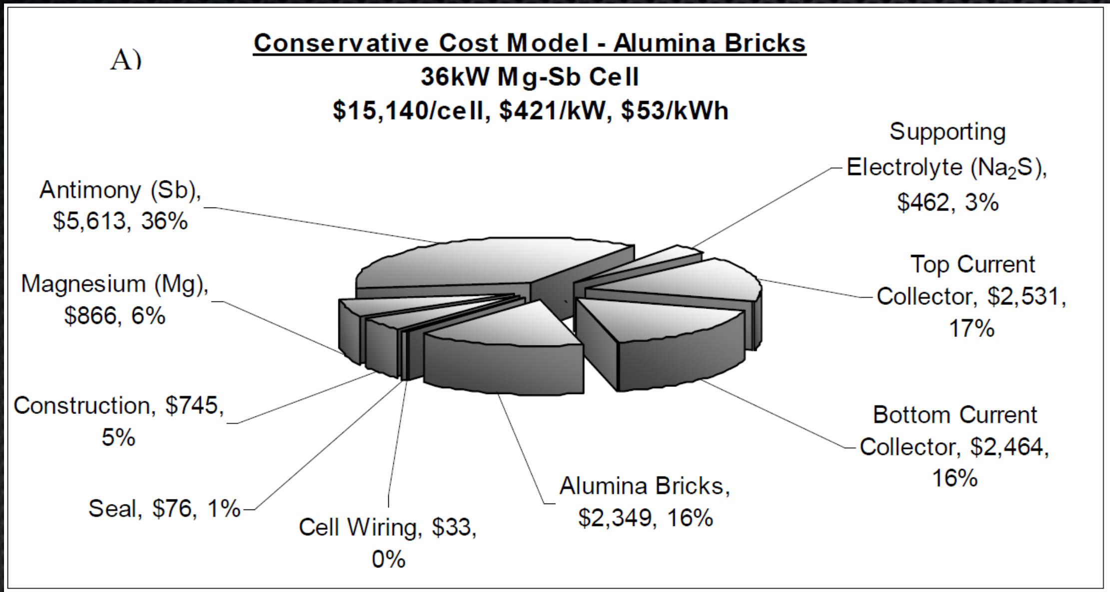


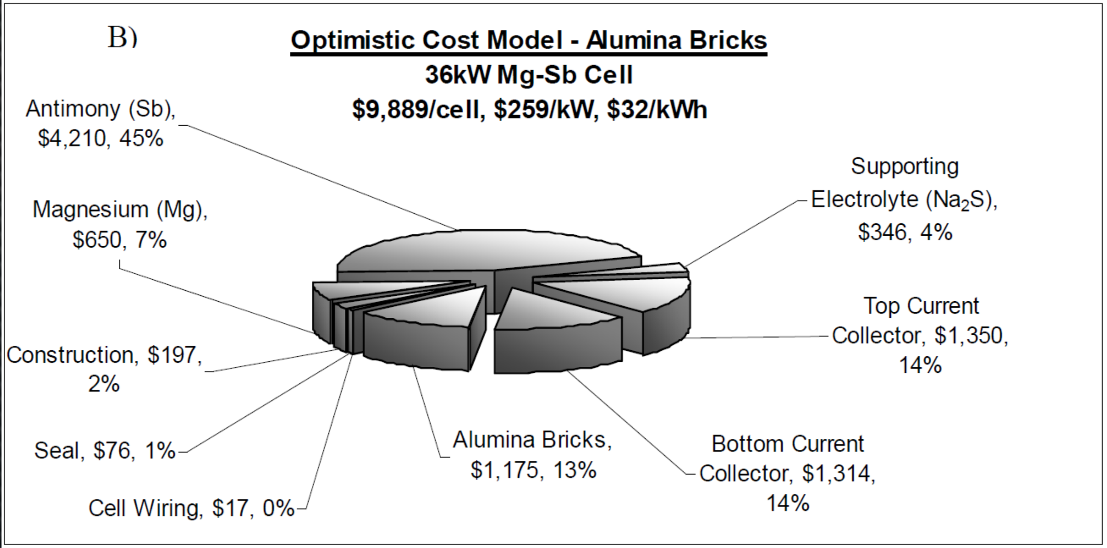
proposed system





cost estimate for 3m × 3m cell





masters thesis #2

Ted A. Fernandez

- similar method of estimating system cost to thesis #1
- did a project based cost estimate and compared multiple storage technologies for each use case
- (nearly) all storage technologies could not produce an NPV break even in 15 years on a single use case
- stacking applications critical

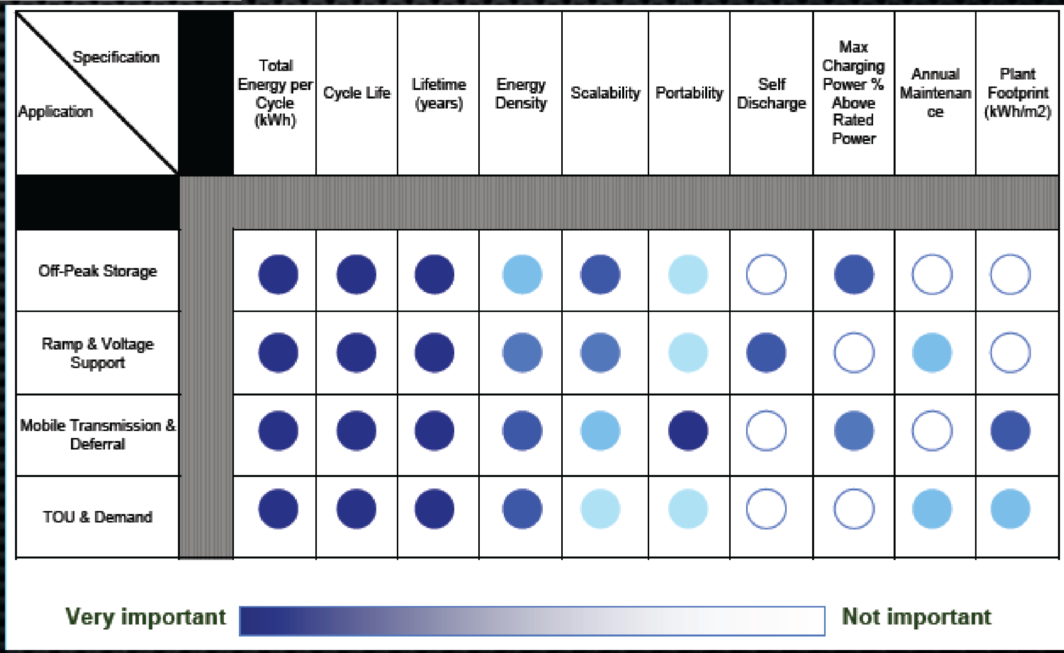
use cases

Use Profiles								
Application	Size	Duration	Response Time	Cycles	Roundtrip Efficiency	Lifetime	Depth of Discharge	Internal Losses
Renewable Off-Peak Storage	30 MW	6 hr	10 min	300/year	80%	10 years	90%	<5%
Ramp & Voltage Support	10 MW	2 hr	10 min	300/year	80%	10 years	90%	<5%
Time-of-Use & Demand Charge Management	1 MW	4 hr	10 seconds	300/year	80%	10 years	70 - 80 %	<5%
Mobile T&D Deferral (Upgrade Factor - .33%)*	4 MW	2 hr	10 min	300/year	80%	20 years	90%	<5%
Mobile T&D Deferral (Upgrade Factor - .50%)*	6 MW	2 hr	10 min	300/year	80%	20 years	90%	<5%

(From an initial 12MW)

strategic analysis

Off-Peak Storage	Ramp & Voltage Support
Total energy Cycle life Scalability Max charge/discharge	Total energy Cycle life Lifetime Self discharge
Mobile T&D Deferral	**TOU & Demand**
Total energy Energy density Portability Plant footprint	Total energy Cycle life Energy Density Plant footprint



evaluation

Off-Peak Storage

- LMB
- Li-OP
- NaS
- LLLA
- Flow Cell
- Li-RE

Ramp & Voltage Support

- NaS
- LMB
- Li-OP
- LLLA
- Li-RE
- Flow Cell

Mobile T&D Deferral

- Li-Op
- LMB
- NaS
- Li-RE
- Flow Cell
- LLLA

TOU & Demand

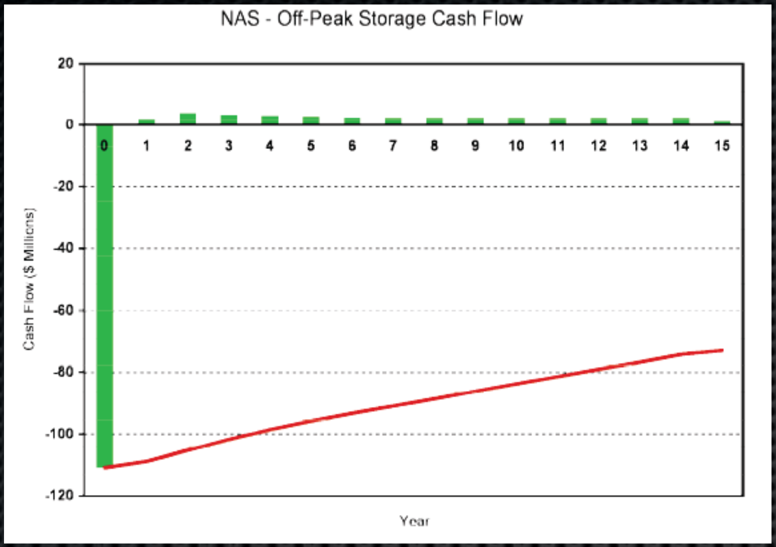
- LMB
- Li-OP
- LLLA
- Li-RE
- Flow Cell
- NaS

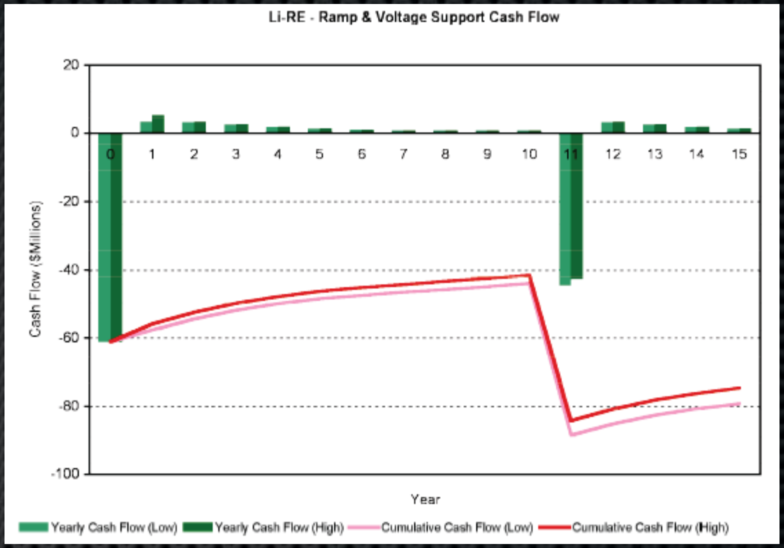
value for use cases

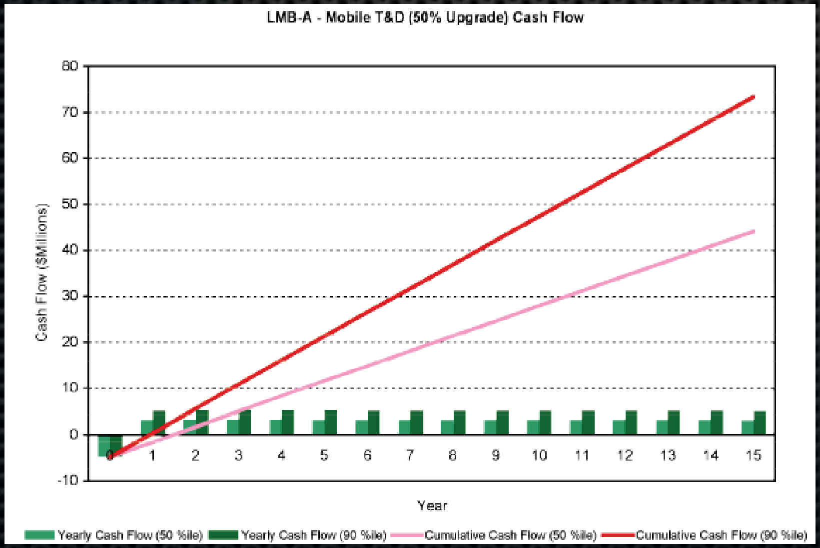
Renewable OPS	R&V Support	Mobile T&D (33%)
$54.2/kW-year	Low $400/kW (over 10 years) High $800/kW (over 10 years)	50th %ile $684/kW-year 90th %ile $1079/kW-year

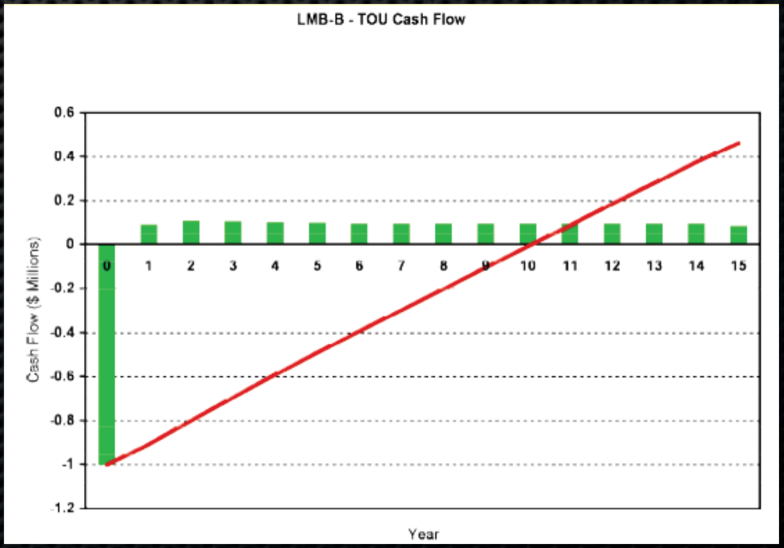
Mobile T&D (50%)	TOU & Demand
50th %ile $1115/kW-year 90th %ile $1821/kW-year	$250.37/kW-year

project NPV analysis

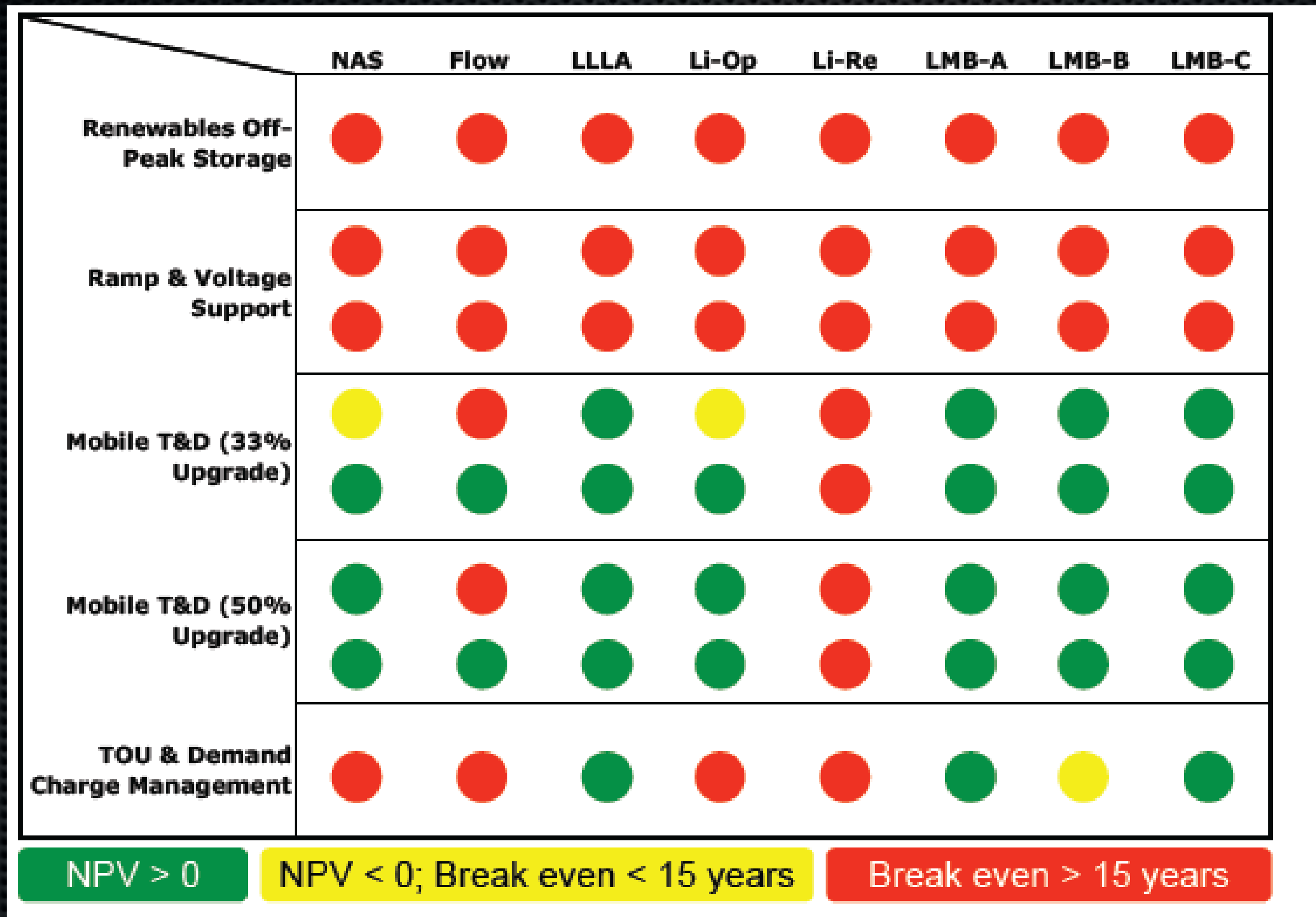








base analysis summary



summary

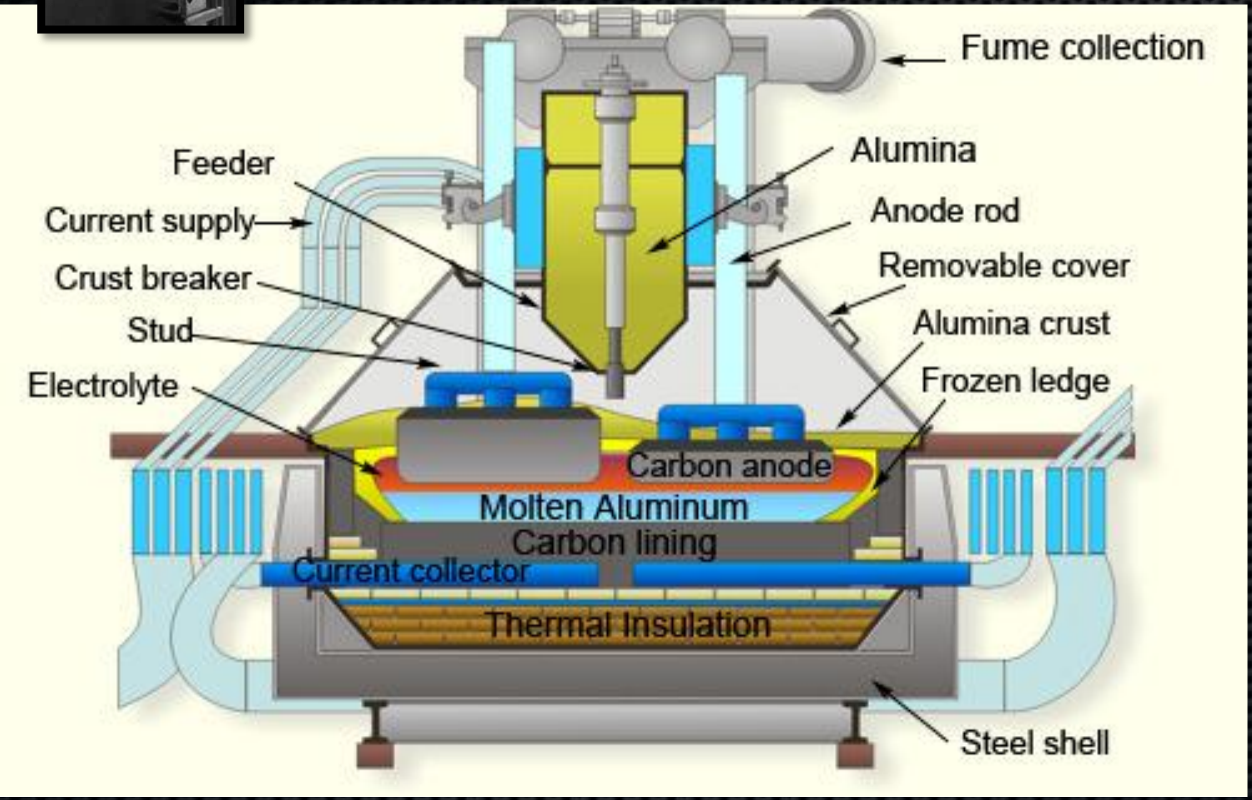
- two key drivers for project profitability
  - ☞ government incentives
  - ☞ stacking applications
- red and yellows turn green

masters thesis #3

Isabel Garos

- used costs from most recent Al smelter
- eliminated unnecessary equipment and estimated cost of additional equipment
- modeled a 4 GWh battery in an area similar in size to a Walmart supercenter
- identified high current (100's of kA) inverter costs as a key cost leader at the system level

Hall-Héroult cell



AP35 Cell

Operating current: 350kA

Pot Size(approx): 10x3.5x1.2m

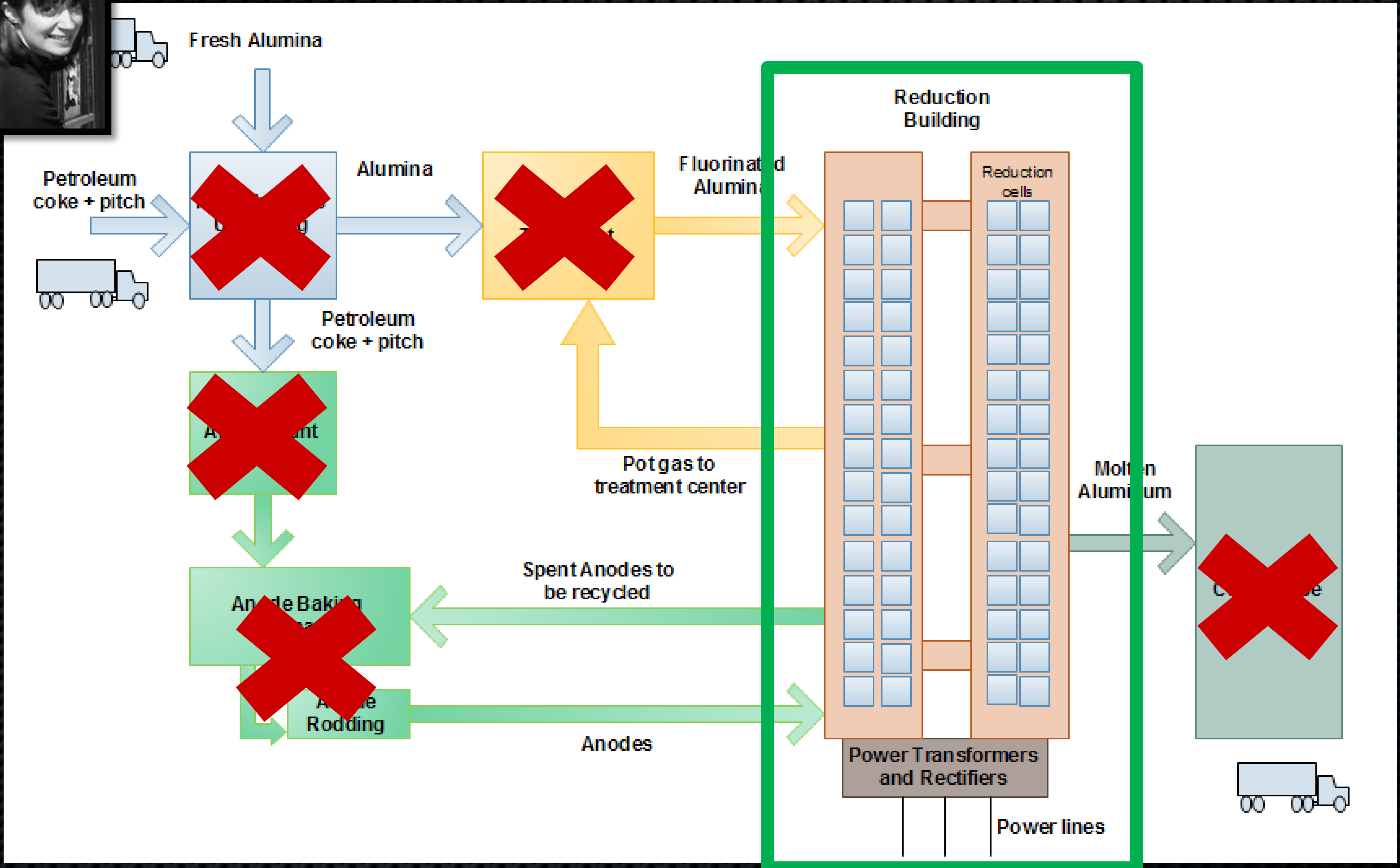
Production: 2.7 tons/pot/day

Consumption: 13,000 kWh/ton

Current efficiency: up to 95.1%

Working temperature: 960°C

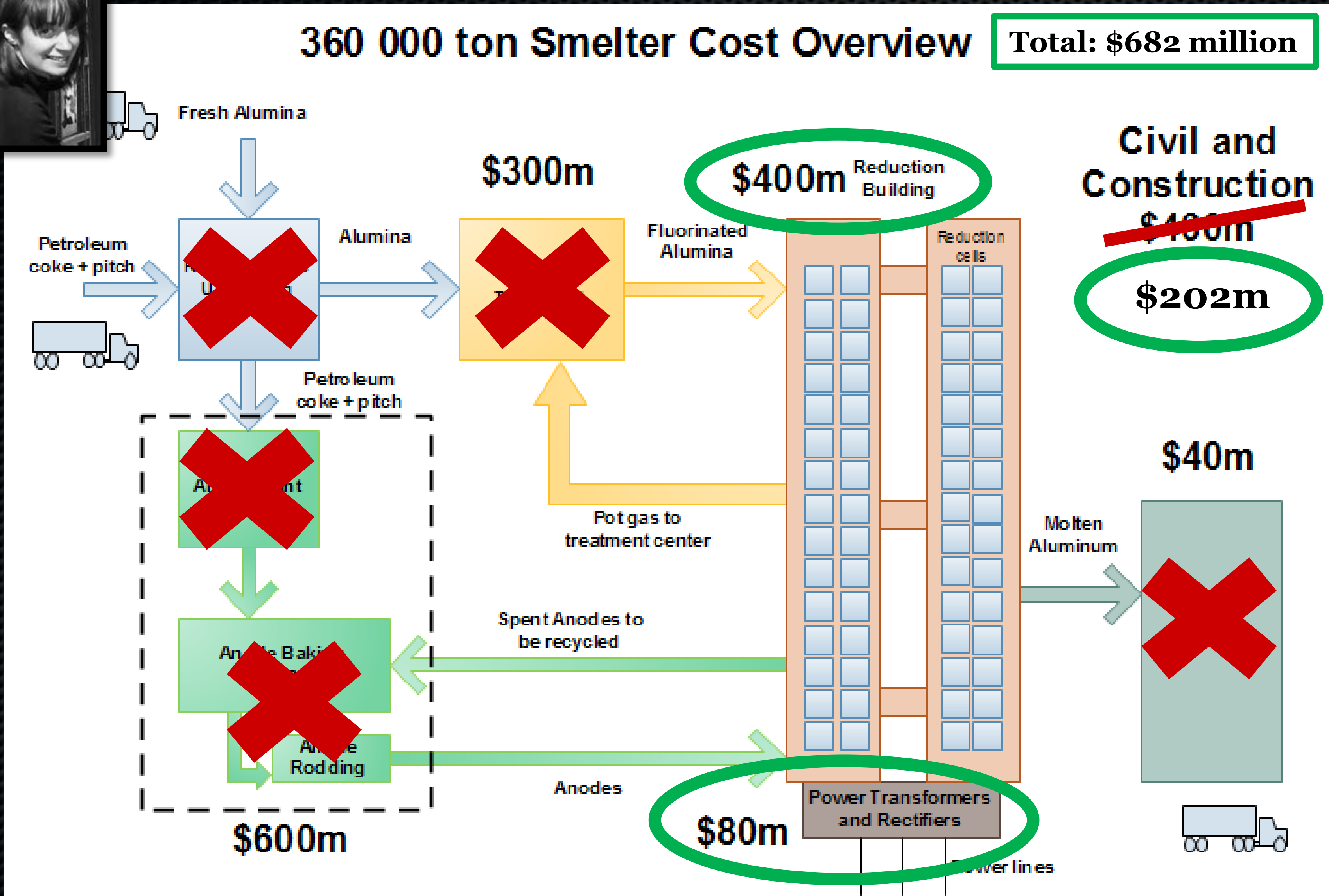
aluminum smelter



smelter investment

- Sohar Smelter:
  - Location: Sohar, Oman
  - Builder: Bechtel
  - Commissioned in 2008
  - Most advanced technology
  - 360,000 tpy, $2,000 million, $5,500/tpy
  - 360 AP35 pots; 350kA; 1,650Vdc
    - 580MW 4.58V/cell
  - 2 pot-rooms, 1km long each
    - 180 pots per room

investment breakdown

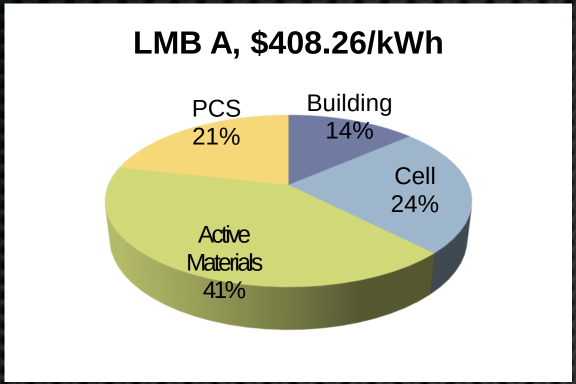


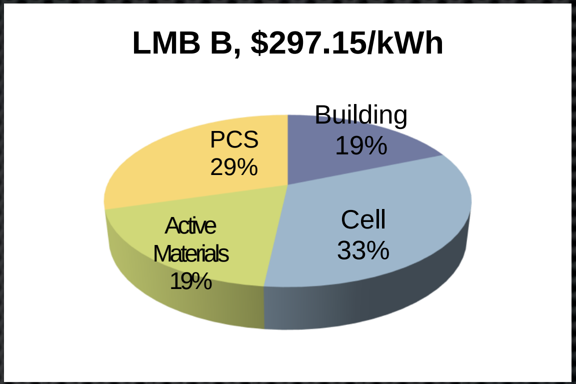
base case

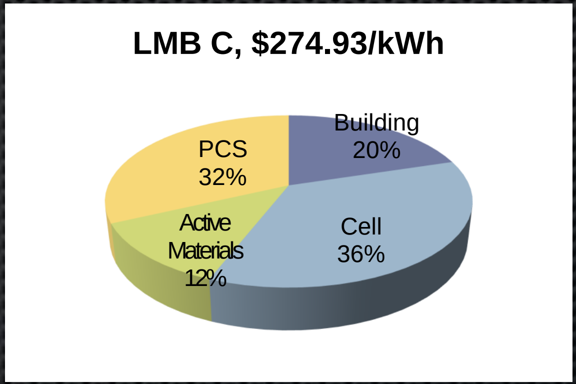
Cell design		
Length	3.5	m
Width	10	m
Height	0.3	m
Cell area	35	m²
Cell characteristics		
Cell voltage	1	V
Current density	1	A/cm²
Total current	350	kA
Cell efficiency	100%	
Roundtrip efficiency	90%	
Charge/discharge time	8	hours
Cell power	350	kW
Cell capacity	2800	kWh

LMB A	**LMB B**	**LMB C**
$150/kWh	$50/kWh	$30/kWh

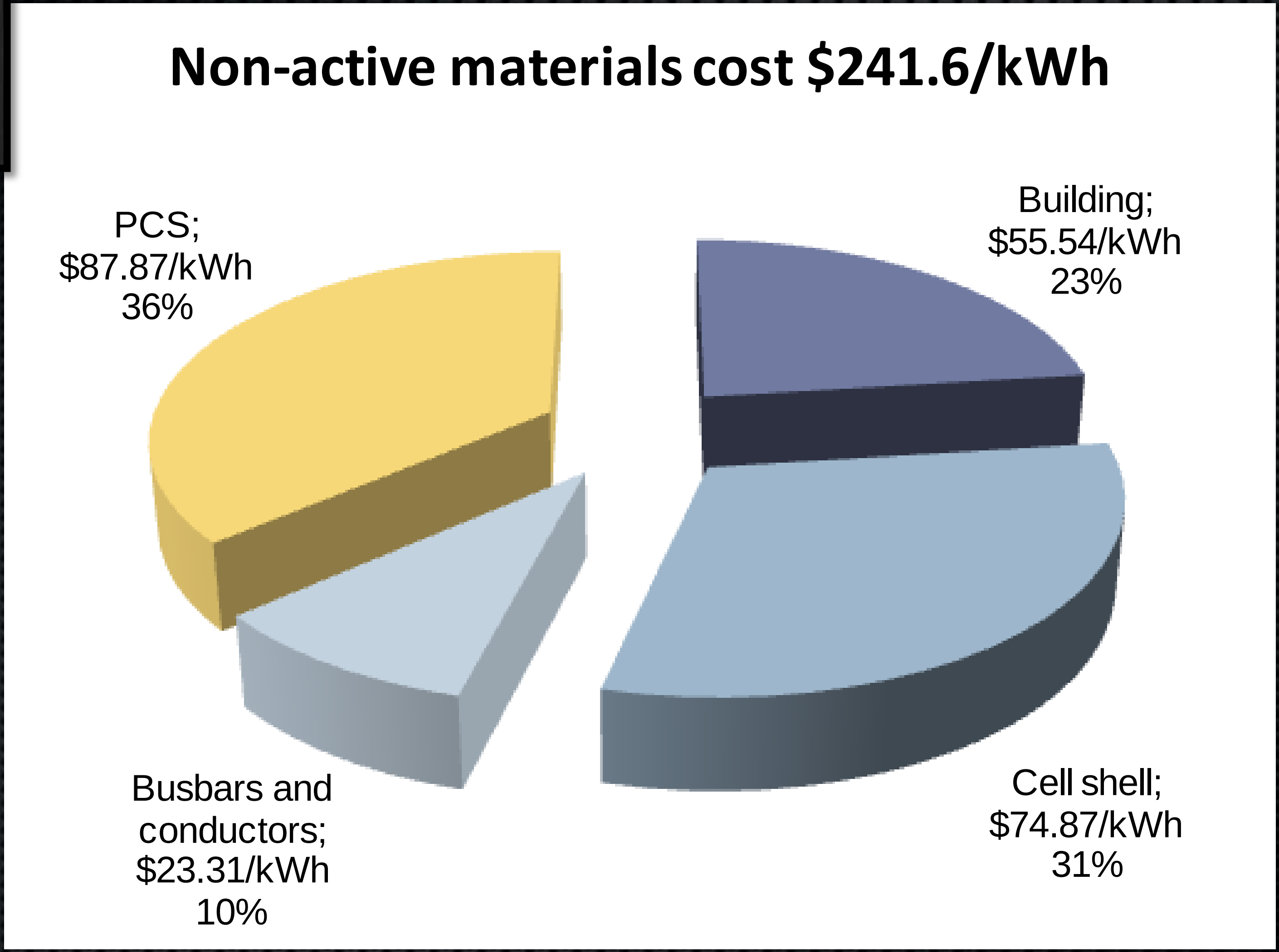
base case: results



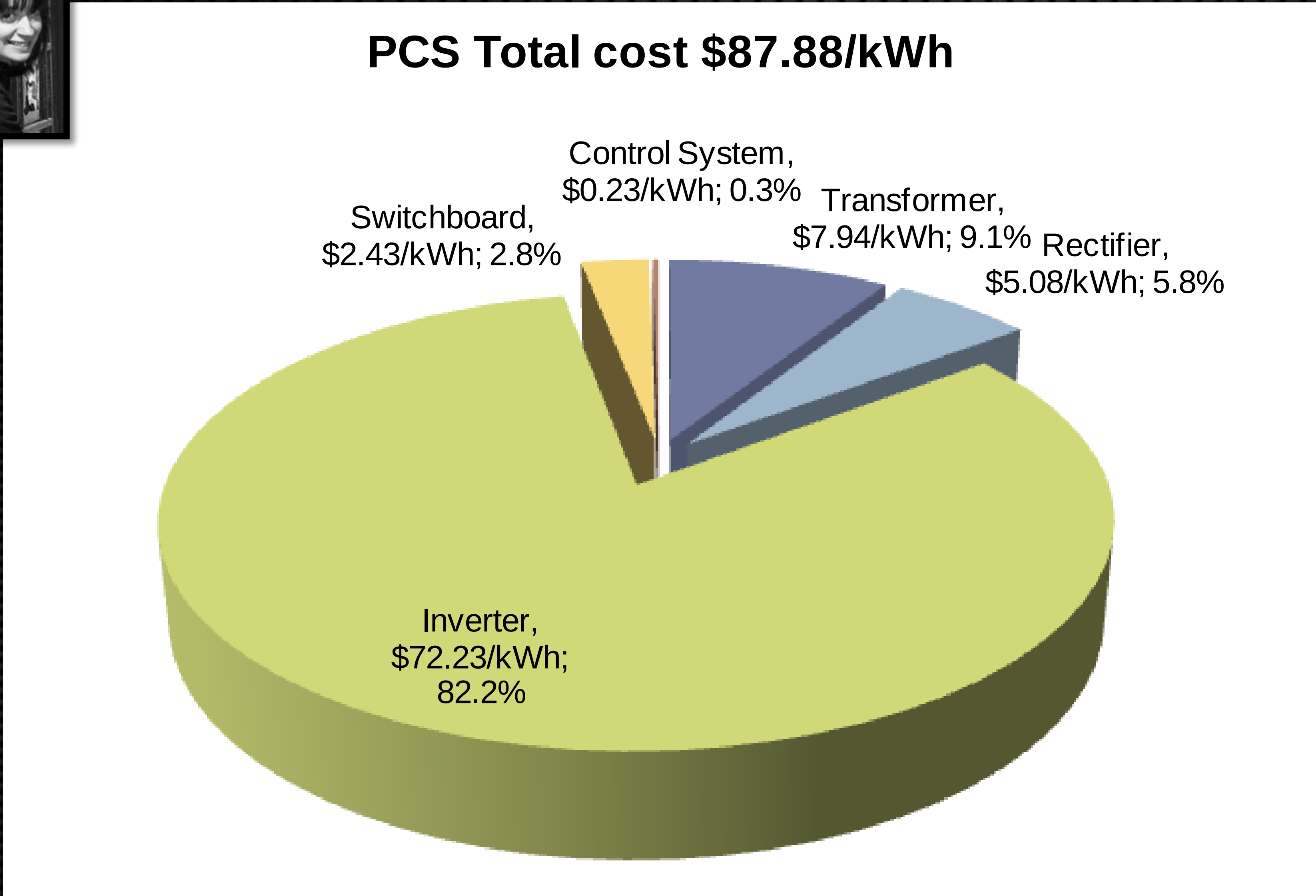




base case


Non-active materials cost $241.6/kWh
PCS; $87.87/kWh 36%
Building; $55.54/kWh 23%
Busbars and conductors; $23.31/kWh 10%
Cell shell; $74.87/kWh 31%

base case


PCS Total cost $87.88/kWh
Control System, $0.23/kWh; 0.3%
Transformer, $7.94/kWh; 9.1%
Rectifier, $5.08/kWh; 5.8%
Switchboard, $2.43/kWh; 2.8%
Inverter, $72.23/kWh; 82.2%

base case

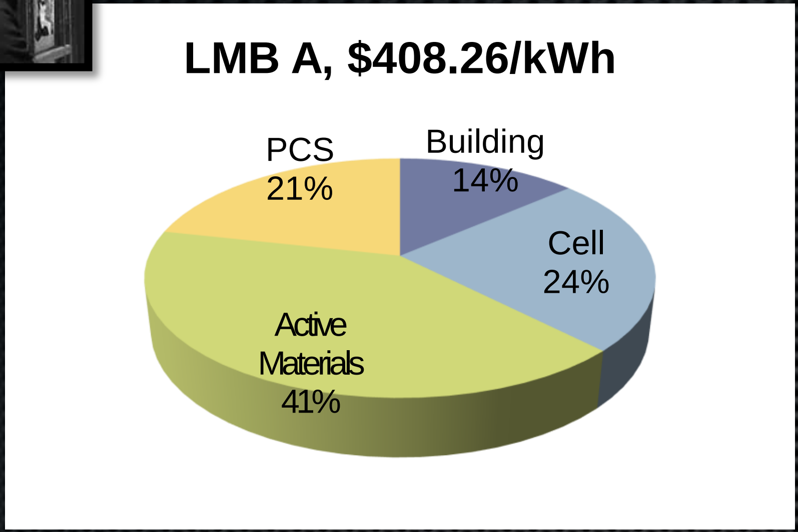
Critical cost:

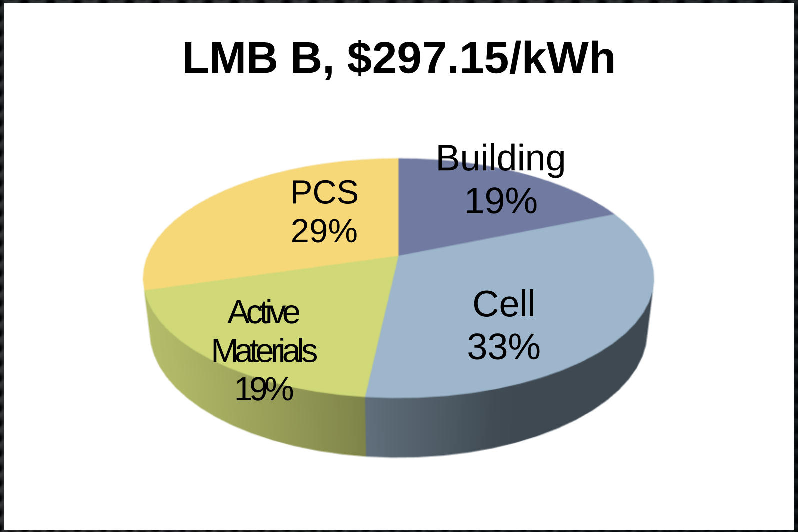
DC-AC Converter → $72/kWh; 82.2% PCS cost

~1/3 Non-active materials cost

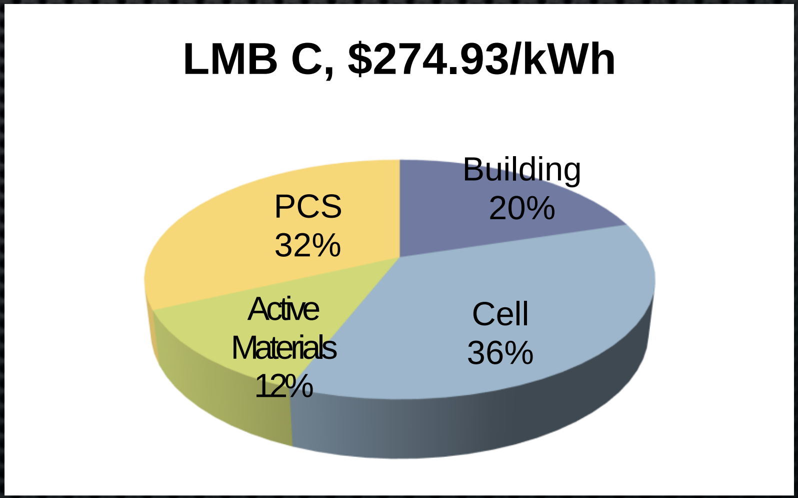
- Decrease in cost expected in the near future (advances in PV central inverters)
- Further development of bidirectional converters
- Analysis of HVDC electrical power transmission

sensitivity analysis



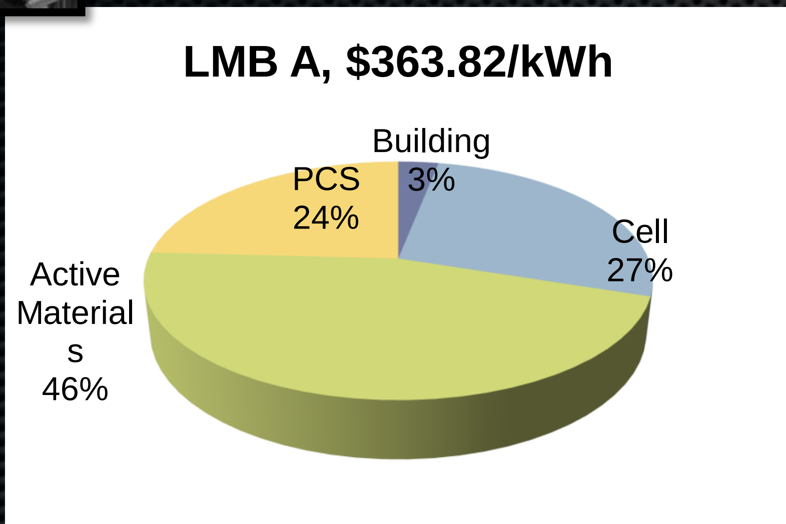


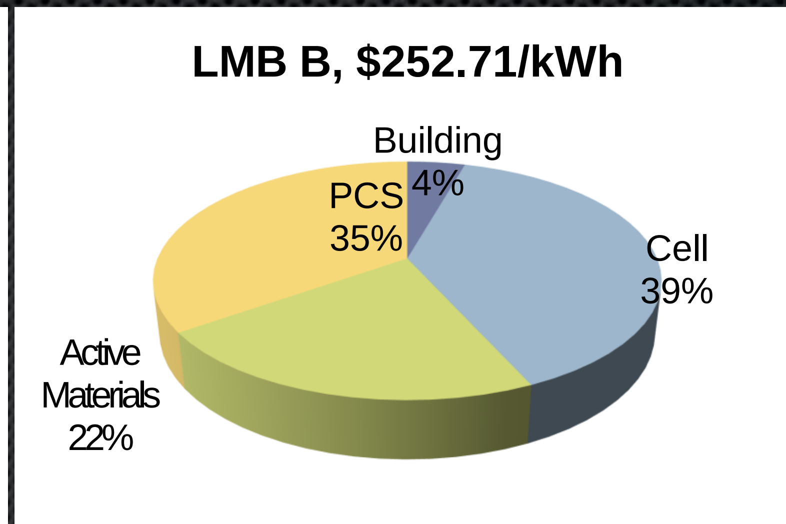
Initial case

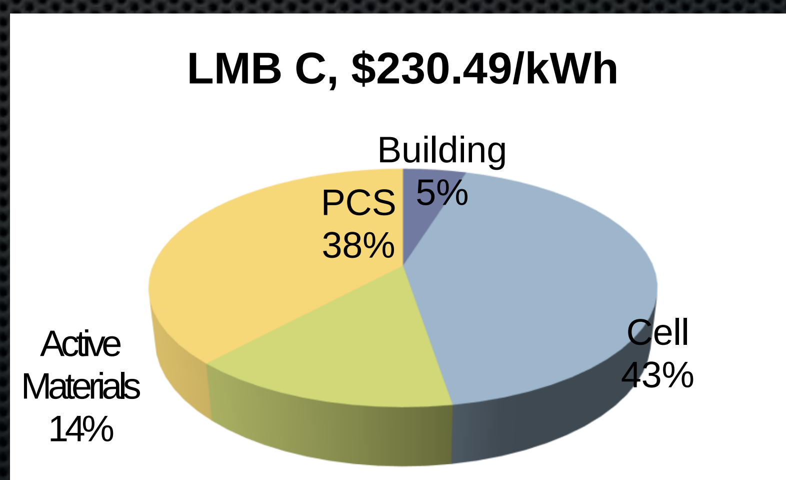


sensitivity analysis

Five Levels of Cells







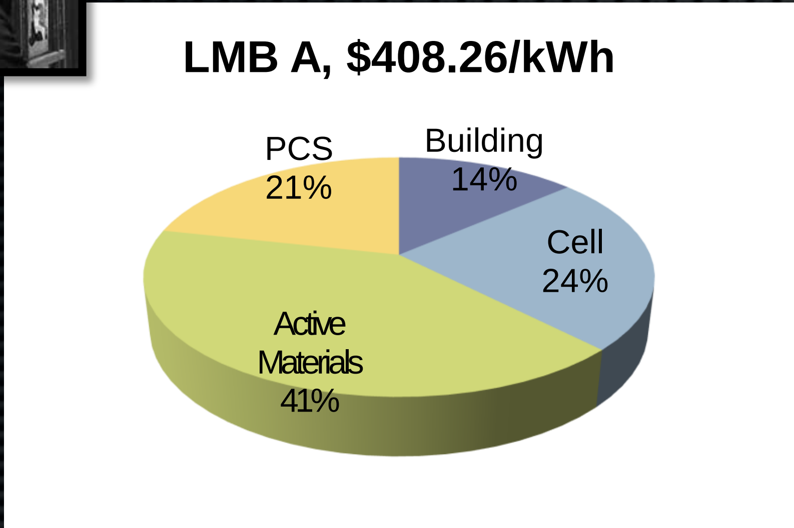
sensitivity analysis

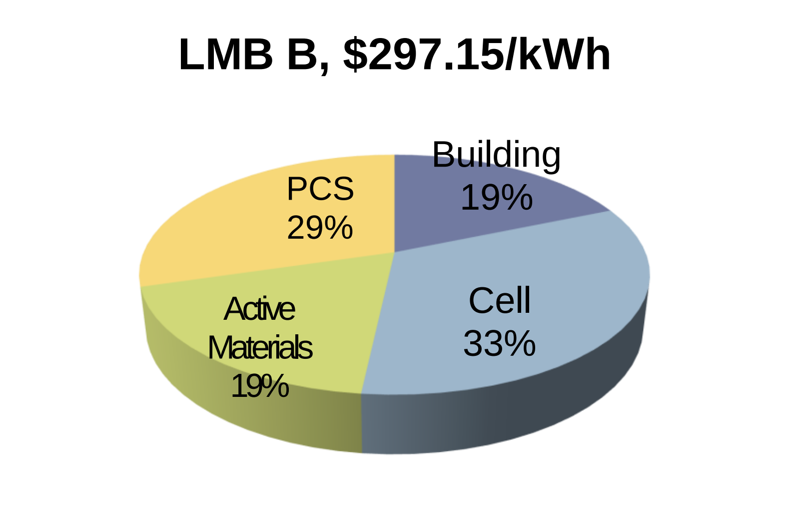
Five Levels of Cells

	LMB A		LMB B		LMB C	
	Base Scen	Scen One	Base Scen	Scen One	Base Scen	Scen One
$/kWh	408.26	363.82	297.15	252.71	274.93	230.49
Ratio	0.89		0.85		0.84	
% Building	14%	3%	19%	4%	20%	5%
% Cell	24%	27%	33%	39%	36%	43%
% Active Materials	41%	46%	19%	22%	12%	14%
% PCS	21%	24%	30%	35%	32%	38%

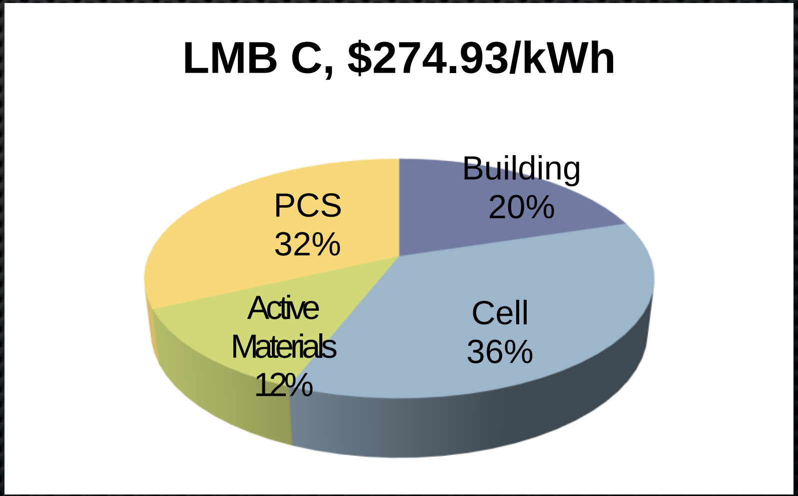
Footprint reduction: 80%
Cost reduction: 11-16%

sensitivity analysis



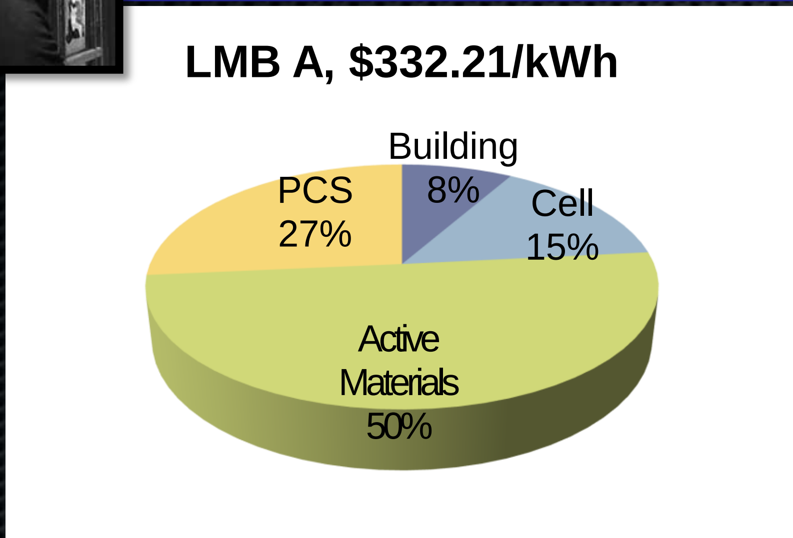


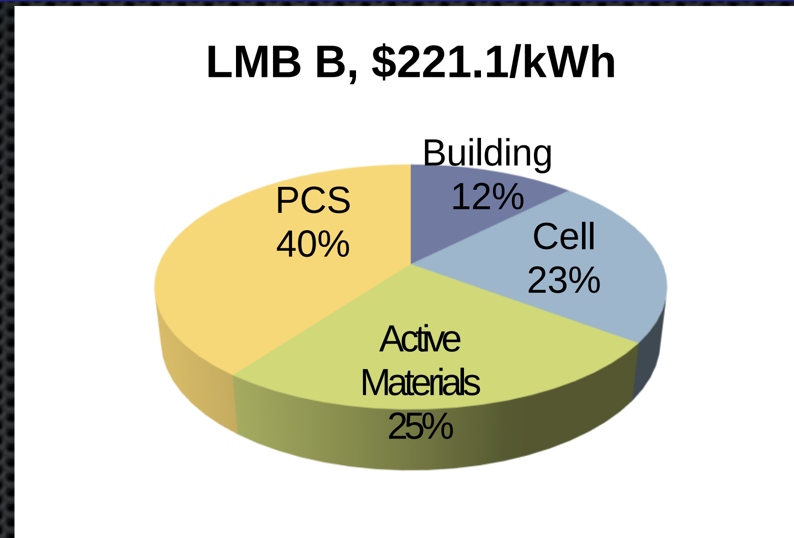
Initial case

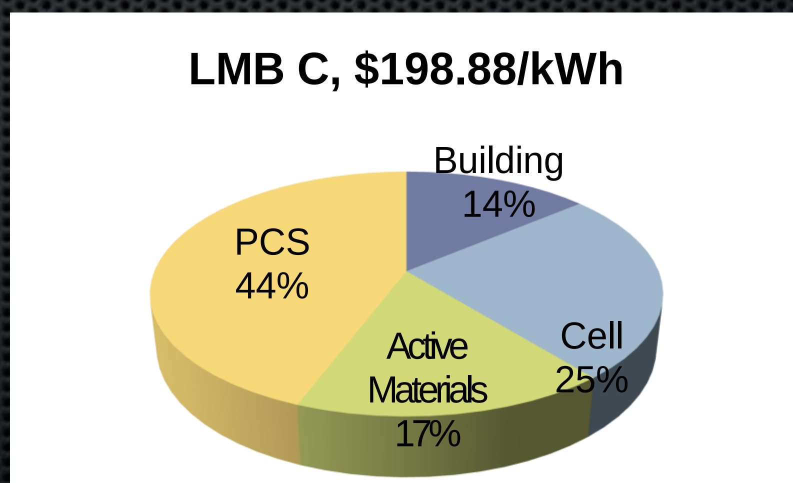


sensitivity analysis

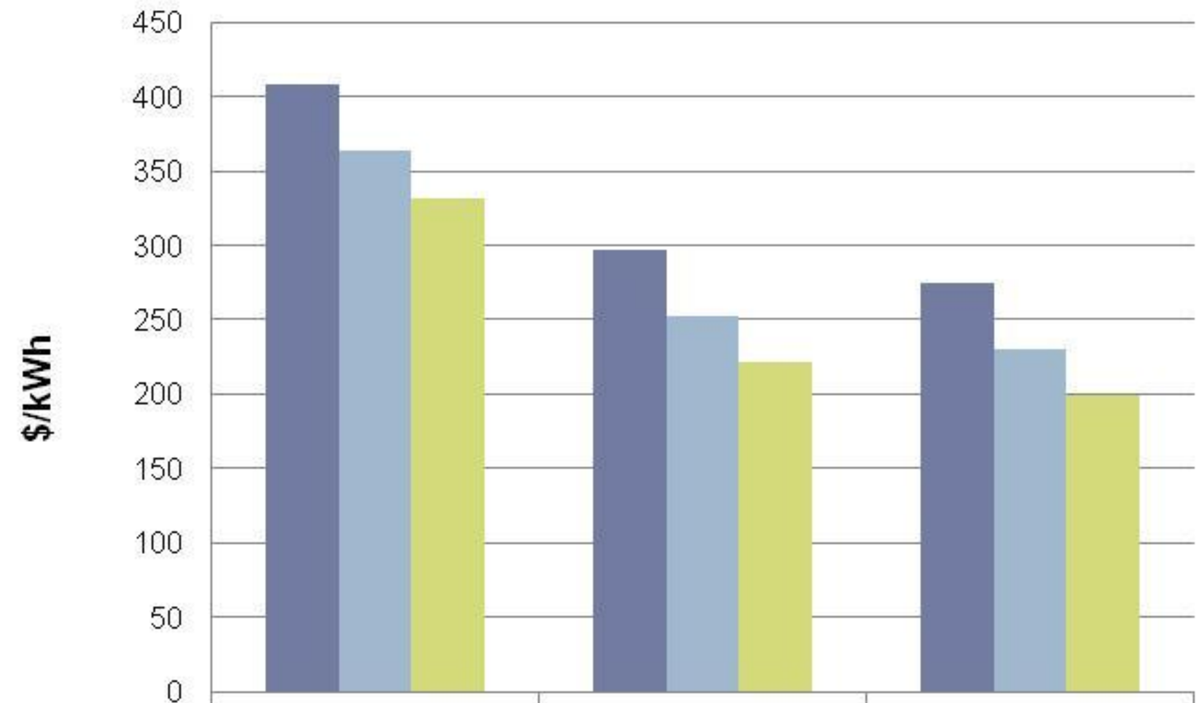
Eight Cells per Group







sensitivity analysis



	LMB A	LMB B	LMB C
Base Scenario	408,26	297,15	274,93
Scenarion One	363,82	252,71	230,49
Scenario Two	332,21	221,1	198,88

conclusion

Critical Points:

· Power Conversion System → need to reduce cost of the inverter

· Current-Efficiency relationship will influence the final cost (chemistry dependent)

·Non active materials cost as presently estimated exceed the market base cost threshold for the entire ESS

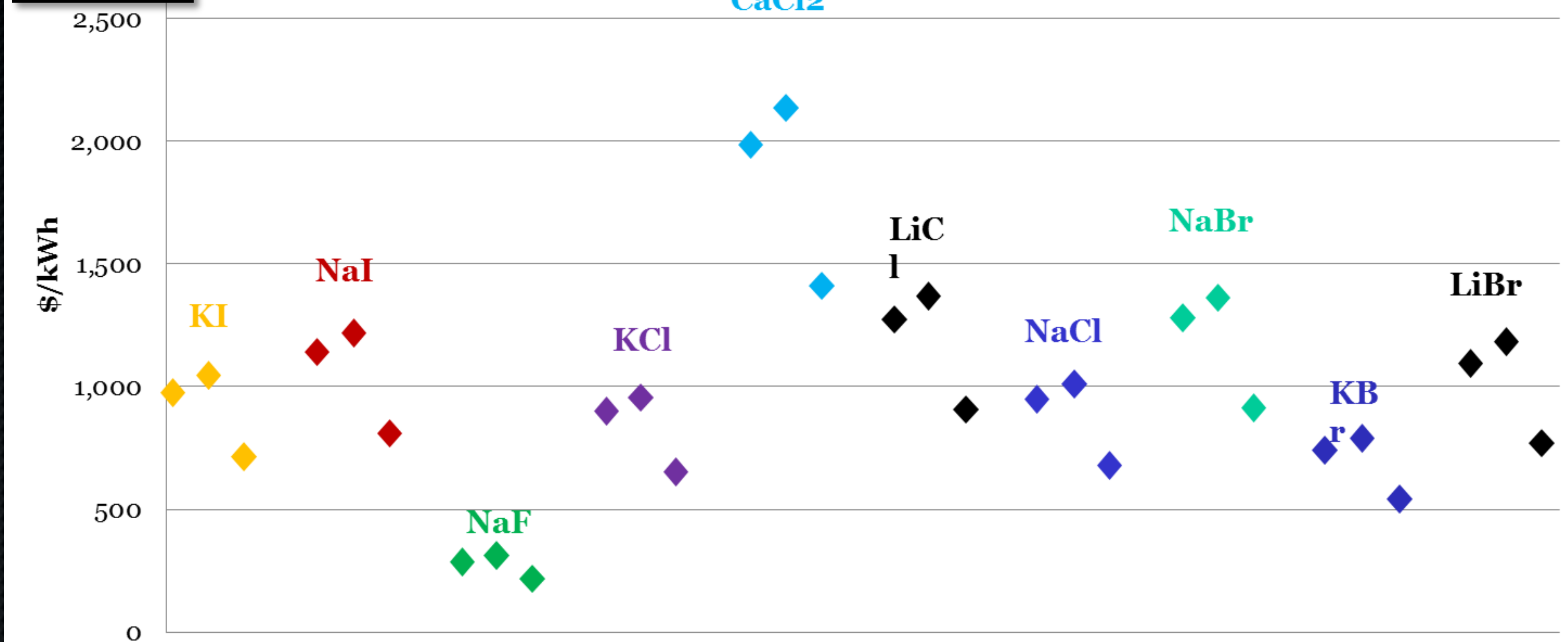
·Specific design of pot for LMB can reduce significantly the cost of ESS

masters thesis #4

Michael Parent

- based on most recent understanding of LMB chemistries and secondary components
- analyzed materials scarcity and cost sensitivity for LMB couples
- modeled total installed cost estimate for LMB systems based on a 1m × 2m cell size
- identified dry salt costs as important cost control target

lab grade salt costs



salts used for testing are extremely expensive

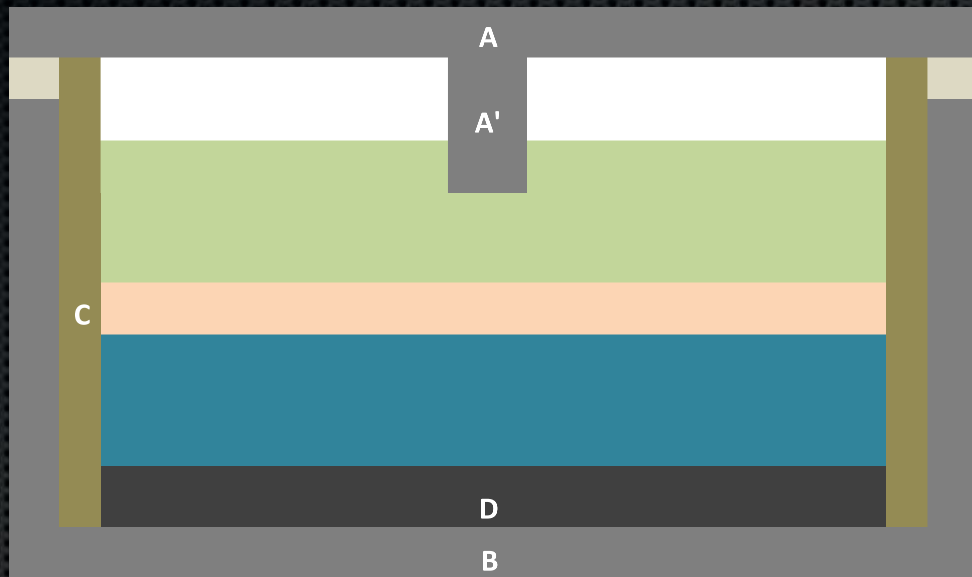
lab scale purification

Salt	Retail ($/kWh)	Bulk ($/kWh)	In-House* ($/kWh)	% Savings
NaF	17	0.35	9	47%
NaI	463	17	246	47%
NaCl	447	0.01	240	46%
NaBr	854	7	458	46%
KCl	780	0.11	419	46%
KI	555	12	296	47%
LiCl	838	10	449	46%
LiI	622	103	314	50%
LiBr	752	15	401	47%
CaCl2	1,220	0.12	656	46%
KBr	414	9	221	47%

*Assumes 93% product yield

Energy cost taken from a Gen 3 cell at 0.5 A/cm^2

cell enclosure cost estimate



Material	Part	Cost ($/kg)	$/kWh
Steel	A,A',B	0.55 [1]	6.7
Alumina	C	100.00 [2]	22.5
Graphite	D	1.50 [3]	1.7
Copper	wiring	9.75 [4]	1.3
various	misc.	NA	2.5

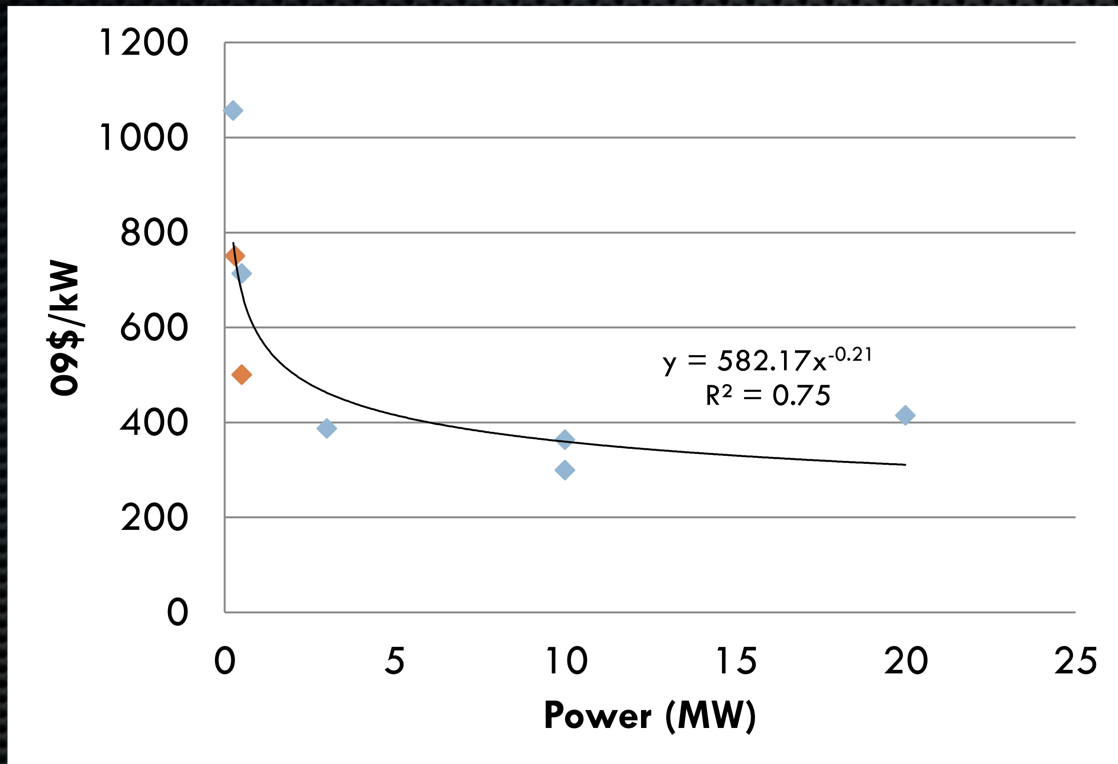
total: $35/kWh

System – Battery Enclosure

structure cost estimate

- footprint cost of $5,000/m^2$
- varies based on stacking structure
  - ☞ $22-$33/kWh for this model

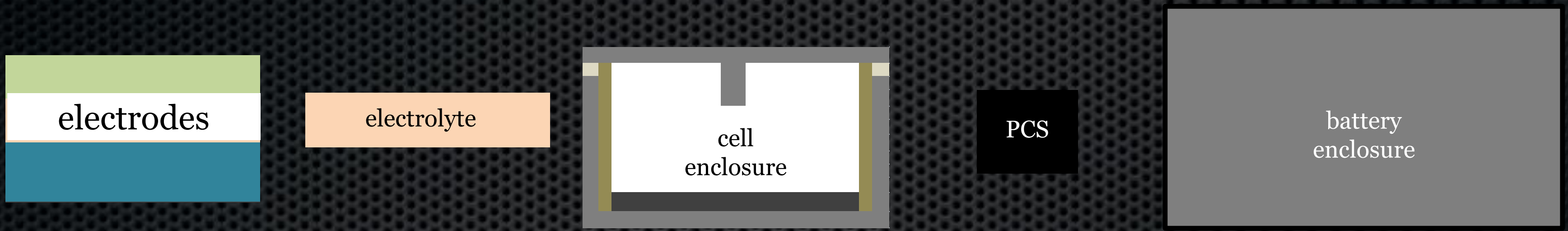
PCS cost estimate



- higher power systems have lower unit costs ($/kW)
- 1 MW → $582/kW
- assume $600/kW ($75/kWh)

data from Sandia Labs report (1997)
data from personal communication with Raytheon

component summary



$34-$486 | $17-$1200 | $35-$203 | $75 | $22-$33

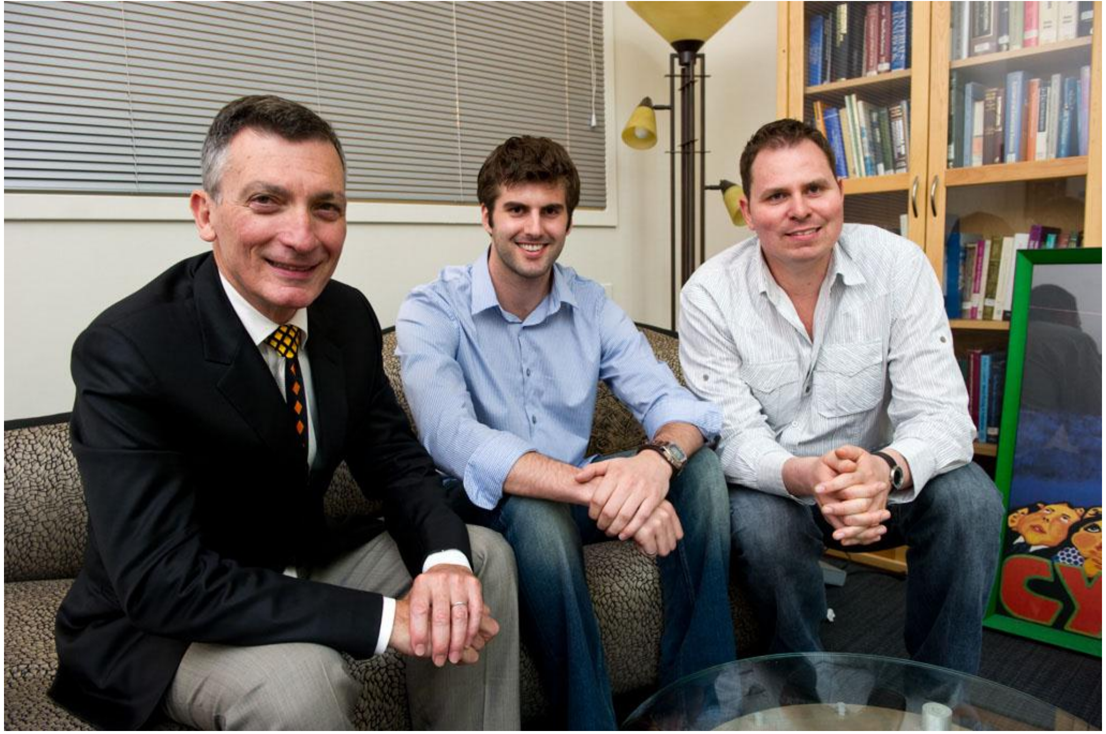
Results – System

results

Technology	Total system cost ($/kWh)
Pb-Acid	750-1000 [1]
NaS	571 [2]
ZEBRA	680 [3]
Li-ion	1500-3500 [1]
LMB-Gen2	1000 [4]
LMB-Gen2	225 [4]

electrolyte
$817/kWh

electrolyte
$20/kWh



LIQUID METAL BATTERY CORPORATION

LMBC

start-up details

- founded 2010
- series A from 'patient' investors
- focus on commercialization & scale-up
- validate manufacturing approach & cost-models

development plan

LMBC

high level technical stages of the company

STAGE 1

Self-heated cell
- Design, build, and operate self-heated cell
- Develop key manufacturing processes

STAGE 2

Stack (demonstration unit)
- Stack of cells
- System performance testing
- Deployable demonstration unit

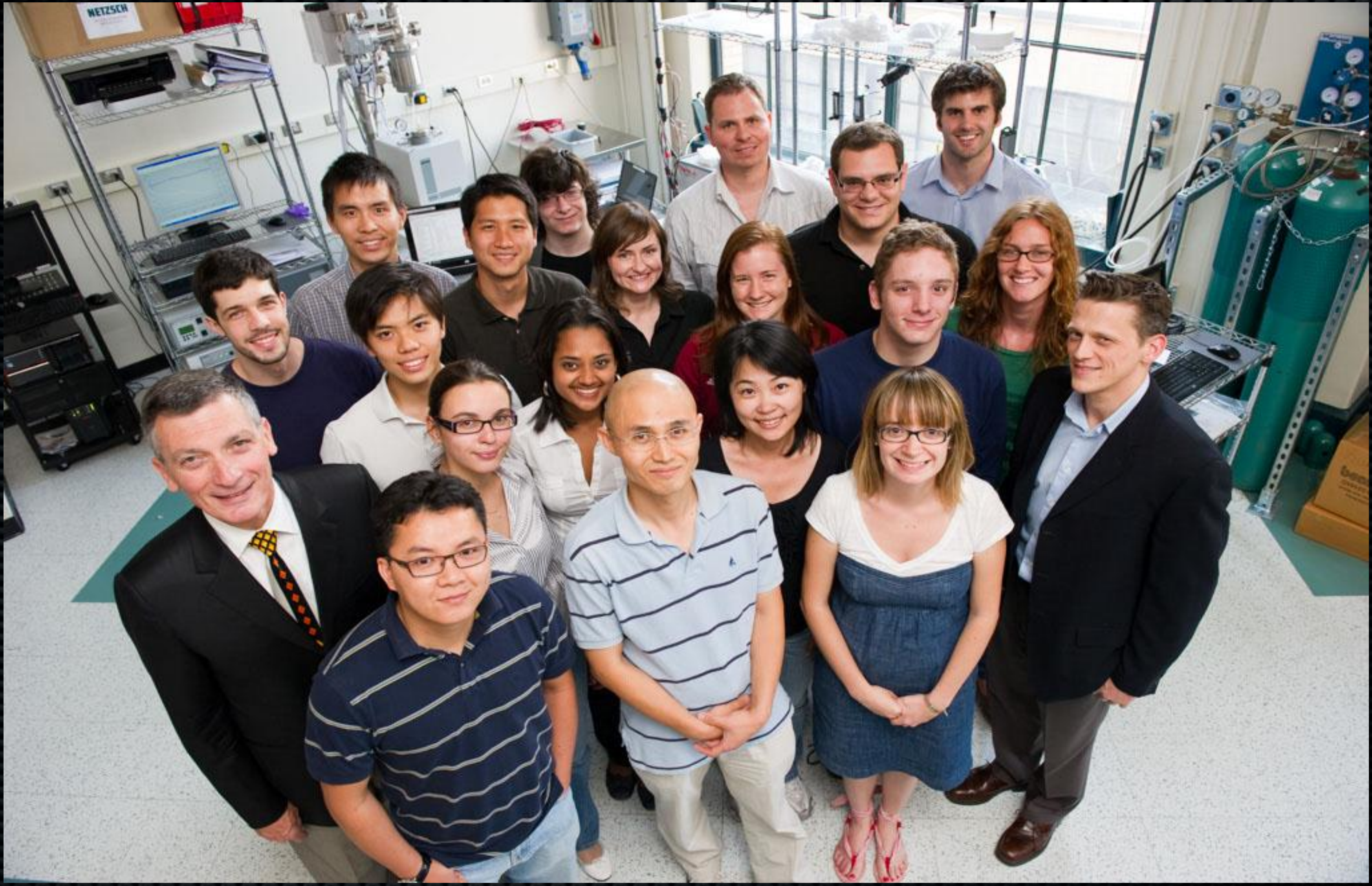
STAGE 3

High volume manufacturing
- Increase production capability
- Sale to commercial buyers

End of Stage 1 Goal (*24 months*)

→ Design, construct, and operate a self-heated cell

Liquid Metal Battery team



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