The BEEST:

An Overview of ARPA-E's Program in Ultra-High Energy Batteries for Electrified Vehicles

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NDIA Workshop to Catalyze Adoption of Next-Generation Energy Technologies

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Why do we care about the Electric Car?

<u>OPPORTUNITY</u>:

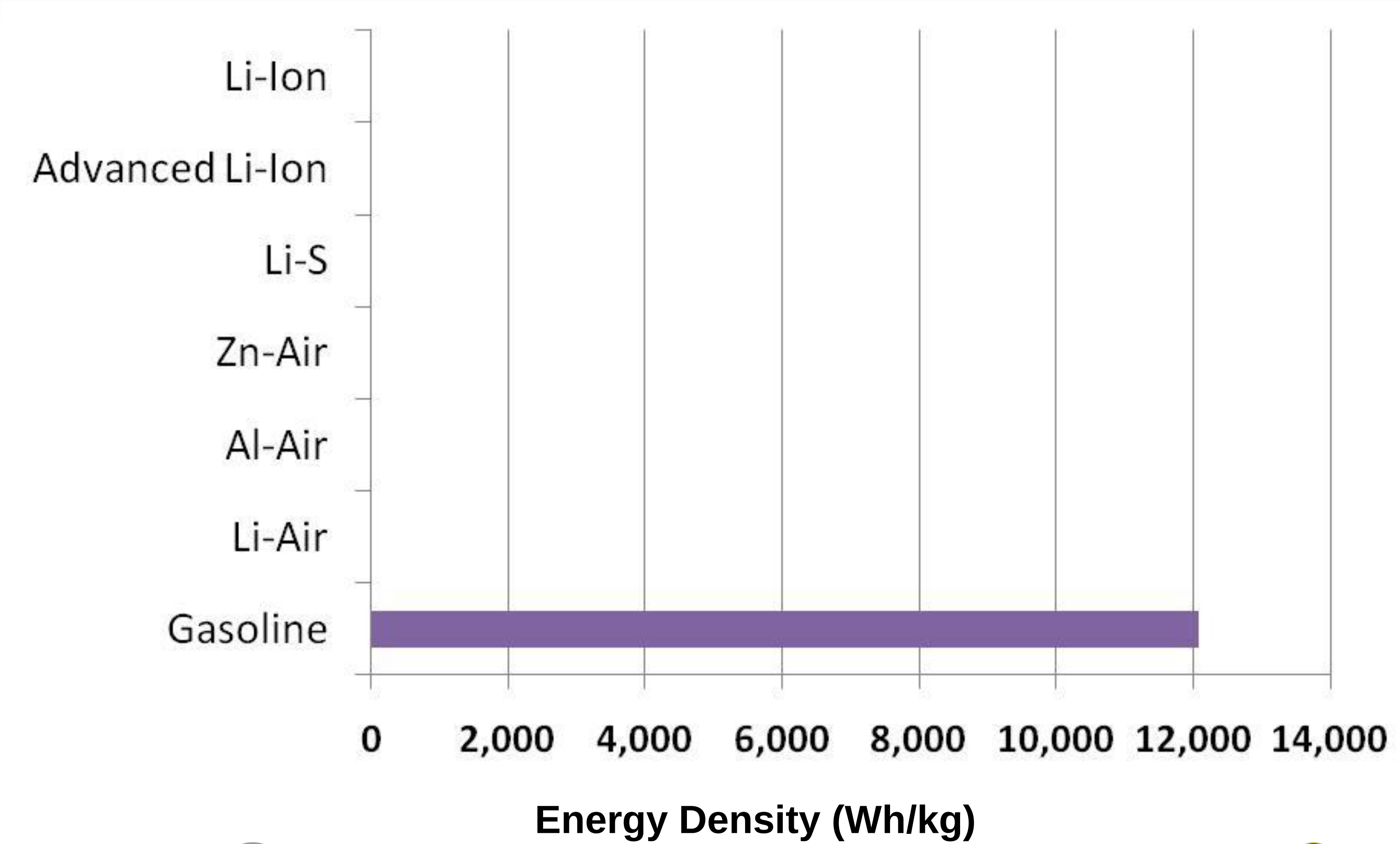
- Reduced Oil Imports
- Reduced Energy Related Emissions
- Lower & More Stable Fuel Cost
  (< $1.00/gallon of gasoline equivalent)

<u>PROBLEM</u>:

Current Battery Technology →

Insufficient Energy Density/Range, Too Expensive

Do batteries have the potential to rival the energy density of gasoline powered vehicles on a system level?



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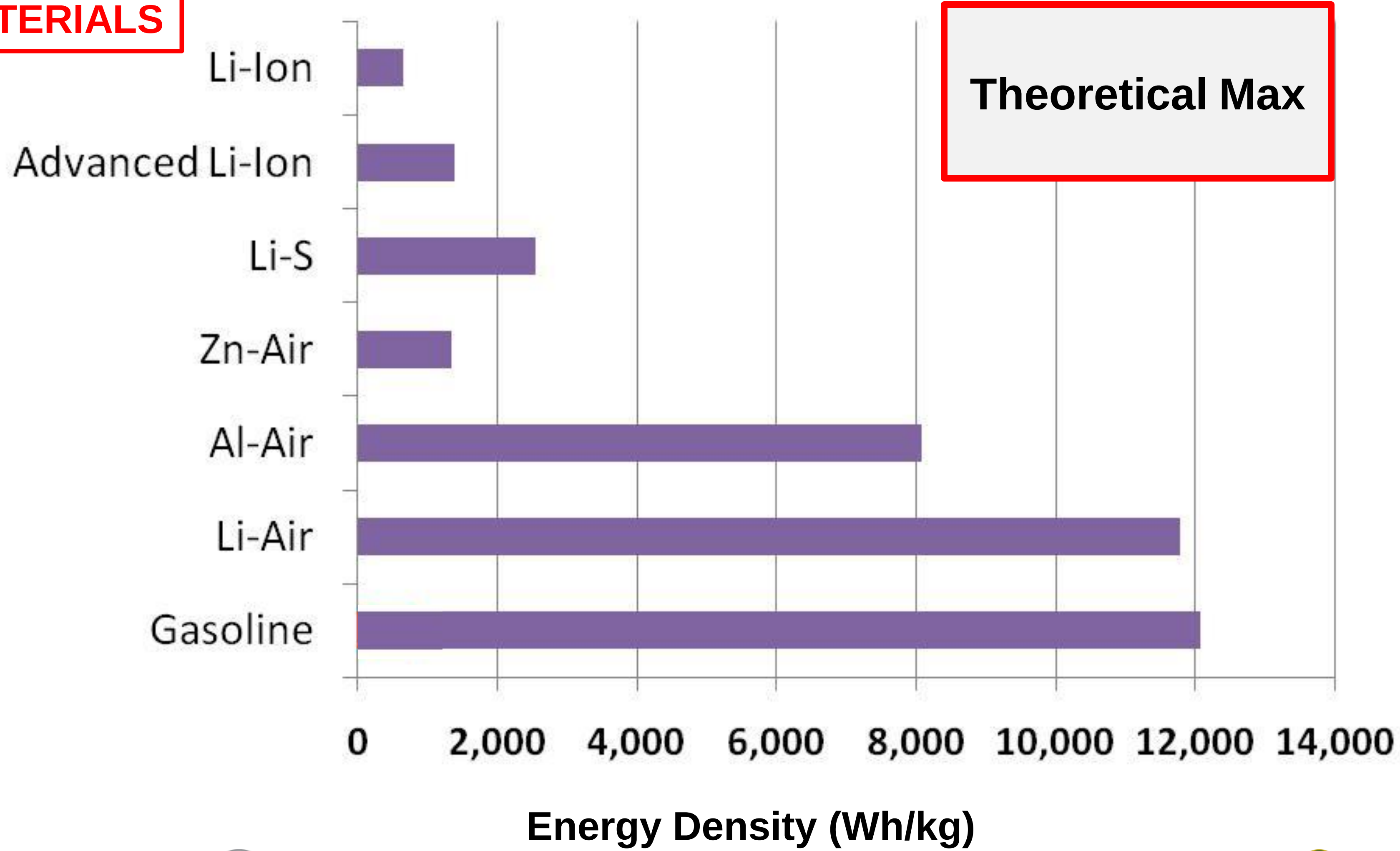
ACTIVE MATERIALS



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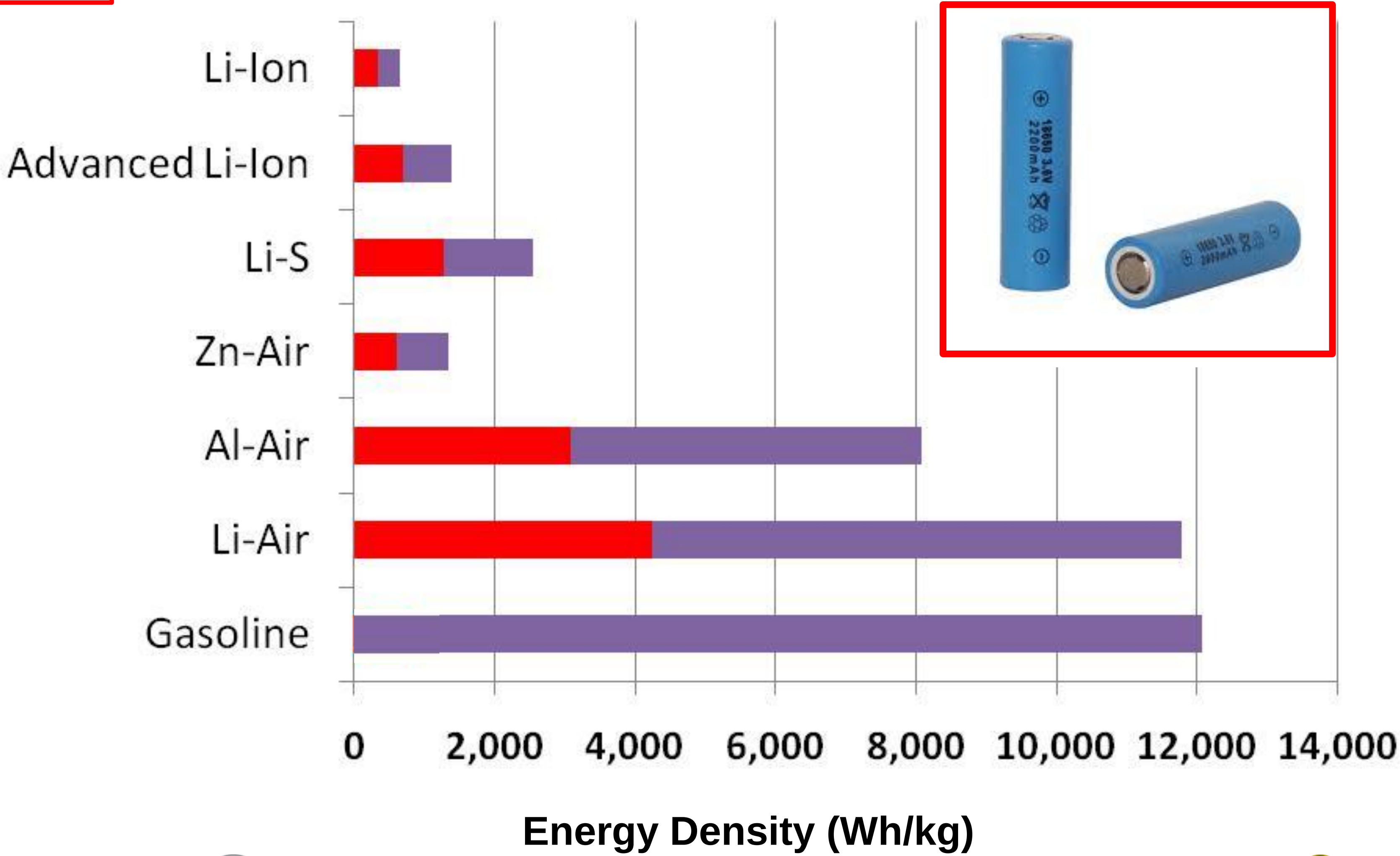
CELL



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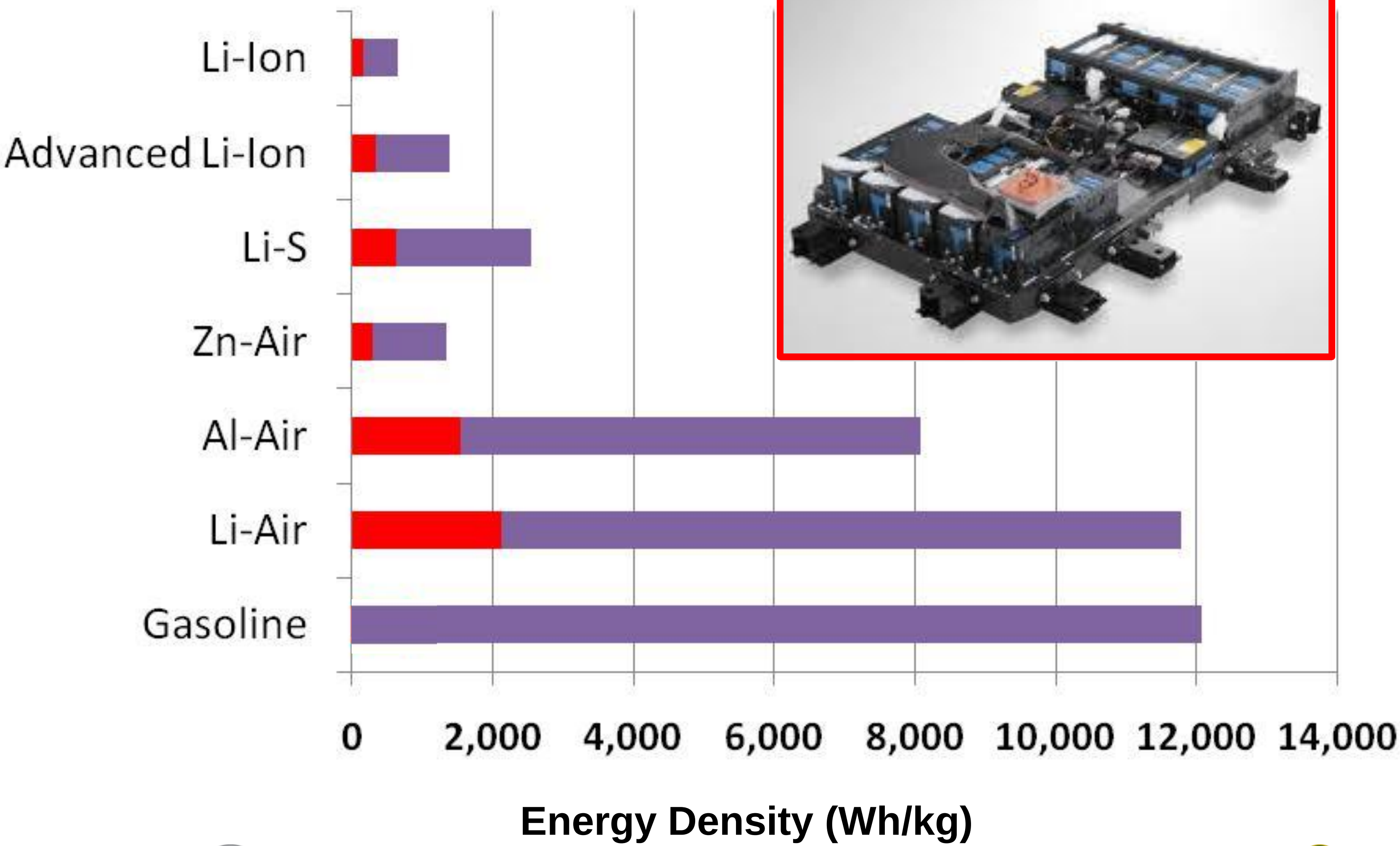
PACK



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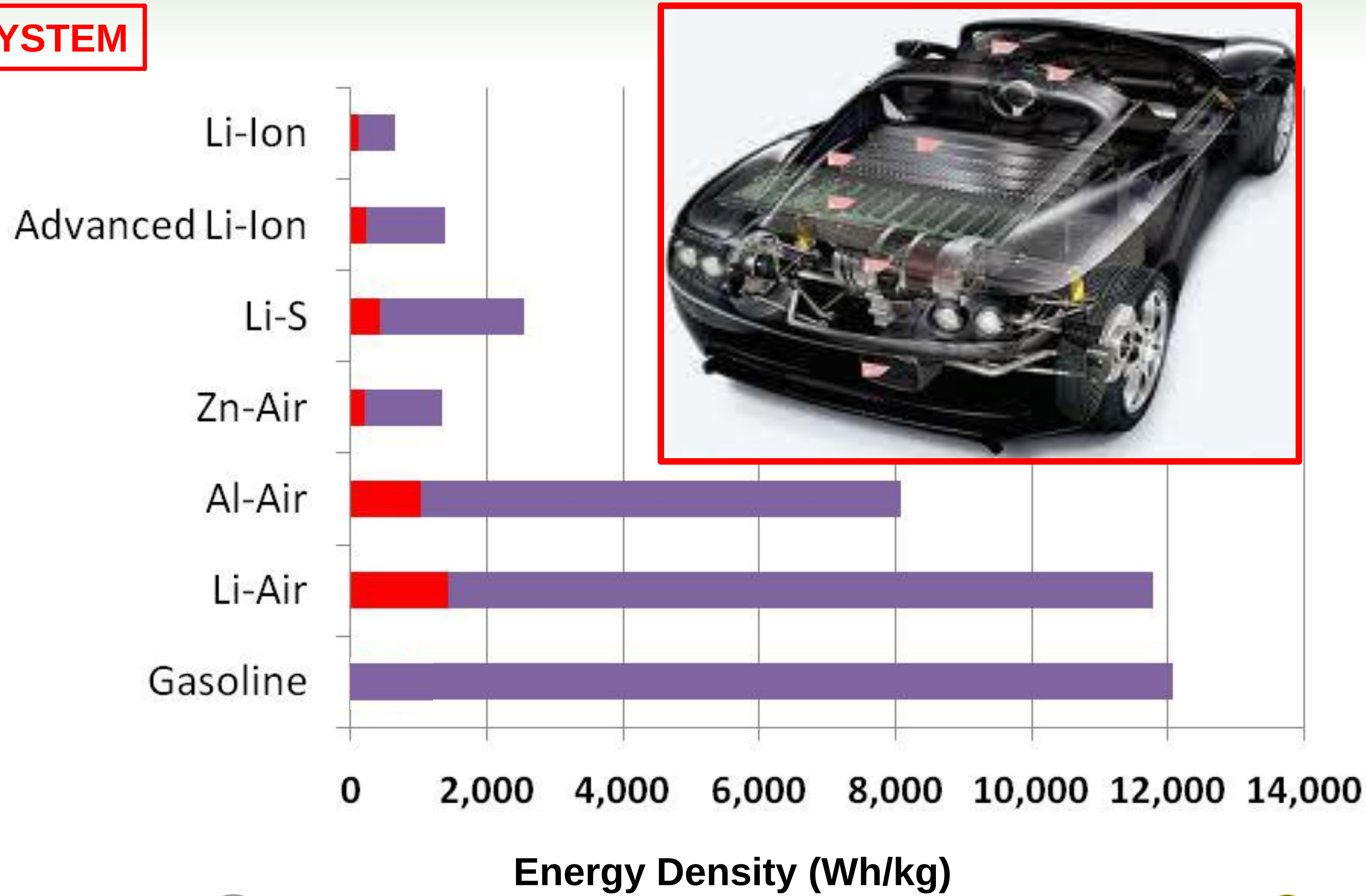
SYSTEM



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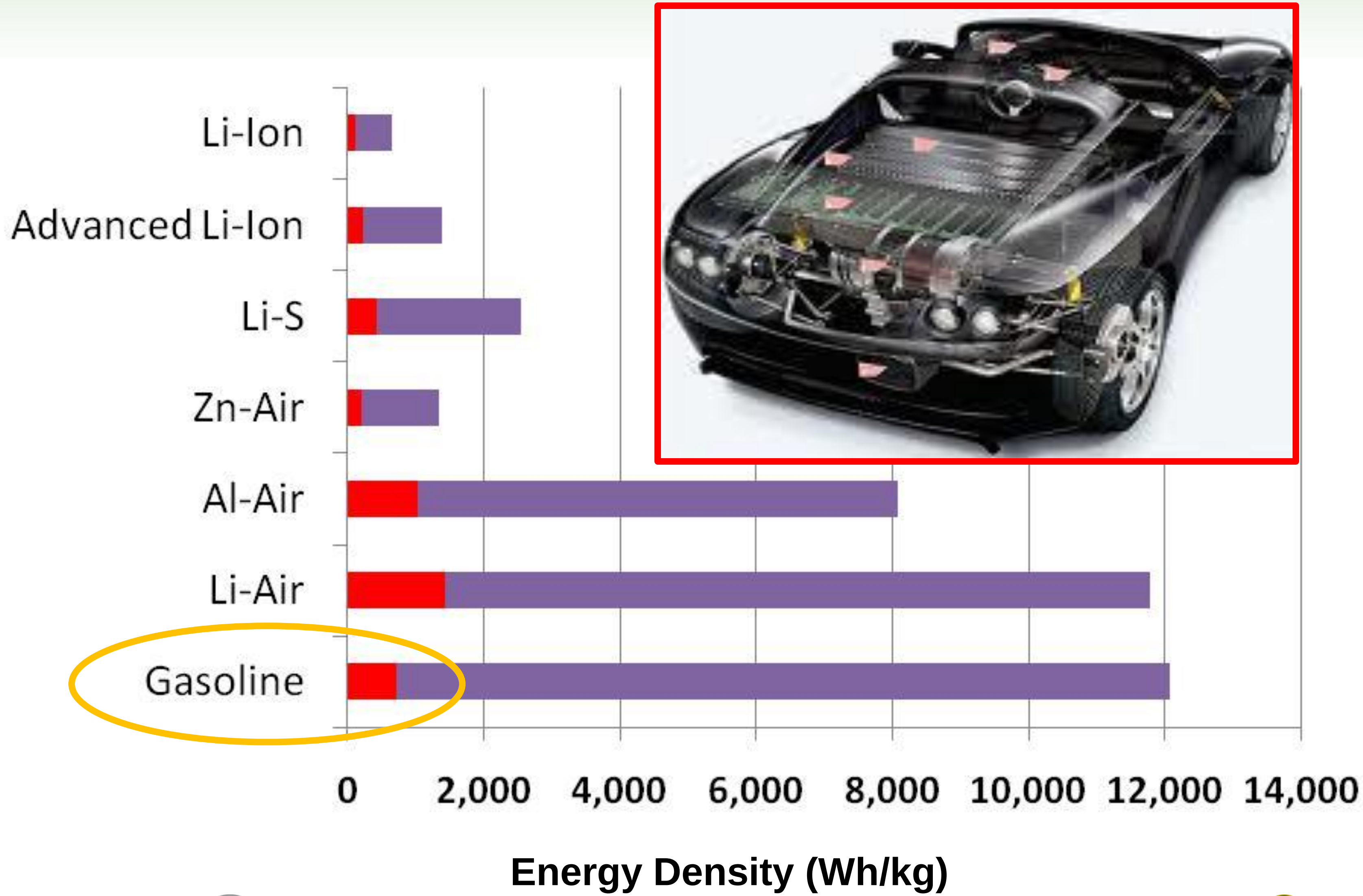
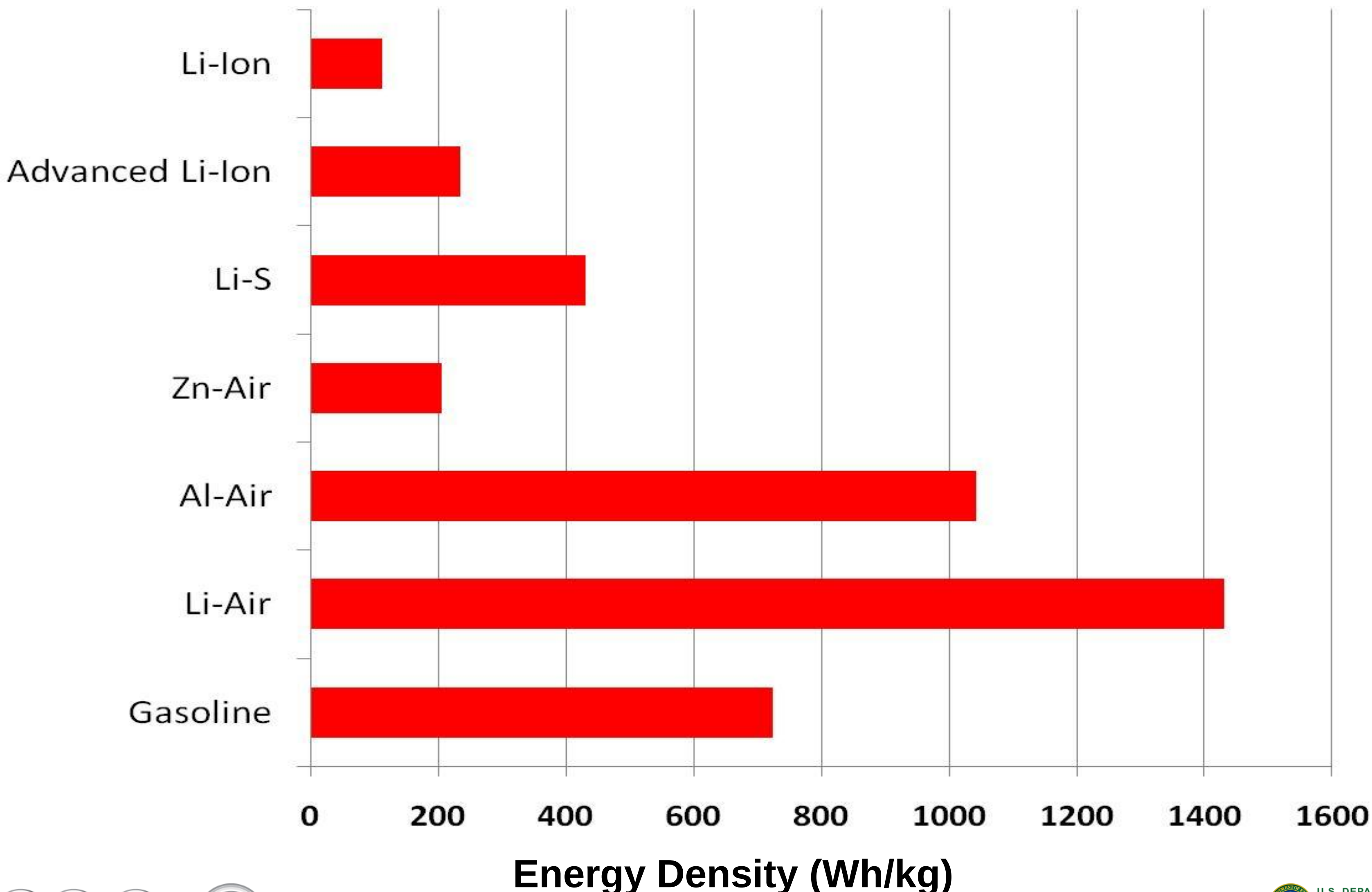


FACT: Batteries have the potential to rival the energy density of gasoline powered vehicles on a <u>system level</u>



Widespread Adoption of EV's Requires LONGER RANGE and COST Parity with Internal Combustion Engine Vehicles

COST: ICE Cost Benchmark ~ **24¢/mile**

RANGE: 250+ mile range needed to eliminate "range anxiety"

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Battery Pack Cost ($/kWh)	Discounted Vehicle Cost per Mile						
600	(0.22)	(0.27)	(0.32)	(0.37)	(0.42)	(0.47)	(0.52)
500	(0.21)	(0.25)	(0.29)	(0.34)	(0.38)	(0.42)	(0.46)
400	(0.20)	(0.24)	(0.27)	(0.30)	(0.34)	(0.37)	(0.40)
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Vehicle Range (mi)	50	100	150	200	**250**	**300**	**350**
Pack Energy (kWh)	12.5	25	37.5	50	62.5	75	87.5
Pack Energy Density (Wh/kg)	**42**	**83**	**125**	**167**	**208** →	**250**	**292**

ARPA-E BEEST Program Primary Goals: $52.8M/3 years

"Batteries for Electrical Energy Storage in Transportation"

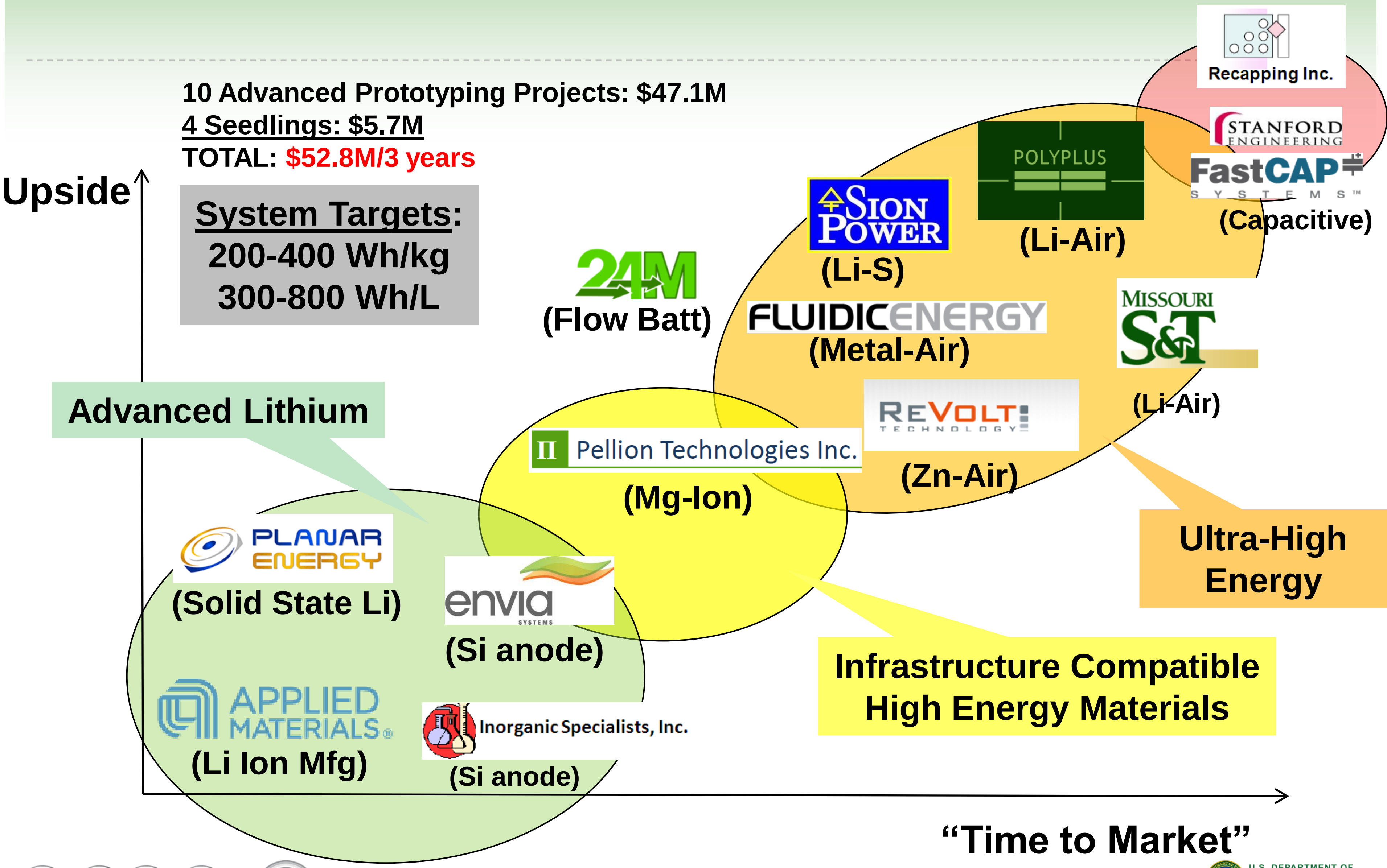
	RANGE		COST
BEEST	200+	300+	<250
	2x	1.5x	3x
Current	100	200	750
	System Energy (Wh/kg)	**System Energy (Wh/L)**	**System Cost ($/kWh)**

ARPA-E BEEST Program: Secondary Technical Targets

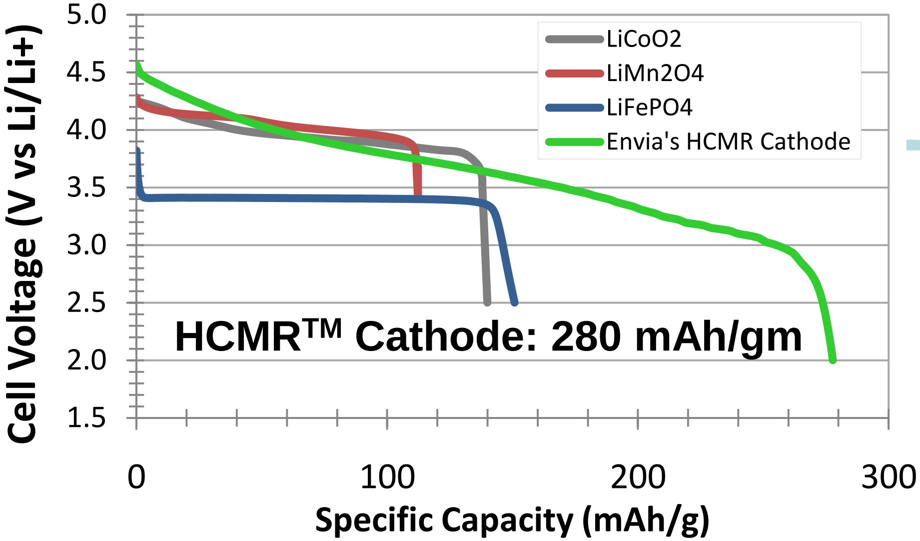
Target ID Number	Target Category	Description
2.1	Specific Power Density (80% Depth of Discharge, 30s)	**400 W/kg** (system) **800 W/kg** (cell)
2.2	Volumetric Power Density (80% Depth of Discharge, 30s)	**600 W/liter** (system) **1200 W/liter** (cell)
2.3	Cycle Life	**1000 cycles** at 80% Depth of Discharge (cell/system), with cycle life defined as number of cycles at which a >20% reduction in any energy/power density metric occurs relative to the initial values
2.4	Round Trip Efficiency	**80%** at C/3 charge and discharge
2.5	Temperature Tolerance	**-30 to 65C**, with <20% relative degradation of energy density, power density, cycle life and round trip efficiency relative to 25C performance
2.6	Self Discharge	**<15%/month** self-discharge (of initial specific energy density or volumetric energy density)
2.7	Safety	Tolerant of abusive charging conditions and physical damage without catastrophic failure
2.8	Calendar Life	**10 Years**

BEEST Portfolio: Advanced Chemistries & Manufacturing

10 Advanced Prototyping Projects: $47.1M
4 Seedlings: $5.7M
TOTAL: $52.8M/3 years

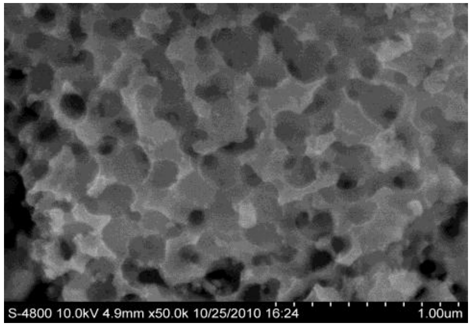


Envia Systems (Newark, CA): $4.0M/2 years
"400 Wh/kg Li-ion Battery" vs 220 Wh/kg state-of-the-art



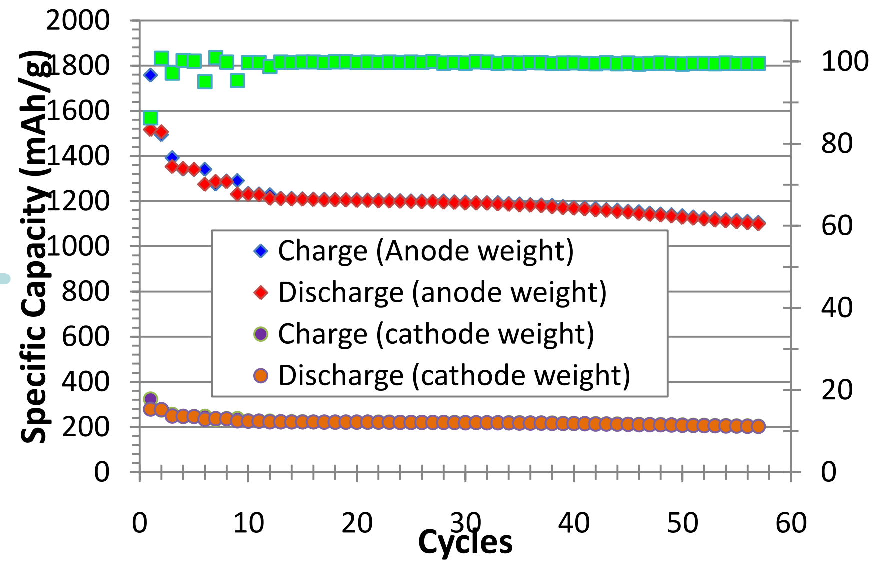
Silicon-Carbon Composite Anode

Capacity:
1200 mAh/g



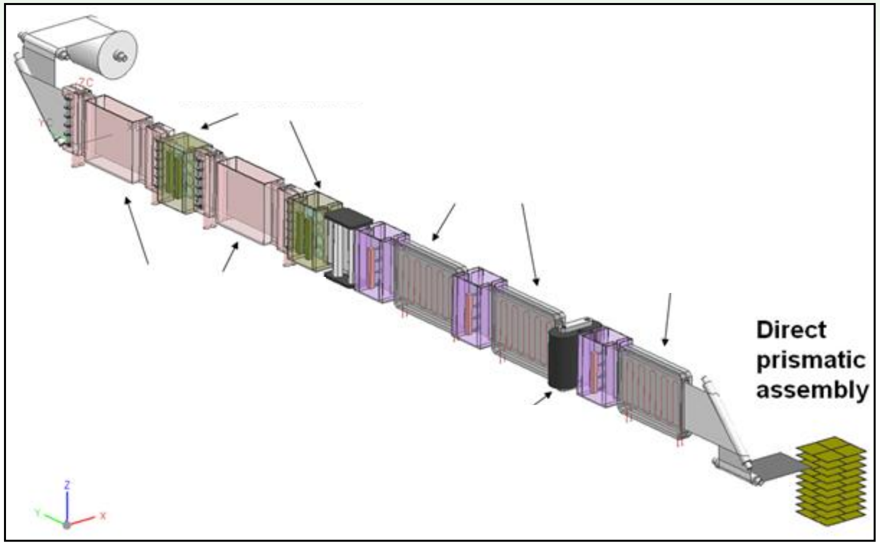
<u>Current Status</u>:

High energy cells in coin cell format exceeding over 100 cycles



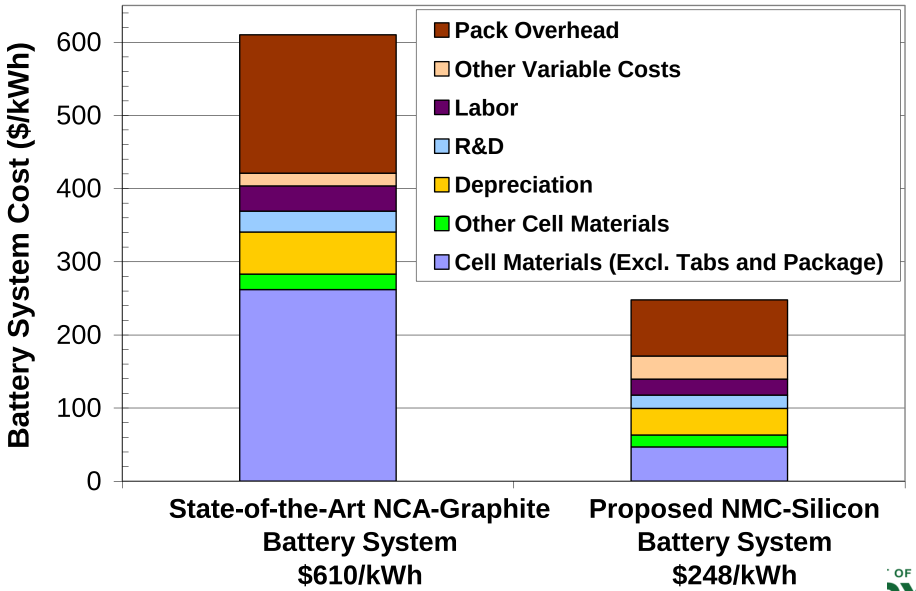
- **$17M follow-on led by GM Ventures**
- **GM agreement to use Envia cathode in next generation Chevy Volt**

Applied Materials (Santa Clara, CA): $4.4M/2.5 years
(Bringing the leading semiconductor equip company into battery manufacturing)

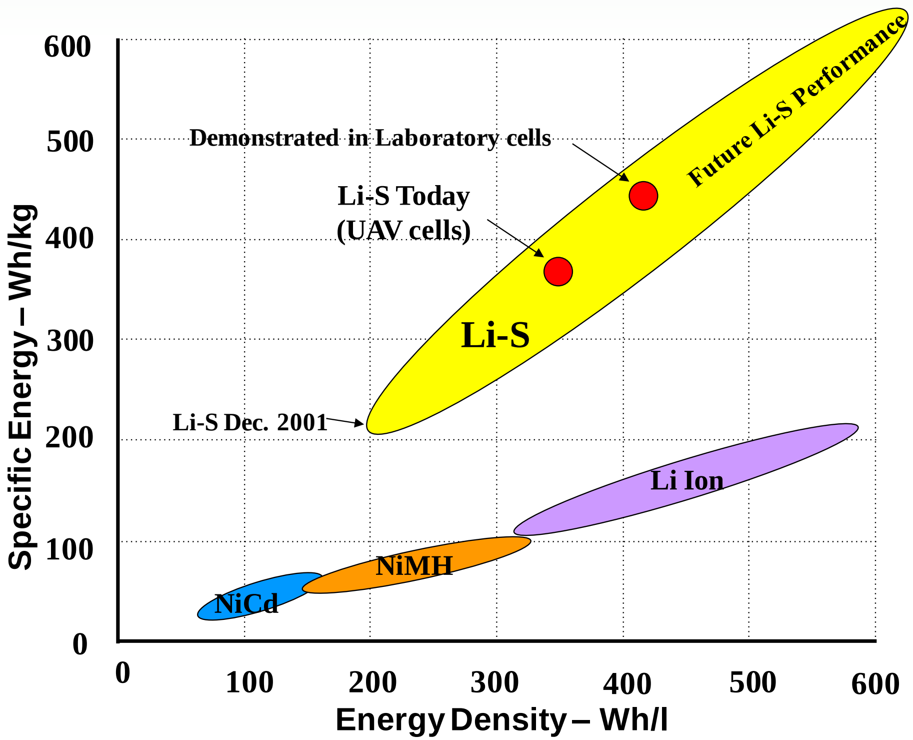


- Platform manufacturing technology
- Dramatic reduction in factory footprint
- 50% reduction in factory cost; battery cost
- Advanced Li-ion materials

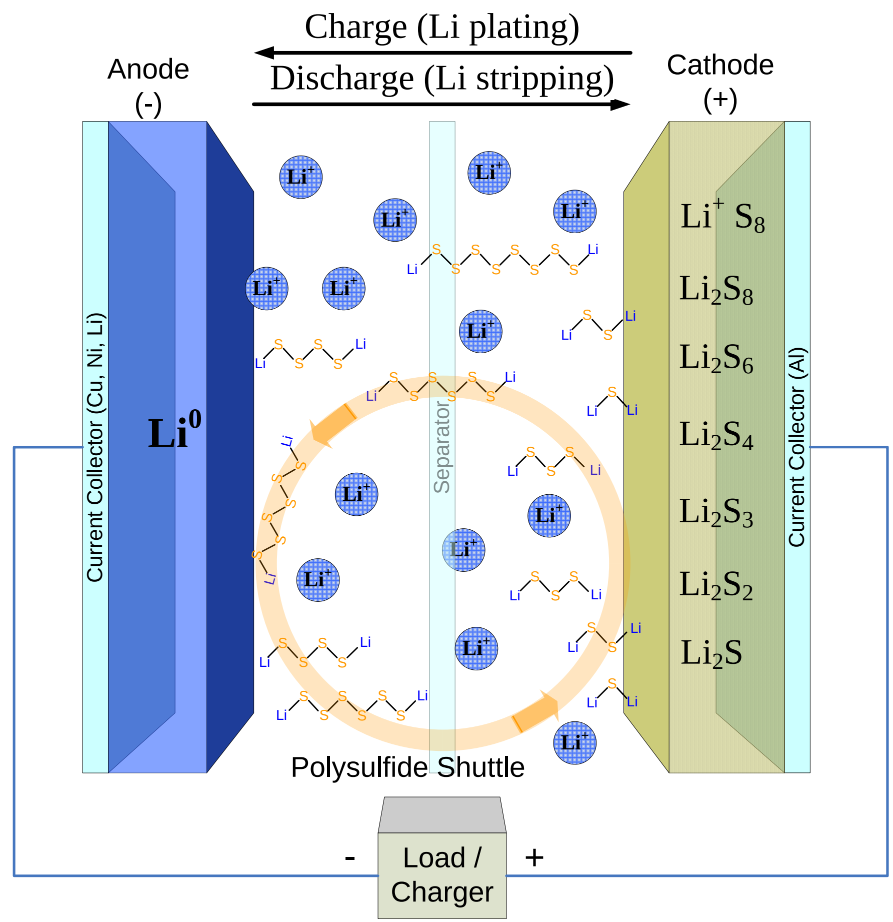
- High capacity cathode: porosity graded
- High capacity Si-based anode
- Integrated low cost separator



Sion Power (Tucson, AZ): $5.0M/3 years

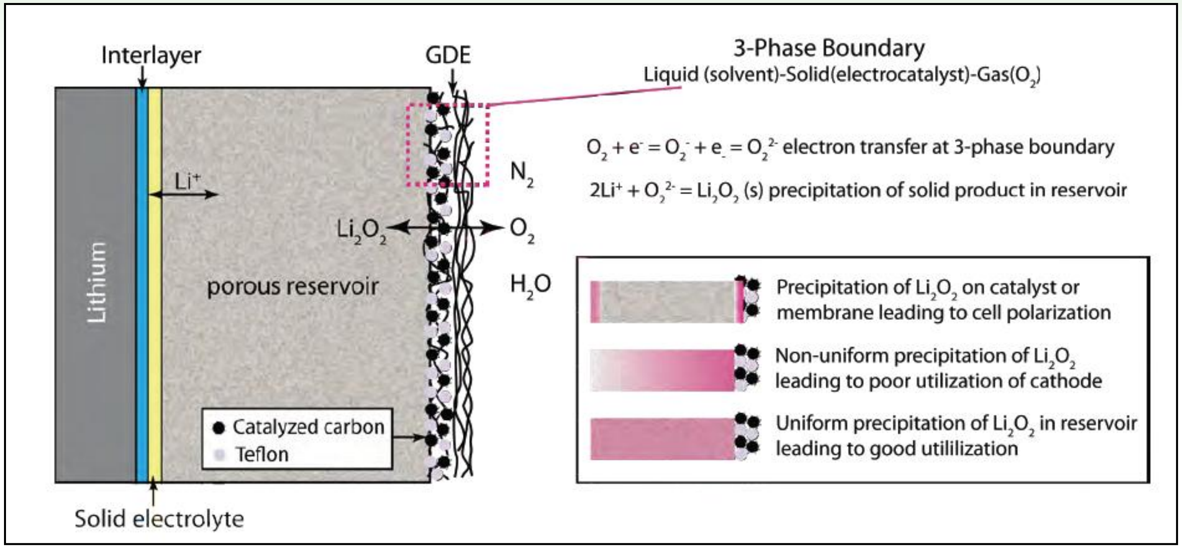


Li: 3,860 mAh/g (vs 370 for graphite)
S: 1,672 mAh/g (vs ~200 for Li-ion cathode)

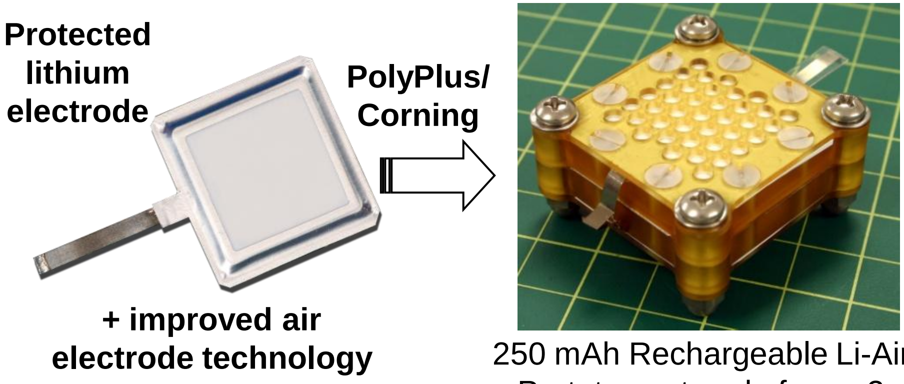


PolyPlus Battery Company (Berkeley, CA): $5.0M/2 years

- The Holy Grail of Rechargeable Batteries -



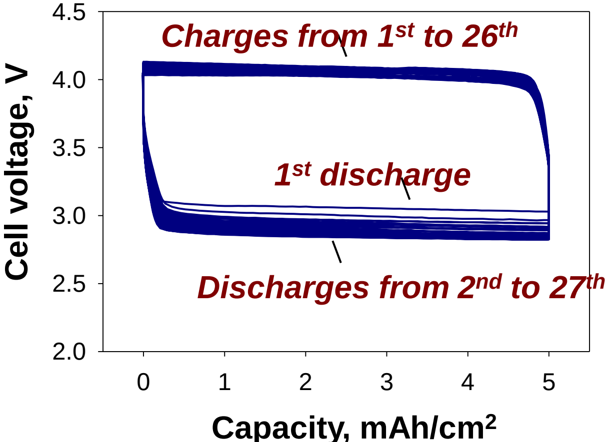
Li: 3,860 mAh/g
O_2: 1,675 - 3,350 mAh/g



250 mAh Rechargeable Li-Air Prototype at end of year 2

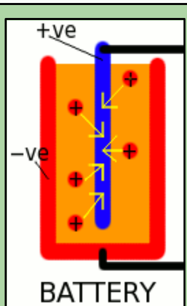
Project Targets: 600 Wh/kg,1000 Wh/l, 1000 cycles

Discharge/charge rate: 1.0/0.5 mA/cm²
Discharge/charge capacity: 5.0 mAh/cm²

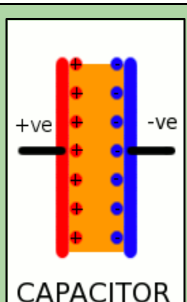


FastCAP Systems (Boston, MA): $6.7M/2.5 Years

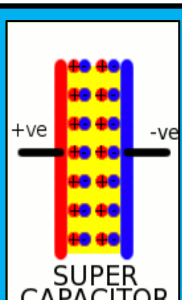
Superconductors are faster cycling than batteries, but store less enegy



Batteries store energy using chemical reactions between an electrolyte and positive and negative electrodes



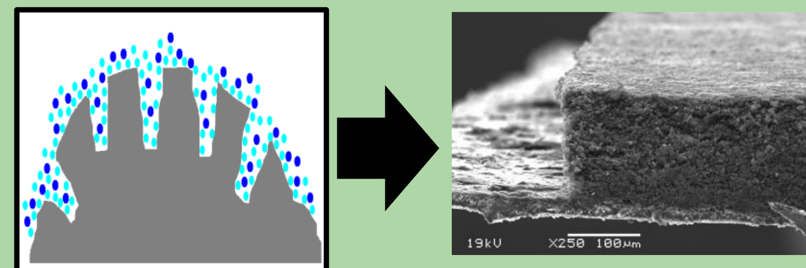
Capacitors store static electricity by building up opposite charges on two metal plates



Supercapacitors store more energy by utilizing a double layer of separated charges between two plates made of porous carbon materials.

Fastcap supercapacitors will compete with today's lithium ion batteries

Today's supercapacitor carbon supports are low surface area, subject to degradation and self-discharge



Fastcap substrates are high-surface area, much more durable, and can hold more charge at higher voltages than SOTA.