GE
Aviation
Systems

Advanced battery systems for More Electric Aircrafts (MEA)

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GE Proprietary Information
For Internal Use Only

Mega trends … requires advances in energy storage technologies

1 **Fuel**

2 **Emission**

3 **Connectivity**

Electrification of Transportation

More/all Electric Aircrafts:

Hybrid/Electric Vehicles:






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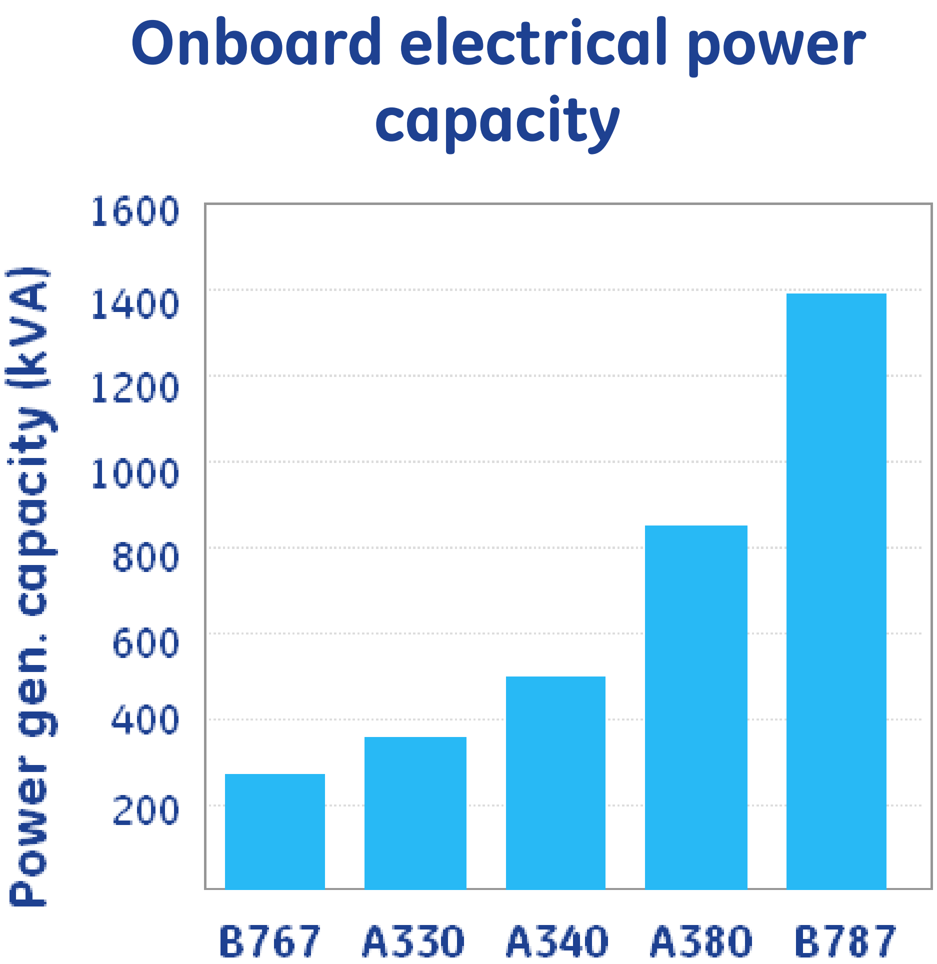
More electric aircrafts (MEA) & drivers



- Efficiency
- Maintainability
- Reliability/redundancy
- Power system flexibility & Utility
- Availability
- Power management
- Reduced power extraction
- Reduced life cycle costs
- Lower emission

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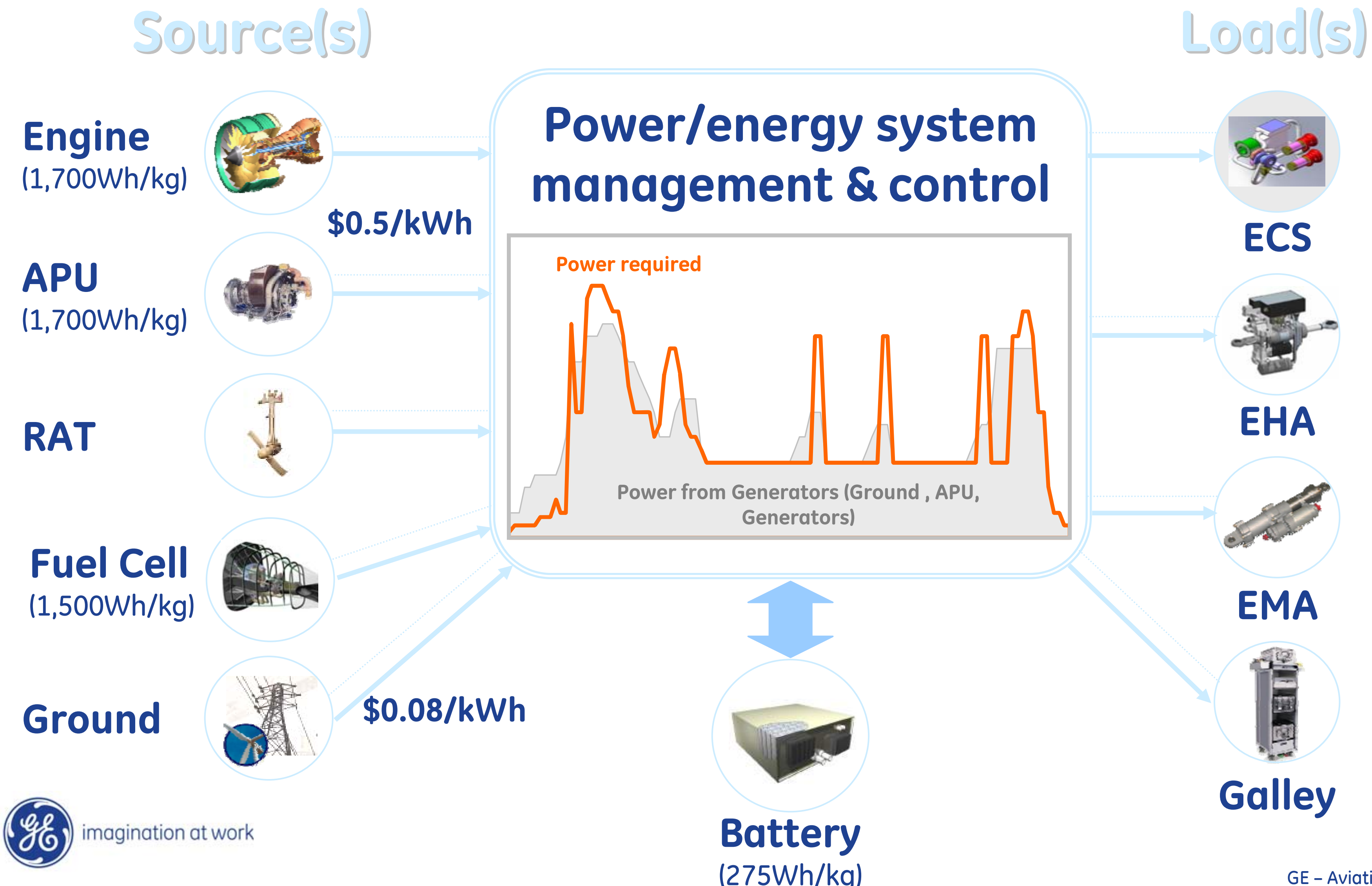
Energy storage in MEA … SmartGrid on aircraft



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What type of a battery … it depends

Functionality Needs

Today

- ☑ Improving power quality
- ☑ Reducing peak loading of generator

Power Battery

Tomorrow

- ☑ Emergency power
- ☑ Arbitrage
- ☑ All electric flight power

Energy Battery

Selection criteria

- Charge, discharge rate
- Life
- Weight & space
- Environment specific performance
- Maintenance
- Cost

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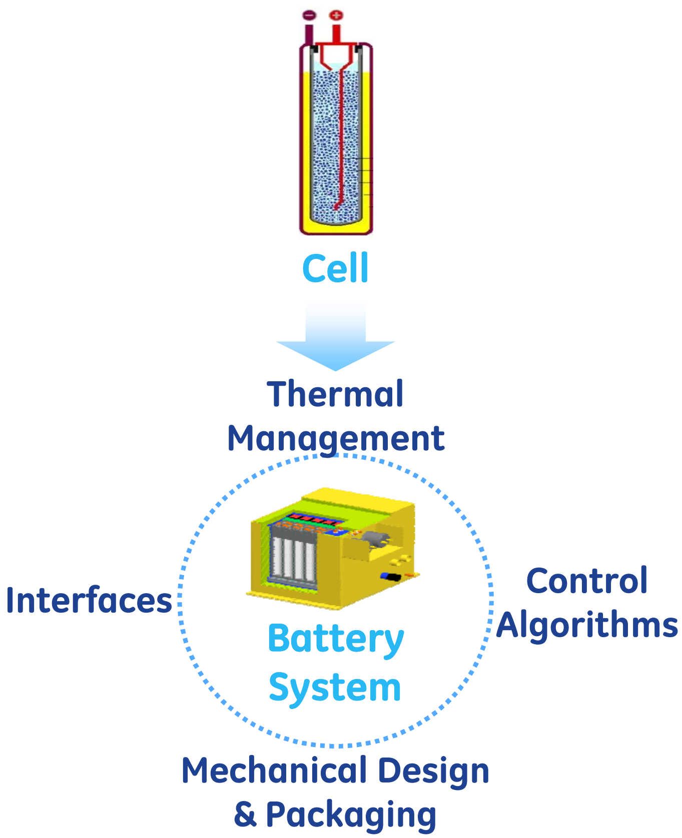
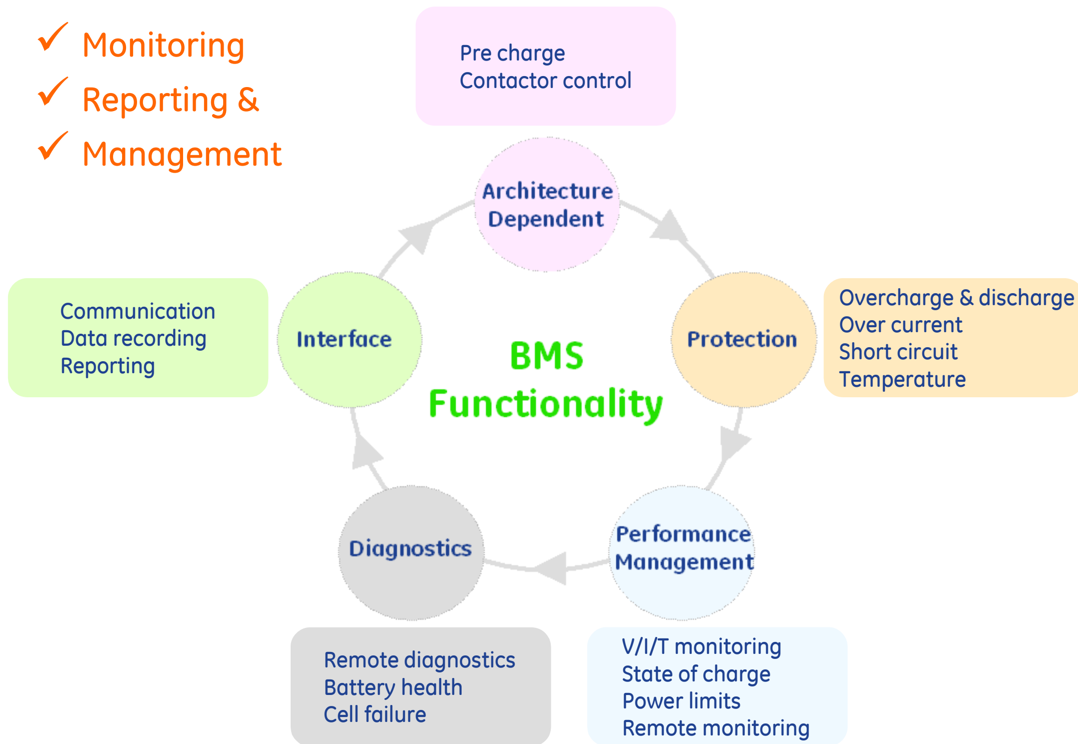
Advanced battery system … requires optimal design per application

Battery construct



Battery management system

- ✓ Monitoring
- ✓ Reporting &
- ✓ Management



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Battery technologies … characteristics & entitlement cost points

	PbA	Power Battery			Energy Battery		
		NiCd	NiMH	Li Ion (Power)	Li Ion (Energy)	GEMx	NaS
		(Nickel based)				(Sodium based)	
Energy Density (Wh/L)	40–90	40-70	60–100	90 - 120	145 - 195	150-200*	170
Specific Energy (Wh/kg)	35–50	30–50	40-80	60-93	95-120	100-125	129
Specific Power (W/kg)	10-200	100-800	170-1000	1100-2000	120 - 380	90-200	16
Life (years)	5	20	10	≥ 10	≥ 10	≥10	15
Maintenance	Yes	Yes	No	No	No	No	No
Toxic Material	Yes	Yes	No	No	No	No	No
Memory Effect	No	Yes	No	No	No	No	No
High Temp. Performance	Degradation					No impact	
Tech. Maturity	Mature	Mature	Mature	Developing	Developing	Partial	Mature
Entitlement* Costs ($/kWh)	$140	$600	$525*	$405	$250	$130-$200	$140
Entitlement Costs ($/kW)	$57	$53	$54	$20	$110	$150	$1,120

*** Entitlement Cost:** Potential production cost when all cost reduction steps are taken, technology is mature and scale benefits are fully realized.

✓ (Li Ion (Power)) ✓ (GEMx)

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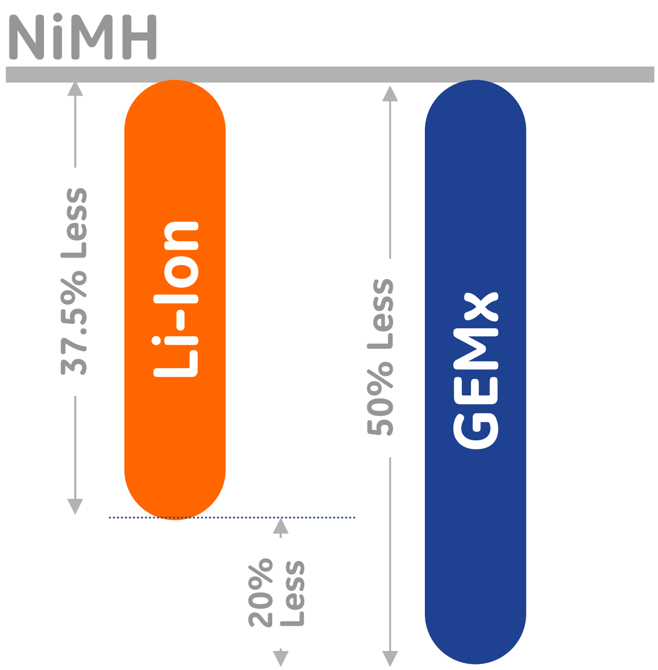
* 2kWh module

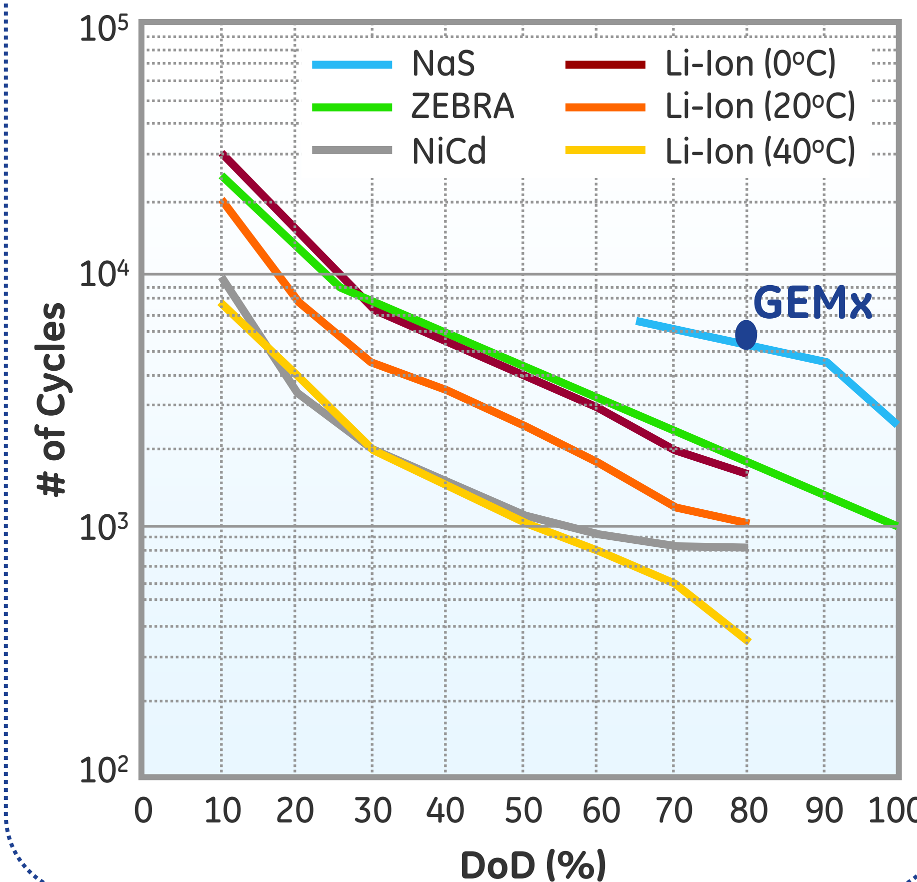
Source: Argonne National Laboratory, Jan 2008; ABIResearch; NGK; Cobasys

Relative cost and life ... life cycle costs

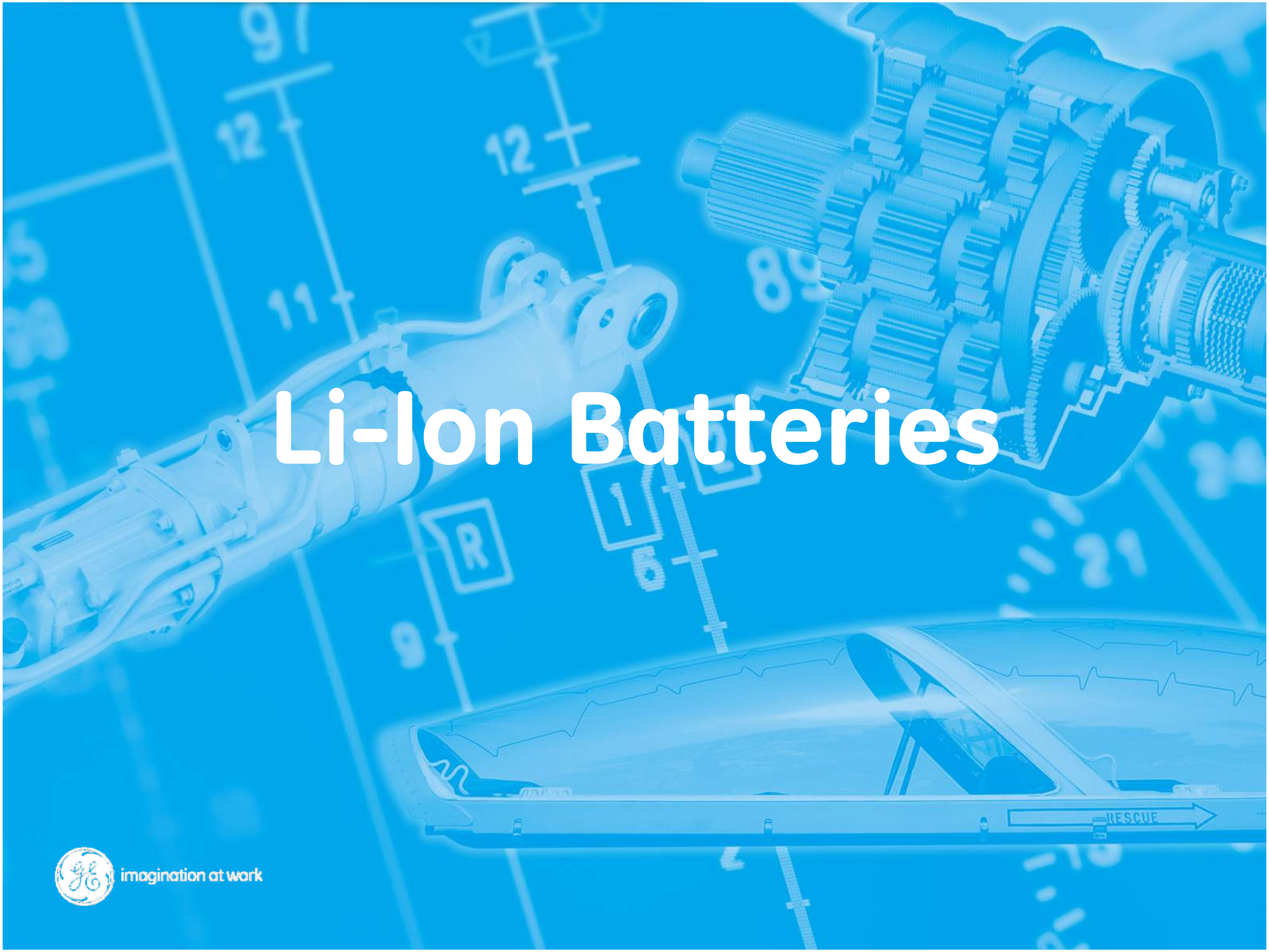
Projected entitlement mfgr. cost Relative to NiMH ($/kWh)



Projected cycle life performance



Source: 2007 ZEV Panel Vehicle Projection ... multiple manufacturers' data – to – average, ABB, GE Analysis & testing



Li-Ion Batteries

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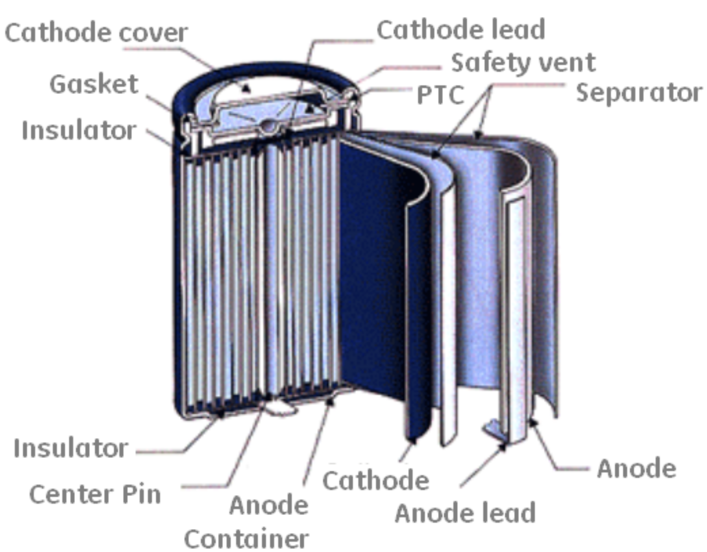
Li-Ion cell constructions

Cylindrical Cell Structure

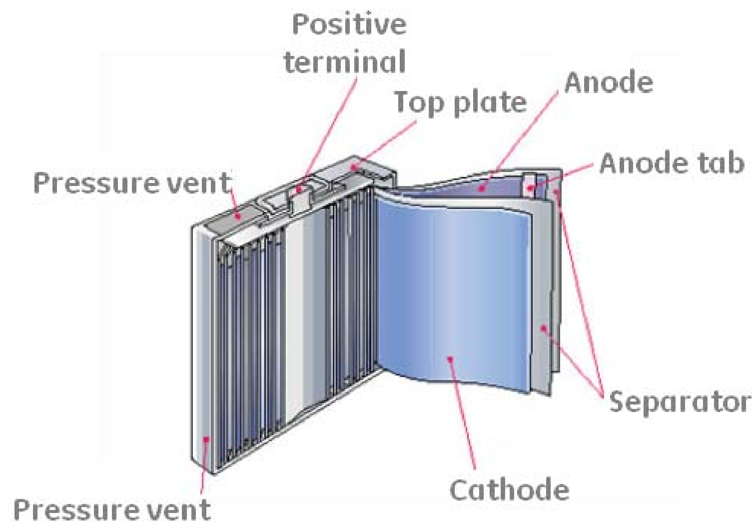


Advantages

- Ease of manufacture
- Good mechanical stability (withstand high internal pressures)

Thermal Map*

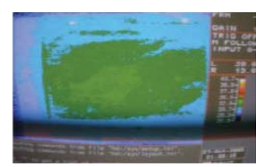
Prismatic Cell Structure



Advantages

- Packaging advantage … space utilization
- Improved thermal performance … for power application

Thermal Map*

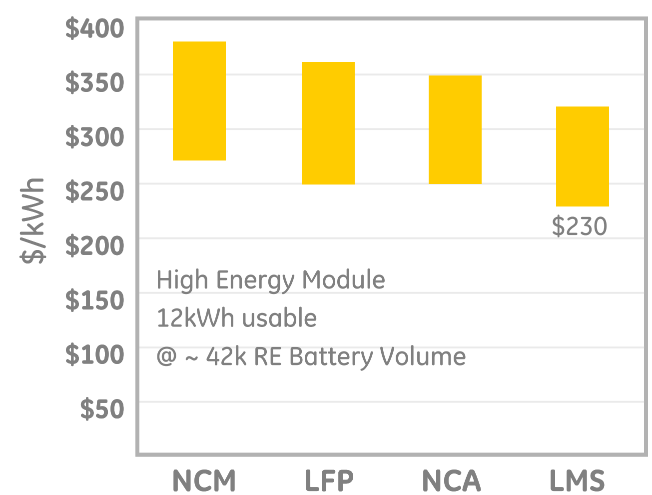


Li-Ion chemistries … overview & trade offs

Cathode Chemistries	Storage Capacity [mAh/g]	Normal Voltage [V]	Wh/kg	Wh/L	Material Cost Range	
					$/kg	$/kWh
$LiCoO_2$ (LCO)	145	4.0	602	3,073	$30-40	$57-75
$Li(Ni_{0.85}Co_{0.1}Al_{0.05})O_2$ (NCA)	160	3.8	742	3,784	$28-30	$50-55
$Li(Ni_{1/3}Co_{1/3}Mn_{1/3})O_2$ (NCM)	120	3.85	588	2,912	$22-25	$30-55
$LiMn_2O_4$ (LMS)	100	4.05	480	2,065	$8-10	$20-25
$LiFePO_4$ (LFP)	150	3.34	549	1,976	$16-20	$25-35

- **LCO** …Been around for long (matured)
- **NCA** … Best life and density
- **NCM, LMS** … Degradation through dissolution of manganese; LMS – more stable b/c spinal crystal structure
- **LFP** … Very new: (1) safe on overcharge (2) low density (3) low cell voltage … more cells required

Projected Li-Ion Battery Mfgr. Costs



Source: Argonne National Lab (Jan, '08); EPRI (Feb, '08)

Li-Ion chemistries … library for desired CTQ (ranked)

	Energy	Power	Life	Safety	Cost
Anode	[1] Graphite [2] Hard Carbon [3] LTS/nanoLTS*	[1] Graphite [2] LTS/nanoLTS* [3] Hard Carbon	[1] LTS/nanoLTS* [2] Hard Carbon [3] Graphite	[1] LTS/nanoLTS* [2] Hard Carbon [3] Graphite	[1] Graphite [2] Hard Carbon [3] LTS/nanoLTS*
Cathode	[1] NCA [2] NCM [3] LCO [4] LFP [5] LMS	[1] LMS [2] LCO [3] NCM [4] NCA [5] LFP	[1] LFP [2] NCA [3] NCM [4] LCO [5] LMS	[1] LFP [2] LMS [3] NCM [4] LCO [5] NCA	[1] LFP [2] LMS [3] NCM [4] NCA [5] LCO

Liquid electrolyte is better for power and cost but NOT for safety …

Potential causes of thermal runaway …
(1) Overcharge
(2) Excessive environmental temp.
(3) Internal/External short circuits

Managed by (IEEE 1725) …
- ✓ Pack design
- ✓ Charge control
- ✓ Power supply accessory

* LTS … Li Ti Spinel

Source: USABC, GE

Selecting a supplier

Company	Li-Ion Chemistry		Cell Shape	Performance Focus Areas
	Cathode	Anode		
A123	LFP	Graphite	Cylindrical	Cost, life, safety
AltairNano	NCM/LCO	nanoLTS	Prismatic	Safety, low temp., power/energy
EnerDel	LMS	LTS	Prismatic	Power, safety, cost
GS Yuasa	LMS/NCA	Hard carbon	Prismatic	Power/Energy, safety
Hitachi	NCM/LMS	Hard carbon	Cylindrical	Power, safety, cost
LG Chem.	LMS	Hard carbon	Prismatic	Power, safety, cost
LTC	LFP	--	Cylindrical	Cost, life, safety
NEC-Lamilin	LMS/NCA	Hard carbon	Prismatic	Power/Energy, safety
Panasonic	NCM	Blend	Prismatic	Energy, cost
Samsung	LMS/NCM	Graphite	Cylindrical	Power/Energy, cost, safety
Saft	NCA/LFP/LCO	Graphite	Cylindrical	Energy, life, cost, safety
Sanyo	NCM/LMS	Blend	Cylindrical	Power, safety, cost
SK Corp.	LMS	Graphite	Prismatic	Power, cost safety
Toyota	NCA	Graphite	Prismatic	Energy, life

Selection criteria:

1. **Chemistry meeting application needs**
2. **Application / system engineering**

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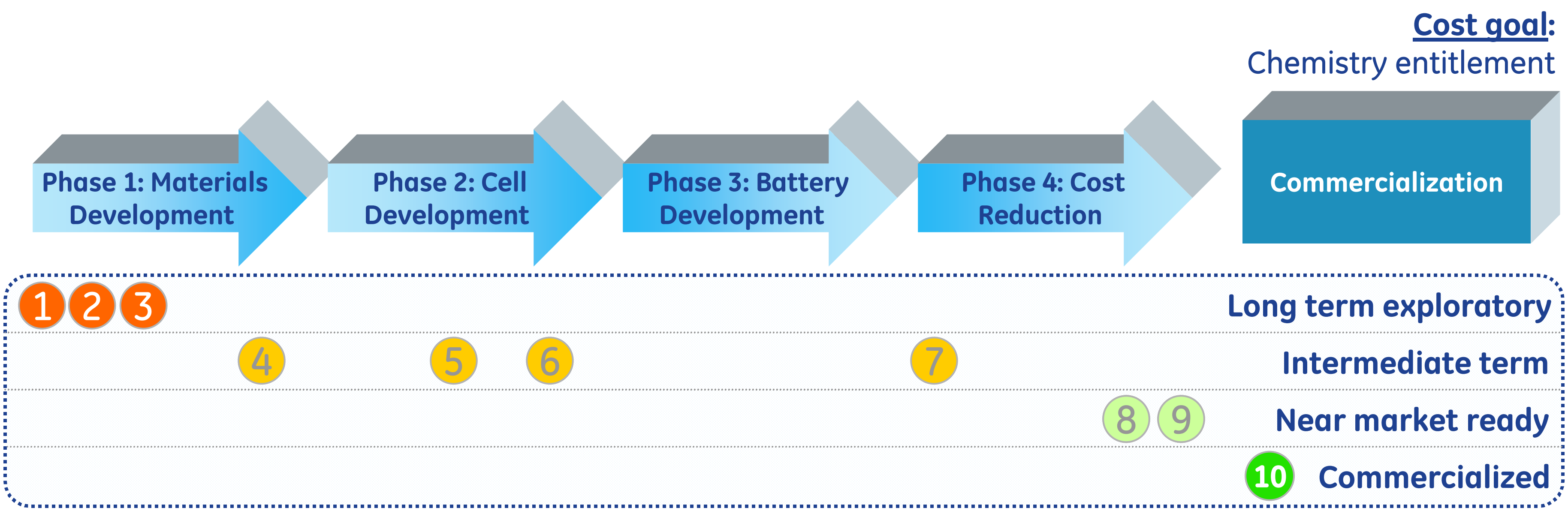
Source: Argonne National Lab (Jan, '08); Idaho National Lab (Sept, '08); GE

State of technology & roadmap …



1. **Li Metal Polymer**
2. **Li/Sulfur system**
3. **Li alloy/high V TMO system**
4. **Li titanate/Mn spinel (LMS)**
   - EnerDel
5. **Graphite/Mn spinel (LMS)**
   - SK, Samsung, Sanyo, Hitachi
6. **Graphite/Iron phosphate (LFP)**
   - A123, Saft, LTC
7. **Graphite/Nickelate (NCA)**
   - Saft, Toyota, NEC
8. **Ultracapacitors**
   - Nesscap, Maxwell
9. **Low cost separators**
   - Celgard, UMT, AMS
10. **NiMH**
    - Cobasys, Saft, Varta

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Source: Argonne National Lab (Jan, '08); Idaho National Lab (Sept, '08); DOE

Sodium Batteries

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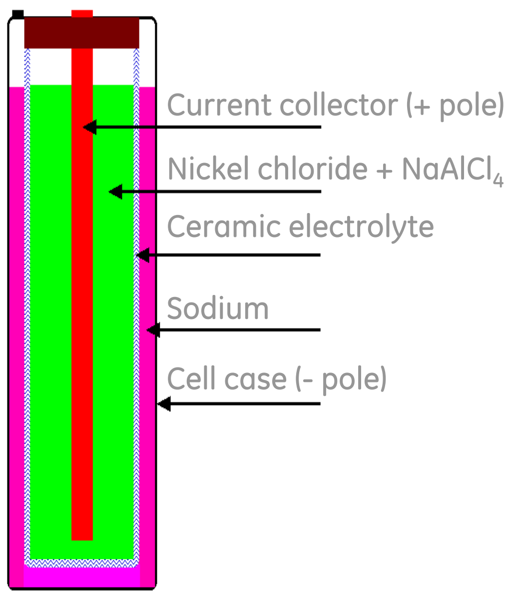
GEMx battery system

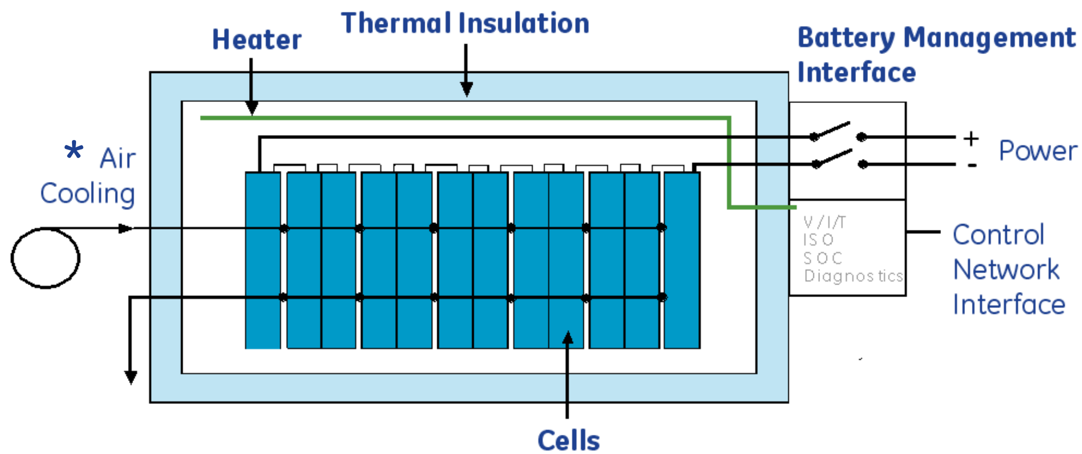
Cell

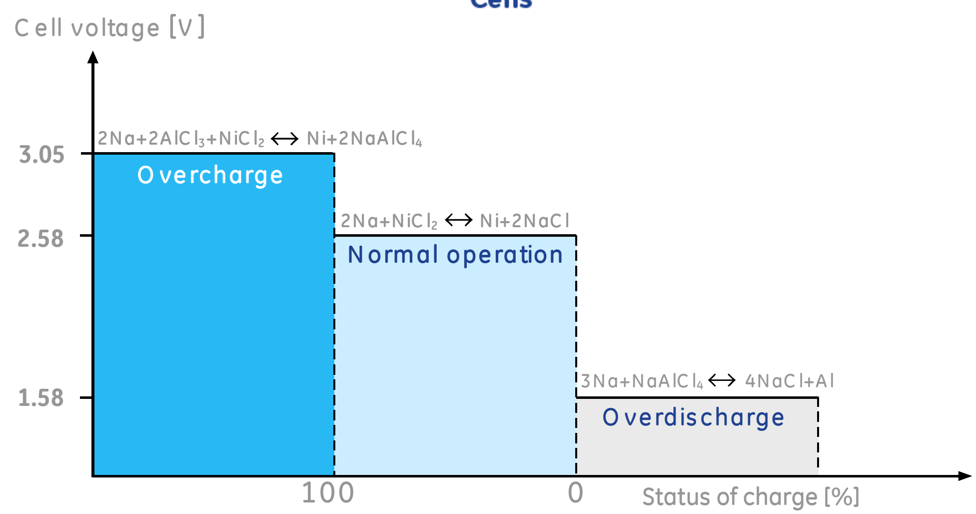


Reaction

$$Ni + 2NaCl \Leftrightarrow 2Na + NiCl_2$$

Battery Construction





* Cooling might require for fast discharge I.e. 15mins and need to reuse ≤12hr

Battery features … GEMx

Energy battery

	PbA	NiCd	NiMH	GEMx	
Energy Density (Wh/L)	40–90	40-100	80–200	150-200*	✓
Specific Energy (Wh/kg)	35–50	40–70	60-110	100-125	✓
Specific Power (W/kg)	10-200	100-800	170-1,000	90-200	Adequate
Life (years)	5	20	10	$\geq$10	✓
Maintenance	Low	Low	No	No	✓
Toxic Material	Yes	Yes	No	No	✓
Memory Effect	No	Yes	No	No	✓

✓ **No high overvoltage safety problem …**
- Cells fail to a low resistance short

✓ **Abuse resistant**
- Overcharge reaction enables cells to be abuse resistant

✓ **Wide ambient operating temperature … -20 to 70°C**
- High temperature chemistry

✓ **Suitable for HV series connection because of partly solid electrolyte**

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* Current GEMx up to 180Wh/l; next generation to go up to 200Wh/l

Technology potential

	Performance	Potential Readiness Timing
1st Gen.	Energy: 150 Wh/L Power: 200 W/L	2012
2nd Gen.	Energy: 200 Wh/L Power: 250 W/L	2013
3rd Gen.	Energy: 200 Wh/L Power: 350 W/L	2014

25% – 30% cost improvement

Likely aviation solution

Dual battery OR battery – fuel cell solution based on architecture

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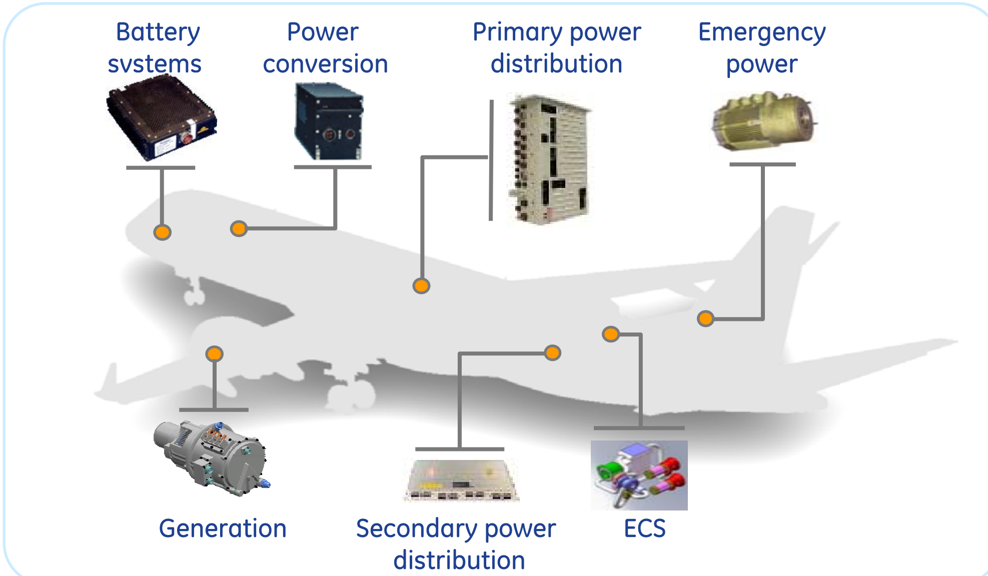
System integration labs in GE

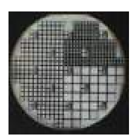
Enables trade studies and energy mgt. systems



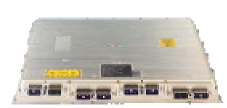
Key technologies & capabilities

Fuel Cells & Integration

Battery technologies
(Li-Ion, Sodium)
& integration



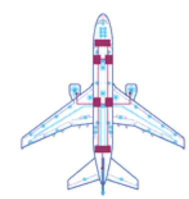
SiC



Modular power tiles

Integrated load controller

Integrated VFG



Systems trades & optimization

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