Key Drivers for Aerospace Batteries.
Today and Future Aircrafts Electrically Powered

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Europe-Japan Symposium

Electrical Technologies for the Aviation of the Future
26-27 March 2015

liten
OUTLINE

✓ CEA Batteries overview
✓ Energy Landscape for AeroSpace Electrification
✓ Energy Storage :
   Today State Of the Art
   What’s next? (>5-10 years)
   Needs for Future Aircrafts Propulsion?
✓ Summary
Embedded Energy: Specific Batteries

Open-gate process: exploit CEA’s resources at every level of the value chain

- Processes
- Materials
- Components
- System integration
- Initial Industrialization
- Demonstration

CEA LITEN develops customized designs conforming to the clients’ own technical specifications

- Mechanical and Electrical conception
- Mecha-thermal modeling
- Electrical architectures
- Smart and Safe Designs
Li-ion Cells Pilot line

- Pilot Line with 1000m² of dry room
- Line capability up to 500kWh/month
- 150-200kWh/month in practice (~3000 cells)

- 500 channels for formation
- 1000 channels for cycling
Pack assembly, integration and monitoring

Battery Modules & pack assembly with e-management

Semi automatic assembly, components can be traced throughout entire process
MODULES & PACKS – VARIOUS EXAMPLES

PHEV: HYPACK modules 7kWh 400V

EV: RC2 module 12kWh 400V

E-Bike: MOBILAB module 6Ah 36V

Fast charging e-Bus: MC2 module 70kWh 700V

E-Boat ZERO CO2 PACK 16kWh 400V
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ENERGY STORAGE TECHNOLOGIES...
MANY OPTIONS (Primary & Secondary)

- Lead-acid batteries …with higher energy and longer life
- Li-ion for High Energy (>250Wh/kg) & High Power (>3kW/kg)
- Li-ion for specific demand (eco-friendly materials, low cost, flexible…)
- Solid State Lithium batteries for safety
- Lithium Sulfur and Li-metal batteries for high energy (>300Wh/kg)
- Li-air batteries - Metal-air batteries (Zn, Li, …) for primary and secondary use
- M-ion batteries (M =Mg…) - (Na-ion within RS2E)
- Ni-Zn batteries for long term and low cost
- Lithium primary batteries
- Supercapacitors
- Fuel cells (PEMFC and SOFC) and electrolyzers
- Flow batteries…
Scope of the survey

Specifications of the application requires a compromise between energy, power, mass and volume.
EMBEDDDED ENERGY STORAGE APPLICATIONS

**Electric Vehicles**: 3C or 4C discharge rates (ca. C/2 continuous); ca. 2000-3000 cycles

**Aerospace**:
- **High Altitude Pseudo-Satellites (HAPS)**, Stratospheric balloons: 400+ cycles to 80% capacity at C/10
- **Satellites**: C/10 charge & C/2 discharge rates; ca. 2000 cycles at 80% DoD (GEO)
- **Launchers**: ca. 40C discharge rate (pulse) and ca. 20C charge rate (pulse) but low life cycle needed (EMTVC)

- **Electric Aircrafts (LSA)**: Continuous C-discharge rate max: 4C discharge rate; ca. 1000-2000 cycles at 80% DoD (Propulsion)
- **Helicopters hybridization**: autorotation powering, fuel saving, engine starting in addition to power supply of the distribution network… 40C discharge (pulse 10-30sec); 200 cycles...

**Defense**:
- **Soldier efficient**: 3C or 4C discharge rates; ca. 300-500 cycles
- **UAV**: 3C or 4C discharge rates; ca. 300-500 cycles
# Future Aircrafts Electrically Powered

For the energy system sizing, one have to consider energy versus power.

![Power density vs Energy density](image)

For instance:

| Mass Energy Density | 600 Wh/kg | Mass Power Density | 1200 W/kg |
Battery Incidents Causes Repartition

Cell design is also key for safety (hard casing with multiple safety devices)
Appropriate unit cell capacity: Safety event on Small cell is easier to manage
Appropriate module and electronics...

Source, SMP, IBS 2008
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TODAY AIRCRAFT Lithium ion Battery / Fuel Cells

Examples:

- **Today…**
  - **Commercial**
  - Boeing Dreamliner

- **Demonstration…**
  - Airbus eFan
  - Boeing Fuel Cells Aircraft
  - 400-600W/kg System
  - 1kg $H_2 = 18$ kWh

**Product/TRL**

- Auxiliary Power Unit (APU) start on the ground & serve as a backup for electronic flight systems / Commercial

**Battery System**

- High Power / Low Energy
- C-rate discharge
- Nominal Energy ~ 4 kWh
- Nominal Voltage = 20–32.2 V
- Pack Weight ~ 40–50kgs
- Pack specific energy ~40–50Wh/kg

- High Energy / Medium Power
- 3 to 4C-rate discharge
- Nominal Energy ~ 20kWh
- Nominal Voltage = 200-250V
- Pack Weight ~ 130kgs
- Pack specific energy ~140Wh/kg

**Cells Specifications**

- 2 Packs 8S1P with LCO Cells 2.5–4V
  - Cells ~90-100Wh/kg

- 2 Packs 59S1P with NMC Cells 2.7-4.2V
  - Cells ~150Wh/kg
Li-ION CELLS BENCHMARK : Wide References...

Various chemistries, various Cells shape and size; Commercial sources:

18650 cells => Stainless steel cylindrical hard casing
Charge at 4.3V to increase capacity => 300 cycles

Today best 18650 cells in energy versions: ca. 250Wh/kg and in power versions 200Wh/kg (up to 10C discharge rates)
Silicon based negative electrodes (low Si content) and Ni rich positive electrodes commercialized

Today Li-ion polymer energy sized cells at ca. 260Wh/kg (100Ah) and in power versions ca. 190Wh/kg (up to 3-4C discharge rates)
At development/demonstration level: 300-400Wh/kg (ca. 40-45Ah) in Li-ion energy version (Silicon / NMC & Silicon / Li-rich)
## Li-ion Technologies for High Energy

<table>
<thead>
<tr>
<th>Technology</th>
<th>Gravimetric Energy Density / Wh.kg(^{-1})</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>LFP/Graphite</td>
<td>120 to 155</td>
<td>Commercial</td>
</tr>
<tr>
<td>NCA-NMC/Graph.</td>
<td>180 to 220</td>
<td>Commercial</td>
</tr>
<tr>
<td>5V Spinel/Graphite</td>
<td>200 to 240</td>
<td>R&amp;D on electrolyte</td>
</tr>
<tr>
<td>Li Rich/Graphite</td>
<td>220 to 280</td>
<td>Under development</td>
</tr>
<tr>
<td>LFP/Si-C</td>
<td>155 to 180</td>
<td>Not a target</td>
</tr>
<tr>
<td>NCA-NMC (Ni Rich)/Si-C</td>
<td>250 to 300</td>
<td>Commercial Consumer market</td>
</tr>
<tr>
<td>Li Rich*/Si-C</td>
<td>280 to 400</td>
<td>Under development / Proof of Concept</td>
</tr>
</tbody>
</table>

*\(\text{Li}_{1+x}\text{M}_{1-x}\text{O}_2\) (\(0<x<1/3\); M = Mn, Ni, …)

High specific capacity > 250mAh/g (vs. 180mAh/g for NMC)
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Li-ion high Energy density Roadmap : What’s Next?

Disruptive Lithium ion technology development by increasing materials capacity to store Li

* double massic energy density vs market battery : 350-400Wh/Kg
* 300 cycles at room temperature

* Li$_2$+xNiTi$_1$-yM$_y$O$_4$ (M=Mo$^{6+}$, V$^{5+}$) Disorder creation by substitution Na/Li, O/F
Specific capacity>250mAh/g ex: Li$_2$NiTiO$_4$ theoretical capa 290mAh/g ex: Li$_2$TiS$_3$ > 400mAh/g

All solid state concept - 5V/Li *

- Energy density x2 (mass and volume)
- Safety
- Pack cost reduction : -30%

Ex: Glass sulfide - Li2S+SiS2+LixMO4…

* From 1st simulations on BATPAC software
Li-ion high Energy density Roadmap (Cell Level)

2015-2017
- GEN 2
  - CATHODE: Li-Rich 250mAh/g
  - ANODE: Si-C 800mAh/g
  - Li-Rich vs Si-C 300Wh/kg 800Wh/L

2020
- GEN 3
  - HEC 270mAh/g 4V
  - HEA Si-C 1000mAh/g
  - HEC vs HEA 400 Wh/kg 1000 Wh/L

2025
- GEN 4
  - HEC 300mAh/g 4.5V
  - HEA Li metal 1930mAh/g
  - HEC vs Li metal 500 Wh/kg 1500 Wh/L

HEC = High Energy Cathode; HEA = High Energy Anode
Lithium Sulfur
LITHIUM SULFUR IP LANDSCAPE: ACTORS

Competition is already very active in the field, lead by several start-up and large companies

**Sion Power (BASF collaboration)**
- Strong work on Li metal protection.
- Expanded graphite

**Oxis Energy**
- New electrolytes based on Lithium Sulfide
- In situ protection of Lithium.

**Polyplus**
- Electrolytes optimized for polysulfide chemistry
- Development of protected lithium
- Experience from Lithium/Air and Lithium/Seawater battery chemistries.

**NOHMs**
- New electrolytes based on ionic liquids silica tethered
- Confinement of polysulfides using inorganic materials

**GS Yuasa**
- Aims To Commercialize Lithium Sulfur Battery By 2020

**Today performance**
- Energy density: 300 Wh/Kg

**Challenges**
- Safety issue, energy density: 600 Wh/Kg, Cycling efficiency

**Constant improvement**, available in 2020
**Key players**:
- SION Power (US) - BASF, Polyplus (US), Oxis Energy (UK), NOHMs (Cornell University, US)
### LITHIUM SULFUR ROADMAP:

<table>
<thead>
<tr>
<th>Year</th>
<th>2014</th>
<th>2015</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Capacity</strong></td>
<td>1000 mAh/g</td>
<td>1000 mAh/g</td>
<td>1200 mAh/g</td>
<td>1200 mAh/g</td>
<td><strong>1200 mAh/g</strong></td>
</tr>
<tr>
<td><strong>Cycles</strong></td>
<td>100 cycles</td>
<td>500 cycles</td>
<td>1000 cycles</td>
<td>2000 cycles</td>
<td><strong>2000 cycles</strong></td>
</tr>
<tr>
<td><strong>Rate</strong></td>
<td>C/10</td>
<td>C/10</td>
<td>C/5</td>
<td>C/2</td>
<td><strong>C/2</strong></td>
</tr>
</tbody>
</table>

| **Energy Density** | 250 Wh/kg | **250-300 Wh/kg** | 300-400 Wh/kg | 400-600 Wh/kg | **200 Wh/kg** |
| **Volume Density** | **300 Wh/L** | 300-400 Wh/L | 400-500 Wh/L | 500-700 Wh/L | **300 Wh/L** |
| **Cycles** | 10-50 cycles | 1000 cycles | 500-1000 cycles | 1000-2000 cycles | **1000 cycles** |

- **150 $/kWh** (cell) **-20/+60°C**
- **1000 W/kg** (cell)
- **200 Wh/kg** (pack) **-40/+80°C**
- **300 Wh/L** (pack) **1000 cycles**
HIGH ENERGY Roadmap overview
System Level

Today, EV
- 3 years: Li rich – SiC (3 years)
  240Wh/kg // 325Wh/L
  300-500 cycles

- 5 years: Li rich – SiC (5 years)
  240Wh/kg // 325Wh/L
  500-1000 cycles

- 10 years: Li-S (5-10 years)
  300Wh/kg // 260Wh/L
  300-500 cycles

Today, Space
- 3 years: SAFT: VES 180 SA 180Wh/kg
  Panasonic 18650 180Wh/kg
  >2000 Cycles

- 5 years: Li-rich – Li (3-5 years)
  290Wh/kg // 375Wh/L
  200-500 cycles

- 10 years: Li-Air (10years +)
  280Wh/kg // 240Wh/L
  300-500 cycles

Lithium Metal
- High Energy Density
- Low Power

Lithium Air
- High Energy Density
- Probably Need Hybridization for Power

Safety Integration
- 150Wh/kg // 230Wh/L
- 750 cycles

SAFT: VES 180 SA 180Wh/kg
Panasonic 18650 180Wh/kg
>2000 Cycles

High Energy Density
Medium-Low Power Density
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✓ Summary
• Energy requirement for the secondary source will be > 500 kWh and will depend on the consideration of fault cases
• Considering a Battery pack, the energy aforementioned represents the amount used from 100% to 20% of SoC (State of Charge)
• Considering the Battery as the choice for the secondary source, it is necessary an energy density of at least 500 Wh/kg at system level

- The use of secondary source during high power phases such as take-off will lead to powers above 1C.
- Durability to be considered for the secondary source is in a first step, 5 years
- The number of cycles per year is from 1000 to 2000 cycles.
- Operating temperature (-40 °C to 50 °C)

**Batteries > 500Wh/kg ???
Lithium-Sulfur, Metal-Air ???
Cells > 700Wh/kg

<table>
<thead>
<tr>
<th>Negative Metal electrode</th>
<th>Capacity</th>
<th>Voltage (Th. / Practical)</th>
<th>Th. Energy (Wh/kg metal)</th>
<th>SoA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li</td>
<td>3867</td>
<td>3.4 / 2.4</td>
<td>13140</td>
<td>R&amp;D (secondary)</td>
</tr>
<tr>
<td>Ca</td>
<td>1340</td>
<td>3.4 / 2.0</td>
<td>4600</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>Mg</td>
<td>2200</td>
<td>3.1 / 1.4</td>
<td>6800</td>
<td>R&amp;D</td>
</tr>
<tr>
<td>Al</td>
<td>2980</td>
<td>2.7 / 1.6</td>
<td>8100</td>
<td>Demonstrators</td>
</tr>
<tr>
<td>Zn</td>
<td>820</td>
<td>1.6 / 1.2</td>
<td>1300</td>
<td>Limited commercialization</td>
</tr>
<tr>
<td>Fe</td>
<td>960</td>
<td>1.3 / 1.0</td>
<td>1200</td>
<td>Commercialization</td>
</tr>
</tbody>
</table>

### RFCS and Lithium Batteries Energy Density Comparison

<table>
<thead>
<tr>
<th>Electric Power System (RFCS or battery)</th>
<th>Yields</th>
<th>Current Voltage limit</th>
<th>Energy capacity limit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System massic energy</strong></td>
<td><strong>Imax</strong></td>
<td><strong>Vnom</strong></td>
<td><strong>kWh</strong></td>
</tr>
<tr>
<td>kWh/s_W, kWh/kg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Wh / kg</strong></td>
<td><strong>W / kg</strong></td>
<td><strong>A</strong></td>
<td><strong>V</strong></td>
</tr>
<tr>
<td><strong>kWh</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**PEM HOGEN C30**
- H₂, O₂ Production: Electroyze
- H₂ Storage: Metal hydrides storage
- O₂ Storage: Pressure 2 bars
- Water storage: Liquid Patm
- Pile electric conversion: PAC CEA 32 kW
- HE Battery: 0,22 kWh/kg
- System massic energy: 178
- Useful power/output: A
- Cyclability: V
- Energy capacity limit: kWh

**PEM HOGEN C30**
- H₂, O₂ Production: Electroyze
- H₂ Storage: H₂ gas storage 2 bars
- O₂ Storage: Pressure 2 bars
- Water storage: Liquid Patm
- Pile electric conversion: PAC CEA 32 kW
- HE Battery: 0,22 kWh/kg
- System massic energy: 238
- Useful power/output: A
- Cyclability: V
- Energy capacity limit: kWh

**PEM HOGEN C31-Opt.**
- H₂, O₂ Production: Electroyze
- H₂ Storage: H₂ gas storage 2 bars
- O₂ Storage: Pressure 2 bars
- Water storage: Liquid Patm
- Pile electric conversion: PAC CEA 32 kW optimized (delay?)
- HE Battery: 0,26-0,42 kWh/kg
- System massic energy: 224-584
- Useful power/output: A
- Cyclability: V
- Energy capacity limit: kWh

**PEM optimized**
- H₂, O₂ Production: Electroyze
- H₂ Storage: 700 bars tank (400Wh/L)
- O₂ Storage: Enriched
- Water storage: Liquid Patm
- Pile electric conversion: 80kW 300kWh embedded energy
- HE Battery: 0,42 kWh/kg
- System massic energy: 720
- Useful power/output: A
- Cyclability: V
- Energy capacity limit: kWh

**SOEC/SOFC**
- H₂, O₂ Production: 2 bars tank
- H₂ Storage: 2 bars tank
- O₂ Storage: Vapor
- Water storage: Vapor
- Pile electric conversion: Vapor
- HE Battery: 0,60 kWh/kg
- System massic energy: 444
- Useful power/output: A
- Cyclability: V
- Energy capacity limit: kWh

**SOEC/SOFC**
- H₂, O₂ Production: 2 bars tank
- H₂ Storage: 2 bars tank
- O₂ Storage: Vapor
- Water storage: Vapor
- Pile electric conversion: Vapor
- HE Battery: 0,60 kWh/kg
- System massic energy: 460
- Useful power/output: A
- Cyclability: V
- Energy capacity limit: kWh

---

A solid oxide electrolyzer cell (SOEC) is a solid oxide fuel cell.
HIGH POWER
Foreseen Aerospace Niche

Helicopters hybridization: autorotation powering, fuel saving, engine starting in addition to power supply of the distribution network...

- Prior criteria: High Power density (W/kg) & Safety
- ca. 50-100 kW 10-30 sec
- ca. 200-2000 cycles
- Low self-discharge
- Stable/Safe behavior
- Very good low temperature capability

=> Limited mass (ca. 30-50 kg)

Radar satellites: Lidar, power actuators, plasmic propulsion...

tens of kW seconds to tens of minutes (up to 3kWh)

- Discharge Power up to tens of kW but with sufficient energy needs (up to 3kWh) at high C-rates in both charge and discharge modes
  >100C discharge / >20C charge from 50000 cycles up to a few million cycles
- Thousand of cycles but under lower temperature (-10°C to 40°C)

=> Limited mass

Launchers: 10 kW (4 kW charge) hundreds of ms... (up to 250 Wh)

Next Ariane Evolution, will feature electrical TVC for the new upper stage

- Power source that sustains ca. 40C discharge rate (pulse) and ca. 20C charge rate (pulse) but
  low life cycle needed

=> Limited mass <25 kg
HIGH POWER Roadmap overview (Cell Level)

- **Auxiliary Power Unit (APU)**
  - High Safety durability
  - LFP-G hard casing
  - 100 Wh/kg - 1 kW/kg
  - 5000 cycles
  - GEN 1

- **Propulsion (micro-hybrid)**
  - Power Density Durability
  - LICs Soft / LFP-LTO hard casing
  - 15/50 Wh/kg–7/2 kW/kg
  - >10000 cycles
  - GEN 1

- **Propulsion (hybrid)**
  - Energy Density Power Capability
  - NMC/NCA-Si/C 250 Wh/kg - 900 W/kg
  - 300 cycles
  - GEN 2

- **HIGH POWER Roadmap overview (Cell Level)**
  - Today: Cobalt Based-G
  - 40-50 Wh/kg – 40-50 W/kg
  - >1000 cycles
  - 2015

  - LFP-G hard casing
  - 100 Wh/kg - 1 kW/kg
  - 5000 cycles
  - GEN 1

  - LFP blend-G
  - 130 Wh/kg - 3 kW/kg
  - 5000 cycles
  - GEN 2

  - Blend-LTO
  - 70 Wh/kg - 6 kW/kg
  - 10000 cycles
  - GEN 3

  - 5V Spinel-post LTO
  - 7-8 kW/kg
  - 10000 cycles
  - GEN 3

- **High Power Roadmap overview (Cell Level)**
  - Depends on level of hybridization

- **2020**
  - LFP blend-G
  - 130 Wh/kg - 3 kW/kg
  - 5000 cycles
  - GEN 2

  - Blend-LTO
  - 70 Wh/kg - 6 kW/kg
  - 10000 cycles
  - GEN 3

  - 5V Spinel-post LTO
  - 7-8 kW/kg
  - 10000 cycles
  - GEN 3

- **2025**
  - NMC/NCA-Si/C
  - 250 Wh/kg - 900 W/kg
  - 300 cycles
  - GEN 2

  - 5V Spinel-post LTO
  - 7-8 kW/kg
  - 10000 cycles
  - GEN 3

- **Today: Cobalt Based-G**
  - 40-50 Wh/kg – 40-50 W/kg
  - >1000 cycles

- **Depends on level of hybridization**
**SUPERCAPACITORS**

**Towards:**

- Higher specific energy hybrid systems
- Low Cost Low T° chemistry
- High Voltage Perspective

<table>
<thead>
<tr>
<th></th>
<th>Power density max</th>
<th>Energy density max</th>
<th>Cycles</th>
<th>Low temperature range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Li-ion battery</strong></td>
<td>3 kW/kg</td>
<td>200 Wh/kg</td>
<td>500 - 1000</td>
<td>0°C to 60 °C</td>
</tr>
<tr>
<td><strong>Supercapacitor</strong></td>
<td>10 kW/kg</td>
<td>10 Wh/kg</td>
<td>1 000 000</td>
<td>-40°C to 80 °C</td>
</tr>
<tr>
<td><strong>Hybrid supercapacitor</strong></td>
<td>5 kW/kg</td>
<td>25 Wh/kg</td>
<td>&gt;10 000</td>
<td>-20°C to 60 °C</td>
</tr>
</tbody>
</table>

**EDLC large Cells Ultracapacitors For High Power with Long Operating Life**

**Li-ion Capacitors (LICs) as Hybrid devices which combine the intercalation mechanism of Lithium Batteries with the cathode of an EDLC**
AT SYSTEM LEVEL

Development of innovative solutions

✓ **Mechanics and Thermal Management**: pack architecture, temperature management, cooling ...

✓ **Inverters**: Low cost, high efficiency, quadratic inverters for primary or secondary batteries / Supercaps systems

✓ **Hybridization**: Pack parallelization systems, management, balancing...

✓ **Connectics**: power busbar, specific connectors...

❖ **Needs R&T in Power Electronic & Systems**

> Inverters, mechanical designs (Composite materials for Lighter weight & Cost reduction), Reliable solutions...
SUMMARY

✓ **Practical battery** electric powered airplanes are today limited to **APU** (Li-ion being introduced)

✓ **Small vehicles** (LSA and Ultra-Light aircraft) and rather short ranges and endurance (neglecting costs) are today **fully electrically powered by the current technology** (batteries and Fuel cells) **at demonstration level** but not for commercial aviation

✓ **Powering larger aircraft** a dramatic improvement in battery technology would be required, starting by **hybridization** (20-30%) mainly to reduce fuel consumption (also true for helicopters)

✓ **Fuel cells are of interest for large autonomy** or high energy to power ratio. To make fuel cells attractive for aviation application, power density of the electrical generator is expected to meet 850 W/kg and 650 W/L, and 1200 Wh/kg and 1000 Wh/L for the net system energy density in the next 10-20 years. Life time is also an important parameter to be enhanced with a target at 50000 hours

✓ Aircrafts electrification will **imply innovative energy distribution** to improve the propulsive efficiency but also possible distribution of energy systems into the aircraft (number of modules and packs) and space allocation to power auxiliaries, doors opening…

✓ **Installation constraints** (plug-in or « rackable » concept), connection of electronics, thermal, structural integration and handling of batteries by operators or automatic machines will have to be fully defined, imagined…
Safety and Flight Testing
(Whoops – wrong button !)

Contact florence.fusalba@cea.fr