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

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Abstract Depending on the targeted class of electric aircrafts, various power systems may be envisioned. While today batteries performances are expected to initiate commercial small full electric aircrafts developments, hybrid and electric propulsion are under investigation for larger aircrafts and at least regional ones [1]. The electric energy storage could provide the additional power required for takeoff. Whatever their mission, if they are for APU or propulsion, key drivers for aeronautic batteries are safety, energy to power density, cycling capabilities & certification. Especially Power to Energy ratio will differ from full electric to hybrid propulsion and thus will drive the technology selection. CEA is expected to adapt technological assumptions to this long-term context, identify technological locks and propose innovative solutions at system level. Various batteries technologies taking in assumption today and expected performances in future will be discussed. Pre-sizing will be assessed for selected technologies through listed driving criteria.

Introduction
Depending on the targeted class of electric aircrafts, various power systems may be envisioned. While today batteries performances are expected to initiate commercial small full electric aircrafts developments, hybrid propulsion are under investigation for larger aircrafts and at least regional ones [1]. Whatever their mission, if they are for APU or propulsion, key drivers for aeronautic batteries are safety, energy to power density, cycling capabilities & certification. Especially Power to Energy ratio will differ from full electric to hybrid propulsion and thus will drive the technology selection.

High Energy: Status/Potential for Lithium-ion and potential for Lithium-Sulfur and Metal-air
Today, Panasonic commercial NCR18650 and NCR18650A Lithium-ion (Li-ion) types achieve respectively 620Wh/L (NCR18650) and 675Wh/L (NCR18650A) thus~230-245Wh/kg over 300 cycles. Panasonic High energy Li-ion cells (18650) foreseen are Nickel based positive electrode material based on LiNiO2 (Panasonic's proprietary). The current design weight energy density is about 252Wh/kg. Panasonic announcement of beginning Silicon alloy anode battery (+30% energy) volume production in 2012 was postponed in 2013. Those 260Wh/kg cells are currently sampled at Panasonic customers. At larger capacity levels, in 2012 Envia, a US Start-Up, demonstrates Li-ion accumulators between 378 & 400Wh/kg from C/10 to C/3 in 45Ah cells. Integrating Silicon-based negative with Li-rich positive, the 45Ah cell initially at 400Wh/kg fades at 300Wh/kg after 4 cycles. ENVIA cells were benchmarked by end-users but so far no advertisement regarding an eventual industrial manufacturing or commercialization was released. Silicon-based negative IP Overview Major patent holders are end-users and fully integrated players (Sony, LG, Samsung, Panasonic), battery manufacturers (Sanyo, GS Yuasa, Hitachi, Hitachi Maxell), material manufacturers (Shin-Etsu Chemical, Sumitomo Metal Industries, Mitsui Mining Smeting, 3M) and institutional players (Argonne National Laboratory, Chinese Academy of Science, AIST (JP), KAIST(KR)). Almost all Li-ion actors (materials providers, cells manufacturers, R&D groups…) worldwide are willing to participate to Silicon Technology Success Story… Consequently, the market may be poised for the entrance of a first wave of higher-energy Si-C cells, with various performances, in the 2015 timeframe.

After Li-ion…
Rechargeable Lithium Sulfur (Li-S) batteries have received ever-increasing attention recently due to their high theoretical specific energy density, which is 3 to 4 times higher than that of Li-ion batteries based on intercalation reactions. Li-S batteries may represent a next-generation energy storage system, particularly for large scale applications. The obstacles to realize this high energy density mainly include high internal resistance, self-discharge and rapid capacity fading on cycling. Competition is already very active in the field, led by several start-up and large companies: Sion Power (BASF collaboration) with a strong work on Lithium metal protection and expanded graphite, Oxis Energy (UK) develops new electrolytes based on Lithium Sulfide and In-situ protection of Lithium, NOHMs proposes new electrolytes based on ionic liquids silica tethered and confinement of polysulfides using inorganic materials. Sion Li-S battery benchmarked by Astrium GmbH for High Altitude Pseudo-Satellites (HAPS) exhibits 350Wh/kg with few cycles (less than 20) with volume specific energy of only 320Wh/L [2]. 500Wh/kg prototypes were designed over 4-5 cycles. Finally, metal-air batteries produce the highest theoretical specific massic energy compared to all other batteries because there is no need to store one of the reactants inside the battery, namely, the
cathode reactant oxygen is supplied from the ambient air. Since this metal-air battery weight (and energy density) is greatly reduced. For example, in the case of a Li-MnO₂ battery, the cathode reactant's weight is 30 times higher than the weight of the metal anode. The Lithium-air (Li-air) battery has a significantly higher specific energy than all other metal-air batteries (Figure 1). For example, the theoretical specific energy of a Zinc-air (Zn-air) is in the range of 1350 Wh/kg, while that of Li-air is 11,140 Wh/kg. In contrast to other metal-air batteries, the Li-air battery is the only one which has a practically rechargeable system even if not demonstrated today.

Today… Next…

Fig. 1: Current batteries technologies and expected 10-20 years developments [1]

At system level
Li-ion has potential for gravimetric and volumetric energy density improvements of factor of ~2 but requires high energy density negative (silicon based) (Table 1). System level volume/mass analysis for Li-S indicates similar weight but substantial increased volume relative to advanced Li-ion. System level volume/mass analysis for Li-air indicates no gravimetric improvement and substantial volumetric penalty relative to Li-ion. Cost is likely higher for Li-Air systems vs. advanced Li-ion.

For higher power to energy ratio, looking to down-size the batteries on board with increasing the payload capabilities (in terms of power and duration), energy battery combined with a bank of supercapacitors may also be investigated as hybrid power source.

Fuel Cells
A 80kW fuel cell exhibits a power density at system level for automotive application without H₂ storage, without power electronic and with no battery hybridization of ca. 0.4 kW/kg (State of the Art according to DOE), therefore 200 kg. This power density is evaluated at ca. 0.27kW/kg for the full system (including power electronic & H₂ storage). This corresponds to a specific energy of ca. 100Wh/kg for 720Wh/kg of H₂ tank storage mass (350-700bars), corresponding to 30kWh embedded energy (42kg).

These data have to be compared with GM calculated battery system specific energies (see above Table 1). However, this specific energy increases with increasing the autonomy factor (embedded H₂) from ca. 100 to 450Wh/kg for ca. from 30 to 300kWh. Therefore, fuel cells are of interest for large autonomy or high Energy to Power ratio with a maximum energy density achievable of 720Wh/kg and 400Wh/l for H₂ tank storage up to 700 bars.

High Energy with sufficient power for LSA
A specific energy is given and depends on a discharge rate and a temperature. Thus values of specific energies to be compared must be measured in similar conditions (discharge rates, temperatures, life expectancy (cycle)) and if not similar, comparable. If we take the case of Tesla (very mediatized) which uses 18650 cells (approximately 210 Wh/kg), the pack is 150 Wh/kg but with ~400kg of embedded battery system to hold rates of 3-4C discharge and 600 cycles (charge at max 1C).

Specification of Light Sport Aircrafts (LSA) like eFan (Figure 2), for instance, pack targets 150 Wh/kg with 200 kg max of batteries (system level) for a rate of 3-4C and 2-3000 cycles (charge at 1C-1.5C). Depending on system form factor (1.2 to 1.4), cells of about 180-200Wh/kg are requested. The notion of safety and aeronautical "qualification" is also missing in these data. These parameters often require the addition of elements of safety (if possible redundancy) to the detriment of the mass performances, in minima. Finally, a reliability of 10⁻⁷ is specified for the aeronautical applications.

**AIRCRAFT Lithium ion Battery**

<table>
<thead>
<tr>
<th>Product/TRL</th>
<th>Today...</th>
<th>Next...</th>
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<tbody>
<tr>
<td>Battery System</td>
<td>High Power / Low Energy</td>
<td>High Energy / Medium Power</td>
</tr>
<tr>
<td>- High Power</td>
<td>2c discharge</td>
<td>3-2c discharge</td>
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<tr>
<td>- Nominal Energy = 6 kWh</td>
<td>Nominal Energy = 10 kWh</td>
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</tr>
<tr>
<td>- Nominal Voltage = 20-32.3 V</td>
<td>Nominal Voltage = 200-250V</td>
<td></td>
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<tr>
<td>- Pack Weight = 66 lbs</td>
<td>Pack Weight ~ 130kg</td>
<td></td>
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<tr>
<td>- Pack specific energy ~45-50Wh/kg</td>
<td>Pack specific energy ~460Wh/kg</td>
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**Cells Specifications**
- 2 Pkcs 8150 with LCO Cells 2.5-4V
- Cells ~180 Wh/kg
- 3 Packs 8150 with NiMH Cells 3.3-4.2V
- Cells ~155Wh/kg

Fig 2 Auxiliary Power Unit (APU) and electric propulsion (for light aircraft) specifications comparison

**High Power with sufficient energy for helicopters hybridization**

Aircrafts hybridization for fuel saving includes wide...
strategies and thus various power to energy ratio, therefore several potential technologies. Hybridization in helicopters may deal with autorotation powering, fuel saving, engine starting in addition to power supply of the distribution network. Prior criteria here are high power density (W/kg) & safety with ca. 100kW requested in 10-30sec under ca. 200 cycles. Low self-discharge for the decrease of costly maintenance and low temperature capability are also needed. Mass limit drives the selection of the technology.

Of particular interest are Li-ion cells, power sized, that retain low internal resistance from a fully charged to a fully discharged state. This feature allows more robust performance and greatly reduces concern about heat generation for high pulse rate applications. Regarding battery materials, the strategy is then to select a « power sized » chemistry to embed more useful capacity (to avoid oversizing) while better operating at enhanced temperature range. With higher power capability but lower energy is the potential use of supercapacitors. Supercapacitors all take into account very high charge and discharge currents, implying important issues of voltage drop and dissipation linked to the high ESR (internal serial resistance) for classic banks of supercapacitors. When sufficient energy is requested, classic supercapacitors (from Maxwell, Nesscap...) do not display sufficient energy to respond to the power mission profile corresponding to the coming applications requested for air hybridization use, whereas the classic Lithium-ion energy batteries do not display sufficient power and are not well adapted particularly in terms of series resistance and charge rates capacity. Therefore hybrid supercapacitors which have a relatively higher energy density with still high power capability are expected to find their way as this technology benefits to higher energy accessible, of course on condition that those performances are not decreased at low temperature.

Scientific and Technology methodology

To develop such innovative power module, a set of several competencies should work together: Firstly, electrochemists to choose the right storage technology in function of chemistry, energy / power performances, safety operating conditions, packaging, and lifetime constraints and to size the storage system on specific aircraft power profiles. Secondly, engineers in electric, mechanic and thermal work on dedicated packaging and power connections to provide assembling consistent integration factor with safety and environmental constraints (thermal, mechanical ...). Thirdly, engineers in electronics design and advanced BMS (monitoring and power hardware and associated software) will provide performance data on innovative solutions. Fourthly, teams specialized in battery pack trade off to preliminary design the whole storage power module (battery, power connections, packaging, and Management Battery System (MBS) integration).

Conclusions

Practical battery electric powered airplanes are today limited to small vehicles and by rather short ranges and endurance. Neglecting costs, the current technology is suitable for small Ultra-Light aircraft, but not for commercial aviation (except for APU). In order to power larger aircraft a dramatic improvement in battery technology would be required. Comparing with today’s technology specific energy values the mass specific energy density would have to be increased at least by a factor of 5 to become useful. More realistic this factor would have to be in the order of 10 to attract commercial interest [1] for larger (regional) aircraft.

Li-ion has potential for gravimetric and volumetric energy density improvements of factor of ~2 but requires high energy density negative. Today system level volume/mass analysis for Lithium-sulfur indicates similar weight but substantial increased volume relative to advanced Li-ion. However today Li-S energy density performance is close to 300 Wh/Kg but is expected to reach shortly (in 2-3 years according to Sion Power and Oxis Energy) 600 Wh/Kg with challenges to overcome as safety issue, internal resistance, self-discharge and rapid capacity fading on cycling.

Cycling efficiency system level volume/mass analysis for Li-air indicates no gravimetric improvement and substantial volumetric penalty relative to Li-ion. Cost is likely higher for Li-air systems vs. advanced Li-ion. Also common questions for Lithium Metal Batteries (Li-air, Li-S...) remain as operation at high C-rates and at low temperature, safety.

Fuel cells are of interest for large autonomy or high energy to power ratio. Moreover, the produced water can be reused for aircraft needs. Further technological improvements are required to make fuel cells attractive for aviation application. In particular, the 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.

Micro hybridization of aircrafts like helicopters require very high power (100kW in tens of seconds) with medium energy to limit the system mass. Current energy storage technologies are expected to respond this need.

Large Aircrafts Hybrid or Electric Propulsion (Regional types [1]) powering system design, modelling and installation concepts request to be assessed using long-term assumptions (10-20 ans)
and investigating battery packs with very high energy contents (several hundreds of kWh). Thus, it is expected to adapt technological assumptions to this long-term context, identify technological locks and propose innovative solutions at system level (low level of maturity is acceptable). This work has to be conducted following aircrafts power sources regulatory issues, general and safety requirements under progress and documents updates in order to ensure foreseen compliance with the future standards.

Aircrafts electrification will imply innovative energy distribution as for distributed propulsion systems 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 (power batteries to start on the ground & serve as a backup for electronic flight systems) or doors opening (supercaps). 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 redefined, imagined.

Batteries are therefore expected to shortly find application where the 'electrification' of functions that were previously powered hydraulically, like actuation, requires high voltage architectures. Lithium technologies are today under assessment for emergency systems, APU & main batteries, LSA, Helicopters hybridization (autorotation powering, fuel saving, engine starting in addition to power supply of the distribution network...), unmanned aircraft (UAV).

While perhaps the nearest term commercial opportunity for fuel cells systems in aviation is in small unmanned aircraft (UAVs) and uncritical embedded system, fuel cells are also assessed for APU or RAT. For larger aircrafts, depending on the hybridization level when over than 500Wh/kg embedded energy is requested, fuel cells become a necessity but probably not sufficient. Otherwise, the fuel cell byproducts might be interesting in term of overall efficiency such as heat valorization, Oxygen Depleted Air (ODA) production and water reuse. Anyway, multisources will be envisioned, hybridization (i.e. supercaps/batteries/fuel cells) but not only, also new electric sources distributions, harvesting, energy saving, energy management... progress being made in materials, aircraft platforms, engines, converters, etc... and breakthrough being still waited in the field of energy generation, storage and conversion of course fitting the economical business model and safety concerns.

References