Key Drivers for Aeronautic Batteries

Today and Future Electrically Powered Aircraft

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Introduction

Depending on the targeted class of electric aircraft, various power systems may be envisioned. While today battery performances are expected to initiate commercial developments for small full electric aircrafts, hybrid propulsion schemes are under investigation for larger aircrafts and at least regional ones [1]. The stockage d’énergie électrique pourrait fournir la puissance supplémentaire exigée pour le décollage. Indépendamment de leur mission, comme APU (unité de puissance auxiliaire) ou pour la propulsion, les critères des batteries pour l’aéronautique sont la sécurité, la densité d’énergie et de puissance, la durée de vie (en cyclage et calendrier) et bien sûr l’accès à la certification. Particulièrement le ratio puissance/énergie différera selon le degré d’électrification (tout électrique ou propulsion hybride) et conduira ainsi le choix des technologies. Le CEA travaille à adapter ces hypothèses technologiques dans un contexte long terme, à identifier les verrous technologiques et propose des solutions novatrices au niveau du système. Les technologies de batteries avec les performances d’aujourd’hui et celles attendues dans l’avenir sont discutées. Leur pré-dimensionnement est évalué pour des technologies sélectionnées en réponse à notre liste de critères.

High Energy: Status/Potential for lithium-ion and potential for lithium-sulphur and metal-air

Today, Panasonic commercial NCR18650 and NCR18650A lithium-ion (Li-ion) types achieve respectively 620 Wh/l (NCR18650) and 675 Wh/l (NCR18650A) i.e. ~230-245 Wh/kg over 300 cycles. Panasonic high energy Li-ion cells (18 650) foreseen are nickel based positive electrode material based on LiNiO$_2$ (Panasonic’s proprietary). The current design weight energy density is about 252 Wh/kg. Panasonic announcement of beginning silicon alloy anode battery (+ 30 % energy) volume production in 2012 was postponed in 2013. Those 260 Wh/kg cells are currently sampled at Panasonic customers.

At larger capacity levels, in 2012, Envia, a US start-up, has demonstrated Li-ion accumulators between 378 & 400 Wh/kg from C/10 to C/3 in 45 Ah cells. Integrating silicon-based negative with Li-rich positive, the 45 Ah cell initially at 400 Wh/kg fades at 300 Wh/kg after four cycles. ENVIA cells were benchmarked by end-users but so far no advertisement regarding a possible industrial manufacturing or commercialization has been released up to now. Silicon-based negative 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 Smelting, 3M) and institutional players (Argonne National Laboratory, Chinese Academy of Science, AIST (JP), KAIST (KR)).

Almost all Li-ion players (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-sulphur (Li-S) batteries have recently received ever-increasing attention 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-sulphide and in-situ protection of lithium;
- NOHMs which proposes new electrolytes based on ionic liquids silica tethered and confinement of polysulfides using inorganic materials.

Sion Li-S battery benchmarked by Astrium GmbH (Airbus Defence and Space today) for High Altitude Pseudo-Satellites (HAPS) exhibits 350 Wh/kg with few cycles (less than 20) with volume specific energy of only 320 Wh/l [2]. 500 Wh/kg prototypes were designed over 4-5 cycles.

Finally, metal-air batteries produce the highest theoretical specific 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 which 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 1 350 Wh/kg, while that of Li-air is 1 1 140 Wh/kg. In contrast to other metal-air batteries, the Li-air battery is the only one which may lead to a practically rechargeable system even if not demonstrated today.

**At system level**

Li-ion has potential for gravimetric and volumetric energy density improvements by a 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.

![Figure 1: Current batteries technologies and expected 10-20 years developments [1].](image)

<table>
<thead>
<tr>
<th>Specific Energy Density - Wh(total)/kg (cell)</th>
<th>Current Li-ion</th>
<th>Optimistic Li-ion*</th>
<th>Optimistic Li-Sulfur*</th>
<th>Optimistic Li-Air*</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>530</td>
<td>550</td>
<td>710</td>
<td></td>
</tr>
<tr>
<td>Specific Energy Density - Wh(total)/kg(system)</td>
<td>150</td>
<td>290</td>
<td>300</td>
<td>280</td>
</tr>
<tr>
<td>Energy density - Wh(total)/liter(cell)</td>
<td>520</td>
<td>1050</td>
<td>620</td>
<td>760</td>
</tr>
<tr>
<td>Energy Density - Wh(total)/liter(system)</td>
<td>230</td>
<td>375</td>
<td>260</td>
<td>240</td>
</tr>
</tbody>
</table>

Table 1: General Motor (GM) high energy battery technologies cell and system comparison [3].
relative to Li-ion. Cost is likely higher for Li-Air systems versus advanced Li-ion.

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

**Fuel cells**

An 80 kW fuel cell exhibits a power density at system level for automotive application without \( \text{H}_2 \) storage, without power electronic (e.g. converters) and with no battery hybridization of ca. 659 W/kg (state of the art according to DOE [4]), therefore 122 kg for 80 kW.

The embedded energy is 145 kWh in case of use at 80 kW during one hour with an overall efficiency of 55 %. It corresponds to a mass of 125 kg of storage system (under 350-700 bar). The associated DC/DC converter mass is estimated at 14 kg [5]. In conclusion and for one hour of use, the full system mass is evaluated at 261 kg with a net power of 80 kW (306 W/kg) and 145 kWh (555 Wh/kg) embedded.

These data can be compared with GM calculated battery system specific energies (table 1). However, this specific energy increases with increasing the autonomy factor (embedded \( \text{H}_2 \)) from ca. 555 Wh/kg to 950 Wh/kg for an autonomy of ca.1 h (145 kWh) to 5 h (725 kWh).

Therefore, fuel cells are of interest for large autonomy or high energy to power ratio with a maximum energy density achievable of 1 500 Wh/kg and 825 Wh/l for \( \text{H}_2 \) tank storage up to 700 bars.

**High energy with sufficient power for Light Sport Aircrafts (LSA)**

Specific energy depends on discharge rate and temperature. Thus values of specific energies to be compared must be measured in similar conditions (discharge rates, temperatures, life expectancy (cycle)) or, if not similar, comparable.

If we take the case of Tesla batteries (very mediatized) which uses 18 650 cells (approximately 210 Wh/kg), the pack is 150 Wh/kg but with ~400 kg of embedded battery system to hold rates of 3-4 C discharge and 600 cycles (charge at max 1 time the nominal capacity (C)). 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 3-4 C and 2-3 000 cycles (charge at 1 C-1.5 C). Depending on system form factor (1.2 to 1.4), cells of about 180-200 Wh/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. A reliability of \( 10^{-7} \) is specified for the aeronautical applications.
High Power with sufficient energy for helicopters hybridization

Aircrafts hybridization for fuel saving embraces 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. Priority criteria are here high power density (W/kg) and safety with ca. 100 kW requested in 10-30 sec under ca. 200 cycles. Low self-discharge for the decrease of costly maintenance and low temperature capability are also needed. Mass limit drives the technology selection.

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.

Supercapacitors offer potential higher power capability but with lower energy. Supercapacitors support very high charge and discharge currents, implying important issues of voltage drop and dissipation linked to the high ESR (electrical serial resistance) for classic banks of supercapacitors. When sufficient energy is requested, classic supercapacitors (from Maxwell, Nesscap…) do not display sufficient energy to cope with the power mission profile corresponding to the coming applications for air hybridization use. On the other hand, 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 is likely to offer access to higher energy levels, of course provided that those performances are not decreased at low temperature.

Scientific and technology methodology

To develop such innovative power modules, a set of several competencies should work together:

- Firstly, electrochemists, in order to select 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 battery system management - BSM (monitoring and power hardware and associated software), to provide performance data on innovative solutions;
- Fourthly, teams specialized in battery pack trade off, to make the preliminary design of the whole storage power module (battery, power connections, packaging and battery system management (BSM) integration).

Conclusions

Battery electrically powered airplanes are today practically limited to small vehicles and hampered 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 is 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 realistically, 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 by a 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. Today Li-S energy density performance is close to 300 Wh/kg but is expected to shortly reach 600 Wh/kg (in 2-3 years according to Sion Power and Oxis Energy) 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 to be higher for Li-air systems vs. advanced Li-ion. Also common questions for lithium metal batteries (Li-air, Li-S...) remain concerning operation at high C-rates and safety, at low temperatures.

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 1 200 Wh/kg and 1 000 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 50 000 hours.

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

Large Aircraft Hybrid or Electric Propulsion (Regional types [1]) powering system design, modelling and installation concepts request to be assessed using long-term assumptions (10-20 years) and investigating battery packs with very high energy contents (several hundreds of kWh). Thus, it is necessary 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 complying with aircraft power sources regulatory issues, general and safety requirements under progress and document updates in order to ensure foreseen compliance with the future standards.

Aircraft 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 applications where the "electrification" of functions 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 Ram Air Turbine (RAT). For larger aircraft, depending on the hybridization level when over than 500 Wh/kg embedded energy is requested, fuel cells become a necessity but probably not sufficient. In addition, the fuel cell byproducts might be interesting in terms 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 to be made in materials, aircraft platforms, engines, converters, etc... and breakthroughs

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being still waited in the field of energy generation, storage and conversion of course fitting the economical business model and safety concerns.

References


