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DISCLAIMER

The Challenges and Opportunities of Battery Powered Flight

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Preface

Aircraft, and the aviation ecosystem in which they operate, are shaped by complex trades among technical requirements, economics, and environmental concerns, all built on a foundation of safety. This perspective explores the requirements of battery powered aircraft and the chemistries that hold promise to enable them. The difference between flight and terrestrial needs and chemistries are highlighted. Safe, usable energy density rather than cost is the major constraint for aviation. A conclusion is that battery packs suitable for flight with energy densities approaching 600 kWh/kg may be achievable in the next decade given sufficient investment targeted at aeronautical applications.

Introduction

The dream of battery powered flight is over a hundred years old. In 1884, the 52m long airship La France took to the air near Paris powered by a 435 kg zinc-chlorine battery. The La France secured its place in history as the first aerial vehicle to complete a controlled, powered round trip flight, about 8km in this case. Its creator, Charles Reynard, pointed out that electric power was in its infancy and would surely mature, as had steam. Such flight was "only a question of time and money".[1] A lot of time and money has indeed been spent on electric power over the intervening 130+ years.

There is now much interest in reviving battery powered flight. A theme common to most vehicle designs and predictions is the presumption that battery performance and cost will improve at a rapid pace. Herein we review the prospects for such improvement.

Airplanes and Electric Flight

The interest in battery powered flight is driven by the possibility that advanced batteries may enable advances such as improved aircraft economics, new aircraft utility such as flying taxis, or, perhaps most importantly, reduce aviation's impact on climate change by reducing carbon emissions. This section lays out aircraft considerations that influence the battery performance needed to realize such outcomes.

Aircraft energy and power needs span seven orders of magnitude, from a few-kilogram drones that fly for minutes to airliners that fly halfway around the globe, Fig. 1(a). A small drone may fly on the energy of a few flashlight batteries, while a large airliner takes off with the energy of 30,000 Tesla cars. The efficiency by which this stored energy is converted to shaft power increases with aircraft size (Fig 1b), mainly due to economic considerations. The vast majority of aviation's economic activity stems from the manufacture, support, and operation of airliners with more than about a hundred seats. These large aircraft are also responsible for more than 95% of aviation direct emissions, with 200+ seat airliners accounting for more than half and 65% from international flights[2]. In contrast, the excitement for new aircraft capabilities is concentrated on much smaller aircraft, such as vertical takeoff and landing (VTOL) drones and air taxis sized to carry seven or fewer people or the equivalent cargo, with startups in this space now valued at over $10B USD[3]. Thus, we focus on the needs of 100+ seat aircraft (airliners) and of small VTOLs. The viability of electric (battery powered) flight requires considerations of specific energy, power, weight, cost, and safety.

The energy needed by electric and fueled aircraft configured for the same mission (payload, range and speed) may differ significantly due to differences in efficiency, weight and volume. First, the efficiency by which stored energy is converted to shaft power can differ, 20-55% for fueled aircraft versus 80-90% for electric.[4,5] Second, the weight of a fueled aircraft decreases during flight, by 5-40% depending on range, so the energy needed to keep it aloft does as well, since energy expended is proportional to weight[6]. Also, on flights shorter than design limits, an aircraft fueled for the shorter mission will weigh less than one with a fixed battery sized for maximum range. In addition to flight energy, aircraft must carry contingency reserves to account for weather, congestion, and commercial considerations such the cost of a diversion. The reserve is costly since it increases the aircraft's weight and thus its energy expenditure. The reserve percentage decreases as mission length grows, from 50% of the total energy on board at 2000 km, to 10-12% at 11,000 km[7,8]. Helicopter reserve requirements are simpler, 30 minutes when flying on instruments.

The major challenge for electric aircraft is the low energy density of batteries compared to liquid fuel (Fig. 2) and, for larger aircraft, the much higher weight of electric drives compared to gas turbines. The energy conversion equipment needed (electronics, motors, cables, cooling) for an airliner is now much heavier than that of a fueled propulsion system but the power-to-weight is forecast to improve by a factor of 2 to 4 in the next two decades.[4] To reduce energy needs, many technologies and nontraditional aircraft designs have been studied. Since most apply to either fueled or electric approaches, there are few comparative gains to be had here.

Aircraft Economics and Batteries

Economics will play a role in the viability of electric aircraft. Aviation provides transportation, economically moving people and cargo quickly and efficiently. Both revenue and cost are important. Revenue is generated by moving people, their luggage, and freight, so payload, range, and hours flying per day (10-14 for an airliner) are metrics. Aircraft volume is a concern since most flights are volume rather than weight limited. If batteries cannot be carried within the wings as is fuel on current airliners, then the size of the aircraft must be increased to maintain payload volume.

Aircraft direct costs include ownership, fuel, maintenance, and crew. Airborne electrical equipment and gas turbines now cost about the same per kilowatt. Aircraft price correlates with empty weight. So, if a battery airliner weighs the same for the same capability, its purchase price will be about the same (battery not included). Accounting for the improved efficiency expected from electric drives, the average cost of electric energy and jet fuel to airlines in the US has been about the same this century (a small operator may pay 3-5 times more).[5] Current engines and electrical equipment cost the same to maintain under contract. Thus, the sum of ownership, energy and maintenance costs would not be expected to be much different for electric airliners.

A major cost element of both battery and fueled flight is periodic battery replacement or engine overhaul. In both cases, useful life is tied to the number of flight cycles and the specifics of those flights (aircraft weight, flight length, ambient temperature, etc.). Engine overhaul costs scale with engine power. Light plane turboprop engines (less than 1MW) require overhauls every few thousand flights which cost about $30-90 per flight hour or cycle.[9] For a single aisle airliner, overhaul of its two 20-30MW engines cost about $350-550 per flight cycle.[10] Battery price is tied to energy rather than power. For example, assume that 42 MWh battery with a life of 1000 flights is adequate to power a single aisle airliner. (This is one-quarter the energy on today's fueled counterpart). For battery replacement to be cost competitive with engine overhaul, the battery should cost no more than $8-13 per kWh. If the battery lasts twice as long, it can cost twice as much.

A well-designed aircraft is a sophisticated trade among all of the above factors. It is important to distinguish between aircraft that can be designed, but with less range, payload, higher cost, etc., and therefore less utility, and aircraft design spaces that do not close, usually due to excessive weight. Compared to airliners, small aircraft fly at slower speeds, lower altitudes, shorter ranges, are more expensive to operate on a per seat basis, and are easier to certify. Also, the efficiency and power-to-weight of existing aircraft engines drop as size decreases (Fig 1b). These factors combine to make battery power much less demanding for small aircraft than large ones.

Reducing Environmental Impact

Major concerns of aviation's environmental impact include noise, local air quality, and climate change. Unlike 20th century designs, the predominate noise sources on modern airliners are the fans and airframes. So, the noise will not change if the fan is driven by an electric motor rather than a gas turbine, assuming constant aircraft weight. Oxides of nitrogen and unburned hydrocarbons are regulated to improve air quality in the vicinity of airports. In the case of battery power, these are eliminated if the energy source is green or moved to the locale of a fossil fuel powerplant.

Carbon dioxide is a major contributor to aviation's impact on climate change. Unlike small aircraft, modern airliners produce less CO_2 per unit energy at cruise than does the world's electric grid on average, by 20-35%.[5] Thus, benefits of battery power will be paced by how fast the grid greens, or limited to regions which enjoy green energy. Aviation energy usage in 2018 was equivalent to about 14% of the world's electricity. Competition for reducing aviation's carbon will come from low and zero carbon liquid fuels including synthetic hydrocarbons, biofuels, electrofuels and hydrogen, all of which have much higher energy density than batteries. Airlines are using a variety of sustainable alternative jet fuels but only tens of millions of gallons per year are currently available, well less than 1% of the world's jet fuel needs.

Enabling capability to add value

Other than light aircraft, replacing fueled aircraft with electric ones is very challenging, with the magnitude of the challenge increasing with size and range. Electric propulsion is more promising in enabling aircraft capabilities that have not been successful before. Short-range, vertical takeoff and landing vehicles may bring value as personal air vehicles, air taxis, and cargo carriers. Current helicopters are noisy, mechanically very complex, expensive to maintain, and inefficient in forward flight. Electric, multi-rotor, distributed propulsion approaches, of which there are many, trade mechanical for electrical complexity at the cost of reduced efficiency in hover.[12] Over 100 firms have announced work on 1-7 seat, short-range urban air mobility (UAM) vehicles.

Both vertical and very short takeoff designs are being pursued. Studies suggest value from UAM flights as short as tens of minutes. Then, batteries in the range of 300-400 Wh/kg would be adequate under current flight rules[13,14]. Distributed electric propulsion can enable very short field length operations for larger aircraft, perhaps in hybrid configuration to realize range.

Hybrid

Hybrid propulsion combines fueled engines with electric drives and batteries. Unlike ground vehicles, there is little benefit possible from braking regeneration since aircraft now efficiently recover potential and kinetic energy as range. Hybrid gains forecast fall into the broad categories of range extension, system optimization, and energy substitution. Range extension uses fueled engines to increase the range over that possible with batteries alone. Some concepts for commuter (fewer than 20 seats) and larger aircraft rely on hybrid approaches, at least in the near term to reach useful ranges with mandated reserves[15]. These hybrids offer little advantage other than reduced carbon at limited ranges in locals with green electric power. System optimization employs on-board electric storage to time-shift power. Studies have shown a potential for a 3-6% fuel savings from mildly hybrid designs with 3-5% of the takeoff power and 5% of the energy available as electric at flight points which stress gas turbine design.[16] Airliners use the vast majority of today's fuel, so this may have the largest potential to reduce carbon emissions in the next two decades. Energy substitution refers to grid charged batteries replacing some of the fuel needed for flight. This may increase total energy expended because the airplane is heavier, but reduce emissions with green electricity. The viability of each hybrid approach is dependent on progress in electric drive and battery weights but is less demanding than battery power alone if range is at issue.[17]

Safety and Certification

Safety is the foundation of aircraft design and operations. An overheated or smoking battery in an automobile means pull over, not so easy at 12km in the air. By law, a manufacturer must demonstrate in a certification process that an aircraft design is safe. Such certification may require specific design features and include analysis and testing, with specifics often derived from experience. Manned aircraft requirements are tougher than those for drones, and in both cases, the requirements become more stringent as the size of the aircraft increases. For example, the chance of a potentially catastrophic failure must be less than one in a million flight hours for a two-seat aircraft, but less than one in a billion for an airliner. It is difficult to over emphasize current concerns with lithium batteries on commercial aircraft. Portable electronics batteries have caused hundreds of fire and fume incidents and are implicated in at least three accidents.[18] Since there is little experience with the much larger batteries needed for propulsion, certification requirements are general and such certification is considered a "special condition"[19]. Requirements can be summarized as, first, the modes, behavior and consequences of a battery failure must be well understood, and second, the aircraft must be designed in such a way as to mitigate those failures, whether on the ground, in the air, or in a forced landing. It's very early days for battery powered aircraft, with little experience to guide the process, so regulators, standard setting organizations, and manufacturers are working together to better understand design standards and certification requirements needed.[20]

Airborne Propulsion Battery Requirements

Principle battery metrics include energy and power density, specific energy and power, cost, life and safety. These attributes reflect on the design of battery cells and the packages and controls around them. The isolated cell energy density is reduced by considerations of packaging, life and safety as illustrated in Figure 3a. The energy remaining is that available-for-flight, Fig 3b. Much of current battery R&D is focused on the needs of ground transportation, portable electronics, and grid storage. Aviation demands differ in some areas important to battery technology.

Due to the relatively large flight energy reserves required, an aviation battery will rarely be discharged to low levels. Only a fraction of the specific energy stored in a battery cell is available for a mission, 26% in the example of fig 3. Therefore, there is value to be had not just in cell chemistries with higher energy density and specific energy, but ones that reduce packaging, life and safety overheads.

C-rate (or E-rate) is a battery's power capability, kW, divided by its energy storage, kWh. Power demand peaks during transients. Light planes require 1.5-2 times more power for about 3 mins. to take-off than cruise while for airliners the ratio is 3:1. Airliners cruise long distances so 1C may be adequate for flight given reserve requirements, although higher C may be desired for fast charging on the ground. It's difficult to generalize for hybrid aircraft since many arrangements are being studied. In general, they will have lower battery energy and so may need higher C-rates. C-rate is most demanding for UAMs which combine short ranges with the high-power demand of vertical takeoffs, 8–20 times cruise, 4-5C or more may be needed.[15]

New, exclusively battery-powered aircraft will require a range of pack specific energies. Lower specific energy can enable minimally-viable aircraft designs that have reduced payload and range. For UAM applications where there is no fueled competition, 300-400 Whr/kg is adequate for intra-city applications[12–14]. As energy density improves, battery power becomes more competitive with fueled aircraft. Commuter aircraft with up to 19 seats need 1200-1800 Whr/kg for ranges half that of current aircraft.[15,17] Larger, 150-180 passenger aircraft would need 1800-2500 Wh/kg to fly all but short-range missions.

A natural question, then, is whether the development trajectory of automotive batteries can meet these targets. Innovation over the past decade has proceeded along the metrics that are primary bottlenecks for automotive batteries; this was energy density and/or specific energy for the initial phase of EV development (2010-2015) towards reaching 200-300 mile range electric vehicles. Current automotive and grid battery cells can deliver ~300 Wh/kg at cell level and 200 Wh/kg at pack level. Today, the most ambitious goal in electric vehicle battery development amongst U.S. government supported programs is 500 Wh/kg (e.g., the DOE "Battery 500" program). At cell and small-pack (comparable to module) level, there have been credible demonstrations of specific energy energy approaching and exceeding 400 Wh/kg[21] [22] [23] [24] [25] Continued progress may therefore result in batteries that satisfy UAM requirements. However, as the energy density of Li-ion batteries has improved, the primary bottleneck for future growth of the electric vehicle market has become cost, where battery pack costs are projected to approach $100/kWh. Given that specific energy and driving range are no longer the primary bottlenecks to deployment of electric vehicles, it is unlikely that the trajectory of automotive battery development will reach the performance metrics necessary for larger, longer-range aircraft. Likewise, grid-storage batteries are cost and life sensitive but weight and volume insensitive, so development focuses elsewhere.[26]

Operating environments for aviation batteries are also generally more extreme than for ground vehicles, although the specific conditions vary depending on aircraft type and mission. To minimize drag, airliners and private jets cruise at or above the tropopause, at altitudes of 10-15 km where the ambient temperature and pressure can be as low as 212°K and 0.26-0.12 atm respectively. Arcing considerations at high altitude limit the system voltage. Studies are ongoing to increase the acceptable voltage beyond the current $\pm$270VDC limitation by a factor of two or more. Commercial aircraft are also rated to operate at 55°C ground temperatures, but may reach temperatures as high as 78°C when parked. Liquid cooling for batteries and drives add weight and drag, but is needed for all but the smallest aircraft.

Furthermore, measures necessary to ensure safety extract a penalty in specific energy and cost. Concerns with lithium-ion batteries include thermal runaway and release of toxic fumes. Current solutions involve mechanically and electrically isolating cells, and venting overboard any gas release. These approaches now impose a weight penalty of about 15% for unmanned and 30-40% for manned aircraft. Thus, cell chemistries that are inherently safer in aerospace applications, along with innovations in packaging, can add value. Also, battery management systems that provide accurate, reliable knowledge of remaining usable pack energy (state-of-charge) are critical.

The need to simultaneously deliver all of the requisite performance metrics forces compromise. Practical batteries need to deliver long cycle and calendar life, adequate power (C-rate) and charge fast, operate over a wide temperature range, and do all of this safely. Achieving all of these simultaneously leads to a significant reduction from the theoretically available specific energy. For example, in lithium metal batteries, extending cycle life is usually done by using excess lithium which lowers overall specific energy.[27] Improving power performance in lithium ion batteries is done by lowering the thickness of electrodes, increasing porosity, and/or blending in non-energy-storing conductive additives, leading to lower specific energy.[28] Enabling cold temperature operation requires modifying electrolyte composition with additives that also lower the voltage range of operation, and thereby lowering the specific energy.[29] These trade-offs lead to an overall reduction in available cell specific energy, Figure 3.

Potential Electrochemical Solutions

Where, then, might solutions lie? We begin with first-principles reasoning regarding theoretical performance metrics (specific capacity, specific energy) with the aim of identifying a set of chemistry options that merit further investigation for aviation applications. As we show, this leads us towards primary battery chemistries and their derivatives, where we analyze the state-of-art and consider possible pathways towards rechargeability of these very high energy density chemistries. In particular, we identify several candidate chemistries that have the energy density entitlement to meet the challenging electric aviation targets (while not attempting to be exhaustive in our coverage of potential future chemistries). Based on this analysis, and assuming that new tools capable of accelerating progress, such as advances in characterization and computation are fully leveraged, and that investment in R&D is adequate, we project achievable battery performance metrics over the next decade.

Lithium ion batteries are based on insertion mechanisms where the Li^+ cation moves back and forth from the anode to cathode to balance the charge of the electrical current flow while the parent phases of the active materials remain largely intact. While this approach has provided high reversibility, the energy content is limited to below 1 electron equivalent per metal center in the cathode, as shown in Fig. 5. The intercalation approach has realized cycle life exceeding 5000 full depth-of-discharge cycles for certain chemistries due to excellent reversibility at both the anode and cathode, but with limited capacity.

Rechargeable Metal Anodes Pursuit of higher battery storage capacity invariably leads to metal anodes. Rechargeable metal anodes, especially lithium metal, are a key enabler for high cell voltage and storage capacity. Dramatic improvements have been made over the last decade in improving the Coulombic efficiency and cycle life of lithium metal anodes, while avoiding catastrophic dendrite-related internal shorting. These advances are ushering rechargeable lithium metal technology towards maturity and commercialization. Despite a number of remaining challenges,[30,31] the significant number of commercialization efforts underway related to lithium metal cells offers great promise that a lithium metal anode delivering all of the performance metrics simultaneously required for electric aircraft will be achieved over the next decade.[23–25,32] In addition, the use of non-flammable solid-state, inorganic electrolytes paired with lithium metal anodes, alone or in hybrid systems with liquid electrolytes, promises to open up new possibilities for cell architectures with improved packaging and safety.[33]

Cathode Options Even assuming successful lithium metal anodes, breakthroughs at the cathode are necessary to reach specific energies of 1000 Whr/kg or more. A short-list of possible cathode chemistry options (both insertion and conversion) that could be paired with lithium and non-lithium metal anodes, and their performance characteristics, are given in Table 1. The table lists the thermodynamic voltage, number of electrons transferred, theoretical capacity and the theoretical specific energy. The thermodynamic voltage is governed by the stability of the discharge product, the number of electrons transferred is governed by the ability of the electrode to store the charge carrier (e.g. lithium), and the theoretical capacity accounts for the amount of charge stored per unit weight of the electrode. Table 1 shows that the highest energy densities are associated with so-called conversion reaction cathodes, which comprise mechanisms having multiple electron transfers per active site, and are generally accompanied by a change in structure and phase as the electrochemical reaction proceeds, Fig. 4.[34] While conversion reactions are often mechanistically complex and require control of structure at multiple length scales from the atomic level on up in order to access the theoretically available storage capacity, these chemistries hold the possibility of increasing energy density at the materials level by a factor of 3 to 5 over current insertion-based Li-ion chemistry.

Table 1: Theoretical electrochemical energy storage performance metrics of various battery chemistries

Chemistry	Voltage (V)	Electrons Transferred	Theoretical Capacity (mAh/g)	Theoretical Specific Energy, (Wh/kg)	Reference
Li metal					
CFx400	4	1	900	3600	35
SF_6	3.69	8	1063	3922	36
BF_3		3	1186		
SO_2	3	1	419	1257	37
$SOCl_2$	3.6	2	450	1620	37
SO_2Cl_2	3.9	2	397	1548.3	37
FeF_2	2.63		571.2	1306.8	38
FeF_3	2.73	3	712.5	1644	38
S	2.2	2	1675	2567	39
O_2	2.96	2	3350	3505	39,40
I_2	3.6	2	211	760	40
Br_2	3.9	2	335	1306	40
Cl_2		2		6294	38
Se	2.1	2	679	1226	40
Non-Li					
Mg/O_2	2.95	2	3350	3924	38
Zn/O_2	1.64	4	662	1086	39

A fairly obvious but important observation regarding the chemistries listed in Table 1 is that most involve elements from the second and third period of the periodic table - a simple, yet powerful selection rule is that the elements considered should be those up to chlorine. The exceptions to this are conversion reactions based on metal fluorides. "Air battery" chemistries (which are actually oxygen batteries) have relatively high theoretical specific energy, but also require additional mechanical systems to bring air onboard, compress it, purify it and exhaust it; this reduces the effective system-level scaling factor significantly.[35] Sulfur-based cathodes are approaching commercialization and nearing use in aviation applications.[36] A more detailed overview of remaining technical challenges associated with and S cathodes can be found elsewhere.[37]

Estimating practical energy densities for future battery technologies from theoretical materials-only values is challenging. Here, we take the approach that achievable practical specific energy at the cell-level is a scaling factor of the theoretical specific energy (SE).

$$SE_{practical} = \alpha_{(t-p)} SE_{theoretical}$$

Based on historical trends, we find that for a well-engineered and mature chemistry, a scaling factor, $\alpha_{(t-p)}$ of about 0.5-0.6 (e.g., graphite/transition metal oxide cathodes)[38] is appropriate for many chemistries. Thus, to achieve the identified specific energy targets, battery chemistries whose theoretical specific energies are ~2 times the required specific energy are necessary.

Making Primary Batteries Rechargeable

This analysis leads us to the conclusion that the most promising approaches to achieving the battery energy densities necessary for widespread electric aviation will involve the use of a rechargeable metal anode with a corresponding rechargeable cathode from the class of chemistries that up to now have been successful only as primary batteries. Among a variety of specialty batteries designed for applications in the military, space and medical fields, Li/CF_x primary batteries have the highest demonstrated specific energy at cell level of about 800 Wh/kg.[39] The development path for these primary batteries has already, in some cases, resolved complex reaction mechanisms and optimized electrode and cell designs to achieve high energy densities. Deliberate pursuit of high energy density primary systems with the goal of rechargeability is warranted. The demonstration of potential rechargeability in a prototype Na/CF_x lab-cell provides reason for optimism.[40] Modernization of cell design from rigid metal cans used in primary cells to automotive pouch-type cells using metallized polymer housings can also increase specific energy.

Nonetheless many technical hurdles remain towards achieving practical rechargeable CF_x batteries.[41] Transferring insights gained from high cycle life transition metal-based fluoride cathodes[42] towards carbon-fluorides is one fruitful avenue for further exploration. Nanostructuring metal fluorides has been a key route to improved electrochemical performance addressing its intrinsic low electronic conductivity and nanoscale intermediate phases. Reversibility of metal oxide conversion materials has benefited significantly from careful control of the active material - electrolyte interface and associated interphase formation. This strategy is expected to be effective in this class of materials as well.

Towards Actionable Targets: Lessons from EV

The USABC (US Advanced Battery Consortium) EV targets have served as an important driver for progress in automotive batteries.[43] Identifying and developing targets for electric aircraft should be a priority for the community, and will encourage cross-collaboration between the aerospace and electrochemical sciences communities. Given the divergent paths of automotive and aviation battery requirements, identifying aircraft-specific metrics will provide critical mile-markers for progress.

One may reasonably question the rate at which progress can be made towards such highly challenging targets. It is clear that new tools that can shorten the cycle time for scientific understanding, and technical innovation must be brought to bear. Scientific advances in characterization have progressed and measurements can now be done inside an active battery,[44] termed in-situ[45] for within the battery and operando[46] during battery use, yielding unprecedented insights into the details of the mechanisms and limitations of battery function. Specifically, there has been an order of magnitude increase in published work with in-situ ('battery and in-situ' 230 in 2010 to 2300 in 2019) and operando ('battery and operando' 5 in 2010, 288 in 288) methods. Concurrently, computational methods,[47] machine learning[48] and robotic experimentation[49] are opening up new approaches to materials discovery and optimization. These scientific advances allow battery materials optimization to progress at unprecedented rates.

Projecting battery performance and cost into the future remains a challenging yet important task[50] as it will inform design of current and future electric aircraft. The bottlenecks for the initial phase of EV development were energy density and specific energy. Currently, the primary bottleneck for EV adoption is cost, and battery costs appear to be approaching the USABC and DOE targets of $100/kWh. The cost target appeared daunting when first announced (2009), but this order of magnitude improvement has been realized in only a decade.

After nearly 40 years of work on lithium metal,[51] one may look at recent progress in the specific energy of electric vehicle batteries using lithium metal as a lower bound for the rate of progress that may be possible in the future given new tools and adequate levels of investment. The launch of DOE's "Battery 500" program has set a new goalpost of 500 Wh/kg at the cell level for the field and this has led to noticeable acceleration. Demonstrations of cell-level specific energy approaching and exceeding 400 Wh/kg have been realized over just three years[21-25]. This rate of improvement, if applied to rechargeable Li-CF_x technology as an example, could result in the achievement of 800-1200 Wh/kg specific energy at the cell level (i.e., 20-30% of theoretical specific energy)[52] while meeting most other performance needs listed in Figure 3 within as little as 3-5 years. Scale-up to production levels could occur over an additional 3-5 years. Along with a cell-to-pack burden significantly reduced from today's numbers of 30-50% to 20-30%, pack-level specific energy of 600-800 Wh/kg could be reached by 2030. All this assumes levels of investment in R&D sufficient to make reaching these targets a priority. In order to reach these goals, the research enterprise has to pivot from current EV goals of cost reduction to the aviation imperative of high specific energy. Achieving the latter may well assist the former, however, given the low cost of chemicals for the promising chemistries in Table 1.

Summary

The combination of the need for high specific energy and specific power, very wide environmental capability, shallow depth of discharge, all underpinned by safety implies that the optimization of both the chemistry and package design for aviation offer new challenges for the battery community. Usable, pack level energy densities exceeding 400 Wh/kg are desired for urban air mobility vehicles, 1200-2000 Wh/kg for commuter aircraft. These performance levels require a fundamental reassessment of battery chemistry. With adequate levels of support, we conclude that pack-level specific energies in excess of 600 Wh/kg may be feasible by 2030. All elements must be in place – battery chemistry, cell and pack engineering, and an almost flawless production system. We are mindful of a recent comment by Elon Musk, "Mass producing batteries is the hardest thing in the world. Prototypes are easy. Scaling production is very hard." [53]

In 1884 a battery powered dirigible flew 8 km with two people aboard. Electric propulsion had disappeared by 1909 when the Wright brothers delivered the first airplane to the US government, capable of carrying 2 people 120 km, about the same capability of the only battery powered air-plane certified today. By 1920, fueled aircraft carried 12 passengers 800 km. Eighty years later, fueled aircraft carry 400 people 12,000 km. Enabling new aircraft capabilities, batteries may be flying again. By the end of this decade, drones and UAMs can be in service. Battery powered aircraft capable of flying the 1920 mission may appear in the following decade.

Competing Interests: V. V. is a technical consultant at QuantumScape Corporation, Chief Scientist at Aionics Inc. Y.-M. C. is co-founder and Chief Scientist at 24M Technologies Inc. M.B. is technical consultant to Electra.aero and Ampaire.

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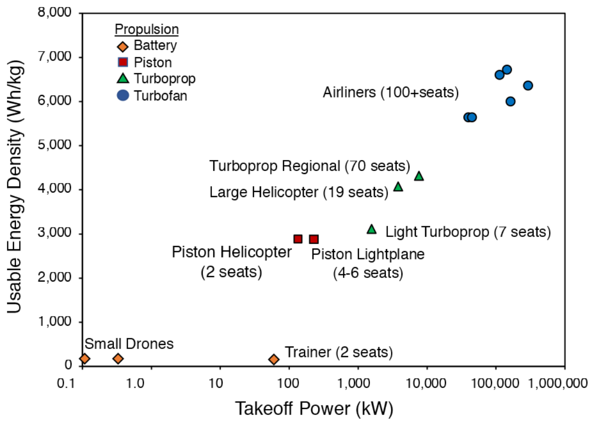
Figure 1: **Energy and power used for flight.** (a) Max power and energy on board for production vehicles. (b) Net energy density (density of the energy source times the conversion efficiency to shaft power) of representative production aircraft as a function of their power. The differences among fueled aircraft reflects engine efficiency increasing with size.



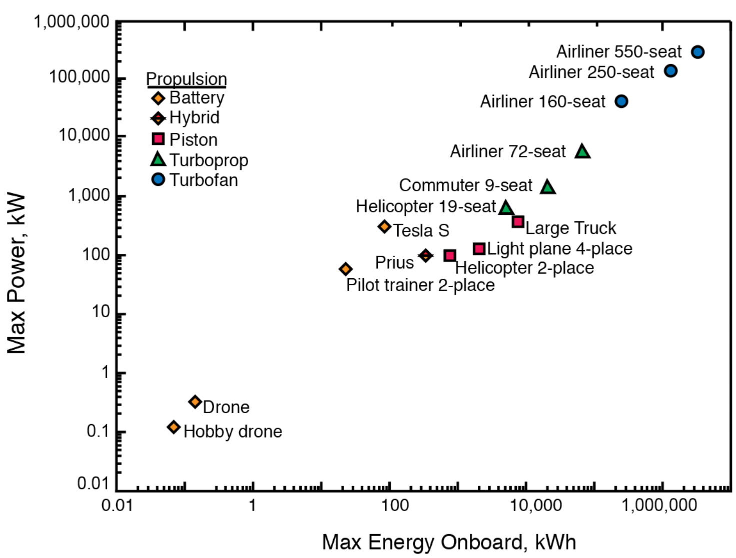


Figure 2: ***History of aviation's usable energy density****, defined as the energy in the fuel or battery times the efficiency of converting that energy into shaft power at cruise. The conversion efficiency for battery powered electric drives is assumed constant at 90%. Battery mass is for the cells only, not accounting for packaging or state of charge limitations required for safety or battery life.*

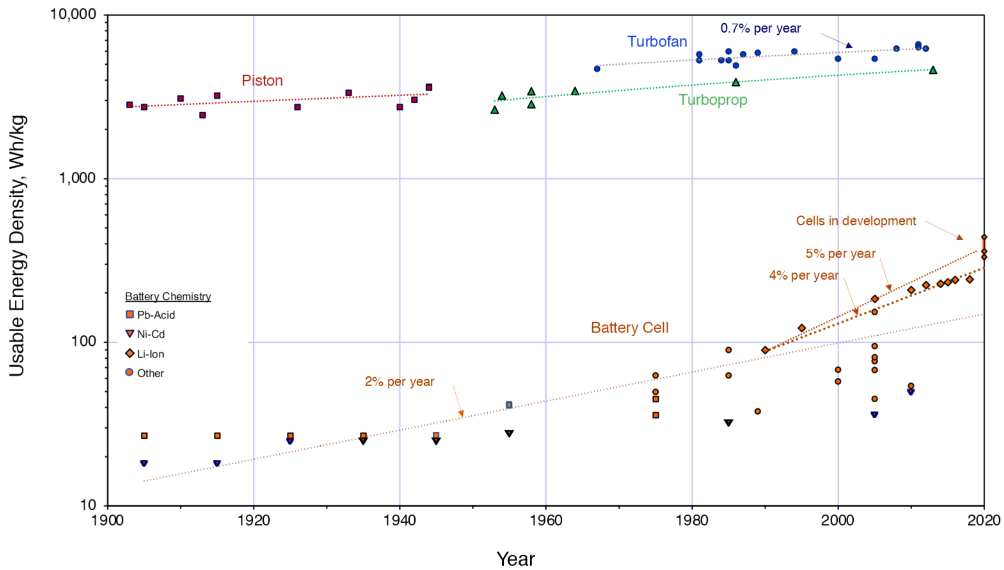


*Figure 3: **Translating battery cell performance to aircraft range** (a) Factors influencing battery energy available-for-flight. Packaging, SOC, and aging allowances consistent with a SOA Li-ion EV battery. Flight reserve is for helicopter-like operation on a one-hour mission. (b) Influence of available-for-flight energy density on range and payload. The curves are battery energy density available-for-flight needed to fly to a notional fixed-wing electric airplane of current technology to the specified range. Payload can be traded for fuel or batteries to extend range. The symbols are the range and payload fractions of representative production aircraft (which have differing usable energy densities, weight fractions, etc.) Modelled electric aircraft: lift/drag=20, no-battery empty/gross weight = 0.4, propulsion eff. including propeller =0.8.*[11]

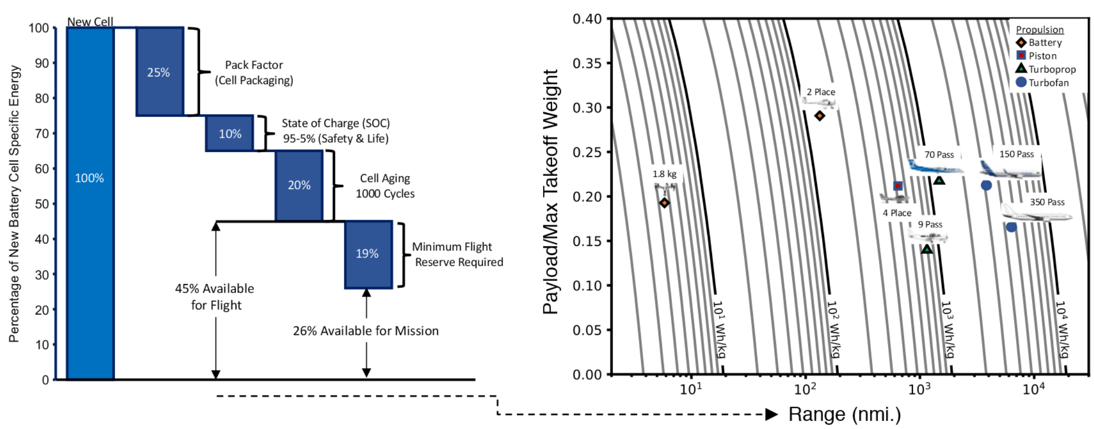


Figure 4: ***Illustration of various losses in practically-achieved specific energy at the cell level****. Practical cells need to simultaneously deliver required cycle life for the use-case, required power for the mission, be cost competitive and pass the necessary safety requirements.*

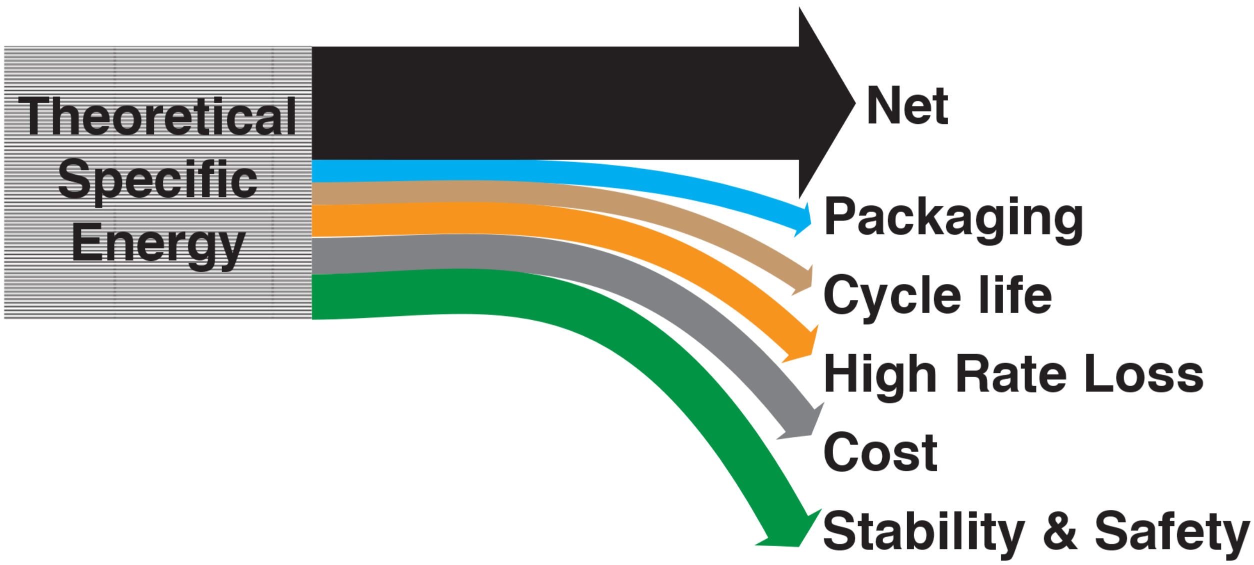


Figure 5: ***Differences in mechanism of current Li-ion batteries based on insertion and possible future batteries based on conversion****. Insertion based approach is typically limited to less than 1 charge carrier (e.g. Li-ion) per metal center, while conversion-based approach can accomodate multiple charge carriers per redox center.*