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VIEWPOINT

Performance Metrics Required of Next-Generation Batteries to Electrify Commercial Aircraft

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Electric aircraft have generated increased interest following the recent success of electric passenger vehicles. Over 4 million passenger electric vehicles have been sold,[1] and there have been numerous announcements regarding the electrification of SUVs, pick-up trucks, and other light commercial vehicles, which represent the majority of the passenger automotive market.[2,3] However, while electrification of ground vehicles is well underway, electrification of aircraft is still in its infancy. Conventional aircraft engines emit greenhouse gases such as carbon dioxide, water vapor, nitrous oxides, sulfates, and soot.[4] They also emit contrails, which could cause up to 50% of aviation-derived radiative forcing.[5] In addition, electrification of aircraft opens new architectures for improving efficiency such as distributed electric propulsion, which can increase the lift−drag ratio and decrease the weight of the propulsion system,[6,7] and boundary layer ingestion, which can increase propulsive efficiency by 8−10%.[8,9]

Alongside, there is great interest in electric vertical takeoff and landing (eVTOL) aircraft for urban air mobility.[10−12] In a recent Viewpoint, we identified the challenging battery requirements for eVTOL aircraft, reiterating the obvious importance of specific energy (defined as the energy available per unit mass) and identifying the importance of power limitations and thermal management requirements during takeoff and landing.[13] While eVTOLs represent a new market for electric aircraft, electrifying existing commercial aircraft is an important step in moving the transportation sector toward net-zero emissions.[14] Efforts are underway toward the introduction and development of electric and hybrid electric commercial aircraft.[15−17] Norway has announced its intention to electrify its entire fleet of aircraft in the near future.[18] Further, the world's largest seaplane operator, Harbor Air, announced their intention to electrify their fleet.[19] Numerous technological challenges remain in the electrification of aircraft, one of the primary uncertainties being the performance metrics required of batteries to do so. Many analyses have presented a comprehensive system-level perspective on transport-sized hybrid and electric aircraft and have identified subsystem component targets for the systems that they analyze.[20−23] Others have presented analyses on greenhouse gas emission reductions, resulting from electrification of aircraft.[24,25] Additionally, some small electric aircraft exist in various stages of the development process.[11,26,27] These analyses tend to be specific to certain classes of transport aircraft, and sometimes specific aircraft, rather than addressing the commercial aviation market as a whole. In this Viewpoint, we aim to identify a comprehensive set of performance metrics required for next-generation batteries to electrify commercial aircraft.

We divide commercial aircraft into three categories: regional, narrow-body, and wide-body. Regional aircraft typically fly short missions, about 500 nautical miles (nmi) and carry low passenger loads (30−75), while wide-body aircraft carry high passenger loads (200−400) and fly much longer missions (>2000 nmi). Narrow-body aircraft fall in between, carrying medium passenger loads and flying ranges of ∼1000 nmi. We find that the major factor in determining the specific energy required of aircraft is the range that the class of aircraft typically flies, meaning that smaller, short-range aircraft will require less demanding battery performance metrics than larger, longer-range aircraft. We find that only next-generation chemistries, like Li−air or Li−CF_x, may be able to meet some of the requirements needed for electric commercial aircraft to achieve the range and payloads required for adoption.

In the course of a mission, an aircraft takes off from the ground, climbs to its cruising altitude, cruises to its destination, descends to near ground level, and then lands.[28] All aircraft are mandated to maintain an emergency reserve energy for contingencies such as diversions or aborted landings. The FAA (Federal Aviation Administration) requires that commercial aircraft be able to abort a landing, climb to normal cruising altitude, fly to the most distant alternate airport (here assumed to be 200 nmi), and loiter for 45 min at normal cruise fuel consumption.[29] As an alternative to the extant FAA commercial reserve, a proposed approach is to house the emergency reserve by maintaining an additional 30% battery state of charge (SoC),[20] and we use the 30% SoC reserve in our analyses.

To calculate energy and power requirements in flight, we first calculate thrust. Four forces act on an aircraft in flight:

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thrust (force generated by the propulsion system), drag (aerodynamic force opposite to velocity), weight (gravitational force), and lift (aerodynamic force normal to velocity).[30] Neglecting acceleration, thrust can be calculated by solving the equations for each of these forces, which are a function of the geometry and operating conditions of the aircraft, including instantaneous velocity relative to the surrounding air (V), the zero lift drag coefficient (C_{D0}), propulsive efficiency (η_{prop}), mechanical efficiency (η_{mech}), wing area (S), the aspect ratio (the ratio of the square of the wingspan to the wing area), and climb or descent angle (γ). To calculate power at any point during flight, we neglect acceleration, and thrust is multiplied by velocity, resulting in eq 1.[31] We calculate energy by integrating instantaneous power over the duration of the flight.

$$P = \frac{\frac{1}{2}V^3 S C_{D0}\rho + \frac{2KW^2}{\rho V S} + WV\sin(\gamma)}{\eta_{prop}\eta_{mech}} \quad (1)$$

Assessing the performance of potential electric aircraft is complicated by the considerable variation of the parameters in eq 1. We calculate density (ρ) and velocity (V) at each point during the flight. We estimate the remaining parameters, namely, the zero-lift drag coefficient (C_{D0}), propulsive efficiency(η_{prop}), mechanical efficiency (η_{mech}), wing area (S), and aspect ratio, using distributions based on current commercial aircraft. K is a function of aircraft geometry and is discussed in more detail in the SI. To estimate mass allocated to payload, energy storage, and aircraft systems, we use the empty mass fraction (ewf), the fraction of aircraft mass with no payload or energy storage to the total takeoff mass of the aircraft. The total mass of the aircraft M_{TO} is given by eq 2, where M_{pax} is the payload mass, S_e is specific energy, and P is the instantaneous power. Detailed descriptions of the calculations of each parameter are available in the SI.

$$M_{TO} = \text{ewf} \times M_{TO} + S_e \times \int P(t)\,dt + M_{pax} \quad (2)$$

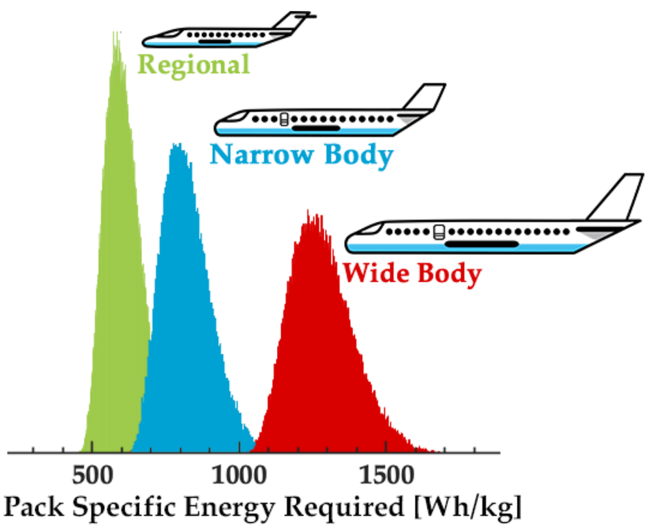

Figure 1. Histograms of specific energy for regional, narrow-body, and wide-body aircraft, illustrating the uncertainty stemming from aircraft design parameters. Larger (and longer-range) aircraft require a higher specific energy than do smaller (and shorter-range) aircraft.

Figure 2 shows the distributions of parameters from historical aircraft showing minimum, maximum, and mean values for each parameter and class of aircraft. These parameters were gathered from current U.S. commercial aircraft (a specific list of aircraft can be found in the SI) and were used in lieu of extensive trade studies to estimate the parameters of potential electric aircraft.

To find the distribution of specific energy resulting from the uncertain parameters in eq 1, we performed Monte Carlo simulations with predefined missions for each class of aircraft. The parameters for the simulations were sampled from the triangular distributions shown in (Figure 2). The range for regional, narrow-body, and wide-body aircraft was set at 350, 500, and 1000 nmi, respectively, and the number of passengers was set to 30, 150, and 300, while the mass for each segment was 50 000, 100 000, and 250,000 kg, chosen based on previous literature and current aircraft of each class. Then, 100 000 iterations were run for each class of aircraft. Results are shown in Figure 1.

The data shown in Figure 1 have means for each segment of aircraft of ~600, 820, and 1280 Wh/kg-pack, with standard deviations of 61, 81, and 105 Wh/kg-pack, respectively. Gnadt et. al estimated a required specific energy for a narrow-body aircraft of 800 Wh/kg-pack, which agrees well with our mean for that class of 820 Wh/kg.[20] The trend of increasing specific energy with aircraft size is not primarily due to the larger size of these aircraft but rather to the longer-range use cases for which they are typically employed. When the range for the narrow-body and wide-body cases is held constant and the same analysis is run, the mean specific energy for the wide-body is ~1280 Wh/kg-pack, and that for the narrow-body is ~1490 Wh/kg-pack. The resulting histograms can be seen in the SI. It should be noted that satisfying these predefined mission requirements does not guarantee that an aircraft is commercially feasible. Small aircraft, such as regional and some narrow-body aircraft, often have cruising ranges that are much lower than their maximum range. However, large aircraft often use a much larger fraction of their maximum range in a typical flight. For example, the Airbus A319, a small narrow-body aircraft, is most likely to fly a range of around 161 nmi in cruise, and the distribution of its flights is skewed toward the lower end of its range. On the other hand, a wide-body aircraft, such as the Boeing 777, nearly always flies toward the high end of its range, with a mode cruise length of 2615 nmi.[32] Therefore, not only are the battery requirements for regional aircraft more feasible than narrow- or wide-body aircraft but the baseline cases for regional aircraft are also more practical than those for narrow- and wide-body aircraft.

To compare potential electric aircraft and conventional aircraft at various battery-specific energies and empty weight fractions, we show the percentage of mean range and passenger nautical miles (pnmi) for each class of aircraft in Figure 3. The regional aircraft is able to achieve the current mean pnmi at around 1400 Wh/kg-pack, with an empty weight fraction of 0.35, while the narrow-body and wide-body aircraft are not able to achieve the current mean pnmi at any specific energy considered in this analysis. The most demanding battery requirements occur in the wide-body case, where even in the most optimistic case presented in this paper only 24% of the current pnmi and 20% of the current range are achieved.

As mentioned above, the scaling effect is not primarily due to the larger size of the aircraft but rather due to the increased range. To illustrate this effect, consider the power profiles of

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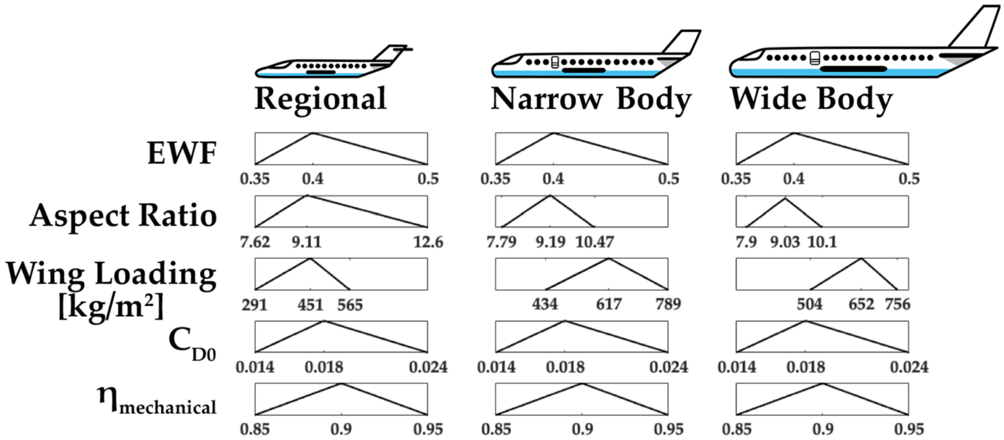

Figure 2. Parameters used to estimate specific energy for various classes of commercial aircraft. The minimum, maximum, and mean of each parameter and aircraft are shown on each plot. These parameters are used to estimate the power and energy of a prospective electric aircraft of each size. The data for these parameters are in the SI.

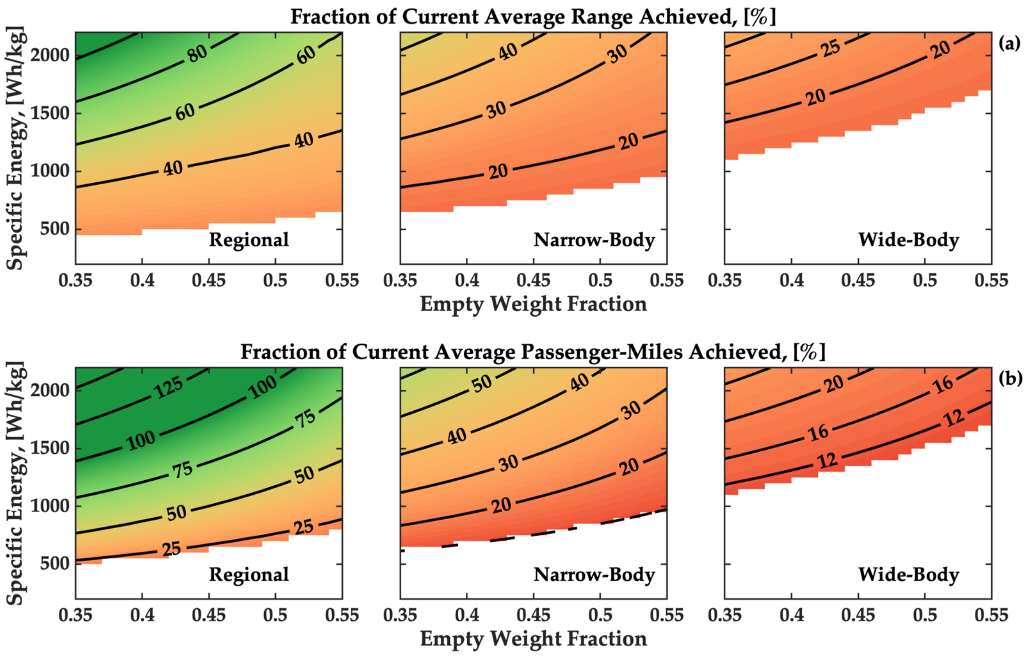

Figure 3. Range and passenger miles achieved by electric regional, narrow-body, and wide-body aircraft shown as a fraction of the current average range in (a) and passenger miles in (b) for the respective categories. We observe that for regional aircraft the current average range is achieved at a pack-level specific energy of about 2000 Wh/kg and current average passenger miles at about 1400 Wh/kg. The threshold for a feasible all-electric regional aircraft is about 500 Wh/kg, achieving about 25% of the current average range. A similar threshold is about 800 and 1700 Wh/kg for narrow-body and wide-body, respectively. However, only 12 and 16% of the current average range is achieved at threshold-specific energies for the narrow- and wide-body aircraft, respectively. At the highest pack-level specific energy considered of 2000 Wh/kg, electric wide-body aircraft can achieve only 19 and 16% of the current average range and passenger miles. On the other hand, at 2000 Wh/kg, regional aircraft achieve a much higher range and passenger miles than the current average.

each of the classes of aircraft for representative ranges flown by each (Figure 4). While the size of the aircraft results in the higher power at each point, the energy required to fly the ranges flown by aircraft (the area beneath the curve) increases as a result of both the increased power and the increased range.

Having identified the energy and power requirements, we discuss the possible battery chemistries and materials needed to achieve the previously identified targets. The specific energy of current generation Li-ion batteries is about 250 Wh/kg-cell, which has steadily increased by about 5% over the past decade.[33] The projected maximum specific energy for future Li-ion batteries is around 400−500 Wh/kg-cell[33] with lithium metal anodes and high-voltage and high specific capacity cathodes. Accounting for packing burden, this is likely insufficient for regional aircraft, the least demanding among the three categories of aircraft considered. The maximum specific energy of a Li−S system is about 500 Wh/kg-pack,[34] which reaches the minimum threshold for regional aircraft, but does not allow for improvements beyond the baseline capability and therefore may not be practical for aircraft development. One of the most promising chemistries is Li−O_2, where the projected maximum pack specific energy could potentially meet some of the targets estimated previously for

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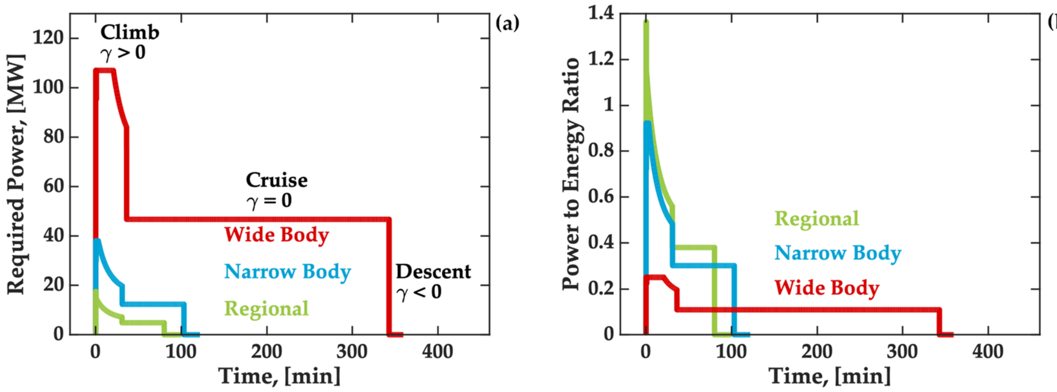

Figure 4. (a) Aircraft power profiles, along with conditions of flight in each segment. This figure illustrates the scaling challenges inherent in electric flight; as MTOM increases, the typical use case range also increases, causing a massive increase in the total energy needed. (b) Comparison of the power demand to energy (total energy over the trip) ratio throughout the mission.

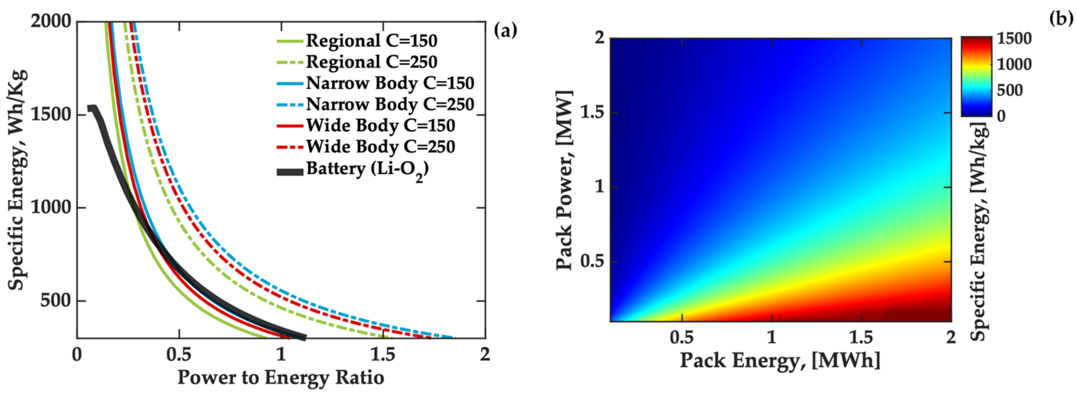

Figure 5. (a) Pack-level specific energy required for various aircraft configurations as a function of power/energy ratio and specific energy achieved by a Li−air battery as a function of power/energy ratio. While for low values of the power−mass ratio (C) all three aircraft could be flown using Li−air batteries, only for regional is a meaningful percentage of current passenger nautical miles achieved. (b) Pack specific energy of Li−air open systems for different pack-level energy and power metrics. As the specific energy tends to zero, it implies that the pack power to pack energy ratio is not achievable.

narrow-body and regional aircraft and allow for improvements beyond the baseline capability in the case of regional aircraft.

While Li−O_2 battery systems have one of the highest specific energies among rechargeable electrochemical batteries,[34] comparable high specific energy primary batteries have been investigated for applications in space exploration.[35] At an operating temperature of about 20 °C, Li/SO_2, Li/$SOCl_2$, Li/FeS_2, and Li/MnO_2 systems provide specific energies in the range of 350−420 and 330−350 Wh/kg-cell at low and medium discharge rates, respectively. Li/CF_x batteries provide up to 730 Wh/kg-cell at medium discharge rates.[35] It remains to be seen if these primary battery chemistries could be made rechargeable and meet the power and specific energy requirements for electric aircraft. In this study, we limit our analysis only to rechargeable batteries for aircraft propulsion, and we intend to explore the performance envelope of these primary batteries in a future study.

To estimate the cell and pack-level specific energy of Li−O_2 systems, we used electrochemical Li−air cell and pack models following the work of Gallagher et al.[34] Both open and closed Li−O_2 systems were considered for this analysis. We chose to focus on an open system, which does not carry oxygen onboard, as opposed to a closed system wherein the O_2 is contained in a pressure vessel because the open system tends to maximize specific energy, although oxygen intake over the course of a discharge will cause the mass of the system to rise over the duration of a flight, resulting in reduced effective specific energy.[34] In such a system, the battery is accompanied by a compressor to account for the changes in atmospheric pressure experienced by an aircraft in flight. The mass of the compressor and the energy that it consumes are accounted for in the model. Using the electrochemical and pack design model, we construct a Ragone plot showing the relationship between the pack specific energy and specific power, seen in Figure 5b. Li−O_2 is capable of providing the specific energy required for regional and many narrow-body flights; however in some cases, the high power requirements of takeoff will limit the specific energy of the battery.

Figure 5a shows the specific energy as a function of power−energy ratio for the Li−O_2 system. It also shows the specific energy required as a function of the peak power to energy (in W/Wh) ratio for each type of aircraft for various values of power−mass ratio (in W/kg). The intersection of these curves represents a feasible operating point for a prospective aircraft, where the battery power and energy meet the aircraft's requirements. For all three categories of aircraft, only the lowest power−mass ratio (150) yields a feasible specific energy. For regional aircraft, the specific energy is around 900 Wh/kg-pack, meaning that a lithium air battery could achieve around 60% of the current passenger nautical miles according to Figure 3. For narrow-body aircraft, the maximum specific energy achieved is around 600 Wh/kg, achieving around 10%

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of the current passenger nautical miles, and for wide-body, no meaningful aircraft can be built at the specific energy identified. Therefore, $Li-O_2$ provides a feasible route forward only for small regional aircraft.

Fully electric aircraft powered by batteries face a number of challenges moving forward. The specific energy of even the most optimistic future batteries enables only small regional aircraft, while larger narrow-body or wide-body aircraft remain outside of the feasibility limits of known electrochemical rechargeable battery systems. Additionally, the achievable small electric aircraft would be heavier than conventional aircraft for comparable performance metrics. It should be noted that this analysis does not consider the energy savings through potential improvements in aircraft design such as boundary layer ingestion and distributed propulsion. Although these technologies could be achieved in conventional aircraft, electrification provides the most feasible avenue for their introduction.[7] While a fully electric aircraft requires significant innovation in battery and aircraft design, a hybrid aircraft[36] could be a potential pathway to help address some of the challenges while increasing aircraft efficiency. In any case, a fully, or at least a more electric, (hybrid) aircraft presents an opportunity to lower the climate impact of commercial aviation. While the exact extent of emission savings depends on external factors such as electricity mix, electrifying aircraft would eliminate aircraft-induced cloudiness. In the near term, hybrid electric and small fully electric aircraft can help mitigate these climatic effects of aviation. In the long term, significant technological improvements in both battery and aircraft technology will aid the further adoption of small electric and larger more electric aircraft.

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■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsenergylett.9b02574.

Details of the aircraft performance model, the PNMi optimization, and a comparison of narrow-body and regional aircraft specific energies at constant range (PDF)

Aircraft parameters (TXT)

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Notes

Views expressed in this Viewpoint are those of the authors and not necessarily the views of the ACS.
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