



BATTERY PERFORMANCE METRICS FOR LARGE ELECTRIC PASSENGER AIRCRAFT

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Abstract

Most literature suggests that a battery specific energy of at least 500 to 1000 Wh/kg at pack level is required for battery-electric aircraft to become feasible for commercial passenger transport in the CS-25/Part 25 space. However, recent aircraft design studies have shown that such aircraft can already present attractive payload-range capabilities with substantially less aggressive battery technology scenarios. In this paper, we assess what the battery performance metrics should be for such aircraft, and how they compare to those of urban-air mobility aircraft and ground-based electric vehicles. We discuss how with a 360 Wh/kg pack specific energy and a 1.2C charge / 1.2C discharge rate capability, a battery-electric range of 800 km is feasible. An analysis of the battery volumes required to sustain a fleet of large electric aircraft shows that, in a scenario where large electric aircraft replace 10% of all flights below 800 km range by 2050, 50 GWh/year of battery production is required. For a limit-case scenario where they replace 100% of all flights below 1000 km by 2050, a production volume of 840 GWh/year is required. This implies that, if large electric aircraft are to play a key role in decarbonization of the aviation sector, the market for aviation cell production, packaging, and recycling will be substantial.

Keywords: Battery-electric propulsion, aircraft design, battery performance, electric aviation

1. Introduction

Several pathways towards climate-neutral aviation are currently being investigated, including hydrogen-powered aircraft, sustainable aviation fuel (SAF), or battery-electric propulsion systems [1]. In this search for sustainable propulsion technologies, battery-electric propulsion is often considered suitable only for small aircraft (< 19 pax) and short ranges (< 400 km) with both current and near-future battery technologies [2, 3]. Many studies conclude that for meaningful applications in the large passenger aircraft (CS-25/Part 25) category, battery packs with a specific energy in excess of 1000 Wh/kg would be required [4, 5]. These values are well beyond current and near-future projections of specific energy for rechargeable batteries with acceptable cycle life and discharge capabilities. Therefore, battery-electric propulsion is often discarded as a solution for “decarbonizing” the aviation sector as a whole, since the vast majority of aviation-related emissions come from large passenger aircraft.

However, recent studies suggest that with the appropriate selection of top-level aircraft requirements and design choices, large passenger aircraft with a nominal mission range (i.e. accounting for reserves separately) of up to 1000 km may be possible with much more near-term battery technology than previously envisioned [6, 7]. Routes up to 1000 km currently account for roughly 50% of all scheduled passenger flights and 20% of all aviation CO₂ emissions [7]. Therefore, if a large battery-electric aircraft can compete cost-effectively with fuel-based aircraft on those routes, the addressable market size and potential reduction in emissions of the aviation sector as a whole is substantial. The

market size for battery production may therefore also be of a different order of magnitude than for small electric aircraft. This raises the question whether batteries for aircraft propulsion will remain a niche application, or whether the market size for such aircraft can become comparable to other sectors in terms of the required battery production volumes. And understanding the potential production volumes is important since they are a key driver of battery costs [8] and will determine whether it is feasible to develop battery cells optimized specifically for large-aircraft applications.

The objective of this paper is therefore two-fold. First, we analyze the battery performance characteristics required for large electric aircraft in terms of basic metrics such as specific energy, (dis)charge rate, cycle life, or packaging overhead. Second, assuming the availability of batteries that match those characteristics, we perform a simplified analysis to investigate the production volumes required to sustain an aviation sector with different levels of market penetration of battery-electric aircraft. Aspects such as cell chemistry and battery costs are not addressed in detail in this study, though several driving factors are discussed. The results of this analysis can serve as guidelines when specifying requirements during the research & development of cells or batteries for aircraft propulsion.

2. Large battery-electric aircraft: reference configuration

Before diving into the required battery characteristics, in this section we first define a reference “large battery-electric aircraft” configuration for context. We take the aircraft design presented in Ref. [7] as reference. The aircraft is designed to carry 90 passengers with a cruise speed of $M = 0.6$ at an altitude of approximately 7.5 km. The targeted nominal mission range is 1000 km, but depends on the battery technology available (see Sec. 3). The aircraft must be able to operate from the same airports as narrowbodies, with a 2000 m runway, a 36 m wingspan constraint at the gate, and a charging time comparable to typical narrowbody turnaround times (see Sec. 3).

The aircraft configuration is illustrated in Fig. 1 and features a four-abreast fuselage, a low wing, wing-mounted landing gear, a T-tail, and a distributed propulsion system. The propellers are driven by electric motors which are in turn powered by the batteries, located inside the wing. The energy for reserves is covered by a fuel-based reserve energy system (RES) located in the tailcone, which must provide electrical power during diversion, loiter, and contingency. The aircraft has a maximum take-off mass of 76 tons, a battery mass fraction of 46% (35 tons), and total maximum continuous and maximum peak (3 mins) shaft powers of 11.2 MW and 13.5 MW, respectively. For a more extensive description of the configuration and the choices behind it, the reader is referred to Ref. [7].

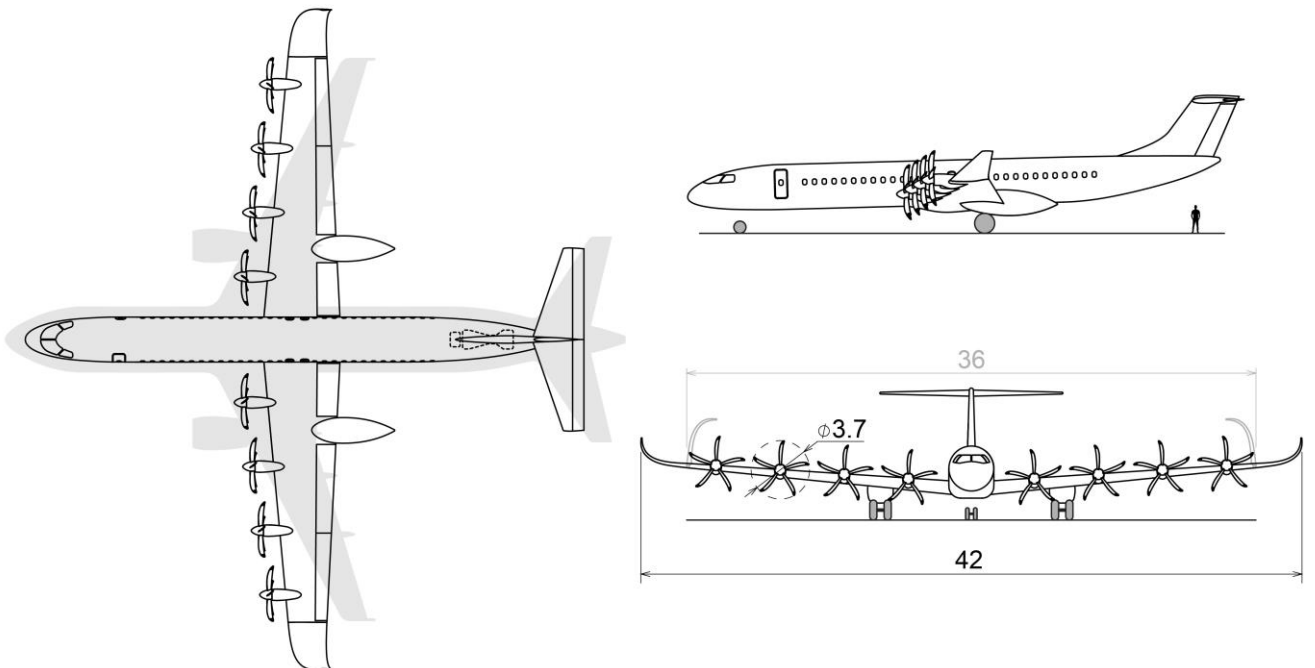


Figure 1. Three-view drawing of a 90-seater, battery-electric passenger aircraft with a gas-turbine-based reserve energy system indicated with dotted lines. A320 planform included in top view for scale. Dimensions in meters. Figure adapted from Ref. [7].

The analyses in this paper focus on aircraft that are comparable to the configuration above, characterized by a high battery-mass fraction (required for higher range, e.g. > 40%), conventional take-off and landing (CTOL) distance requirements (no short (STOL) or vertical (VTOL) take-off and landing capabilities), a gas-turbine-based reserve energy system, and a relatively high passenger count (e.g. 50+ seats). While the battery performance metrics may also be applicable to smaller aircraft (e.g. a CS-23/FAR 23 category CTOL aircraft), they differ from more radical aircraft configurations such as electric VTOL (eVTOL) aircraft, as discussed in the following section.

3. Battery Performance Requirements

In this section, we discuss the most important battery requirements for the aircraft presented in Sec. 2, focusing on cell specific energy, discharge rate, charge rate, cycle life and packaging overheads. We conclude the section by comparing these requirements to other applications for urban-air mobility (UAM) and ground-based modes of transport.

3.1 Cell specific energy

The range of a battery-electric aircraft is, in first approximation, directly proportional to the specific energy¹ of the battery (see e.g. Ref. [9]). Therefore, achieving a high usable specific energy is key for large electric aircraft, even if this requires compromises on other metrics such as specific power or cycle life. However, the usable, end-of-life, pack-level specific energy can be significantly lower than the specific energy of a new cell. Reference [10] provides a clear overview of some of the “knockdown” factors involved. In this section, we start by focusing on the specific energy of a new cell. An overview of some relevant developments in high-specific-energy cells is given in Ref. [11].

As the cell specific energy continues to evolve, in this paper we set future development targets rather than to taking it as a given. Note that it takes several years to complete the detailed design and certification of a new aircraft, and that parts of these steps cannot be done until the battery technology is proven. This implies that, assuming an aircraft entry-into-service (EIS) in the 2030+ timeframe, the cell chemistry must have been produced and tested before 2030. In other words, the development times “available” to create and test new high-specific-energy cells for such an aircraft is in the order of several years, and not decades. With this in mind, we define three cell specific energy scenarios in Table 1:

- 300 Wh/kg: This is considered a conservative case since such cells already exist today with the appropriate (dis)charge rates and cycle life (see Fig. 2). This allows for a usable mission range of 500 km.
- 450 Wh/kg: This is taken as a realistic target for a 1st generation aircraft which must enter into service in the 2030+ timeframe. With this, a usable mission range of 800 km is achieved.
- 550 Wh/kg: This is the cell specific energy required for a 2nd generation aircraft to fly a usable mission range of 1000 km.

Table 1. Nominal mission range obtained by the reference aircraft configuration with a fixed total battery mass, for various battery technology scenarios. Ranges are quoted at approximately 3% cell capacity degradation (i.e. one-third into their useful life on the aircraft).

	Conservative	1 st gen aircraft	2 nd gen aircraft
Cell specific energy	300 Wh/kg	450 Wh/kg	550 Wh/kg
Pack specific energy	240 Wh/kg	360 Wh/kg	440 Wh/kg
Total battery capacity	8.4 MWh	12.6 MWh	15.4 MWh
Usable range	500 km	800 km	1000 km

¹ Cell specific energy is often referred to as “(gravimetric) energy density”. We use the term “specific energy” here to avoid confusion with the *volumetric* energy density (generally expressed in Wh/liter).

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The quantity that actually matters for aircraft range is the pack-level specific energy, also shown in Table 1 and discussed in Sec. 3.5. The cell specific energy targets listed in Table 1 assume a given packaging overhead; if this overhead is reduced, the required cell specific energy lowers, and vice versa. Analogously, the cell specific energy targets of Table 1 must be achieved at the required charge (Sec. 3.2) and discharge (Sec. 3.3) rates, and at the appropriate cycle life (Sec. 3.4). It is important to stress that the cell specific energy alone is not the challenge: it is the cell specific energy *in combination with* the other requirements. For example, recent research has demonstrated a lithium-ion cell with a specific energy above 700 Wh/kg [12], but this was achieved at extremely low dis/charge rates and an extremely limited number of cycles, and is therefore not representative of a rechargeable cell for aircraft applications.

To illustrate this trade-off, Fig. 2 shows a Ragone plot of various high-specific-energy cells whose performance has been reported publicly, including the specific energy and power that would be required throughout the mission of the large electric aircraft for the three scenarios given in Table 1. The figure focuses on existing cells rather than on future cell projections due to the high uncertainty

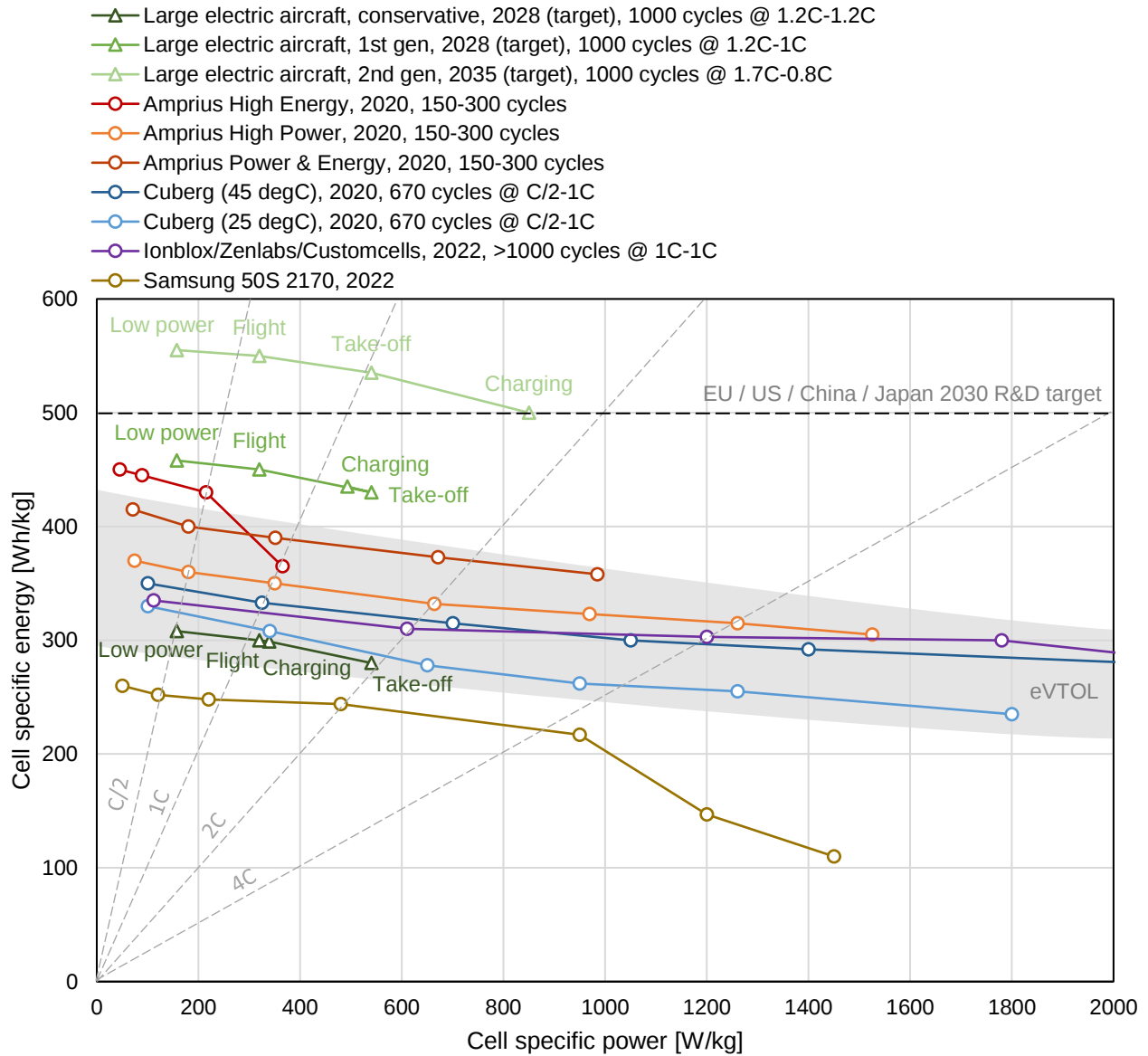


Figure 2. Ragone plot indicating cell specific energy and specific power of various state-of-the-art high-specific-energy cells, based on Refs. [13–15]. International R&D targets and notional eVTOL requirements based on Refs. [16–18]. Cycle life in legend entries corresponds to number of cycles at 100% DoD to 80% state-of-health, tested at [charge]C – [discharge]C rates.

of the latter. In the figure we can see how the specific energy of a given cell reduces with increasing specific power, since the internal losses increase with discharge rate and thus the actual energy that can be extracted from the cell decreases. Looking at the values of specific energy required for the electric aircraft, we observe that the conservative scenario is already exceeded by current cell technology at the appropriate levels of cycle life and specific power (discussed in the following sections). Focusing on the baseline “1st gen generation aircraft” target, we see that e.g. the “Amprius High Energy” cell approaches the required specific-energy levels, but not yet at the required cycle life and specific power. Finally, the figure also shows how the “2nd generation aircraft” requires a significant improvement in specific energy, though still substantially less than most literature suggests is necessary for large electric aircraft to become feasible.

3.2 Cell discharge rates

The aircraft configuration presented in Sec. 2 requires 13.5 MW of shaft power during take-off. Assuming a 90% powertrain efficiency for simplicity, this would correspond to 15 MW power required from the battery. However, since large electric aircraft must carry a significant amount of energy in their batteries (12.6 MWh for the “1st gen aircraft” in Table 1) in order to maximize range, the actual power required *per cell* is relatively low: in this case, it corresponds to a discharge rate of approximately 1.2C². This C-rate requirement is substantially lower than that of eVTOL aircraft [19], which need much more thrust to take off and land vertically (thrust > weight) than CTOL aircraft, where the wing generates the vertical force (thrust << weight). As a result, compared to typical high-specific-energy cells developed for eVTOL applications, the specific power required for large electric passenger aircraft is much lower. This difference is reflected in Fig. 2, where the “1st gen” electric aircraft requires a specific power of 540 W/kg, while smaller eVTOL applications require specific powers well beyond 1000 W/kg during take-off and landing. Figure 2 also shows how the specific power required for take-off is identical for the three electric-aircraft scenarios since the weight of the aircraft and the battery are the same, although this corresponds to higher C-rates for the “1st gen” aircraft than for the “2nd gen” aircraft due to the lower total battery capacity.

While take-off is generally the most power-intensive phase for electric aircraft (see Ref. [7]), there are other important points during the mission. Figure 3 schematically shows the discharge rates and corresponding states of charge of the different mission phases. The figure shows how the C-rate (and thus, power) required in cruise is roughly half the value required in take-off, and is practically zero during descent. However, for the reference aircraft used in this study—as well as for many other electric aircraft configurations—the most demanding moment for the cells is the go-around. In the most critical scenario, the aircraft must be able to perform a go-around at full (take-off) power solely on battery power after having flown the maximum-range mission, before the reserve energy system is activated (note that turbogenerators cannot switch on instantaneously). The battery continues to supplement power throughout the climb segment until the aircraft reaches the diversion altitude, beyond which the rest of the flight is carried out with energy provided by the reserve-energy system.

To illustrate the relevance of the go-around, Fig. 4 shows a simplified cell discharge curve calculated following Ref. [10]. The first and last 5% of the state of charge of the cell are assumed to be unusable for safety and cycle-life considerations (see e.g. Ref. [4]). The voltage discharge curve in Fig. 4a shows how the modest C-rates do not lead to substantial voltage drops for the cell model analyzed. However, Fig. 4b demonstrates how, for a same total power in MW required in take-off and in a go-around, the current required from the cell is much higher in the latter. The high current peak, combined with the increased internal resistance that cells typically present at low states of charge, implies that heat production will be maximum at this point along the mission. Although this situation rarely occurs, the cells, the thermal management system, and the other downstream elements of the electric powertrain must be able to handle this peak in current. In this regard, it is important for the go-around

² The C-rates of the battery pack and of each individual cell are expressed relative to the capacity (in Ah) of the pack and individual cell, respectively. In this paper, we assume all cells in the pack to be the same and therefore use the “C-rate” interchangeably since it is identical at cell and pack level. Note, however, that the actual capacity, voltage, and current of the pack will depend on how the cells are connected in series and parallel.

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to be performed prior to the voltage drop-off at low states of charge (depth of discharge $\geq 90\%$, in the case of Fig. 4a). Thus, from a discharge capability perspective, the most critical condition for the cell is to be able to provide 1.2C around 10% ~ 15% state of charge.

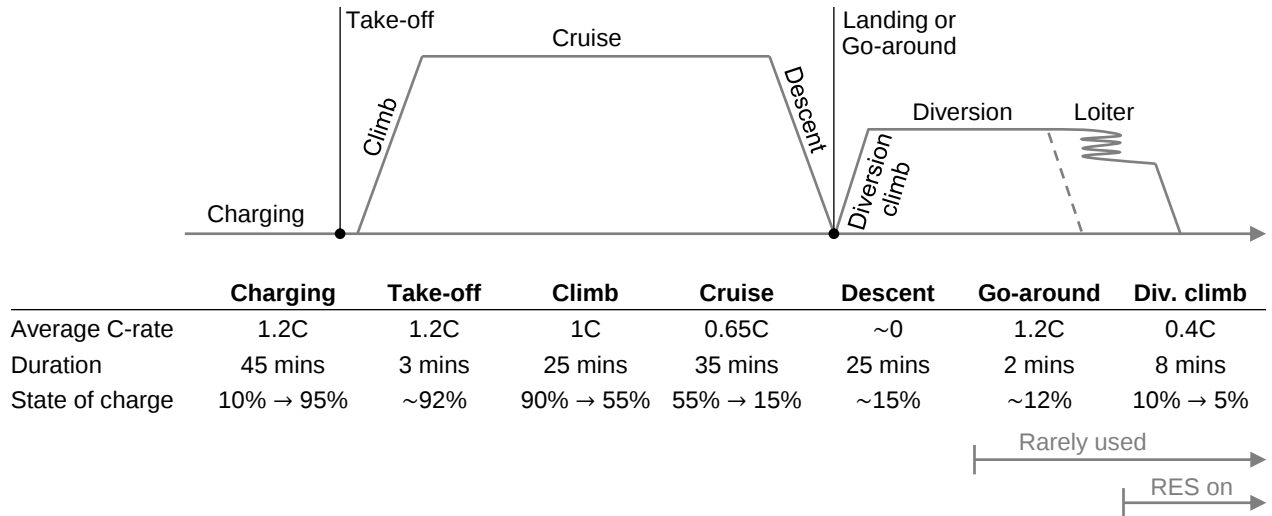


Figure 3. Average (dis)charge rates and corresponding states of charge for different mission segments for a “1st gen” aircraft flying the maximum-range mission, including a potential diversion to alternate after reaching the destination airport.

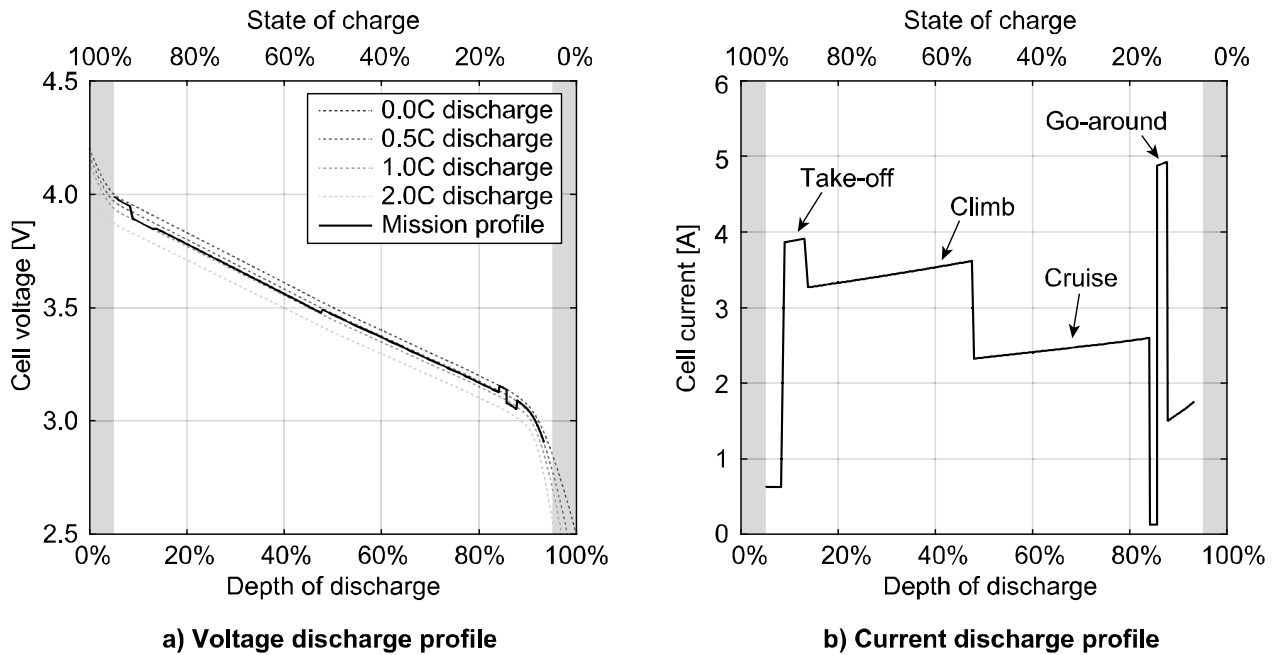


Figure 4. Example of a cell discharge curve throughout the mission, including reserves, for a notional Li-ion cell based on Ref. [10].

3.3 Cell charge rates

Selecting the appropriate performance target in terms of cell charge rate is a trade-off between the charging time of the aircraft and the specific energy and cycle life, which can generally achieve higher values if the cell is designed for lower charge rates. The charging time is crucial as it sets a lower bound on the turnaround time of the aircraft, which in turn has a large impact on its operating economics. In this study we assume that the turnaround time is limited by and comparable to the charging time. This therefore assumes that connecting and disconnecting the batteries to and from the ground power source are among the first and last steps of the ground operation, respectively, and that passengers may board and deboard the aircraft while it is being charged.

Based on these considerations and the turnaround times of current aircraft, which are typically at least 25 mins – 45 mins for regional and narrowbody aircraft, Table 2 presents the selected charging-time requirements for the three aforementioned battery technology scenarios. For the 1st generation aircraft, a maximum turnaround time of 45 minutes is established, corresponding to a mean charge rate of roughly 1.2C. However, it is important to note that the average charging time during day-to-day operation will be lower, since the aircraft does not always fly the maximum-range mission. Based on network data provided by a large international airline we assume an average depth of discharge (DoD) of 60% over all missions (compared to a 85% DoD for the maximum-range mission), which corresponds to an average mission range of roughly 550 km for the “1st gen” aircraft. Assuming linear scaling (i.e. mean charge rate independent of DoD) for simplicity, the corresponding average charge time in the fleet would be 30 minutes.

On their own, the C-rates reported in Table 2 are easily achievable with existing battery technology, with the automotive sector targeting fast charges in less than 15 mins, i.e. at C-rates above 4C [20]. This is especially the case if the battery can be temperature-controlled during the charging process, as proposed by several eVTOL manufacturers. The challenge therefore again does not lie in developing a cell that can handle the C-rate itself, but in developing a cell that combines this C-rate with high specific energy and an acceptable cycle life. The turnaround times can be reduced if the charging C-rate is increased; however, if that comes at the expense of e.g. a reduced specific energy, it may not be desirable from an operational perspective since the maximum range of the aircraft would be reduced. The optimal combination ultimately depends on operator requirements.

Table 2. Targeted charging times and the corresponding mean C-rates during charging (i.e. not the peak C-rates) for various high-specific-energy battery technology scenarios.

	Conservative	1st gen aircraft	2nd gen aircraft
Max charge time (10% → 95% SOC)	45 mins (1.2C)	45 mins (1.2C)	30 mins (1.7C)
Average charge time (35% → 95% SOC)	30 mins (1.2C)	30 mins (1.2C)	~20 mins (1.7C)

3.4 Cycle life

Prescribing a specific cycle-life requirement for electric aircraft batteries is challenging because the cycle life does not affect the actual performance of the aircraft, but is a key driver of the overall life-cycle emissions and, especially, operating costs per seat-kilometer. Moreover, it is more of an operational choice than a hard limit. As the state of health of the battery degrades, the maximum range of the aircraft decreases. However, operators flying short routes may find the shorter range acceptable and opt to use the battery for more flight cycles, thereby reducing operating costs. This is feasible from a technical perspective as long as the cell performance remains predictable and e.g. the thermal management system is designed to handle an increased heat production if the internal resistance of the cell grows over time.

The cycle life of current battery cells varies greatly depending on the design and chemistry, with the automotive sector targeting batteries with over 2000 cycles to 80% capacity retention [20]. Recent advancements in LFP cells for EV applications show much promise in this regard. However, the high specific energy required for large electric aircraft often comes hand-in-hand with a lower cycle life, which is in the order of several hundred cycles for some of the cells shown in Fig. 2. To put this into perspective: an aircraft doing six flights per day on average would perform roughly 2200 flight cycles per year (short-range aircraft often fly more than 6 legs per day, but also spend some time on the ground each year for maintenance). Therefore, the battery replacement is likely to occur one or more times per year. However, replacing a 35 ton, 12.6 MWh battery (see Table 1) is likely a time-consuming activity which is part of a planned maintenance schedule; e.g. during a “B check”. While installing a new battery once or twice per year is costly and has a non-negligible environmental impact, this use of batteries is effective on a per-passenger-kilometer basis due to the high utilization rate of aircraft. In

other words, while an EV battery generally outlives the car itself, the airframe far outlives the battery—and despite this, the contribution of battery production to life-cycle emissions per passenger-kilometer can be comparable or lower for a large electric aircraft than for EVs [7].

Based on these considerations, we assume in this paper that the battery must retain 90% of its capacity after 1500 flight cycles. A “final” state of health of 90% is selected instead of the usual 80% because it directly affects the range of the aircraft and therefore airlines may choose to retire the battery “ahead of time” to preserve range. A battery with 90% capacity remaining is also likely suitable for second-life applications. However, it is unclear how the 1500 flight cycles relate to the actual battery cycle life provided by the manufacturer. The latter is generally quantified at a constant (dis)charge rate and for a 100% depth of discharge per cycle, but we must realize that an aircraft does not always fly the design range, but a *distribution* of ranges. In other words, the 1500 flight cycles contain a distribution of depths-of-discharge. Based on airline data provided to this study, of the 1500 cycles, approximately 450 out of 1500 cycles (30%) correspond to “deep” discharges above 70% DoD, for the 1st Gen aircraft with 800 km range. Since deep discharges are more detrimental for cycle life, we assume here that 1500 flight cycles is equivalent to 500 cycles at 100% DoD. Hence, assuming linear degradation for simplicity, the cycle life target shown in Fig. 2 corresponds to 80% capacity retention after 1000 cycles at 100% DoD. The hypothesized relation between 1500 flight cycles and 500 equivalent discharge cycles to 100% DoD requires further investigation with tests of specific cell designs.

3.5 Packaging overhead

While our discussion has focused on cell characteristics, the pack-level properties are what ultimately matter from an overall vehicle perspective, as discussed in Sec. 3.1. Thus, in the following paragraphs, we briefly touch upon some of the assumptions that have been made to translate the overall vehicle-level performance requirements into cell-level performance requirements. For the level of detail addressed in this paper, the two most important parameters in this regard are the pack mass overhead, $(m_{\text{pack}} - m_{\text{cell}})/m_{\text{cell}}$, and pack volume overhead, $(V_{\text{pack}} - V_{\text{cell}})/V_{\text{cell}}$.

In an integrated design, defining what constitutes a battery pack can be ambiguous. For this preliminary discussion, we consider a battery pack as a “box” comprising everything necessary to connect a number of cells in series and parallel to a single output terminal at the bus voltage, including components for structural integrity, thermal control, and safety. The design of the pack is influenced by many variables such as the cell format, cell size, cell chemistry, number of cells in series/parallel, installation space, vibrations, etc. Two particularly important design requirements for commercial aviation³ are non-propagation and containment of thermal runaway [21]. The former states that thermal runaway in a single cell may not propagate to the adjacent cells, and the latter states that if e.g. 20% of all cells inside a pack enter thermal runaway, then this must be contained such that adjacent packs or elements of the aircraft are not affected. Furthermore, given the importance of maximizing specific energy while meeting the cycle life and (dis)charge-rate targets listed in the previous sections, an active thermal management system is considered to be necessary to keep the cells in the desired temperature range. This system must be integrated in the pack design. Note that, while from a requirements perspective there is a trade-off between what is required from the cell and what is required from the pack, in practice these two cannot be decoupled. For example, increasing the cell capacity often improves the cell specific energy, but requires additional mass on the pack to contain thermal runaway.

In this study, we assume a 25% mass overhead is required to account for battery pack components (i.e. a cell-to-pack ratio of 0.8). This target is conservative compared to the targets established in several roadmaps [22] and eVTOL manufacturers have been said to achieve overheads below 25%, though achieving this with higher-energy-density cells remains uncertain [23]. Figure 5 shows this margin along with the knockdown factors discussed in previous sections. The figure shows how, with these performance targets, the usable specific energy of the battery pack at the end of life is 35% lower than the cell energy densities reported in Table 1.

³ Regulations on thermal runaway propagation and isolation are currently applicable to smaller (eVTOL) aircraft; however, the future regulations for large passenger aircraft can be expected to be equally or more stringent.

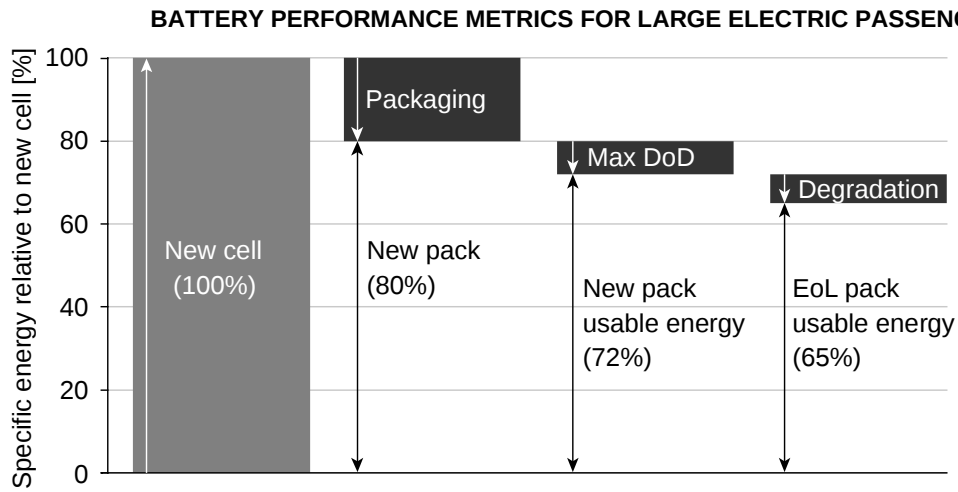


Figure 5. Waterfall chart showing relationship between the specific energy of a new cell and the usable, end-of-life, pack-level specific energy. Adapted from Ref. [7].

Finally, regarding the volumetric requirements, Ref. [7] suggest that approximately 23 m^3 of volume is available in the wing box. If the battery pack occupied all the available space, it would present an effective mass density of 1500 kg/m^3 . This implies a volume overhead of the order of 33%, relative to a typical cell mass density of 2000 kg/m^3 . For a 450 Wh/kg cell, this corresponds to a volumetric energy density of 900 Wh/liter at cell level.

3.6 Comparison to other electric-vehicle applications

Having established the performance metrics required for a large electric aircraft, we can now compare these to the developments needed in other sectors. Figure 6 compares the cell specific energy, maximum discharge rate, cycle life, packaging mass overhead, and cell cost targets of large electric aircraft to the batteries required for electric vehicles (EVs), long-distance trucks, and eVTOL aircraft for urban air mobility. The values shown in the chart are considered representative of a typical application of each type of vehicle, but the exact values may change depending on the application. The cycle life is compared at 80% state of health (SoH, i.e. 80% capacity retention) and refers to actual use cycles, not cycles at 100% DoD. Cell costs on a dollar per kWh basis are included in Fig. 6 to give an indication of the relative cost targets.

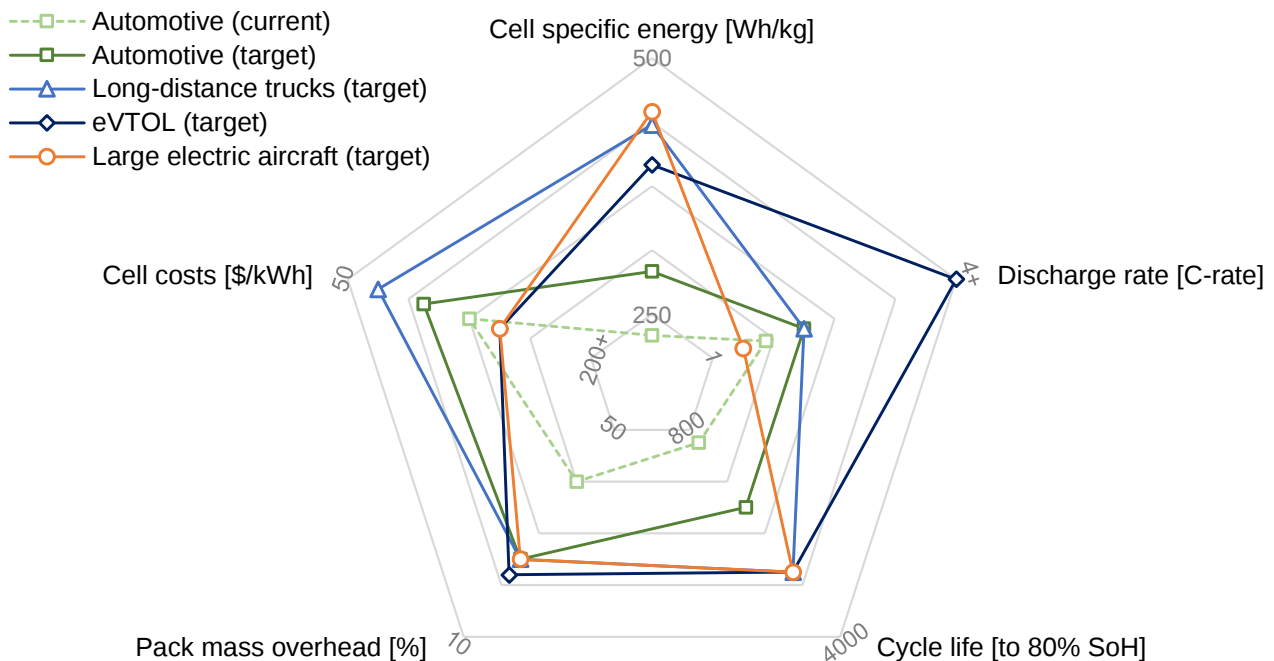


Figure 6. Notional spider chart comparing battery performance requirements of large electric aircraft to those of other forms of transport, based on internal calculations and Refs. [19, 22, 24].

Comparing the battery metrics for a 1st generation large electric aircraft to eVTOL aircraft in Fig. 6 shows that the former requires a higher specific energy, though at a much lower C-rate. Comparing the large electric aircraft to the development targets of electric cars again shows how important specific energy is, and that additional developments in cycle life may also be required. However, the required C-rates are again lower for the large electric aircraft. Finally, if we compare the large electric aircraft to the battery requirements for long-distance trucking, we see that the targeted metric values are comparable or easier to meet for the electric aircraft than for the truck. Overall, Fig. 6 demonstrates that the battery requirements for large electric aircraft are not extreme compared to other fields, though maximizing specific energy remains crucial.

4. Battery Production Volumes

The previous section presented how the battery-performance requirements for large electric aircraft are different from other transport applications. But does this open a new market that is worth developing for the battery industry, or can this actually be a showstopper since the costs to develop a new cell and its production line(s) are too high? This will largely depend on the battery volumes required, since the costs are very scale-sensitive [8]. To provide a first estimation of these effects, this section presents the market size in terms of the battery production volumes needed to replace part of the aviation sector with large battery-electric aircraft. Since such an analysis requires projections that are inherently uncertain, different scenarios are assessed.

4.1 Revenue passenger kilometers and number of aircraft required

For an estimate of battery production volumes, we first need to assess the market size for the electric aircraft themselves. For this, the amount revenue passenger kilometers (RPKs) flown below a determined range was computed based on 2019 data in Ref. [25]. Based on ICAO and IATA figures, the RPKs in 2023 are considered to be the same as in 2019 (prior to the COVID-19 pandemic), and a 3.6% annual growth rate is assumed. The resulting evolution of RPKs is shown in Fig. 7 for three ranges: 500 km, 800 km, and 1000 km, corresponding to the range that the reference aircraft can fly for the three battery technology scenarios listed in Table 1. In this analysis, it is assumed that the distribution of flights versus range does not vary over time, but simply scales proportionally to the annual growth rate.

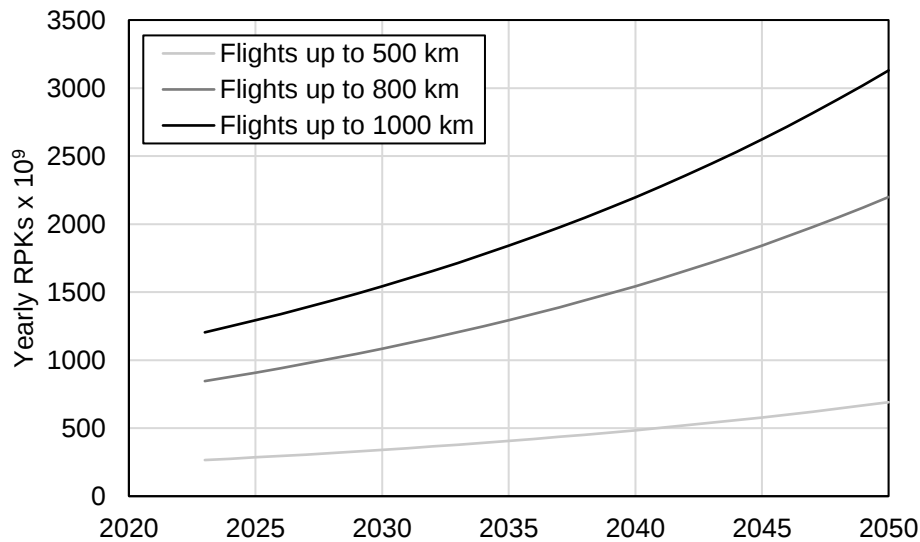


Figure 7. Revenue-passenger-kilometers (RPKs) produced annually by the aviation sector below a determined range.

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Zooming in on the case with 800 km range, Fig. 8 shows the number of 90-seater (electric) aircraft that would be required over time to cover part of the RPKs produced below 800 km. The curves are presented for three market penetration scenarios, where the market share of electric aircraft grows linearly from 0% at a hypothetical entry-into-service in 2032 to a 10%, 33%, or 100% share in the year 2050. Note that the 100% adoption scenario would require 25,000 electric aircraft to be in service by 2050 (for context, as of 2024, there are roughly 20,000 narrowbody aircraft in service [26]). The production rates required to reach this are not realistically achievable today by a single aircraft manufacturer, indicating that multiple manufacturers or significantly increased production rates would be necessary to reach this. Nevertheless, the 100% market adoption scenario is included here as upper bound and to present what it would take to reach zero emissions in 2050 for these ranges using electric aircraft.

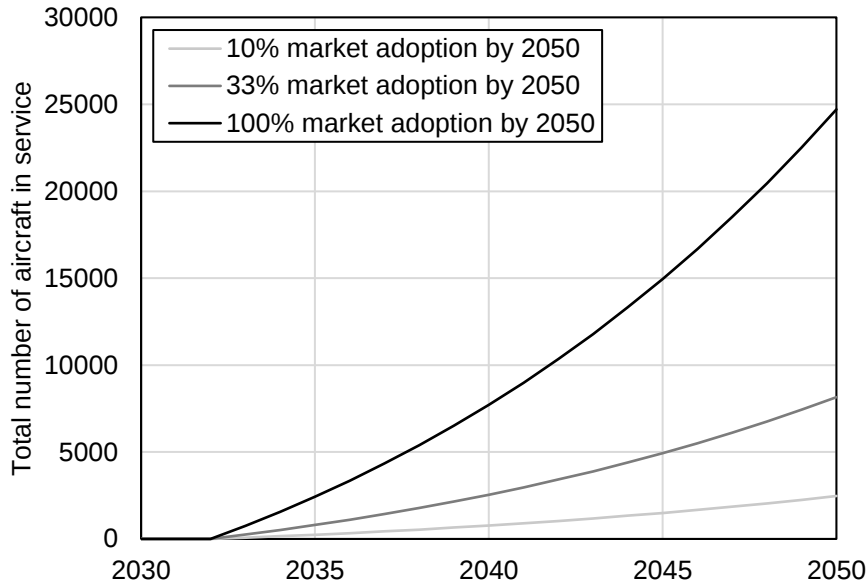


Figure 8. Number of 90-seater aircraft that would be required to cover all RPKs below 800 km range, for three different scenarios of market share by 2050.

4.2 Battery volumes required

The data from the previous section can be combined with the targeted cycle life of 1500 flights (Sec. 3.4) and the “1st gen” battery capacity of 12.6 MWh (Table 1) to calculate the annual volume of batteries required for installation on new aircraft and replacement of batteries on the aircraft already in service. Assuming an average of 7 flights per day leads to the battery being replaced 1.6 times per year on average. The resulting battery volumes are shown in Fig. 9. The results show how, independently of the market penetration scenario, the required battery volumes rapidly reach multi-GWh-per-year levels. By the year 2050, 50, 168, and 508 GWh/year are required for the 10%, 33%, and 100% market adoption scenarios, respectively. This implies that several dedicated battery gigafactories, which are typically in the order of 5 – 30 GWh/year capacity, would be needed to cover this demand.

Based on the multi-GWh-per-year volumes observed in Fig. 9, even in the most conservative “10% adoption” scenario, two conclusions can be drawn. First, these volumes warrant the R&D efforts to develop a cell specifically for these kind of applications. And second, the volumes are sufficient to create the necessary production economies of scale, where manufacturing costs typically reach a plateau beyond 3 – 5 GWh/year output [8]. To a certain extent, this leads to a chicken-and-egg situation: without a battery being produced with the right performance metrics, large electric aircraft have limited market potential, and without the large electric aircraft, the batteries with those characteristics have limited market potential. Thus, for electric aviation to successfully decarbonize the lower end of the aviation spectrum, it is key that the battery technology development and production ramp-up occur in parallel to the aircraft.

BATTERY PERFORMANCE METRICS FOR LARGE ELECTRIC PASSENGER AIRCRAFT

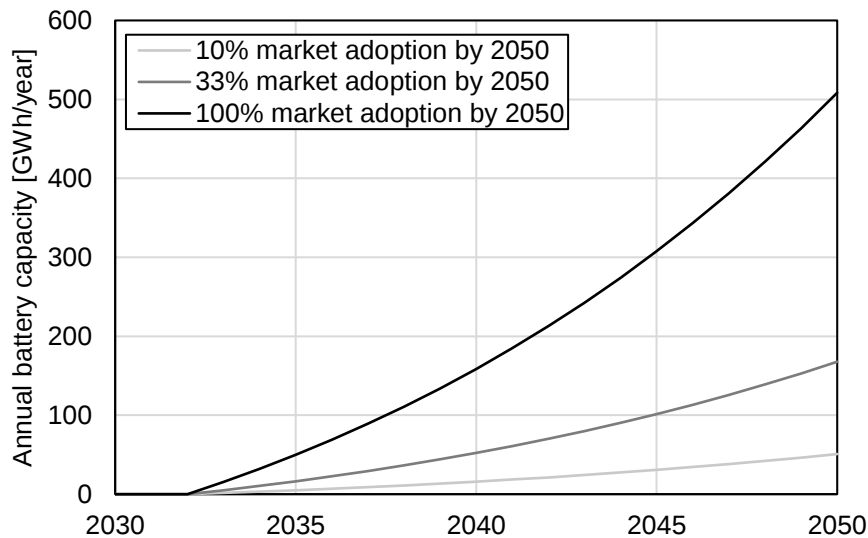


Figure 9. Annual production rate of batteries required over time for electric aircraft covering ranges below 800 km, for different market adoption scenarios by 2050.

4.3 Discussion: Comparison to other sectors

Given the relatively large volumes presented in the previous section, the final question is: how large are these numbers in the bigger picture of the energy transition? To this end, Fig. 10 compares the annual battery production volume required for large electric aircraft to the projected battery volumes required for personal EVs. Note that this is not the complete picture since the two sectors address different transport needs and there are other industries—such as consumer electronics or stationary storage—that also require batteries. However, the EV sector is expected to remain the largest consumer of batteries [27] and therefore this comparison helps to put things into perspective.

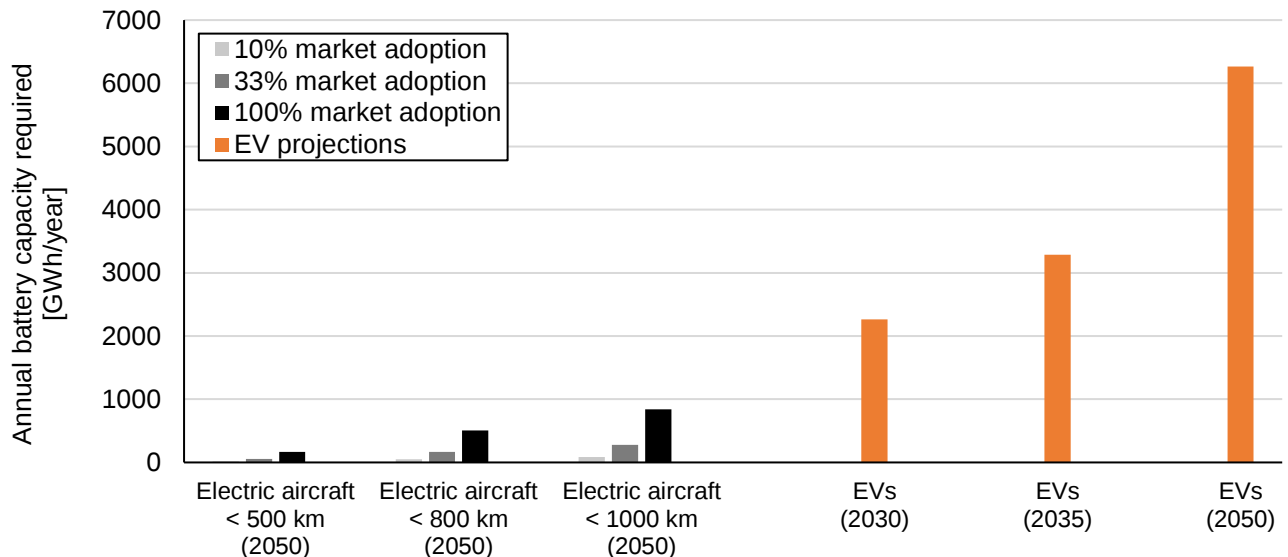


Figure 10. Comparison between the annual battery production volumes required for the aviation sector in 2050 and projected battery volumes required for the EV sector. EV projections estimated as an average of Refs. [28–31].

In the most extreme scenario of 1000 km range and 100% market adoption up to that range, large electric aircraft would require 840 GWh/year. Figure 10 shows how, despite being large volumes in an absolute sense, they are small relative to the demands of the automotive sector, equivalent to up to

13% of the battery demand of the EV sector in 2050 in the limit scenario, and being negligible in most other scenarios. The battery demand for aviation could therefore be in the same order of magnitude as the global battery demand for consumer electronics. However, although the total battery volume requirements of the aviation sector are small compared to the EV sector, the size of battery supplier contracts are not necessarily smaller than in the EV sector. This occurs because certification requirements and long airframe lifetimes would require long-lasting supplier relationships, and because the high utilization rate of aircraft requires the batteries to be swapped much more often than in EVs.

The amount of batteries required may also raise concerns about the sustainability of the supply chain. Although the volumes required for the large electric aircraft are small compared to the EV sector and will therefore not pose a major bottleneck in the broader picture, the high-specific-energy requirement can lead to chemistries which contain expensive or rare materials (e.g. NMC cathodes, while the EV sector is moving toward LFP cathodes). For this reason, it is important for the components of the battery to be recyclable. The large volume throughput can also foster the development of a recycling industry, since there will be a steady supply of depleted batteries which can play an important role in satisfying the demand for new ones [27].

Before recycling, second life applications for the batteries should also be explored. While there are numerous challenges related to second-life applications, batteries used for aircraft propulsion can present two advantages, compared to other sectors. First, strict safety regulations likely require an accurate tracking of the usage of the batteries, which means that at the end of life on the aircraft, the state of health of the cells is uniform and well-known. And second, if the battery is retired from the aircraft when 90% of the capacity remains (see Sec. 3.4), more additional cycles can be extracted than for other applications where the battery is retired after degrading to e.g. 80% capacity. It is worth emphasizing that, even if the battery is neither recycled nor used for second-life applications, the climate impact of using batteries for aircraft propulsion is small compared to other sources of aircraft (lifecycle) emissions, in terms of CO₂-equivalent emissions per passenger kilometer. This is also the case compared to SAF or hydrogen-based aircraft [7]. Recycling the batteries, or finding second-life applications, would further reduce this environmental impact.

5. Conclusions & Outlook

Battery-electric aircraft can play an important role in moving the aviation sector to a more climate-neutral future. This paper examines the required battery performance metrics for a 90-seater battery-electric aircraft equipped with a fuel-based reserve energy system. For a “1st gen” large electric aircraft with 800 km nominal mission range, the following battery requirements are discussed:

- A cell specific energy of 450 Wh/kg (at ~1C discharge)
- A max discharge rate of 1.2C at low state of charge (10%~15%), i.e. 540 W/kg specific power
- An average charge rate of 1.2C from 10% to 95% state of charge
- 10% capacity degradation after 1500 cycles, of which 450 are “deep” discharges (>70% DoD)
- A pack mass overhead of 25%, with a volume overhead of 33%

A comparison with existing high-specific-energy cells illustrates that specific energy remains the primary challenge for such aircraft applications, while the C-rates required are much less stringent than for other applications such as eVTOL aircraft for urban air mobility or even ground-based EVs. Furthermore, an analysis of the associated battery production volumes shows that 50 GWh/year would be required by 2050 for a scenario where electric aircraft cover only 10% of flights up to 800 km. This figure increases to 840 GWh/year for a limit-case scenario where electric aircraft cover all flights up to 1000 km. Although these numbers are small compared to projections for the EV market, the multi-GWh-per-year output required for large electric aircraft suggests that it is feasible to develop cell designs and production lines that are optimized for this application.

While the figures of specific energy, (dis)charge rates, and cycle life are much more within reach than most literature suggests is necessary for large electric aircraft, several uncertainties remain. These include the evolution of pack overhead for larger, higher-energy-density cell designs, the relation between flight cycles and cycle life at constant (dis)charge rate and depth-of-discharge, and a more detailed assessment of cradle-to-cradle emissions including potential second life applications and

recycling of aerospace batteries. Further investigation into these topics and the development of high-specific-energy cells are key enablers for large electric passenger aircraft. Be it with an aircraft comparable to the reference used in this study or with a different configuration—some form of propulsion-system electrification is expected in the coming decades. The availability of batteries with the right performance metrics will be key to ensuring that these new aircraft configurations put us on track towards the goal of zero emissions by 2050.

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