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Perspective

Challenges and key requirements of batteries for electric vertical takeoff and landing aircraft

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SUMMARY

Electric vertical takeoff and landing (eVTOL) aircraft have attracted considerable interest as a disruptive technology to transform future transportation systems. Their unique operating profiles and requirements present grand challenges to batteries. This work identifies the primary battery requirements for eVTOL in terms of specific energy and power, fast charging, cycle life, and safety, revealing that eVTOL batteries have more stringent requirements than electric vehicle batteries in all aspects. Notably, we find that fast charging is essential for downsizing aircraft and batteries for low cost while achieving high vehicle utilization rates to maximize revenues. We experimentally demonstrate two energy-dense Li-ion battery designs that can recharge adequate energy for 80 km eVTOL trips in 5–10 min and sustain over 2,000 fast-charge cycles, laying a foundation for eVTOL batteries.

INTRODUCTION

Traffic congestion at rush hours is inescapable in most metropolitan areas of the world. Statistics show that on an average, Americans lost 99 h in 2019 sitting in traffic, which amounts to US$ 88-billion loss in productivity.[1] With growing urbanization and the emergence of new mega cities, the congestion issue will worsen worldwide. The United Nations projects that 68% of the world's population will live in urban areas by 2050, up from 55% in 2018.[2]

Urban air mobility (UAM)—an ecosystem unlocking the airspace for on-demand passenger and cargo transportation by flying vehicles—has the potential to disrupt urban mobility systems.[3] It is predicted that even a small fraction of traffic diversion to air taxis can substantially reduce the traffic vehicle fuel use,[4] suggesting the potential for flying cars to resolve traffic congestion as well as reduce the carbon footprint of personal travels. Electric vertical takeoff and landing (eVTOL) aircraft, combining helicopters' convenience of local takeoff and landing, airplanes' efficient aerodynamic flight, and electric powertrains' low noise and environmental impact, have emerged as the most promising candidate for UAM.[5–7] A recent report from Roland Berger[8] identifies 95 ongoing eVTOL projects worldwide, and predicts that commercial passenger-UAM routes will take off before 2025, with revenues prospectively soaring to US$ 90-billion a year by 2050.[8]

Batteries, the energy sources, are the linchpin of eVTOLs. The past decade has witnessed remarkable battery technology advancements, particularly in Li-ion batteries (LiBs), with the boom of EVs. Compared with EVs, eVTOLs have unique operating profiles and hence drastically different battery requirements. However, research

Context & scale

Electric vertical takeoff and landing (eVTOL) aircraft, also known as flying cars, have emerged as the most disruptive technology to transform future urban mobility systems. Their unique operating profiles and requirements present formidable challenges to batteries. This work analyzes the primary performance metrics required for eVTOL batteries compared with electric vehicle (EV) batteries. We reveal that eVTOL batteries operate at higher C-rates and have longer peak-power durations than EV batteries. Also, it is vital to fast charge sufficient energy in passenger-swapping gaps to ensure continuous eVTOL operation in rush hours, and the high vehicle utilization rate poses a critical challenge to battery cycle life. Further, eVTOL batteries should continue functioning even after a safety incident occurs until a safe landing.

Notably, we highlight the importance of fast charging, which is essential for downsizing aircraft and batteries to reduce cost while achieving high vehicle use rates to maximize revenues. We stress that any fast-charging technology should fulfill three metrics simultaneously—charge time less than passenger swapping (5–10 min), charged on eVTOL batteries is still scarce—only a handful of papers have analyzed eVTOL battery performance metrics,[9–11] and experimental work has not been reported until recently.[12] This perspective explores the primary battery requirements for eVTOLs in contrast to EV batteries. Notably, we reveal that fast charging is essential for achieving low cost and high revenue simultaneously and, therefore, critical for large-scale eVTOL commercialization. Recognizing the significance of fast charging, we experimentally demonstrate two energy-dense LiB designs that can recharge adequate energy for 80 km eVTOL trips in 5–10 min and sustain greater than 2,000 such fast-charge cycles. We hope that these initial designs will spur exciting development of eVTOL batteries.

energy sufficient for the next trip, and a long cycle life. We experimentally demonstrate two energy-dense Li-ion battery designs that can recharge adequate energy for 80 km eVTOL trips in 5–10 min and sustain over 2,000 fast-charge cycles. We hope that these initial designs will spur exciting development of eVTOL batteries.

RESULTS AND DISCUSSION

EVTOL battery requirements

Specific power

We start by analyzing the operating requirements of eVTOLs and the associated demands on batteries. A typical eVTOL trip (Figure 1A) contains five phases: takeoff-hover, climb, cruise, descent, and landing hover.[13] Figure 1B shows a representative battery power profile for a sample vehicle design (Table S1) over an 80-km trip. We note that takeoff and landing hovers have the highest power demand that determines the battery's peak discharge rate, and the cruise power defines the battery's continuous discharge rate. The power in each flight phase can be estimated by Equations S1–S4. Dividing the power by battery mass gives the required battery specific power for hover and cruise:

$$SP_{hover} = \frac{1}{\omega_{bat}} \frac{g}{\eta_h} \sqrt{\frac{\sigma}{2\rho_{air}}} \quad \text{(Equation 1)}$$

$$SP_{cr} = \frac{1}{\omega_{bat}} \frac{g}{\eta_c} \frac{V_{cr}}{L/D} \quad \text{(Equation 2)}$$

Notably, the specific power (*SP*) depends highly on battery weight fraction (ω_{bat}) and aircraft configuration—disk loading (σ) for hover-power and lift-to-drag (*L/D*) ratio for cruise power. Figure S1 summarizes the disk loading and L/D-ratio of various eVTOL vehicle configurations currently being pursued by the industry (according to Uber's survey[14]). Typically, there is a trade-off between hover and cruise efficiencies: e.g., vectored thrust eVTOLs have wings for efficient cruise but are low in hover efficiency; wingless multirotor eVTOLs have large disk actuator surfaces for efficient hover but low cruise efficiency.

Figure 1C converts the disk loading versus L/D-ratio plot to battery's SP in hover versus in cruise using Equations 1 and 2 with parameters from Table S1 at ω_{bat} of 0.3. We see that the SP is ∼150–350 W/kg for cruise and 500–900 W/kg for hover, which translates to a discharge C-rate of 0.75–1.5C in cruise and 2.5–4.5C in hover for a 200 Wh/kg battery. Note that the C-rates would be even higher for lower specific energy or smaller ω_{bat}. Hence, we can infer that eVTOL batteries operate at much higher C-rates than EV batteries. Figure S2 displays the power profiles of the 75-kWh battery in Tesla Model-3, estimated by the vehicle dynamics model in the supplemental information. The average C-rate of the EV battery is ∼0.3C in highway-driving and ∼0.1C in city driving, whereas the sample eVTOL battery in Table S1 averages at ∼1C over the 80 km trip (Figure 1B).

The demand for high SP—both for peak and continuous discharges—poses critical challenges to eVTOL batteries. First, batteries face a power-energy trade-off: an increased discharge power inevitably reduces the deliverable energy, as typically

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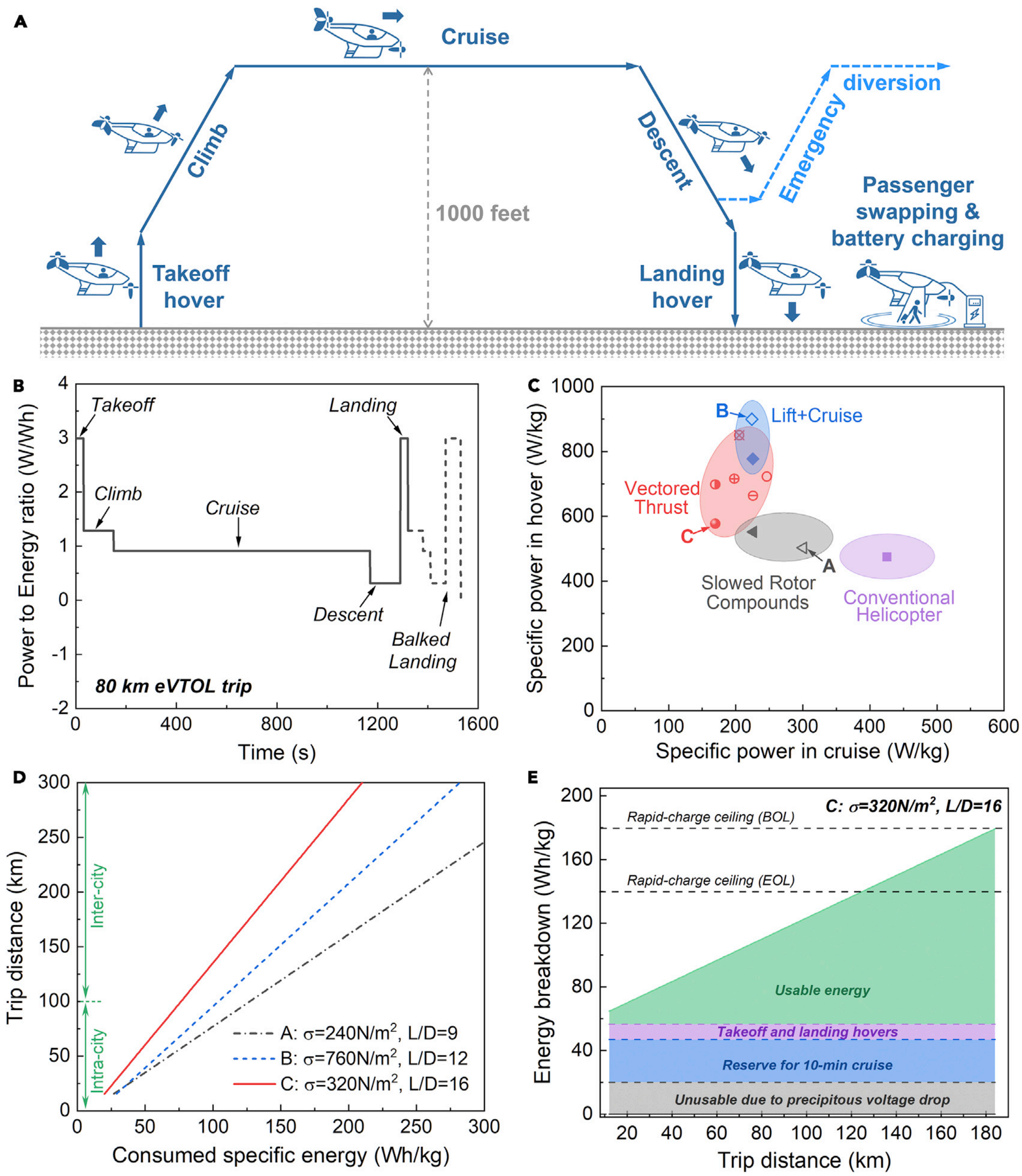

Figure 1. EVTOL requirements on battery specific power and energy
(A) Schematic illustration of a typical eVTOL trip.[13]
(B) Representative battery power profile during an eVTOL trip. The profile is for the sample vehicle design in Table S1 based on the operating profile in Table S4.
(C) Required battery specific power in hover versus in cruise for the aircraft configurations being pursued by the industry. The specific power is calculated by Equations 1 and 2 with the disk loading and L/D-ratio in Figure S1 and the other parameters from Table S1.
(D) Trip distance versus consumed specific energy for three representative aircraft configurations (A, B, and C as marked in Figure 1C).
(E) Battery energy breakdown for eVTOL trips with design-C and a 200 Wh/kg battery pack (see Figure S3 for designs A and B). Only a portion of energy is available for nominal trips. The battery EOL is defined as 20% energy loss. The results in (D and E) are calculated by the range model in Note S2.

noted in Ragone plots.[15] Therefore, the battery pack size should be optimized (to tailor ω_{bat}) for a specific vehicle configuration to ensure sufficient energy output at the designed C-rates. Second, both battery energy and power decrease substantially at freezing temperatures. Even for EVs, the cruise range could fall by >40% as the temperature drops from 24°C to −7°C.[16] At much higher C-rates, eVTOL operation would prove more troublesome in cold weather than EVs, possibly grounding vehicles.

Specific energy

EVTOL batteries have high demand on specific energy on which the cruise range depends heavily, as can be noted from the Breguet range equation[5,17]:

$$R_{trip} = SE_{trip}\frac{L}{D}\frac{\eta_c}{g}\omega_{bat} \quad \text{(Equation 3)}$$

where R_{trip} denotes trip distance, SE_{trip} the specific energy consumed for the trip, and η_c the system efficiency. Note that R_{trip} is directly proportional to SE_{trip} and ω_{bat} in the asymptotic limit of long range where energy consumption during takeoff and landing becomes negligible. Note S2 presents a more comprehensive range model considering the energy consumption in each eVTOL phase. Figure 1D plots the model-predicted R_{trip} versus SE_{trip} relationship for three representative aircraft configurations (A, B, C referring to Figures 1C and S1) at ω_{bat} of 0.3. Design-A represents the worst-case scenario (lowest L/D-ratio) of the eVTOL configurations currently being pursued (Figure S1), and design-C denotes the best-case scenario having a high L/D-ratio for efficient cruise as well as a low disk loading for efficient hover.

It should be noted that only a portion of battery energy is available for nominal eVTOL flights, as illustrated in Figures 1E and S3 for the three representative designs with 200 Wh/kg battery packs. First, given the high power for landing, a battery should not discharge to state of charge (SOC) below 10%, as voltage drops drastically in this region and leads to current spikes.[18] On top of that, eVTOL batteries should have reserve energy for balked landing or diversion to alternative locations. To date, there is still no official regulation on eVTOL reserve energy. Existing US Federal Aviation Administration (FAA) regulations mandate reserve fuel for 30-min additional cruise, which is for aircraft with long-haul trips and can be relaxed for eVTOLs when ubiquitous vertiports are available. Nonetheless, we estimate with Equation 2 (assuming $\omega_{bat} = 0.3$, $\eta_c = 0.85$, V_{cr} = 240 km/h) that even a reserve for 10-min cruise amounts to 48 Wh/kg for design-A and 27 Wh/kg for design-C, corresponding to 24% and 13.5% energy, respectively, of a 200 Wh/kg battery. Moreover, there is a SOC ceiling (e.g., 90%) above which the charge current must diminish, resulting in a long charge time. Thereby, only 112 Wh/kg out of the 200 Wh/kg battery in design-A and 133 Wh/kg in design-C are available for nominal trips at the beginning of life (BOL), rendering a maximum range of 87 km for design-A (Figure S3A) and 184 km for design-C (Figure 1E). We should note that this range would shrink further as the battery degrades. If we define battery end of life (EOL) as 20% energy loss, the maximum range for nominal trips will drop to only 54 km for design-A and 126 km for design-C, as shown in Figures 1E and S3.

Note that the above specific energy refers to the pack level. For state-of-the-art (SOA) EV batteries, the gravimetric cell-to-pack (GCTP) ratio—the ratio of pack-specific energy to cell-specific energy—is only ~0.55–0.75 due to overheads such as structural-support beams, cabling, thermal management systems, etc.[19] Thus, SOA EV batteries only have ~170 Wh/kg at the pack level. There are two primary ways to improving specific energy. One is to enhance cell-level-specific energy using materials with higher specific capacity (silicon-graphite anodes, nickel-rich layered-oxide cathodes) as well as raising the areal loading of active materials.[20] The second is to improve pack integration efficiency. For instance, several companies have adopted so-called cell-to-pack (CTP) technology, which assembles large-format cells directly into a pack without modules, boosting the GCTP ratio to ~0.85.[19] Energy-dense Li-ion cells with advanced pack designs can potentially enhance the pack-specific energy to 250 Wh/kg (e.g., 300 Wh/kg cells with a GCTP ratio of 0.85), thereby extending the eVTOL range to ~230 km at the BOL (e.g., design-C with 66% usable energy, Figures 1D and 1E). Further extending the range would demand battery chemistries beyond Li ion (Li metal, Li air, Li sulfur, etc.), but these technologies are currently in infancy.

The future passenger-UAM market is envisioned to be dominated by three use cases—city taxi, airport shuttle, and inter-city flights.[8] The first two are intra-city hops with short trip distances. Daskilewicz et al.[21] analyzed the range requirement for daily commutes in San Francisco and Los Angeles areas and found that most trips are under 50 km and only a few trips exceed 100 km. Husemann et al.[22] studied the UAM demands in the Upper Bavaria district, Germany, and found that most trips are between 10–25 km. Thus, we can note from Figures 1D and 1E that SOA LiBs are already viable for intra-city eVTOLs, though more advanced LiBs with higher cell-specific energy and GCTP ratios are needed for long-range inter-city flights. It is worth mentioning that all-electric regional aircraft (Airbus-A320 or Boeing-737-sized), another area with growing interests in electrification, have standard missions up to 600 nautical miles (~1,100 km), which would demand a significant battery breakthrough (e.g., specific energy to exceed 800 Wh/kg) to be technologically feasible.[23,24]

Fast charging and cycle life

Another feature of eVTOLs is that they generate revenue primarily in rush hours (6–10 am and 4–8 pm per workday). Every minute in this period is precious. Typically, there is a 5–10 min gap between two trips for passenger swapping. The ideal scenario is to refill the energy needed for the next trip within this period. Based on Equation 3, the charge time can be estimated by:

$$t_{char} = \frac{SE_{trip}}{SP_{char}} = \frac{R_{trip}}{SP_{char}} \frac{g}{\eta_c \omega_{bat} L/D} \quad \text{(Equation 4)}$$

where SP_{char} is the specific charge power (in W/kg). Notably, fast charging should fulfill not only the time requirement but the specific energy requirement, as the refilled SE_{trip} determines the added R_{trip}. As a reference, the US Department of Energy (DOE) is dedicating efforts to develop extreme fast charging (XFC) technology, whose target is to charge 180 Wh/kg energy in 10 min without appreciable degradation.

Note S3 presents an economic model for estimating an eVTOL vehicle's annual revenue at various R_{trip} and SP_{char}. Following Uber's analysis,[7] the model assumes a four-seat vehicle with a load factor (seat occupancy) of 67%, a deadhead ratio (fraction of non-revenue trips) of 20%, a distance-dependent ticket price similar to today's Uber-XL, and operation of 8 h per workday for 260 workdays per year. As a longer R_{trip} requires a higher SP_{char} to refill the energy within the 5-min passenger-swapping limit (Figure 2A), the rush-hour utilization ratio (RHUR, the fraction of rush hours generating revenues) increases exponentially with SP_{char} until the charge time falls below the 5-min limit (Figure 2B). Also, the maximum RHUR is higher for longer trips due to fewer stops for swapping passengers. More importantly, the vehicle's annual revenue has similar dependencies as the RHUR on the SP_{char} and R_{trip}—a longer trip with sufficiently fast charging yields more revenue (Figure 2C).

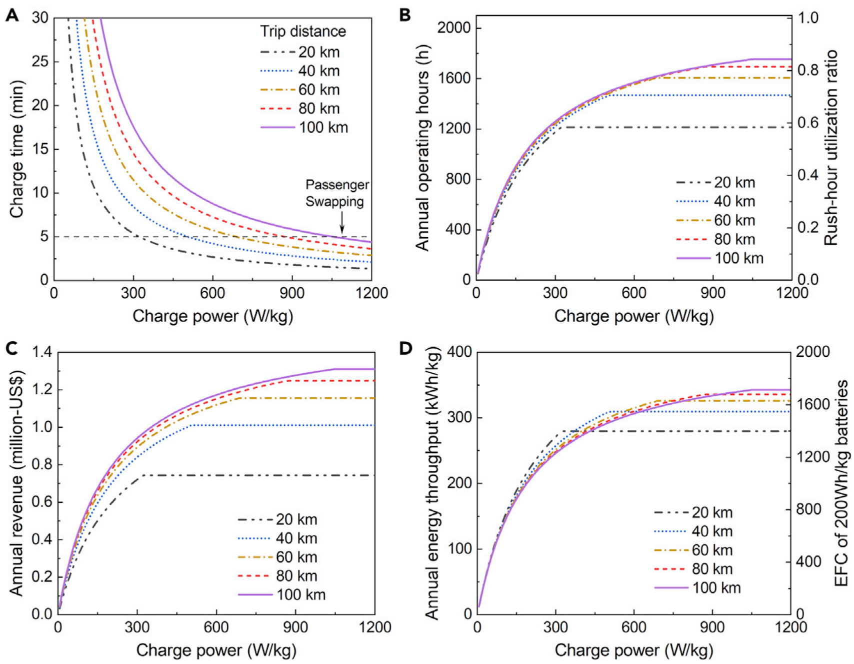

Figure 2. Importance of fast charging and cycle life to eVTOL batteries

(A–D) Effects of battery charge rate and trip distance on (A) battery charge time, (B) annual operating hours and rush-hour utilization ratio, (C) annual revenues, and (D) annual discharge energy throughput and equivalent full cycles with respect to a 200-Wh/kg battery. The results are based on the economic model in Note S3.

Thus, we can conclude that fast charging is critical for maximizing vehicle utilization rates and hence eVTOL revenues.

We should also note that most charging events of eVTOL batteries are fast charging (only those outside rush hours can be slow), which is another notable difference from EV batteries. For EVs, though fast charging is indispensable for boosting the range confidence, most charging events are slow charging at home or the workplace.

It is worth noting that battery swapping could be an alternative way to circumvent the battery-charge-speed limitation. However, there are formidable challenges for it to become a viable business. For instance, making battery packs interchangeable would require standardization among battery and aircraft manufacturers, stifling innovation, and market competition for consumers.[25] Moreover, battery swapping requires multiple sets of reserve battery packs stored at each vertiport, raising significant cost and space concerns.

The high utilization rates, especially the high frequency of fast charging, demand long cycle life. With sufficient fast charging, eVTOL batteries can operate ~1,600 h per year (Figure 2B), and the annual discharge energy throughput reaches 320 kWh/kg (Figure 2D), corresponding to 1,600 equivalent full cycles (EFCs) of a 200 Wh/kg battery. For reference, on an average, Americans drive 13,476 miles per year,[26] which translates to ~337 driving hours (at 40 mph average speed) and 45 EFCs for a 300-mile-range EV.

We should also note that many EVs (Tesla Model-3, BMW i3) warrant batteries for eight years or 100,000 miles at 70% capacity retention, corresponding to 385 battery

EFCs for a 260-mile-range Model-3 and 650 EFCs for a 153-mile-range BMW i3. Converting to eVTOL scenarios (e.g., 1,600 battery EFCs per year), such an EV battery warranty means that the batteries should be replaced every 3–5 months, raising critical cost and maintenance issues. Indeed, even a one-million-mile EV battery (a life of ~3,300 EFCs) can only sustain a two-year eVTOL operation, falling far short of an aircraft's lifespan—commercial aircraft are typically designed for 25+ years of service, though eVTOL aircraft may have reduced lifetime demand given the high-frequency utilization (e.g., Uber assumes a 13-year service life in their analyses[7]). Hence, we can note that eVTOLs are extremely demanding for long battery cycle life. Also, an aircraft needs to be designed to accommodate the evolution of battery technology for decades.

Safety

The rate of catastrophic failure for commercial LiBs has been reported to be only one in 40 million cells.[27] Tesla reported that from 2012 to 2020, their vehicles' rate of fire incidents was one for 205-million driving miles.[28] Regardless, the failures that did occur created significant notoriety for their spectacular release of energy. It would take very few incidents to ground aircraft altogether. As a proof of this, the thermal runaway incident in a small (~2 kWh) LiB aboard the 787 Dreamliner grounded the entire fleet for several months, causing severe financial consequences for Boeing and the operators alike.[29] For eVTOLs, it will likely be a mandatory requirement that an aircraft should prevent any cell-to-cell propagation events, and more stringently, be able to continue flying on reduced power to allow for an emergency landing. Novel features such as self-healing electrodes and separators[30] and individual cell temperature monitoring abilities[31] have been in development. Furthermore, as most eVTOL battery charging events are fast charging that takes place in all weather conditions, it is essential to develop all-climate, plating-free, fast-charging technologies, as plated Li metal is highly reactive that can trigger thermal runaway even without internal shorting.[32,33] Rapid thermal stimulation to charge at an optimized plating-free temperature has been demonstrated to achieve safe and durable fast charging even at −50°C ambient.[34]

Furthermore, the high discharge rates of eVTOL batteries pose a critical challenge to battery thermal management systems (BTMS). As battery heat generation rate is proportional to the square of current, we can infer by comparing Figure 1B with Figure S2 that the heat generation of an eVTOL battery (at ~1C rate) is 9× the heat generation of EV batteries in highway-driving (C/3) and 100× that in city driving (C/10). Hence, a potent BTMS is essential for the safe implementation of eVTOLs. However, it is equally vital to limit BTMS mass to minimize the loss in pack-level-specific energy.

eVTOL versus EV battery requirements

The above discussion reveals that eVTOL batteries have more stringent requirements than EV batteries in all aspects (Figure 3). The high cruise power leads to a larger average discharge rate for eVTOL batteries. Thus, the specific energy of eVTOL batteries should be rated at a higher C-rate (e.g., 1C) than EV batteries (C/3, even C/10). In addition, eVTOLs require high power for takeoff and landing, which typically lasts 30–120 s. Hence, the peak power of eVTOL batteries should be evaluated for a longer timescale than EV batteries (typically 10 s). Furthermore, charging a sufficient amount of energy in 5–10 min is essential for maximizing eVTOL revenues. The high fast-charging frequency and utilization rates make eVTOL batteries operate up to ~1,600 h and ~1,600 EFCs per year, posing critical challenges to battery life. We can also infer that cycling-induced aging is more important than calendar aging for eVTOL batteries. Note that battery life is <10% of the lifespan of an

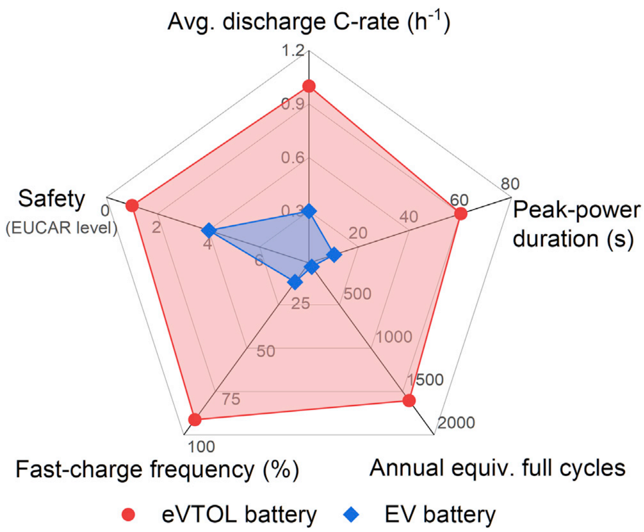

Figure 3. Battery requirements for eVTOLs versus for EVs

The average discharge C-rates are from Figures 1B and S2. Note EV batteries could have even lower C-rate (C/10) in city driving. The peak-power duration is typically 30–120 s for eVTOL takeoff or landing and ~10 s for EVs. For annual EFCs, we estimate ~1,600 EFCs for eVTOL battery (Figure 1D) and ~45 EFCs for EV battery (based on an annual mileage of 13,476 miles for a 300-mile-range EV). For fast-charge frequency, we assume continuous 50 km eVTOL trips for 4 h (Figure S4)—only the charge event before the first trip (1 out of 12) can use slow rate. For EVs, fast-charge frequency is <20%. For safety, eVTOL battery should be able to continue functioning even after a safety incident. Hence, there should be no irreversible cell damage (meeting at least the European Council for Automotive R&D (EUCAR) level 1).

eVTOL aircraft, hence, the aircraft should be designed to accommodate battery technology advancements over decades. Finally, eVTOL batteries have more stringent requirements on battery safety. Not only should they prohibit any fire or explosion, but they should also continue functioning even after a safety incident occurs until a safe landing.

Importance of fast charging

We see from Equation 3 that raising ω_{bat} is another way to extend eVTOL range. A higher ω_{bat} also favorably reduces the required SP (Equations 1 and 2) and fast-charge rate (Equation 4). Indeed, energy-dense Li-ion cells face the challenge of poor fast-charge ability due to the issue of Li plating. To ensure high-frequency operation during rush hours, eVTOL vehicles tend to carry large batteries to have a small SOC consumption per trip so that the charge rate can be relaxed by recharging only partially the needed energy in passenger-swapping gaps (Figure S4). However, large batteries have high costs. Uber estimated that aerospace batteries could cost 4.1× more than automotive batteries on a US$/kWh basis.[35] Moreover, raising ω_{bat} is constrained by the payload, as:

$$m_{pay} = GTOM\left(1 - \omega_{bat} - \omega_{empty}\right) \quad \text{(Equation 5)}$$

where m_{pay} is the payload, $GTOM$ the gross takeoff mass, and ω_{empty} the empty weight fraction. ω_{empty} is an essential parameter of an aircraft; a lower ω_{empty} is favorable but can only be achieved at a higher GTOM.[36] The ω_{empty} of eVTOL aircraft reportedly ranges from 0.43 to 0.65.[9,11,37] For simplicity, a constant ω_{empty} is typically assumed in eVTOL vehicle design and optimization, which, according to Equation 5, means that raising ω_{bat} without sacrificing the payload requires increasing GTOM as well. However, vehicle acquisition cost, the highest cost for eVTOLs, depends heavily on the empty weight (~US$700 per pound empty weight in the near term[35]). Hence, using heavy aircraft with large batteries to ensure continuous rush-hour operation faces critical cost issues. We should further note that the driving factor in reducing cost is to expand the market size, as each doubling of production rate can reduce cost by ~15%.[7] Expensive eVTOL aircraft have low values for the general public and would limit the market to the wealthy, which feeds back to further limited production. Indeed, the cycle of low production rate and high cost is the primary reason commercial helicopters are still a cottage industry after decades of existence.

An alternative way to ensure continuous rush-hour operation at low costs is to adopt small but fast-rechargeable batteries, as shown in Figure S4. A smaller battery size (and ω_{bat}) can reduce battery cost and achieve the same payload at lower aircraft weight (Equation 5) and hence lower aircraft cost. Though it reduces the maximum range and increases the consumed SOC per trip, the aircraft can operate continuously as long as the battery can be charged sufficiently fast during passenger swapping. Thus, we can conclude that fast charging is essential for downsizing the eVTOL vehicles and batteries for low costs while ensuring high vehicle utilization rates for maximized revenues.

We should stress that fast charging requires fulfilling three metrics simultaneously—charge time less than passenger swapping (5–10 min), charged energy sufficient for the next trip, and a long cycle life. The combination of all three metrics, unfortunately, excludes the vast majority of existing fast-charging solutions. For instance, the entire class of flash-charging (e.g., charging from zero to a low SOC to give a smartphone an hour of usage or a car a hundred kilometers) is limited to low SOCs (inaccessible for eVTOL trips) and cannot reflect the charge speed at medium-to-high SOCs. For example, Tesla's latest superchargers can charge a Model-3 from 0% to 23% SOC in 5 min at 250 kW but take another 5 min to charge from 50% to 62% SOC, as the charge power falls below 120 kW at >50% SOC.[38] The 5-min added energy from 50% to 62% SOC amounts to 31 Wh/kg at the cell level and—even with an improved GCTP ratio of 0.8—only 25 Wh/kg at the pack level, which is insufficient for eVTOL takeoff (Figure 1D). Another conventional fast-charging solution is to adopt high-power (ultrathin) electrodes, which apparently cannot offer adequate specific energy for eVTOLs. Besides, various attempts to optimize charge algorithms merely manage the absence of Li plating without fundamentally relaxing the underlying electrochemical and transport limitations and hence can only incrementally expand the fast-charging ability.

Thus, the technological challenge for eVTOL batteries is the ability to charge a substantial amount of energy very fast and do so without causing excessive degradation to the batteries, which requires overcoming the scientific barrier to fast charging—Li plating. Fundamentally, Li plating occurs due to a restricted rate of either of the three physicochemical processes: (1) ion transport in electrolytes, (2) intercalation reaction at graphite-electrolyte interfaces, and (3) solid-state diffusion in graphite particles. For high-energy LiBs, ion transfer in the electrolyte is typically the limiting factor due to the thick and dense anodes.[39,40] Therefore, research efforts have focused on optimizing electrolyte recipes to enhance electrolyte conductivity, diffusivity, and transference number,[41–44] and developing novel electrode architectures to reduce tortuosity.[45–47] Due to the trade-off nature of LiBs, it is always challenging to improve one parameter without sacrificing others. For instance, adding esters as co-solvents can enhance electrolyte diffusivity and hence the fast-charging ability, but it often considerably deteriorates electrolyte stability and battery life in normal operations.[48,49]

Two benchmark batteries for eVTOLs

Another way to prevent Li plating is through thermal stimulation. For instance, our group reported an asymmetric temperature modulation (ATM) method[50] that charges LiBs at ~60°C while limiting the cell exposure to 60°C to the charging step. The elevated temperature can accelerate all the three processes mentioned above (e.g., increasing from 20°C to 60°C boosts graphite intercalation kinetics by 13×, graphite solid-state diffusivity by 5.6×, and electrolyte conductivity by 1.9×), thereby effectively preventing Li plating. On the other hand, the limited exposure time to 60°C controls materials degradation, primarily solid-electrolyte-interphase (SEI) growth. We showed that the ATM method could charge an energy-dense pouch cell by 167 Wh/kg in 10 min at the BOL and 144 Wh/kg after 2,500 cycles.[50] Very recently, we extended the ATM method with the same cells to eVTOL applications[12] and demonstrated sustainable 5-min charging for 80 km eVTOL trips. To the best of our knowledge, this is the only experimental work on eVTOL batteries reported so far. In the following, we will review the results of these cells, denoted as 215 Wh/kg cells based on the nominal specific energy, and analyze the aging behaviors under eVTOL operations with a particular focus on the EOL criteria for eVTOL batteries. Subsequently, we will present another type of 271 Wh/kg cells that enable larger payloads.

Table S2 summarizes the design parameters of the 215 Wh/kg cells, which have a cathode areal capacity of 2.85 mAh/cm^2 that gives 215 Wh/kg at C/10 rate and 196 Wh/kg at 1C in a scaled 35-Ah format. We use 1C specific energy to estimate eVTOL battery size and payload. Assuming a GCTP ratio of 0.8, the specific energy at pack level is 157 Wh/kg, which gives a 150 kg payload for a small aircraft with a maximum range of ~150 km (Table S3). Note that the vehicle in Table S3 has a similar maximum range as the vehicle in Table S1, as they have a similar ω_{bat}*SE (see Equation 3).

Figure 4 shows the cycling-test results of the 215 Wh/kg cells. Each cycle includes an ATM charging for 5 min and a discharge following the UAM power profile in Table S4. Note that the profile also includes a portion representing balked landing. As shown in Figures 4A and 4B, an ATM charging includes rapid heating to raise cell temperature to ~60°C, followed by a constant-current-constant-voltage (CCCV) charge with 6C and 4.15 V for 5 min. A control cell with the same 5-min CCCV charge, but no preheating was added for comparison. We see that the ATM cell exhibited a lower voltage in charging than the control cell (Figure 4A), suggesting a much-reduced internal resistance at the elevated temperature, which helped prevent Li plating. On the other hand, the cell stayed at 60°C only in the charging step (5 min per cycle), minimizing the negative impacts associated with the high temperature. Thereby, the ATM cell exhibited remarkable stability, retaining 92.3% capacity after 2,000 cycles (Figure 4C), or 870 EFCs (Figure 4D). For comparison, the control cell lost 20% capacity in only 150 cycles (68 EFCs) due to severe Li plating.

Power retention is also vital for eVTOL batteries due to the high power demand for takeoff and landing. Figure 4E displays the SOC window of the two cells during cycling. We note that even the fresh ATM cell can only be charged to ~84% SOC, confirming the rapid-charge SOC ceiling for eVTOL operation. Also, the consumed SOC per cycle is 39.4% (44.4%–83.7%) for the fresh cell and 41% (33.3%–74.3%) after 2,000 cycles. As the total discharge energy is the same in each cycle, the slight increase in SOC (capacity) consumption indicates a minimal drop in average discharge voltage and hence a mild power fade upon cycling. Figure 4F further displays the minimum cell voltage in the landing and balked landing. We can see that the ATM cell retained good power capability after 2,000 cycles, staying >3.25 V in landing and >3.15 V in balked landing.

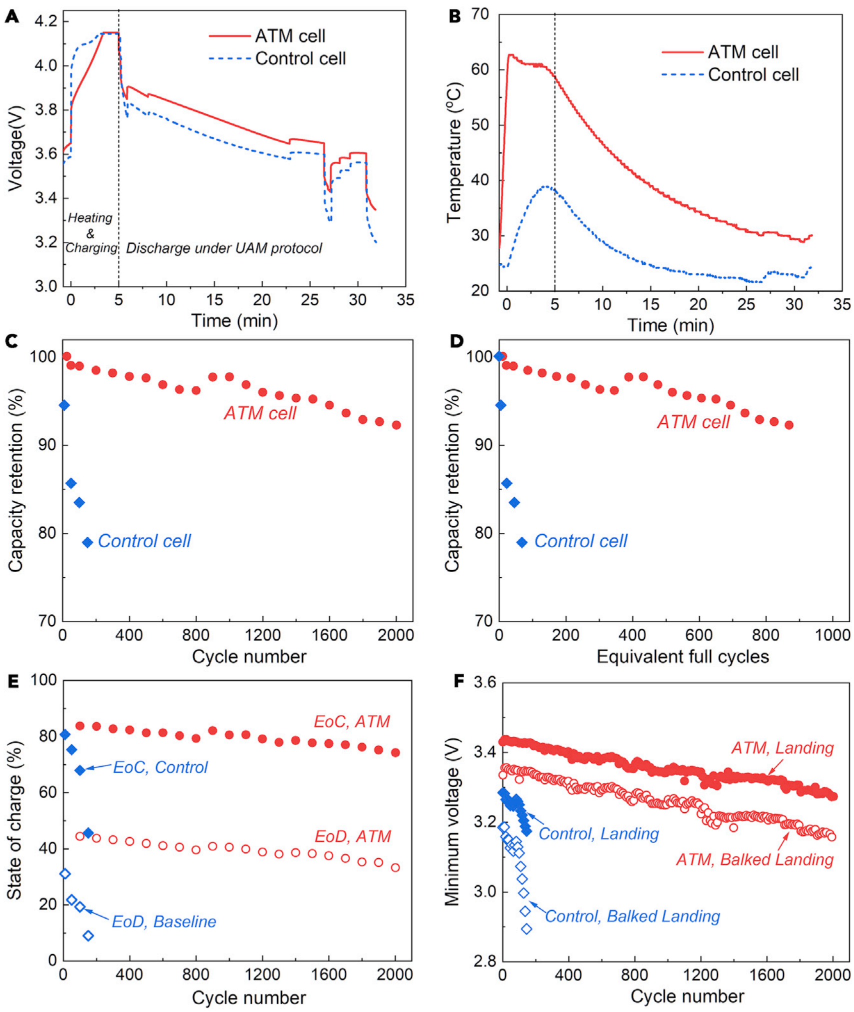

Figure 4. A 215-Wh/kg cell capable of 5 min charging for 80-km eVTOL trips

(A and B) Evolutions of (A) cell voltage and (B) temperature during one eVTOL cycle. The ATM cell has a rapid-heating step to raise cell temperature to ~60°C before charging. The control cell was charged at room temperature without preheating. Both cells use the CCCV charging protocol with 6C rate and 4.15 V cutoff voltage for 5 min. The discharge step follows the power profile representative of an 80 km eVTOL trip detailed in Table S4.

(C and D) Capacity retention versus (C) cycle number and (D) equivalent full cycle number.

(E) Evolutions of battery state of charge at the end of charge (EoC) and EoD upon cycling (see experimental procedures for details).

(F) The minimum cell voltage in landing and balked landing.

One thing worth discussing is the EOL criteria for eVTOL batteries. For EV batteries, EOL typically refers to 20% capacity fade. If applying this criterion to eVTOL batteries, we project a lifespan of 6,000 cycles for the 215 Wh/kg cells with ATM charging (Figure S5A). However, eVTOL batteries must retain reserve energy and sufficient power for landing. If we use the end-of-discharge (EoD) SOC as a criterion (e.g., >25%SOC to ensure a 10-min additional cruise), the cycle life is predicted to be ~3,800 cycles (Figure S5B). Furthermore, if using the minimum voltage as the criterion to account for power fade (e.g., V_{min} > 3 V in balked landing), a similar life of ~3,800 cycles is projected (Figure S5C). Thus, we can infer that power fade and reserve energy requirement should play more significant roles than capacity fade

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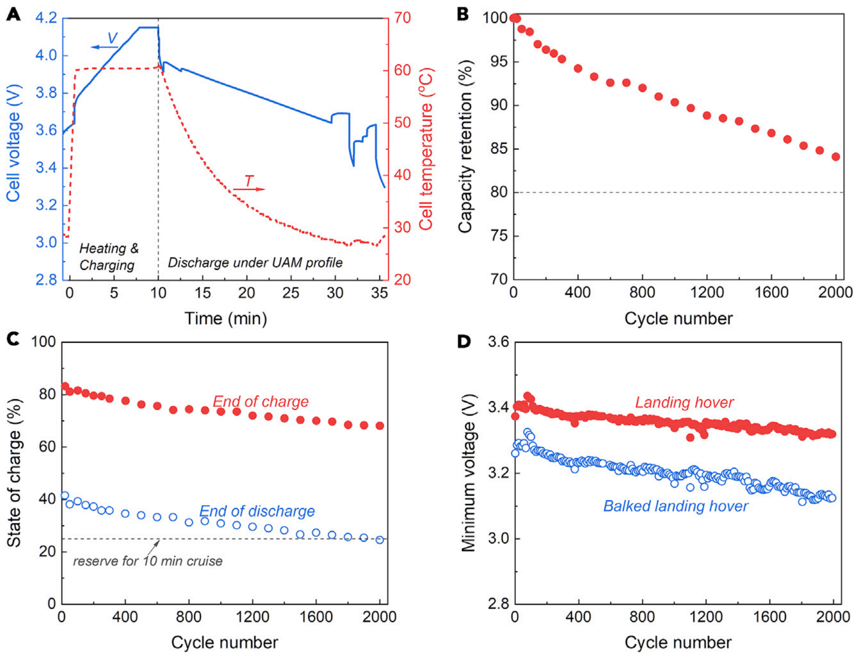

Figure 5. A 271 Wh/kg cell enabling high payload and 10 min charging for 80 km eVTOL trips

(A) Evolution of cell voltage and temperature during one eVTOL cycle of the 271 Wh/kg cell. The cell was charged with the ATM method, which involves a rapid heating to 60°C, followed by CCCV charging with 3C limited by 4.15 V for 5 min. The discharge follows the power profile in Table S4.

(B) Capacity retention versus cycle number.

(C) Evolution of cell state-of-charge window during cycling.

(D) The minimum cell voltage in landing hover and balked landing hover.

in defining the EOL of eVTOL batteries. It would also require accurate economic forecasting with empirical feedback to predict when the battery should be replaced for maximum profitability. Fortunately, even a 3,800-cycle lifespan will ensure the 215 Wh/kg cells operate for one year before replacement.

The primary limitation of these 215 Wh/kg cells (157 Wh/kg at 1C in pack levels) is the small payload—only 150 kg for the 150-km-range aircraft design. To enhance the payload, we developed more energy-dense pouch cells using NMC811 cathodes and graphite anodes at an areal capacity of 3.41 and 3.76 mAh/cm^2, respectively, as detailed in Table S5. Such a design achieves 271 Wh/kg at C/10 and 250 Wh/kg at 1C in a scaled 50-Ah format. With a GCTP ratio of 0.8, the 1C specific energy can reach 200 Wh/kg at pack levels, enlarging the payload to 400 kg for the 150-km-range eVTOL (Table S1). We should note that the thick anodes due to the increased areal capacity make the cells more susceptible to Li plating. Thus, these 271-Wh/kg cells were charged with a reduced rate of 3C for an extended time of 10 min per cycle using the ATM method (Figure 5A). The discharge protocol was the same as the 215 Wh/kg cells. We saw that the 271 Wh/kg cell retained 81% capacity after 2,500 cycles (Figure 5B), or 1,100 EFCs. The EoD SOC dropped to 25% (the 10-min reserve energy limit) after 2,000 cycles and 21.8% after 2,500 cycles (Figure 5C). Furthermore, the minimum voltage stayed >3.3 V in landing and >3.05 V in balked landing after 2,500 cycles (Figure 5D). Based on the above discussion on EOL criteria, these 271 Wh/kg cells have a life of at least 2,000 cycles.

Future outlook

An eVTOL vehicle is typically designed for tens of years in service, meaning that it is designed for batteries available in the near term as well as in the following decades. We note from the above discussion that the maximum range of an eVTOL vehicle is essentially proportional to $\omega_{bat}*SE$ (Eqution 3). Hence, future eVTOL batteries should continue to push for higher SE to (1) achieve a larger payload at smaller battery size (i.e., a larger m_{pay} at a smaller ω_{bat}, Equation 5) for short-range intra-city commutes and (2) meet the range demand for long-range inter-city flights.

A practical approach to enhance specific energy is to raise the areal loadings of active materials further. A critical barrier is the reduced fast-charging ability. For instance, the above 215-Wh/kg cells can be charged with 6C using the ATM method, enabling 5-min charging for 80 km trips, whereas the 271 Wh/kg cells can only withstand 3C charge even at 60°C, thereby requiring 10 min to charge the energy for 80 km trips. An even higher areal capacity would further reduce the charge rate, considerably limiting eVTOL revenues. Thus, it is vital to develop advanced technologies that can fast-charge ultrahigh-energy LiBs.

We should stress that eVTOLs are extremely demanding on battery cycle life due to the high utilization rates (up to 320 kWh/kg energy throughput per year, Figure 1D). Any improvement in specific energy and fast-charging ability shall not sacrifice the cycle life. For instance, pairing Ni-rich oxide cathodes with silicon or Li-metal anodes are promising paths to higher specific energy, but fast charging can cause significant volume expansion of silicon particles, or dendrite formation of Li metal, resulting in low cycle life. The best Li-metal pouch cells reported so far can only charge with ultralow rates (e.g., C/10) and sustain merely ~200 cycles.[51,52] More advanced chemistries like Li-S and Li-air are in even earlier infancy. In essence, significant improvements in fast charging and cycle life are essential for these advanced battery technologies to be viable for eVTOLs.

Another path to higher specific energy is to improve CTP integration efficiency. An example is the recently reported CTP technology that boosts the GCTP ratio to ~0.85.[19] A potential method to enhance the GCTP ratio further is to replace a liquid-cooling BTMS with aspirated air cooling by operating the battery at an elevated temperature (e.g., 60°C). It has been revealed that elevating the operating temperature can reduce the cooling need by an order of magnitude due to reduced heat generation rates and enlarged temperature differences between cells and ambient.[50,53] The elevated temperature also boosts battery power capability. Furthermore, by adding electrolyte additives such as triallyl phosphate to passivate cathode and anode materials, the batteries exhibited exceptional safety and life.[53] Indeed, the thermal modulation structure enables outstanding battery performance at low ambient temperatures, while the use of stable materials renders high safety and durability at high temperatures. Such a synergistic combination has the potential to achieve high-performance, durable, and safe eVTOL operation in all climates.

EXPERIMENTAL PROCEDURES

Models

The battery power in each eVTOL phase (Figures 1B and 1C) is calculated by Equations S1–S4 in Note S1. The R_{trip} versus SE_{trip} plot in Figure 1D and battery energy breakdown in Figures 1E and S3 are calculated by the eVTOL range model in Note S2. The vehicle utilization rates and annual revenues (Figure 2) are obtained using the economic model in Note S3. The battery power profiles of the 75-kWh EV battery (Figure S2) are calculated by the vehicle dynamics model in Note S4.

Cell materials and fabrication

Two types of mass-produced industrial electrodes are selected for pouch cell fabrication. The 215 Wh/kg cells utilize $LiFePO_4$(LFP)-coated $LiNi_{0.5}Mn_{0.3}Co_{0.2}O_2$ (NMC532) as cathode materials at an areal loading of 15.92 mg/cm^2 (90% NMC532 and 10% LFP), or 2.55 mAh/cm^2, and artificial graphite as anode materials at a loading of 8.39 mg/cm^2, or 2.94 mAh/cm^2. Detailed cell design parameters are listed in Table S2. The 5.2 Ah cells were used for the fast-charging tests (Figure 4). The large-format 35-Ah cells were for evaluating the specific energy. The 271-Wh/kg cells use $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ (NMC811) as cathode materials at 16.8 mg/cm^2 or 3.41 mAh/cm^2, and artificial graphite as anode materials at 10.6 mg/cm^2 or 3.71 mAh/cm^2. Detailed cell information is given in Table S5. The 3.2 Ah cells were used for the cycling tests (Figure 5). The specific energy in the 50-Ah format was estimated using commercial software GT-Autolion. All the cells use the self-heating Li-ion battery structure[54] with a thin nickel (Ni) foil embedded inside as an internal heater. One end of the Ni foil is welded with anode tabs, and the other end extends outsides to form a third terminal, called activation (ACT) terminal. A switch is added between the positive and ACT terminals to control the on and off of cell heating.

Electrochemical test

All cells were tested at an ambient temperature around 20°C. The cells charged with the ATM method have a heating step to raise cell temperature to ~60°C before charging. Details on implementing the rapid heating through the self-heating structure have been presented in Yang et al.[50] After heating, the cells were charged with the conventional CCCV method. All the cells were discharged in a constant-power mode following the power profiles listed in Table S4.

The cycling tests were performed with 100 cycles as a group. In the first cycle of each group, the 215-Wh/kg cells were charged with 6C rate and 4.15 V cutoff voltage until the charge current in the constant-voltage stage fell below 3C. The charged SOC in the first cycle was utilized to estimate the EoC-SOC in Figure 4E. In the remainder 99 cycles of the group, the cells were charged with 6C and 4.15 V until the charge time reached 5 min. After finishing the 100th cycle of the group, the cell was discharged with a C/3 rate to 2.8 V to calibrate the remaining capacity, which was used to estimate the EoD SOC in Figure 4E. Thereafter, a reference performance test (RPT) was performed by fully charging the cell (C/3 charge to 4.15 V, and CV@4.15 V until the current fell below C/20) and then discharge at C/3 to 2.8 V to calibrate the capacity fade (Figures 4C and 4D). The 271 Wh/kg cells were cycled similarly to the 215 Wh/kg cells. The only differences are that the charge C-rate was reduced to 3C, and the charge time per cycle was extended to 10 min to prevent Li plating.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.joule.2021.05.001.

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AUTHOR CONTRIBUTIONS

X.-G.Y. and C.-Y.W. conceived the idea and wrote the manuscript. X.-G.Y. performed the modeling analyses. T.L. performed the cycling tests. S.G. fabricated the cells. All authors contributed to analyses of the results.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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