Essay #5 in Aspen Fly Right's public-education series, 12 Jan 2023 (+XS 15 Jan), rev 25 Dec 2023
All essays, and the advertisements they elaborate, are posted at https://aspenflyright.org

Flight without fossil fuel

Executive Summary

Buckle up. The aviation revolution is upon us. When the ASE Vision process recommended and Pitkin County Commissioners set Aspen Airport strategy in 2019–20, they considered only airplanes commercially available or expected soon from major makers *in 2019*. They thought replacements for the airlines' CRJ700 fleets were needed soon and must be bigger (last week's essay shows why not), needing the new airside now planned. They also thought superefficient, electric, and hydrogen aircraft would be small, short-range, and far off. A 19 October 2022 County-invited analysis, first published 12 January 2023, found the opposite. Here's its essence:

Efficient and electric planes—just as with cars

The 3–5× better airplane efficiency and lower impacts found feasible by major aerospace teams in the past decade are now old hat. A plane 8× as efficient as a standard business jet was announced in 2020, months before the Commissioners' decision, but was mistakenly dismissed as having only six seats (as an executive-plane market entry point), overlooking its doubled-size version with severalfold more seats and its design's extensibility to at least regional-jet size. Such superefficiency also greatly reduces the challenges of electric or hydrogen propulsion, bringing both at least a decade closer.

This virtuous cycle has already transformed the automobile industry. A decade ago, electric vehicles (EVs) were widely thought impractical in payload, range, and cost, because batteries were too wimpy, heavy, and expensive. But smartphones spawned advanced batteries; their higher energy density made EVs feasible; mass production made the batteries tenfold cheaper and EVs affordable. Lighter, sleeker cars could drive farther on less energy, needing fewer batteries and saving more weight and cost. Ranges passed 300, 500, 740 miles. EVs won on lifecycle cost and are about to hit sticker-price parity. Now two startups' even more advanced vehicles, 2–3× more efficient than a Tesla, need so little energy that they can run largely or wholly on their own solar cells without even plugging in! And today the same forces that created EVs are animating game-changing electric planes (EPs).

Rapid evolution driven by lower costs and impacts

The EV and EP industries coevolve swiftly, but EPs evolve faster. Some EP electric motors are tenfold lighter, and batteries severalfold lighter, than today's EVs use. Sleeker, lighter planes also need smaller motors and batteries. Top analysts now agree EPs will have lower capital and operating costs than fueled planes, driving rapid adoption for commercial and private aviation.

EPs have scores of skilled, serious, and amply funded developers, nearly 1,000 orders (with up to 30 seats), and 55 intending operators. Over a thousand electric vertical-takeoff-and-landing taxis, innumerable drones, and military R&D further enrich the e-aviation ecosystem. United, American, Delta, and other leading airlines are heavily invested, involved, and already ordering EPs. United is keen to use EPs to serve smaller airports at lower cost. Aspen could be among them.

Superclean planes can serve Aspen in years, not decades

Besides 2024–25 vertical-takeoff air taxis to Denver, Rifle, or Vail, expected electric or hydrogen planes fitting ASE's size limit include 9–19 seats flying 250 nautical miles (nm) in 2025, both 40–80 and 100 seats flying 800 nm in 2026, then rapidly rising size and range. These sizes are ideal for more frequent direct service connecting ASE with more places at similar or lower cost. With some ingenuity, our airspace can safely do that, just as it accommodates General Aviation growth.

These electric planes will have vastly lower impacts than our community's goals seek—hardly any CO_2, pollution, or noise. And this flowering of innovation will make the proposed new airside unnecessary before it could be built. That new airside is far more likely to be late than the whole portfolio of advanced ultraclean airplanes from so many ambitious makers.

Fasten your seat belts: the imminent aviation revolution will be quite a ride. We just need to see it coming before spending $200+ million now planned for a staid, slow, bigger-planes era that's already been overtaken by events.

The ASE Vision leaders rightly warned that Aspen's aviation policy needs vigilance and agility[1]:

> While such recent announcements [as vertical-takeoff-and-landing electric air taxis] do not affect the Vision Committee's current recommendations for our future airport, they do underscore the rapid technological changes that will likely alter the aviation landscape over the next ten to twenty years. The Committee's Final Report stresses the need to monitor carefully the growth and functionality of our new airport and to make nimble course corrections as needed to achieve our four Core Community Goals. Rapid technological change offers one more reason to remain watchful.

They were absolutely right—except that their "next ten to twenty years" proved roughly fivefold too long. ASE Vision's 15-month process was mandated to plan for 30 years ahead[2], but scarcely looked five (perhaps ten for the terminal). Its aircraft assessments became obsolete even sooner, in 2020–21. This essay a year later therefore seeks to inform the vigilance and enhance the agility needed to catch up with today's aviation realities.

ASE Vision examined emerging aviation technologies only in cursory fashion[3], as briefly summarized[4] in the Common Ground Recommendations. Fleet choices were restricted to selected aircraft previously or currently sold or well along in development by five major manufacturers *in 2019*[5]. As pointed out to the Board of County Commissioners (BOCC) long before their 2020 decision[6], at least two new aircraft far superior to any considered by ASE Vision, and expected to enter commercial service in the mid-2020s, were announced months before the BOCC's December 2020 decision but were not assessed.

ASE Vision's Technical Working Group did not, as the BOCC was assured, study "every conceivable alternative that could be considered for this airport in the future[7]": indeed, it never analyzed *any* post-2019 aircraft technology. Thus its brief mentions of emergent aircraft were already outdated when its report was issued in December 2019. So was the ASE Vision report of April 2020, built on those findings. Now both reports are obsolete, because the aviation technology revolution is moving about a decade faster than expected—somewhat like biological evolution's Cambrian explosion, but measured in years, not ten-odd million years.

The Airport Advisory Board (AAB), like ASE Vision before it, gets virtually all its information from County Staff and their consultants, and has not yet been apprised of these developments. Its limited remit doesn't include new aviation technologies, and some members may not be well equipped to assess them. The AAB was also told to rely on the original ASE Vision data and to implement its BOCC-edited-and-adopted recommendations "to the greatest extent possible." This instruction could be read as restricting the AAB's authority to update and augment the 2019 analysis, which (if so) must be adopted and perpetuated—the opposite of the vigilance and agility now required. These structural factors could make it difficult or impossible for the AAB, despite its admirable membership and intentions, to carry out the BOCC's instruction to evaluate the new Fleet Mix Study. As currently informed and advised, the AAB might not realize how profoundly the competitive landscape has shifted since the 2019 Doerr-Hosier symposium.

The challenge of choices

Pitkin County's capable aviation technical consultants are charged to prepare the new Fleet Mix Study and Airport Layout Plan as a "consistent, aligned story"[8] to convince the Federal Aviation

Administration (FAA) to approve and fund the airside expansion as desired by the County. That puts them in a difficult position. Having spent three cordial and constructive hours hearing and discussing Amory Lovins's invited technical brief on 19 October 2022, they now know that the current Airport plans' bedrock assumption—the supposed need for bigger airplanes—is in grave doubt. His brief documented "a swarm of gamechangers that will become important within about 5 years and cross major tipping points within 10 years." The consultants and Airport Director were invited four times to express any corrections to or concerns with the brief summarized below, but they had none[9]. It remains to be seen how they will reconcile these contrary views.

They're in the unfortunate position of a hypothetical consultant asked around 2012—four years after Tesla's proof-of-concept battery-electric Roadster, and just as the Model S car entered production—to make a 30-year forecast of where the US would sell how much gasoline to how many of what kinds of automobiles, to help plan the right filling stations and fuel infrastructure. In hindsight, it would have been wise to consider whether those early Teslas could change everything. Since then, battery-electric cars' global annual sales rose ~80-fold and their global market share passed ~13%[10], portending disruption to an oil industry that has made decadal investments based on forecasting just modestly better gasoline autos because, as everyone knew, electric autos were impractical, unaffordable, and too far in the hazy future to think about.

Now the County's consultants are being asked for a similar forecast of Aspen aviation. This can hardly feel comfortable. New questions are needed, new ways of thinking about the future, new ways to invest prudently to meet future needs while avoiding costly mistakes and stranded assets. Traditional assumptions, tools, and ways of thinking no longer suffice.

To understand how fundamentally the aviation future has changed since ASE Vision, this essay summarizes the revolution in aviation technology, in three interlinked parts: radically improved aerodynamic efficiency, taking planes farther with less energy; cleaner and more-efficient ways to propel them, using clean liquid fuels or stored electricity or hydrogen; and shifts in how airline networks operate. We'll now explore these three revolutions in turn, where they're headed, and how quickly they're moving.

Superefficient airplanes

Airplanes[11] use thrust—air or jet exhaust blasting backwards—to propel them into and through the air. Air moving swiftly over specially shaped surfaces generates aerodynamic lift that keeps the airplane aloft against the pull of gravity. Lighter weight needs less lift to support it. Generating lift with less weight and speed needs less thrust. Since friction and turbulence also rob energy as the airplane moves air aside, less aerodynamic "drag" needs less thrust to overcome it. An airplane with less weight, more lift, less drag, or preferably all three therefore needs less thrust. (Creating lift also induces drag, but how much depends on the aircraft's aerodynamic efficiency. The ratio of lift to drag, a useful figure of merit, shows how little energy is needed to sustain level flight, or how far the airplane can glide down without power.)

A propeller, fan, or jet's propulsive thrust is generated by burning stored fuel in a jet turbine or in an engine to turn a shaft, or by turning an electric motor using electricity from a battery, chemical fuel cell, or generator. All that propulsive equipment is called the "powertrain." An advanced

powertrain can use even less fuel or electricity by more effectively converting their energy into thrust. The most efficient airplanes will thus need little thrust *and* will produce that thrust from little fuel or electricity. These successive efficiencies multiply to require less energy per seat-km.

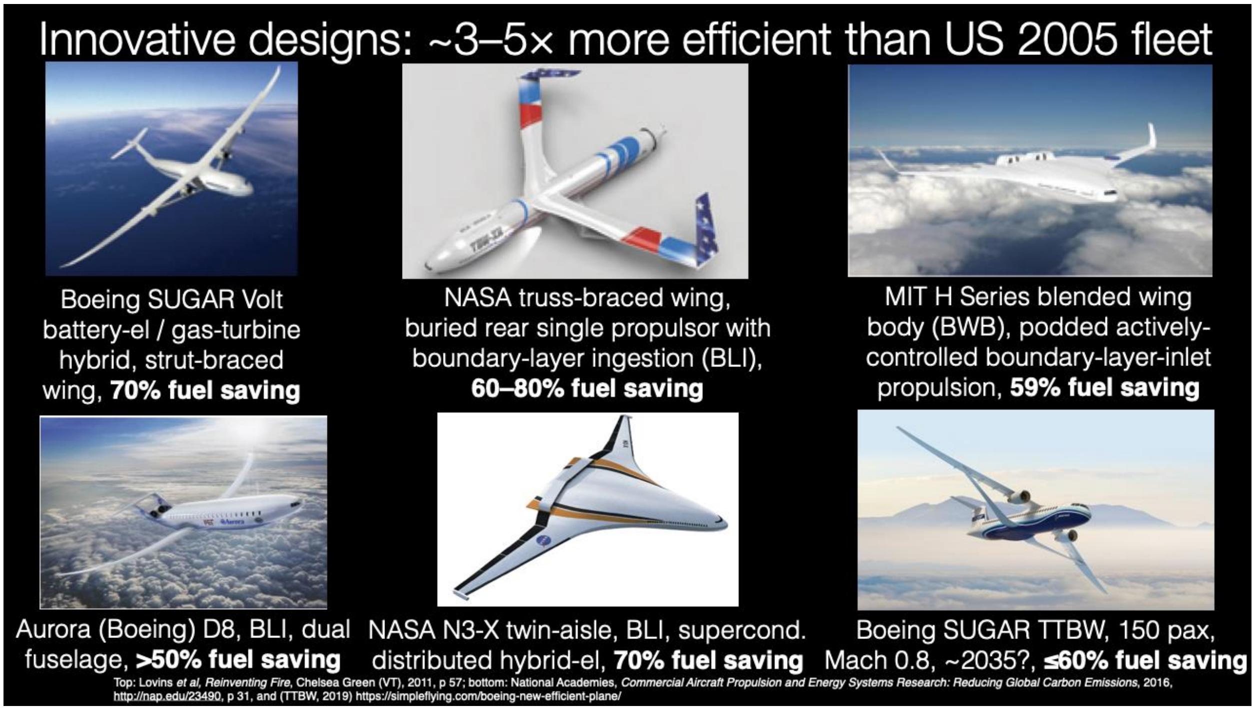
A complication: a fueled airplane loses weight as it burns fuel, so it can become more efficient during its journey. Conversely, fuel needs extra fuel to carry it, reducing the airplane's range. It takes most of a gallon to carry a gallon across the Pacific, so you must take off from Denver with about 1.5–2 gallons for every gallon you want to land with in Tōkyō.

These factors are all intricately related to each other and to stability, flyability, flexibility, safe and agile handling in adverse conditions, interior comfort, noise, emissions, beauty, and capital and operating costs. Designing airplanes is thus a very complex and difficult science and art.

Aviation's inherent hazards, and the resulting rigorous regulatory framework, make airplane manufacturers shun risk. One defective product can shatter or endanger a giant company. Ferocious competition and vulnerability to external shocks like economic downturns, wars, and pandemics make most commercial air carriers risk-averse too, and often financially crimped. Airframe manufacturers, engine and other equipment producers, plus their air-carrier customers (and lessors in between) form the immensely complex commercial aviation industry. Its investments to reduce high and volatile fuel costs tend to be slow and incremental. In fact, aviation firms are so staid, raising efficiency 2.1%/y in 1990–2019[12], that a 2004 RMI analysis for the Pentagon was able to anticipate new-jetliner fuel efficiency in 2025 within a few percent[13].

More than a decade ago (Fig. 1), innovators at Boeing, NASA, MIT, and elsewhere published designs for jetliners ~30–60% more efficient (fewer liters per seat-km) than the 2005 US commercial fleet. They typically used lightweight carbon-fiber-composite structures, longer wings braced with slender struts or trusses, more-advanced aerodynamics[14], and more-efficient engines (sometimes ingesting air from the slow-moving "boundary layer" along the fuselage to minimize drag), plus smaller but significant improvements in accessory loads like comfort-conditioning, lighting, and electronics. RMI's 2004 analysis found that saving 45% of officially projected fuel use would cost ~45¢ per saved gallon using tube-and-wing designs, or ~65% at unchanged or lower cost with the less familiar blended-wing-body or "flying wing" shapes: in short, profitably saving ~2–3× in fuel and CO_2 emissions. This vision was consistent with NASA's 2013 finding of 50% potential fuel savings by 2020 and 60% by 2025, with 79% less NO_x and 42 EPNdB less noise[15]. Then in the past decade, the potential savings rose to about 3–5×.

Fig. 1. Examples of far more efficient civilian airplanes designed about a decade ago (top row) and in the past few years (bottom row). They offer potential fuel and emissions savings of ~3–5× (that is, using about 67–80% less fuel per seat-km) compared with the 2005 US fleet average. Two designs are hybrid-electric, with fueled gas-turbine-assisted takeoff and range reserve but electric cruise. "Pax" is aviation lingo for passengers. Mach refers to the speed of sound (1,235 km/h at sea level); today's big jetliners normally cruise at about Mach 0.85.



Yet these striking improvements[16] far from exhausted the opportunities. Among the most obvious prospects, advanced polymer composites (often using carbon fiber) will lighten aircraft by at least another 20% beyond today's half-composite models like Boeing's 787 and Airbus's A350[17], and enable an elliptical fuselage more advantageous than today's round metal tubes. Yet today's state of the shelf can cut a plane's empty weight much more than 20%. A Joint Strike Fighter design at the Lockheed-Martin Skunk Works in 1984–86 was one-third lighter *and two-thirds cheaper* than its 72%-metal base design. Even one-third lighter is far from a limit. NASA's latest ultralight aeronautical structures, like a 98.3% lighter (but stronger) wing tested in a high-speed wind tunnel in 2019, stretch a tough polymer membrane over an airy lattice of centimeter-scale molded engineering-plastic cells to form any desired shape[18]. This can also eliminate moveable flight surfaces: the entire wing passively adapts like a bird's wing to optimize continuously to real-time flight conditions. This revolutionary path to radically lighter weight, better aerodynamics, and lower cost was initially prototyped in simple forms as an airplane for Airbus and as a car for Toyota—probably not for amusement.

Morphing wing technology, being adopted in certain supercars and Air Force planes, can save over 10% of fuel in new "clean sheet" designs and over 3% in retrofits while cutting noise by 10 dB[19]. ANA, Lufthansa, and SWISS are testing or adopting sharkskin-like riblet films developed by camera-maker Nikon to cut drag, saving up to 2% of fuel[20]. Laminar vortex flow imitating how fluids flow efficiently in nature, and reshaped Fibonacci-mathematics propulsors exploiting it, hold unexpected prospects for drag reduction[21]. Hydraulic/mechanical actuators can be replaced by electric actuators 3× lighter, 5× more durable, and far cheaper[22]. Next-generation turbofan engines entering the market in 2024–25 are expected to save 17–25% of fuel compared with their current-generation predecessors[23].

But more-radical opportunities often go unnoticed. Thus in early 2019, NASA Langley's Chief Scientist said that truss-braced wings with advanced aerodynamics were still in their infancy, their potential only half-used, and that highly refined versions could raise the lift/drag ratio from the 787's 21 with an advanced tube-and-wing design, or ~22–23+ with blended-wing-body designs, to an extraordinary ~40–60+ (comparable to very-long-winged sailplanes, the best of which exceed 70), while markedly reducing weight[24].

Some established solutions may also give way to better ones. Thus Lovins's 2019 ASE Vision speech mentioned that longer wings are often used to raise efficiency, but can "fold up when needed—Boeing's been selling those hinges for a decade…."[25] Nine months later, that debate was bypassed and the whole industry was startled when a stubby-winged design demonstrated far greater efficiency. Its story illustrates the astonishing speed and potential of today's aviation innovations, and the deep well of skills and imagination from which they flow.

Otto Aviation's Celera efficiency revolution

Four months before the Pitkin County BOCC approved its Aspen Airport policy resolution, a small but skilled California firm[26] founded by William Otto, ex-Chief Scientist/Avionics of the B-1 bomber, revealed a bulbous airplane called the Celera 500L, which Lovins inspected in June 2021 and discussed with Mr. Otto and team (Fig. 2). He thought it may be the most important new airplane in decades, for both what it does and what it portends. Airport planners who see it only through the lens of today's big-plane fleets and hub-and-spoke routes ignore it at their peril.

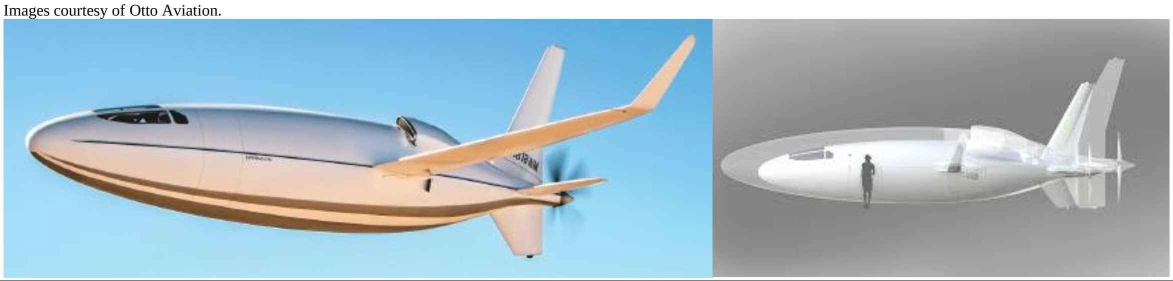
The Celera 500L's airflow is extensively laminar (extremely smooth) all over its fuselage, wings, and tail, cutting drag by 50% below normal business jets' more-turbulent flow. Its lightweight composite structure cuts maximum takeoff weight to 40% less than the Learjet 40 carrying just one more passenger. The 500L needs only the lift of *short* aft wings spanning just 52′. Its initial powertrain is a twin-six aluminum diesel engine[27] that can burn any liquid fuel, including up to ~100% climate-friendly Sustainable Aviation Fuel, driving a five-bladed pusher propeller set all the way aft. Its six luxury seats, widely misconstrued as a size limit, simply reflect a potential entry market as a $5-million executive aircraft with long range and ~400-knot airspeed. Its 3,500-nautical-mile (nm)[28] range, comparable to a 737's, could serve virtually all 5,000+ US regional and municipal airports and many abroad *nonstop from Aspen, at or below current commercial ticket prices*. With *one-eighth* a private jet's expected operating cost, it looks set to blow up both commercial and private fleets' business models.

Soon Otto Aviation had designed a double-sized 1000L variant, also extensively laminar, with a ~70′ wingspan and manyfold larger passenger capacity. Further upping the ante in 2022, hydrogen powertrain developer ZeroAvia announced a joint effort with Otto Aviation to produce a 19-seat (for cheaper type certification), 1,000-nm-range midsized hydrogen version[29]. An electric variant is also being considered. Both variants should have even lower drag than the 500L, and even better operating economics due to lower-maintenance powertrain and cheaper fuel.

Fig. 2. On 26 August 2020, Otto Aviation's Celera 500L (L image) emerged from 12 years in stealth mode as a 37′-long, 52′-wingspan, spacious, extensively-laminar-flow, jet-speed, fuel-flexible, 6-luxury-seat air taxi. It has 6′2″ cabin headroom; the production version will add normal windows. Its glide ratio is 22 (vs. a Learjet's 16)—more like an inefficient glider than an efficient business jet—and set to rise further[30]*. With svelte 12,500-lb maximum takeoff weight, 50% lower drag, and superefficient powertrain, it uses* one-eighth the fuel *of a typical business jet while increasing range to 3,500 nm. Its multifuel diesel engine emits about half the* CO_2 *per passenger of today's best large intercontinental jetliners like the 787 (if both are burning oil-based fuels). Its 20%-longer, nearly-doubled-volume 1000L variant (R image) with a ~70′ (~35%-longer) wingspan—one-fourth below ASE's current 95′ limit—could hold a dozen commercial first-class and eight coach seats, or more with denser configurations, though exceeding 19 seats raises certification costs by manyfold*[31]*. Larger than 1000L is also feasible in this decade; Airbus flight-testing*[32] *indicates laminar flow is feasible at regional-plane scale. Such superefficient planes would be ideal for point-to-point service between Aspen and any of 5,000+ US airports, plus many in Canada and in Central and South America and arguably some in western Europe. The chubby fuselage also offers important options for roll-on-roll-off cargo.*

The Celera 500L's skilled developers expect FAA type certification and commercial service by 2025; ZeroAvia targets 2027 for the hydrogen 750L[33] *version; and one or more electric versions could be in service in this decade, followed by expanded range as batteries and fuel cells keep improving. Their manyfold lower operating cost will make smaller planes more economical than big ones, encouraging the shift from hub-and-spoke to point-to-point route architectures. Even the diesel version, burning sustainable or conventional fuels, will far surpass our community's most ambitious environmental goals. And even further efficiency gains are possible*[34].

Images courtesy of Otto Aviation.



Superefficiency enables fuel-free propulsion

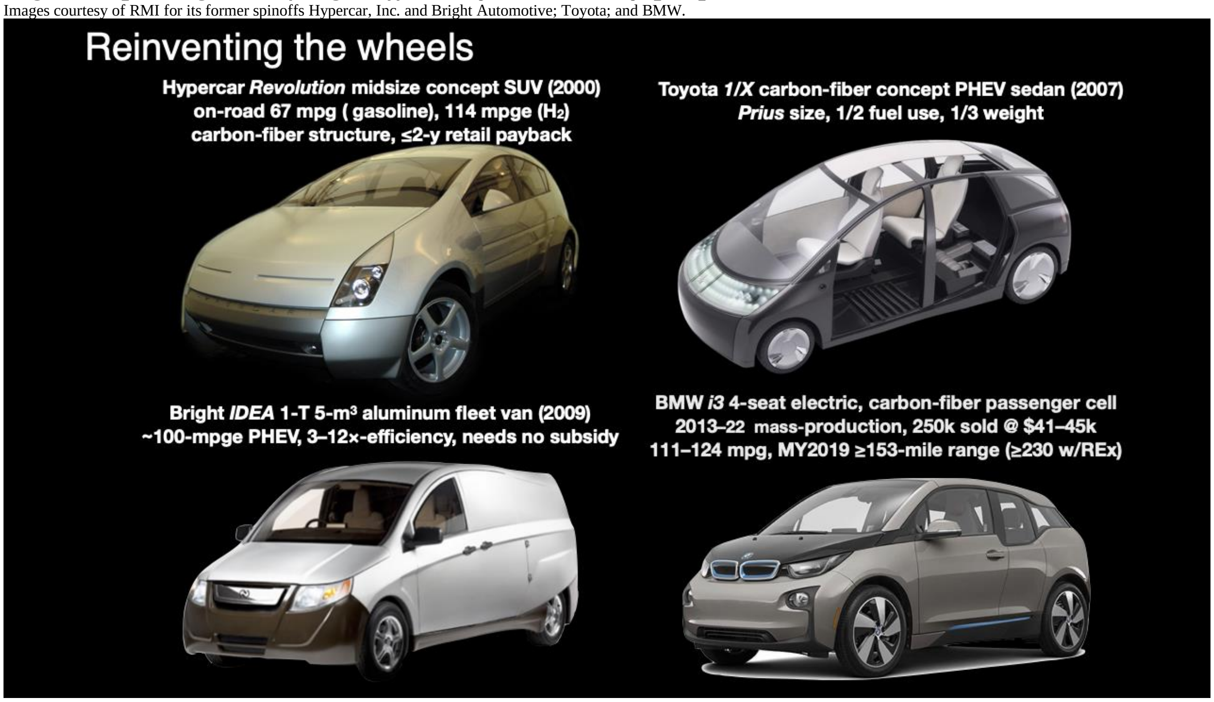
A decade ago, Airbus's predecessor EADS published a provocative technical design study[35] for a 68-passenger turboprop with largely laminar flow, bulbous shape, and a big pusher fan aft—like a precursor of the Celera family. It had just one-fifth the 500L's range, though, because it raised energy efficiency by only 25%. But its important finding was that even a 25% saving could reverse more than half of the near-doubling of weight from electrifying propulsion. This in turn allows more range and capacity from milder battery progress. "[T]ypical payload/range missions flown today can thus be realized with 750 Wh/kg battery systems"—one-fourth lower energy density than previously needed. That was true in 2011. A decade later, strongly integrating today's far better technologies—Celera-class aerodynamics, ultralight structures, better batteries and motors and power electronics, and even ultralight but superefficient solar cells—could rival if not surpass the key parameters of today's kerosene-fueled jetliners, and at least match those of many regional jetliners with battery packs well *below* 750 Wh/kg energy density.

This dynamic has already played out in automobiles. Most analysts used to think battery-electric cars were, as a Dutch critic put it, "cars for carrying mainly batteries—but not very far and not very fast, or else they would have to carry even more batteries." Now, thanks to the genius of engineers like Tesla's cofounder JB Straubel, few electric-vehicle (EV) owners would dream of going back. Today's best beat fossil-fueled cars on every criterion but sticker price, which will reach parity in a few years, and EVs already win on lifecycle cost.

It's been quite a journey. Amory Lovins invented the Hypercar® concept in 1990/91—an ultra-lightweight, low-drag, electric-traction family of autos with gamechanging efficiency plus un-compromised safety and performance. In 2000, RMI and its industry partners virtually designed the *Revolution* Hypercar concept car[36]—a carbon-fiber midsize SUV with 53% less weight, 4–6× greater efficiency (67 mpg as a gasoline hybrid, 114 mpge with a hydrogen fuel cell), and a retail payback time under two years. Sharing its design methods then helped Toyota in 2007 to design the "1/X" carbon-fiber plug-in hybrid concept car, with the interior size of a Prius but half its fuel use and 70% less total weight[37]—still the open-literature record for ultralighting.

In 2013–22, BMW profitably sold a quarter-million of the carbon-fiber i3 electric car getting 111–124 mpg-equivalent. It proved the radically simplified manufacturing and smaller power-train (especially fewer batteries) that, as RMI had claimed in the 1990s, made ultralighting approximately free[38]. Even without using carbon fiber, another RMI spinoff in 2009 road-tested an aluminum hybrid-electric fleet van whose one-ton-lower weight saved over half its batteries, cutting cost so much that its 3–12× efficiency gain would need no subsidy. The lesson of all these designs, and many more from industry, is that optimizing autos as whole systems, not as a pile of parts, can yield energy savings severalfold bigger than usually assumed, yet cheaper. This also turned out to increase by severalfold ultralight autos' "mass decompounding": saved mass compounds or snowballs because the less weight you have, the less weight you need for suspen-sion to support it, brakes to stop it, powertrain to accelerate it, etc., so lightness multiplies.

Fig. 3. A petting zoo of high-efficiency electrically propelled automobiles, 2000–2013.
Images courtesy of RMI for its former spinoffs Hypercar, Inc. and Bright Automotive; Toyota; and BMW.



Today’s electric cars teach the same lesson (Fig. 4). Lucid’s Air (520-mile EPA range for the Dream Edition) and Mercedes’ EQXX demonstrator (747-mile test range) make battery cars’ range as irrelevant as the speed of your modem. They achieve extraordinary ranges with smaller and cheaper batteries, because the designers removed so much drag and tire rolling resistance (and some weight, with more to come if they adopt carbon fiber). The EQXX’s battery pack, an EV’s costliest component, shrank by half. Yet carbon-fiber structures’ digital manufacturing techniques (developed by, among others, former RMI spinoff Fiberforge in Glenwood Springs) now make ultralight composites highly competitive in automaking too. The main barriers are no longer technological or economic but cultural. They may be more easily vaulted by startups than by venerable, skilled, tradition-bound auto giants. When competitive forces motivate that shift, batteries will shrink further, speeding EVs’ takeover. And already, the startups are coming.

Fig. 4. The most efficient EVs: Lucid Air (2021 production) and Mercedes EQXX (shown 2022 with expected 2023–2024 availability of a productionized version). Their drag coefficients are respectively 0.21 and 0.17; most production cars are in the upper 0.2s to upper 0.3s range.

Images courteso of Lucid and Mercedes.

The battery-electric EQXX’s efficiency is equivalent to an impressive 252 miles per gallon. But meanwhile, a Dutch firm whose engineers won the world solar car race six years in a row has just entered production (by a respected Finnish factory) of Lightyear 0—a similarly aerodynamic (0.175), 450-mile-range, battery-electric 5-seat sedan getting 251 mpg-equivalent, proving that a spunky startup can match Mercedes. This twice-Tesla efficiency lets the Lightyear 0’s topside solar cells add eight miles of range for each hour in the sun, supporting normal daily driving for many summer months (in Amsterdam) without plugging in to recharge (Fig. 5). That’s right—an uncompromised, normal-sized car run largely or wholly on its own solar cells.

Next on that path is San Diego startup Aptera, with 100,000+ reservations for a moderately priced, 2-seat, radically simplified[39], crashworthy, composite electric 3-wheeler equivalent to 343 mpg or triple Tesla efficiency. Like the Lightyear 0, whose solar cells cover a two-thirds larger area, Aptera’s sleek vehicle, licensable and insurable as a motorcycle, is unlikely to need plugging in except for a long road trip (of up to 1,000 miles if you buy the biggest battery). It’s as if the car magically added two gallons of fuel to its tank each day you park it outside. How? It’s 65% lighter than normal EVs, teardrop-shaped (Fig. 5), and so slippery that its total air drag is said to be less than that of the side-mirror or the windshield wipers on a standard pickup truck. Some say it looks more like an airplane[40], with wheels rather than wings. It even offers offroad and camper versions. It doesn’t fly, but looks as if it might try to.

Fig. 5: Two 2022–2023 superefficient EVs that can drive for weeks or months without recharging: Aptera (upper left 4 and lower left images), and Lightyear 0 (upper right 2 and bottom right 2 images). Images courtesy of Aptera and Lightyear.

Electric vehicle (EV)–electric plane (EP) evolutionary parallels

A decade of the EV conversation has already evolved beyond all expectations. At first, the conventional wisdom was that batteries would be too costly and heavy, allowing scant range or payload. But then the huge cost premium offered by smartphone-makers for more battery life from smaller batteries drove new energy-dense lithium-ion chemistries that made EVs feasible with marketable range. (Hybrid cars also provided interim range extension as batteries evolved.) Led by Tesla's skill and ambition, EV firms sprouted to exploit that emergent potential. They achieved such manufacturing volume—now over 10 million a year—that high-energy batteries became cheap, creating a vast new EV industry. Radical simplification also cut autos' weight, hence battery needs, hence cost and complexity. For example, of five high-voltage modules in Chevrolet's Bolt, Tesla needed two. Model Y's "octovalve" and heat pump boosted range 10%[41].

The next stage of evolution, now underway with platforms like Lucid's Air and EQXX's 2023–24 commercial expression, further cuts tractive load, saving still more batteries and their weight and cost. Ultralighting the major structures and chassis components, as RMI and Tier Ones designed in 2000 (coming to the capital market just as it crashed, alas), is the next big step.

Thus the conversation shifted from electric vehicles' being infeasible[42], to impractical, to unaffordable, to unreliable, to…dependent on harmful mining and child labor in Congolese cobalt mines (the first manageable, the second obsolescent[43]), and finally to…oh, obvious all along!

This evolution continues as strong lightweighting by Aptera, some by Lightyear, and great aerodynamics by both illustrate the next and most radical frontier in superefficiency: onboard solar recharging. That's so radical that the onboard batteries shrink even further, as do the energy and infrastructure needed to recharge them—a major pain point in today's EV revolution. And economically, this evolutionary sequence yields ever cheaper vehicles to buy and to run, driving their evolution and adoption ever faster in a virtuous spiral. Watch your neighbor's driveway.

Now apply this logic to the evolution of electrically propelled airplanes (regardless of where their electricity comes from). Many analysts have already leapt the first hurdle of supposing that electric airplanes can't carry enough passengers far enough to be worthwhile: that assumption flows, just as it did with early EV analyses, from assuming inferior old components in heavy, high-drag platforms. In 2022, some respected analysts like Bloomberg New Energy Finance (BNEF) started to see that light, sleek planes need fewer and milder batteries and could therefore make a decent business and operational case. Meanwhile, the most farsighted developers realized that advanced electric airplanes could be not just affordable and practical but also *cheaper to buy and to operate than fueled planes.* Next comes the dawning realization that e-planes will take over not just short-haul but some medium-haul markets, competing against petroleum fuel and Sustainable Aviation Fuel burned in existing airplanes.

To be sure, it's harder to electrify planes than cars because they're supported not by wheels but by aerodynamic lift, which induces drag—but that very need, plus mass decompounding, makes it *more valuable* to save aviation fuel than road fuel. Taking a pound out of a commercial airliner typically saves around $1,000 in present-valued fuel. That justifies exotic ultralight materials even without counting their simplified manufacturing, freedom from corrosion, very high fatigue resistance, and other side-benefits that can reduce or even eliminate the cost premium[44]. Moreover, in countries from Canada to Korea to New Zealand, commercial electricity in 2019 was already cheaper than jet fuel per unit of aviation propulsion, because the electric powertrain is about three times as efficient as a fueled one[45]. (Jet fuel contains about 51× more energy per pound than a near-term aviation battery pack at 211 Wh/kg, but the electric powertrain's tripled efficiency shrinks that disadvantage to about 17×, and BNEF's detailed analysis suggests 234–304 Wh/kg by 2030—shrinking it to 12–15×—and then higher. Electric planes, like electric and hybrid-electric autos, can also recover energy by coasting down.) The emerging parameters of e-planes strongly suggest that some pioneers will soon demonstrate superior economics at scale for significant and expanding market segments and use cases, just as Tesla did for EVs.

Importantly, EVs and EPs (if we may so dub electric planes) don't evolve in isolation from each other. They share many technologies, ideas, and innovators. Each inspires, reinforces, supplies, and speeds the other. Each builds on the other's vast base of skills, insights, methods, materials, and suppliers. Some collaborate directly, such as Airbus with Renault[46]. The main difference is that if anything, *EPs are evolving faster.* Electric aviation enjoys virtually unlimited capital, Tesla-like (not Detroit-like) speed, vibrant competition, and huge ambitions. And major innovation-drivers may lurk unseen outside our system boundary. Who would have thought that our smartphones would spawn advanced lithium chemistries and efficient circuits, making EVs practical—via consumer-electronics brands like Panasonic and LG—and enabling Tesla to make batteries so cheap that they're now revolutionizing the electricity industry? What new drivers of electric aviation will be obvious only in hindsight?

Even the last step in the car story so far, the solar EV, already has an analogy in aviation. In 2001, the remotely piloted ultralight Helios airplane powered by solar cells alone ascended to nearly 97,000′ above the Earth—more than two miles above the previous record for winged aircraft—and stayed above 96,000′ for over 40 minutes[47]. Today, combining ultralight membrane-and-lattice structures with the strength of bulk elastomers but the gossamer lightness of aerogel, advanced aerodynamics and batteries, and the kinds of solar cells that can now keep special military planes aloft indefinitely—capturing energy reflected up from below, not just from above—may in the coming decades become able to fly commercial payloads across oceans with no fuel. That's not assured, but it's not against the laws of physics, and it's where convergent technologies are heading. Whether or not electric planes go all-solar, adding thin, lightweight, rugged solar cells to their skin can extend their range with less weight and cost than bigger batteries.

What does this astonishing story teach? It took just ten years for electric cars to go from a butt of jokes to the global market winner, set to displace 140-year-old internal-combustion-engine technologies and the oil they burn. Now electric airplanes are repeating that story ten years later—but they're not starting from scratch. They use the same technologies and skills, but push them harder, prove them faster, feed them back to cars, and benefit from automakers' skills, supply chains, and production volumes. Both these industries are highly regulated, airplanes more so, but the FAA, challenged by drone regulation, is also learning faster, and so are its counterparts around the world. It's therefore now plausible that electric planes could evolve *faster* than electric cars, going from small and short-range to taking over significant markets—including those that serve Aspen—before a new airside could even be built for the fueled planes they'll make obsolete: bigger planes with longer wings and slow, incremental evolution over decades.

To test this hypothesis that the County's plans for Aspen Airport may already have been overtaken by events, let's come back to earth, get severely practical, and assess what is rapidly emerging from *today's* technologies—and how soon it could transform aviation's prospects.

Electric airplanes

On 2 December 2022, Bloomberg New Energy Finance—the go-to source for hardnosed business analysis of the cutting edge of the energy transition—reported[48] on the electric aviation revolution. It found a recent surge in orders (989[49], all so far with 30 seats or fewer) for small battery- or hybrid-electric aircraft, and 55 aircraft operators, including some major ones, that have ordered or intend to use electric aircraft. BNEF also documented impressive progress across electric plane propulsion that "promises to outcompete conventional aircraft in terms of greenhouse-gas emissions, operating costs, and airframe design flexibility."

While still better technologies are needed, the solutions now emerging from the lab and heading for market will support "lengthy and costly type certification" far sooner than anyone had expected just a few years ago. Small, short-range, early planes are rapidly giving way to surprisingly aggressive development paths—especially where firms like Eviation, Heart Aerospace, and Faradair are designing new airframes from scratch rather than adapting heavy old ones. All the main engine-makers are also developing hybrid-electric propulsion for big planes, and Rolls-Royce apparently for regional planes too. Let's look at some key technologies and how they can fit together.

BNEF identified an ecosystem of at least 59 firms, from aerospace incumbents to startups to component and charger developers, with some working on more than one part of the value chain. Some major air carriers like United, Air Canada, and DHL Express have made significant orders or direct investments. These focused funds and skills are already starting to pay off. Diving in:

Progress with light but powerful motors and batteries

Most EVs use electric **motors** producing just 1–2 kilowatts per kilogram (kW/kg), delivering shaftpower around or modestly above 100 kW. Yet today, at least ten firms' electric airplane motors are approaching 1 MW (1,000 kW), one at 2 MW (Wright Electric), and producing typically 3–6 kW/kg[50]. Wright Electric expects 10 kW/kg at 2-MW ratings, ARPA-E's ASCEND R&D program targets 12 kW/kg, some specialized US and EU firms report motors in the 10–20 kW/kg range[51], and noted Toshiba supplier DENSO joined with Honeywell since 2019 to develop an air-cooled motor for Lilium's Jet with an astonishing *25* kW/kg—100 kW output from a 4-kg motor[52]. That's more than ten times the power density of the motors in many EVs today.

Even more important and closely followed is progress in **batteries**' Wh/kg energy storage capacity. In 2011, it averaged ~200 Wh/kg at the cell level (many cells, plus packaging and other shared components, make up a pack). In 2015, the most advanced civilian *solar* airplane (Dr. Bertrand Piccard's *Solar Impulse 2*) could store 260 Wh/kg in its lithium battery pack—enough to circle the globe with its 2,000-kg maximum takeoff weight. (The battery-maker, H55.ch, is now partnered with Pratt & Whitney for its hybrid engine developments.) Seven years later, at least three firms (C4V, Sion Power, Solid Energy) had doubled smartphone batteries' energy density to 400–500 Wh/kg. The National Academies had said in 2016 this would take 20 years; it actually took 3–6 years. By April 2022, just five of the 50+ battery startups tracked by BNEF (17 added in the past year), nearly all in the US and Europe, had a market capitalization totaling $12.3 billion, half of it in QuantumScape, and battery technologies were "moving rapidly towards higher energy density, lower cost, better safety and longer cycle life" due to interlinked advancements in not just cathodes (the past decade's focus) but also anodes, electrolyte, manufacturing, and software[53]. The near-absence of profiled Asian firms doesn't mean they're inactive. Surprises may be expected from that direction, as hinted by dominant Chinese dronemaker DJI, EV-maker BYD, and battery-maker CATL and by top Japanese and Korean battery skills.

BNEF's 2022 review confirms significant gains from now-commercial silicon anodes, and shows 2022 R&D cell-level energy densities up to 500 Wh/kg with solid-state electrolytes, which can also make lithium-metal-anode batteries safe with twice traditional lithium-ion energy densities—even better in some early production models. (Fire risk in conventional lithium-ion batteries is mainly from their flammable organic liquid electrolyte.) Cuberg[54], now in Northvolt, has made stable 380 Wh/kg lithium-metal cells. BNEF expects 434 Wh/kg in 2030 cells, and over 500 for further-refined lithium-ion cells; the pack-level energy densities are 234 and 304 Wh/kg (Piccard's pack beat 234 in 2015). Encouragingly, BNEF reports that NASA's single-package sulfur-selenium stacks, saving ~30% of pack weight, already got 500 Wh/kg at a pack level[55].

Some other chemistries show promise too, such as the 400 Wh/kg sulfide cells SVolt is readying for production, and aviation-focused new types (especially for smaller drones) like Lyten, Sionic, Ecelix, and others surveyed by BNEF. BNEF's projections to 2030 do not reflect any break-

throughs in battery chemistry, though some are now in the lab. Some R&D battery types look capable[56] of practically approaching or achieving 1,000+ Wh/kg, even using only earth-abundant materials. Further system integrations, now being explored, could also build large-area batteries, or ultracapacitors, or both into the airplane's skin and structure. And Society of Automotive Engineers standardization and commercial innovation are meanwhile creating the charging equipment to recharge both electric planes and electric ground equipment.

Battery improvements then converge with more-efficient aeronautics (lighter weight, more lift, less drag) to produce whole-aircraft design solutions with rising capacity and range. For example, a conservative analysis found that 250 Wh/kg batteries in nominal conventional planes can carry 9 passengers for 140 km with reserve range; doubling battery performance to 500 Wh/kg could carry 90 passengers for 280 km; but reducing the plane's empty mass fraction *would nearly quadruple commuter planes' market coverage—15× for turboprops*[57]. Or Eviation Alice's 30% lightening from a DHC-6 Twin Otter lets it carry 33% more batteries[58]. *Any* combination of energy-denser batteries and more-efficient aircraft will do—they're fungible—but markets are signaling that we'll get both, especially the latter, delivering better results sooner.

Battery-electric airplanes: early, surprising, very rapidly evolving

Fig. 6 offers four electric-plane examples[59] with their target in-service dates as of the end of 2022. Some dates may slip, but many contestants have the skills and drive to succeed on time, and scores more are in the race. E-planes need *not* be small, short-range, and slow to develop.

Fig. 6. Four examples—out of at least scores of innovators—of rapidly advancing electric airplane designs: clockwise from upper left, Heart ES-30 (2028, 30 pax), Eviation Alice (2025–27, 9 pax), Wright Spirit (2026, 100 pax), and Embraer Energia Hybrid E9-HE (2030, 9 pax). Ranges and other details are discussed next. Images courtesy of respective developers' websites.

Here are fuller summaries:

- Heart Aerospace[60], a startup in vehicle-technology hub Göteborg, Sweden, is developing a rapidly evolving family of electric aircraft. Its initial offering was the 19-passenger, 216-nm[61], short-takeoff-and-landing, steep-approach-capable ES-19 with 75′ wingspan. Due in service in 2026[62], it was expected to be competitive with a 70-seat turboprop: the capital cost of its electric motor was said to be ~20× lower than a similar-size turboprop and ~100× lower than the cheapest turbofan, with maintenance cost >100× lower. In September 2022, strong airline demand led the company to drop the ES-19 and leapfrog[63] straight to the ES-30—a 30-passenger regional airliner with 100.9′ wingspan[64] and a nominal electric-only range of 108 nm (fast-recharging on 1 MW in 30–40 minutes), extended to 216 nm by the Sustainable Aviation-Fueled hybrid-electric drive, or 430 nm for the hybrid with 25 passengers. The ES-30 is planned as a proof-of-concept aircraft in 2024, with flight testing from 2026 and commercial service in 2028 after a total of 8 years for development and certification under a standard that simplifies US entry[65]. As batteries evolve, Heart expects in the mid-2030s to achieve 162 nm 30-passenger range with just batteries or 270 nm with a hybrid, and then by the late 2030s, 216 nm battery-electric or 324 nm hybrid (all ranges include reserves). The ES-30 would have zero emissions at airports and on routes up to 108 nm (200 km), or farther with better batteries. With current batteries, the hybrid's emissions would be less than half those of today's 50-seat turboprops, its cash operating cost per seat similar, and its cash operating cost per trip "significantly better." Operating costs for energy and maintenance are also expected to fall over time as those of fossil-fueled aircraft rise. Flying "over mountainous terrain, where the flight distance is significantly less than the road routes available," is noted as an early market[66]. Heart's partners and investors include United, Mesa, Air Canada, SAAB, the European Commission, and noted green investors including Break-through Energy Ventures. In mid-October 2022, Heart reported 230 orders, 100 options, and letters of intent for 99 more airplanes.
- Eviation's Alice electric aircraft, spawned in Israel and now developed in Arlington WA, had a bumpy start but after 2021 redesign[67] and executive changes now seems a credible entrant. This 9-passenger battery-electric regional plane is due for 2025–27 airline deliveries. Its fuselage produces some extra lift from a flattened underside and bulbous top—the same "lifting body" concept as the bulging upper nose of a 747 jumbo jet—to augment lift from its 63′ wingspan. Alice's lift/drag is estimated at an impressive 25[68]. It's expected to carry a 2,500-lb payload for 250 nm (day VFR range) at 260 knots airspeed with 18,400 lb maximum takeoff weight (it's 95% composite). Executive, commuter, and cargo configurations are proposed, with a roomy, wide cabin and zero carbon emissions. Now in flight-testing, it has booked 125 sales to two regional carriers (Cape Air, reportedly for ~$4 million each, and Global Crossing Airlines), 12 to DHL Express, 25 to Germany's Evia Aero (letter of intent), and up to 23 to Air New Zealand. By 7 December 2022, letters of intent were said to exceed 300[69]. Eviation expects normal commercial ticket prices in the commuter configuration.
- US startup Wright Electric aims to make all single-aisle flights below 800 miles zero-emissions by 2040, and notes that 45% of all aviation emissions are from single-aisle aircraft. It therefore focused on making the largest electric powertrains that can serve the emissions-dominating larger aircraft, then using powertrains as a springboard into its own aircraft. Rather than starting with a clean sheet, Wright Electric is first building on the proven and available 100-passenger BAe146 passenger jet (which operated in Aspen

during 1985–2006 and has an 86.4′ wingspan) by replacing its four jet engines with Wright's own megawatt-class electric powertrain[70]. The nominal one-hour flight radius (nominally 400[71]–800[72] nm including reserves) of this initial Wright Spirit, expected in service in 2026, could serve such US city pairs as NYC/BOS, NYC/DCA, SFO/LAX, or ATL/ORL. The firm's follow-on clean-sheet aircraft, Wright 1, targets 2030 for a ticket-price-competitive zero-emissions plane carrying 186 passengers for a reported 800 nm, with 10 × 2 MW motors comparable to the total engine power of an A320. Wright Electric's partners include easyJet, NASA, USDOE, USAF, US Army, and Honeywell.

- The main airframe makers are seldom announcing their own plans for new electric airplanes, with one important, if sketchily described, exception: Embraer's introductory 9-seat, 500-nm Energie Hybrid E9-HE is expected in service by 2030, the 19-seat and 200-nm E19-H2FC by 2035, and a 35–50-seat 500-nm E50-H2GT by 2040. These three models would respectively have 90–100% lower CO_2 emissions and 80% lower noise; 100% and 70%; and 100% and 60%.

Notice that none of these illustrative market entrants yet uses extreme lightweighting or ultra-laminar flow. None assumes any electric-storage miracles, though some may be emerging[73]. Many potentially important entrants, especially from Asia, have not yet revealed their plans. And our examples exclude short-range offerings attractive in some markets. For example, Italian airplane-maker TECNAM, with decades of experience and a RollsRoyce partnership, plans to deliver its P-Volt 9-seat battery-electric plane for short-range 2026 service[74] with Widerøe, Scandinavia's largest regional airline, and is developing the H3PS hybrid with EU funding[75].

Investors are paying close attention: BNEF estimates $441 million in capital raises by 23 electric-plane startups since 2017, excluding substantial sales and deposit revenues. As of 9 November 2022, BNEF counted[76] 330 orders or options for regional e-planes (up to 30 passengers), 409 for commuter e-planes (up to 19 seats), and 196 for e-planes up to 9 seats—a total of 835—plus 1,368 options in these categories. That doesn't include 187 orders for very light (1–2-seat) e-planes, nor roughly a thousand e-VTOLs, nor 732 deposit-paid orders of unspecified types from Bye Aerospace by January 2022 (as endnoted on p 11 above). Essentially all developers intended to come to market by 2030, some much earlier. Some fleets, notably in Scandinavia[77], combine strong use cases, governmental and public support, policies to decarbonize aviation by 2040–45, and a hence good prospect of leapfrogging and speeding other markets.

What are major airlines saying? United Airlines[78] "expects electric planes to hit the market in 2028," ordered 100 ES-30s to begin service in 2028, and invested in their maker, Heart Aerospace. "In a twist, United's plan is not to replace big jets [often flying between its hubs] but to focus the new planes on regional service" and on inducing customers to fly rather than drive for several-hour trips. The VP Corporate Service and head of United Ventures said, "We cannot continue doing and operating our business the way we do. It is is imperative that we change it and the way we're going to change it is through investing in technology." His expectations include strong synergies with EVs; half-hour electric-plane charging so planes can fly 10–11 hours a day to offer high asset utilization and more flexible schedules; new or restored service to more cities with greater frequency (allowing a round-trip on the same day); and lower cost for 30–50-seat electric aircraft than for larger traditional aircraft. In United's view, electric aviation is not a blip but a big piece of the future. A sustainable-aviation portfolio "177 companies deep"

has just been invigorated by the Inflation Reduction Act of 2022, with many "viable startups that you'll hear about United Airlines and United Ventures investing in in the coming months." United's confidence confirms many of the views expressed in this essay. Of course, many skeptical views are also still heard. Heart Aerospace's excellent Frequently Asked Questions section[79] addresses some of the errors most often encountered:

> **Is all-electric propulsion only viable for very small aircraft?** No, and this is a common misconception. The range of an electric aircraft is determined by the aerodynamics and the percentage of the aircraft weight that's made up of batteries. For today's jet aircraft, larger aircraft have better performance with regards to both aerodynamics and fuel-mass fraction, [and] there is no reason to believe that this wouldn't be the same for electric aircraft.
>
> There are, however, more practical considerations as to why we start with a 19-seater aircraft. The certification process is easier, the technology overlap is largely similar to that of electric cars and buses (charging, motor design, etc), and it's an overall less risky and expensive endeavour. However, we are planning for larger aircraft in the future.
>
> **Don't we need to wait several decades for the technology to mature?** This is one of the most common misconceptions about electric aircraft, and it is wrong in two ways. Firstly—the technology is already here (we have already built full-scale demonstrators of the propulsion system). However, there is still a lot of work to design, certify and manufacture these aircraft. That is why we need to start now. Technological process does not occur automatically—it is the result of large investments and dedicated engineering work.
>
> **Aren't batteries expensive? Will an electric aircraft be unaffordable?** Heart's ES-19 will have a similar acquisition price and offer direct operating costs (energy and maintenance) 50–70% lower than competing fossil fuel powered aircraft. In the full aircraft context, battery acquisition costs are less than 2% of the aircraft price. This is very different to road EV's where batteries comprise about 30% of the car cost. Battery cycle amortisation costs are less than 10% of the ES-19[']s direct operating cost.
>
> **What will the onboard experience be like?**
> The ES-19 is much quieter than any fossil-fuel aircraft, and the engine vibrations that can be felt on smaller aircraft are virtually eliminated. The aircraft is fully fly-by-wire, and actively compensates for turbulence, ensuring a smoother ride in all weather conditions. The all-metal fuselage is fully pressurised.

This assessment also doesn't include more than a dozen main electric Vertical Takeoff and Landing (eVTOL) makers like Joby (4 pax, 150 nm range), which got Toyota and Delta investments and just applied for Japanese certification in collaboration with the FAA, or Archer[80], whose eVTOL gained FAA airworthiness certification and completed its first successful hover flight in 2021. It's due to market in 2024, carrying four passengers 60 miles at up to 150 mph, and United ordered 100, plus 200 from Eve. In 2025, Lilium expects to certify its Jet (six pax, 135 nm, 175 mph). There are many more[81], like American-Airlines-invested Vertical (4 pax, >150 mi). Some are still in stealth mode. Some eVTOLs will soon gain Aspen-to-Front Range operability, adding some cross-Divide missions to local ones and thus helping to relieve pressure on ASE's scarce airspace and even on some kinds of road traffic, such as limos from Rifle and Vail Airports.

BNEF says some urban air mobility firms aim to come to market around 2025, are working with regulators to get type certificates, and have received thousands of conditional orders. Their price

ambition is to compete with Uber Black premium car service, though that may take pilotless versions. Then again, we are used to operatorless subways and high-rise elevators, and many customers have their own remote-controlled drones. Regardless of the development trajectory, eVTOLs and drones—including military versions—are an important part of the technical and commercial ecosystem and will accelerate electric-airplane commercialization.

Hydrogen-aircraft competitors

Nor have we yet discussed hydrogen-based aviation powertrains[82], which can use fuel cells to generate electricity or gas turbines to burn hydrogen. Liquid-hydrogen "cryoplanes" are widely, though not universally, considered attractive for transcontinental and transoceanic trips in or after the 2030s[83]. Perhaps the best-known developer of hydrogen propulsion for aviation, ZeroAvia, has published its commercial-service targets in Fig. 7. It has ordered 500 hydrogen engines, and is aided by such partners as the UK Government, British Airways, ~15 regional operators worldwide, Amazon, United, MHIRJ, de Havilland Canada, Alaska Air Group, Royal Schiphol Group, and others. Of course it has competitors with their own plans, but for our purposes here, ZeroAvia's example suffices.

Fig. 7. ZeroAvia's late-December 2022 timeline for commercial offerings of its hydrogen aviation powertrains. Airplanes to use them would normally be developed in parallel, with broadly similar target dates, consistent with the battery-electric targets described above and, together with hydrogen powertrains, summarized in Fig. 8. Importantly, ZeroAvia's strategy emphasizes retrofitting *packaged hydrogen powertrains (including fuel storage) into existing airframes, greatly shortening development and certification times except for the longest-range aircraft, which would require complete redesign to accommodate the bulkier liquid hydrogen.*

Many readers will be surprised to learn that the 2024 twofold range disadvantage of hydrogen airplanes is expected to disappear by 2026, and that hydrogen advocates consider them "a superior propulsion system overall." Most battery-electric developers disagree. Competition will tell. Technologies and system concepts on both sides, and implementation steps like airport pilot projects, are evolving very quickly[84].

The choice of energy carrier has major systems implications, including the option of superconducting motors cooled by the cryogenic liquid hydrogen—potentially combining with lightweight and highly efficient fuel cells to yield about twice the efficiency of turbofan engines

burning the same hydrogen[85]. ZeroAvia plans to use compressed gaseous hydrogen in composite cylindrical tanks (well proven since the 1990s) until ~2028–29, then expects to switch to liquid hydrogen, perhaps using new very-thin-walled composite tanks holding ~69% hydrogen by total mass[86]—6–10× the best mass fraction available a few decades ago.

As with cars and trucks[87], fierce rivalry is likely between battery-electric and hydrogen visions (and others) as both gradually find their best use cases. For our purposes here, it doesn't matter who wins in which applications. Competition only heightens the likelihood of and incentive for success: it spurs developers, diversifies risks, fits more opportunities, and fits airports like Aspen's equally well. Indeed, Aspen could join the electric and hydrogen pilot projects now emerging at airports from Edmonton to Scotland. Hydrogen would probably not be trucked into airports as a superchilled liquid, but *made onsite* from solar electricity that could also recharge battery-electric planes and ground equipment. The solar capacity would be equally useful for recharging both kinds of batteries, powering the Airport, making hydrogen, and contributing to upper-Valley grid resilience—of great interest to Holy Cross Energy.

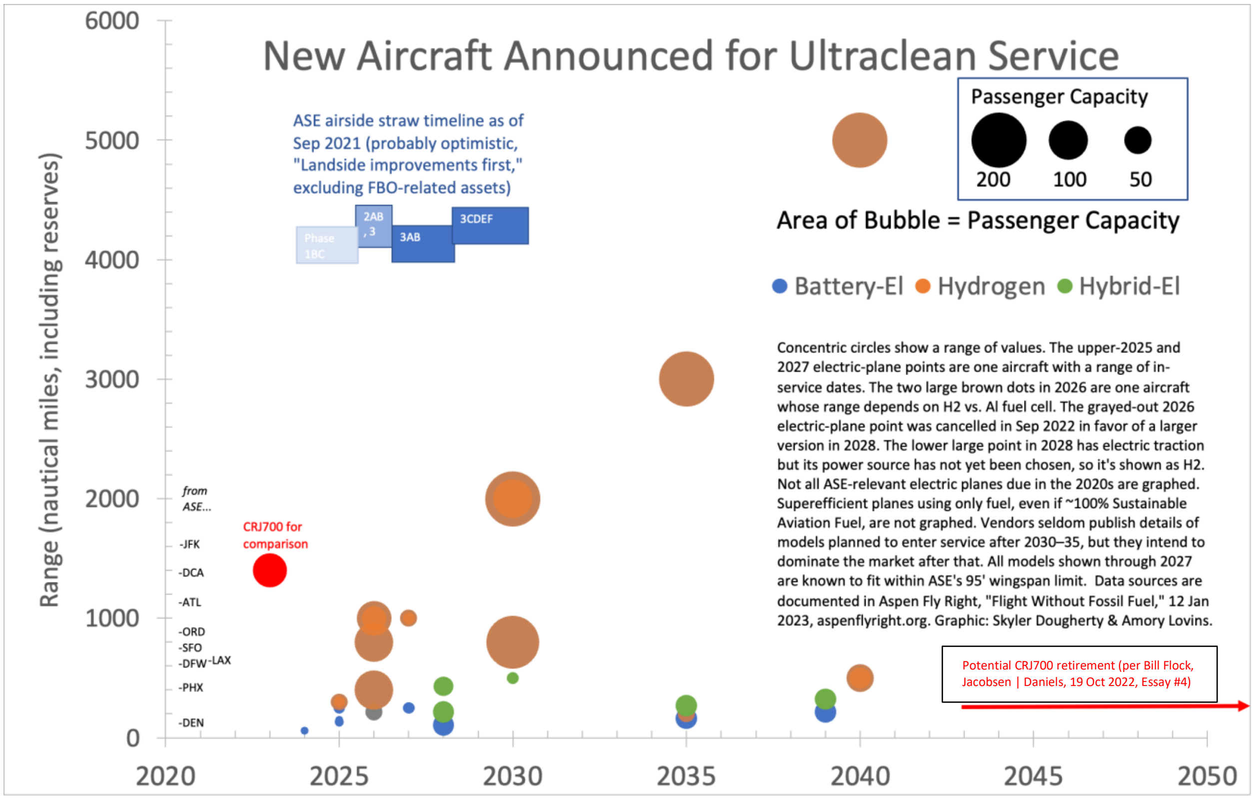
Air-portable power is also not limited to batteries or hydrogen: Wright Electric[88], among others, is particularly interested in aluminum-air fuel cells, which it reckons can yield up to ~1.6 kWh/kg (*vs.* up to 2.6 kWh/kg for hydrogen fuel cells with greater difficulty). Cartridges of oxidized aluminum would be returned to smelters, usually hydropowered, to be reduced back to metal. And of course fueled hybrids—with the option of using Sustainable Aviation Fuel—can initially supplement and complement batteries, then fade from the market as batteries improve, just as occurred in cars.

How soon can aircraft get off fossil fuels?

Most importantly, these serious market entrants, using batteries or hydrogen, are not 10–15–20+ years off, as ASE Vision assumed, but mostly just *2–5* years for missions similar to today's, or about 7 years for planes with even more capacity and range. Thus it's now reasonable *to expect electric airplanes to land in Aspen before there's even an FAA-approved Airport Layout Plan, and to achieve requisite capacity and range before the proposed new airside could be built.* Fig. 8 compares the examples just presented with the Airport's latest straw development timeline, which if anything looks overoptimistic. Serious delay seems less likely for all the new aircraft shown than for the County's timeline to admit bigger planes by 2030.

Fig. 8. Timeline of expected in-service dates and passenger (pax) capacities for some very-low-or-zero-emissions aircraft using electric or hybrid propulsion, as of the end of 2022. Three 2024–25 electric Vertical Takeoff and Landing examples are shown, but not the follow-on eVTOL swarm. The superefficient, 3500-nm, all-SAF-fuelable diesel Celera 500L and its doubled-size 1000L variant are not graphed. They and all the electric entrants through 2029 except the Heart Aerospace ES-30—that is, three of the four ultraclean aircraft announced for the 2020s—meet Aspen's current wingspan limit. The 2030+ entrants' wingspans haven't yet been announced, and the non-Otto ZeroAvia airframes' wingspans haven't yet been determined. The timing targets for ZeroAvia's hydrogen systems are for the powertrains, not the aircraft that will adopt them (except the announced Otto Aviation 750L), but those new models are expected to be planned and certified to converge as closely as possible with powertrain certification. Not

all Aspen-relevant 2020s options are graphed. The blue blocks near the upper left show a rather optimistic timeline for proposed ASE airside revisions during 2023–2030 to accept bigger planes. By then, at least five kinds of planes far cleaner and quieter than the BOCC's long-range goals should be in commercial service with capacities and ranges comparable or superior to the current CRJ700 fleet (in red at the far left)—which the County's top aviation technical consultant also expects ~~to~~could remain in service to nominally ~2042–52[89]*, as shown by the red arrow at the lower right.*



We won't dwell here on turbine- or engine-hybrid-electric designs, which may well have an important transitional role much as they did for cars. But as with cars, that role may prove briefer than hybrids' expert practitioners now expect (think Toyota). Nor will we prognosticate on hydrogen *vs.* batteries *vs.* other options in short- and midhaul markets. Markets will decide that. But the automotive history, where superefficiency is now revealing once-unthinkable *solar*-powered cars, suggests that the same inexorable trends are at work in aviation. Actual timing and details may differ, but there's little doubt about the shared destination. It is not the one the County now apparently intends—bigger planes with longer wings, and slow, incremental aviation evolution over decades. It's quite the opposite. Now is the time for vigilance and agility.

The timeline in Fig. 8 confirms that ASE Vision's and the County's vision for airside development has already been overtaken by aviation innovation. Aviation innovation is likely to surpass by threefold or more the BOCC's 2020 targets for reducing carbon, other air pollution, and noise by 30%, before the proposed new airside could be built, and without having to build it.

Unexpected driving forces

Fierce ambition and competitive ardor far beyond historical norms in the traditionally slow aviation sector are already driving remarkably brisk progress, often in small, agile firms with nontraditional culture and speed. But as climate, health, security, and economic concerns converge, and civil society's demands become more insistent, new public policies may emerge to reinforce the currents already swirling around aviation businesses. Let's mention just two.

First, under an adopted EPA rule[90] and implementing an obligation under the International Civil Aviation Organization's adopted standards[91], the Federal Aviation Administration's forthcoming Part 38 rule will soon add a new fuel efficiency metric and standard to reduce US civil aviation's CO_2 emissions[92]. It applies to new subsonic jets and large turboprop and propeller aircraft not yet certified and to new airplanes or modifications from 1 January 2028[93], except specialized types like firefighting, crop-dusting, and amphibious. It combines range with geometric factors to yield a universal Fuel Efficiency Metric (FEM) that, to oversimplify a bit, is analogous to miles per gallon per square foot of pressurized space—analogous to US footprint-based fuel-intensity-per-unit-size efficiency standards for road vehicles.

The FEM value must initially improve by enough (typically on the order of 15%) that in practice, compliance will usually require integrated attention to aerodynamics, mass, and propulsion. If history and climate logic are any guide, this new standard may ratchet up in the future. While it doesn't apply to in-service aircraft no longer produced or still being produced, it is triggered by modifications, such as new engines. Like past ratcheting noise rules, it can therefore be expected to cause some inefficient old planes to sunset in the coming years as they come due for routine modifications, thus accelerating their replacement. The new standard does not require immediate or radical changes, but it will exert a steady and probably increasing evolutionary pressure on the industry and help speed its progress.

Second, in 2019 Amory Lovins keynoted the global aviation industry's Air Transport Action Group (ATAG) Montréal conference, then addressed ICAO, both sponsored by Boeing and very warmly received by Airbus too and by the major suppliers. He offered an implementation concept that many of them loved. In today's circumstances there are some emerging signs that it may take off quickly and help bring to fruition many of the technical ambitions described above. The concept was simple and powerful:

> For a decade, we've had the technology to create 3–5×-more-efficient airplanes if someone would make them and someone would buy them. Why take a century to do that incrementally when we can leapfrog straight to it? Major airplane buyers, even if they have the capital, are understandably risk-averse. Airframe makers don't want to risk huge development investments for a radically better product that might not sell. So incrementalism continues as we squander fuel, money, carbon budget, and precious time. The climate crisis won't wait. Business-as-usual won't work. Aviation's license to operate will erode. Our shareholders, voters, and children will judge us negligent.
>
> So what if a powerful consortium of major customers—airlines, lessors, delivery and air logistics firms, the Pentagon—relieved the airframe makers' market risk so they could fully focus their skill and ambition? The buyers could collectively solicit a superefficient airplane by publishing very demanding specifications—very clean and at least quadrupled-efficiency—and collectively commit to buy *x* copies a year for *y* years at price *z* from whoever first brings it to market, with a

> consolation prize for the runner-up. This elicits and rewards innovation for the airplanes they'll buy anyway. Unbundling buying airplanes from buying innovation changes the suppliers' culture and brings out the best talent of their best innovators. This yields a very different product slate, reducing risk to both parties but most of all to airplane buyers.
>
> This "golden carrot" method is sometimes called Advance Market Offerings or Advance Market Commitments. It has worked well since 1990 for >20 diverse solicitations in countries from Sweden to France and America to India. It's time we seriously considered it for airplanes. That could decouple flying from climate change. Unlike carbon offsets, it could also slash fuel costs and the risks of fuel-price volatility. It could greatly increase energy security and national security. And it could unleash a huge burst of innovation that could transform aviation forever.

One of the industry's most venerable pioneers, asked about this concept in 2015, immediately said to sign him up—he wanted to be the first. Industry interest remains strong. Discussions continue. We hope 2023 will be the year this concept finally takes flight. And meanwhile, other major industry shifts are at work too.

Shifts in airlines' route architectures and business models

In parallel with the revolution in aircraft technology, but often unperceived, is an emergent shift in how airlines organize their routes and move their passengers. The hub-and-spoke architecture designed by many airlines can enhance their profits from monopolizing slots and gates at "fortress hubs" is efficient for airlines but not for customers. United Airlines' then-President (now CEO) Scott Kirby said in 2018[94], "A hub-and-spoke airline is really a manufacturing company, and it is about manufacturing connections. The more connections you can drive at a hub, the higher profits you drive at that hub, the more customers flow through that hub, and it's exponential"—especially if it links more passengers to lucrative international routes. True, but what it exponentiates for customers is inconvenience. A customer wanting to go from A to B must often fly first to C, perhaps in the wrong direction, then become self-sorting cargo at C to rush anxiously to a plane back to B, and perhaps suffer misconnection or lost luggage. Being able to fly straight from A to B as we once did would reduce delays, tensions, mishaps, emissions, perhaps illness, and now ticket prices—because emerging ultraclean aircraft are often well sized for more frequent service to more destinations, eliminate one or more segments, *and deliver lower capital and operating costs to support* this point-to-point route architecture at lower total cost per ticket.

Both the tension and the complementarity between these two coexistent route architectures[95] (most airlines mix both) is complex and evolving. Southwest Airlines's point-to-point emphasis (plus some "soft hubs") built profits and the largest airline in 23 of the largest 25 US travel markets[96]. But then it melted down in a vast winter storm at the end of 2022, attracting wide criticism that the lack of hubs prevented ready substitution of concentrated aircraft and crews. Of course, most other airlines had similar episodes in the past, regardless of their route architectures. Southwest's basic problem in late 2022 was antiquated[97] software and procedures that would have caused any airline's operations to break under the storm's stress. It will take at least months to understand how the point-to-point model would have fared with modern software to locate and re-marshall resources. But in any case, such rare events don't determine the best route model or mix of models. They also ignore the complementary weakness that common storms disrupting smaller regions, like a hub's, can shut down a vast network for days, stranding passengers with few alternatives—hardly a resilient design, and long considered an inherent hub weakness.

As recently as 2020, United, currently the #3 US carrier, added "nearly two dozen new domestic routes that bypass [its]…hub airports….[W]ith all the historical models essentially useless [during the pandemic,]…the company is ready to try something different and see if it can generate a bit of revenue." This shift reflected United's "data driven approach to add capacity where customers are telling us they want to go." So if you live in the Midwest or Northeast, and you want a January flight to Florida, do you really want to have to go through Chicago or New York or Dulles rather than taking a nonstop to Florida? That may determine whether you fly United or such point-to-point competitors as Southwest, Frontier, Spirit, and JetBlue. Your choice will depend too on relative price, and on whether you are more time- or price-conscious[98].

Airlines continue to explore and debate route architectures' performance, virtues[99], faults[100], and complementarities, especially during their still-unfolding recovery from the pandemic that devastated the industry and required a temporary retreat to hubs to try to sustain mainline revenues[101]. It was also obvious that serving many flights clustered into brief pulses at the hub, to coordinate passenger transfers without long layovers, incurred huge peak-capacity costs for all kinds of airport infrastructure and staff—though the pandemic slump offered temporary relief to many overstretched airports[102]. Other persistent issues[103] include emissions from circuitous connecting routes and increased passenger time and stress. But now, as has happened several times historically, the biggest factor advantaging point-to-point is evolving aircraft technology. Small and medium planes are becoming able to profitably serve smaller cities and less-traveled routes rather than having to gather and concentrate more passengers onto fewer, bigger planes between hubs. This better fits customer preferences, environmental concerns, hub decongestion needs (important to customer experience), and stress relief for all parties. That's why the former CEO of Spirit Airlines wrote in 2020[104] that "newer airplanes, lighter airplanes, more efficient engines, more fuel-efficient airplanes are going to drive more and more point-to-point service."

Regional jets first opened much of this load-spreading, hub-relieving, complexity-reducing, more-precise-crew-scheduling potential, but they often had higher operating costs per seat-mile. Planes roughly the size of the CRJ700 increased their advantage over smaller first-generation regional planes[105]. But now in this decade, new ultraclean versions promise markedly *lower* operating costs (plus lower capital costs) than even modern big planes. This should further disrupt hub-and-spoke routing and support more frequent, affordable, and convenient service to and from smaller cities. It can also more gracefully accommodate seasonal markets by making assets more flexible and less critically value-concentrated[106]. Long-range regional and medium aircraft, whether superefficient like the Celera family in this decade or hydrogen-fueled in the 2030s, will thereby add more value in serving far more city pairs directly under future uncertainties, while battery-electric and hybrid planes move from short to medium ranges and capacities.

A steadier flow of moderately sized aircraft would also help relieve stress on airport infrastructure—and could directly connect destinations like Aspen to more cities, both by traditional airlines and by private services. Later essays in this series will consider some ways to reduce stress on Aspen's airspace, and thus help relieve constraints that supposedly now prevent accommodating more commercial flights.

[1] J. Bennett, M. Haynes, J. Francis, cover letter "Vision Committee Final Report to BOCC," 16 Apr 2020, https://aspenairport.wpenginepowered.com/wp-content/uploads/2020/09/Work-Session-10-Agenda-and-Board-Packet.pdf.

[2] As mandated by By-Law II.2(6), implying a planning horizon of 2050.

[3] The Technical Working Group charged with assessing new technologies referred to emergent aircraft designs only in two sentences on p 4 of its 20 Dec 2019 report: "**Aircraft efficiency:** historically, commercial aircraft have improved efficiency (fuel burn per passenger-km) at a rate of ~2.5% per year. Electric propulsion, hydrogen fuels, new materials, and other technical advances are sure to foster continued progress in reducing aviation emissions[.]" No actual analysis of future aircraft was conducted. The only relevant input to the TWG appears to have been a sketchy qualitative slide deck on RollsRoyce's electrification research (https://aspenairport.wpenginepowered.com/wp-content/uploads/2020/09/Meeting-2-Rolls-Royce-ElectRRification-Presentation-—-Richard-Goodhead-PDF.pdf). ASE Vision did also convene, and ~200 citizens attended, a 13 Nov 2019 public forum at Doerr-Hosier, addressed by three outside experts including Amory Lovins ("The Future of Aviation in a Carbon Constrained World," 13 Nov 2019, https://youtu.be/IWMvV_d2pEQ). However, there is no sign of its having influenced any ASE Vision process or work product, except a mention of the obsolete and misinterpreted assumption that efficient planes mean longer wingspans (Ref. 4).

[4] In two short paragraphs on p 11. The first paragraph quotes a wider-wingspan remark from Amory Lovins's 13 Nov 2019 talk (Ref. 3), without noting that it was both irrelevant due to folding wings (Ref. 25, and used in the 777X aircraft coming to market in late 2024) and superseded by later developments, as notified three times to the BOCC (Ref. 6, particularly on pp 2–3 of the 22 Nov 2020 memo). The second paragraph says Aspen-serviceable electric planes "are likely still 10–15 years away and are likely initially to be 10 to 15 passengers in size. Fully electric aircraft carrying 75 passengers to the destinations currently served by ASE are farther in the future." That timeline is now seriously outdated. This essay describes radically accelerated prospects. For example, as of summer 2022, an ASE-sized 19-seat electric plane was due in 2026, and at end 2022, a 19-seat ASE-sized hydrogen plane is due in 2027, with an ASE-sized 100-seater and 40–80-seaters of unknown wingspan due ~2026.

[5] Staff's consultants began with 15 such planes in the TWG meeting #1 ("Available Aircraft," https://aspenairport.wpenginepowered.com/wp-content/uploads/2020/09/Meeting-1-Available-Aircraft-PDF.pdf), expanded to 20 in meeting #2 (https://aspenairport.wpenginepowered.com/wp-content/uploads/2020/09/Meeting-2-Technical-Working-Group-Presentation-—-September-18th-PDF.pdf), whose audio recording has apparently been taken down. Lean Engineering's 25 Aug 2018 airspace report presented in meeting #1 (https://aspenairport.wpenginepowered.com/wp-content/uploads/2020/09/Meeting-1-Airspace-Impact-and-Aircraft-Feasibility-Assessment-Update-August-25-2018-PDF.pdf), p 67, ignored the Dash 8-Q400 due to "the general decline in fleet totals" in "the North American market" (presumably they meant the US market, as >175 remain in Canadian service today), and excluded the CRJ900 as "previously determined to not be capable of operating at ASE" (a misdescription, as summarized in essay #4, https://aspenflyright.org/wp-content/uploads/2023/01/ABL-essay_4.-Fleet_01Jan2023.pdf). The only aircraft that Lean Engineering found feasible for scheduled operations at the current Aspen Airport (p 2) were the CRJ700, the EMB-175LR with Enhanced Winglets (subject to limits set by stage length and climatic conditions), and *if* wingspans over 95′ were allowed, the A319-115, CS100-A210, and conceivably the 737-8MAX.

[6] In a 30/31 August 2020 memo midway through the public-comments section for the BOCC's 8 Sep 2020 packet at https://pitkincoco.civicclerk.com/Web/UserControls/DocPreview.aspx?p-1&aoid=2089, a 22 October 2020 public forum "Timing Our Choices for the Safer and Better Airport: Proceed Now, or Pause and Learn?," with Tom Keough and Dick Arnold, posted 28 Oct 2020, streamable at https://www.youtube.com/watch?v=F-MVGgaVk-k (at p. 14 of its opening remarks, which are at https://civicclerk.blob.core.windows.net/stream/PITKINCOCO/a11424564f.pdf?sv=2015-12-11&sr=b&sig=jYcXIov2KMyC6o1d2oJ27R8cRrj3dYmmoJoEdIanrKg%3D&st=2022-12-08T21%3A14%3A29Z&se=2023-12-08T21%3A19%3A29Z&sp=r&rscc=no-cache&rsct=application%2Fpdf, pp. 105–120), and a 22 November 2020 technical memo (tenth hit on "Lovins" search at https://pitkincounty.com/DocumentCenter/View/26724/ASE-Public-Comments-Comb-121620-Redacted). The third of these noted that "missing or erroneous information given to the Technical Working Group…could not be detected and corrected within the Vision process because independent expert contributions were not allowed: as members have publicly confirmed, outside experts were permitted only if chosen, engaged, and instructed by County staff."

[7] Bill Tomcich, statement to BOCC public hearing, 10 Nov 2022, at 1:00:54, https://www.pitkincounty.com/374/County-Webcasts. He also very sensibly added (1:05:27), "[L]et's not lock ourselves into commitments based on what we know today. Even though we know a lot, we know that more change is still coming."

[8] AAB 20 Oct 2022 meeting, https://drive.google.com/file/d/1l2__1SScBHeXRn4J87bKWSM0F5AAPHG7/view, at 1:43:28.

[9] The recording is at https://drive.google.com/file/d/1I8-LR-uA6jvN0yRs-VERgB_m9FMGfuzj/view?usp=sharing. Introductions start at 1:48 and Lovins's presentation at 4:45. A PDF of Lovins's technical brief including Presenter Notes, "The clean-aviation revolution and Aspen Airport's evolution," is at https://aspenflyright.org/background/.

[10] Battery-electric cars' sales rose from 120,000 in 2010 (per IEA) to more than 10 million in 2022. In the first half of 2022, plug-in cars (73% battery-electric, 27% plug-in hybrids) had 21% market share in China (whose exports were 29% electric), Europe 18%, and the US 6.5%: "Global EV Sales for 2022 H1," https://www.ev-volumes.com, updated through October by https://insideevs.com/news/625651/global-plugin-electric-car-sales-october2022/, 8 Dec 2022.

[11] Like Boeing, we often call them "airplanes," while many pilots call them "aircraft." Those terms mean the same. We refer here only to heavier-than-air, fixed- (not rotary-) wing aircraft. An excellent introduction to basic aeronautical principles is at https://www.faa.gov/regulations_policies/handbooks_manuals/aviation/phak/media/07_phak_ch5.pdf.

[12] However, often ignored, the initial gains were just making up lost ground, because "the last piston-powered aircraft were as fuel-efficient as the [2005]…average jet." P.M. Peeters, J. Middel, & A. Hoolhorst, "Fuel efficiency of commercial aircraft: An overview of historical and future trends," NLR-CR-2005-669, National Aerospace Laboratory NLR (Netherlands), 2005, https://www.transportenvironment.org/wp-content/uploads/2021/05/2005-12_nlr_aviation_fuel_efficiency.pdf.

[13] Just by extrapolating decades of steady historical efficiency gains, cross-checking with a bottom-up original analysis, and validating against MIT, Airbus, and Technical University of Delft studies. A. Lovins *et al.*, *Winning the Oil Endgame*, RMI, 2004, https://rmi.org/insight/winning-the-oil-endgame/, especially pp 79–83.The 2025 match was with the reported efficiency of Boeing's 2025 NMA ("797"), which ultimately was not produced.

[14] For example, active boundary-layer control, though technically challenging, appears able to halve cruise drag, consistent with test results in the Celera 500L that achieves extensively laminar flow passively: N. Beck *et al.*, "Drag reduction by laminar flow control," *Energies* **11**(1):252, 10.3390/en11010252. Blended wings, increasingly common in military aircraft, could often save >40% of the fuel in civilian ones if we changed manufacturing and boarding/deplaning methods.

[15] D. Van Zante & F. Collier, "The Environmentally Responsible Aviation (ERA) Project—A technology development project," NASA, Sep 2016, pp 27 & 33. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwjGlqb9xJ38AhWbBDQIHd_0A0MQFnoECAIQAQ&url=https%3A%2F%2Fntrs.nasa.gov%2Fapi%2Fcitations%2F20170004101%2Fdownloads%2F20170004101.pdf%3Fattachment=true&usg=AOvVaw1iTk5GtvRgvMGbScYY2F_2.

[16] Ref. 23's smaller savings illustrated on p 16 compare with "likely the latest aircraft models available today."

[17] A lay introduction to these airplanes' advanced composites use is at https://simpleflying.com/787-a350-composite/. The B787 is 50% composites by mass, 80% by volume, cutting its total weight by 20%. The A350 is 53% composites by mass, halving its structural maintenance tasks.

[18] N B Cramer *et al*., *Smart Mater. Struct*. **28** 055006, 1 Apr 2019, https://doi.org/10.1088/1361-665X/ab0ea2, https://mit.edu/archive/spotlight/shape-changing-plane-wing/, http://cba.mit.edu/docs/papers/19.03.MADCAT.pdf.

[19] For example, the FlexSys (flxsys.com) morphing surface can make seamless, jointless, hinge-free wings whose edges can morph swiftly and deeply. First commercial use is expected in 2023. It's also scheduled for Aston-Martin's MY2024 Valhalla car and probably a competitor's. Pending flight tests, USAF expects to deploy it on several hundred planes to save ~2–11% of fuel.

[20] I. Wilson, "Shark-Skin Technology Lets Planes Planes Fly Fast With Less Fuel," 2 Sep 2022, https://www.bnef.com/insights/29673 (subscriber product).

[21] J. Harman, *The Shark's Paintbrush*, White Cloud Press (Ashland OR), 2013.

[22] According to the retired dean of this field, Prof. Del Tesar (personal communications to A. Lovins, 2006–2019). BNEF [p 6] cites a Collins Aerospace estimate that ~8% of aircraft fuel runs hydraulics and pneumatics, reducible to 2–3% by electrifying just half of them (https://simpleflying.com/more-electric-aircraft/)…but Tesar contends, from more than a half-century of field experience, that essentially all are better electrified.

[23] T. Kawahara, "Aircraft Technology Outlook: Fuel Efficiency," 16 May 2022, pp 10–13, Bloomberg New Energy Finance (BNEF), https://www.bnef.com/insights/28953/view (subscriber product).

[24] Personal communication to A. Lovins, 26 May 2019.

[25] As in Boeing's 777X design, offered for airports that wanted longer-winged planes like the 777 without incurring major redesign costs. A. Lovins at 1:10:10–11:02, "The Future of Aviation in a Carbon Constrained World," 13 Nov 2019, https://youtu.be/IWMvV_d2pEQ. The comment about hinges was overlooked as advocates misrepresented his longer-wings remark as an argument for airside redesign. Of course, longer wings are far from the only efficiency solution for regional-sized planes, where major aerodynamic and structural gains remain untapped.

[26] Ottoaviation.com. The following description was updated 4 Jan 2023, more recently than the website material.

[27] The German-made RED A03 engine—a 500-hp 5.9-L V-12—could be considered redundant because its two halves run independently. Without power, the plane can glide down ~120 miles from 30,000′.

[28] The original design was rated at 4,500 nm. Range is also very sensitive to payload. One nautical mile (traditional for aviation distances) is 1.151 statute miles or 1.852 km. One nm per hour is a speed of one knot.

[29] Using the 600-kW ZA600 powertrain that's about to fly in a 19-seat Dornier 228 testbed, targeting 2024 powertrain certification and commercial service: https://www.zeroavia.com/dornier-228-in-hollister.

[30] E.g. by replacing the diesel cooling blisters with an internal heat exchanger, eliminating the large diesel air intakes (which look like small jet engines but aren't), and adding additional turbocompressors to raise the operating ceiling from 30,000 to 50,000′ or 65,000′.

[31] A common rule of thumb is that exceeding 19 seats (going from Part 23 to Part 25 certification) raises US type certification costs by ~8×.

[32] Described by Airbus in 2017 at https://www.aerospace-technology.com/projects/airbus-breakthrough-laminar-aircraft-demonstrator-europe-blade/, and last reported a few years ago, e.g. https://simpleflying.com/airbus-blade-test-a340/. We understand Airbus has not lost interest.

[33] Typical announcements are at https://www.zeroavia.com/otto-aviation, 15 Jun 2022, and https://www.futureflight.aero/news-article/2022-06-15/otto-reveals-plan-hydrogen-powered-19-seat-celera-aircraft.

[34] Even in this impressively refined prototype, inspection disclosed further opportunities to substitute advanced composites for metal; the propellers may be improvable by Jay Harman-style Fibonacci shaping; and most straightforwardly, digital valves could replace the diesel engine's camshaft-driven valves. Based on Sturman Industries' proven camless truck diesels, this could probably yield ≥60% efficiency, >50% higher torque, >30% smaller size and mass, >10% lower cost, reduced maintenance, and extremely low emissions (essentially eliminating NO_x) while burning any fuel on the fly.

[35] https://www.icas.org/ICAS_ARCHIVE/ICAS2012/PAPERS/521.PDF.

[36] A. Lovins & D. Cramer, "Hypercars®, hydrogen, and the automotive transition," *Intl. J. Veh. Design* **35**(1/2):50–85, 2004, https://www.rmi.org/insight/hypercars-hydrogen-and-the-automotive-transition/.

[37] That is, 420 kg curb weight as a plug-in hybrid, but 400 kg (according to its lead designer) as a plain Prius-style hybrid without the plug-in option. The smaller 4-seat *Edison2* that won the 2010 Automotive X PRIZE weighed 377 kg and was later trimmed to 322 kg.

[38] A. Lovins, "Reframing Automotive Efficiency," *SAE Int. J. Sust. Trans., Energy, Env., & Policy* **1**(1):59–84 (2020), 5 May, Society of Automotive Engineers International, https://doi.org/10.4271/13-01-01-0004.

[39] A striking digital video of assembly sequence for the production-intent Delta version was published 3 Jan 2023 at https://www.youtube.com/watch?v=PQuLuHzR52M.

[40] Aptera has measured a drag coefficient C_d of 0.13, far below Lightyear's impressive 0.175, and approaching the ~0.045–0.07 of the world's best one-seat solar racecars with a nearly prone driver. It also benefits from being a 2-seater with greatly reduced frontal area.

[41] K. Field, "Tesla's Octovalve Enabled A Staggering 10% Increase In Range For The Model Y," 3 Aug 2020, https://cleantechnica.com/2020/08/03/teslas-octovalve-enabled-a-staggering-10-increase-in-range-for-the-model-y/.

[42] Perhaps the last professional statement that "The low energy density of batteries means that purely electric flight is not practically possible" was in 2016, and from an unexpected source: P. Peeters *et al.*, "Are technology myths stalling aviation climate policy?," *Transp. Res. Part D: Transport and Environment* **44**:30–42 (2016), https://doi.org/10.1016/j.trd.2016.02.004. Peeters had somewhat moderated this view by 2021 ("Zero CO2 emissions aviation," with C. Lyle & H. Goodwin), Breda U. of Applied Sciences, https://www.cstt.nl/userdata/documents/decarbonisingaviationstrategypub_buas_format_03_fin.pdf).

[43] A. Lovins, "Six solutions to battery mineral problems," RMI, 28 Jan 2022 and https://cleantechnica.com/2022/01/28/6-solutions-to-battery-mineral-challenges/.

[44] Ref. 38.

[45] T. Kawahara, "Electric Aircraft Propulsion: Technology and Industry," 2 Dec 2022, BNEF, https://www.bnef.com/insights/30267 (subscriber product), at p 3 and Appendix A.
[46] https://www.airbus.com/en/newsroom/press-releases/2022-11-airbus-and-renault-group-to-advance-research-on-electrification; Ref. 45, p 16, reports that these collaborators aim to double battery energy density by 2030.
[47] https://en.wikipedia.org/wiki/AeroVironment_Helios_Prototype.
[48] Ref. 45. Helios had a 247′ wingspan, longer than a 747's.
[49] BNEF (Ref. 45) at p 12 says this total excludes 732 deposit-paid orders announced by Bye Aerospace by Jan 2022, including ~300 small models, because the types are not specified. Bye, in Arapahoe County, Colorado, makes a two-seat electric trainer to cut pilot-training operational costs ~80% from the 11,000 old fueled 2-seaters.
[50] *Id.*. Fig. 17, and unpublished 2022 industry analysis by Amory Lovins.
[51] For example, Oxford YASA Motors at ~15 kW/kg spun out Evolito for aerospace applications, then in 2021 sold the rest, chiefly for automotive use, to Mercedes-Benz.
[52] DENSO/Honeywell press release, 24 May 2022, https://www.denso.com/global/en/news/newsroom/2022/20220524-g01/. A report the previous day hints at possibly even better results: https://aviationweek.com/shownews/ebace/lilium-honeywell-denso-announce-electric-motor-partnership.
[53] BNEF, "Battery Startups 2022: Key Trends," 10 May 2022, https://www.bnef.com/insights/28905, and "Company Profiles: 2022 Battery Startups," 18 May 2022, https://www.bnef.com/insights/28973 (subscriber products).
[54] At cuberg.net.
[55] Ref. 45, p 16, and https://www.nasa.gov/aeroresearch/nasa-solid-state-battery-research-exceeds-initial-goals-draws-interest, 7 Oct 2022.
[56] E.g. W. Cao, J. Zhang, & H. Li, "Batteries with high theoretical energy densities," *Energy Storage Materials* **26**:46–55 (Apr 2020), https://doi.org/10.1016/j.ensm.2019.12.024.
[57] J. Mukhopadhaya & B. Graver, "Performance Analysis of Regional Electric Aircraft," July 2022, https://theicct.org/publication/global-aviation-performance-analysis-regional-electric-aircraft-jul22/. See also https://theicct.org/publication/global-aviation-performance-analysis-regional-electric-aircraft-jul22/.
[58] Ref. 45, p 17.
[59]They're not the only examples of "clean-sheet" redesign of superefficient planes, such as two hybrid-electric designs: US startup Ampaire (newly partnered with Air France Industries KLM Engineering & Maintenance—see 19 Oct 2022 press release at https://www.prnewswire.com/news-releases/ampaire-and-air-france-industries-klm-engineering--maintenance-lay-the-foundations-to-advance-electric-aviation-301649813.html), whose 2-seat demonstrator recently flew 1,135 miles and whose ambitions include a clean-sheet 19-seater—and UK startup Faradair's hybrid-electric 1BEHA M1H 9-seater, convertible to a 5-ton cargo configuration in 15 minutes (https://www.faradair.com), and again with just a 57′ wingspan and exceptionally low noise.
[60] This paragraph is informed by heartaerospace.com and by the 14 Oct 2022 orders at https://heartaerospace.com/sevenair-loi/.
[61] N. Sampson, "Swedish startup reveals electric powertrain for ES-19 regional airliner," 24 Sep 2020, https://www.aerospacetestinginternational.com/news/electric-hybrid/swedish-startup-reveals-electric-powertrain-for-es-19-regional-airliner.html.
[62] "Our major milestones towards certification are to complete a Preliminary Design Review (PDR) in Q3 2022, a Critical Design Review (CDR) in Q3 2023, a first flight in Q4 2024, and a Type Certificate in Q3 2026. Entry into service would follow in Q4 2026." Certification is planned for CS-23 at its highest stage, Level 4. See https://heartaerospace.com/faq/ and https://www.futureflight.aero/news-article/2022-06-21/heart-switches-cs-25-certification-plan-es-19-electric-regional-airliner.
[63] T. Harrington, "Heart Aerospace switches its 19-seat electric aircraft to a 30-seat version with reserve-hybrid power," 22 Sep 2022, https://www.greenairnews.com/?p=3435.
[64] D. Perry, "Heart details dimensions of ES-30 as Swedish start-up pushes ahead with 30-seater," , 16 Sep 2022, https://www.flightglobal.com/airframers/heart-details-dimensions-of-es-30-as-swedish-start-up-pushes-ahead-with-30-seater/150231.article.
[65] The change from the EU's EASA CS-23 to CS-25 standard was requested by the United and Air Canada partners and announced in June 2022: https://www.futureflight.aero/aircraft-program/heart-electric-airliner/.
[66] https://heartaerospace.com/faq/.
[67] B. Corliss, "Eviation announces firm configuration for battery-powered 9-seater," 1 July 2021, *Leeham News and Analysis*, https://leehamnews.com/2021/07/01/eviation-announces-firm-configuration-for-battery-powered-9-seater/.
[68] Ref. 45, p 21. That's also reported (https://cleantechnica.com/2020/11/06/eviation-set-to-deliver-first-9-passenger-electric-airplane-in-2022/) for the pre-2021-redesign original model with wingtip motors.
[69] D. Coldewey, "Eviation's all-electric Alice aircraft makes its maiden flight," 28 Sep 2022, https://techcrunch.com/2022/09/28/eviations-all-electric-alice-aircraft-makes-its-maiden-flight/; M. Godlewski, "Air New Zealand Inks Deal for Up to 23 Eviations' 'Alice'," 14 Dec 2022, https://www.flyingmag.com/air-new-zealand-inks-deal-for-up-to-23-eviations-alice/.
[70] Wright Electric's 2-MW motors are rated at 10 kW/kg—both twice today's aerospace norm. The motors can scale from 0.5 to 4 MW. The firm says its motors can enable 10 more passengers per flight on an A320-class plane. See https://medium.com/@jeff_60994/wright-has-begun-testing-our-2-mw-aviation-grade-motor-for-transport-category-zero-emissions-79cb01c2cfc6, 7 Sep 2021. Also important are the halved-loss 2-MW 1-kV 20 kW/L inverters. The entire electric powertrain is said to deliver twice normal power with one-fourth the weight and half the size (https://www.weflywright.com/technology#propulsion).
[71] B. Sampson, "Wright Electric's first aircraft will be a 100-passenger plane based on the BAe146," 5 Nov 2021, https://www.aerospacetestinginternational.com/news/electric-hybrid/wright-electrics-first-aircraft-will-be-a-100-passenger-based-on-the-bae-146.html.
[72] J. Richardson interview with CEO J. Engler, "Wright Electric Shares Details About Passenger Plane Retrofit & 2-Megawatt Motor Testing," 20 Dec 2021, https://cleantechnica.com/2021/12/20/wright-electric-shares-details-about-passenger-plane-retrofit-2-megawatt-motor-testing/.
[73] It is not against the laws of physics to store more electricity per pound than liquid fuel does, and some inventors think they know how. A safe storage device with that energy density would take over aviation and all transport.
[74] https://www.tecnam.com/rolls-royce-and-tecnam-join-forces-with-wideroe-to-deliver-an-all-electric-passenger-aircraft-ready-for-service-in-2026/. The current range with 30-minute VFR reserve and 90%-SOH end-of-life battery is 85 nm, expected to rise to 145 nm by 2030 (https://www.aviacionline.com/2021/11/dubai-2021-tecnam-unveils-the-p-volt-an-electric-aircraft-based-on-the-p2012-traveller/); or (with reserve unspecified) as 100 nm with a battery at 80% of its service life (https://www.avweb.com/aviation-news/tecnam-updates-two-electric-

aircraft-projects/). Many flights in Norway's extensive regional network (where Widerøe serves 44 routes) are shorter than 100 nm due to rugged topography dissected by numerous fjords.
[75] https://www.tecnam.com/tecnam-p-volt-lifting-the-world-to-sustainable-energy/.
[76] Ref. 45, p 12.
[77] A. Jeffrey, "The Nordics and the Future of Electric Flights," 5 Sep 2022, https://knowhow.distrelec.com/defence-aerospace-and-marine/the-nordics-and-the-future-of-electric-flights/.
[78] T. Mullaney, "How United Airlines expects electric planes to change the way passengers make travel decisions," 28 Oct 2022, ESG Impact, https://www.cnbc.com/2022/10/28/how-united-expects-electric-planes-to-change-the-way-passengers-think.html.
[79] https://heartaerospace.com/faq/.
[80] https://www.aircharter.co.uk/about-us/news-features/blog/how-close-are-we-to-electric-planes.
[81] The better-known include Lilium, Joby, Beta, KittyHawk, Vahana (Airbus), Aurora, Uber, Zee, Blackfly, SkyRyse, Ampaire, Volocopter, Wisk, Ehang, Terrafugia, Sabrewing, etc. They typically use ultralight (10–20 kW/kg) motors, composite structures, ducted fans/rotors, advanced sensors and software, and novel system concepts and architectures. Many of the >100 developers expect, and some will probably achieve, flight operations in the early-to-mid-2020s. Urban roofs and mushroom-like stalks could then act as nano-airports. Those and other "vertiports" should affect the granularity, scale, and business models of airports and carriers; the need for airports; energy; congestion; stranded costs; and risks. A useful new digest of the field is C. Alcock, "Pioneers Push to Accelerate Green and Autonomous Aviation," 3 Jan 2023, https://www.ainonline.com/aviation-news/business-aviation/2023-01-03/pioneers-push-accelerate-green-and-autonomous-aviation.
[82] Contrary to popular misconceptions, hydrogen handled with proper skill and respect (like any fuel) has basic attributes that can make it safer than conventional jet fuels. See the safety section at https://www.zeroavia.com, including USDOE's quotation concurring with that view, and RMI's still-useful 2003 then-industry-standard white paper at https://rmi.org/insight/twenty-hydrogen-myths/.
[83] Boeing's 2003 767-class cryoplane analysis, and fuel-cell developments of similar vintage, are summarized in slide 44 of Lovins's 19 Oct 2022 technical brief (Ref. 9). Airbus's analyses in the past few years have been less sanguine, but it's not yet clear why.
[84] A useful two-day Dec 2022 ZeroAvia industry symposium can be viewed at https://www.zeroavia.com/annual-summit-2022-recap. ZeroAvia's *Newsroom* tab is useful to revisit.
[85] This line of design thinking by Dutch aviation engineer P.M. Peeters, following NASA's Chris Snyder, is summarized on slide 44 of Lovins's deck at Ref. 9.
[86] https://www.compositesworld.com/articles/zeroavia-advances-to-certify-za600-in-2025-launch-za2000-with-liquid-hydrogen-in-2027; https://www.compositesworld.com/news/hypoint-partners-with-gtl-to-extend-zero-emission-flight-with-ultralight-liquid-hydrogen-tanks.
[87] We haven't told the heavy-trucks story here, but it's similar to autos. Battery-electric medium and heavy trucks were at first ridiculed, and many European makers emphasized hydrogen instead. Some hydrogen trucks will doubtless succeed, but their use cases are likely to prove quite limited. Just consider Tesla's *Semi* Class 8 truck now in customer testing for 2023 volume production (planned for two years earlier but postponed so battery and car production could catch up). Originally slammed for supposedly reduced payload to carry lots of heavy batteries, it turned out to carry normal payload—or less if Tesla takes even more weight out of the rig's structure—because it also displaces three tons of diesel powertrain and fuel. Also important is its 40% sleeker aerodynamics. In trucks as in cars and airplanes, platform efficiency displaces costly batteries and their weight, saving even more powertrain cost and weight, and thus carrying more payload with less investment. Slide 45 in Lovins's brief (Ref. 9) shows how this logic works in hydrogen cars too.
[88] Wright Spirit White Paper, Wright Electric, April 2022, v2.0, https://docsend.com/view/faijiijzkvqdccjg.
[89] See our essay #4, https://aspenflyright.org/wp-content/uploads/2023/01/ABL-essay_4.-Fleet_01Jan2023.pdf, p 7 and n 32. Of course, they could be superseded by superclean competitors like the new aircraft graphed in Fig. 8.
[90] https://www.govinfo.gov/content/pkg/CFR-2021-title40-vol36/pdf/CFR-2021-title40-vol36-part1030.pdf
[91] https://theicct.org/wp-content/uploads/2021/06/Aircraft_CO2_Standard_US_20181002.pdf.
[92] 87 FR 36076–36091, 15 June 2022, https://www.federalregister.gov/documents/2022/06/15/2022-11556/airplane-fuel-efficiency-certification.
[93] §38.1.2 has a separate standard for planes with <20 seats and MTOW ≥12,563 lb, applying for original type certification from 1 Jan 2023.
[94] S. Miller, "Damn the hubs; nonstop flights ahead for United," 13 Aug 2020, https://paxex.aero/damn-hubs-nonstop-flights-united/.
[95] M. Alderighi *et al.*, "Network competition: the coexistence of hub-and-spoke and point-to-point systems," *J. Air Transp. Mgt.* **11**(5):328-334 (2005), https://doi.org/10.1016/j.jairtraman.2005.07.006.
[96] M. Cramer & M. Levenson, "What Caused the Chaos at Southwest," *NY Times*, 28 Dec 2022, https://www.nytimes.com/2022/12/28/travel/southwest-airlines-flight-cancellations.html.
[97] Z. Tufekci, "The Shameful Open Secret Behind Southwest's Failure," *NY Times*, 31 Dec 2022, https://www.nytimes.com/2022/12/31/opinion/southwest-airlines-computers.html.
[98] P. Ghazizadeh, R. Mukkanala, & J. Creedon, "Choosing point-to-point versus hub-and-spoke flights: a genetic algorithmic approach," *Procs. 2012 Sympos. Emerging Applns. of M&S in Industry & Academia*, 2012, 7, https://dl.acm.org/doi/abs/10.5555/2338790.2338797.
[99] L. Marti, R. Puertas, & C. Calafat, "Efficiency of airlines: Hub and Spoke *versus* Point-to-Point," *J. Ec. Studies* **42**(1):157–166 (2015), https://doi.org/10.1108/JES-07-2013-0095.
[100] C. Wheeler, "Strategies for Maximizing the Profitability of Airline Hub-and-Spoke Networks," *Transp. Res. Record* 1214, 1989, https://onlinepubs.trb.org/Onlinepubs/trr/1989/1214/1214-001.pdf.
[101] S. Georgilidakis, "Covid-19 killed the jumbos—and revived hub & spoke?," 29 Nov 2020, https://mentourpilot.com/covid-19-killed-the-jumbos-and-revived-hub-spoke/; A. Curran, "Hub And Spoke Vs Point To Point – How COVID Will Change Both Models," 13 Aug 2020, https://simpleflying.com/hub-and-spoke-vs-point-to-point/.
[102] IATA projected before the pandemic that by 2028, only four of the world's largest hundred airports would have adequate capacity: J. Bouwer, V. Krishnan, & S. Saxon, "Will airline hubs recover from COVID-19?," 5 Nov 2020, https://www.mckinsey.com/industries/travel-logistics-and-infrastructure/our-insights/will-airline-hubs-recover-from-covid-19.
[103] Bouwer *et al.* (Ref. 102) and P. Bhutia, "Explained: Will the hub-and-spoke model of airlines still remain relevant post Covid?," 25 Jun 2021, https://travel.economictimes.indiatimes.com/news/aviation/international/explained-will-the-hub-and-spoke-model-of-airlines-still-remain-relevant-post-covid/83830069.
[104] B. Baldanza, "Point-to-Point versus Hub & Spoke," 23 May 2020, https://inpractise.com/courses/spirit-airlines-managing-a-crisis/airlines-point2point-vs-hub-spoke.
[105] J. Compton, "From Spoke & Hub To Long & Thin: How Airline Routes Are Changing," *Forbes*, 31 Jul 2018.
[106] Ref. 101.