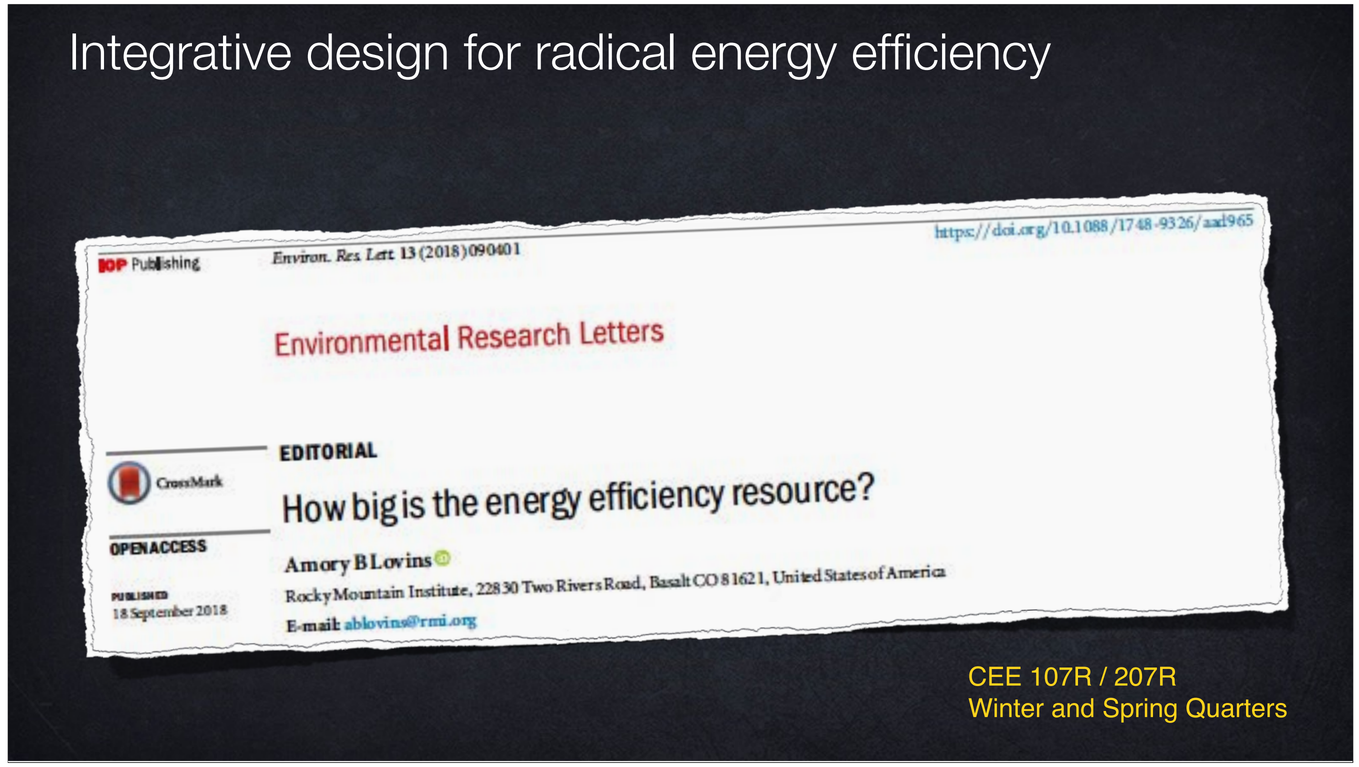
* = click to build/animate/transition

[small type] = details not spoken

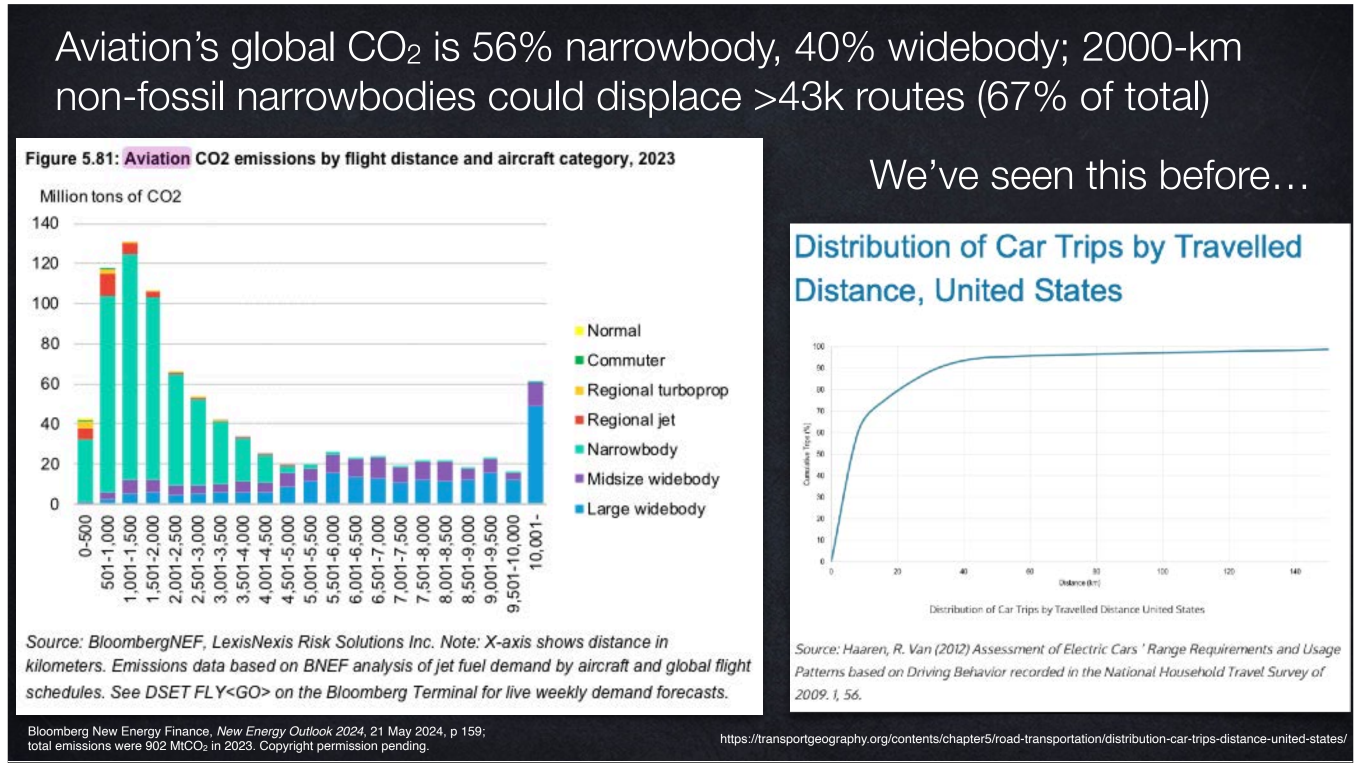
50m target, 84m actual; needs to shrink by 20–30m

Good evening. Thank you all for coming, especially Professor Alonso, Professor Harris, and other distinguished scholars, and thank you, Holmes [Dr. Holmes Hummel], for kindly arranging this glimpse of the aviation revolution. I'll address just aircraft—not airports, route architectures, business models, or Sustainable Aviation Fuel (which will dominate short-term aviation climate solutions). All those are changing too. /

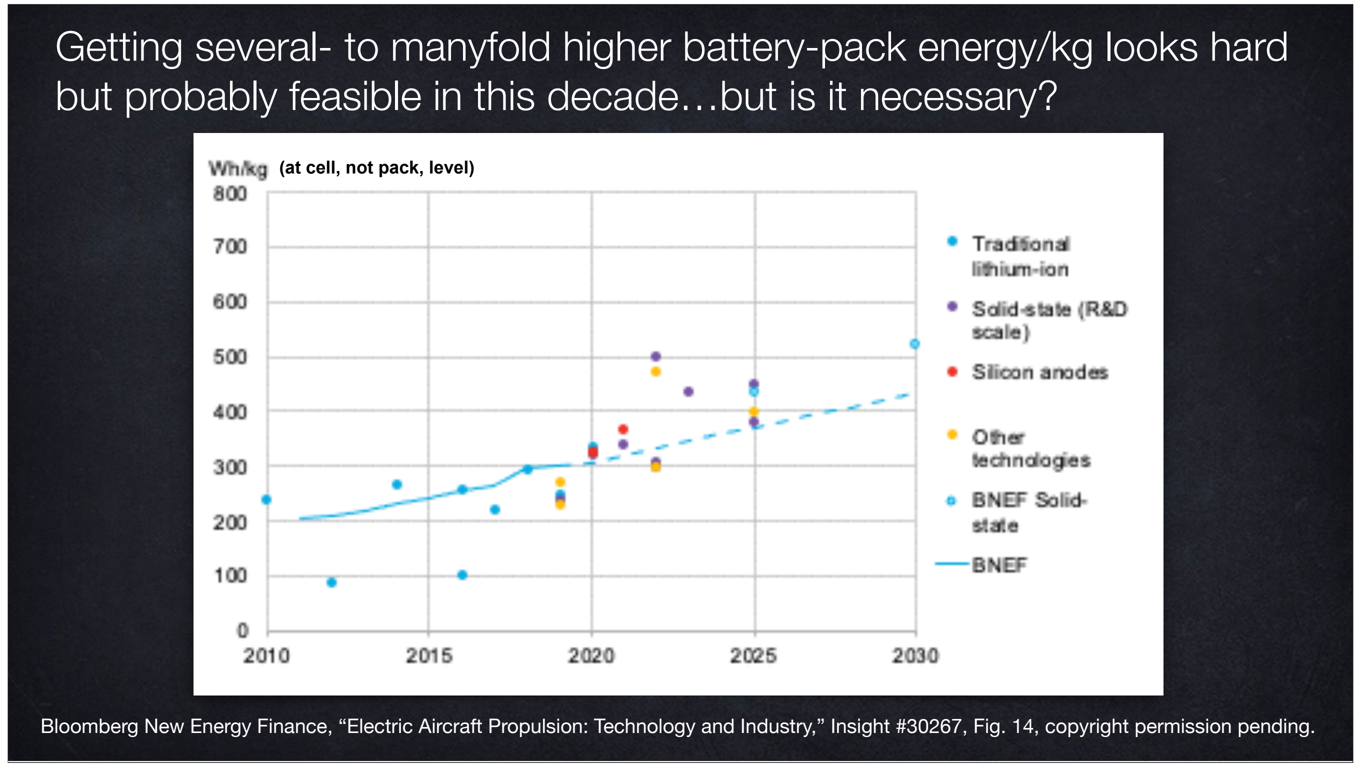
Here's tonight's story. Not so long ago, electric vehicles (EVs) were widely thought impractical in payload, range, and cost, because batteries were inherently too wimpy, heavy, and expensive. But then smartphones spawned advanced batteries; their higher energy density made EVs feasible; mass production made the batteries tenfold cheaper and EVs affordable. Importantly, too, lighter and sleeker cars could drive farther on less energy, needing fewer batteries and saving more weight and cost. Ranges passed 300, 500, 740 miles. More-efficient EVs with better batteries won on lifecycle cost and are about to hit sticker-price parity; some already have. So over 40 million EVs, once thought impossible, are on the road. They're taking over the world market. Some even more advanced EVs need so little energy that they can run largely or wholly on their own solar cells without plugging in! / Well, now that history is repeating itself. The same forces that created EVs are now animating game-changing electric planes (EPs). The EV and EP industries coevolve swiftly with shared technologies, innovators, and supply chains, but EPs evolve faster, because electric aviation enjoys virtually unlimited capital, Tesla-like (not Detroit-like) speed, vibrant competition, and higher ambitions (as it must because it's harder). So I'll explain why EPs' emerging evolutionary pattern will at least closely rhyme with that of EVs. *



I'm originally a recovering physicist, but for the past half-century I've been a practitioner designing superefficient vehicles, buildings, factories, and equipment. Each Winter and Spring Quarter, Joel Swisher and I teach an experiential course on how "integrative design" can make the energy-efficiency resource severalfold bigger, but at much *lower* cost, and often with *increasing* returns—because, as this article shows, we use not *more or fancier* widgets but *fewer and simpler* widgets, more artfully chosen, combined, timed, and sequenced. In 70-odd years and many millions of miles as an airline passenger, I've observed that airframe makers, though very skilled, could get much better at integrative design. *



What's their challenge? How far do airplanes need to fly? My ~12,000-km flight a week ago from Sydney to San Francisco is in the right-most bar of Bloomberg New Energy Finance (BNEF)'s distance histogram. But such long routes are very exceptional. Of last year's [2023] global aviation carbon emissions, over half came from short trips on narrowbody or smaller planes—the dominant four aqua bars furthest to the left. Just a 2,000-km range could cover two-thirds of the routes. Indeed, over a sixth of the emissions come from 1,000-km or shorter routes. That's a big entry market to grow volumes, improve technologies, and cut costs. /
* We've seen this before. When Tesla introduced the first lithium-ion battery car in 2009, ~80% of US car trips were <20 km and 96% were <100 km. That two-seat *Roadster* adopted electric drive in a lightweight Lotus *Elise* fiberglass-and-aluminum sports car. That combination had an impressive 393-km range, making range "a nonissue" according to *Car and Driver* magazine. But many customers still worried about it with no fast-charging networks. The 53-kWh battery pack was also expensive and the powertrain was handmade, so the real sticker price was four times that of a four-seat *Model 3* today. While providing ample range to win early adopters' confidence, Tesla needed time to build production volume, cut cost, reduce the car's energy use per kg by 16%, raise its top range by 40% for long road trips, and store 42% more energy per battery-pack kg [from 118 to 168 Wh/kg in the Long Range AWD model; the RWD is LFP]. The dominance of short trips bought that time. /
Now electric planes can apply the same strategy by starting with abundant short-haul markets and building out from there. *



However, while autos drive on roads, planes need lift to keep them up in the air. Most aviation experts assert that for electric flight to get off the ground, if it ever can, it'll need battery packs to store 2–3× more electricity per kg than the best battery packs in today's EVs, yet stay safe, durable, cheap, and high-powered. That won't be easy, but does look feasible and is authoritatively forecasted [BNEF forecasts 434 and 519 Wh/kg solid-state cells by 2025 and 2030 respectively]. Fortunately, though, I think this tough supposed “requirement” is asking and answering the wrong question. It simplistically compares fuel vs. battery energy density and propulsive efficiency *in today's aircraft*, without properly redesigning the whole aircraft as electric propulsion enables. It's a classic case of optimizing isolated components and thereby pessimizing the system. As we'll see, integrative whole-system design of far more efficient airplanes can make the battery requirements far less daunting. *

Misconceptions of Electric Propulsion Aircraft and their Emergent Aviation Markets

Mark D. Moore[1] and Bill Fredericks[2]
NASA Langley Research Center, Hampton, Virginia 23681

Over the past several years there have been aircraft conceptual design and system studies that have reached conflicting conclusions relating to the feasibility of full and hybrid electric aircraft. Some studies and propulsion discipline experts have claimed that battery technologies will need to improve by 10 to 20 times before electric aircraft can effectively compete with reciprocating or turbine engines. However, such studies have approached comparative assessments without understanding the compelling differences that electric propulsion offers, how these technologies will fundamentally alter the way propulsion integration is approached, or how these new technologies can not only compete but far exceed existing propulsion solutions in many ways at battery specific energy densities of only 400 watt hours per kilogram. Electric propulsion characteristics offer the opportunity to achieve 4 to 8 time improvements in energy costs with dramatically lower total operating costs, while dramatically improving efficiency, community noise, propulsion system reliability and safety through redundancy, as well as life cycle Green House Gas emissions. Integration of electric propulsion will involve far greater degrees of distribution than existing propulsion solutions due to their compact and scale-free nature to achieve multi-disciplinary coupling and synergistic integration with the aerodynamics, highlift system, acoustics, vehicle control, balance, and aeroelasticity. Appropriate metrics of comparison and differences in analysis/design tools are discussed while comparing electric propulsion to other disruptive technologies. For several initial applications, battery energy density is already sufficient for competitive products, and for many additional markets energy densities will likely be adequate within the next 7 years for vibrant introduction. Market evolution and early adopter markets are discussed, along with the investment areas that will fill technology gaps and create opportunities for the effective, near-term electric aircraft products. Without understanding both the context of how electric propulsion will integrate into the vehicle system, and evolve into the market place it is likely that electric propulsion will continue to be misunderstood.

American Institute of Aeronautics and Astronautics 2014–0535, *52d Aerospace Sciences Meeting*, Jan 2014, https://doi.org/10.2514/6.2014-0535, kindly cited by BNEF's Head of Commercial Transport, Nikolas Soulopoulos ,in his 9 Feb 2024 San Francisco Summit talk. A complementary 2021 technical overview by just-retired NASA Langley Chief Scientist Dennis Bushnell is at https://ntrs.nasa.gov/api/citations/20210021985/downloads/NASA-TM-20210019851FINAL.pdf.

This was explained a decade ago in a remarkable technical paper by two distinguished NASA Langley aeronautical engineers. I found it accidentally just days ago in a recent BNEF speech. As the highlighted parts of their Abstract say, the authors strongly validated my longstanding impression that electric aviation propulsion (whether from batteries or fuel cells) has "compelling differences" that "will fundamentally alter the way propulsion integration is approached." Integrative design then enables electric propulsion to "not only compete but far exceed existing propulsion solutions in many ways at [pack-level] battery specific energy densities of only 400" Wh/kg, yielding "4–8 time[s] improvements in energy costs with dramatically lower total operating costs, while dramatically improving efficiency, community noise, propulsion system reliability and safety," and zero greenhouse-gas emissions if powered by carbon-free electricity (30% of world electricity today, 42% in 2028 forecast by the International Energy Agency, then quickly rising toward 100%). The NASA authors showed a decade ago that "for several initial applications, battery [energy] density [was]…already sufficient for competitive products" in some entry markets, and for many additional markets[,] energy densities will likely be adequate within the next 7 years for vibrant introduction." As we'll see, that foresight proved accurate and in some ways conservative. As with the solutions EV-makers found, only oil-industry propagandists and their ideological allies don't yet see this coming for EPs, but they will as startling EP products enter the market. *

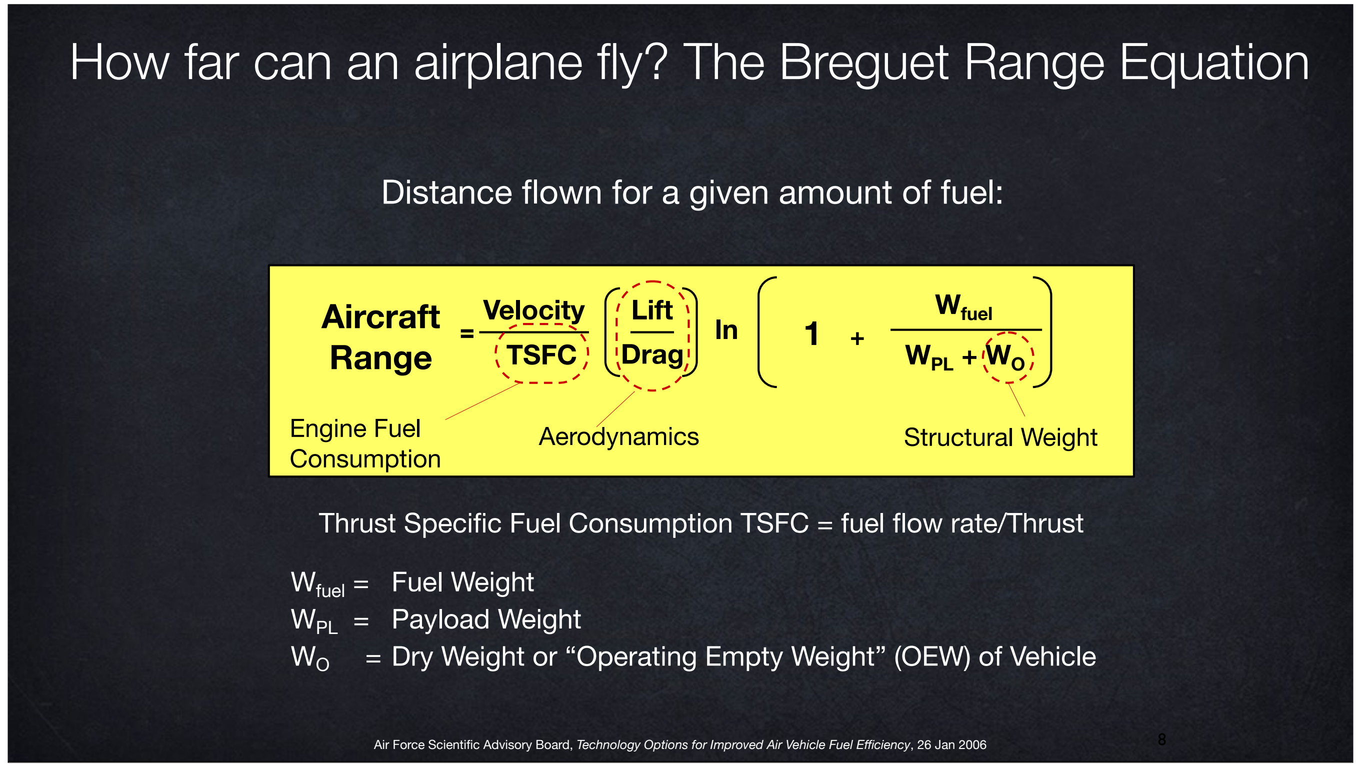
How do different design *questions* yield such completely different answers?

- Electric propulsion isn't just a drop-in; it transforms *whole-aircraft* design.
- Isolated propulsion-system comparisons are fundamentally misleading.
- Asset utilization is far higher and operating cost far lower for EPs than EVs; capital cost is generally lower too, and can fall far faster with production volume.
- Focusing on big airliners 15+ years out misses the big market in front of us, so laggard firms expecting slow introduction will be seriously disrupted.
- Batteries' energy density is relevant, but offset by many other advantages:
  - Electric propulsion has storage weight/cost penalties, constant weight, and some novel safety/certification issues—but 6× better motor power density and 3–4× higher engine efficiency (both scale-independent), high efficiency for ≤30–100% power, high reliability, greater redundancy, continuously variable transmission without gears, +100% power surge for 30–100 s, less engine-out sizing penalty, no power lapse with heat or altitude, potentially superior aerodynamics, extremely quiet, zero emissions, ~10× lower energy costs, and lower (then rapidly falling) capital costs.

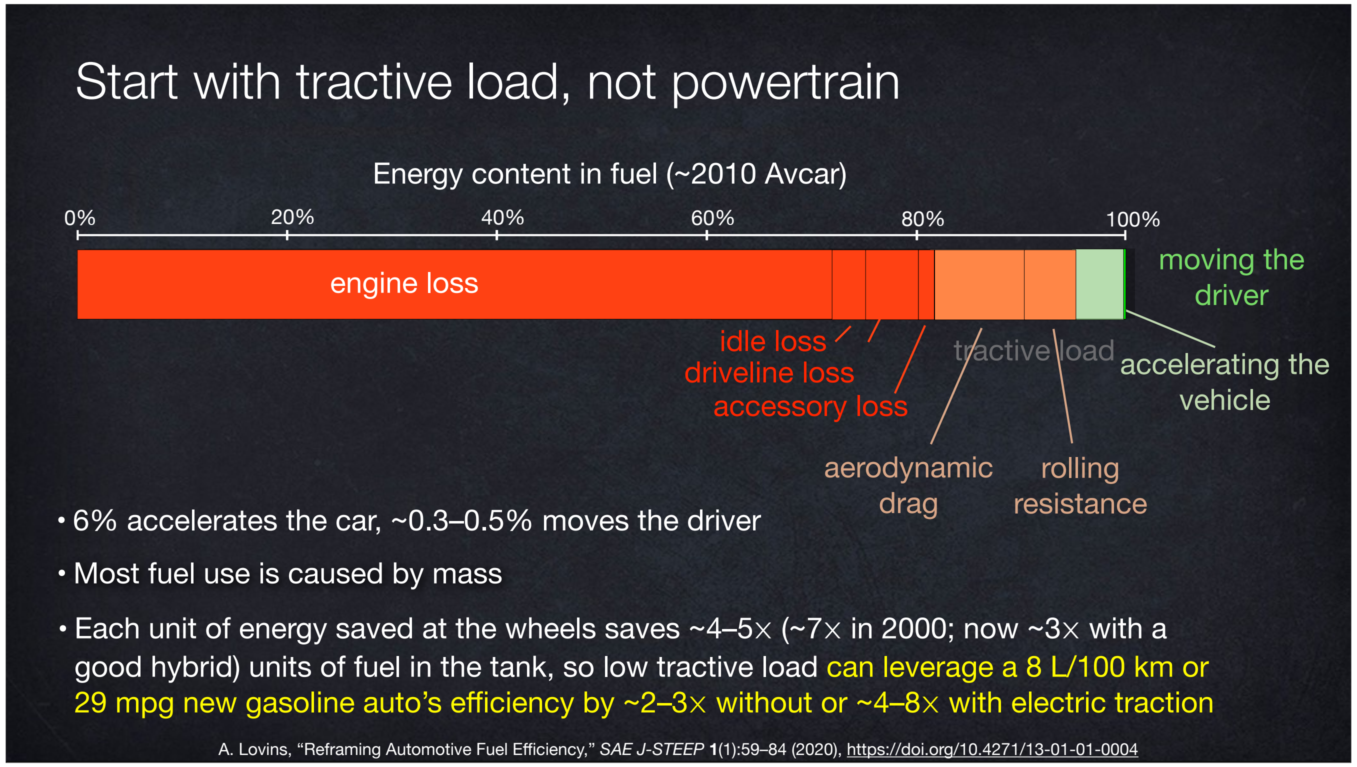
Their paper shows that electric propulsion * isn't just another way to produce thrust, but creates important advantages and degrees of freedom not previously available, profoundly changing how the whole aircraft is designed. * It's fallacious, though common, to compare propulsion systems in isolation. * The economics are also far better for electric propulsion, changing market realities. * This business opportunity is here and now, so people who think it's faraway risk grave disruption. /

* While batteries' energy density is important, it's already adequate (as we'll see) if offset by whole-aircraft improvements. Specifically, * batteries do cost and weigh more, don't get lighter as they're drawn down, and need meticulous safety and certification. However, electric propulsion has many offsetting advantages. It has manyfold lighter powertrain and higher efficiency than fuels do, over a huge range of scale that invites exciting distributed architectures—many small motors, not a few giant gas turbines. Efficiency stays high over most of the power range. Torque rises. Thrust is widely variable without gears, and regenerative on descent. No combustion means no intake air or exhaust. Reliability and safety improve through greater redundancy, radical simplicity, and major power-surge capability. Noise and engine dependence on density altitude nearly vanish. Higher altitude is feasible. Maintenance shrinks. Emissions disappear. Energy costs (price times use) fall by an order of magnitude. Capital costs shrink even at low production volumes, then quickly fall further as volumes build. Aerodynamics can fundamentally improve. These and other advantages are at least as big as the drawbacks, and can make electric airplanes better, safer, and cheaper than fueled airplanes. /

I won't try to get into this important NASA paper's technical details, but I'll offer you some simple examples and analogies that can help you understand and perhaps extend those authors' compelling logic. And while I'll address mainly energy efficiency, economics merit equal depth and emphasis because it determines what markets actually do, and in aviation, saved opex far outweighs any extra capex. As Kyle Clark said in a wonderful *Volts* interview 19 June 2024 with Dave Roberts, electricity is about as much cheaper than fuel as batteries are heavier than fuel; and once you buy a battery-electric aircraft, you can probably upgrade its batteries to double its range and quadruple its served cities in each decade thereafter, so it adds ever more value—unlike fueled airplanes, which steadily deteriorate throughout their lives. *

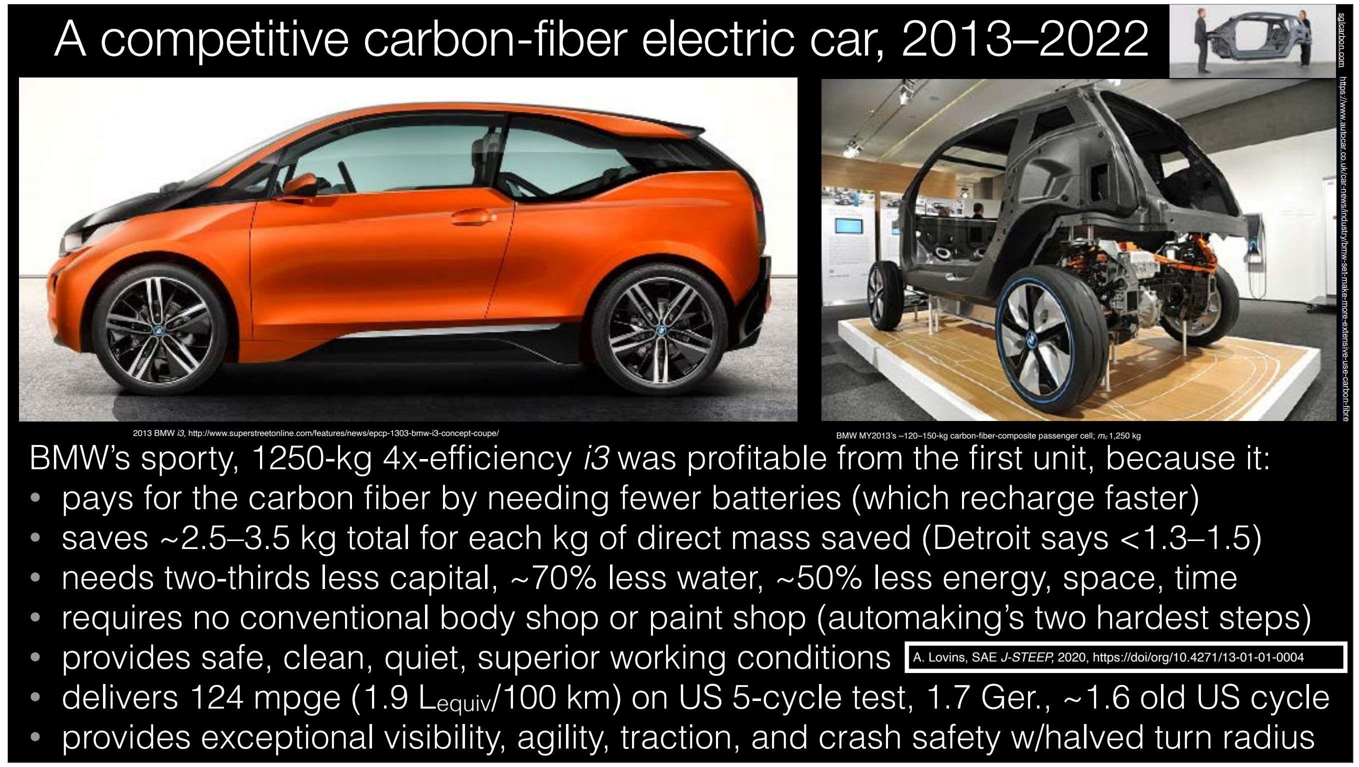


Here’s our one equation for this evening. Airplanes’ fuel efficiency is proportional to three things: engine efficiency (the reciprocal of fuel use per unit thrust), aerodynamic efficiency (the ratio of lift to drag), and a logarithmic term based on the ratio of fuel weight to gross weight (structure plus payload). That third term is needed because the plane gets lighter as it turns fossil fuel into ~6–8% of climate change. So putting aside that fuel burn and other complexities, the three prime variables are propulsive efficiency, aerodynamic efficiency, and mass efficiency: in short, thrust, sleekness, and lightness. However, these three all interact, sometimes favorably, often not. Their interactions can be understood only by full systems studies that I’m not equipped to perform. Therefore the many technology and design opportunities I’ll mention do not *simply* combine in a real aircraft at the systems level, nor across a full mission profile that includes not just cruise but also conditions like landing and maneuver.
Keeping that caution in mind, now back to the story. /
Planes go ~10x faster than cars, and aero drag rises as the cube of speed, but reducing weight is crucial too. Of course the numbers differ for planes and cars, but ultralight weight plus low drag crucially enables non-fossil-fueled propulsion of both kinds of vehicles, so let me show you the automotive physics analogy. *



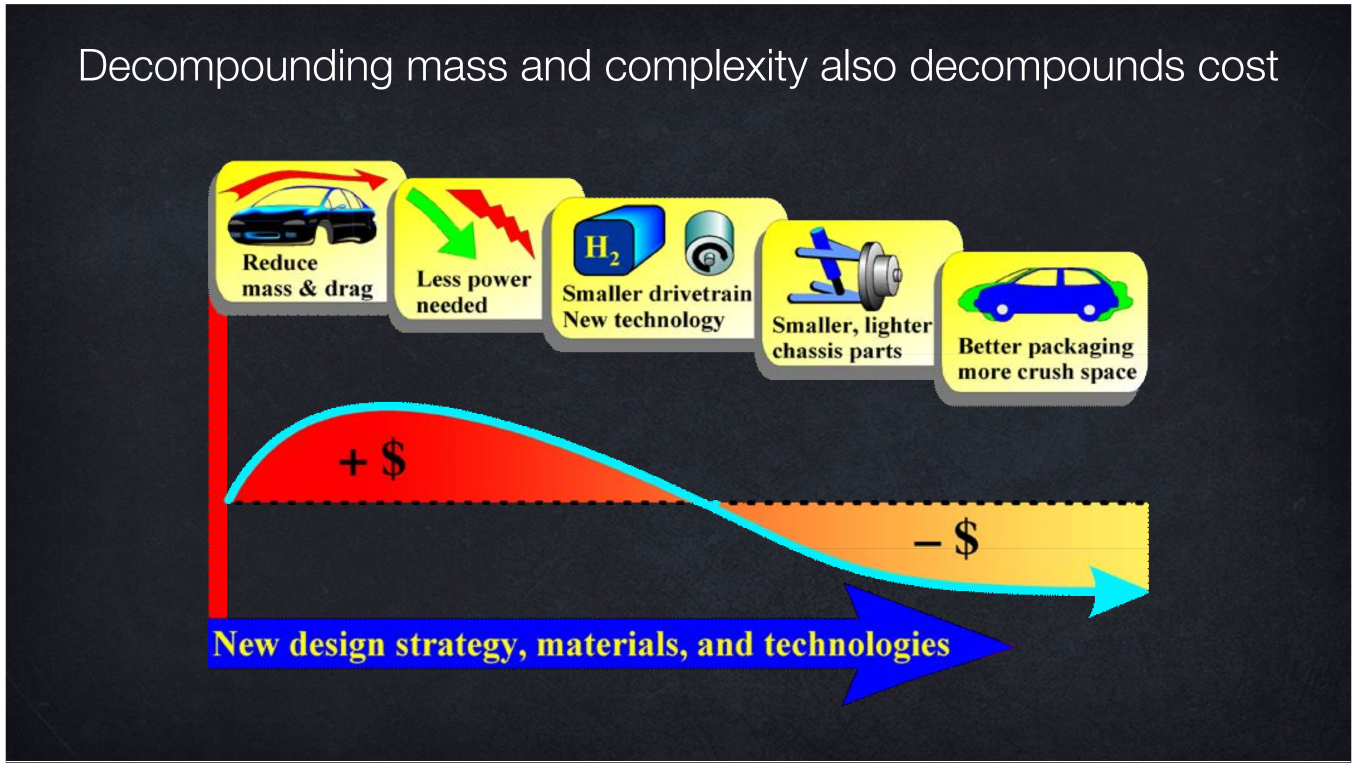
* Just one-fifth of a modern nonelectric car's fuel energy reaches the wheels and moves the car. Of that * "tractive load"—the energy needed to move the car—nearly half (rising as the cube of speed) heats the * air that the car pushes aside; most of the rest heats * the tires and road. * Only the last * ~6% of the fuel energy accelerates the car and then heats the brakes when you stop. But 19/20ths of the mass you're accelerating is the heavy steel car, so just 1/20th of that 6%, or about * 0.35%, of the fuel energy ultimately moves the driver. Both acceleration and rolling resistance depend on mass, * which therefore causes most of the tractive load. / Automakers cut losses mainly in the powertrain where the big losses are. That's harder than reducing tractive load, and far less rewarding, because saving one unit of energy in the powertrain saves only *one* unit of fuel in the tank—while * saving one unit of energy at the wheels avoids 3–4 additional units lost in *getting* that energy to the wheels, leveraging 4–5 units of fuel saved in the tank. Then we can *double or triple efficiency in a fueled car without changing how it's propelled, or we can roughly quadruple to octuple efficiency by combining low tractive load with electrification.* The utility industry's Electric Power Research Institute just found that making EVs more efficient *before* they're electrified can cut U.S. costs of electricity, grid, and recharging infrastructure by more than $200 billion per year [by 2050]. We should therefore *first* reduce tractive load, *then* improve the powertrain—which then shrinks for the same acceleration, saving more mass and also saving capital cost to help pay for the lightweighting. How can that lovely synergy work in practice? *

[EPRI, "Valuing improvements in Electric Vehicle Efficiency," 9 April 2024, https://www.epri.com/research/products/000000003002030215]



This * carbon-fiber electric car I drive, * 55 kg lighter than a 2-seat 2009 Tesla *Roadster*, was profitable from the first unit sold in 2013, and for all quarter-million units sold over the next nine years. It's made from carbon fiber, which automakers say is far too costly. * But its carbon fiber *was paid for by needing fewer batteries to propel the lighter-weight car* (and fewer batteries recharge faster, needing less electricity and infrastructure). Its ~300 kg saved weight * snowballs spectacularly, saving ~1.5–2.5 kg of secondary weight for each kg of saved primary weight. * Its assembly saves two-thirds of the normal capital and water and half the energy, space, and time. It also * eliminates the two hardest steps in automaking, and * it's much better for workers.* Its quadrupled efficiency is without compromise and * with many driver advantages. This design logic could also save up to two-thirds of the scarce battery minerals, then five other multiplicative forms of efficiency could manage the rest. /
* BMW finished producing this model in June 2022, though there are calls to resume production. Meanwhile, BNEF says that China's strategy for its 2030 flagship cars includes carbon-fiber structures displacing four-fifths of their iron and steel. If that happens, it could flip the global car industry. China already makes good EVs priced at just $5,000–10,000, so other countries' automakers couldn't just stand idly by if China took out another half to two-thirds of its EVs' costliest ingredient; they'd have to follow suit or lose share. *

[BNEF: A. Restauro & J. Attwood, "Auto Lightweighting Scenarios in the U.S., EU and China," 15 Oct 2019, https://www.bnef.com/insights/21575]

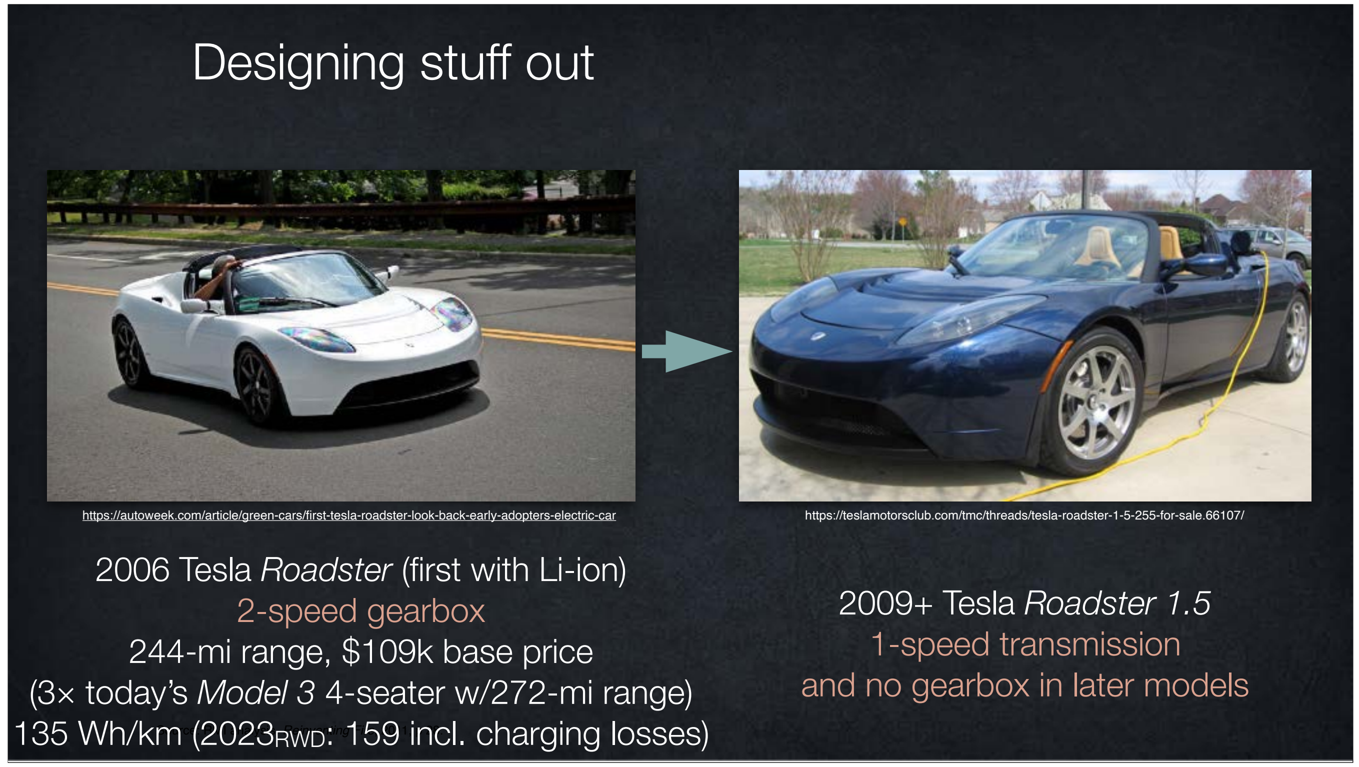


Lightweighting is especially important because of mass decompounding—the snowballing of saved weight, achieved by going repeatedly around the "design spiral" [as it's called in naval architecture] or "design cycle" [as it's called in aerospace]. /

First you make the vehicle light and slippery, cutting its tractive load in half and enabling smaller and more advanced powertrain and smaller, lighter chassis components. Those leave more packaging volume and crush space. Then you go around the spiral again, making components smaller as structural loads shrink, because the less weight you have, the less weight you need. Lightness multiplies. But such recursions can also *eliminate* components: a good series hybrid doesn't need transmission, clutch, flywheel, driveshaft, U-joints, axles, differentials, starter, or alternator! Each of those nine eliminated parts triggers another cycle of mass decompounding. /

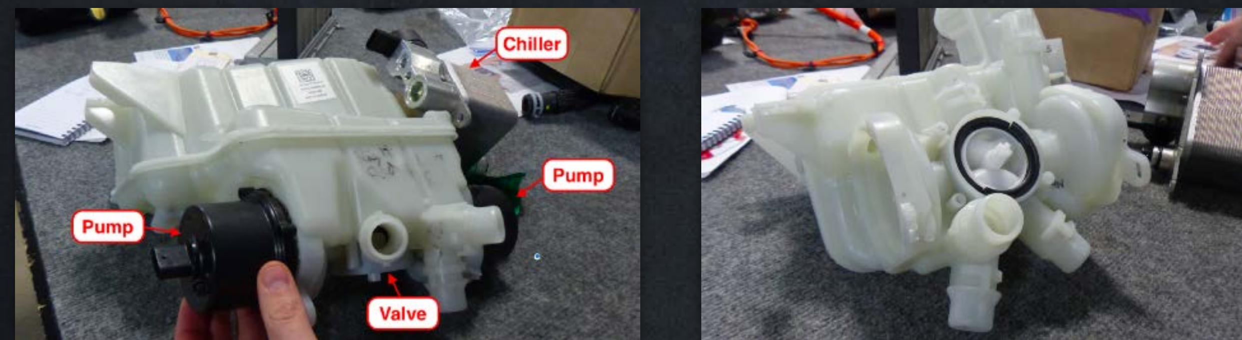
At first the special materials, powertrain, and design might seem too costly. But after many recursive cycles of mass decompounding, you need so little carbon fiber and such a small powertrain that with the simplified manufacturing, total cost can revert to normal or even less. Of course, that's cost per *car*, the way we buy cars—not cost per part or per kilogram, which is how most automakers (and even many aviation firms) still mistakenly think about cost. /

Aerospace designers are much more sophisticated about saving weight, but often not yet enough, and not only about weight. I asked a roomful of the best designers at a top airframe maker what it's worth—whole-system, end-to-end lifecycle cost of ownership—to take a watt of electric load out of their planes. Half of them didn't know the number, but were sure someone else in the company did. The other half scratched their heads and said, "Nobody in the company knows that number, because we never asked that question before. It's an important question, it's complicated, and we'd better figure it out." They still need to. *



This takes radical simplification. Let me tell you a little story. Tesla's original *Roadster* had a two-speed gearbox that kept blowing up because it couldn't deliver both 0–60 mph in 4.6 s and the 125-mph top speed. After two manufacturers failed, chief engineer JB Straubel was griping one day, and I said the right answer was probably *no gearbox* (just a single-speed reduction gear). He thought it over, and one day told his team, "Let's insource this problem to our core capability. We're electrical engineers. If our motor produces one-third more torque, we won't need the gearbox. Then we'll tweak the power electronics and software to match." They protested, "But the motor will overheat, and you'll have to Band-Aid on a baroque cooling system." He replied, "Don't worry—we'll figure out what's getting hot and give it better conductivity or a bigger cross-section." And so was born the * 2010 *Roadster 1.5.* Eliminating that gearbox gained 16 km of range, over 6 kg lighter weight, 30 kW more tractive power, less noise and maintenance, less warranty cost, and three-digit fewer manufacturing dollars in an industry that'll kill for a nickel. This story, and its competitive implications, later triggered a major US automaker's electrification revolution.*

Radical simplification



https://jalopnik.com/the-tesla-model-3s-superbottle-easter-egg-is-a-fascin-1830992728

Tesla *Model 3*'s "Superbottle": a single molded unit cascades heat and coolth sequentially, routed by a "heart" whose rotary valve sends heat to many changing destinations as sources, needs, and temperatures all shift throughout each driving cycle

Modular, compact, serviceable, fewer hoses/brackets, lighter, cheaper, faster assembly

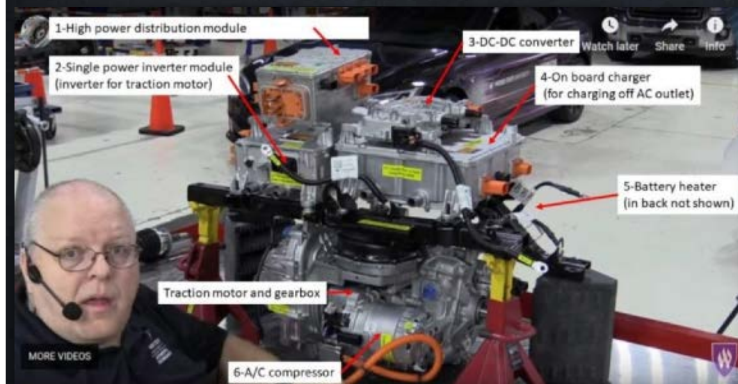
Increases range by ≥10 miles, recharges faster, cuts price

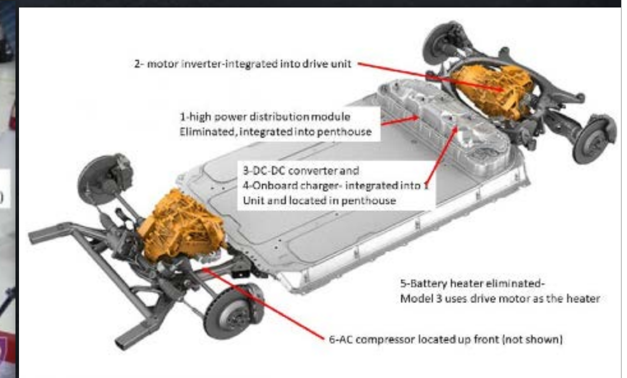
Source: RMI analysis, *Reinventing Fire*, 2011, p.28.

The same relentless pressure for simplification is now overcoming automakers' tendency to equip components with individual heating and cooling systems or forests of hoses. Tesla's *Model 3* instead used a single molded plastic "heart" whose 4-way valve redirects thermal energy real-time from where it is to where it's needed, optimally sequencing and cascading temperatures. * It was so elegantly simple that it took Sandy Munro more than a week to figure it out. The many benefits include at least 10 miles of extra range. The *Model Y*'s "octovalve," plus a redesigned heat pump, reportedly increased range by an astonishing 10% and spread to other models. Amazing work. *

[https://cleantechnica.com/2020/08/03/teslas-octovalve-enabled-a-staggering-10-increase-in-range-for-the-model-y/. A striking comparison with the Mach-E thermal system—severalfold bigger, heavier, and more complex—is at https://insideevs.com/news/520725/ford-mache-thermal-system-tesla/.]

Designing stuff out





https://insideevs.com/tesla-model-3-vs-chevy-bolt-high-voltage-components/, reporting Kohn Kelly (Weber University) analysis and video

Chevrolet *Bolt*'s high-voltage system stuffs five modules into its small front compartment.
Tesla Model 3 eliminates two and combines the functions of two pairs into one component.

Modular, compact, serviceable, fewer wires & connectors, lighter, cheaper, faster assembly
Increases range, recharges faster, cuts price

Source: RMI analysis, *Reinventing Fire*, 2011, p 28.

Likewise, of five separate power-related modules in the Chevrolet *Bolt* (stacked together in the left photo), Tesla's *Model 3* eliminates two and consolidates two more into other modules, radically simplifying the system and achieving * the same familiar suite of benefits. Airplanes could benefit too. *

Encouraging foresight: *ask history* how low can we go (SAE, https://doi.org/10.4271/13-01-01-0004)

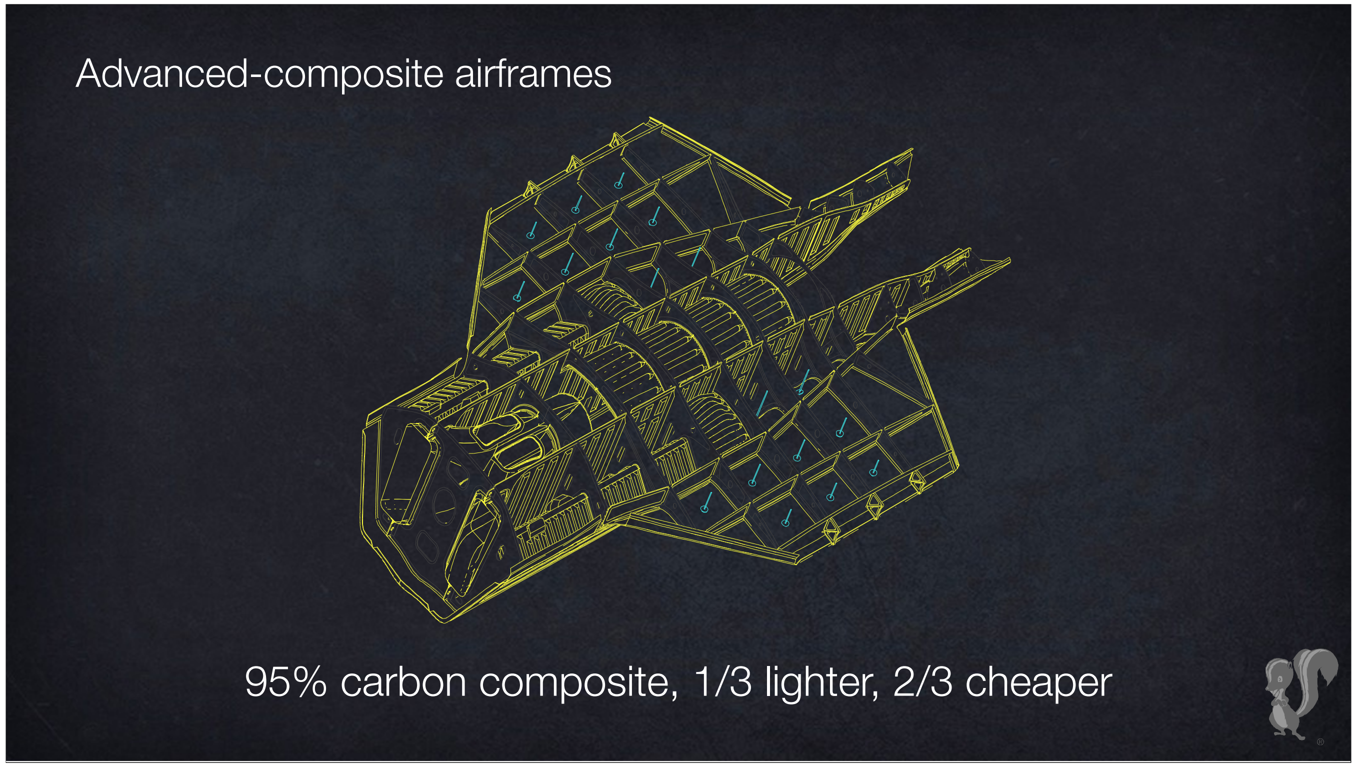
parameter	Lovins publications (NRC '91, ECEEE '93, VPATC#3 '95, SAE '95, ACEEE '95, IBEC '95, RMI '95, EVS '96, SAMPE '96,...)	modern empirical examples
curb mass m_c (kg) of carbon-fiber 4-seater	400 (advanced "Ultima")	2007 Toyota concept *1/X*: 420 plug-in hybrid, 400 hybrid; part-metal 1987 Renault concept *Vesta II*: 473; 1984 Citroën concept *ECO 2000*: 449
regenerative braking efficiency (% wheel-to-wheel)	70 (industry expectations in early 1990s were ≤20)	2004 *Prius:* 66; 2012 *Volt*: 70–73 (if ≥0.14 *g*); 2007 Tesla *S*: ~64–80
coefficient of rolling resistance r_0 (%)	0.5 ("Imagina")	2013 Michelin tires for VW *XL-1*: ≤0.5, probably ≤0.4
practical vehicles' coefficient of aerodynamic drag C_d	≤0.19	1991 GM *Ultralite,* 1987 Renault *Vesta II*, 1996 GM *EV1*: 0.19; 2013 VW *XL-1*: 0.189; 2022 Mercedes EQXX: 0.17; 1983 Ford passive *Probe IV:* 0.152 (= *F-16*), 1985 active *Probe V:* 0.137; 2022 Aptera: 0.13
practical vehicles' C_dA (m²)	0.27	2013 2-seat VW *XL*-1: 0.277 (*A* = 1.50 m²); cf. 2007 Renault 4-seat concept *Vesta II*: *A* = 1.64 m²; 1991 GM 4-seat concept *Ultralight*: *A* = 1.71 m²
4-seater mpge	146 ("Gaia" with η-0.30 ICE, ~1990 EPA cycle)	2013 2-seat VW *XL-1* (NEDC): 235 (diesel-only: ~120); B-class 2014 Renault 4-seat concept *Eolab:* ~235 and Audi concept *Crosslane*: 214; 2015 BMW 4-seat *i3* (EV): 124; 2022 5-seat Lightyear: 251; [2022 2-seat Aptera: 343]

How low can autos' tractive load go? This table from my 2020 Society of Automotive Engineers paper "Reframing Automotive Fuel Efficiency" shows * my early-1990s analyses of six critical platform parameters, seeking to infer, from historic concept-car and component data, what efficiencies production cars should be able to achieve by about now. Those empirically grounded estimates were heavily criticized, but three decades later they're eerily close to market offerings. Such over-the-horizon radar signals are vital if you want to substitute accurate technological foresight for marketplace shocks. I think collecting weak but real signals can enable accurate inferences about future aviation, since whatever exists is possible. So let me offer some further examples. *

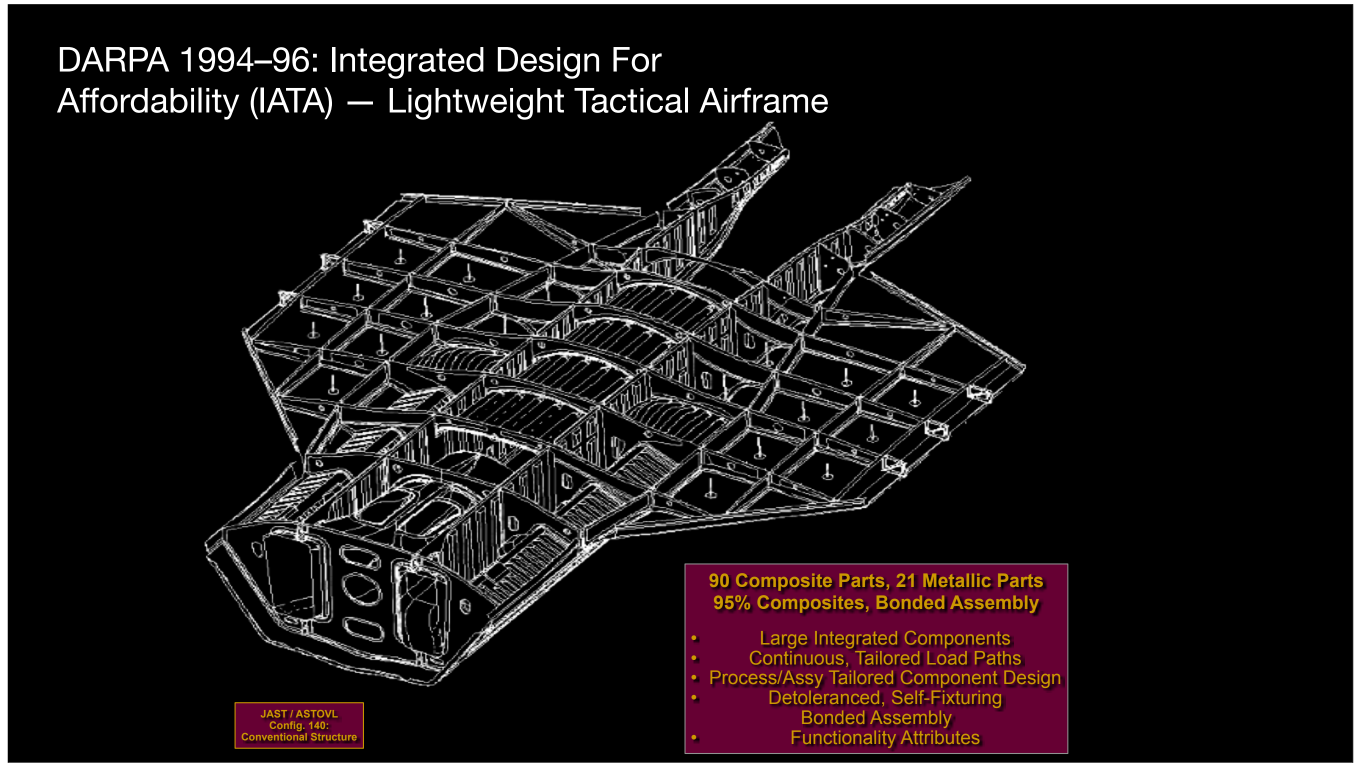
[VW *XL1*: 795 kg due largely to heavy powertrain, 111 km/L gasoline; BMW *i3*: 1250 kg, efficiency 124 mpge pure-electric, or 2014 ReX EPA rated 117 mpge el-only, 39 gasoline-only]

Remember how saving automotive energy by taking out mass or drag leverages much larger fuel savings at the tank? The same is true in planes, but it's even more valuable. A 40-odd-percent efficient jet engine saves >2 units of fuel directly—more with mass decompounding—for each one unit of mass or lift/drag saved in the airplane. This multiplier also raises the value of saving onboard electricity. Even a quite efficient *787* drawing ~400 kW of electric power at cruise isn't yet fully optimized. Optimization for whole-system lifecycle value might reveal very different strategies for thermal comfort. It might show, to make up an example, that replacing a $20 coffeepot with a $200 vacuum-superinsulated internal-element coffeepot might save thousands of dollars' worth of fuel each year. Boeing estimated that optimizing electric loads might add a couple of percentage points to the *787*'s roughly 20% gain in fuel efficiency—even more when smart wiring and power management save a lot of heavy copper and complex wiring. But I wouldn't dream of providing, say, thermal comfort in a building the way we do in airplanes. And we still have a long way to go with some fundamentals, like taking out weight—even operational weight that's not built into structures. *

Taking 1 kg of weight out of a typical airplane is worth ~$2k in present-valued fuel cost—even more on long flights where each liter you want to land with requires another half to one liter to carry the first liter across the Pacific. I was once hitchhiking on a KC-135R military tanker and * noticed a * lot of * heavy objects that * didn't need to be there. Next morning I briefed my observations to two US Air Force 2-stars, that afternoon they launched a treasure-hunt, and they found $2b worth of weight and hence fuel savings in that aircraft class, then >$10b in all heavy classes—weight that nobody had been responsible or rewarded for taking out. Likewise as an airline passenger, I notice uneven attention to weight—sweating the details of lightweight toilet-paper and magazines while overlooking heavy tray-tables and (until very recently) galley carts. And airframe makers could do far more with basic structural weight too. *



Our lightest big passenger planes are still only half carbon-fiber composites by mass. But three decades ago, Dave Taggart at the * Lockheed-Martin Skunkworks led for DARPA [in 1994–96] the design of a 95%-carbon-composites advanced-tactical-fighter airframe that was * 1/3 lighter *but 2/3 cheaper* than the 72%-metal base design for this Joint Air Strike Technology, later called the Joint Strike Fighter. *



Here’s a closer and flatter look… *

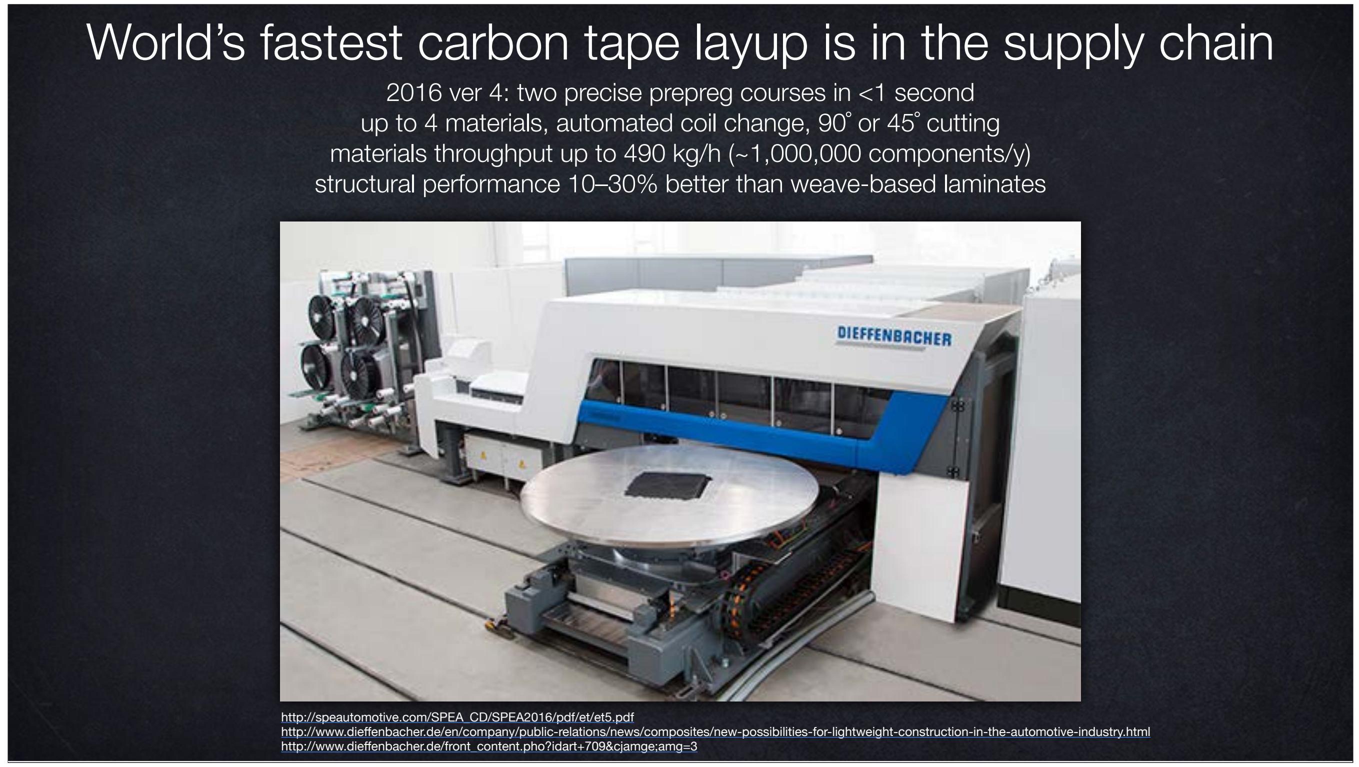
Benchmark comparison: –65% cost, –33% mass at 100th copy

IATA Final Cost / Weight Comparison of Preferred System Concept to Baseline 140

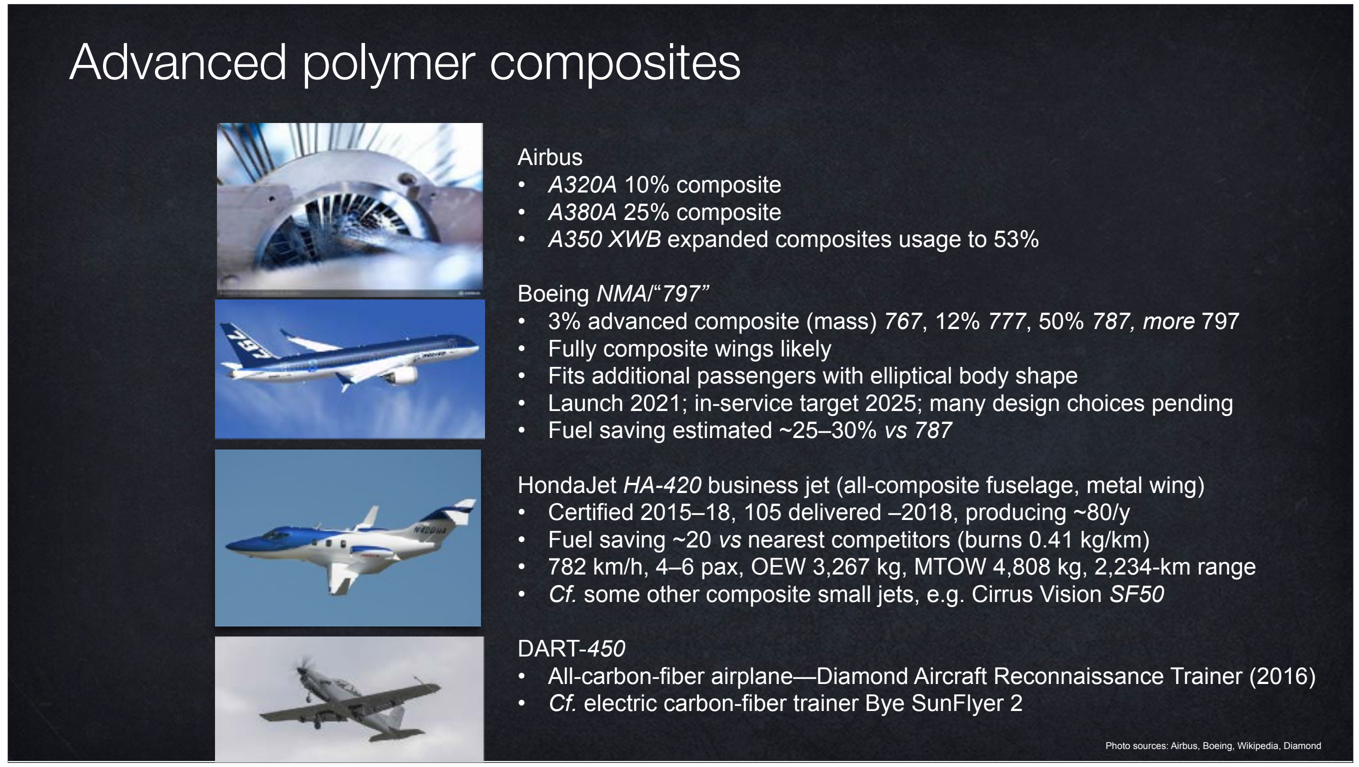
	Weight (lbs)	Total Recurring Production Cost ($)			Total Cost per Weight ($ / lb)		
		T1	T100	T250	T1	T100	T250
Total IATA PSC Wing / Body	3,341.3	$5,004,231	$2,023,334	$1,680,545	$1,498	$606	$503
Total JAST/ASTOVL Wing / Body	4,962	$22,147,044	$5,709,476	$4,548,296	$4,463	$1,151	$917
IATA / JAST 140 Ratio	0.67	0.23	0.35	0.37	0.34	0.53	0.55
% Change	-33%	-77%	-65%	-63%	-66%	-47%	-45%

- **90 Composite Components, 21 Metallic**
- **65% Reduction in T100 Rec. Production Costs** ($3.68M savings)
- **48% Reduction in Non-Recurring Production Costs** ($30.2M savings)
- **33% Reduction in Weight** (1621 lbs savings)
- **95% Composites** (vs 30% in Baseline)
- **Orders of magnitude part count reduction**
- **Conservative PSC Estimates:**
  - 6% "Intangible" Cost and Weight Added to PSC
  - Full Recurring Engineering Added to PSC
  - Full Extent of E-beam Cost Advantage Not Included
  - No Credit for Material Forms to Enhance Producibility
- **Commensurate Reductions in LCC Anticipated**

…and some of the benchmark numbers. The 3–4× lower production cost for this 735-kg-lighter airframe showed, as BMW later did for cars, that ultralighting needn't cost more and may cost less. And the cost would be even lower today, because the leader of this Skunk Works project moved to RMI in 2000 and led our Hypercar spinoff's development of a cost-effective SUV with half normal weight and 4–6× greater efficiency. A team led by another RMI engineer at that spinoff, now head of advanced composites at Apple (where BMW's *i*-project leader then led the Titan car project), later developed… *

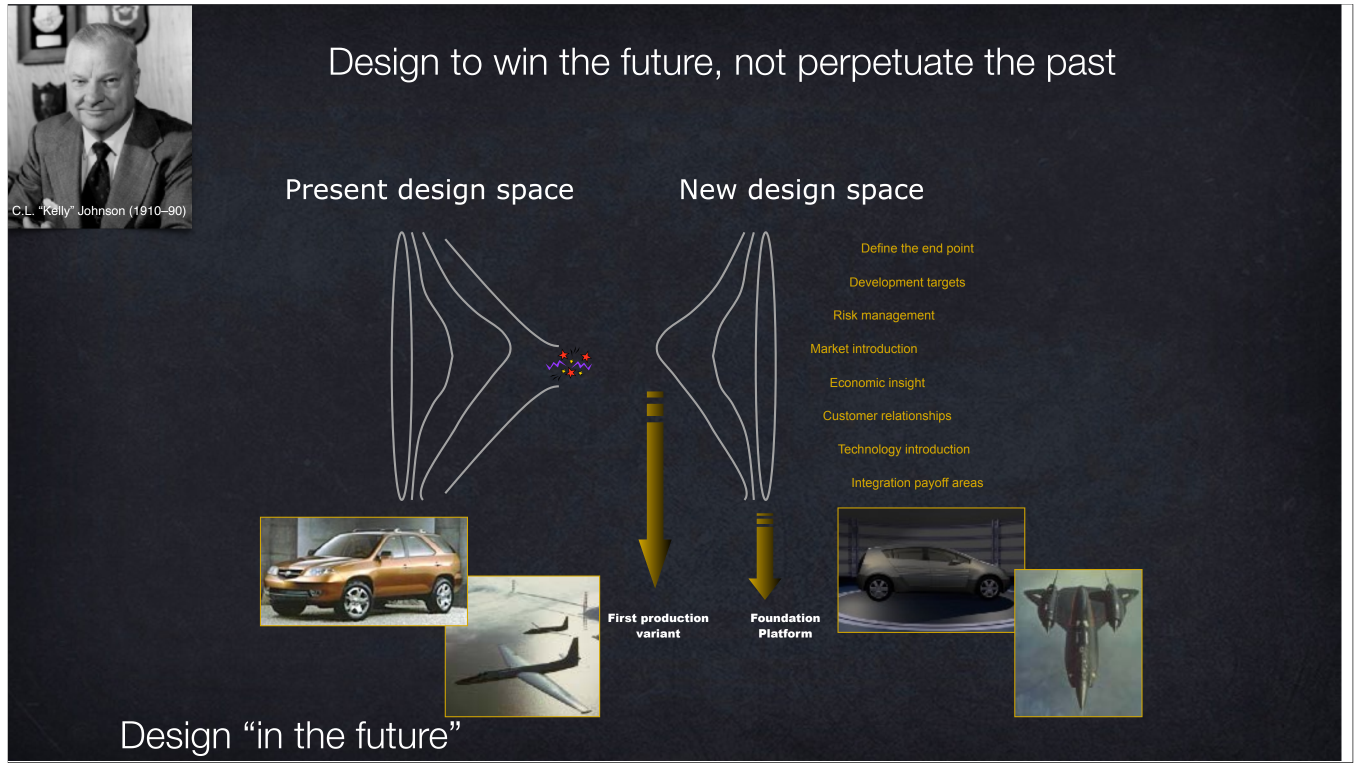


…the Fiberforge® process that makes competitive structural carbon-fiber parts. [made this test piece *[show]* for military ballistic helmets in one minute 15 years ago. It then] It made many airplane parts, like composite window frames that went from concept to commercial flight in six months. We sold the technology to a German Tier One pressmaker in 2013. This process, as embodied in this machine released three years later, can make a complex 2×2*m* structural carbon-fiber part in one minute, or over a million smaller aerospace parts per year. It could become severalfold faster if desired. [**show samples**] I mention this technology in case you think making advanced-composite airplanes and their structural components must be slow and costly. *



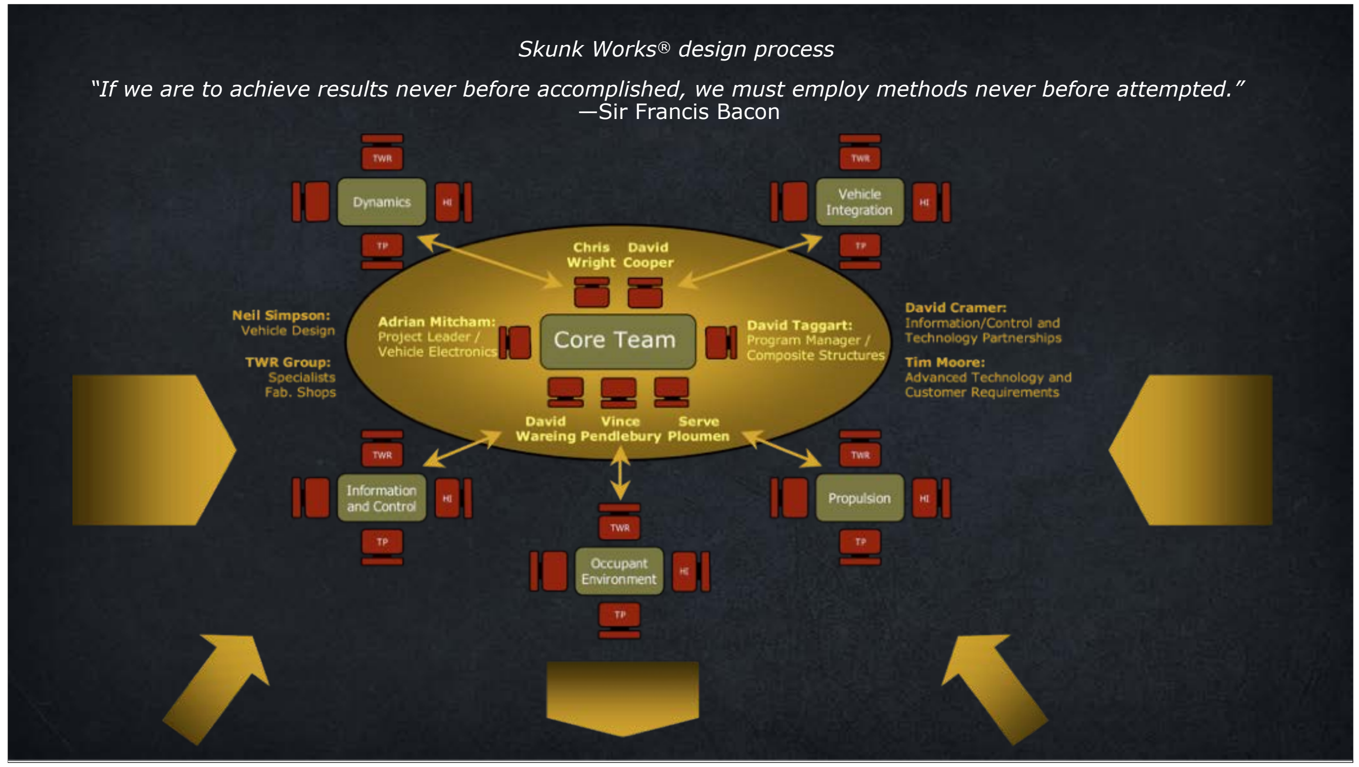
To be sure, advanced composites are slowly and incrementally displacing metal. Current trends include carbon-fiber wings and elliptical fuselage forms with a *787*-like passenger compartment atop a skinnier *737*-like cargo hold, thus fitting more seats with less drag and weight. But many components still made of metal shouldn't be. The barriers are not mainly technical or economic but cultural. *

(Source: AeroDynamic)

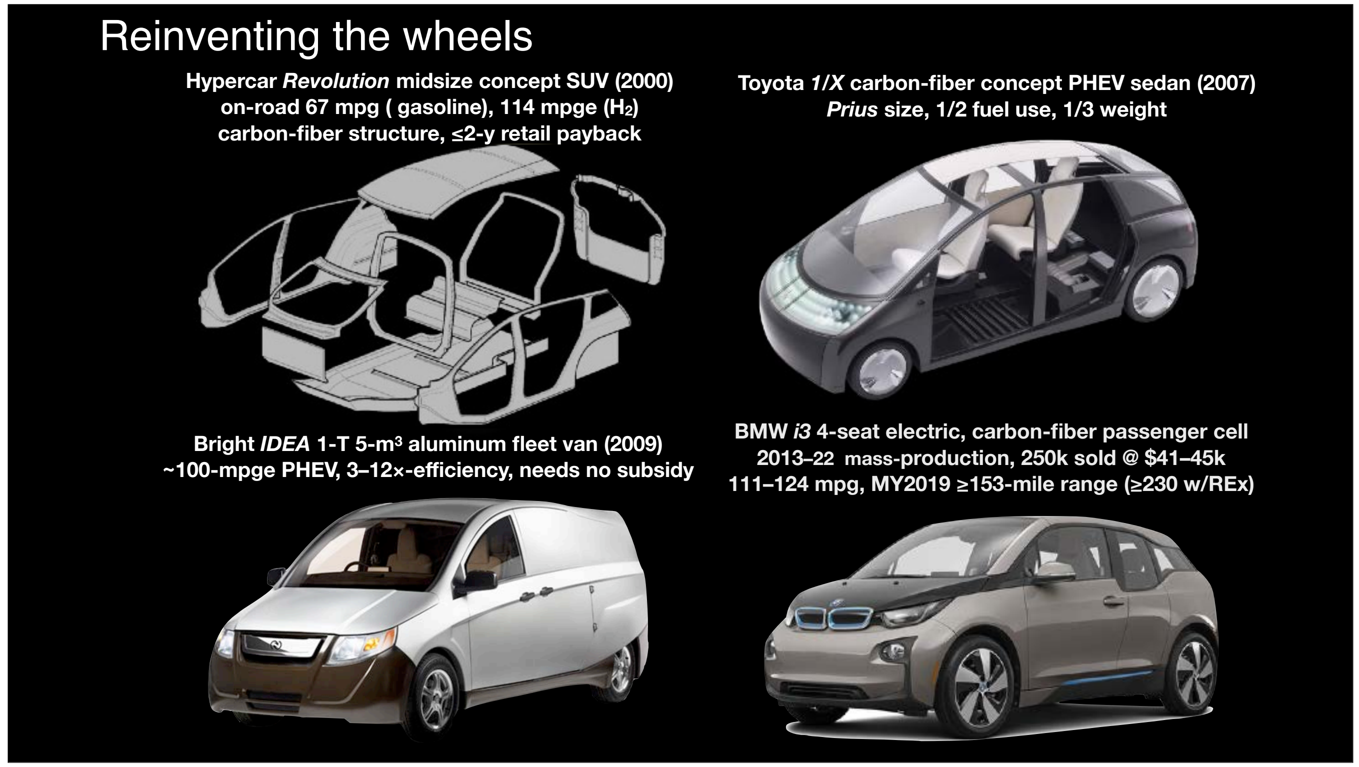


Radical designs like that 95%-carbon-composite Joint Strike Fighter airframe require revolutionary design mentality—designing in the future, not in the past. When the Soviets shot down * Francis Gary Powers's *U-2* spy plane in 1960, Kelly Johnson didn't say, "I'm going to design a slightly better *U-2*"; he said, in paraphrase, "I want to own the skies for decades, so * we'll design a Blackbird [SR-71]; I don't know how, but we'll figure out." And they did—in ~13 months. /

Johnson understood that such an airplane was impossible within the conventional design context, because design is * like a rubber band: if you try to stretch it too far from the conventional design space, you encounter more and more resistance, and eventually it breaks. But if you * jump to the new design space you aspire to, you can stretch the rubber band back to fit technologies not yet ripe, and then as they mature, the rubber band relaxes to where you want to be. *

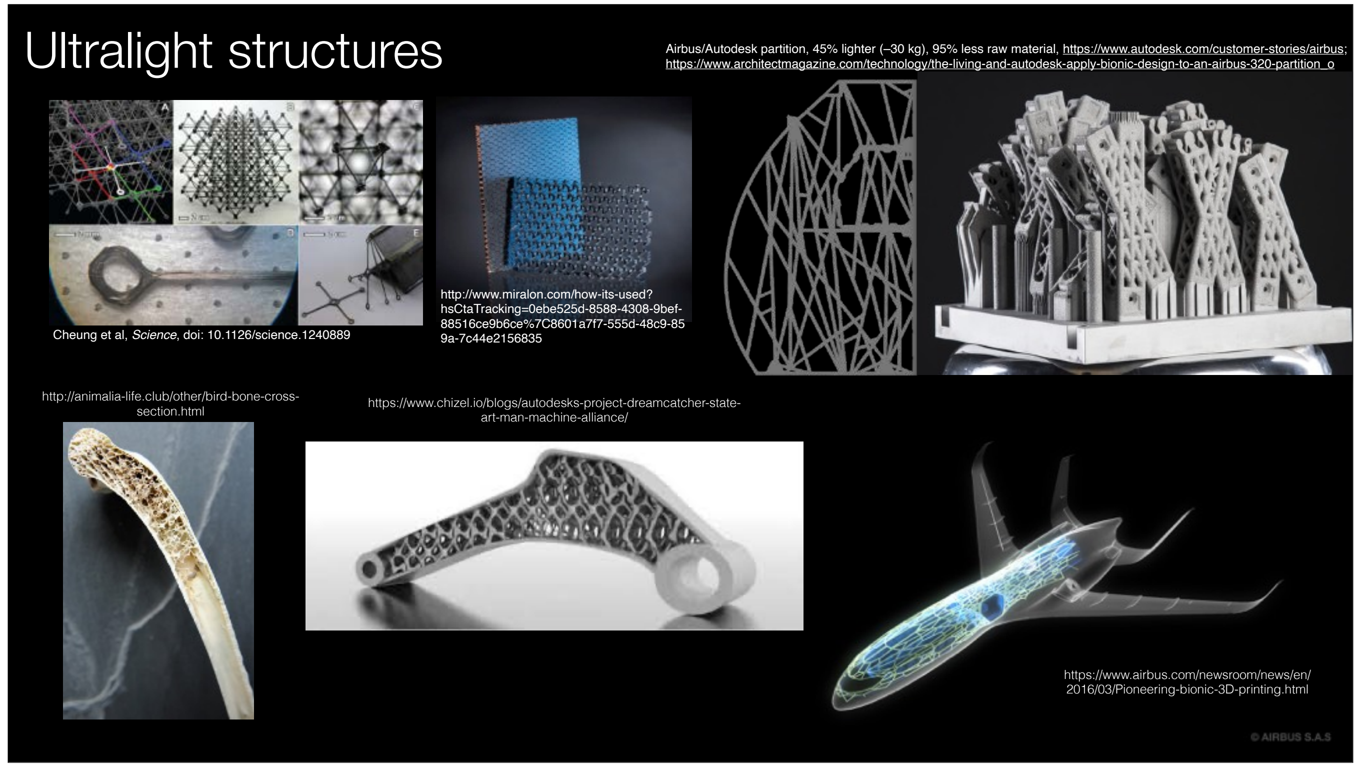


Ultralighting requires not just smart and uninhibited designers, but also * organizing them differently. Dave Taggart brought from the Skunk Works our *Revolution* SUV's design process. It made * seven engineers, all around the same table, collectively responsible for dauntingly ambitious *whole-vehicle* requirements that the industry had no idea how to meet. Each engineer *also* owned one major vehicle system or function, but for those we deliberately wrote *no* requirements, because we didn't want him to make his problem into her problem—we wanted to make the *whole team* design a highly integrated vehicle *together*. Two engineers weren't comfortable without their very own requirements, so we replaced those folks in the first week or two, and then it went great and we got the intended result. Toyota asked us how we did it, we told them, and in 2007, out came the 70%-lighter (400-kg) *1/X* carbon-fiber hybrid concept car. *

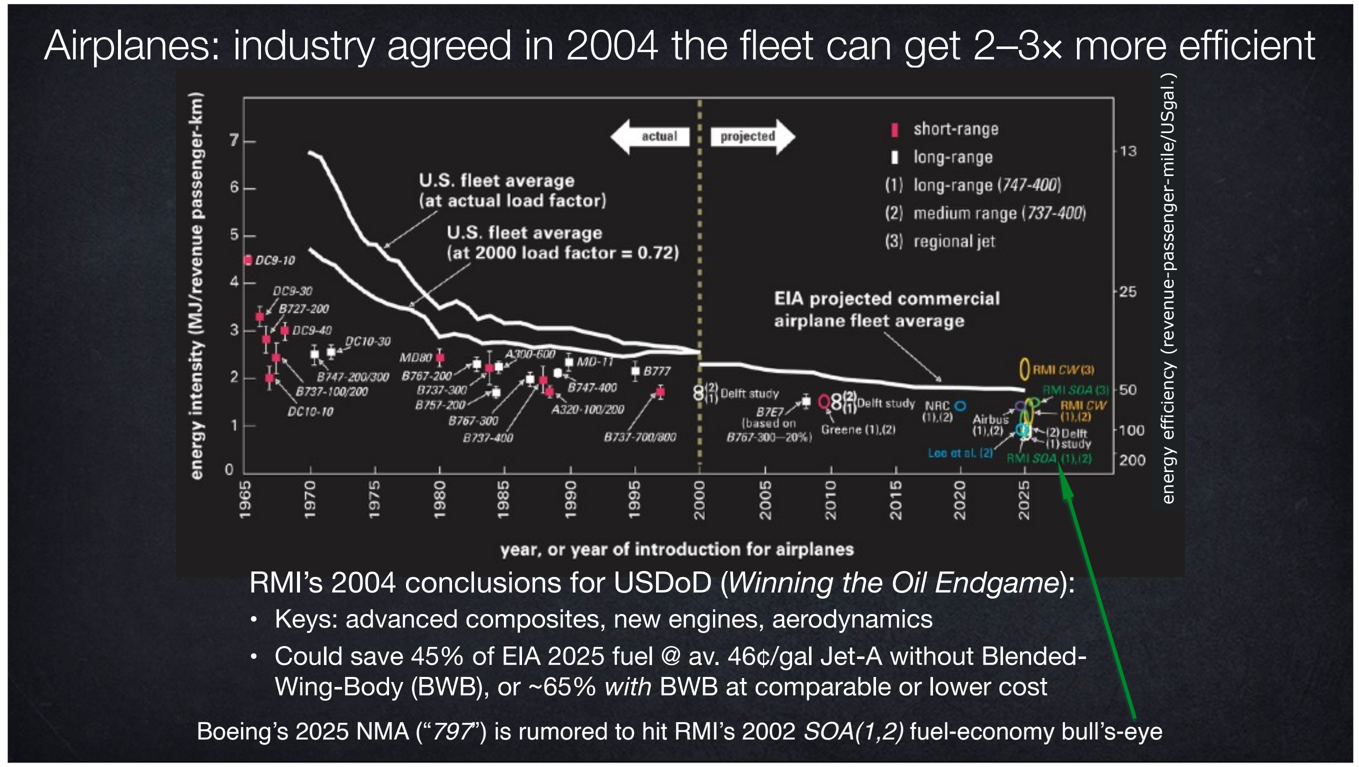


Thus the ultralight carbon-fiber electrified Hypercars that I invented 33 y ago [1991] and we * designed with industry 24 y ago developed design methods that Toyota * used 17 y ago * to design that 70%-lighter hybrid. Similar methods * entered the market in 2013 with this profitable * BMW *i3,* described earlier. But * even one-ton-lightened *aluminum* fleet vans, like this hybrid that another RMI spinoff developed and road-tested in 2009, could save a fifth of US auto fuel at lower lifecycle cost with no subsidy. And * carbon-fiber autos made in our simplified way at normal cost could save more oil than Saudi Arabia lifts, at an extra cost that a decade ago was <$18 per saved barrel, today is ~$0–7, and within ~2–5 y will fall below zero. In fact, two-thirds of the EVs made in China are already at or below sticker-price parity, saving oil at negative capital cost. *

Now, aeronautical structures could be made in radically different ways that Kelly Johnson would have been all over. Five years ago [2019], MIT’s Center for Bits and Atoms introduced a flexible lattice structure illustrated by this 4.3m test structure *59× less dense* than a typical metal airplane wing. That’s 59 *times*, not 59 percent. Such a structure has the strength of elastomers but the gossamer density of aerogel. It can also eliminate moveable flight surfaces: every part of its entire shape *passively* adapts to optimize continuously for real-time flight conditions, like a bird’s wing. Thousands of such identical, anisotropic, molded-polymer little cells can be assembled by swarms of programmed robots (or grad students, whichever are cheaper) into an airplane of any desired shape. This cutting-edge technique opens revolutionary prospects for lightweighting, aerodynamics, and cost reduction. It’s been prototyped as an airplane for Airbus and as a car for Toyota. It could even form a vacuum balloon, buoyant but crushproof in air; a big one could lift two dozen times the payload of a *747*. *

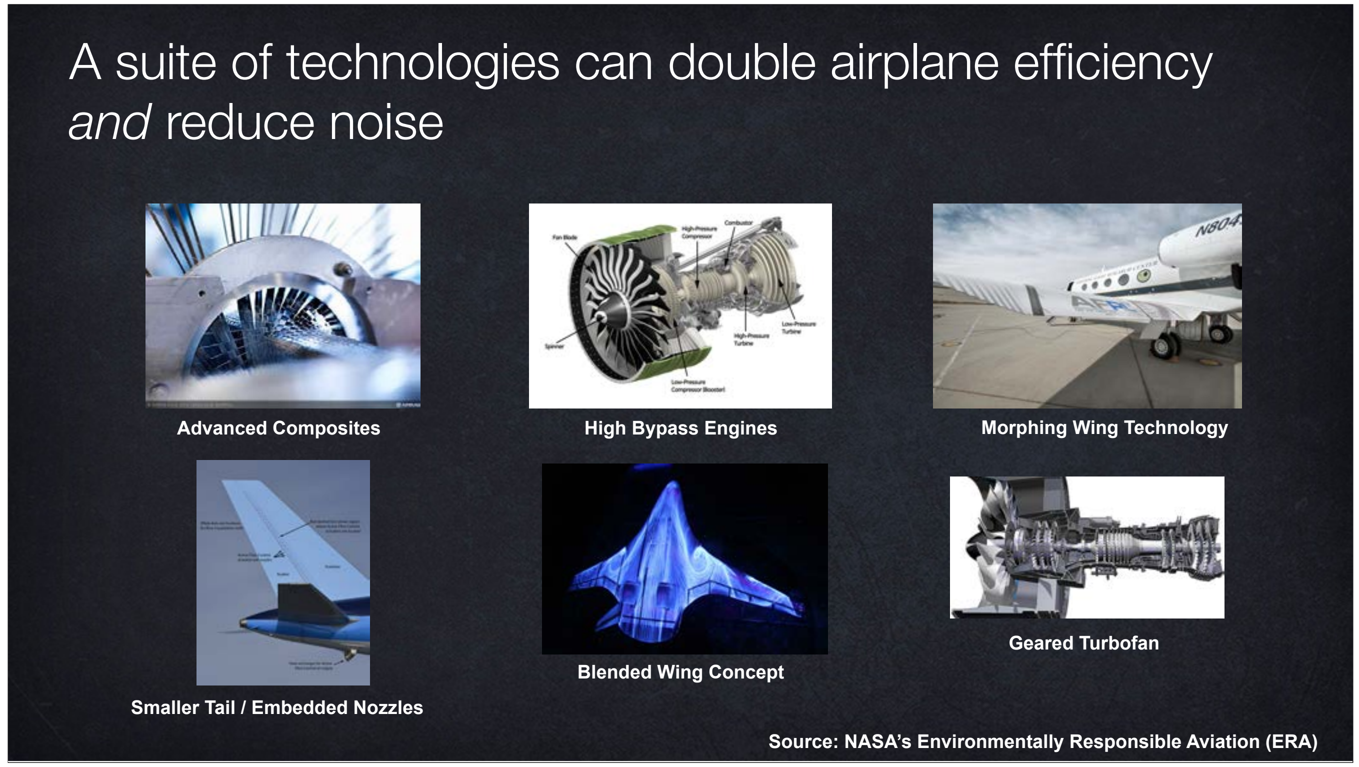


Using other approaches, those hook-together miniature structures are as strong and stiff as solid structures but are up to 90% air. * They don't even use carbon fiber. After carbon fiber could come * Miralon's or Dexmat's carbon-nanotube structures with up to 10× higher mechanical performance—and now we can make similar near-nanotubes from sugar, water, and sunlight via the bacterial enzymes hummingbirds use to weave their nests. Another approach uses nanoprinted metals with optimized microstructures. * Airbus's collaboration with Autodesk generated this 45%-lighter partition for the *A320*, and * exciting design concepts for whole airplanes. Of course the same logic applies to * 3D-printed metal parts * as to bird-bones; as usual, nature has done all this before. *



Of course, airplanes have long been getting more efficient. Those US-certified from 1960 to 2000 cut fuel intensity by 70%—half by better engines, half by better airframes. That progress remains on such a steady and plodding course that Boeing's *NMA*/"*797*" * was expected to hit in 2025 * exactly the efficiency bull's-eye we estimated in 2004. But because of uncertain and often cash-short customers, incremental thinking, restricted vision, market turbulence, and Boeing's recent deculturation, the industry's trajectory is too slow, raising efficiency by just 20% per generation. At that rate it could take another century to do what we knew how to do a decade ago. By then we're cooked. Aviation now does ~6–8% of the cooking.

[Our assessment's conservatisms included not assuming any adaptive engines (VAATE, ADVENT,…), integrated adaptive structures such as morphing aircraft forms and flight surfaces, powered wheels, inductive runway integration, efficient high-speed propeller propulsion, pneumatic blowing, plasma boundary-layer, or electric propulsion. We also didn't account for system benefits of integrating blended-wing-body, or other advanced technologies, nor any use of liquid hydrogen fuel.] *



Next-generation options are well-known, effective, and profitable. Among the most obvious prospects already emerging, advanced composites will lighten aircraft by at least another 20% and enable the elliptical fuselage. Morphing wing technology can save over 10% of fuel in new ”clean sheet” designs and over 3% in retrofits while reducing noise by 10 dB. Geared turbofans can be 15% more efficient than conventional jet engines. Blended-wing-body designs could often save >40% if we change manufacturing and boarding/deplaning. But many more innovations are available, and they're often even more important in synergistic combinations than separately. *

How efficient can conventional jet aircraft become in the near future?

Potential Impacts
Vehicle Level - Best Performers

TECHNOLOGY BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6) v2013.1		
	N+1 (2015)	N+2 (2020**)	N+3 (2025)
Noise (cum margin rel. to Stage 4)	-32 dB	-42 dB	-52 dB
LTO NOx Emissions (rel. to CAEP 6)	-60%	-75%	-80%
Cruise NOx Emissions (rel. to 2005 best in class)	-55%	-70%	-80%
Aircraft Fuel/Energy Consumption‡ (rel. to 2005 best in class)	-33%	-50%	-60%

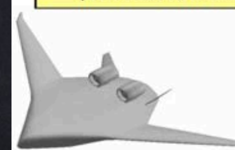
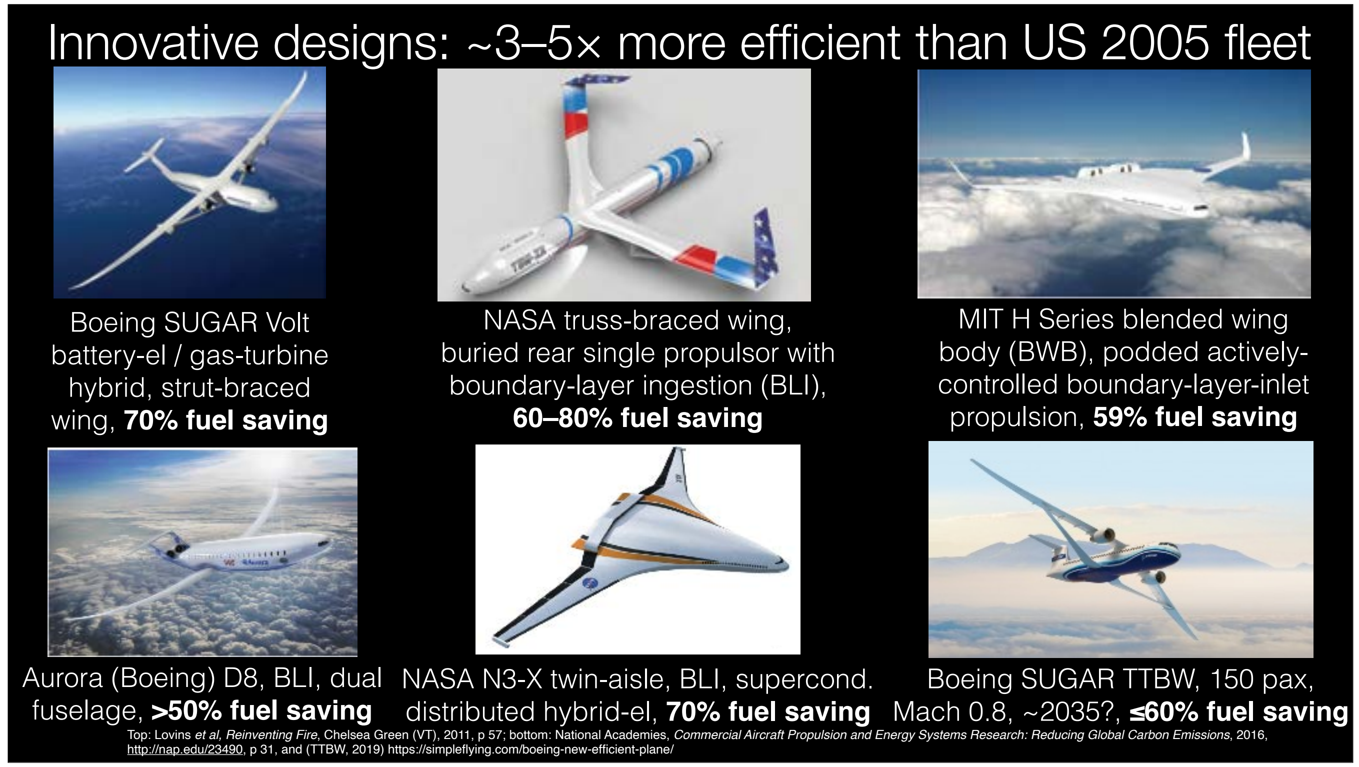


Table 15. N+2 HWB-GTF Concept Performance Summary

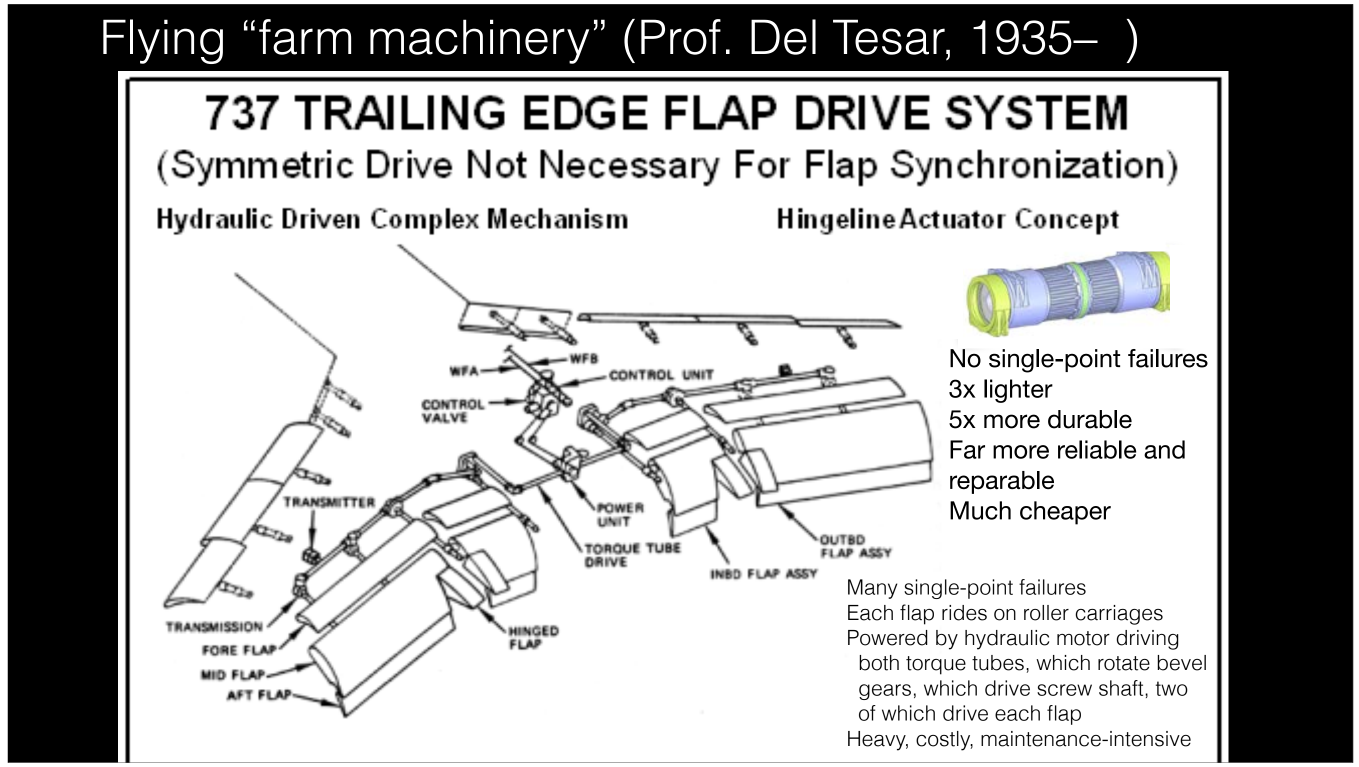
	Noise	Fuel Burn	Emissions
ERA Target	-42 dB Cumulative Margin to Stage 4	-50% Block Fuel Burn Relative to 2005 Best-in-Class	-75% LTO Nox relative to CAEP/6
HWB301-GTF	-40.3	-47	-79
HWB400-GTF	-40.3	-49.4	-79

Combining available with near-ready technologies can dramatically raise fuel efficiency. NASA's 2013 roadmap foresaw 50% fuel savings available by 2020 and 60% by 2025. These technologies are pretty obvious…. *

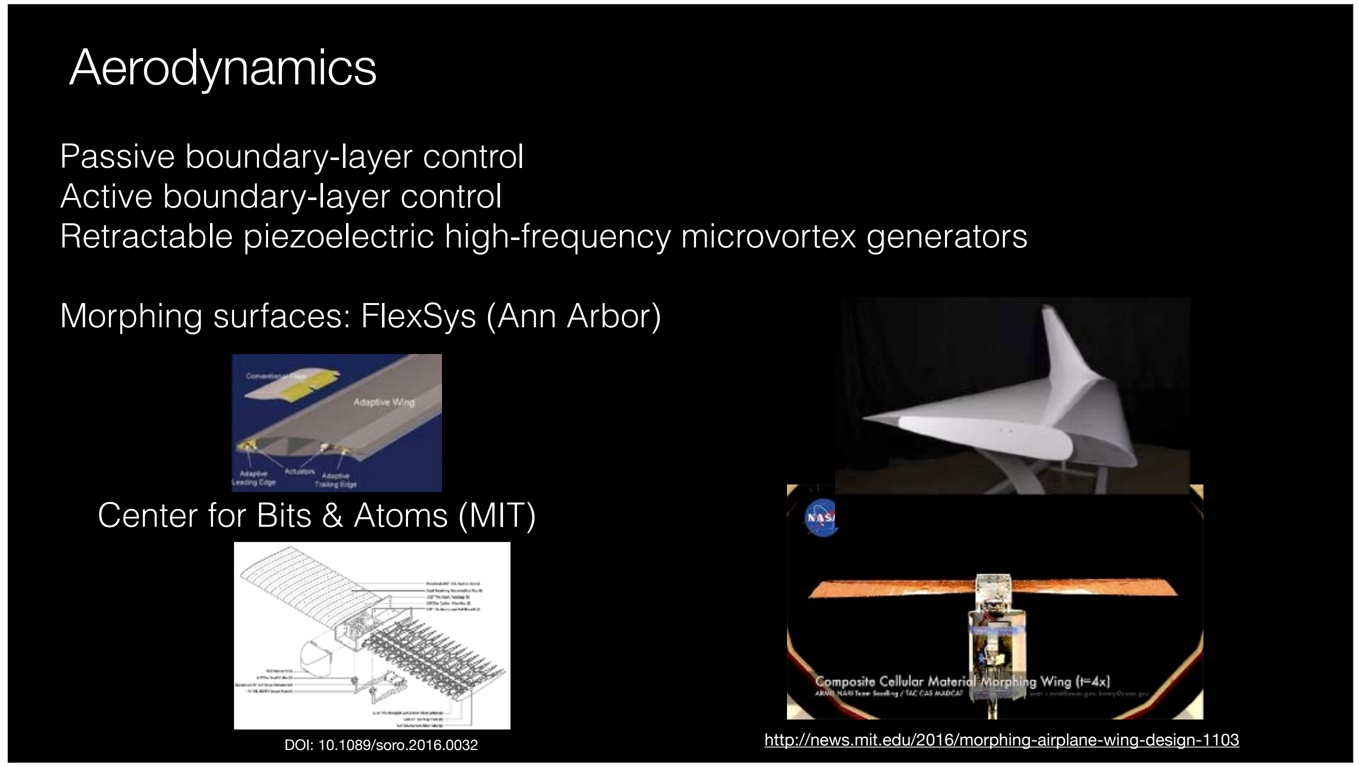


Indeed, thanks to designs like these, more-ambitious combinations of current technologies can boost the US fleet's efficiency cost-effectively by *3–5x* over its 2005 level. The upper three designs from Boeing, NASA, and MIT are a decade old, while the lower three are several years old, but both sets can save *~50–80%* of fuel vs. 2005 best-in-class or today's fleet, via strut-braced or truss-braced wings, riblets, advanced-composite structures, hybrid-electric propulsion with gas-turbine-assisted takeoff and range reserve but electric cruise, podded or buried propulsors, boundary-layer ingestion, some blended-wing-body designs, and other expanding innovations. NASA Langley's then Chief Scientist, Dennis Bushnell, told me five years ago [early 2019] that just proper application of truss-braced wings with advanced aerodynamics can raise the lift/drag ratio from ~18–19 with tube-and-wing or 22–23 with blended-wing-body to *40–60+* while considerably reducing weight^. Swiss laminar-flow wizard Werner Pfenninger even designed L/D as high as 100, nearly 5× current norms. Bushnell suggests further adding other refinements, such as thrust vectoring from fully-aft propulsors to eliminate the empennage (tail), and replacing landing gear and heavy brakes—totaling on the order of half the fuselage weight—with lower-impact automatic landing and deployable parachutes for refused takeoffs. So there's still lots of hidden treasure. *

[^He wrote in July/Aug 2022 that such braced wings "would at least double" lift/drag: "Emissionless air travel: how it might be achieved," aerospaceamerica.aiaa.org. Further technical details are at https://ntrs.nasa.gov/api/citations/20210021985/downloads/NASA-TM-20210021985 1FINAL.pdf.]



Even simple changes can be highly effective. Looking out the window as an old plane lands, I’ve seen the flaps extended by a hydraulic/mechanical system that the wizard of electric actuators—originally a farmboy gearhead—rightly calls “farm machinery.” It’s heavy, unreliable, and costly to buy and maintain. It doesn’t belong on an airplane. He’d replace it with a * 5× more durable, far more reliable and reparable, and much cheaper hingeline electric actuator that cuts overall system weight 3×. *



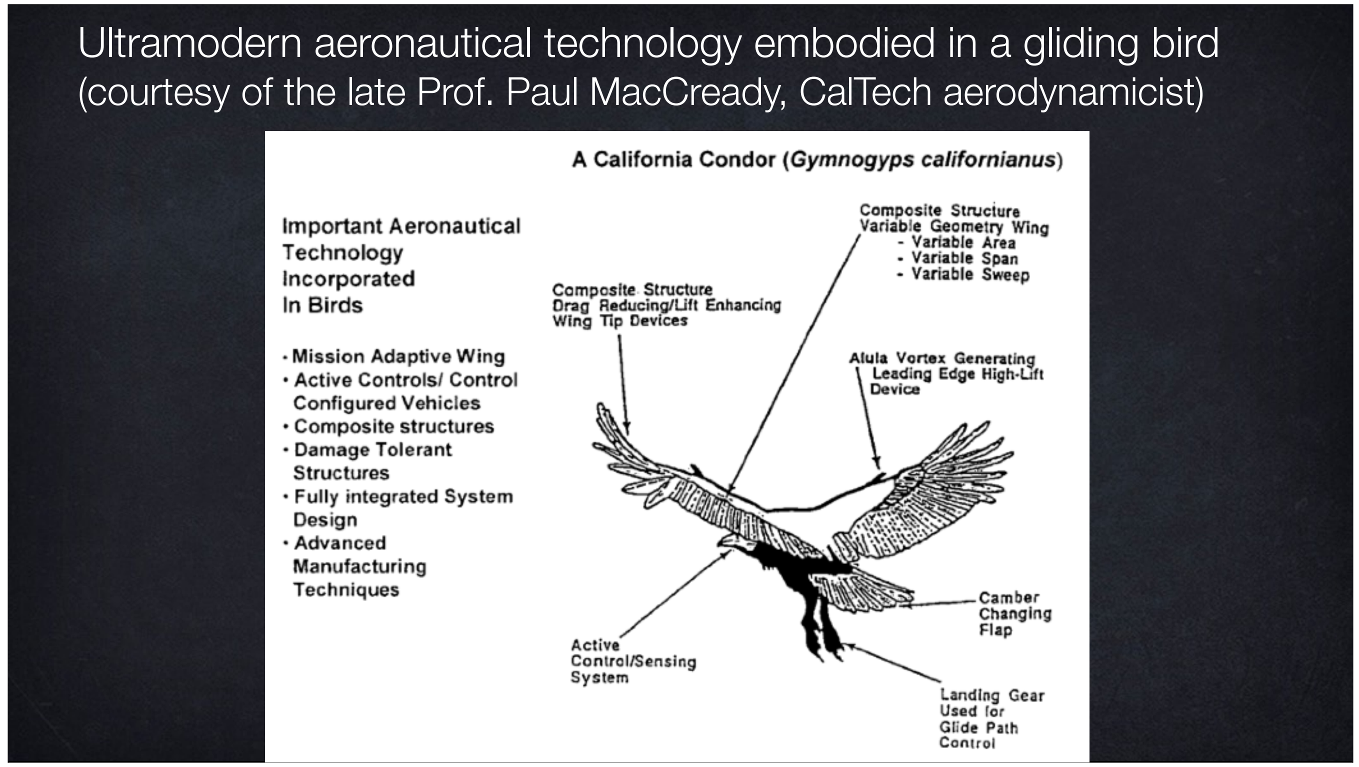
[Innovations in boundary-layer control are no longer the only big aerodynamic opportunity.] But now, like the Wright Brothers' bendable canvas and wood, flight surfaces can morph real-time to adapt to flight conditions, leaving the surface and airflow smooth, as in these two methods. The first method, now starting to enter the supercar market, [is to go in Aston-Marton's MY2024 *Valhalla* car and is expected to be adopted by a competitor. It's] is also expected to save ~2–11% of fuel in planes; USAF has committed to deploy it on several hundred planes once flight tests are completed.
The second method is the lattice-and-membrane structure you just saw. *

[* FlexSys can make seamless, jointless, hinge-free wings whose edges can morph swiftly and deeply. First commercial use is expected next year.

* Another approach by MIT's Center for Bits and Atoms can morph for pure lift and roll as well as a standard wing but with lower weight.] *

Alsomitra macrocarpa (tropical Asian climbing gourd) seed

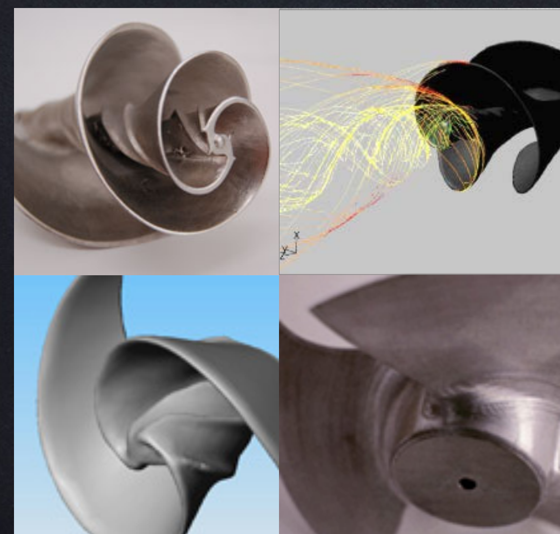
Nature is rich in great aeronautic designs like the tropical cucumber seed that can glide for hundreds of meters—not to mention…*



…the California condor. Besides all its advanced geometries, structures, and controls, I especially like the “Fully integrated system design” and “Advanced manufacturing techniques.” *

Can biomimicry raise propulsion efficiency? Jay Harman, an Australian naturalist and sea-captain, has imitated the Fibonacci structure in natural vortices to make superefficient pump and fan rotors, like this tulip-shaped pump rotor that can spin underwater at thousands of rpm with no cavitation. If your ~100,000 km of fractal blood vessels had the design and friction of standard industrial piping, you'd need a heart bigger than your body—very inconvenient. But your 1/3-kg, 1.5-W heart suffices because your bloodstream uses laminar vortex flow. Airplanes don't yet use it. They should. (Disclosure: I own about a thousandth of Jay's holding company, Pax Scientific.) *

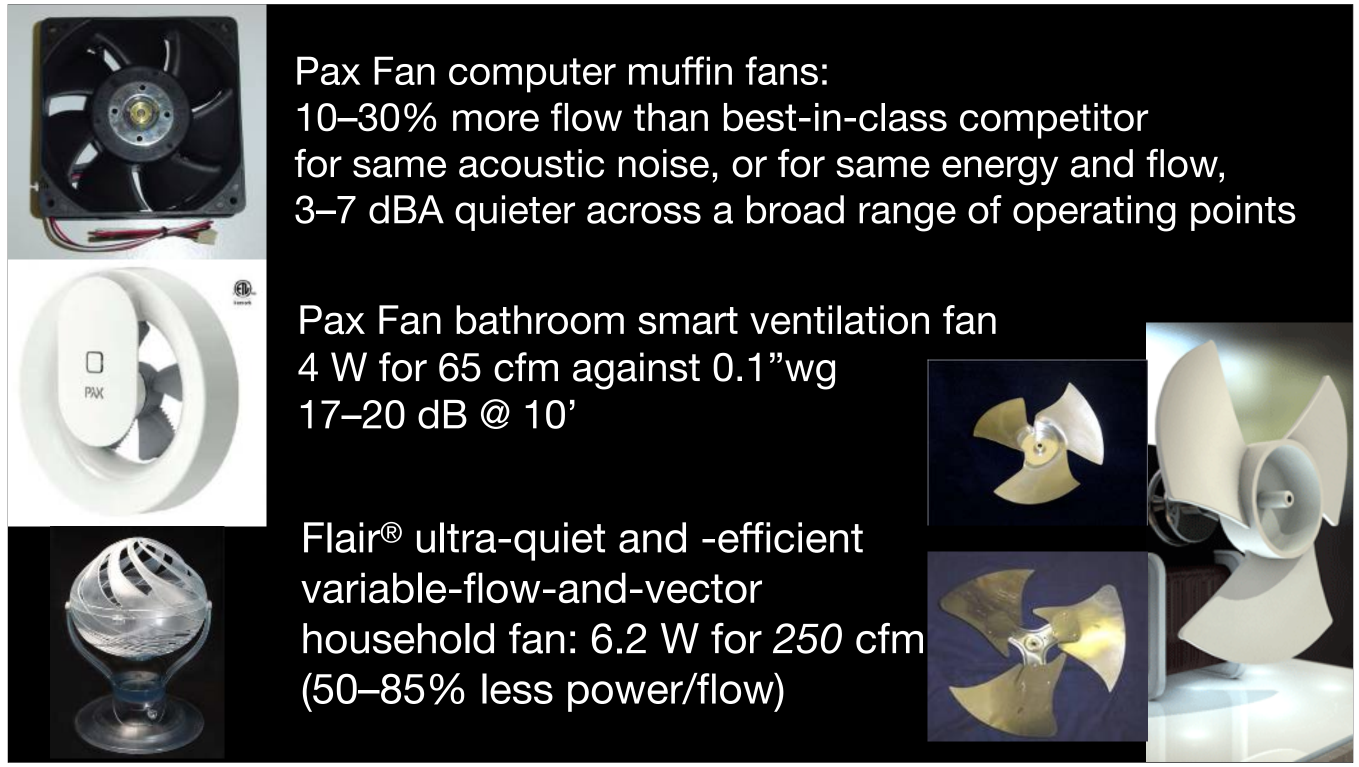
Biomimetic hydrodynamics



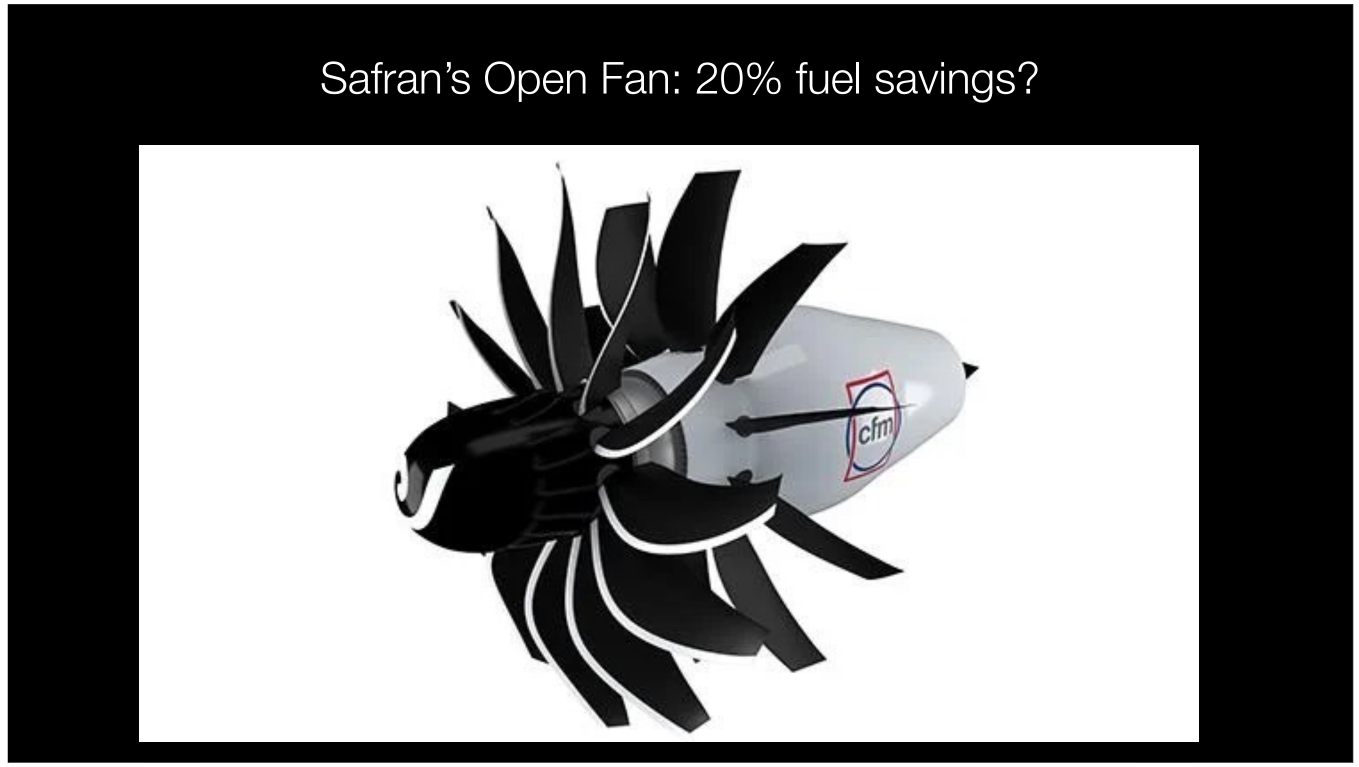
- In fans, pumps, turbines, and turboexpanders, laminar vortex flow can raise efficien-cy by 20–30% and cut noise
- Fish can pass unharmed
- Computer muffin fans get +30% flow/W or −10 dBa
- Read *The Shark's Paintbrush*
- Devices are starting to enter the market

Such rotors can empirically raise pump and fan efficiency by ~20–30%, not quite violating the pump equation. [After intensive effort by a team of Cambridge PhD hydrodynamicists, c] Computed and observed pump behavior now match up nicely. *

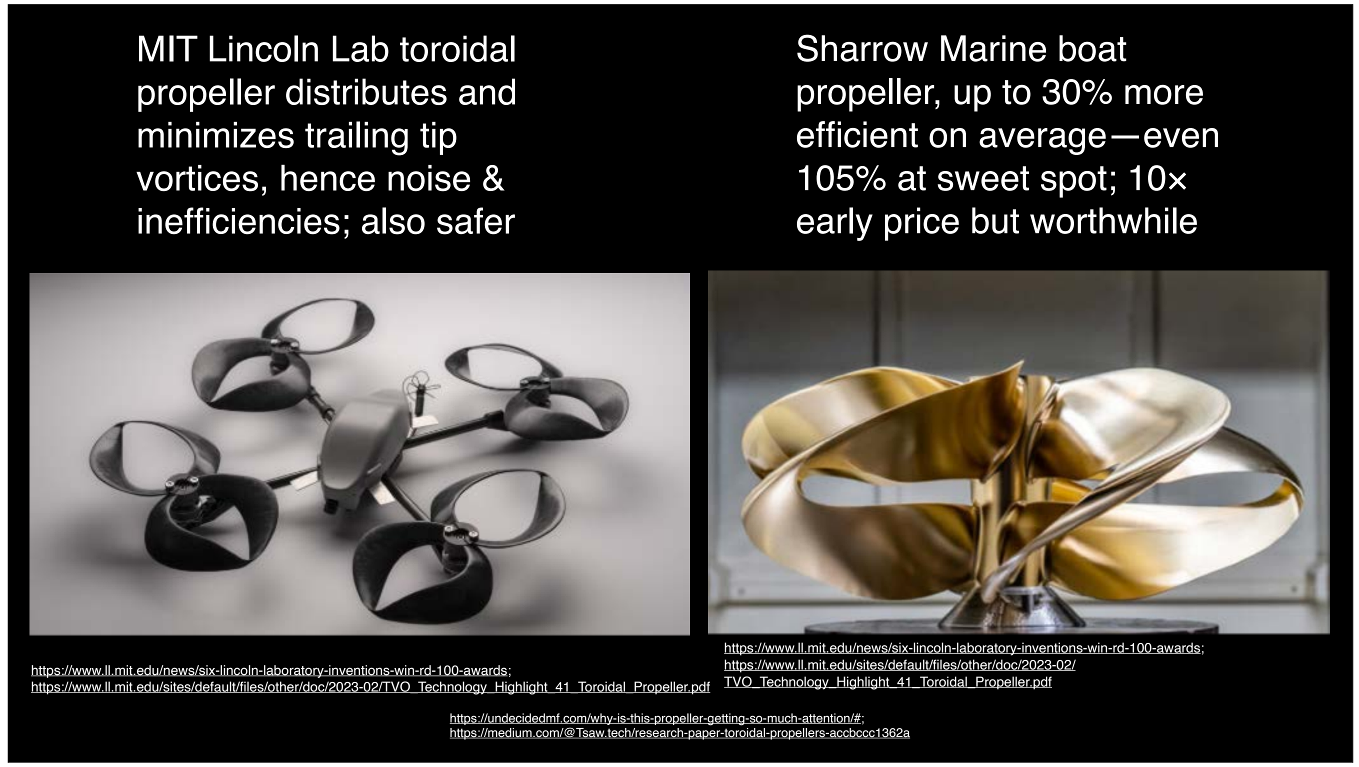
Some of Pax’s diverse superefficient fans, propulsors, winglets, and hulls are now on or entering the market. Remarkably, their efficiency gains are independent of scale *and of Reynolds number*, so for air as for water, cheaply converting standard fuselage airflow to laminar vortex flow or toroidal flow regimes can cut drag—in one early torpedo trial, by 14%. *



Pax’s household fans are far more efficient and quieter than conventional ones. The latest, at the bottom, uses 50–85% less power per unit of flow than its Holmes, Vornado, and even Dyson competitors, while providing higher air velocity with far less noise. Might its principles yield more-efficient propulsors? *

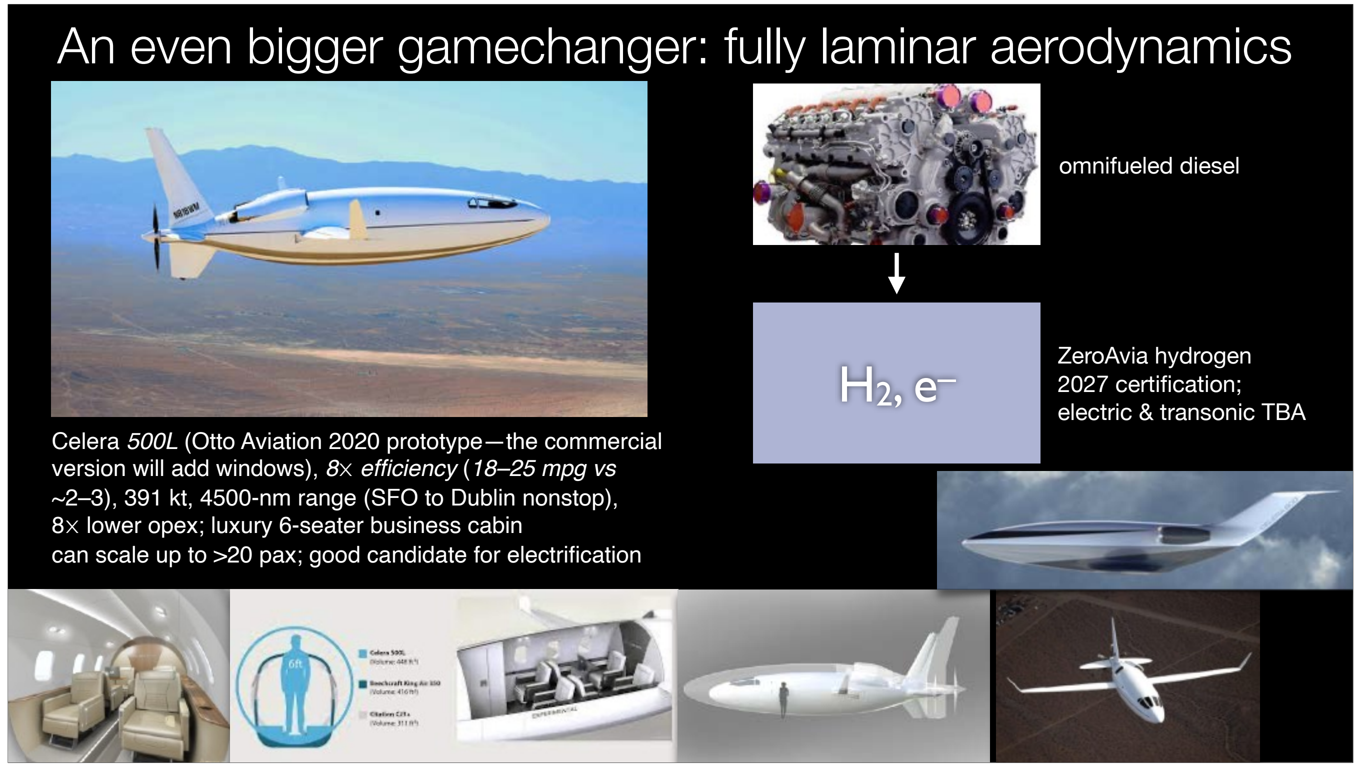


Safran and GE’s joint venture CFM International is testing an unducted or open rotor with one rotating stage and one stage of nonrotating variable-pitch blades, with a bypass ratio >70 (vs. 10 for a giant 777 engine with its carbon-fiber blades). A 20% fuel saving is expected, in-service by the mid-2030s. I wonder if such designs could benefit from subtle Fibonacci shapes like Harman’s biomimetic fan blades. *



Another suggestive innovation, rediscovering a 120-year history with over 160 patents [https://en.wikipedia.org/wiki/Toroidal_propeller], is the award-winning toroidal propulsor for quiet drones developed by MIT Lincoln Lab aerodynamicist Tommy Sebastian and intern Christopher Strem working on ring wings—an old concept said in the US Patent [#10836466B2] to improve lift/drag by 40–60% compared to a linear wing. Some 35–40% of a typical aircraft's drag is due to wingtip vortex formation, and the toroidal propulsor has no wingtips. It may weigh more or perhaps less per unit thrust, depending on materials.

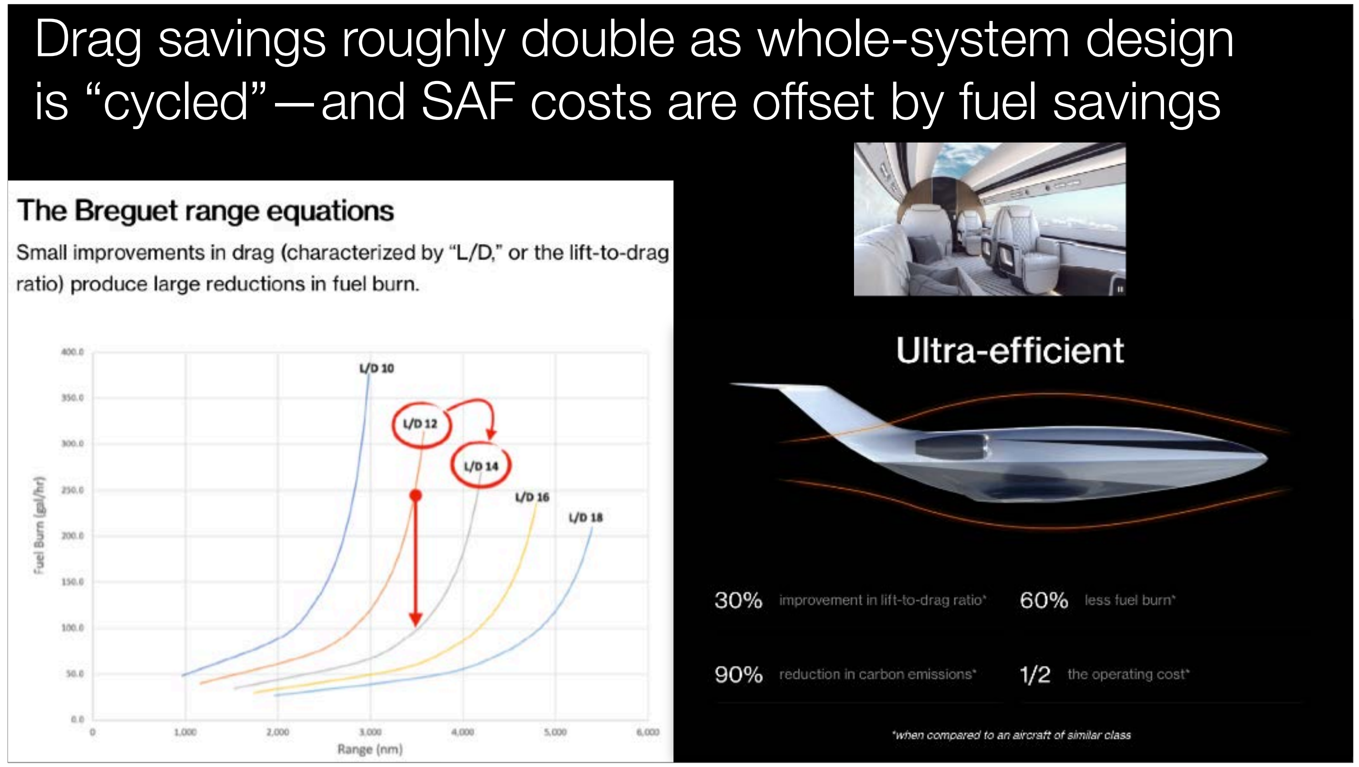
* A parallel development by a musician seeking to abate annoying drone noise has been successfully commercialized as a marine propeller, available 3D-printed from online makers or in elegant marine bronze from Sharrow Marine. Both air and marine versions can save fuel and cut acoustic signatures, attracting military interest. *



Now let's start putting these pieces together. Three years ago [2021] I visited William Otto Sr. and his team in southern California [at the Los Angeles Logistics Airport]. Bill was Chief Scientist/Avionics for the *B1*. Since 2007, his firm has been developing this radically optimized plane that exited stealth mode in 2020 and has demonstrated ~59% lower drag than a standard business jet, thanks to highly laminar flow over the entire fuselage, wings, and tail. Critical areas have no rivets, seams, gaskets, or gaps. [Its 52' wingspan—skinny, stubby, set far aft—illustrates an alternative approach to longer wings for extreme efficiency.] [Scores of flight tests systematically validated the flight envelope, emphasizing wheels-up and flaps-up, flying up to 15,000' and >250 mph with no surprises.] This *500L* initial design aimed at type certification by 2025 as a $5m business plane with 6'2" stand-up cabin height and longer range than a *737.* [Its chubby fuselage also offers important RORO cargo options. MTOW is 12,500 lb. Glide ratio is 22 for up to 120 miles of glide from its 30,000' ceiling. That ceiling rises to 38,000 and 50,000' by adding more turbocompressors; 65,000' is targeted. Balanced field length targets 3,500–4,000', comfortable on Aspen's 8,006' runway.] /

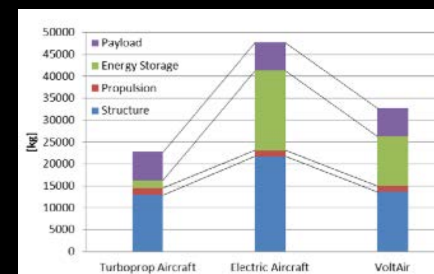
But after three years of successful flight tests, the firm decided to leapfrog straight to bigger models. [The first doubled-size variant could hold two or three dozen seats.] Superlaminar flow is clearly feasible in regional-jet size (~70 pax) and, as Airbus work suggests, looks possible up to about *737* size. But all sizes could blow up GA and carrier business models, because smaller, cheaper planes are perfect for rapidly emerging point-to-point route architectures serving any of >5,000 US airports. /

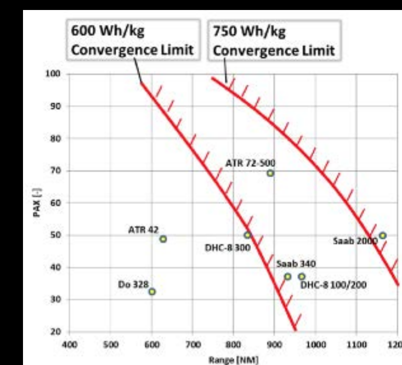
The 500SL's initial engine is a 500-hp aluminum [5.9-L V-12] turbodiesel [, designed in Russia for the Yak-152 trainer and produced by RED in Germany as the A03]. It can burn any fuel including 100% SAF. FAA considers this twin-6 to be two independent engines for safety purposes because its halves can run separately. The single pusher prop is also safety-qualified. But a diesel engine isn't the only option. Two years ago [June 2022], Otto Aviation confirmed plans for a 19-seat (for cheaper certification), 1,000-nm-range midsized 2027 version powered by a ZeroAvia hydrogen fuel-cell system. That [600-kW ZA600] powertrain has already flown in a 19-seat [Dornier *228*] testbed and is being tested as one of four engines in a Dash8/Q-400 turboprop. Its operating economics should beat even the ultra-cheap diesel *500L* due to even lower drag [(eliminating the big diesel air intakes and cooling blisters)], less propulsion-system maintenance, and cheaper fuel. Electric designs are also underway and look very promising, because the superefficiency displaces many heavy batteries. [Having spent a day inspecting the plane and grilling the team.] I think this may be the most important new plane family in decades. [Airport planners who see it only through the lens of today's hub-and-spoke big-plane fleet ignore it at their peril.] And now Otto Aviation is starting to talk about its * transonic, super-laminar Celera *800* design. /



As is usual with integrative design, benefits compound. Greater lift-to-drag ratio reduces fuel volume and weight for a given range. Less fuel means smaller wings, powertrain, and structures, so a 30% drag reduction compounds into a 60% fuel saving. Moreover, Sustainable Aviation fuel’s higher price is more than offset by fuel savings, so direct operating costs using SAF can be half those of a standard business jet burning Jet A. The Celera *800* design’s carbon emissions, 36 gCO_2/seat-mile, are virtually identical to those of common EVs (~34). Another nice innovation is * panoramic digital windows, called “supernatural windows,” that save weight, improve laminar flow, promote thermal and visual comfort, and make the cabin 20% bigger. *

A 2011 predecessor to *Celera*— EADS's *VoltAir* or *Voltaire*





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

In 2011–12, EADS, now Airbus, published a provocative technical design study for a * largely laminar-flow, bulbous, pusher-fan 68-pax turboprop with 900-nm range and some basic efficiency improvements. Its 25% greater energy efficiency, hence smaller batteries, and then the resulting decompoundings of mass and other burdens, * could reverse more than half of the near-doubling of weight from electrification. This means we can do far more with milder battery progress. * The EADS authors concluded that "typical payload/range missions flown today can thus be realized with 750 Wh/kg battery systems, compared with 1000 Wh/kg, which are necessary for the conventional configuration." In other words, you can do the same thing with far less ambitious batteries *if you also get efficient*. That was correct in 2011. Now we can do much better. It wouldn't surprise me if ultralighting, ultralaminar flow, and other efficiency advances already proven and starting to enter the market could converge with better batteries, motors, power electronics, and even ultralight photovoltaics (some already commercial at 40% efficiency) to make electric planes rival if not even surpass the key parameters of today's kerosene planes. /
Lest you think this absurd, let me remind you that it's exactly what has happened with battery-electric cars. Even I used to think those 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 I own two fine battery-electric cars and wouldn't dream of going back. To-day's best battery-electric cars beat fossil-fueled cars on every criterion I can think of except sticker price, which will reach parity in the next few years, and does today in some categories; and already, EVs virtually always win on lifecycle cost. *

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

This needn't depend on new materials: as our aluminum van showed 15 years ago, you can do a lot even without carbon fiber. Lucid[, led by former Tesla executive Peter Rawlinson,] is now selling its *Air* model—the *MotorTrend* 2022 Car of the Year[—at a $77–169k base price]—whose compact powertrain helps fit a spacious luxury interior into a midsize package. Its efficiency focus won it a record 516-mile EPA range rating with a big [118-kWh 900-V] battery that can soon enable bidirectional charging. Power up to 1,234 hp (921 kW) gives it 0–60-mph acceleration in 1.9s. Can your gasoline car do that? Will your neck tolerate it? [However, its all-aluminum monocoque and battery mass compounding bring its curb mass to 5,345 lb / 2,425 kg—~87% above the five-seat and still-all-metal Lightyear One (with a 450-mile range), and nearly six times Toyota's 2007 *Prius*-size but very functional PHEV carbon-fiber *1/X* concept car. I hope dramatic lightweighting is in Lucid's future.]

[M. Kane, https://insideevs.com/photo/5174383/lucid-air-tri-motor-race-car/, 30 Oct 2021; F. Markus, https://www.motortrend.com/news/lucid-air-2022-car-of-the-year/, 15 Nov 2021. Lightyear range is in WLTP [Worldwide Harmonised Light Vehicles Test Procedure) terms.]

Mercedes's 2022 developmental car gets [~7.48 mi/kWh or] 252 mpge, thanks to 95% battery-to-wheels efficiency, exemplary 0.17 C_d, and curb mass [(1755 kg / 3869 lb)] 87% above that of a standard-range Tesla *Model 3*. But the *EQXX*'s range was tested at *1202 km / 747* mi [nominally 2.75× the *Model* 3's range, or 1.45× the Lucid *Air*'s, but not comparably expressed]. The battery is sized for a compact EV, but this much bigger car's drag and rolling resistance are so low that cruising at 81 mph / 132 km/h needs just 14 hp / 10 kW. There's even a rooftop solar array to help run accessories. /

The [nearly 100-usable-kWh 900-V] battery pack [weighs 495 kg—200 Wh/kg at >900 V—] is 30% lighter and 50% smaller than the production model *EQS*'s [108-kWh] battery—showing how quickly batteries are evolving with the help of electric racecar technologies. [The EQXX battery, slated for MY2024/5 production, looks akin to the in-production Farasis battery at 330 Wh/kg (220 at pack level), 750 Wh/L, over 1,000-cycle life (soon over 1,500), and 10–80% fast charging in <20 minutes.] /

Designs like this confirm that range anxiety will become as obsolete as the speed of your modem. And this sedan, despite some fiberglass, is basically made of steel and aluminum, not advanced composites. It therefore leaves more efficiency and range on the table, even though it's 28% lighter than the [2,425-kg] shorter-range Lucid *Air Grand Touring*. [Some of its powertrain components are to enter the market in the electric CLA model starting late this year—2024, in MY2025]. *

[https://www.mercedes-benz.com/en/vehicles/passenger-cars/concept-cars/vision-eqxx-the-new-benchmark-of-effiency/; Mercedes-Benz image from Gallery, https://www.caranddriver.com/photos/g38646501/mercedes-benz-vision-eqxx-concept-revealed-gallery/?slide=10]

“NeverCharge” solar-powered Hypercar®-class 2-seat el. vehicle (aptera.us): up to 1,600-km range, but most drivers *will need no recharging*, because it’s so efficient (≤0.7 L/100 km) that its 3 m^2 PVs capture enough energy for ~18,000 km/y. It has half a Tesla’s mass, and less air drag (C_d 0.13) than the wipers or side mirrors of a US pickup truck! 2024 release (if $); $26–45k, depending on range.

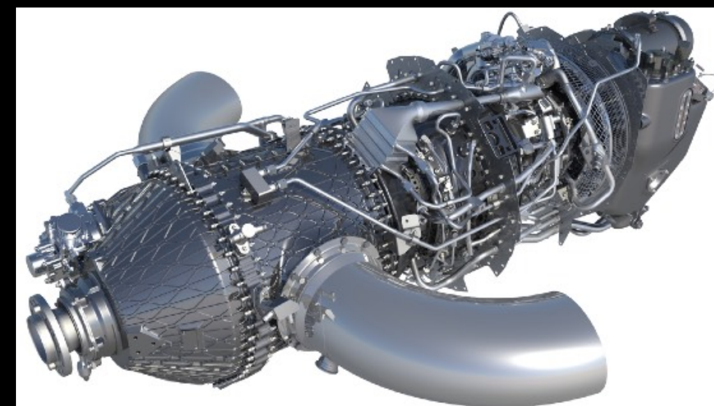
“Lightyear One” mostly/all solar-powered (5 m^2, 21.5%-efficient, ~12 km charge/h) 5-seat 4-wheel sedan, 0.78–1.7 m^3 cargo, C_d 0.175, 0.9 L/100 km, 725-km range, awaiting capital (lightyear.one).

Now the *next* efficiency leapfrog is emerging. Two solar-powered Hypercars®, both from firms I advise, are ready to mass-produce as soon as they finish raising production capital. Most drivers will never need to recharge this 2-seat electric vehicle, because its solar cells capture enough energy to drive ~40–60 km/d. It’s as if your present car magically added two gallons of fuel to its tank each day you park it outside. To make a long trip, you can quickly recharge the tiny batteries with household electricity for ranges up to a thousand miles. My BMW and Tesla electric cars are among the most efficient now sold, but this 2-seat vehicle, with a very crashworthy composite body, will nearly triple Tesla efficiency to [≤0.7 L_{equiv}/100 km or] 343 mpge! * The Dutch firm Lightyear is also ready to produce a 5-seat, 4-wheel, 725-km-range, light, very aerodynamic [C_d 0.175], car whose 5 m^2 of solar cells and [0.9 L/100 km or] 251-mpge efficiency [matching Mercedes’s EQXX, 83 Wh/km WLTP, 97%-efficient powertrain] can add ~12 km of range per hour in the sun. So the charging infrastructure that others must pay for, these superefficient vehicles aim to bypass. And even they can be further improved.

There’s a similar story in electric heavy trucks. Tesla’s *Semi* 18-wheeler triples to sextuples current fleet efficiency with impressive economics, but critics initially thought the extra battery weight would reduce payload. Not true: the propulsion equipment is much lighter, so displacing 3 t of diesel powertrain and fuel keeps payload unchanged with modest platform lightweighting, which can go further if Tesla chooses to *raise* standard payload. *

GE Additive’s 35%-3D-printed engine for Cessna (2017)

https://www.ge.com/reports/mad-props-3d-printed-airplane-engine-will-run-year/



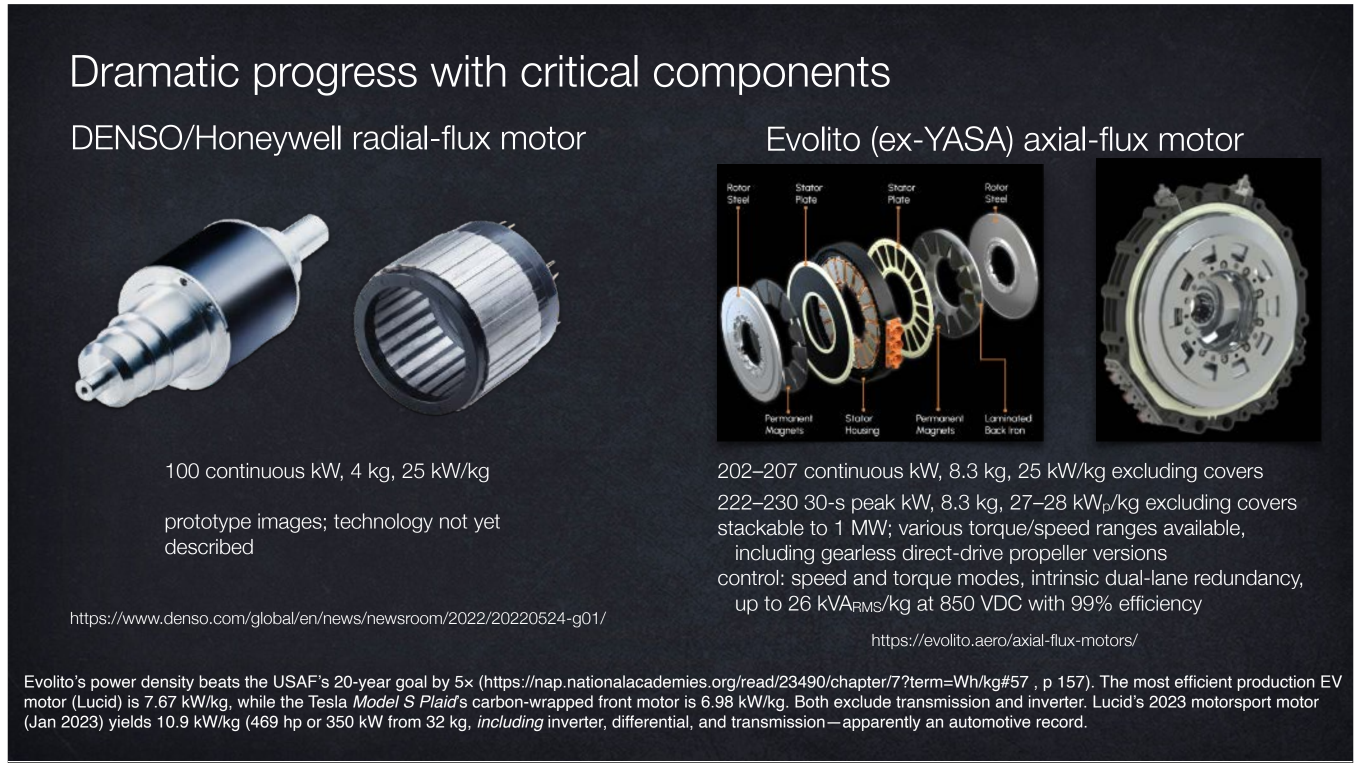
20% less fuel, 10% more power, 38% higher efficiency
1,000 more hours between overhauls
5% lighter; from 855 parts to 12; halved development time

So what’s happening in *aviation* propulsion? In gas turbines, the National Academies expect several more decades of 7%/decade efficiency gains beyond the current 55+%. GE’s 3D-printed complex fuel nozzles that helped make one engine one-tenth more efficient. In 2017, this business-jet turbofan delivered 10% more power from 5% less weight with 20% less fuel and 99% fewer parts. GE’s production version, called Catalyst, has a *16*:1 pressure ratio [for 850–1600 SHP]—the first clean-sheet turboprop engine in over a half-century. [This bodes well for the expected return of advanced turboprops in competition or combination with electrification. They’ll compete with electrics, often in the same model like the *Dash-8.* Competition is good.] This year [2024], GE is investing over $650 million in full-scale production of 3D-printing-enabled engines for bigger planes, including one with over 300 3D-printed parts—the GE9X engines for the giant *777X* planes. And GE’s ceramic-matrix composite turbine blades have one-third the weight of steel but remain strong at 1,315˚C, above many superalloys’ melting point.
*

Battery storage advances are *one* big key to replacing fossil-fueled flights—not the only determinative factor

Everything is changing at once—as it must

Yet coming up fast in the outside lane are electric and hydrogen-powered airplanes, the latter sometimes using gas turbines but usually fuel cells. I'll sketch some highlights in a moment. There is also *very* extensive and longstanding military investment in these technologies and in others. It ultimately finds its way into the civilian sector, but is not yet visible in the unclassified world or reflected in market expectations and planning forecasts, but it cannot fail to accelerate what I'll describe next. It's no accident that the maker of the most advanced always-aloft solar airplanes is the same firm [AeroVironment] that makes the Switchblade backpack-portable drones now in Ukraine—and it also makes my BMW EV's charger. And with drone innovation now critical to the outcome of Putin's War, and 200 Ukrainian drone-makers scaling up to a million units a year, new techniques will reach our civilian aviation much faster. *



A critical technology is the electric motors in between the power source and the propulsor. Some powerful EP electric motors are now 2–10× lighter than today's EVs use. The best aviation motors now deliver 25–28 kW/kg, nearly 3× more power-dense than the best EV motors or 2× better than the best e-racing motor. The example on the right, stacked to 1 MW, beat the Air Force's 20-year goal by 5×. Sleeker, lighter planes also need smaller motors and batteries, but those don't suffer lower efficiency as smaller gas turbines do. Top analysts now agree EPs will generally have lower capital and operating costs than fueled planes, driving rapid adoption in both commercial and private aviation.

[In 2011, the EADS team found aviation electric motors needed order-of-magnitude scaleup from the best high-power-density motors, which were then below 7–8 kW/kg and ~0.1–0.2 MW. Today's best aviation motors at up to 2+ MW offer 15–*25* kW_p/kg, even continuous kW/kg with peak efficiencies up to ~98%. Axial-flux, printed-circuit, aircore, stacked, hybrid reluctance/magnet, inside-out, and water-cooled designs are rapidly evolving—it's a zoo.] Lest you worry about critical materials, many fine light motors, both induction (asynchronous) and reluctance machines, have no permanent magnets, and iron-nitride supermagnets containing no rare earths (but promising up to twice their strength) have entered the market. Inverters are progressing from silicon switches to silicon carbide to nearly lossless, passively cooled gallium nitride. Kilovolt SiC switch ratings now make wiring small and light. [(Swiss powertrain maker H55.ch, with 19 years' experience on four remarkable electric planes, provides 1200 V and expects a C-23 EASA type certificate by the end of 2023.)] Mercedes's EQXX boasts 95% powertrain efficiency, Lightyear's EV 97%, and the best e-racing motors and inverters each around 99%. *

Electric drones: 0 to $12b/y in 10 years…next add pax

- Composite structures + ultralight, powerful motors (25–28 kW/kg) + ducted or open fans / rotors + sensors + software + novel system concepts/architectures…
- Efforts/firms emerging: Beta, Lilium, Joby, KittyHawk, Vahana (Airbus), Aurora, Uber, Zee, Blackfly, SkyRyse, Ampaire, Eve, Volocopter, Ehang, Terrafugia, Sabrewing….
- >100 total developers; more electric than fueled aircraft on order (McKinsey 1/24)
- Complements e-propulsion for normal planes; type certification processes 2020–
- With modern green electricity, optionally made onsite, electric or hydrogen propulsion can be zero-emissions and almost silent (except fueled hybrids)
- Joby ($2b) plans 2025 Uber-priced Manhattan–JFK 4-pax/1-pilot 7-minute service

lilium.com

Might visions of electric VTOL (eVTOL) air taxis like this 4 pax+pilot, 280 km/h, 250+-km Lilium get real, with urban roofs and mushroom-like stalks acting as nano-airports? What might this imply for the granularity, scale, and business model of airports and carriers? the need for airports? energy use? congestion? stranded costs? risks?

Thus electric flight is * becoming practical because * *many* diverse technologies, not just better batteries, are converging in a vast Cambrian explosion of innovation. * EPs have scores of skilled, serious, and amply funded developers (the total may be >200 for bigger platforms and is >1000 for Urban Air Mobility vehicles), about 9,000 orders for types with up to 30 seats, and at least 55 intending operators. In January 2024, McKinsey estimated a Future Air Mobility order book of more than 21,300 aircraft (not all firm) worth $118 billion—*more aircraft than commercial aviation's 16,500 order boo*k. Of the alternative aircraft, over 9,000 electric vertical-takeoff-and-landing taxis, more than a million drones delivered last year [2023] alone, and military R&D further enrich the e-aviation ecosystem. Joby's planned 2025 eVTOL taxi service from downtown NYC and L.A. to JFK and LAX looks on track so far (the first delivery to DoD was last year). The firm has raised $2b from such investors as Toyota, Intel, and Delta Airlines, and had $0.9b cash at end 1Q2024.

Timely regulation is the biggest uncertainty. FAA fell behind in setting drone certification standards, slowing piloted-plane certifications too; some developers stumbled; the pandemic slowed everyone; but some e-aviation type certifications are well along and FAA is rising to the challenge. Happily, flight without fossil fuel and without combustion can start resolving communities' CO_2, air-pollution, and health concerns by eliminating emissions and turbine noise, just as in ground vehicles. * / Whether or not electric VTOL [eVTOL] air taxis become common, electrification will present new challenges and opportunities to airports and to carriers[—especially those with fortress-hub rather than point-to-point route architectures]. * To run planes of all sizes and shapes, competition between advanced biofuels, electricity, power-to-fuel, and hydrogen will turn airports into integrated transport *and energy* hubs, probably using distributed models and designed for resilience. But electric air taxis will almost certainly use a lot more energy than electric ground taxis, collisions are more serious in the air, there are some real security concerns (like using eVTOLs to deliver bombs, as they now disruptively do in Ukraine), and if you liked congestion in two dimensions, you'll love it in three dimensions, so eVTOLs will need careful foresight. /

But first of all, will electric planes actually take off in the market, or are the skeptics right that they'll never fly? *

A snapshot of the global electric plane ecosystem, 2 Dec 2022 (old!)

Bloomberg New Energy Finance, “Electric Aircraft Propulsion: Technology and Industry,” Insight #30267, copyright permission pending.

Figure 9: Electric propulsion industry landscape

If you think EPs are pie in the sky, you might consider whether this Who’s Who of vendors and operators of electric planes all got it wrong. I hope skeptics will carefully read Kyle Clark’s *Volts* interview mentioned earlier (19 June 2024) and ask themselves if they’re surprised that Beta’s eVTOL has flown a ~600-lb payload for 386 nm. Some may need to reconsider papers like one eminent aeronautical engineer’s widely circulated screed, “The total impracticality of electric aviation,” which concludes that “Electric aircraft can never be more than expensive toys.” We shall see. How many of these firms would you like to bet against? *

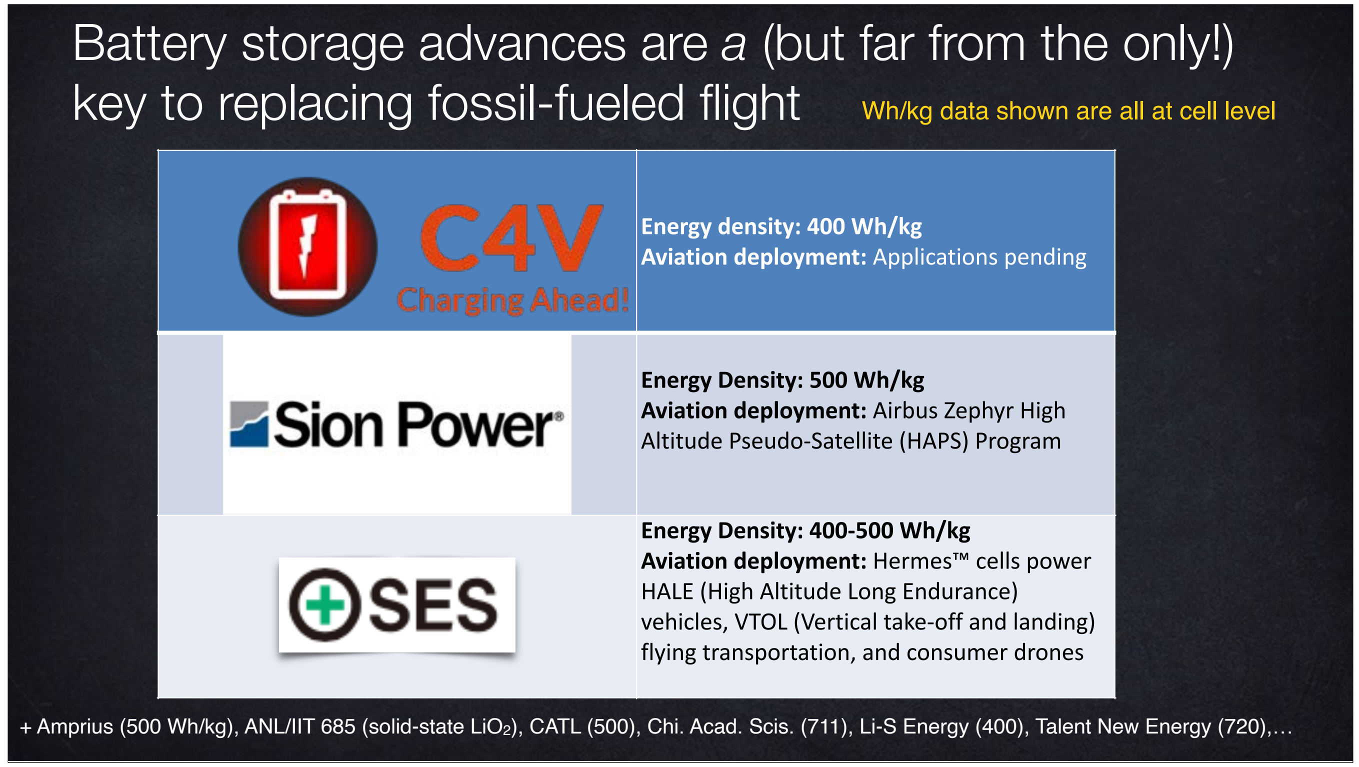
A snapshot of the global hydrogen plane ecosystem,16 June 2023

Bloomberg New Energy Finance, “Hydrogen Aircraft Propulsion: Technology and Industry,” Insight #31627, copyright permission pending

Figure 12: Hydrogen propulsion industry landscape

Source: BloombergNEF, company websites. Note: This is not an exclusive list of companies. Some companies are active in more than one value chain.

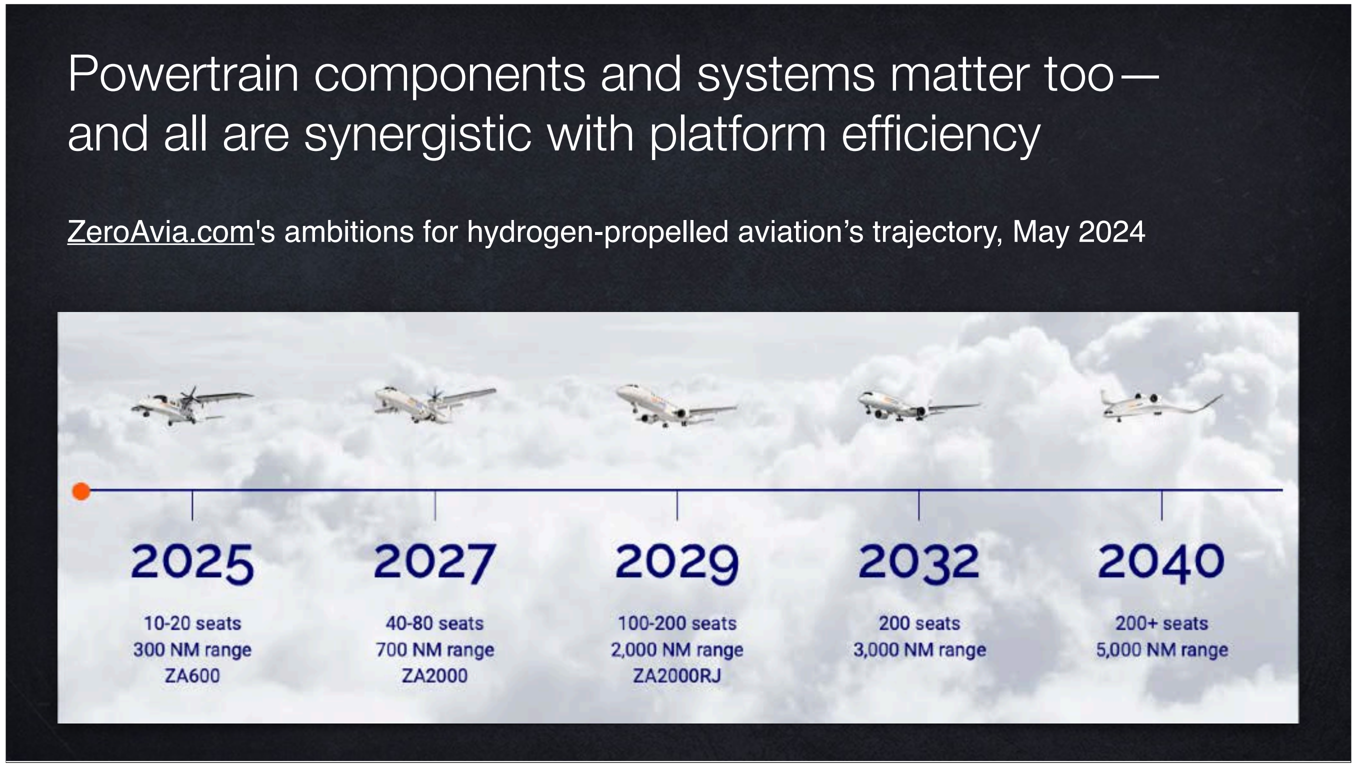
Or consider these counterparts in the hydrogen-plane ecosystem. I think it’s more likely that incrementally minded incumbents and commentators are deceiving themselves and about to miss their flights.*



Of course, top-of-mind for many people is battery energy density. The most advanced civilian *solar* airplane in 2015 was my friend Bertrand Piccard's *Solar Impulse 2* at 260 Wh/kg (pack level). With 2,000-kg MTOW, it circled the globe. Now, nine years later, at least three firms have doubled smartphone pouch cells' energy density to *400–500* Wh/kg—about three-fourths of the pack energy density that the National Academies said in 2016 would take 20 years—and several other firms are well over 500, at least on the lab bench. But 500 enables short-haul electric planes immediately, moving into medium-haul starting in this decade. Large-area batteries (or ultracapacitors or both) might also eventually form the airplane's skin *and* structure. / Already, lithium-metal-anode batteries offer twice traditional lithium-ion energy density, and some production models are even better. But as we saw, *battery energy density is fungible with platform efficiency*—only more so due to mass decompounding! Thus ICCT says 250 Wh/kg packs (the Panasonic 21700 cells in Tesla's Model 3 get 253), if put in nominal conventional planes and accounting for reserves, can carry 9 pax for 140 km; doubling that pack energy density to 500 Wh/kg (just reported by NASA with S-Se packs) could enable 280-km missions with 90 pax; but *reducing the plane's empty mass fraction would nearly quadruple commuter planes' market coverage—15× for turboprops!*^ Platform efficiency is the key. /

I've been riffing back and forth between the aviation and automotive revolutions because they inform, supply, and feed on each other. Planes do go faster than cars—and the same now seems true of their respective innovations. And major innovation drivers may lurk unseen outside your system boundary. We have EV batteries today mainly because smartphone makers strongly incentivized battery life, thus driving advanced lithium chemistries and efficient circuits. That made EVs possible, so Tesla built volume and made batteries cheap. Who would have thought that our smartphones would have birthed our electric cars—via brands like Panasonic and LG, mainly associated with consumer electronics? What new drivers of electric aviation by nonadjacent industries will be obvious only in hindsight? *

^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/.



Another way to power motors is fuel cells that electrochemically convert green hydrogen into electricity, pure water, heat, and nothing else. They're progressing rapidly. So are electrolyzers—essentially fuel cells backwards—to split hydrogen out of water using wind and solar power. These hydrogen technologies are now about a decade ahead of the predictions of three years ago. In late 2021, Chinese chemical giant Bǎofēng's 1-GW solar farm was making $2.7/kg hydrogen cheaper than from coal, so their chemical plant was switching over to solar hydrogen. Now there's a path to ~$1/kg. [RMI, Bloomberg New Energy Finance, and the Energy Transitions Commission publish good syntheses of this accelerating green hydrogen revolution.] /
Now combine the advances in electric *or* hydrogen propulsion with at least *some* platform efficiency gains and you get timelines like * this one from British hydrogen-powertrain maker ZeroAvia (partnered with BA, UA, Alaska, Schiphol Airport, and a host of others). These numbers will probably err in some direction and details; we only know that progress is very rapid and continues to accelerate. Notice how quickly this credible firm thinks hydrogen aviation will move from regional-jet into full-fledged jetliner size, rivaling today's midhaul planes in both capacity and range *in this decade,* then more. This February [2024], a California competitor successfully ground-tested an end-to-end liquid-hydrogen-to-propeller system for the equivalent of 3 h and 500 nm (with reserves) if installed in an *ATR72* regional jetliner. ZeroAvia plausibly foresees *40–80-pax hydrogen planes going 700 nm by 2027*. The firm says it's "initially targeting a 300-[nautical]-mile range in 9–19 seat aircraft by *2025*, and up to 700-[nautical]-mile range in 40–80 seat aircraft by *2027*" [emphasis added]. They might not exactly meet that goal, but someone may. It's unwise to stand with your back to a stampeding herd of techno-bison. *

[https://hydrogen.aero/press-releases/universal-hydrogen-successfully-powers-megawatt-class-fuel-cell-powertrain-using-companys-proprietary-liquid-hydrogen-module/]

After kerosene, cryoplanes (liquid H_2 fuel, –253˚C) with zero carbon?

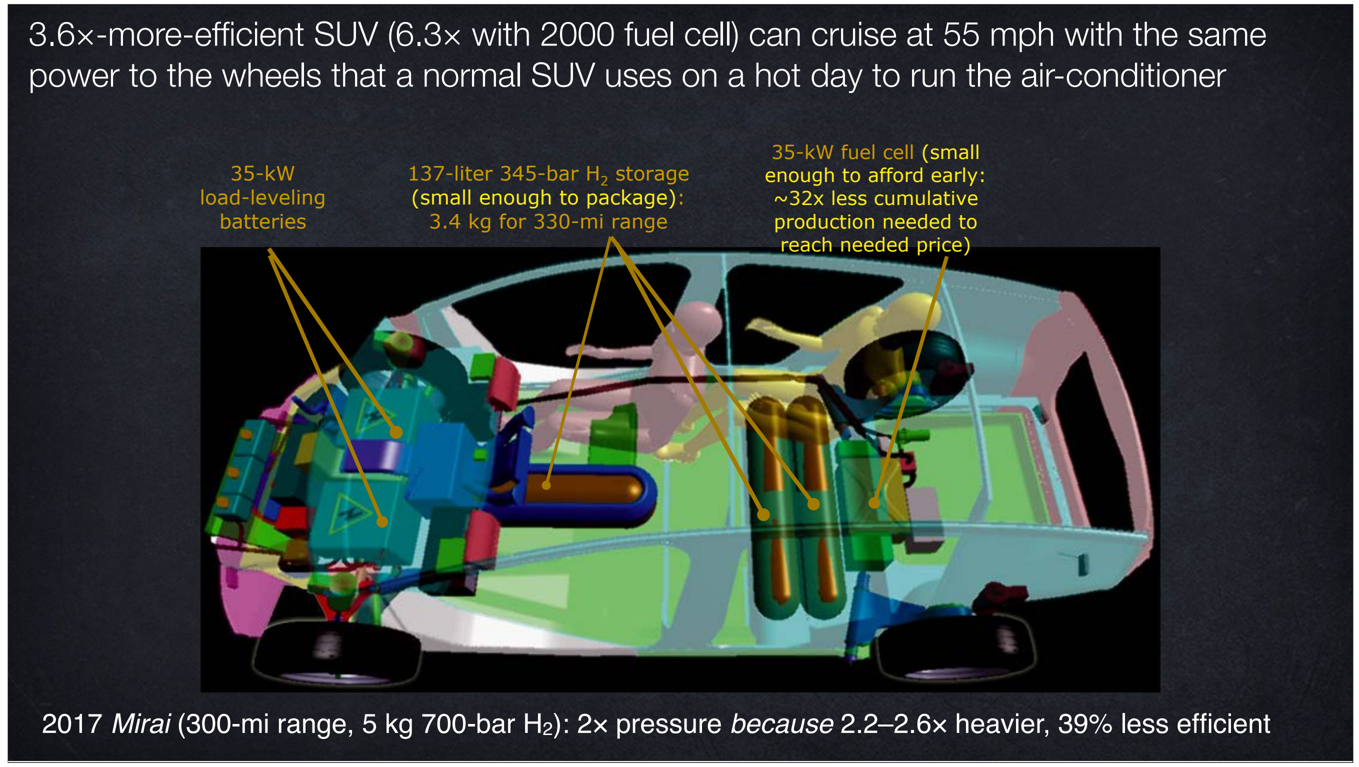
https://www.fzt.haw-hamburg.de/pers/Scholz/dglr/hh/text_2001_12_06_Cryoplane.pdf

- LH_2 is 4× bulkier but 2.8× lighter than Jet A—and clearly safer*
- Designed & tested: Airbus, Boeing, Tupolev *(TU-154* '88)*,* USAF
- Typical (*767*-class) Boeing 2003 study w/mass decompounding
  - Bad: empty weight (OEW) +8%, drag +11% (because bulkier)
  - Good: *takeoff* weight (MTOW) –24%, Initial Cruise Altitude Capability +13%, better climb characteristics, less engine maintenance burden
  - Net: ~4–5% *better* energy efficiency tank-to-flight based on airframe performance alone, or ~10–15% with H_2-optimized engines (contrary to 2000–02 Airbus consortium)
  - Liquefaction 300➝20K @ modern 4–5 kWh/kg (12–15% of LHV) roughly offsets airplane's efficiency gain; well-to-tank effciency is comparable to oil's, but with no hydrocarbons or CO_2 release
- –NO_x, 0 smoke/particulates/CO/HC/onboard CO_2; H_2O vapor?†
- Fuel cells are emerging for APUs—but maybe for propulsion too. P.M. Peeters (following NASA's Chris Snyder) thinks lightweight fuel cells & superconducting-motor unducted fans could *double* efficiency *vs.* LH_2 turbofan planes: his 415-pax conceptual design (7000 km, 0.75 LF) uses 55% less fuel than *747-400*; his 145-pax (1000 km, 0.70 LF) uses 68% less fuel than *737-400* (and at Mach 0.65, block time increases only 10%; might be *faster* if hubless, point-to-point, GPS-free-flight, ultralight, lower aero drag)
  - Thus ~20% long-haul and ~50% short-haul savings *beyond* RMI's 2004 analysis that assumed no LH_2

*NASA-Glenn CR-165525 & CR-165526 †Gauss *et al.* 2003, *J Geophys Res* **108**(D10):4304, say climate impact is ~15x smaller than avoided CO_2 (kerosene *vs* climate-safe hydrogen in a huge subsonic fleet), but do discourage stratospheric and polar flight—a reform MIT has now shown how to operationalize for all aircraft

What about intercontinental ranges? I won't dwell here on turbine- or engine-hybrid designs, which probably have an important transitional role much as they did for cars. But automotive history, where superefficiency is taking us to once-unthinkable *solar*-powered cars, hints that similar and inexorable trends are at work in aviation. It may even become possible in your lifetime for a wholly solar-powered superduperefficient ultralight plane to carry commercial payloads across oceans. Solar power alone flew a *Helios* pilot to nearly 97,000' 25 years ago [1999]. This year [2024], Airbus targets initial telecoms and reconnaissance services by its solar-powered stratospheric (>60kft) Zephyr platform, expecting close to a thousand in the air within a decade, each flying for 200–300 days at a time. / Happily, photovoltaic or PV-and-battery airplanes will get to compete with a more conventional solution: replacing transoceanic planes' kerosene with liquid hydrogen in redesigned "cryoplanes" such as Airbus is developing. This lightest known fuel (hence rocket fuel), cooled to 20˚K, is 2.8× lighter than JetA but * 4× bulkier, requiring * wholly new airplane designs. * Boeing's *767* study found in 2003 that a well-designed cryoplane with reoptimized engines could be ~10–15% *more* efficient than the current JetA version—enough to offset the liquefaction energy. And today's cryogenic tanks have walls just millimeters thick. * Today's cheap renewable electricity makes liquid hydrogen environmentally far superior to Jet A, and economically interesting for intercontinental flight. * Dutch designer Paul Peeters found that a fuel cell and high-temperature superconducting motors can push airplanes' established 3–5× efficiency gain to ~6–7×. That was before we had options like super-laminar flow and extremely lightweight motors, so now that number is probably >8×. Hydrogen has its own issues, but is getting cheaper and could be a real competitor for long missions. /

[As always, I mention such extreme technologies not to imply they're directly relevant to current choices in Aspen, but to help you envisage the durable processes and drivers that will keep transforming aviation beyond recognition and hence affect the short term. Even the earliest stages of those shifts, just over the next ~5–6 years, will be highly disruptive, and will probably make your current airside plan obsolete before it could be built. That's why it's so premature.] *



Returning for a moment to the automotive analogy, radical vehicle fitness enables *all* kinds of advanced powertrain. Our original carbon-fiber electric SUV design in 2000 illustrates this. It used an early fuel cell (long before cheap batteries), but its ⅔-lower tractive load made its H_2 tanks ⅔ smaller for the same range, so 1990s off-the-shelf gaseous *345*-bar (5,000-psi) cylindrical carbon-fiber tanks packaged easily and could safely carry H_2 up to 10–12% of their own filled mass. We didn't need 700-bar tanks like Toyota's 1,850-kg *Mirai.* I'm in awe of *Mirai*'s doubled-power-density, 95%-cheaper-in-9-years [*vs* 2008 Highlander *FCV-adv*] fuel cell—but the fuel cell and hydrogen tanks could be 2–3× smaller if put in Toyota's concept carbon-fiber *1/X* rather than the 4.6×-heavier *Prius V* platform.

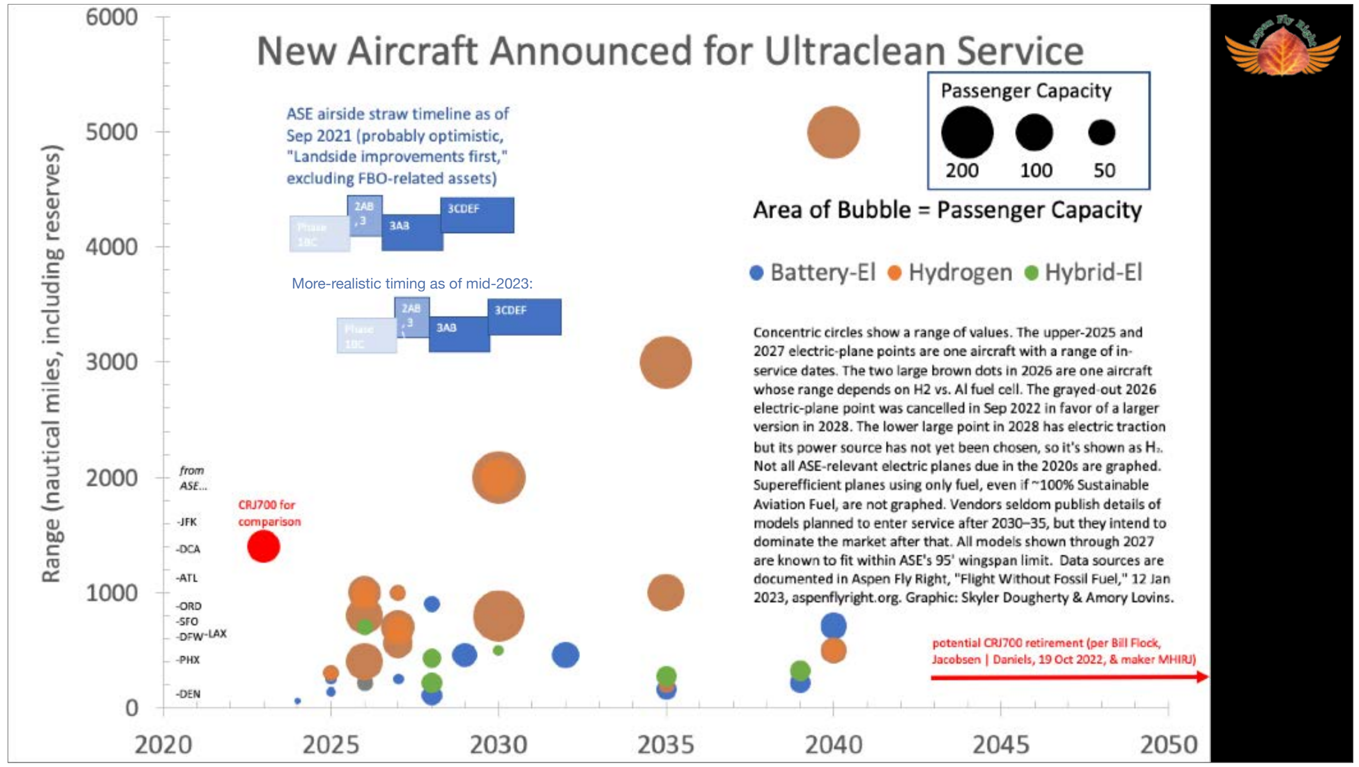
Indeed, our SUV's low tractive load made its fuel cell 3× smaller [tradeable with the buffer battery according to their relative prices], so you can pay 3× more per kW. At a standard 80% experience curve, you'd then need ~32× less cumulative production volume to reach competitive cost, speeding the hydrogen transition by a decade or two [, using the integrative infrastructure solutions we described to the National Hydrogen Association in 1999. That strategy integrates mobile and stationary uses of hydrogen and fuel cells so each speeds the other]. Exactly the same logic applies to efficient planes that enable both hydrogen and battery-electric clean aviation. *

While we're on the subject, liquid hydrogen is safer than Jet A. Hydrogen tanks are better protected, and are designed for higher pressure. If hydrogen does escape, it doesn't explode, and it doesn't pool like kerosene. Rather, it diffuses and burns upwards with a brief, clear flame that can't burn you at a distance. That's why nobody in the *Hindenberg* dirigible disaster was killed by the hydrogen fire—only by jumping out, or by the diesel fire, or by the ignition of the canopy made of flammable cloth coated with powdered-aluminum rocket fuel.

To illustrate these basic safety features, these photos show a side-by-side worst-case test of deliberate hydrogen release on the left, draining a car's high-pressure gaseous hydrogen tank at the highest possible rate in ~100 s, vs., on the right, a small hole leaking gasoline with 60% less energy [left: 1.54 kg = entire tank volume in ~100 s, 185 MJ; right: 1.6-mm hole, 2.37 L, 74 MJ]. The hydrogen flame is visible only because of sodium in particulates naturally present in the salty coastal air. [This test assumed a leak at the tank's Pressure Relief Device (yielding the fastest possible loss) and failure of the standard H2 sensor, pressure-drop, and flow-comparator shutoff devices. A hydrogen leak under a fuel-cell vehicle designed to standard protocols would require failure of those three safety devices and of the fuel line.]

The hydrogen flame radiates so little heat that it barely warms the outside of the back window, while the gasoline fire quickly turns into a carbeque. I'd sure rather have a hydrogen fire—but that requires not a single tank hole but the simultaneous failure of the fuel line plus three safety devices. *

To summarize: new kinds of very clean and quiet aircraft are often said to be small, slow, short-range, and far off. Of the scores of capable developers, here are nine examples of speed and ambition, most backed by solid performance tests and supply chains. There are many more. These examples have projected in-service dates between 2025 and 2035, some (like the *BAe-146* at the bottom center) retrofitting fossil-free propulsion into longstanding airframes. / [In the top row, the left and middle images show the thoroughly flight-validated Otto Aviation air taxi with stubby wings but extraordinary aerodynamics that can scale way upe. This version burns any liquid fuel, including pure SAF, at 8× normal efficiency. A 9–19-seat, 1000-nautical-mile hydrogen version is expected in service in 2027, and larger electric versions in this decade. The upper right image is a 76-seat *Dash-8/Q400* turboprop that the #5 US airline donated for a hydrogen retrofit test this year [2024]. This hydrogen retrofit targets a 700-nm range with 40–80 seats by 2027. The maker has $10b in pre-orders from big global airlines, and has announced that a 60-seat, 560-nm-range hydrogen retrofit of the popular *CRJ700* regional jet that brought me here today is also feasible with zero emissions and low noise. I conservatively estimate it could be in service around 2027—two years after Universal Hydrogen targets for a competing *Dash-8* and *ATR72* fuel-cell conversion kit. /
The middle row shows three new electric planes: on the left, a 30-seater due in 2028; in the middle, a 19-seater due in 2025–27; on the right, a 19-seater due in 2028. (Many makers start at 19 seats because staying below 20 makes initial certification many-fold cheaper.) /
At the lower left is a 9-seat hybrid-electric Embraer for 2030, starting late but launching a series rising to 300 seats and 500 nm in 2040. The lower middle image is an *electric retrofit* of the 100-seat BAe146 jet, now due back in electric service in 2026 with an 800-nm range, depending on its source of electricity, rising to 186 seats [...] in 2030. On the right is Airbus's hydrogen 100-seater for 2035 service entry.] /
To be sure, these and scores of other ultraclean and very quiet planes are still targets promised to investors, not yet fully developed and certified realities. Some specs and dates will slip. But so many and so capable firms are unlikely all to fail; these are only one-fourth of the industry plans we analyzed, which are in turn a fraction of the total; and many competitors aren't yet announced. Thus this little petting zoo is just one corner of a large bestiary. To see what that implies for strategy, consider when we can expect what new aircraft to come fly to, say, my very demanding high-altitude home airport in Aspen, Colorado, where a major expansion is proposed to fit bigger fossil-fueled planes. I'll illustrate the potential timing in one eyechart that's simpler than it looks. *



The Aspen Airport Forecast, following the FAA's guidelines, allows no technologies after 2016, so here are a few dozen examples of the omitted technologies. Each bubble represents one new kind of advanced airplane. Each plane's passenger capacity matches the area of its bubble, as in the black-box legend at the top right. Each bubble's color shows its propulsion system: battery-electric in blue, hybrid-electric in green, hydrogen in brown. Today's *CRJ-700* is shown in red for comparison. Its maker and Aspen Airport's chief forecaster expect its routine retirement could start in the red date range at the lower right—2–3 decades hence, plus any life extension. / Each new plane's announced in-service date is shown on the horizontal axis. How far it can fly is on the vertical axis, whose little scale at the lower left shows city distances from Aspen. / Importantly, *this graph doesn't include superefficient fueled planes like those at the top of the previous slide, nor some electric planes very relevant to Aspen*. *All planes shown through 2027 fit Aspen's current airfield. All are well suited to more frequent direct service connecting Aspen with far more airports at similar or lower ticket price.* Most fossil-free planes planned for after 2030, when the industry expects to be taking over the market, aren't shown either. Only three of numerous eVTOL air taxis are shown for comparison (the tiny bubbles in the next few years). By about 2025, some eVTOLs should be able to carry ~9 passengers between Aspen and Denver without needing Aspen's runway or airport, starting next year [2025] at some major airports. Some eVTOLs exceed 200 mph and 10,000'. Size, range, and altitude ratings will rapidly improve. First type certifications are expected as early as this year [2024], commercial service a year later. Already, a flyover 500 m overhead can be barely audible./
Thus many ultraclean airplanes are expected in commercial service *in this decade*—some bigger and longer-range than the *CRJ-700*. Now compare their timing with the two evolving blue construction timelines at the upper left for Aspen's proposed new airside, aiming two years ago for 2030 completion or now for ~2032. [Both schedules exclude the FBO rebuild and assume landside improvements are done first.] But by then, a swarm of ultraclean, superquiet, cheaper-to-buy-and-fly planes that fit Aspen's existing airside will probably be flying into Aspen, even if they're years delayed. When the Forecast ends in 2042, its aircraft will be as antique as a 1997 Buick is today—and at least as unlikely to compete with a Tesla. / Global airlines, including Aspen's, have invested heavily in the electric plane industry. United, which has three-fourths of Aspen's airline market, wants electric planes to serve smaller airports, like Aspen, at lower cost. The new planes' lower costs, zero emissions, and low noise will, I believe, prove potent competition for all the fossil-fueled planes that Aspen's Forecast says we need to build for. The view through the windshield, not the rear-view mirror, says a community like Aspen can crush its environmental goals and sustain vibrant commercial service *without rebuilding the airfield.* Our County officials are too busy promoting bigger planes to have taken a future-aviation brief like this one for 21 months. But meanwhile, a January 2024 BNEF analysis found an order backlog of zero-emission aircraft around 4,000, including nearly a thousand of regional-jet size. Technology is far outrunning local politics. *

[Let me end with two simple ideas. The first is that the enormous and accelerating uncertainties in aviation demand, route architectures, business models, and designs and technologies for both efficiency and clean propulsion make it imprudent—frankly, foolish—to design and buy a very costly airside reconfiguration that we may not need and could well come to wish we'd never heard of. Designing for bigger planes, based on outdated assumptions and an impoverished analytic framework, could create the biggest policy disaster in Colorado's history. / There's no rush. Wait for the mists to clear and the mud to settle. When speeding in fog, slow down. The foundation of this whole exercise, that the *CRJ-700s* are about to retire, was never true, is ever less true (its proponents will be embarrassed), and has been quietly abandoned. The wise course here is to temporize, fix only what's really broken (like resurfacing the runway as needed), and exercise disciplined restraint until we can figure out what we'll need. All we *know* we'll need is patience, adaptability, and flexibility. There's much to do meanwhile to improve safety and fix the landside. / Every airport is a forecast. Every forecast is wrong. The forecast we have is probably as wrong as it could possibly be, for many reasons we can't control or foresee. On major airside moves, this is a time, as Napoleon said, for masterly inactivity. It's time to sit down and rethink from scratch, because the emerging aviation world is like nothing we've ever experienced. /
Second,]

Let me close with a challenging opportunity that I offered the global aviation industry in keynoting its 2019 ATAG Montréal conference, then addressing ICAO, both sponsored by Boeing and very warmly received by Airbus too and by the major suppliers. I offered an implementation concept that many of them loved. Now there are some emerging signs that it may take off quickly and help bring to fruition many of the technical ambitions I've described. /

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. Now even greater gains are clearly in sight. Why take a century to do this 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. / What are we waiting for? [And can't Aspen lead, nationally and beyond, in its potentially influential part of the bigger aviation solution? The water in this pot is getting hotter. Our frog must just learn not to sit there and croak but to leap. / Thank you for your kind attention.] *

https://digital.library.unt.edu/ark:/67531/metadc627445/, https://www.nrel.gov/docs/legosti/old/7281.pdf
https://www.cee1.org/content/golden-carrots-beginning; *Winning the Oil Endgame* (RMI 2004), pp 199–203.