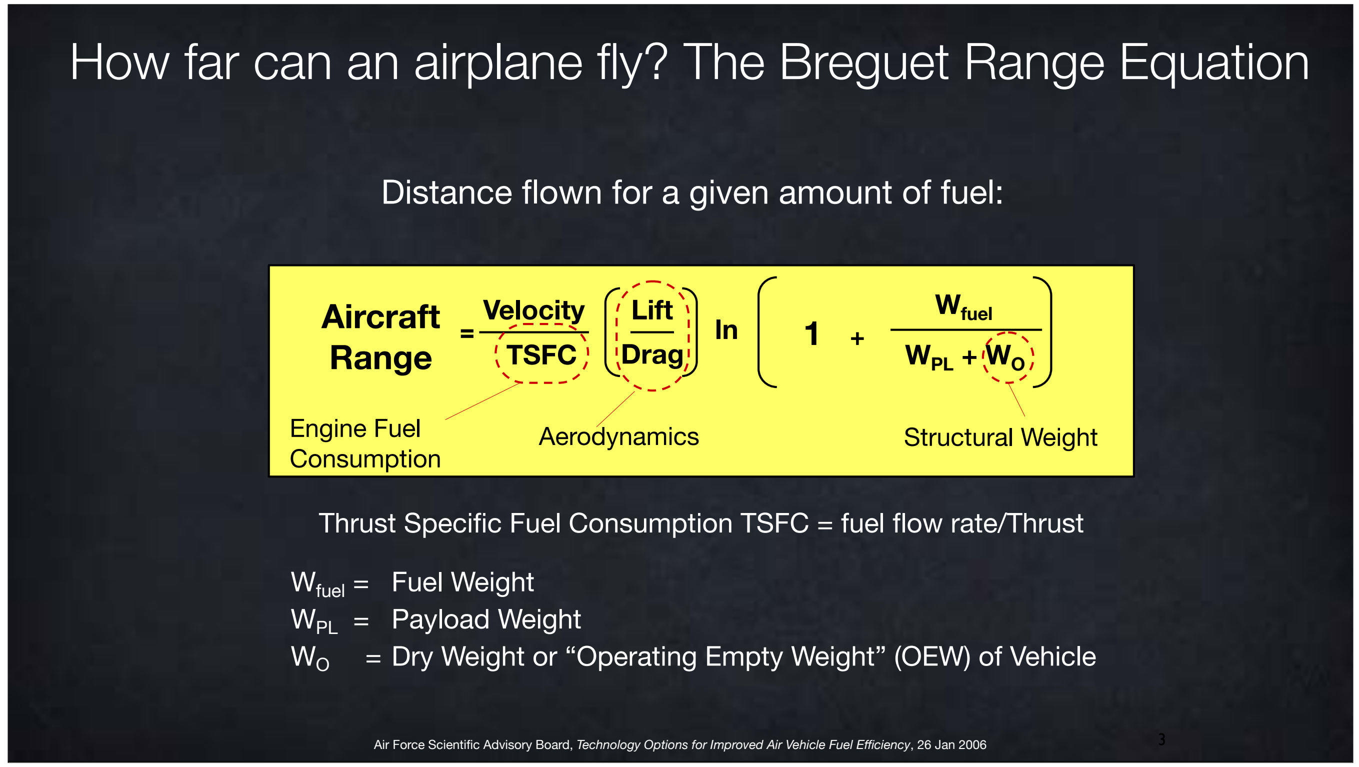
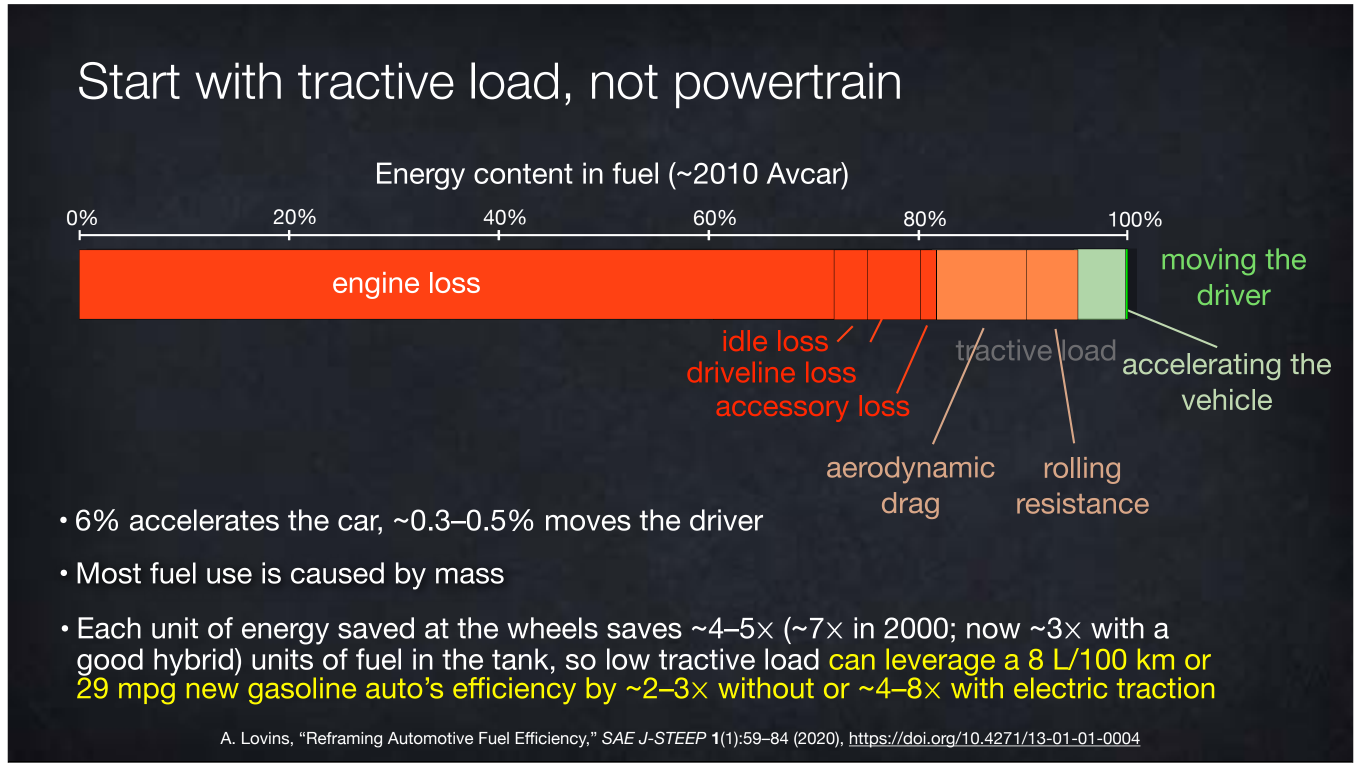
[target ~50m, actual **TK**]

Good day. I'm Amory Lovins, a recovering experimental physicist and passive-solar banana farmer from Old Snowmass with an interest in aviation. Thank you, Dan, for this kind invitation, and welcome to our guests from Jacobsen | Daniels. I've provided a summary of my background. You wrote me that "the purpose of the meeting is to garner input from you [i.e. from me] as an expert in the field of transportation electrification and how that applies to the aviation fleet mix at ASE." This discussion is solely in my personal capacity as a private citizen, not representing or involving my current and former employers, two of which are mentioned for identification on this title slide. I'll focus especially on new developments since my 21-minute brief to the Vision process's Doerr-Hosier event on 13 Nov 2019. That brief has proven prophetic but understated. / My time horizon is 30 y and beyond, as yours should be (not 20), but as we'll see, a swarm of gamechangers will become important within ~5 y and cross major tipping points within 10 y. / I won't cover Sustainable Aviation Fuel or ordinary incremental aviation improvements, though they'll become increasingly important. I also won't review here the extensive analyses I've submitted to the Pitkin County Board of County Commissioners over the past two years, trying to improve the planning and decision process now underway for the Aspen Airport airside. And I won't try to guess what airplanes might use our airport, nor think there's any point trying to tell airlines which qualified planes to use or what attributes they should have, because (as my 19 Apr 2022 letter put it) "the County lacks authority, the operator lacks motive, and there's no qualifying jetliner in sight." So putting all those tedious historical issues aside, I'll try to help you all peer into our cloudy strategic future, chock-full of granite rocks.

* We can't meaningfully discuss propulsion without first discussing the underlying physics and efficiency of the aircraft we're propelling, because they're intimately related. I'll therefore organize my remarks, via 47 slides, around aeronautical efficiency, then electricity and hydrogen, then some brief conclusions. This deck is a draft—a work in progress—that I hope you can help me improve. I've provided a PDF of the slides and Presenter Notes, and will correct any errors I discover from this discussion, so I warmly welcome your corrections and suggestions for improvement so we can keep evolving these insights. *



You'll recall that airplanes' fuel efficiency is proportional to engine efficiency, to lift/drag ratio, and to a logarithmic term based on the ratio of gross weight (structure plus payload) to fuel weight. Propulsive, aerodynamic, and mass efficiency are the three prime variables (putting aside some other complexities). Even though planes go ~10x faster than cars, and aero drag rises as the cube of speed, reducing weight is crucial too, because planes need energy to stay up in the air, whereas tires rest on the road. Of course the numbers differ for planes and cars, but ultralight weight, along with low drag, crucially enables non-fossil-fueled propulsion of both kinds of vehicles, so let me show you the automotive analogy. As we proceed, you'll see how richly these examples are intertwined. *



* Here's the basic physics of car efficiency. Just one-fifth of a modern nonelectric car's fuel energy reaches the wheels and moves the car. Of that * "tractive load," 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 19/20$^{\text{ths}}$ of the mass you're accelerating is the heavy steel car, so just 1/20$^{\text{th}}$ 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, or roughly quadruple to octuple efficiency by combining low tractive load with electrification.* To achieve this, we should *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 work in practice? *

A competitive carbon-fiber electric car, 2013–22

sglcarbon.com

2013 BMW *i3*, http://www.superstreetonline.com/features/news/epcp-1303-bmw-i3-concept-coupe/

BMW MY2013's ~120–150-kg carbon-fiber-composite passenger cell; m_c 1,250 kg

https://www.autocar.co.uk/car-news/industry/bmw-set-make-more-extensive-use-carbon-fibre

BMW's sporty, 1250-kg 4x-efficiency *i3* was profitable from the first unit, because it:

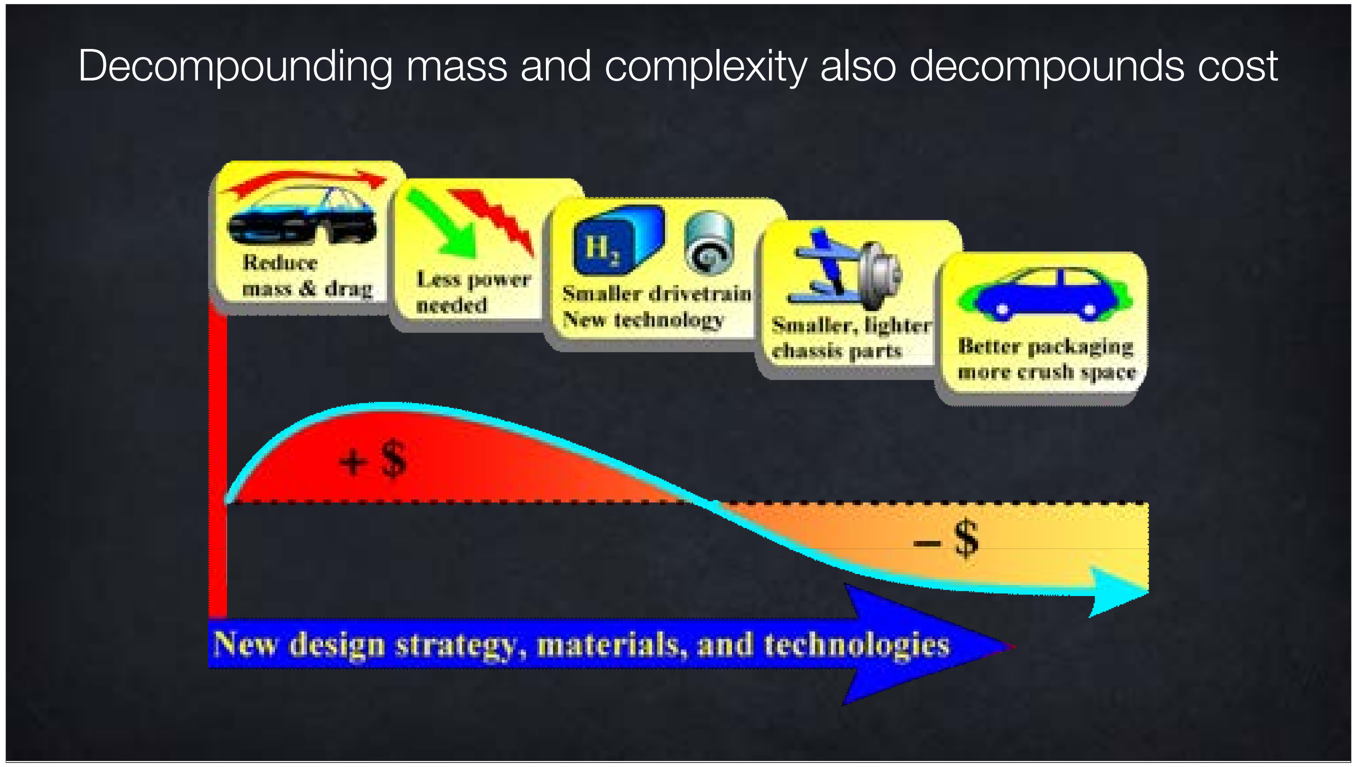
- pays for the carbon fiber by needing fewer batteries (which recharge faster)
- saves ~2.5–3.5 kg total for each kg of direct mass saved (Detroit says <1.3–1.5)
- needs two-thirds less capital, ~70% less water, ~50% less energy, space, time
- requires no conventional body shop or paint shop (automaking's two hardest steps)
- provides safe, clean, quiet, superior working conditions
- delivers 124 mpge (1.9 L_{equiv}/100 km) on US 5-cycle test, 1.7 Ger., ~1.6 old US cycle
- provides exceptional visibility, agility, traction, and crash safety w/halved turn radius

A. Lovins, SAE *J-STEEP*, 2020, https://doi/org/10.4271/13-01-01-0004

This * carbon-fiber electric car I drive * was profitable from the first unit sold nine years ago [2013] and for all quarter-million units sold since. * 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 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 conventional body and paint shops, and * it's much better for workers.* Its quadrupled efficiency, to 124 mpge, comes without compromise and * with many driver advantages. Thoroughly applying this design logic could also save up to about two-thirds of the scarce battery minerals, and five other multiplicative forms of efficiency could manage the rest. *

BMW finished producing this model four months ago [June 2022], but Bloomberg New Energy Finance reports that China's strategy for its 2030 flagship cars includes carbon-fiber structures displacing four-fifths of their steel. *

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



Let's return for a moment to 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.

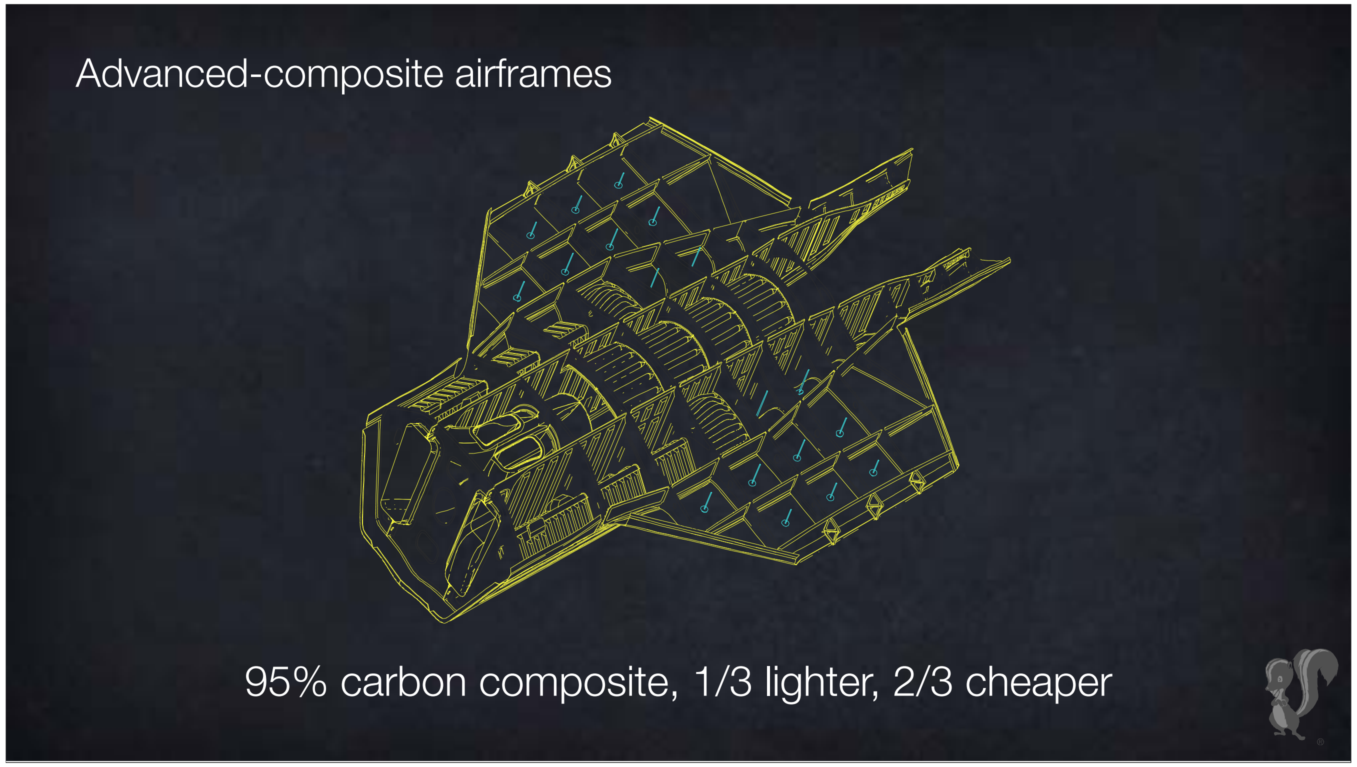
At first the special materials, powertrain, and design might seem too costly. But after many recursive cycles of mass decompounding, you need so little carbon fiber and such a small powertrain that with the simplified manufacturing, total cost can revert to normal or even less. Of course, that's cost 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. I asked a roomful of the top 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." Looking at their recent products, I'm not sure they did. *

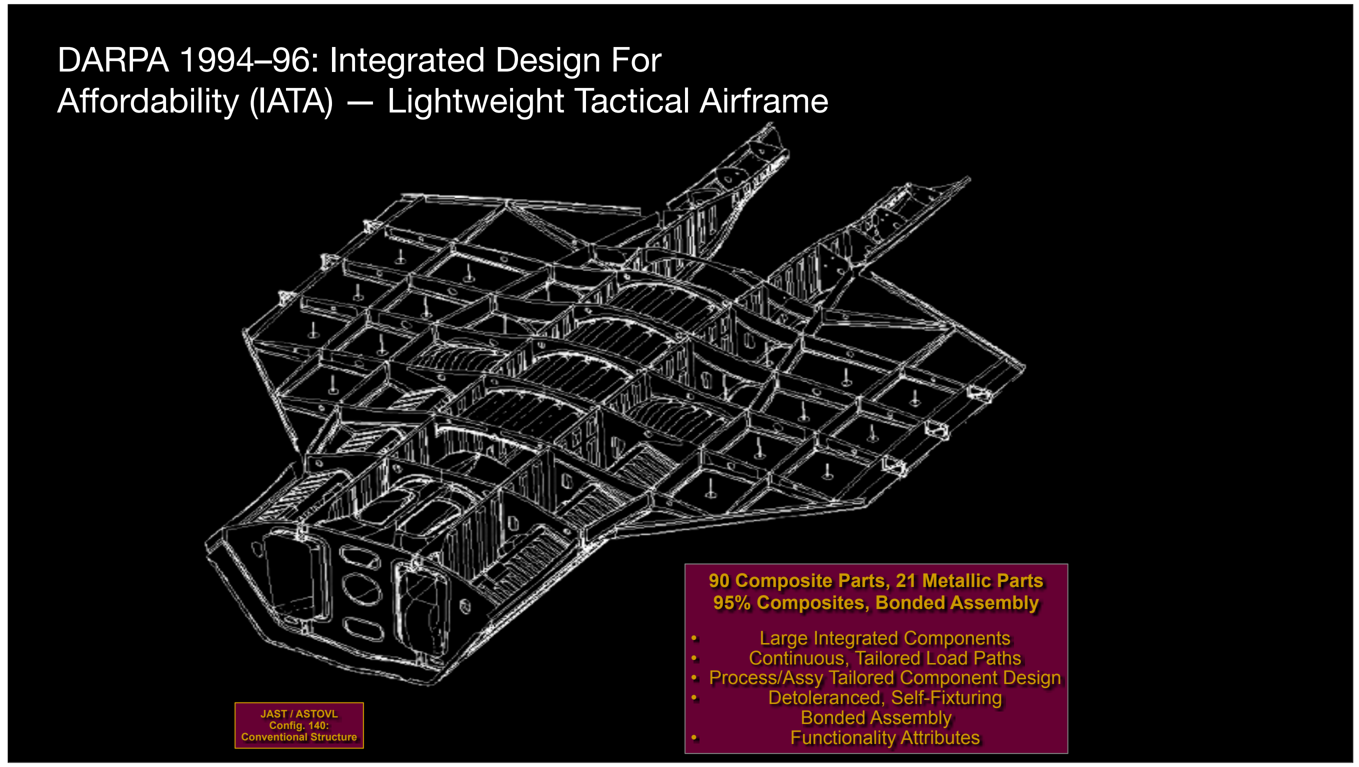
What is a saved watt worth?
Are we buying enough negawatts?

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 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. *

Taking a pound of weight out of a typical airplane is worth ~$1k in present-valued fuel cost—even more on long flights where each gallon you want to land with requires another half to one gallon to carry it across the Pacific. I was once hitchhiking on a KC-135R military tanker and * noticed a * lot of * heavy things that * didn't need to be there. I briefed my observations to two US Air Force 2-stars, they launched a treasure-hunt that day, and it found $2b worth of weight and hence fuel savings in that 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 galley carts. And airframe makers, as we'll see, could do far more with basic structures. *



Our lightest big passenger planes are still only half carbon-fiber composites by mass. But 28 years 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

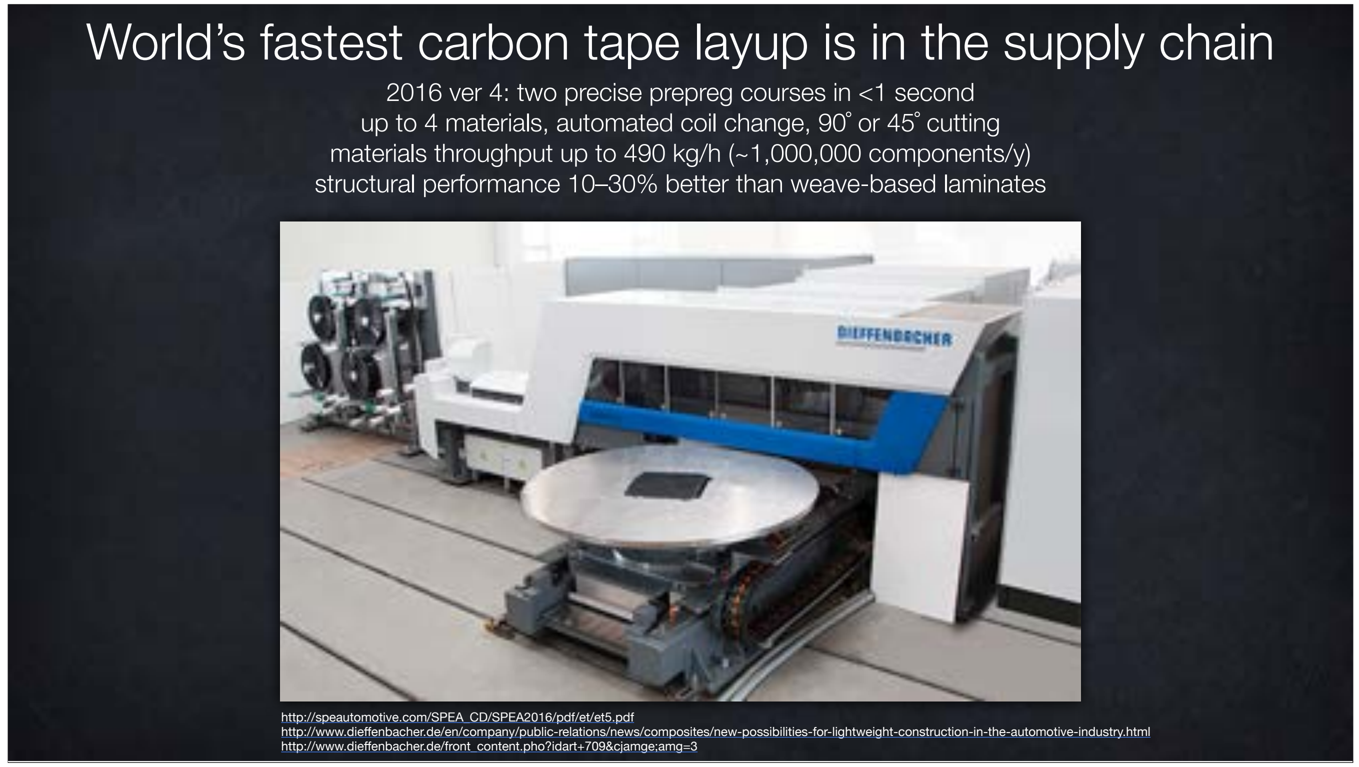
IATA Final Cost / Weight Comparison of Preferred System Concept to Baseline 140

	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%

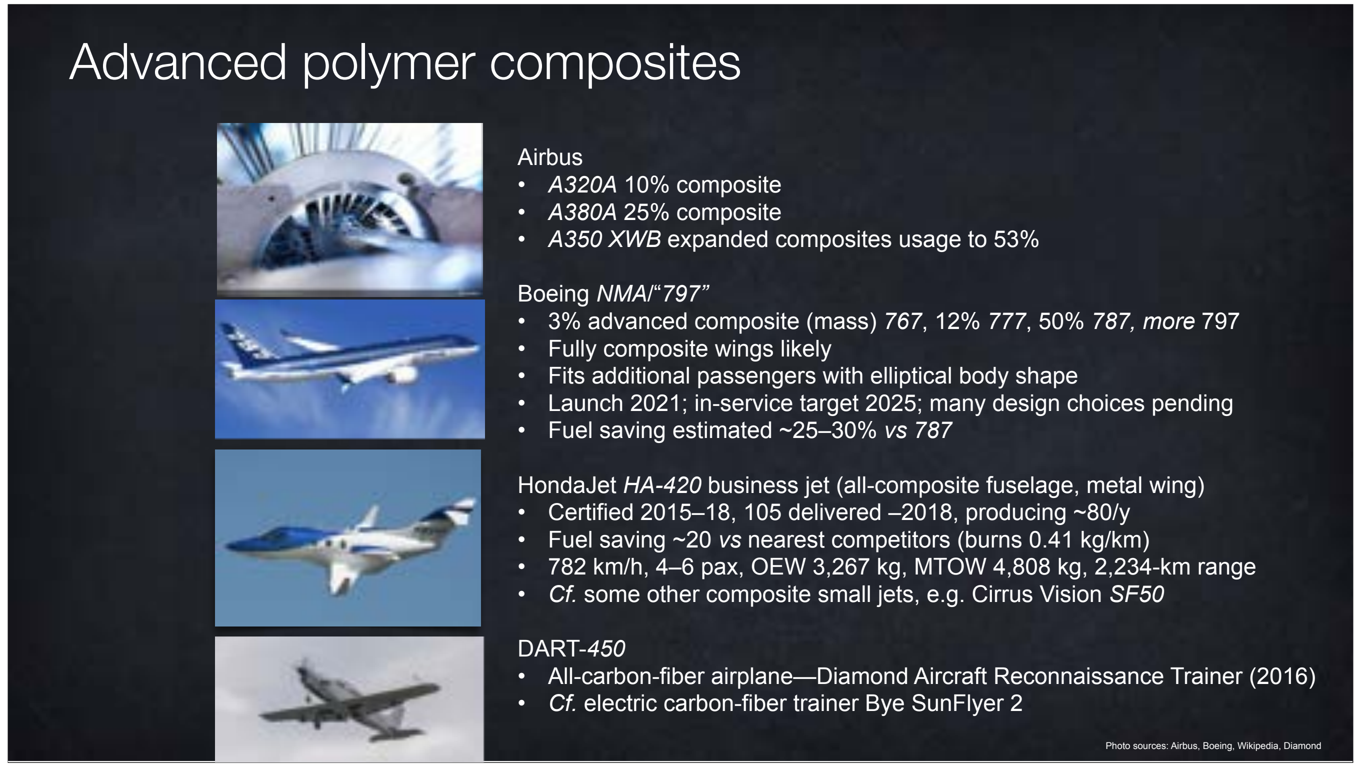
- **90 Composite Components, 21 Metallic**
- **65% Reduction in T100 Rec. Production Costs** ($3.68M savings)
- **48% Reduction in Non-Recurring Production Costs** ($30.2M savings)
- **33% Reduction in Weight** (1621 lbs savings)
- **95% Composites** (vs 30% in Baseline)
- **Orders of magnitude part 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**

10/31/18

…and some of the benchmark numbers. The 3–4× lower production cost for this 1,621-pound lighter airframe showed, as BMW 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 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 now works too), later developed… *

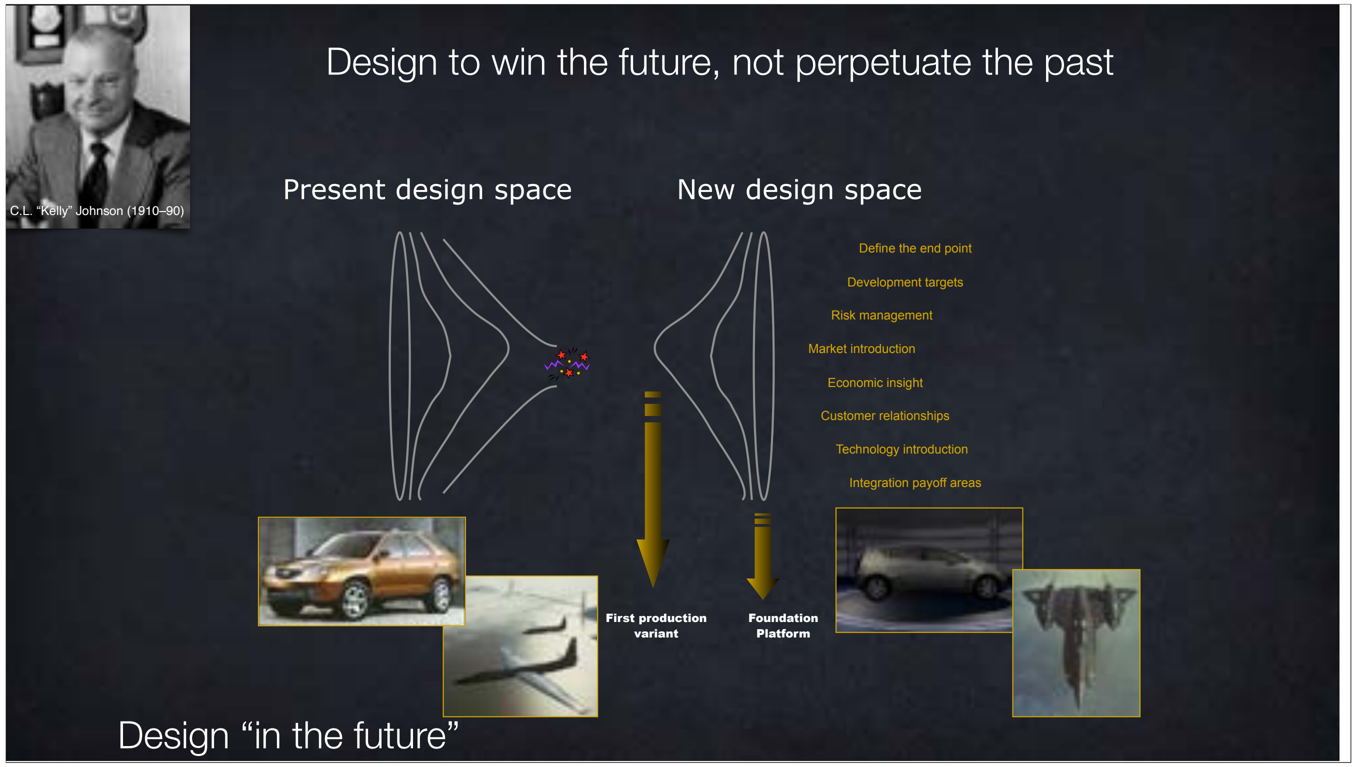


…the Fiberforge® process that made this test piece *[show]* for military ballistic helmets in one minute 15 years ago. It then made many airplane parts for the industry, like composite window frames that went from concept to commercial flight in six months. We sold the technology to a German Tier One pressmaker in 2013. This process, as embodied in this machine released three years later, can make a complex 2x2*m* structural carbon-fiber part in one minute, or over a million smaller aerospace parts per year. It could become severalfold faster if desired. I mention this in case you think making advanced-composite airplanes and their structural components is still necessarily slow and costly. *



To be sure, advanced composites are 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. *

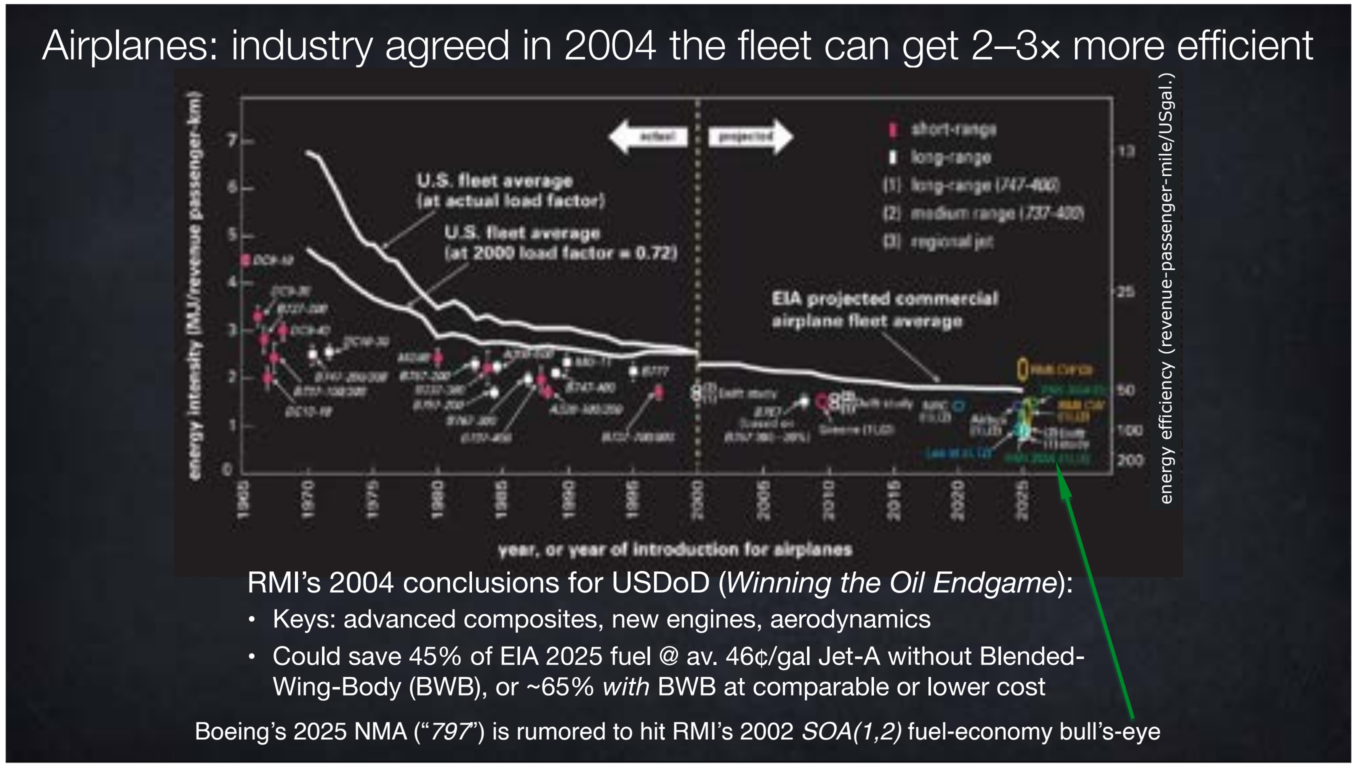
(Source: AeroDynamic)



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.

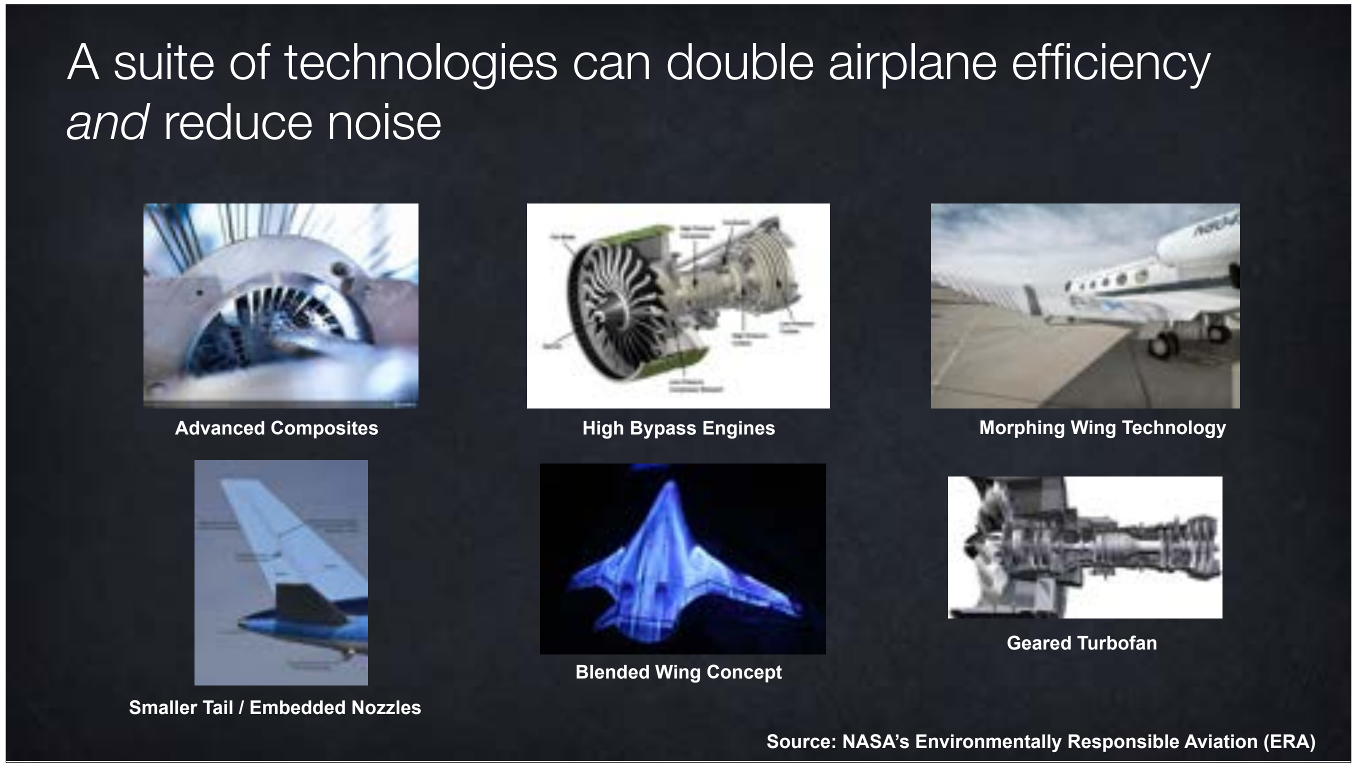
Johnson understood that such an airplane was impossible within the conventional design context, because design is * like a rubber band: if you try to stretch it too far from the conventional design space, you encounter more and more resistance, and eventually it breaks. But if you * jump to the new design 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.

I mention this because we need revolutionary design mentality, starting with beginner's mind or child mind—shedding all assumptions and preconceptions—to design not just airplanes but also air*ports*. *



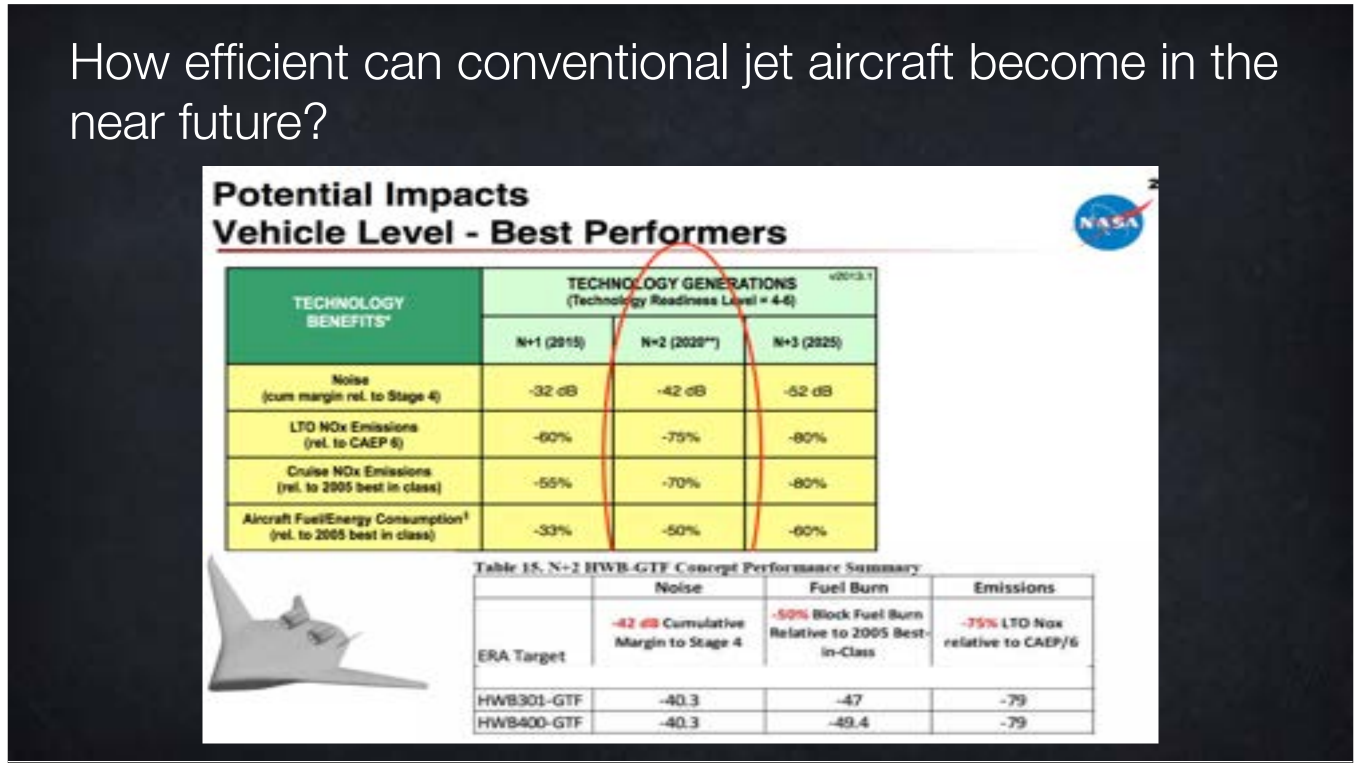
Of course, airplanes have long been getting more efficient. Those US-certified from 1960 to 2000 cut fuel intensity by 70%—half by better engines, half by better airframes. That progress remains on such a steady and plodding course that Boeing's *NMA*/"*797*" * was expected to hit in 2025 * exactly the efficiency bull's-eye we estimated in 2004. But because of uncertain and often cash-short customers, incremental thinking, restricted vision, and market turbulence, 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.

[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. But many more than these are available, and they're often even more important in synergistic combinations than separately. *

[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 could be 15% more efficient than conventional jet engines. Blended wings could often save >40% if we change manufacturing and boarding/deplaning.]



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

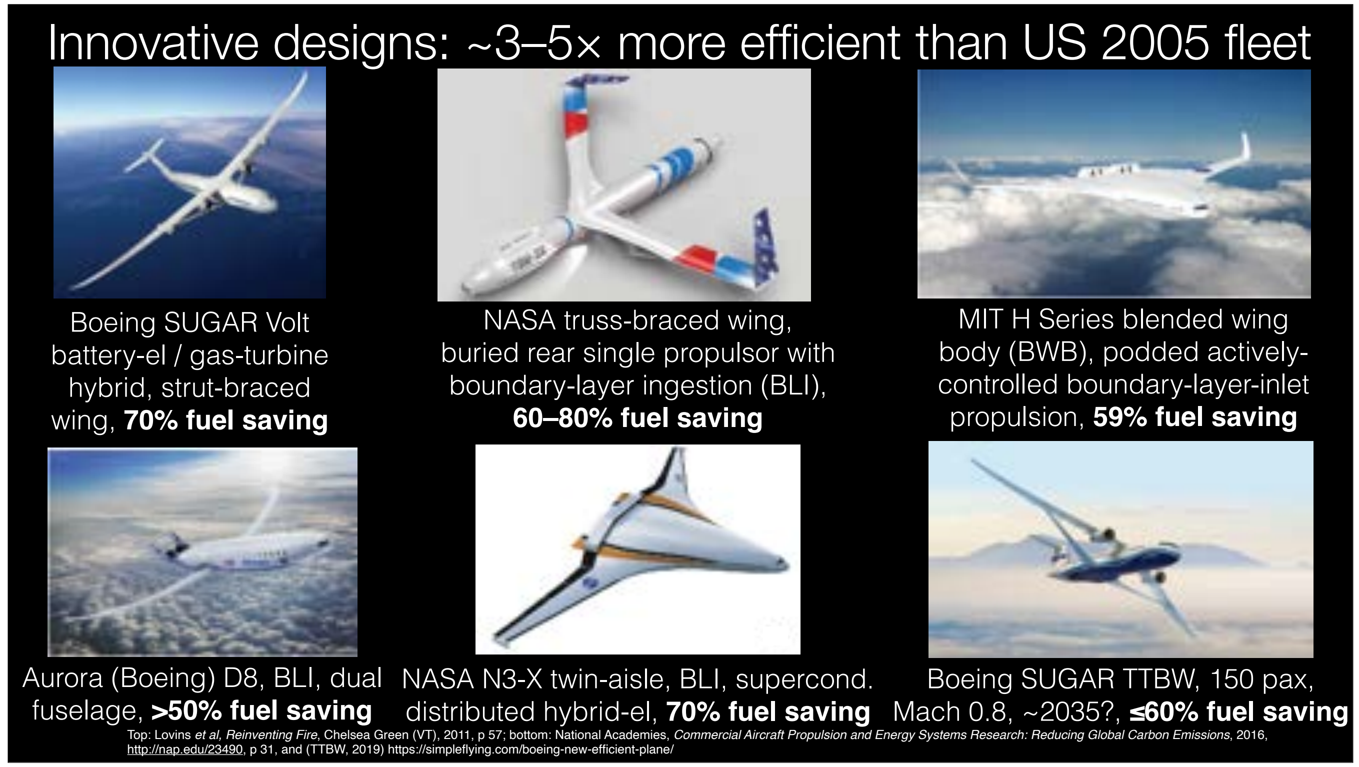
Potential Impacts
Vehicle Level - Best Performers

TECHNOLOGY BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)		
	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[1] (rel. to 2005 best in class)	-33%	-50%	-60%

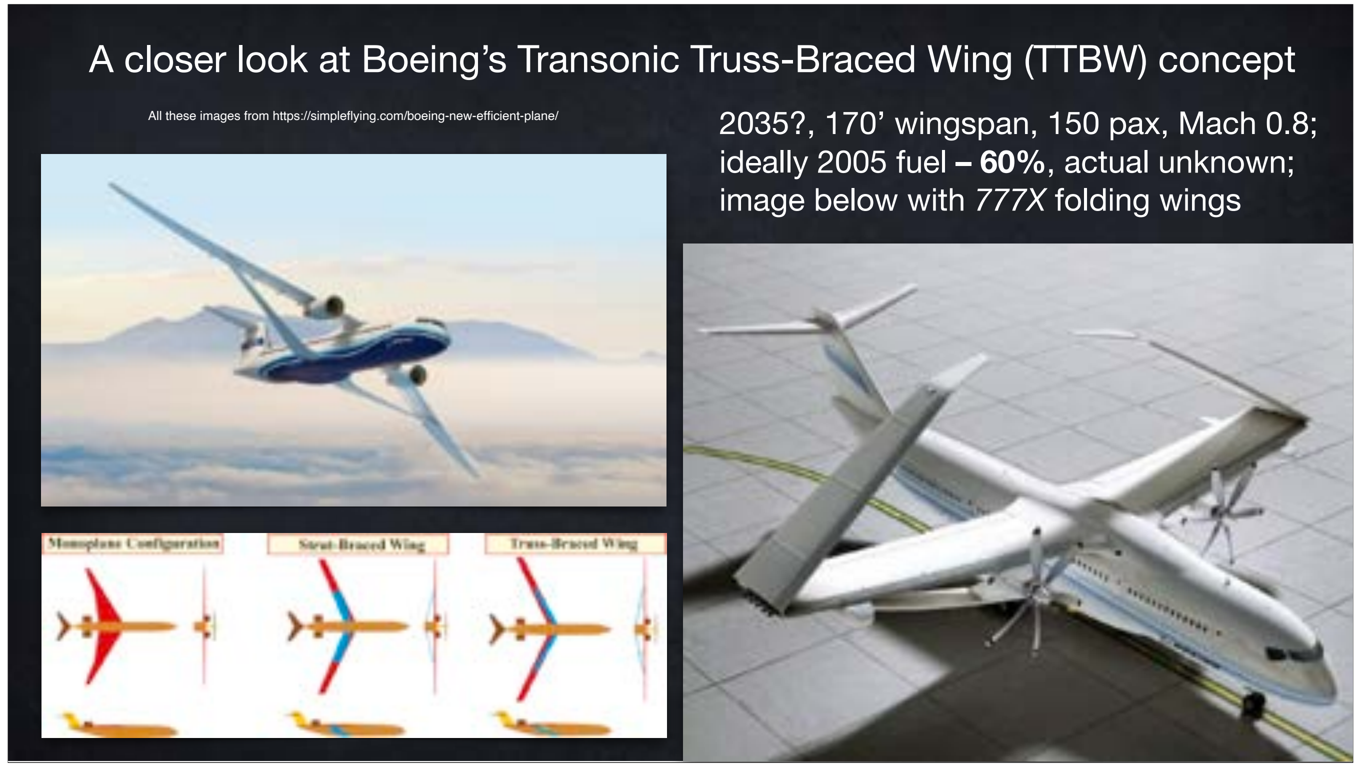
Table 15. N+2 HWB-GTF Concept Performance Summary

	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

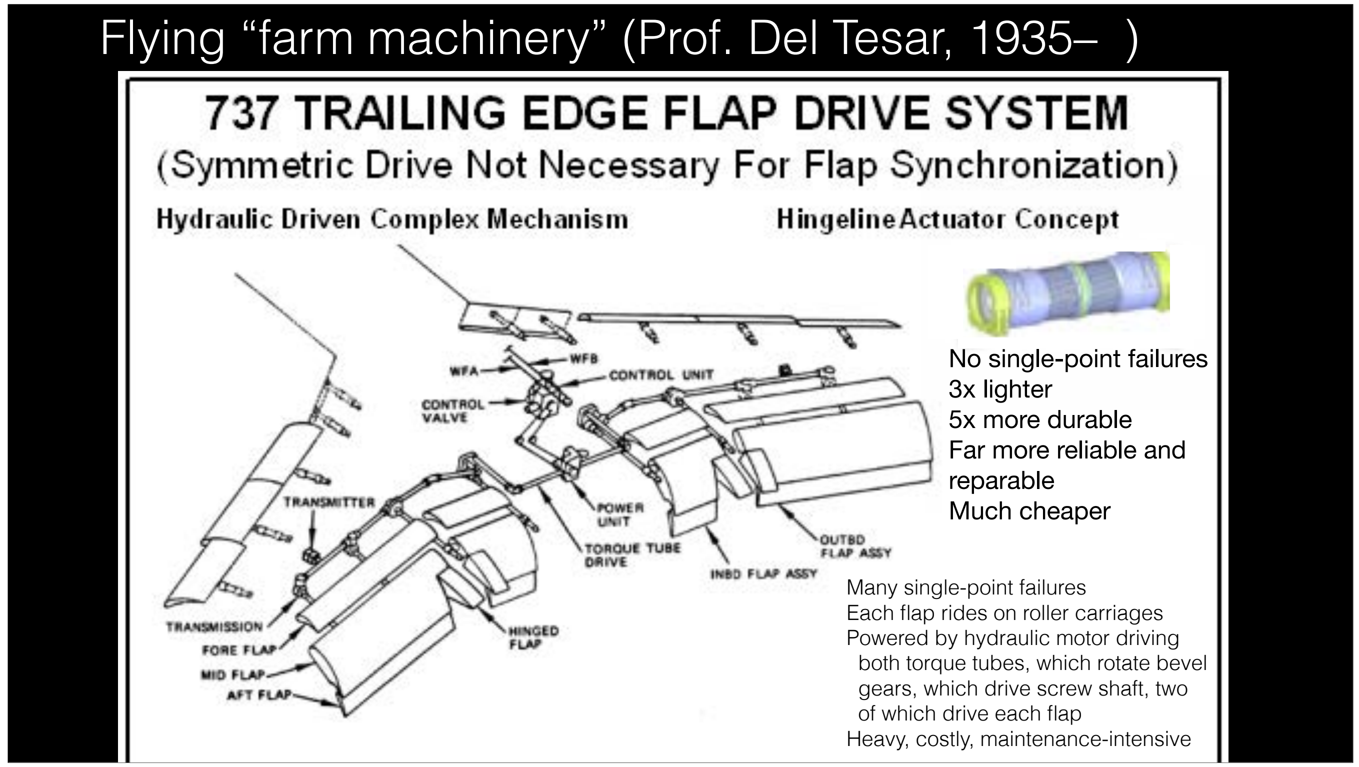
Combining available with near-ready technologies can dramatically raise fuel efficiency. NASA's roadmap less than a decade ago [2013] foresaw 50% fuel savings available by 2020 and 60% by 2025. These technologies are pretty obvious…. *



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, 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, 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's Chief Scientist told me nearly four years ago [early 2019] that proper application of truss-braced wings with advanced aerodynamics can raise lift/drag ratio from ~18–19 with tube-and-wing or 22–23 with blended-wing-body to *40–60+* while considerably reducing weight. So there's still lots of hidden treasure here. *



This example of a truss-braced wing design to lengthen and strengthen a high-aspect-ratio wing also illustrates why bigger wingspan isn’t necessarily an airport layout constraint. Boeing has been selling folding wings for years, precisely to avoid major airport redesign costs as wings got longer on platforms like the *777*. *

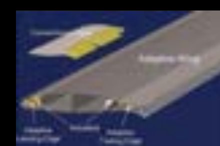


Even simple changes can be highly effective. Looking out the window as an old plane lands, I've seen the flaps extended by a hydraulic/mechanical system that the wizard of electric actuators—originally a farmboy gearhead—rightly calls "farm machinery." It's heavy, unreliable, and costly to buy and maintain. 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×. *

Aerodynamics

Passive boundary-layer control
Active boundary-layer control
Retractable piezoelectric high-frequency microvortex generators

Morphing surfaces: FlexSys (Ann Arbor)



Center for Bits & Atoms (MIT)

DOI: 10.1089/soro.2016.0032

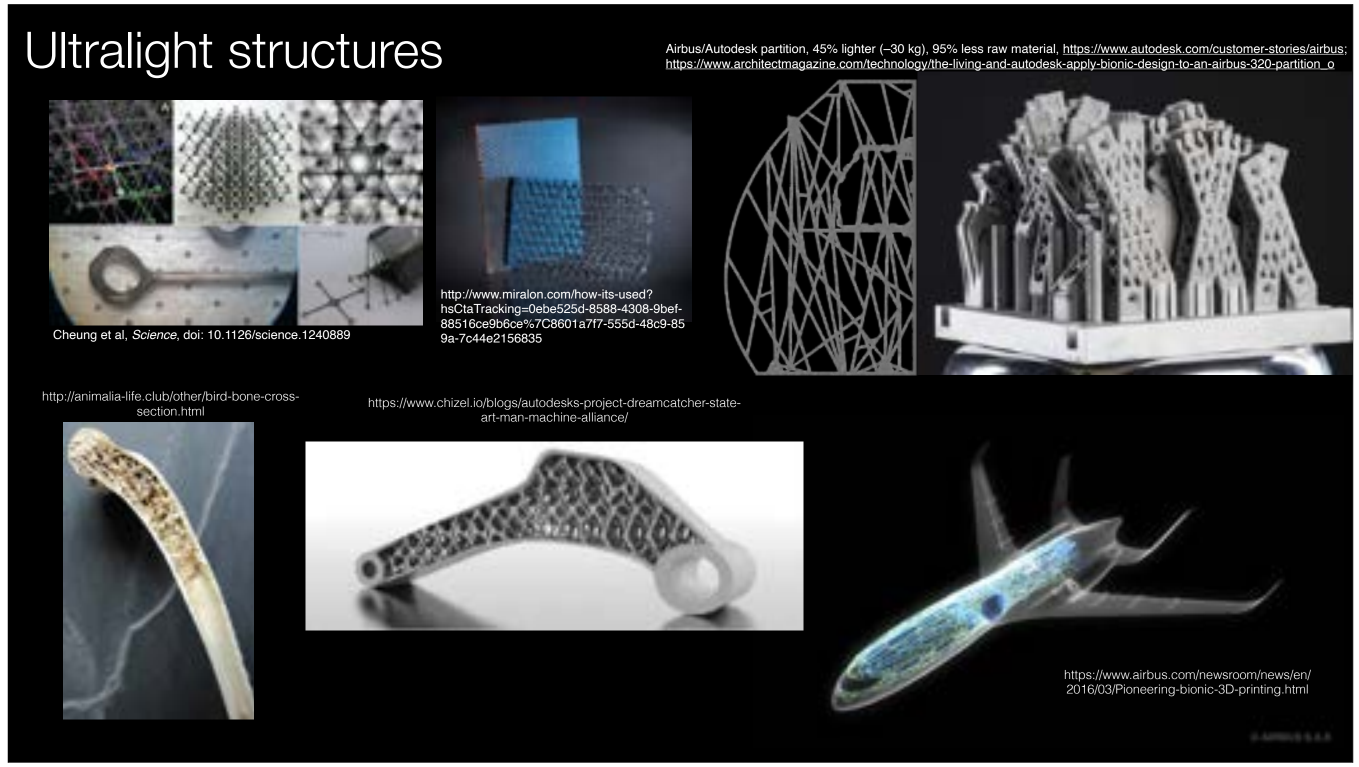
http://news.mit.edu/2016/morphing-airplane-wing-design-1103

[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 is in commercial service in cars and was scheduled for planes in 2020, expected to save ~2–11% of fuel. *

[* 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.] *

The second morphing innovation, a flexible lattice structure from MIT’s Center for Bits and Atoms, produced four years ago [2019] a 4.3m test structure *59x less dense* than a typical metal airplane wing. You heard me correctly: such a structure has the strength of elastomers but the gossamer density of aerogel. Eliminating 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 parts can be assembled by swarms of programmed robots 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*. *



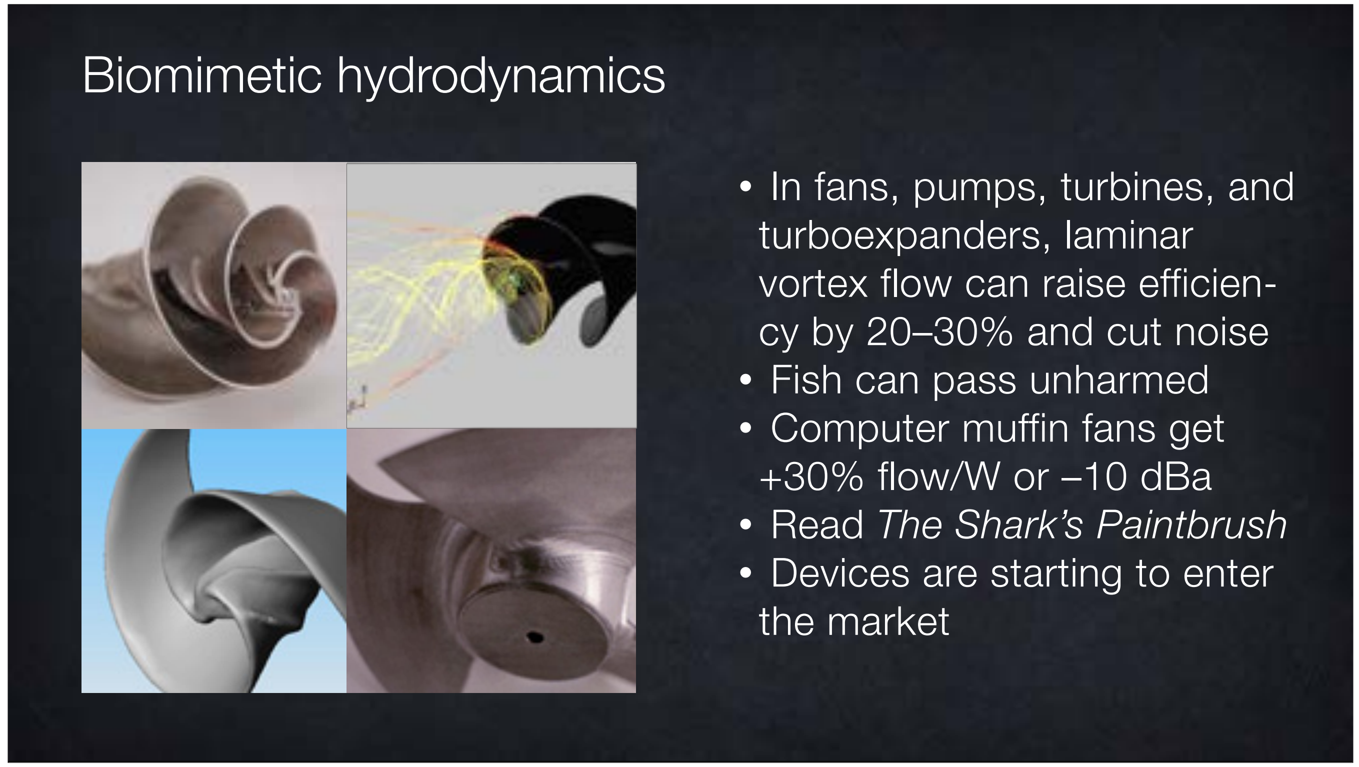
Using other approaches, those hook-together miniature structures are as strong and stiff as solid structures but are up to 90% air. * They don’t even use carbon fiber. After carbon fiber could come * Miralon’s carbon-nanotube structures with up to 10× higher mechanical performance—and now we can make similar nanotubes from sugar, water, and sunlight via the bacterial enzymes hummingbirds use to weave their nests. * 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. *

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…*

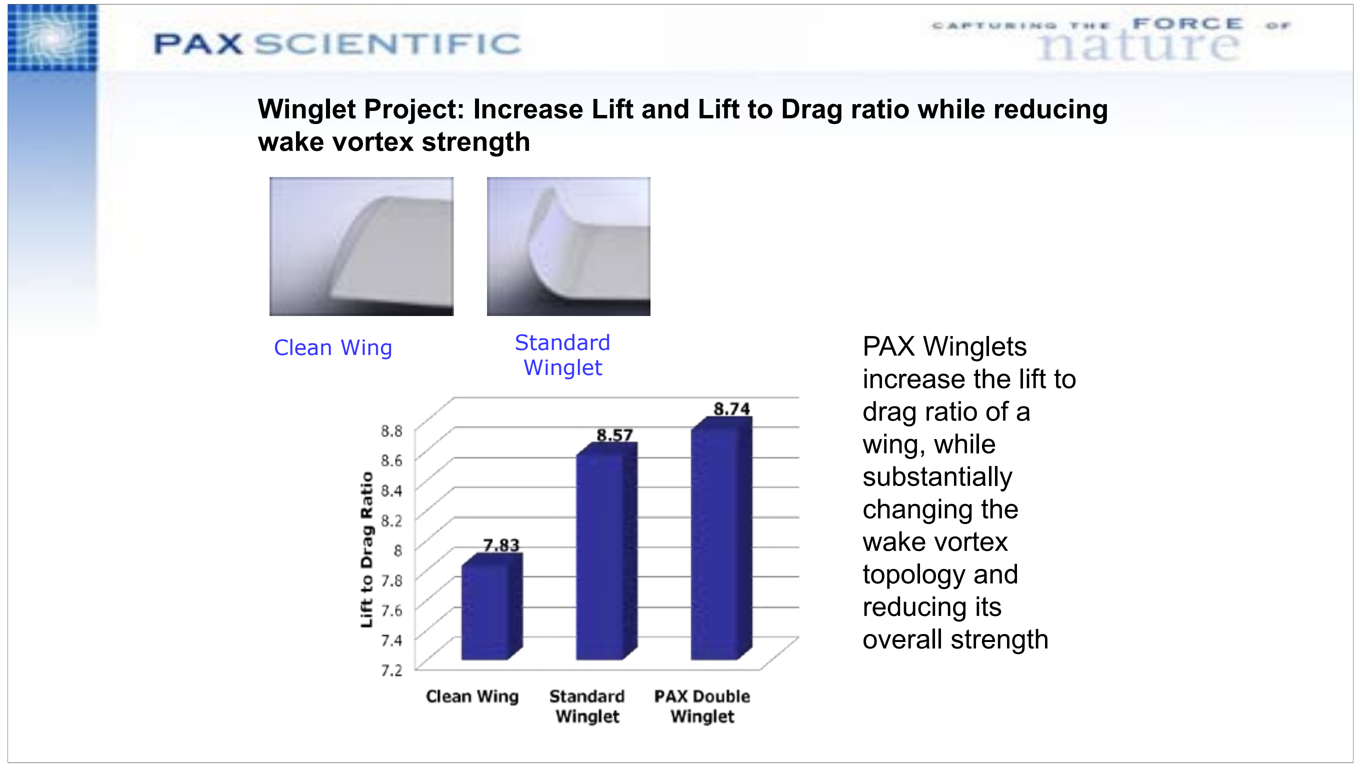
…the California condor. Besides all its advanced geometries, structures, and controls, I especially like the “Fully integrated system design” and “Advanced manufacturing techniques.” *

In an emergent application of biomimicry, Jay Harman—an Australian naturalist and sea-captain—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.) *

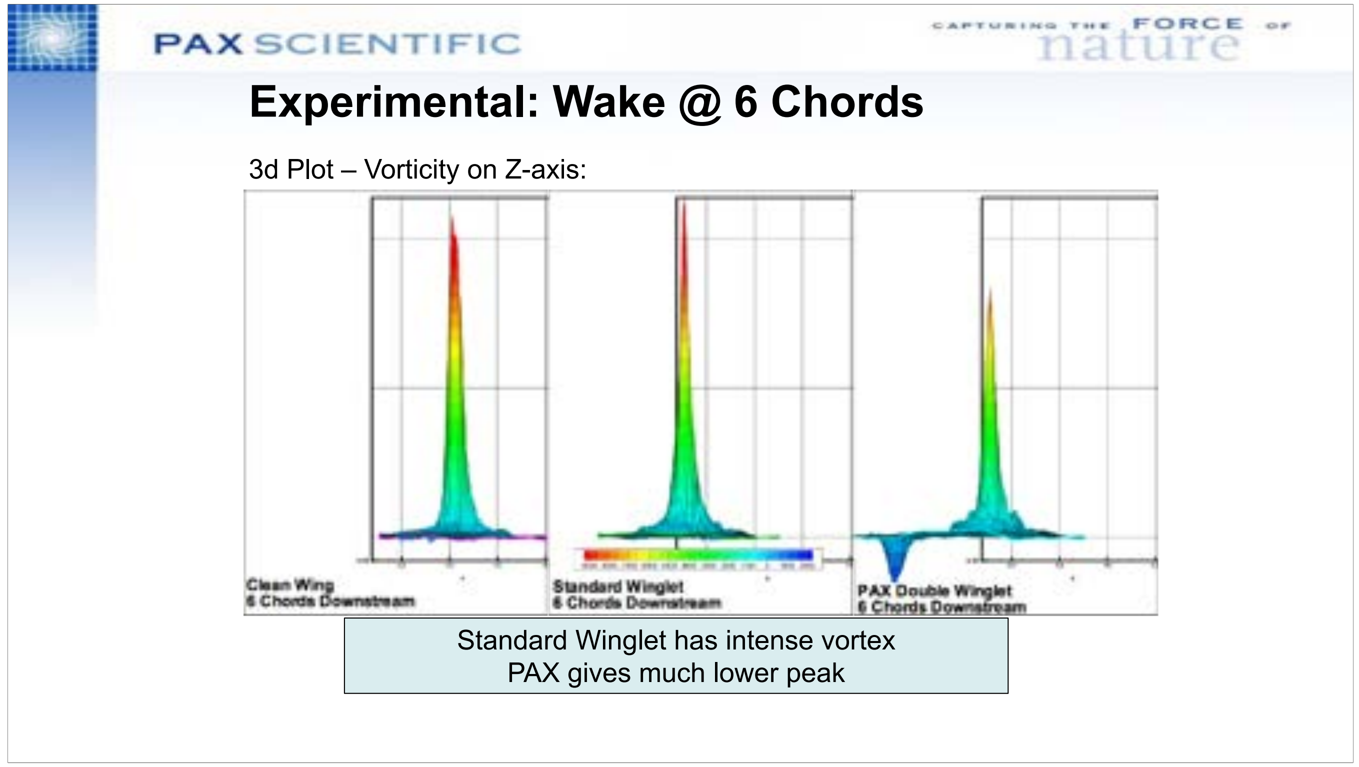


Such rotors can raise pump and fan efficiency by ~20–30%, not quite violating the pump equation. [After intensive effort by a team of Cambridge PhD hydrodynamicists, c] Computed and observed pump behavior now match up nicely….*

…yielding diverse superefficient fans, propulsors, and hulls, some now on or entering the market. But 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 trial, by 14%. *



In a small initial example, Harman's small and light but precisely compound-curved duplex winglets improve wing lift/drag ratio 2%… *



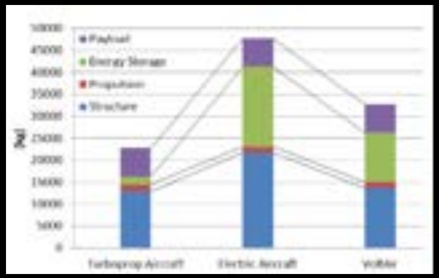
…while making wake vortices weaker and shorter, permitting closer spacing between planes. *

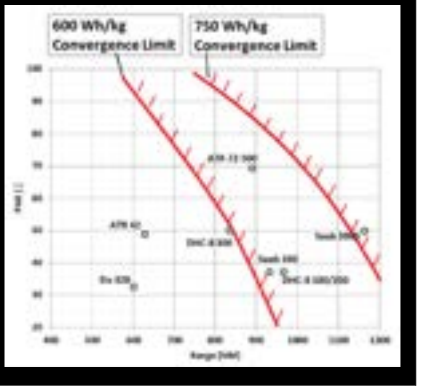
That's the tip of a vast iceberg: the most surprising aviation efficiency breakthroughs are still in aerodynamics. Let me offer one example now largely in the public domain. I was impressed last year [2021] by a visit to William Otto Sr. and his team at the Los Angeles Logistics Airport. Bill was Chief Scientist/Avionics for the *B1*. Since 2008, his privately held firm has been developing this radically optimized plane that exited stealth mode in August 2020 and has demonstrated ~59% lower drag than a standard business jet, thanks to fully laminar flow over the entire fuselage, wings, and empennage. Its 52' wingspan—skinny, stubby, set far aft—illustrates an alternative approach to longer wings for extreme efficiency. This plane's 55 flight tests from 2017 to late 2021, and more since, have systematically validated the flight envelope, emphasizing wheels-up and flaps-up, flying up to 15,000' and >250 mph with no surprises. The *500L* model aims at type certification in 2023–25, initially as a $5m luxury 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 unpowered 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. /

Those who dismiss this luxury air taxi as too small to matter are mistaken. It could gracefully accommodate considerably more seats if less lounge-like, but a doubled-size variant already designed could hold more than two dozen premium seats, or a comfortable configuration plausibly well into the 30s. Still larger versions may be possible. But all sizes could blow up GA and carrier business models—especially because those smaller planes are perfect for rapidly emerging point-to-point route architectures, so the *500L* could serve any of >5,000 US airports. /

The *500L*'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 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. This 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 is about to fly in a 19-seat Dornier *228* testbed (already runway-tested at high speed), aiming at *2024* commercial service. 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), lower propulsion-system maintenance costs, and cheaper fuel. Electrification also has the team's design attention and should offer excellent prospects. Having spent a day inspecting the plane and grilling the team, I think this may be the most important new plane 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. /

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

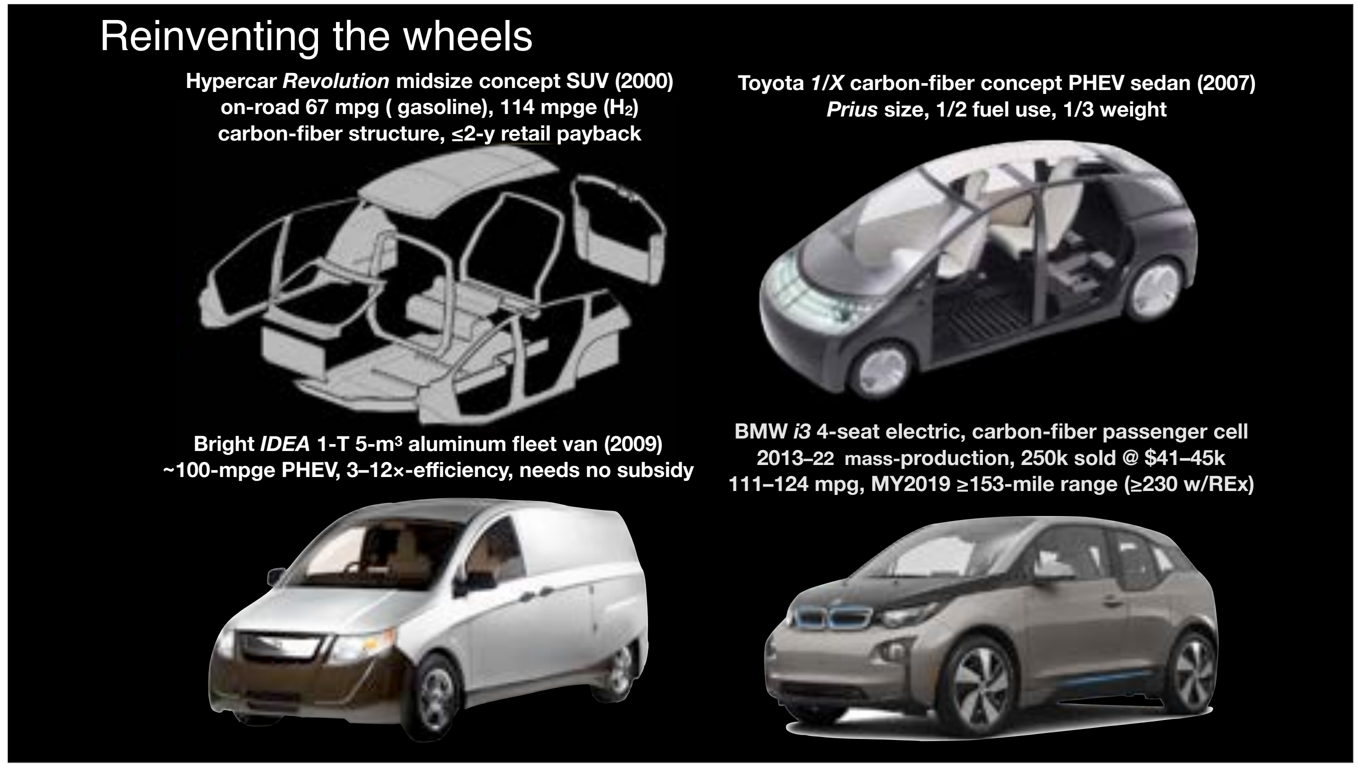




https://www.icas.org/ICAS_ARCHIVE/ICAS2012/PAPERS/521.PDF

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, 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 right in 2011. But since then, I think the kinds of technological and design advances I've summarized, if strongly integrated, can now greatly strengthen that 2011 conclusion. It would not surprise me if ultralighting, ultralaminar flow, and many other efficiency advances already proven and starting to enter the market could converge with better batteries, motors, power electronics, and even ultralight high-efficiency photovoltaics 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, thanks largely to the genius of JB Straubel, I own two fine battery-electric cars and wouldn't dream of going back. Today'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; already they virtually always win on lifecycle cost. *

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



It's been quite a trip to reach these goals. When I was the anchor tenant on Bill Ford's Transformation Advisory Council in 2007–09, talking to his executives about battery-electric cars could get you laughed out of the room. Today, Ford can't make enough of its brilliantly positioned and wildly popular *Lightning* electric pickup truck. Here are a few steps I helped take on that long road. The ultralight carbon-fiber electrified cars that I invented 31 y ago [1991], we * designed with industry 22 y ago, and Toyota * used our shared methods 15 y ago * to design as a 70%-lighter carbon-fiber plug-in hybrid, * entered the market in 2013 with this profitable * BMW *i3* that I 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 far more oil than Saudi Arabia lifts, at an extra cost that ten years ago was <$18 per saved barrel, today is <$7, and within ~3–5 y will fall below zero. *

Let's look more closely at our 22-year-old carbon-fiber midsize SUV called *Revolution*. Its * airframe-inspired body—suspended from rings, not built up from a tub—had just 14 parts, each made with one low-pressure dieset, saving ~95–99% of the tooling cost. Each part can be lifted in one or two hands with no hoist. The biggest part, on the side, I can briefly lift with one *finger*. * The parts then snap precisely together for bonding, self-fixturing and detoleranced in two dimensions, without the robotic body shop. Laying color in the mold can nearly eliminate the paint shop. There go the two hardest, costliest steps in automaking, * saving ~80% of manufacturing capital. * That plus the two-thirds-smaller powertrain pays for the carbon fiber, *making the ultralighting approximately free*. I suspect we can do the same or better with ultralight commercial airplanes. /

This car design was Stage Two of RMI's effort to revolutionize the global auto industry. Stage One had developed my 1990–91 Hypercar® concept, initially validating it with GM and other automakers. But after two years it became clear that GM was culturally unready to collaborate, so RMI's Board told us to take the concept to the whole industry. In 1993 *we opensourced it*, making it free like Linux software, and I got most of the world's automakers worried that their competitors would do it first. By 2000, that tactic had leveraged our $2–3 million of philanthropically funded R&D investment into >*$10 billion* of industry commitments, sped Japanese hybrid releases (Honda's *Insight* and Toyota's *Prius*), and gotten serious lightweighting efforts underway. Then our Hypercar spinoff and two Tier Ones designed *Revolution.* Unfortunately, we sought production capital in Nov 2000 just as capital markets collapsed. Bad timing. But our design intrigued and inspired automakers, so as you saw, in 2013, 20 years from our opensourcing, our Fiberforge process entered the supply chain and BMW, our #1 target of influence, sold the first Hypercars. I've been driving one since 2016. Ultimately, technical and market potential do get realized. At the end, I'll suggest a way to do this for airplanes too. *

You can do a lot even without carbon fiber. Lucid, led by former Tesla executive Peter Rawlinson, is now selling its first model, *Air*—the *MotorTrend* 2022 Car of the Year[—at a $77–169k base price]. Its compact powertrain helps fit a spacious luxury interior into a midsize package. Its efficiency focus won it a record 520-mile EPA range rating with a big 118-kWh 900-V battery set up for bidirectional charging. Power up to 1,111 hp (828 kW) gives it 0–60-mph acceleration in 2.5s. Can your gasoline car do that? [However, its all-aluminum monocoque and battery mass compounding bring its curb mass to 5,200 lb / 2,361 kg—~82% 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 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 recently tested a 2022 developmental car getting ~7.48 mi/kWh or 252 mpge, thanks to 95% battery-to-wheels efficiency, exemplary 0.17 C_d, and curb mass [(1750 kg / 3858 lb)] 9% 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 1.44× the Lucid *Air*'s, but not comparably expressed]. The battery, sized for a compact EV, is so effective in this much bigger one because drag and rolling resistance are so low that cruising at 81 mph needs just 14 hp. There's even a rooftop solar array to help run accessories.
The nearly 100-usable-kWh 900-V battery weighs 495 kg—200 Wh/kg, but impressively, at >900 V. Yet that battery pack is 30% lighter and 50% smaller than the production *EQS*'s 108-kWh battery—a sign of how quickly batteries are evolving with the help of electric racecar technologies. The EQXX battery, slated for CY2023/4 production, looks akin to the in-production Farasis battery at 330 Wh/kg, 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—especially when you realize that this sedan, despite some fiberglass, is basically made of steel and aluminum, not advanced composites, so it leaves a lot more efficiency and range on the table. *

[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! Late-2022 release; $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, late-2022 release (lightyear.one).

Now the *next* efficiency leapfrog is emerging. Two solar-powered Hypercars® are expected to enter the market late this year [2022], both from firms I advise. 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 about 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 ~8 miles 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 more than triples 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, and there's lots more potential 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 recently 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 just released the production version, called Catalyst, with 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.
*

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

But coming up fast in the outside lane are electric and hydrogen-powered airplanes, the latter sometimes using gas turbines but usually using fuel cells. I'll quickly sketch for you some highlights of this journey beyond oil. But importantly, better batteries are only part of a much bigger and more complex story. I'll sketch some of its civilian dimensions.

Remember there is also *very* extensive and longstanding military investment in the same 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 that makes the Switchblade backpack-portable drones now in Ukraine—and it also makes my BMW's charger. *

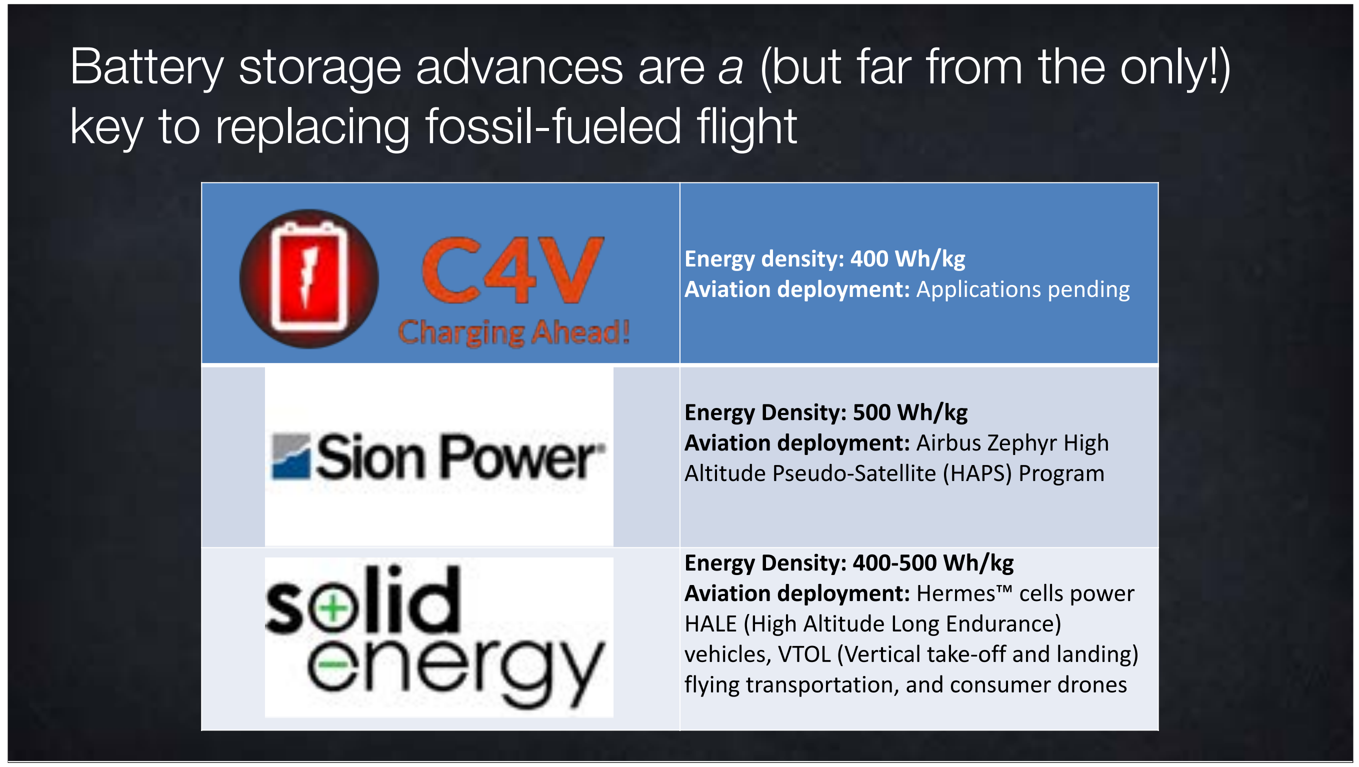
Electric drones: 0 to $6b/y in 10 years…next add pax

- Composite structures + ultralight, powerful motors (10–20+ kW/kg) + ducted fans / rotors + sensors + software + novel system concepts/architectures…
- Efforts and firms emerging: Lilium, Joby, KittyHawk, Vahana (Airbus), Aurora, Uber, Zee, Blackfly, SkyRyse, Ampaire, Volocopter, Ehang, Terrafugia, Sabrewing….
- >100 total developers, many expecting flight operations in early-to-mid-2020s
- Complements e-propulsion for normal planes; type certification processes 2020–
- With our green electricity—and much more ASE could make onsite—all electric or hydrogen propulsion is zero-emissions and almost silent (except fueled hybrids)

lilium.com

Might visions of electric VTOL (eVTOL) air taxis like this 4 pax+pilot, 300 km/h, 300-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?

Electric flight is now * becoming practical because * *many* diverse technologies, not just better batteries, are converging in a vast Cambrian explosion of innovation. * Though only a few models have yet flown, upwards of * a hundred startups (maybe >200) are reported, mainly in the US, China, and Germany. 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 Aspen Airport's CO_2, air-pollution, and health concerns by eliminating the 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 e-VTOLs to deliver bombs), 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? *



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, seven years later, at least three firms have doubled smartphone batteries' energy density to *400–500* Wh/kg—which the National Academies [in 2016] said three years ago would take 20 years. This enables short-haul electric planes immediately, moving into medium-haul 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; SVolt is readying 400 Wh/kg sulfide cells for production; and the EADS team's 2011 prediction of safe *750–2000* Wh/kg lithium-air packs by ~2030 now looks realistic in performance and conservative in timing. But keep front-of-mind that *battery energy density is fungible with platform efficiency*—only more so due to mass decompounding! Thus ICCT says 250 Wh/kg batteries in nominal conventional planes can carry 9 pax for 140 km (accounting for reserves); doubling that battery energy density to 500 Wh/kg 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 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! Electric aviation has virtually unlimited capital, Tesla-like (not Detroit-like) speed, vibrant competition, and huge ambitions. 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 that we mainly associate with consumer electronics? What new drivers of electric aviation will become 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/.

Powertrain components and systems matter too—and all are synergistic with platform efficiency

ZeroAvia.com's ambitions for hydrogen-propelled aviation's trajectory, October 2022

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 offer 10–15+, maybe 20, kW_p/kg, even continuous kW/kg, with peak efficiencies up to ~98% and sizes up to at least 2 MW. Axial-flux, printed-circuit, aircore, stacked, hybrid reluctance/magnet, inside-out, and water-cooled designs are rapidly evolving—it's a zoo. Many fine light motors have *no* permanent magnets, and iron-nitride supermagnets containing no rare earths (but promising up to twice their strength) have entered the market. Inverters have progressed from silicon switches to silicon carbide to nearly lossless, passively cooled gallium nitride. Kilovolt switch ratings now make wiring small and light. Competing to run the same motors as the batteries, fuel cells to convert green hydrogen into electricity, pure water, heat, and nothing else are 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 a year or two ago. Already, last November [2021] Chinese chemical giant Baofeng's 1-GW solar farm was making $2.7/kg hydrogen cheaper than from coal, so the chemical plant was switching over to solar hydrogen. 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 often like * this one from British hydrogen-powertrain maker ZeroAvia (partnered with BA, UA, Alaska, Schiphol, 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 speed *in this decade,* and tripling to quintupling payload while quintupling range by 2040. ZeroAvia plausibly foresees *40–80-pax planes going 1000 nm by 2026*. The firm says it's "initially targeting a 300-mile range in 9–19 seat aircraft by *2025*, and up to 700-mile range in 40–80 seat aircraft by *2027*" [emphasis added]. They might not exactly meet that goal, but someone may; and even if the dates slip, they're still probably sooner than you could build your airside. It's unwise to stand with your back to a stampeding herd of techno-buffalo. *

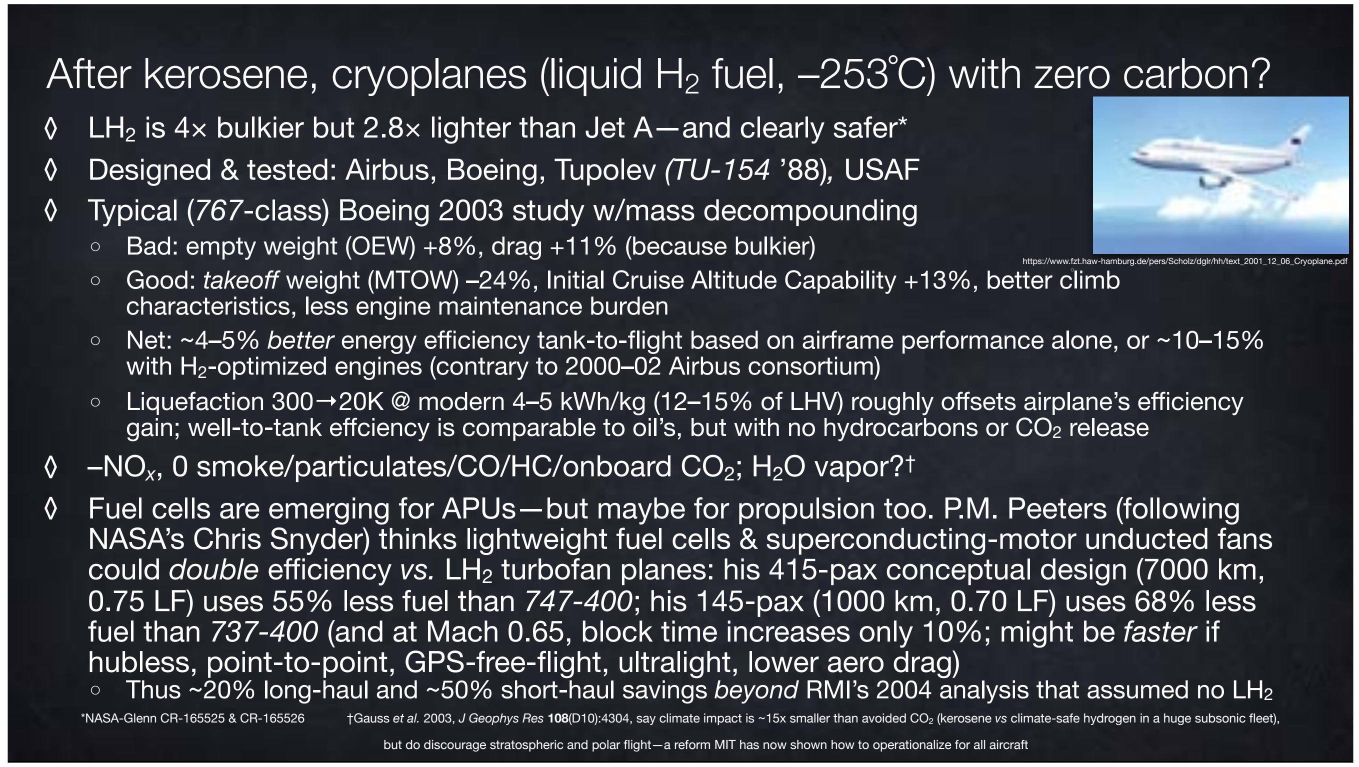
Examples of battery-electric aviation's trajectory, Oct 2022

vendor, model	*key parameters*	*expected timelines*	*status*
heartaerospace.com *ES-30*	30 pax typ 200 km all-electric 400 km el+hybrid 800 km el+hybrid if 25 pax 30-min fast charge 101' wingspan, 1100m runway (not @ density alt)	late '20s: 200 km el / 400 hybrid mid-2030s 300/500 late 2040s 400/600	230 orders, 100 options, 99 LOIs; UA, AC, Mesa, Saab,…
Wright Electric *Spirit,* then *Wright 1*	100 pax, 1 h 186 pax, 800 mi	2026 2030	NASA, ARPA-E,…; 2-MW motor scales 0.5–4 MW; *1* uses 10×2MW, *~A320*
eviation.com *Alice* (redesigned since Paris-show ver)	9 pax, 2×630kW motors 440-nm range, lifting body 1134-kg payload, 95% com-posite, 63' span, 2.8h @ MTOW, typ mission 150–250	2025 type cert	flew 27 Sep 2022; 137 sales to Cape Air & DHL; maker predicts normal commercial ticket prices

…and many, many more—often still in stealth mode

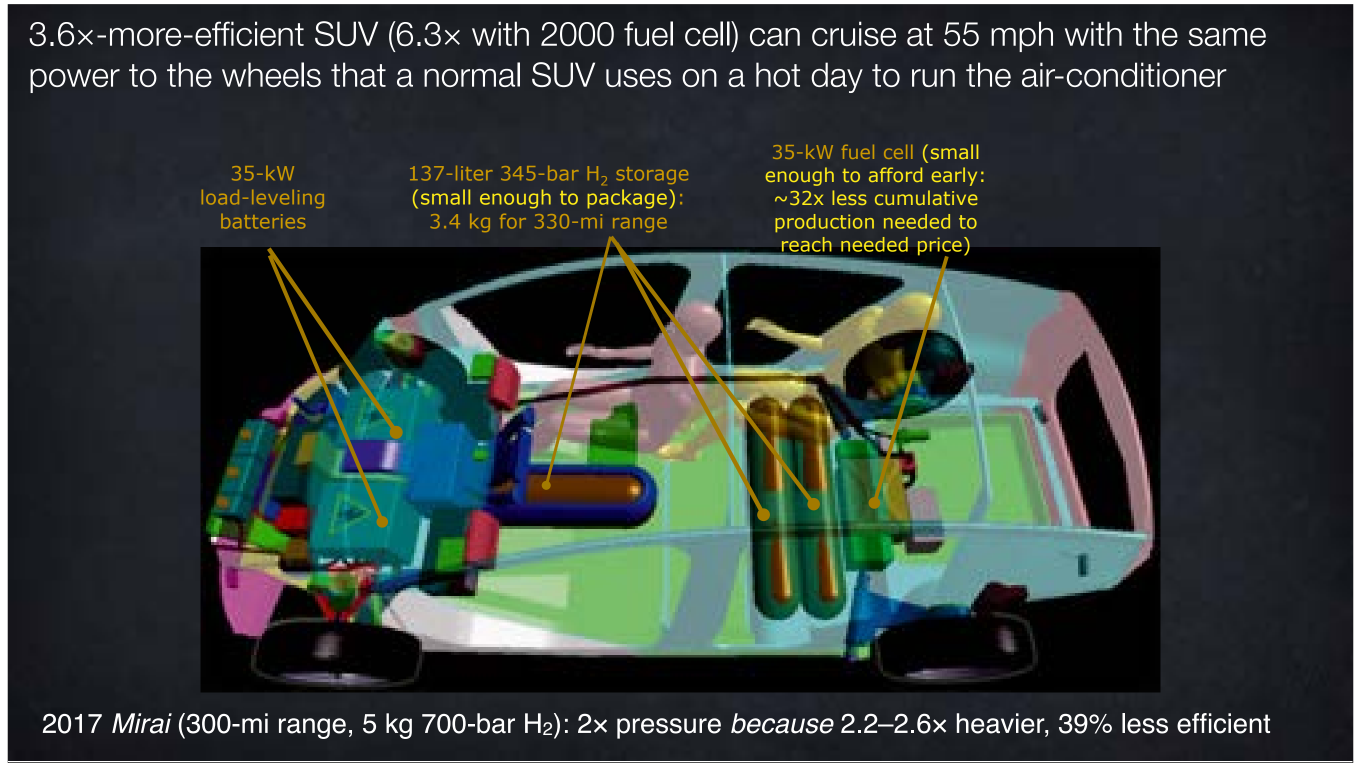
Battery-electric aviation is evolving at least as quickly as hydrogen aviation. Vendors target different initial market segments, but clearly we're likely to have capable all-electric planes in the ~30–100-pax range before a new Aspen airside could be built. For example, here are the ambitions of three of the better-known vendors among 100–200-odd. Swedish maker Heart Aerospace is initially in the 30-pax market with both pure- and hybrid-electric propulsion, expecting to go from 200 km electric (or 400 km hybrid-electric) late this decade to 2–3× that range over the following two decades. It has strong orders and backers; several Nordic countries plan to go rapidly all-electric for all domestic flight. Wright Electric expects to carry 100 pax for an hour by 2026, then 186 pax 800 miles by 2030. Wright focuses especially on big efficient motors, so its bigger model's ten 2-MW motors will have about the same power as an *A320*. The Israeli firm Eviation, after a bumpy start, still expects to bring a 9-pax, 2.8-hour plane to type certification by 2025. It has significant sales (as always, contingent on performance), mostly to the island-hopping Cape Air. Notice that all these illustrative market entries hope to start deliveries in the next *~3–6 years*. And none of them yet uses extreme lightweighting or ultralaminar flow. This list also doesn't include (see slide 40) a half-dozen main eVTOL makers like Joby, which just applied for Japanese certification in collaboration with FAA. / I expect electric planes to land at ASE before you have an approved ALP. Aspen (like Heathrow for a year) could welcome them by waiving landing fees for all-electric-or-hydrogen planes. Onsite PVs could recharge them and help build upper-Valley grid resilience. /
I won't dwell here on turbine- or engine-hybrid designs, which probably have an important transitional role much as they did for cars. Nor will I prognosticate on hydrogen *vs.* batteries in short- and midhaul markets. Markets will decide that. But the automotive history, where superefficiency is now taking us to once-unthinkable *solar*-powered cars, hints that the same 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' 23 years ago [1999]. *

[https://www.jobyaviation.com/news/joby-applies-for-japan-aircraft-certification/, 18 Oct 2022]



Happily, there’s an easier longhaul solution than photovoltaic airplanes. We can simply replace 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. * 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’ 3–5× efficiency gain to ~6–7×. That was before we had options like fully laminar flow and extremely lightweight motors, so now the number is probably >8×. /

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. *



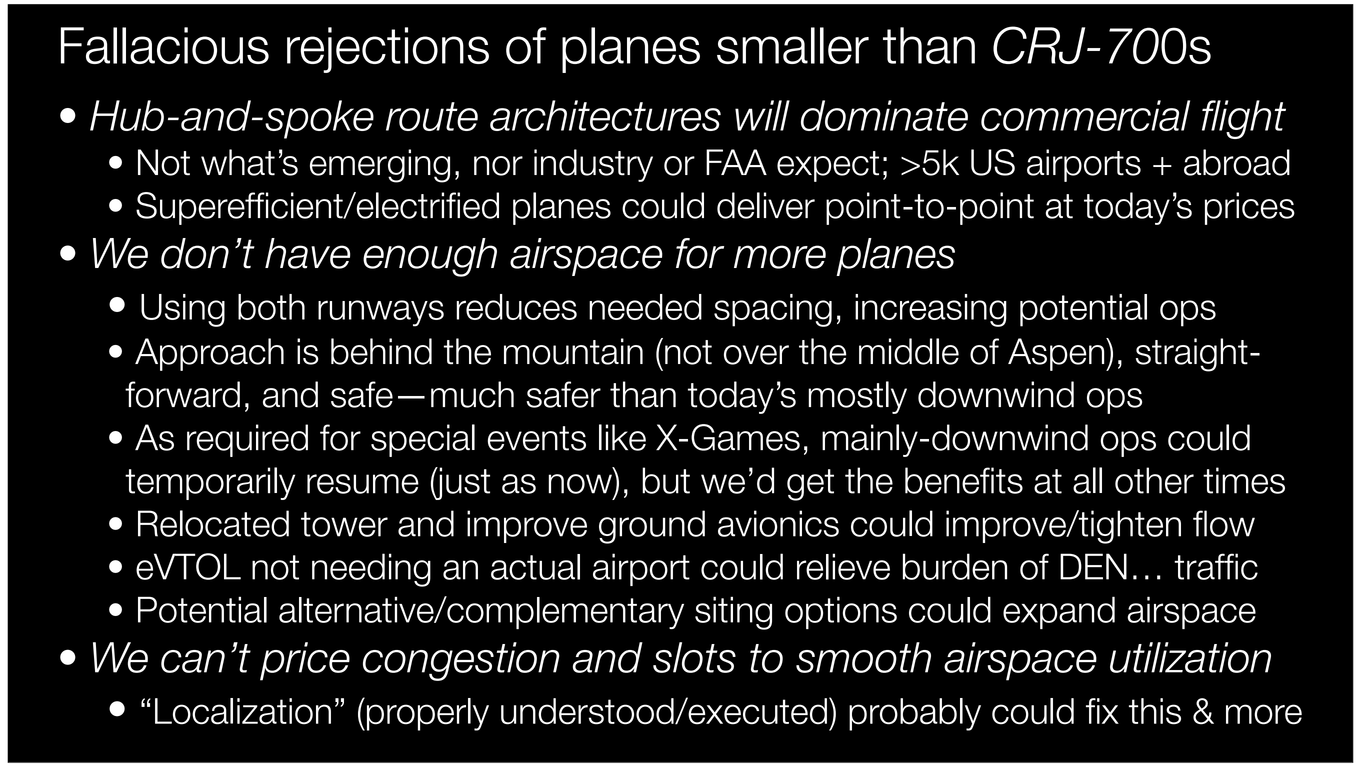
And to return for a moment to the automotive analogy, radical vehicle fitness enables *all* kinds of advanced powertrain. Our original carbon-fiber electric SUV design in 2000 illustrates this. It used an early fuel cell (long before cheap batteries), but its 2/3 lower tractive load made its H_2 tanks 2/3 smaller for the same range, so 1990s off-the-shelf *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 enabling both hydrogen and battery-electric clean aviation. *

And 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 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 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. /

Now my last two slides will suggest some conclusions important for Aspen Airport planners and citizens. *



We often hear claims that Aspen Airport, our little aircraft-carrier in the sky, is so unavoidably constrained that more but smaller planes—even if needed to capture the climate, health, noise, and economic benefits of electrification—cannot handle existing guest traffic, let alone more. This objection seems to me to reflect siloed thinking. *Integrating* related solutions in industry structure, airport ops and layout, regulation, and other variables could instead solve many problems at once—especially the primary challenges of safe, clean, and green aviation. * I think the rapidly emerging industry shift from hub-and-spoke to point-to-point route architectures will change everything. This may be your biggest planning contingency. Industry and FAA take it very seriously. * Ignoring it locks you into intractable and worsening problems as the airside layout becomes ever less fit for purpose. * Very efficient and electrified planes with 9, 19, dozens, or other sub-70 seats will increasingly match or beat commercial ticket prices while delivering far superior point-to-point service to many thousands of often nearby, quick, and uncrowded airports, in the US and abroad: today's commercial carriers could quickly evolve to look more like NetJets or other GA. But that could smooth out peaky commercial passenger flows, reducing capacity needs and congestion in the terminal and in ground transport. * Current dominantly downwind operations, contrary to FAA safety doctrine and common sense, need to be fixed by stopping head-to-head traffic at least most of the time. I think we agree that if feasible, this could reduce spacing and hence better utilize the airspace for more ops with greater safety. * This does not mean landing over town. The required inbound vector jog is only ~3˚. Taxiway congestion could fall. * Special events at Buttermilk could revert landings to current practice but are rare. * Better radars and other electronics, tower visibility, and GA pilot training could densify spacings while improving safety. * Some traffic could go to air taxis not needing the airport, or could probably use other sites not yet considered. * And if the County could stop misunderstanding the opportunities in what I call "localization," that could probably unlock sensible local regulation that could better manage and rebalance demand for scarce airspace resources without raising statutory or equity objections. * There's more. But *combining* most or all of these options could solve most of the Airport's problems with better safety, lower impacts, lower costs, and far lower impacts and risks. Only such a highly integrated approach, not piecemeal siloed thinking, can succeed. *

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 them an implementation concept that many of them loved. In today's circumstances there are some emerging signs that it may take off quickly and help bring to fruition many of the technical ambitions 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. Why take a century to do that incrementally when we can leapfrog straight to it? Major airplane buyers, even if they have the capital, are understandably risk-averse. Airframe makers don't want to risk huge development investments for a radically better product that might not sell. So incrementalism continues as we squander fuel, money, carbon budget, and precious time. The climate crisis won't wait. Business-as-usual won't work. Aviation's license to operate will erode. Our shareholders, voters, and children will judge us negligent. /

So what if a powerful consortium of major customers—airlines, lessors, delivery and air logistics firms, the Pentagon—relieved the airframe makers' market risk so they could fully focus their skill and ambition? The buyers could collectively solicit a superefficient airplane by publishing very demanding specifications—very clean and at least quadrupled-efficiency—and collectively commit to buy *x* copies a year for *y* years at price *z* from whoever first brings it to market, with a consolation prize for the runner-up. This elicits and rewards innovation for the airplanes they'll buy anyway. Unbundling buying airplanes from buying innovation changes the suppliers' culture and brings out the best talent of their best innovators. This yields a very different product slate, reducing risk to both parties but most of all to airplane buyers. This "golden carrot" method is sometimes called Advance Market Offerings or Advance Market Commitments. It has worked well since 1990 for >20 diverse solicitations in countries from Sweden to France and America to India. It's time we seriously considered it for airplanes. That could decouple flying from climate change. Unlike carbon offsets, it could also slash fuel costs and the risks of fuel-price volatility. It could greatly increase energy security and national security. And it could unleash a huge burst of innovation that could transform aviation forever. /

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. *

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https://www.cee1.org/content/golden-carrots-beginning; *Winning the Oil Endgame* (RMI 2004), pp 199–203.