[target 20m, rehearsal 21, actual 21]
* = click for build/transition/animation
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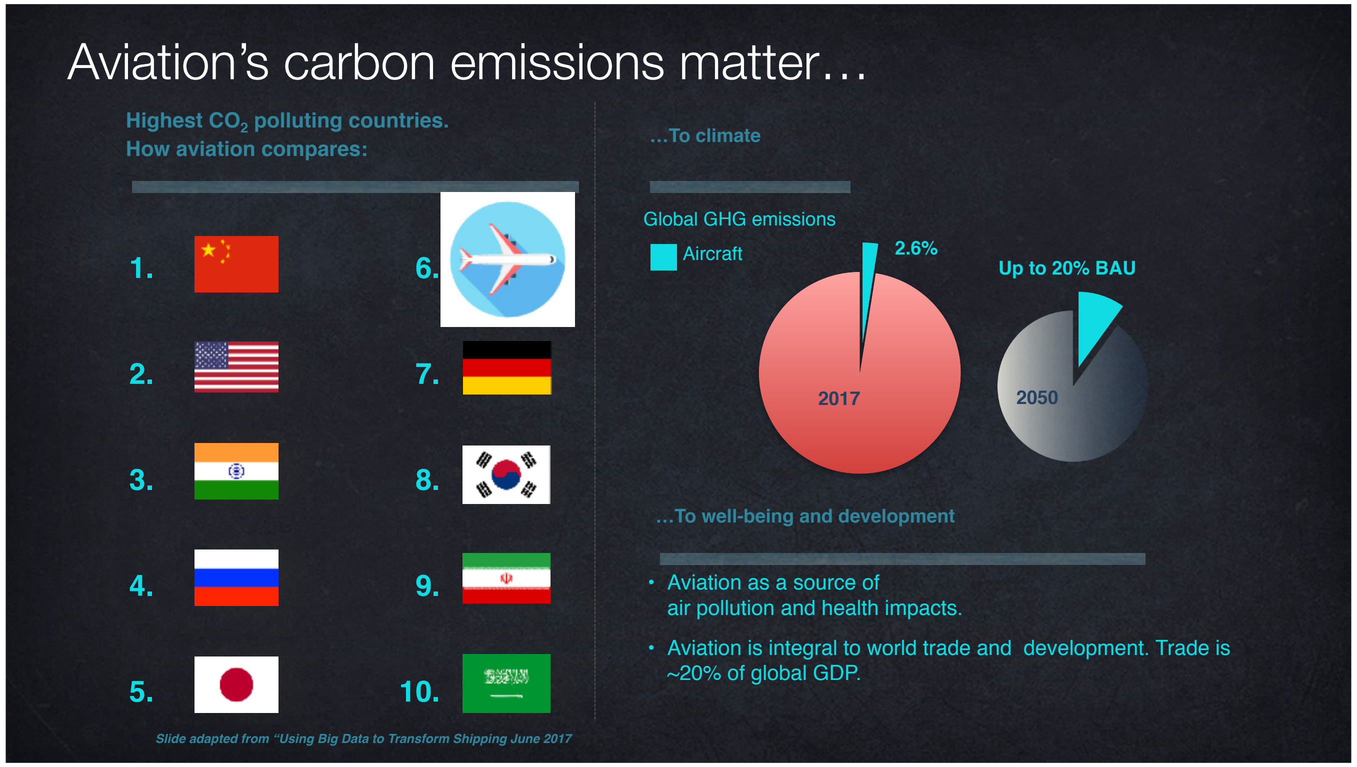
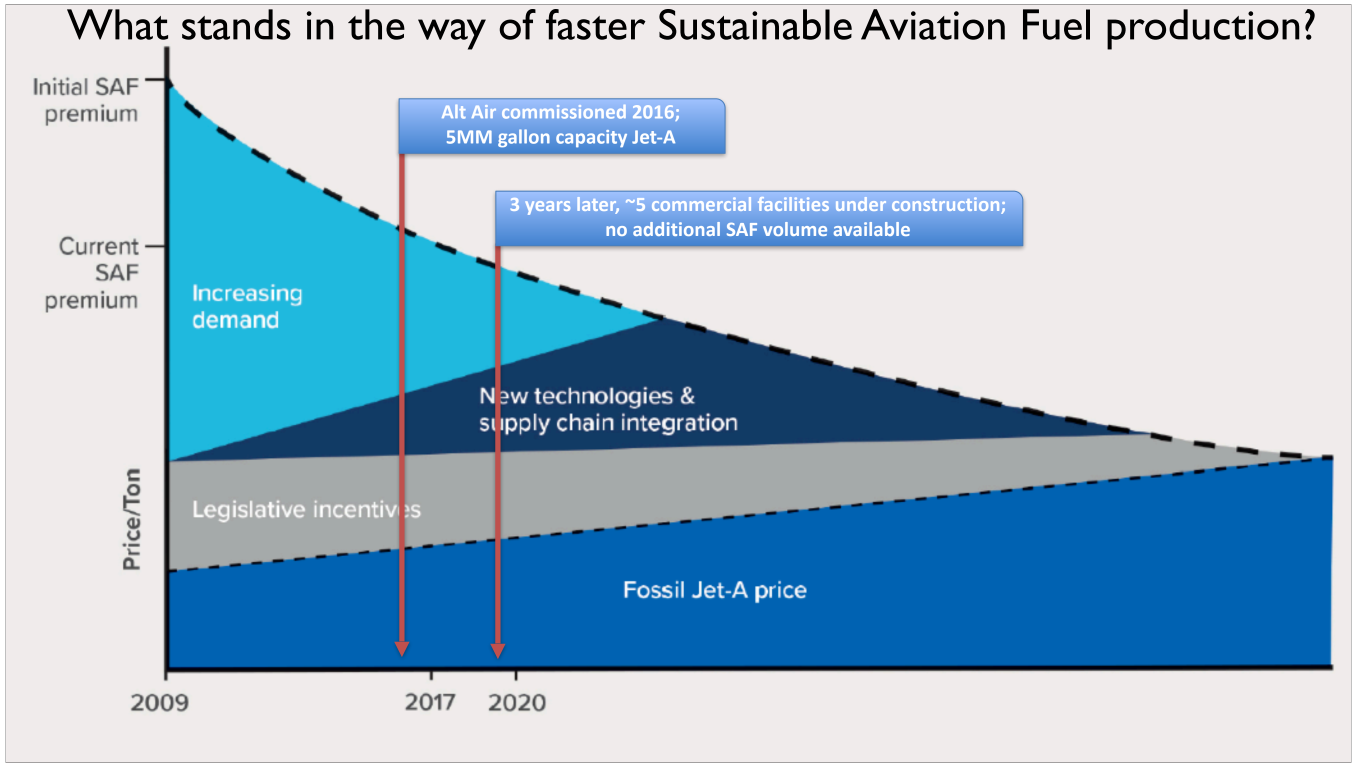
Thank you for the honor of sketching the efficiency revolution in commercial aviation. *

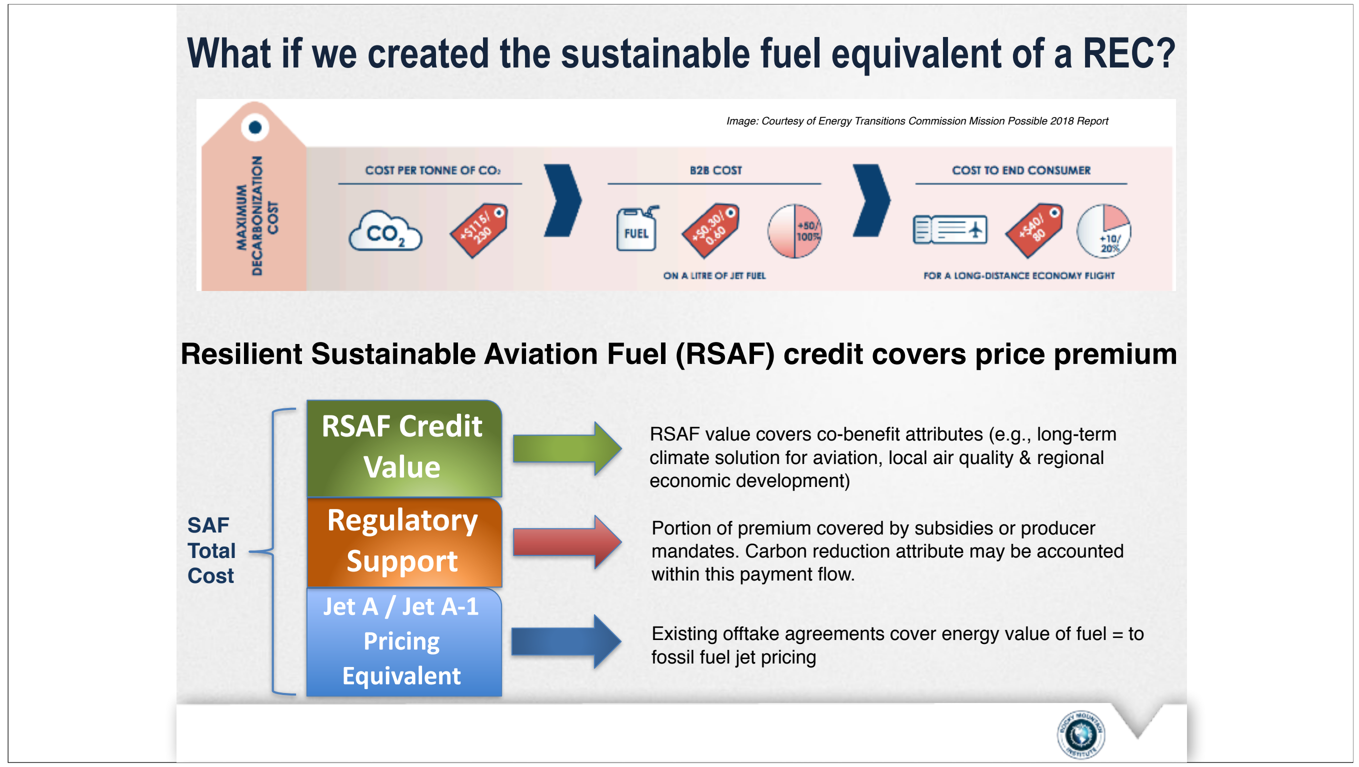


If aviation were a country, its annual emissions would sit between Japan and Germany, with around 850 million tonnes of CO_2. That's less than 3% of the global total, but by 2050, forecasted growth plus reductions committed by other sectors could bring aviation's share to 20% without a change of course. That trajectory is misaligned with science-based targets, and already for many of us, flying is our largest source of personal greenhouse gas emissions. / Leaving out all the worthy improvements you're already making in routing, route architectures, airports, ground ops, etc, I'll therefore focus on two main opportunities to protect and advance the industry's interests by decoupling aviation from climate: first briefly commenting on sustainable aviation fuels, and second, exploring radical airplane efficiency and how to expedite its profitable development and scaling.*

IATA estimates 849 MMTonnes CO2 from Aviation in 2017 vs. 32.5 MMTonnes in global total emissions (International Energy Agency)

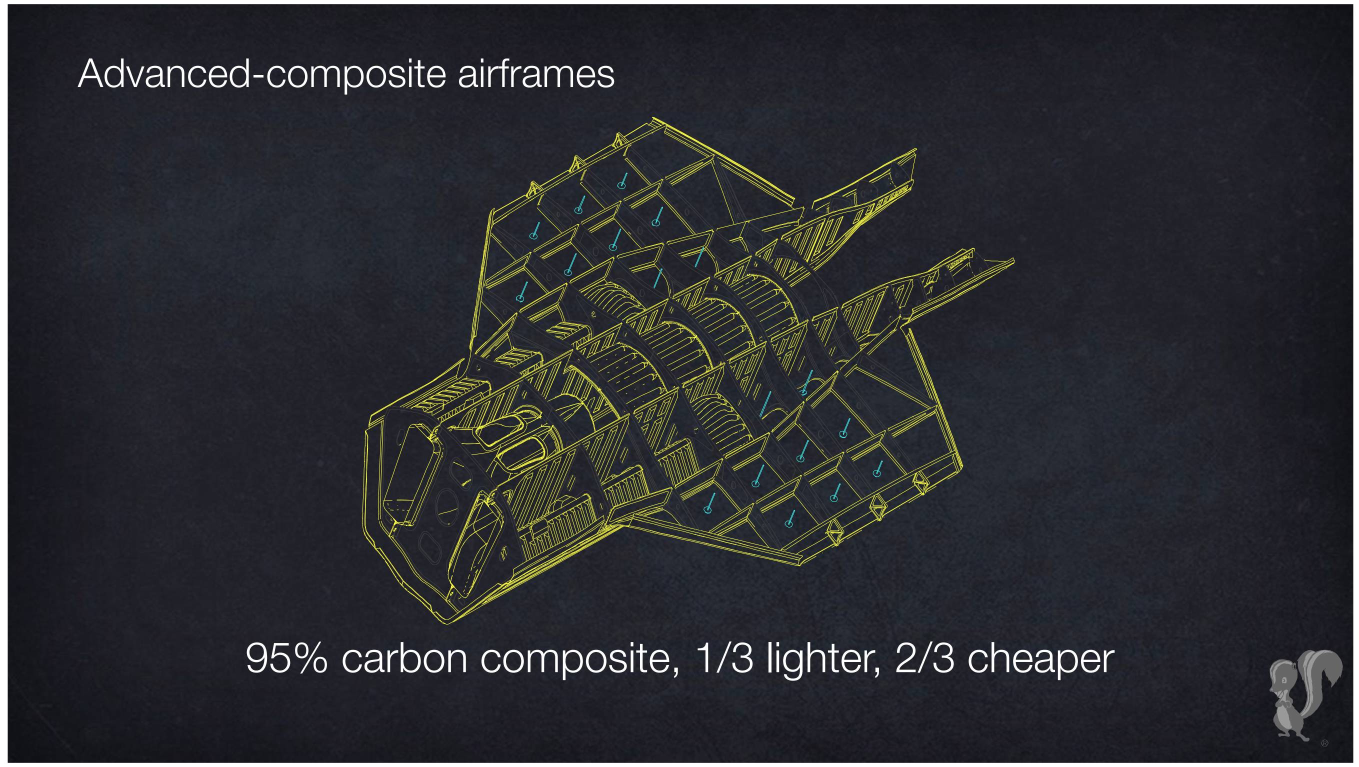


To protect the climate and themselves, airlines now focus on operational fuel savings and, usually far less, on Sustainable Aviation Fuel (SAF). That typically costs ≥2–3x Jet-A, so scaleup is slow. With profit margins averaging <$12 per ticket, carriers don't want to raise their biggest operating cost. Conversely, even in as favorable an environment as California, biofuel producers make >20% higher margin making road fuels than Sustainable Aviation Fuel, which therefore isn't a top priority for promising new potential producers like Fulcrum and Carbon Engineering. Without a clear market, lenders and investors will stay on the sidelines. Supportive airport policies like Seattle's can help. So, perhaps, could another option. *

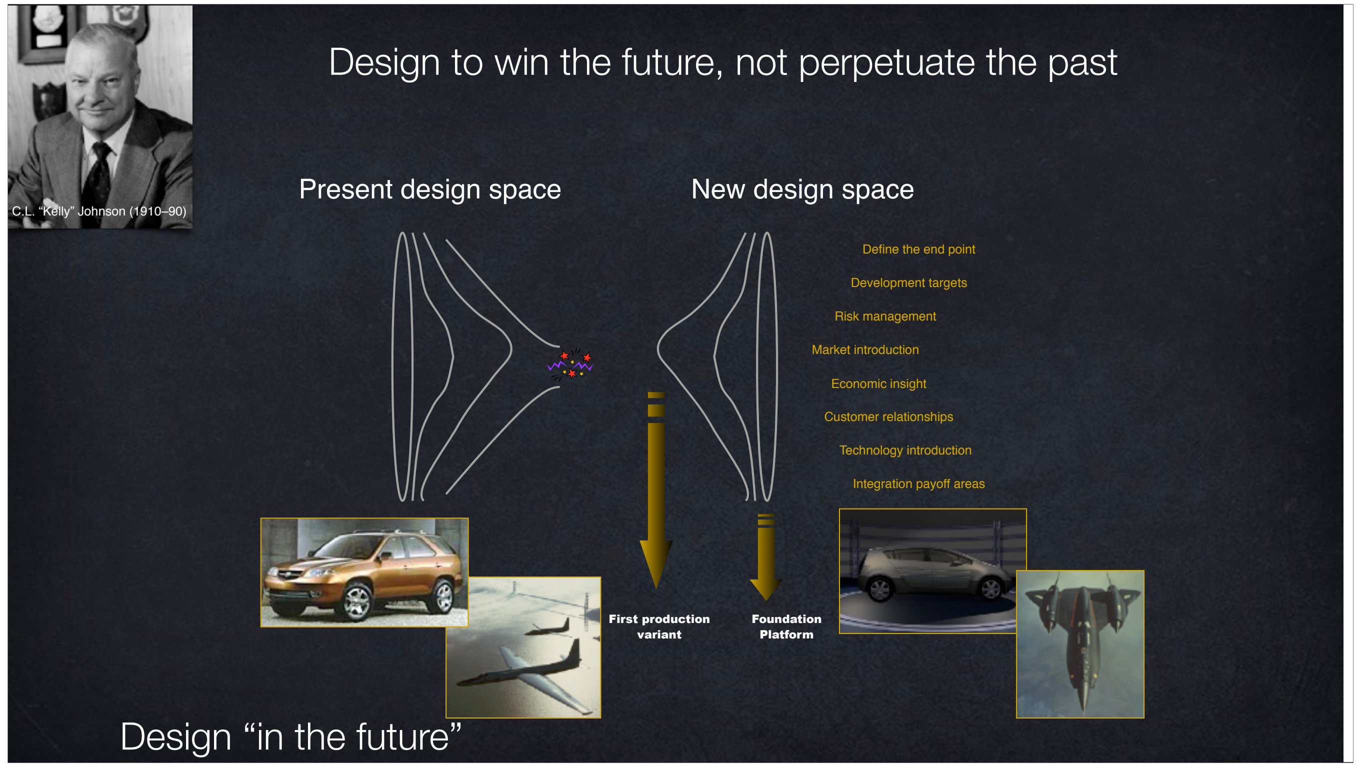


The Energy Transitions Commission's findings imply that decarbonizing jet airplane movement would add 10–20% to the average ticket price. But if airlines can't cover this gap, businesses flying in their airplanes can. Rocky Mountain Institute is therefore developing the "Resilient Sustainable Aviation Fuel" or "RSAF" ["AR-saff"] credit concept to create a product that can bridge this gap. It would work like the Renewable Energy Credits (RECs) widely used to unbundle and transfer solar- and wind-generated electricity's attributes to buyers, but RSAFs should be worth more because they're truly "additional" and they cover the actual price gap. RSAF credits may also be linkable to new production capacity, similar to RMI's successful spinoff, the Renewable Energy Buyers Alliance. They're akin to what SkyNRG's "Board Now" program with a single biorefinery, and can be compatible with other regulatory regimes. [RSAF credits could be sold even if the carbon value is already counted within fuel regulations like the Low Carbon Fuel Standard, because the buyer is then investing not in eliminating a specific amount of carbon but in aviation's long-term carbon solution. RMI strongly endorses climate policy frameworks that make aviation climate actions additional to COP Nationally Determined Contributions, so carbon reductions from SAF feedstock cultivation are counted once and only once.] / But while we urgently seek to scale up sustainable aviation fuels, we also need airplanes that use radically less fuel. *

Above all this means light weight. Taking 1 kg 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 liter 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 could do far more with basic structures. *

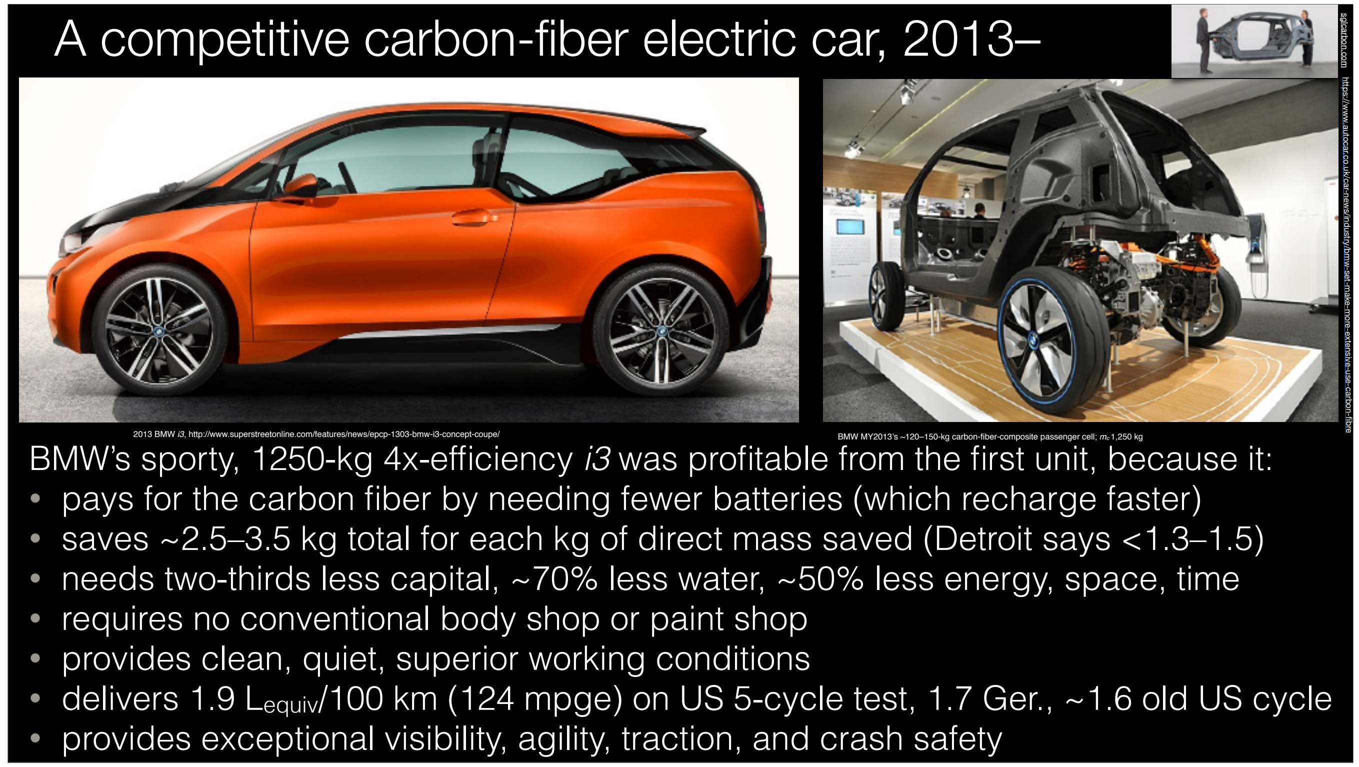


Our lightest big passenger planes are still only half carbon-fiber composites by mass. But 23 years ago, Dave Taggart at the * Lockheed-Martin Skunkworks led for DARPA [in 1994–96] the design of a 95%-carbon-composites advanced-tactical-fighter airframe that was * 1/3 lighter *but 2/3 cheaper* than the 72%-metal base design. *

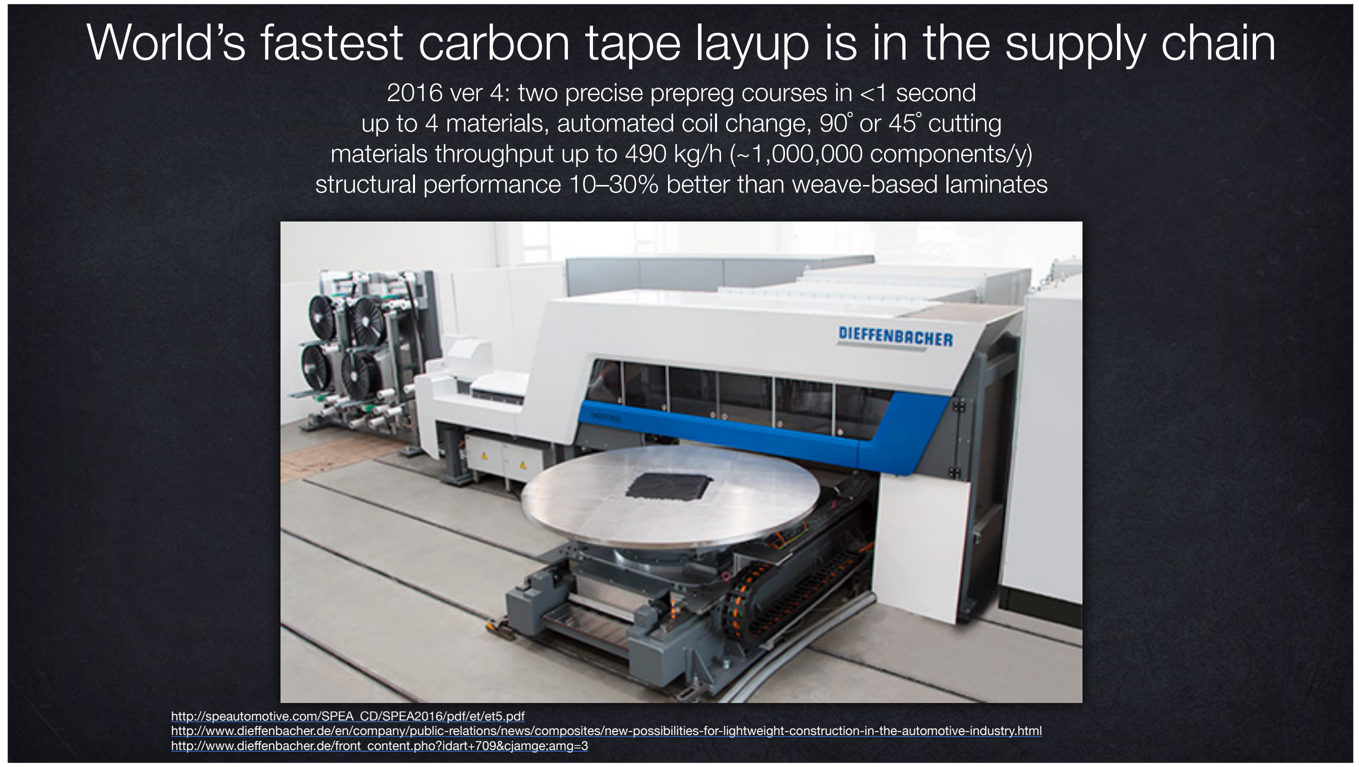


That requires revolutionary design mentality—designing in the future, not in the past. When the Soviets shot down * Francis Gary Powers's U-2 spy plane in 1960, Kelly Johnson didn't say, "I'm going to design a slightly better U-2"; he said, in paraphrase, "I want to own the skies for decades, so * we'll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

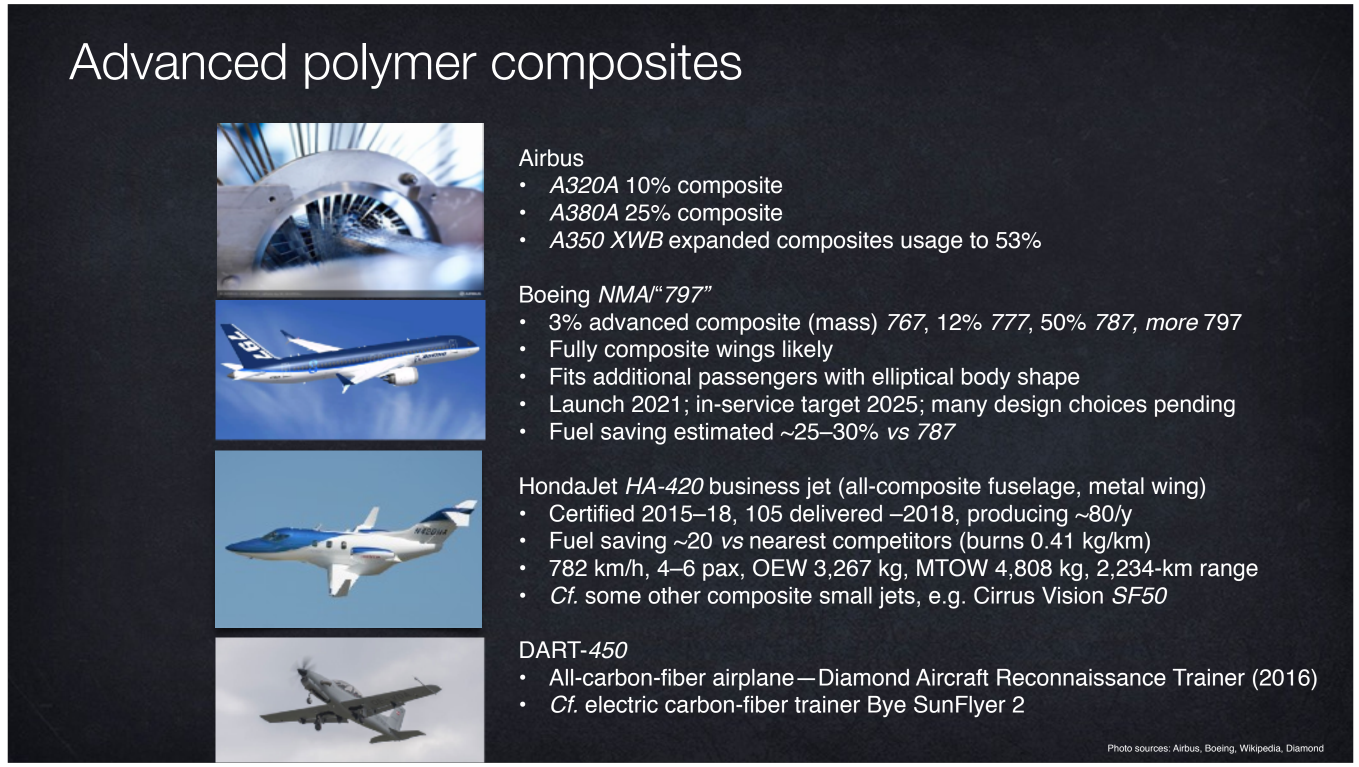
Johnson understood that such an airplane was impossible within the conventional design context, because design is * like a rubber band: if you try to stretch it too far from the conventional design space, you encounter more and more resistance, and eventually it breaks. But if you * jump to the new design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



Such visionary leadership by Ulrich Kranz enabled BMW to develop the *i3* carbon-fiber electric car I drive. * It reportedly made money *from the first unit off the assembly line*. Sandy Munro, the normally understated dean of automotive costing, called it the "most significant vehicle since the [Ford] *Model T*" and "the most advanced vehicle on the planet." * Its carbon fiber is paid for by the batteries that its lightness saves (and fewer batteries mean faster recharging). Its integrative design * makes weight savings snowball far more than normally assumed. Its * manufacturing is radically frugal, * confirms the elimination of conventional body and paint shops, and * is much better for workers. And overlooked synergies between ultralight materials and electric traction * quadruple efficiency without compromise and * with many driver advantages. *



A process my team developed made this test piece *[show]* for military ballistic helmets in one minute 12 years ago. It then made many airplane parts for some of you, like composite window frames that went from concept to commercial flight in six months. Sold to a Tier One pressmaker, this process can now make a complex 2x2*m* carbon-fiber part in one minute, or over a million smaller aerospace parts per year. Ultralighting cars this way is approximately free—paid for by a two-thirds-smaller propulsion system and by radically simpler and cheaper automaking. Ultralighting airplanes is worth even more. *

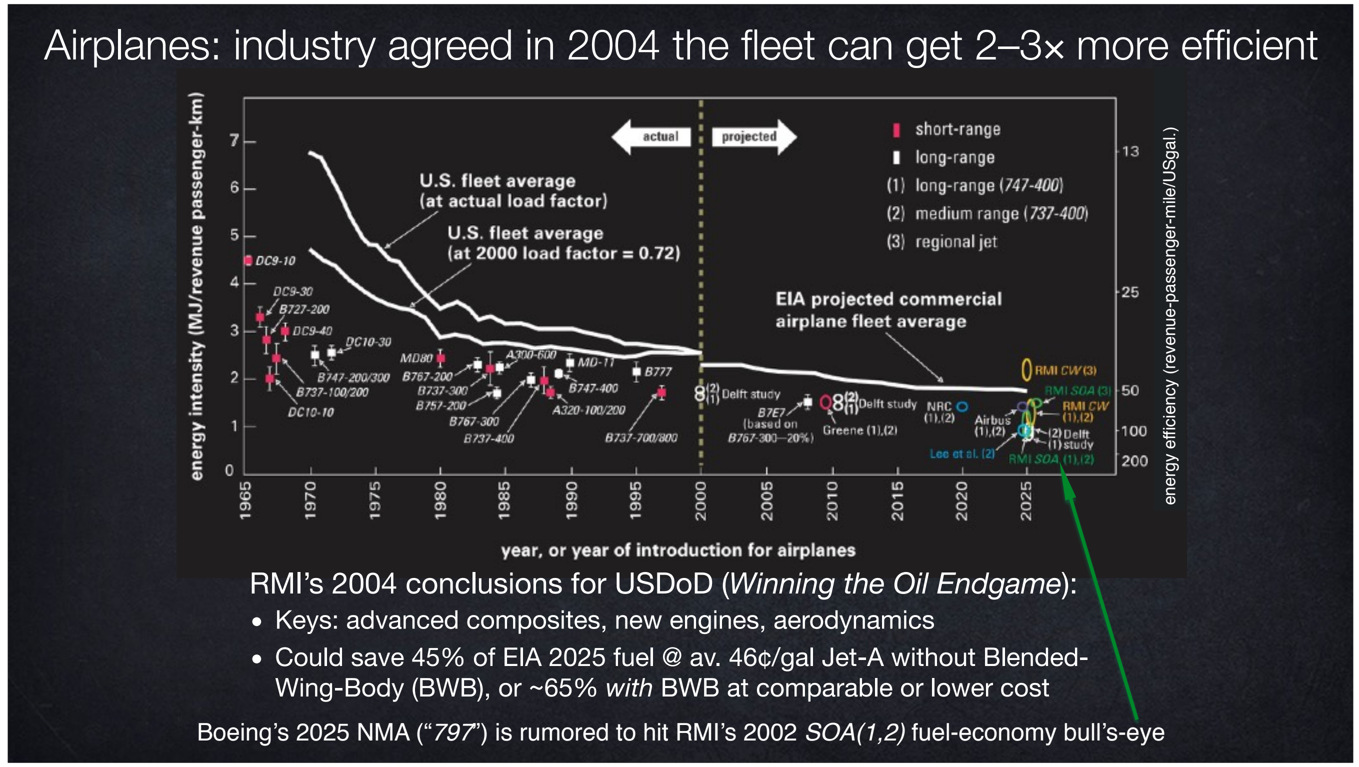


To be sure, advanced composites are incrementally displacing metal. Current trends include carbon-fiber wings and elliptical fuselage forms with a *787*-like passenger compartment atop a skinnier *737*-like cargo hold, thus fitting more seats with less drag and weight. But many components still made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

(Source: AeroDynamic)

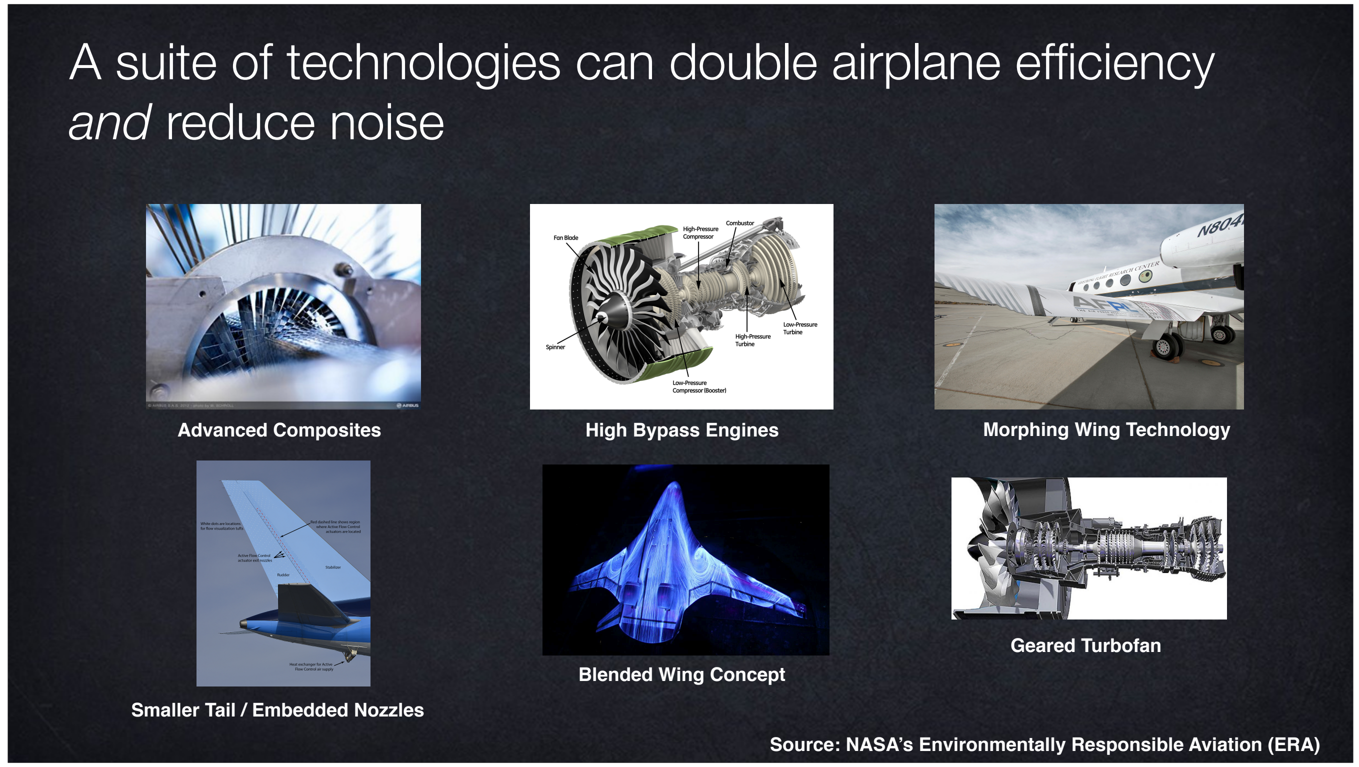
What is a saved watt worth?
Are we buying enough negawatts?

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 electricity 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. *



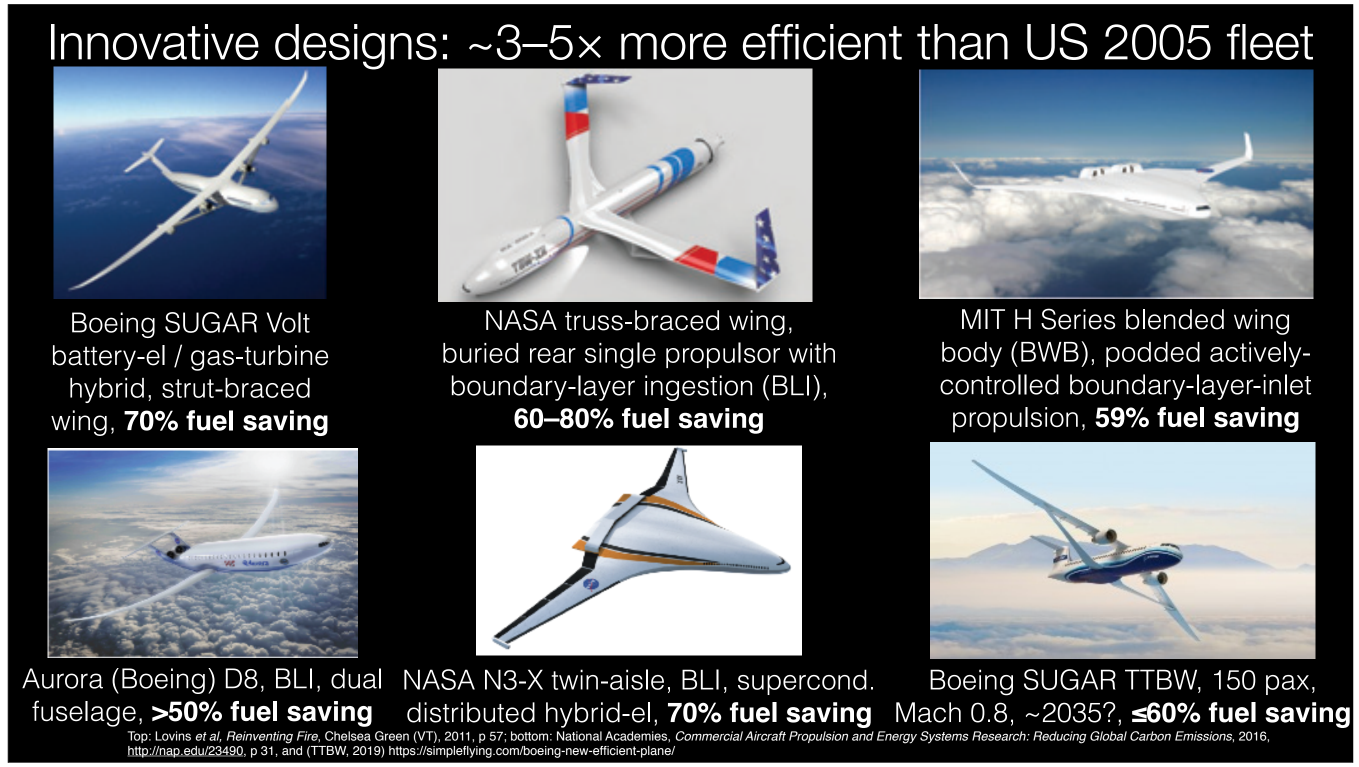
Of course, airplanes have long been getting more efficient. Those certified from 1960 to 2000 cut fuel intensity by 70%—half by better engines, half by better airframes. That progress remains on its steady course, so Boeing's *NMA*/"*797*" * is expected to hit our * 2004 bull's-eye for 2025. But because of uncertain and often cash-short customers, the industry's trajectory is too slow, raising efficiency by just 20% per generation.

[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, adaptive engines, or other advanced technologies, nor any use of liquid hydrogen fuel.] *



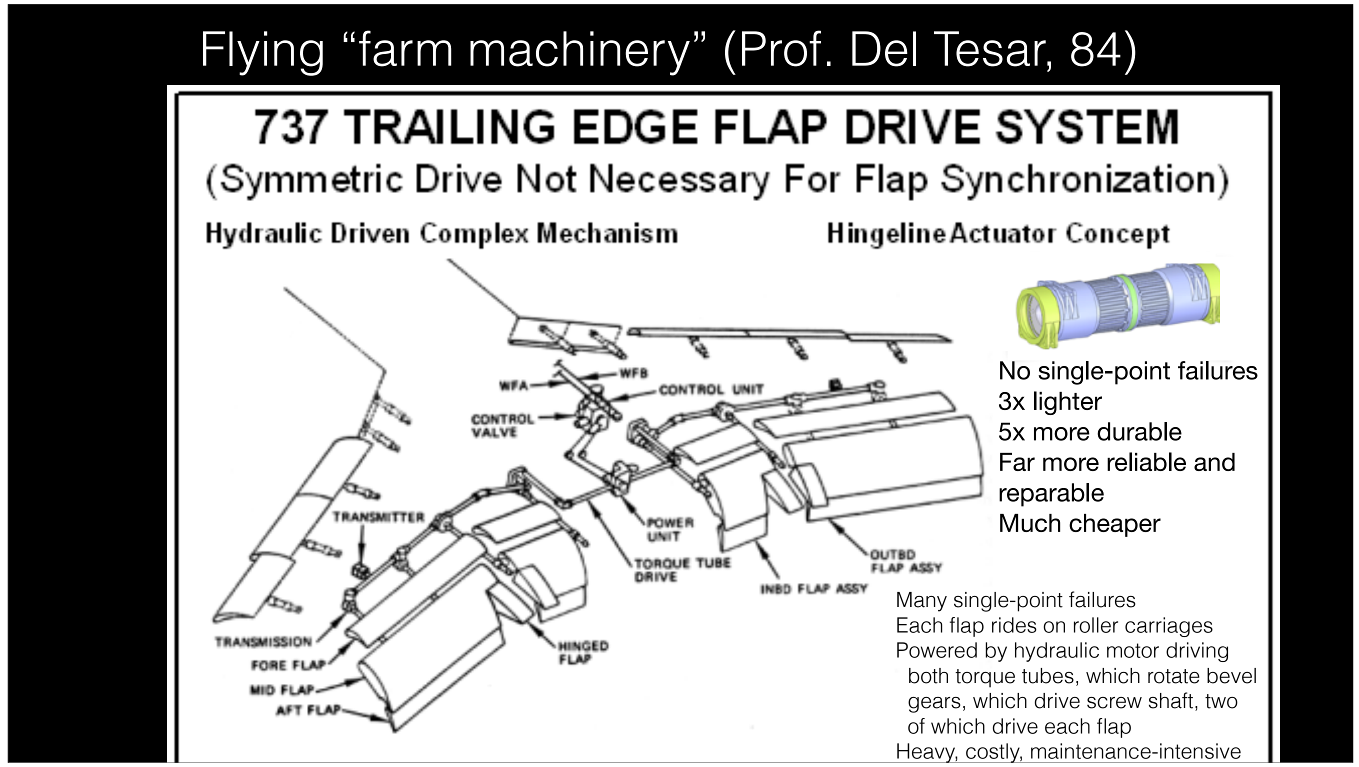
Next-generation options are well-known, effective, and profitable. But many more are available. *

[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.]



More-ambitious combinations of current technologies can boost efficiency cost-effectively by *3–5x*. These upper three designs from Boeing, NASA, and MIT are a decade old, the lower three 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.

[Longhaul "cryoplanes" fueled by liquid hydrogen may raise these efficiency gains to ~5–7x. Rockets use liquid hydrogen because it's the lightest fuel, and its cold enables lightweight superconducting motors.] *

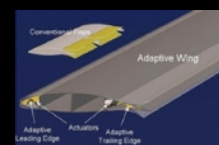


Even simple changes are effective. Looking out the window as an older plane lands, I’ve seen the flaps extended by a hydraulic/mechanical system that the wizard of electric actuators calls “farm machinery”—heavy, unreliable, and costly to buy and maintain. He’d replace it with a * 5x more durable, far more reliable and reparable, much cheaper hingeline electric actuator that cuts overall system weight 3x. *

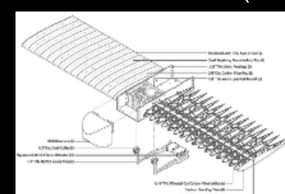
Aerodynamics

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

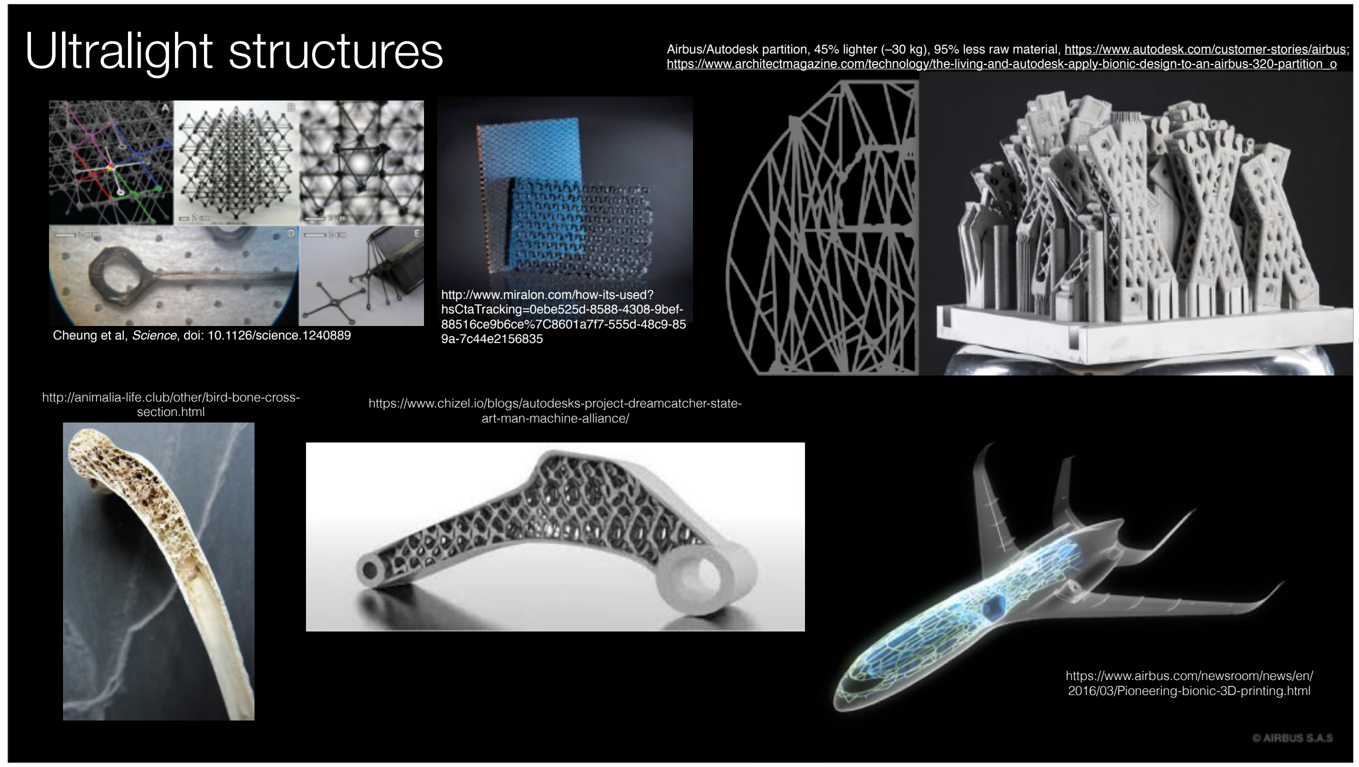
http://news.mit.edu/2016/morphing-airplane-wing-design-1103

[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 should enter commercial use next year.

[* 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.] *

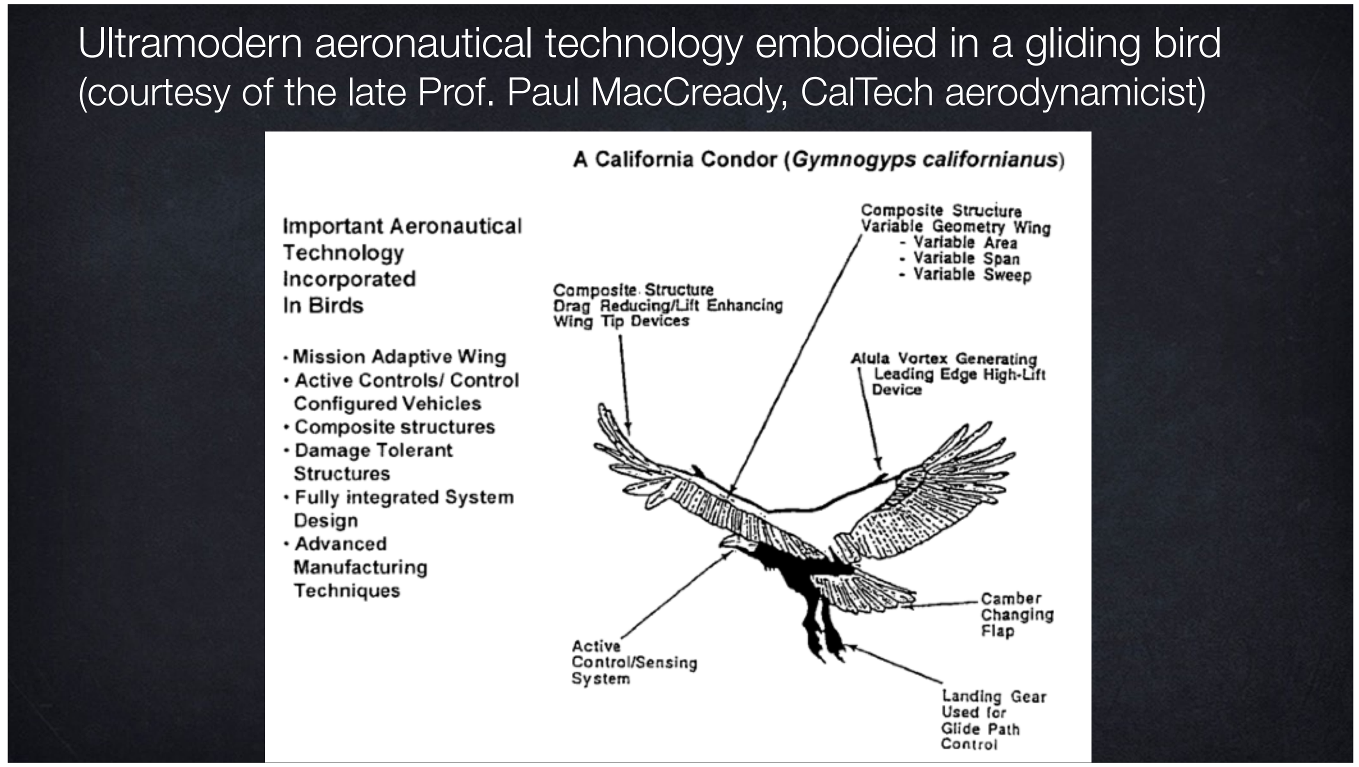
The second just produced at MIT a 4.3m test structure *59x less dense* than a typical aircraft wing. You heard me correctly: such a structure has the strength of elastomers but the gossamer density of aerogel. Eliminating moveable flight surfaces, every part of its entire shape *passively* adapts to optimize continuously for real-time flight conditions. 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. *



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 10x 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

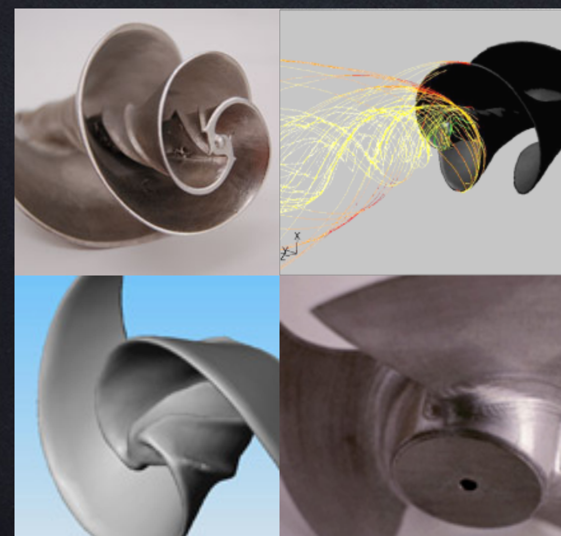
Nature is rich in great aeronautic designs like the tropical cucumber seed that can glide for hundreds of meters—not to mention…*



…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. *

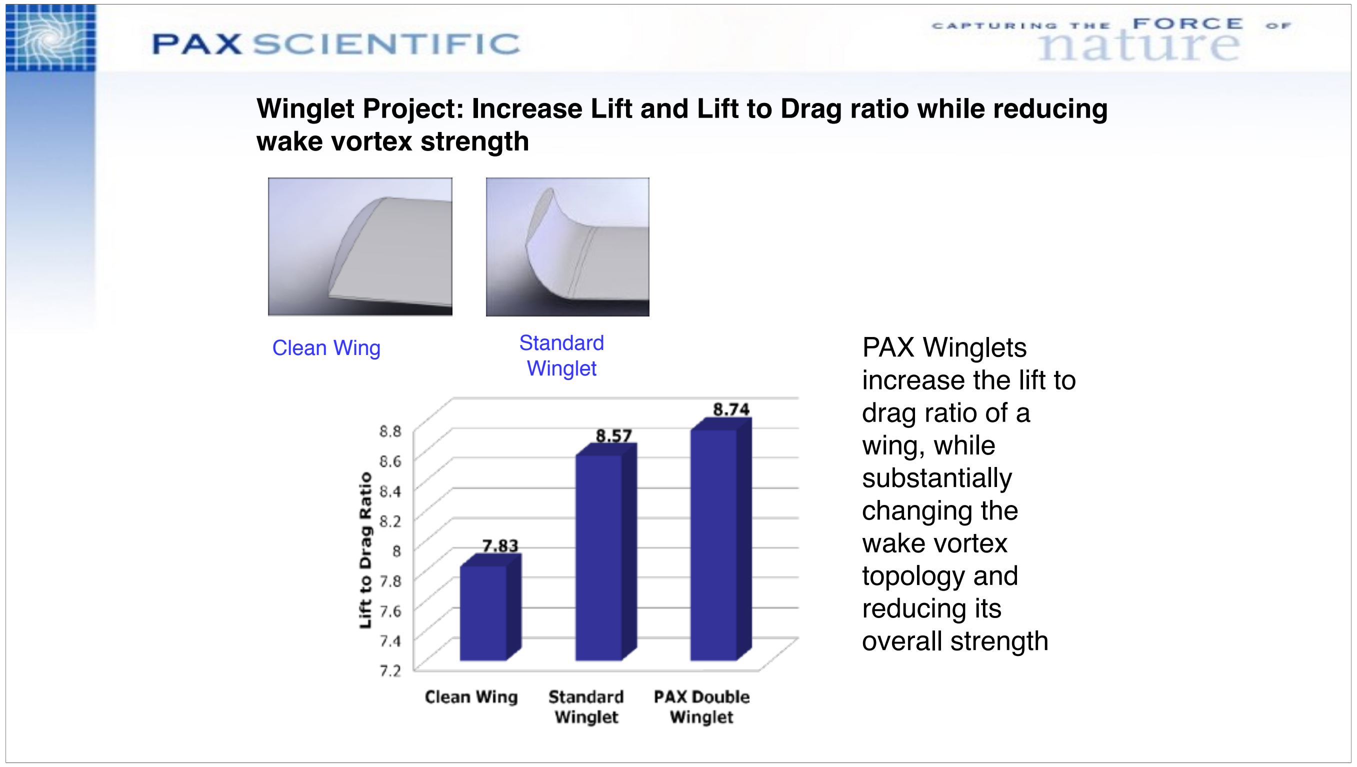
Biomimetic hydrodynamics



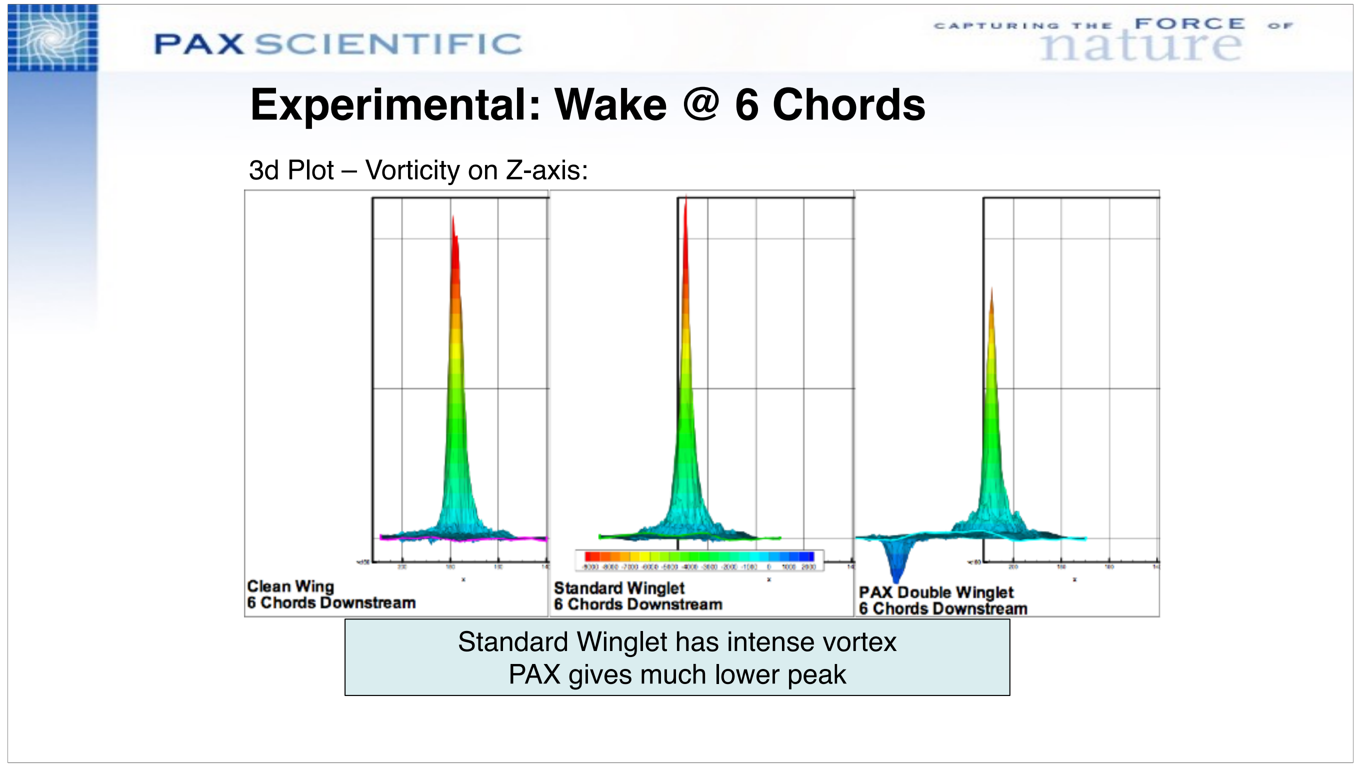
- In fans, pumps, turbines, and turboexpanders, laminar vortex flow can raise efficiency by 20–30% and cut noise
- Fish can pass unharmed
- Computer muffin fans get +30% flow/W or –10 dBa
- Read *The Shark's Paintbrush*
- Devices are starting to enter the market

Such rotors can 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….*

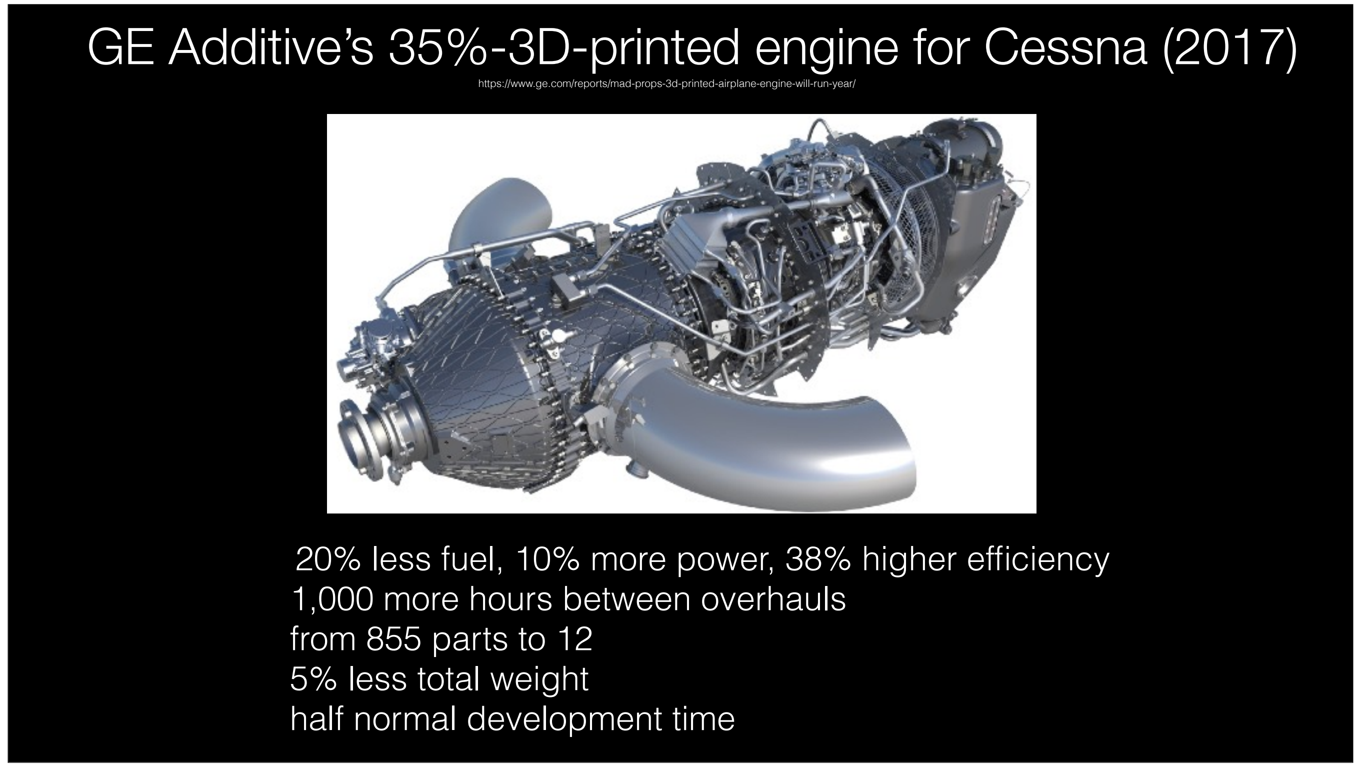
…yielding diverse superefficient fans, propulsors, and hulls, some now on or entering the market. Their efficiency gains are independent of scale *and of Reynolds number*, so for air as for water, converting standard fuselage airflow to laminar vortex flow or toroidal flow regimes can cut drag—in one early trial, by 14%. *



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



…while making wake vortices weaker and shorter. *

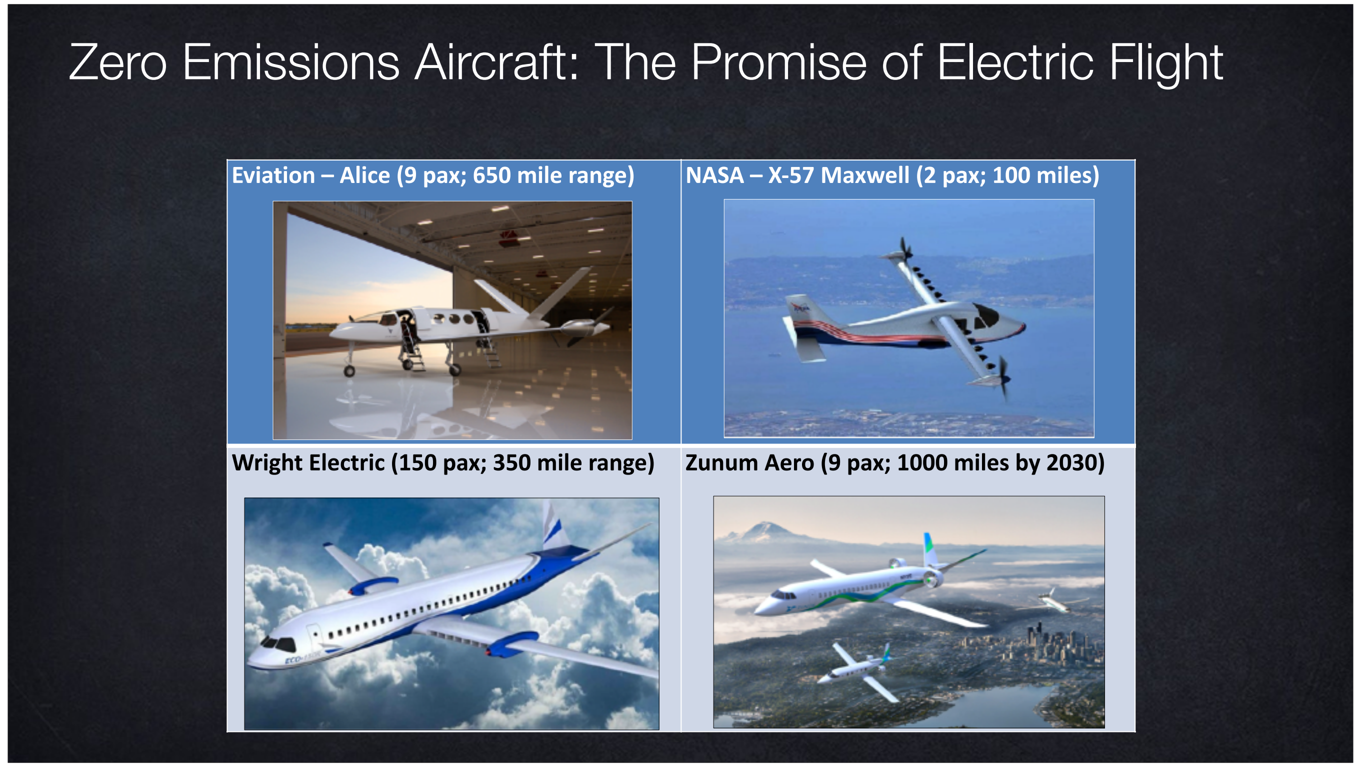


Turning now to propulsion, the National Academies expect several more decades of 7%/decade gains in gas turbines' efficiency from the current 55+%. GE recently 3D-printed complex fuel nozzles that helped make one engine one-tenth more efficient. This business-jet turbofan delivers 10% more power from 5% less weight with 20% less fuel and 99% fewer parts. *

Battery storage advances are the key to replacing fossil-fueled flights

C4V Charging Ahead!	**Energy density: 400 Wh/kg** **Aviation deployment:** Applications pending
Sion Power	**Energy Density: 500 Wh/kg** **Aviation deployment:** Airbus Zephyr High Altitude Pseudo-Satellite (HAPS) Program
solid energy	**Energy Density: 400-500 Wh/kg** **Aviation deployment:** Hermes™ cells power HALE (High Altitude Long Endurance) vehicles, VTOL (Vertical take-off and landing) flying transportation, and consumer drones

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. That enables short-haul electric airplanes—ultimately perhaps even medium-haul with emergent battery types. Large-area batteries (or ultracapacitors or both) might also eventually form the airplane's skin *and* structure. *



Renewably recharged electric airplanes can offer zero-carbon flights with less noise, no NO_x or particulates, and optionally VTOL using a small pad, not a runway. That could shift many airport operations to downtown roofs. Smaller versions like NASA *X-57*, Eviation and Zunum's future models demonstrate viability. Wright Electric's vision to provide 150-pax aircraft is interesting because short hauls are more carbon-intensive per passenger-km. Descent and landing can even recover some electricity, just like regenerative braking in a hybrid or electric car. Heathrow has waived landing fees for a year for the first electric airplane. *

So how can Norway commit to electric aviation by 2040?

Norway's pioneering national goal [, with strong cross-party commitment,] is to electrify nearly all domestic flights by 2040—many by 2025. Hybrid electric planes will offer ranges up to [1,500 miles] 2,414 km, covering 82% of trips [, according to the BTS]. *

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

- Composite structures + light, powerful motors (5–10+ 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, Eviation….
- >100 total developers, many expecting flight operations by the early 2020s
- Complements Wright Electric, Zunum,… electric propulsion for normal planes—FAA plans first certifications by 2020

Might visions of electric VTOL (eVTOL) air taxis like this one (Lilium) get real?
What might that imply for the granularity, scale, and business model of airports and carriers?
How about energy use? congestion?

Electric flight is now * practical because * *many* diverse technologies, not just better batteries, are converging in a vast explosion of creativity. * Though only a few models have yet flown, upwards of * a hundred startups are reported, mainly in the US, China, and Germany. First certifications are expected by 2020. * Whether or not electric VTOL [or 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. ** Competition between advanced biofuels, electricity, power-to-fuel, and hydrogen will turn airports into integrated transport *and energy* hubs, probably using distributed models. But electric air taxis will almost certainly use a lot more energy than electric ground taxis, collisions are more serious in the air, and if you liked congestion in two dimensions, you'll love it in three dimensions, so all this needs careful foresight. *

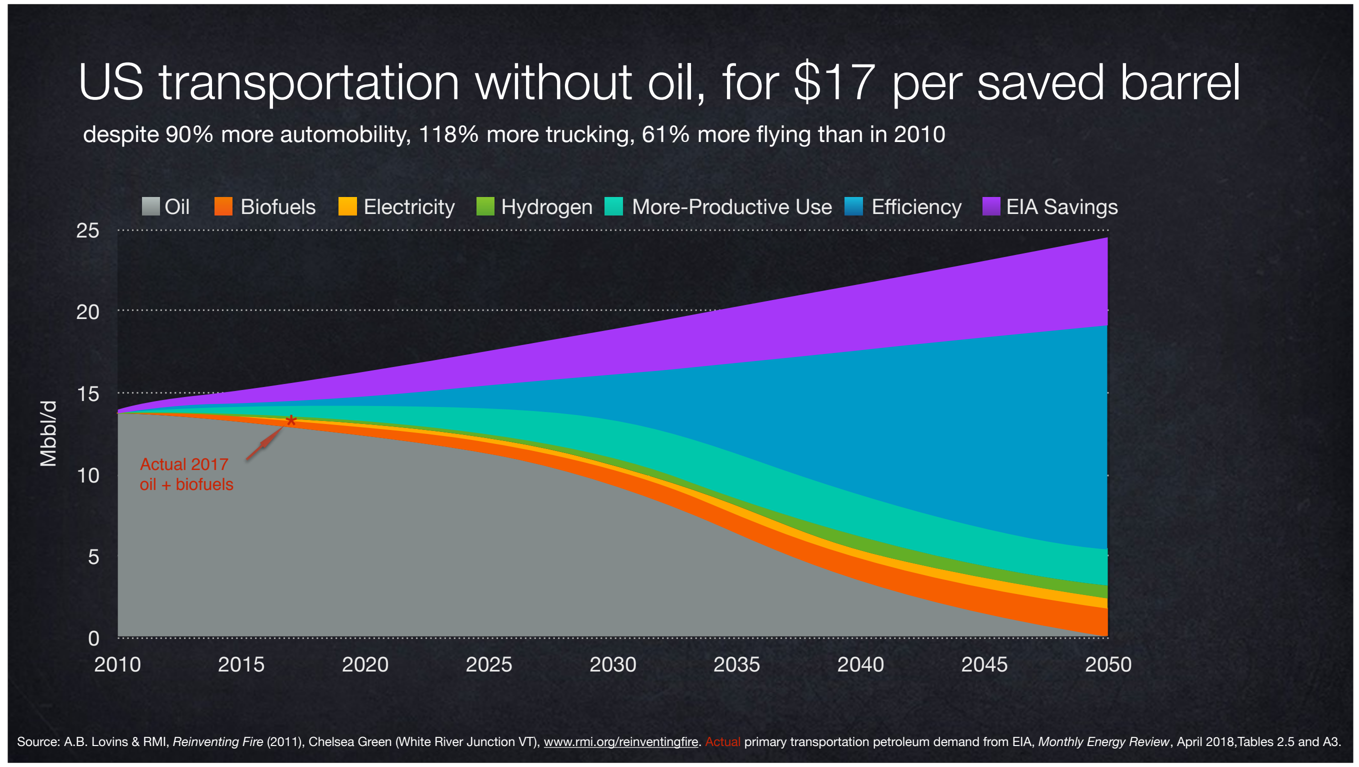
After kerosene, cryoplanes (liquid H_2 fuel, –253˚C) with zero carbon?

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 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

* Liquid hydrogen is 2.8x lighter than JetA but * 4x bulkier, requiring * new airplane designs. * Boeing’s *767* study found in 2003 that a well-designed liquid-hydrogen plane or “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 JetA, and economically interesting for intercontinental flight. * Dutch designer Peeters thinks a fuel cell and high-temperature superconducting motors can push airplanes’ 3–5x efficiency gain to ~6–7x. *



Our 2011 synthesis *Reinventing Fire* showed how US mobility can be greatly enhanced (see subtitle) while * phasing out oil with an Internal Rate of Return >17%. / We can first get efficient by * technologies included or * overlooked in the 2010 official forecast, * and use vehicles more productively. Then we can switch fuels, but there's not much left to switch. / Superefficient autos can use any mixture of * hydrogen fuel cells, * electricity, and * advanced biofuels. Heavy trucks and airplanes can realistically use advanced biofuels or hydrogen. Doubled-efficiency ships can use biofuels, LH_2, or NH_3. But no vehicles will need oil. Any biofuels needed could be made two-thirds from wastes, without displacing cropland or harming climate or soil, and will have to compete with power-to-gas based on cheap renewable electricity * So far, this US vision looks on track: as the little star shows, our 2011 *Reinventing Fire* graph matches the top of the orange biofuel wedge. The global equivalent could be broadly similar. *

Let me leave you with a challenging opportunity. For a decade, we've had the technology to create 3–5x-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, and precious time, taking a century to apply what we already know. But the climate crisis so starkly mapped in the IPCC's 1.5° Special Report won't wait, so business-as-usual won't work. Our license to operate will erode. Our shareholders and our children will judge us negligent. /
So what if a consortium of major customers—airlines, leasing firms, 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 solicit a superefficient airplane by publishing very demanding specifications and collectively committing to buy *x* copies a year for *y* years at price *z* from whoever first brings them to market, eliciting and rewarding 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 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. It could also—unlike offsets—slash fuel costs and the risks of fuel-price volatility. And it could unleash a huge burst of innovation that could transform aviation forever.
What are we waiting for?
Thank you for your good work and 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.