Distributed Electric Propulsion (DEP) Aircraft

5th Symposium on Collaboration in Aircraft Design
Naples, Oct 12, 2016

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Near-Term Electric Propulsion Evolution Strategy

- **Can electric propulsion impact aviation over the next decade, or is battery specific energy too constraining?**

- **What value does electric propulsion offer aviation in the near-term in terms of carbon emissions, and how can low carbon solutions be incentivized in the aviation market without dependency on carbon taxing?**

- **If electric propulsion is a ‘disruptive technology’ enabling low carbon aviation, what is the likely evolutionary technology path?**

Electric Propulsion:
Not Only Propulsion, But An Integration Technology

- **Electric propulsion offers fundamentally different characteristics, that are highly enabling to the distributed propulsion solutions due to their scale-free nature.**
- **New integration strategies are enabled that would have never before been feasible; providing completely new Degrees of Freedom in aircraft design.**
- **High technology accelerations exist across the battery, motor, controller markets.**
  - **Batteries have achieved an average rate of improvement in energy density of ~8% per year over the past 30 years. Current available cells are ~250 Whr/kg at 2C ratings.**
  - **Electric motors are currently being tested at 4-6 hp/lb specific power with 95% to 97% efficiency.**
  - **Controllers are currently being tested at 10-20 hp/lb with extremely high precision rpm capability.**

Electric Propulsion Benefits

1-6x the motor power to weight
2-4x efficiency of SOA Engines
Scale-free efficiency and power to weight
High efficiency from 30 to 100% power
+100% Power for 30-120 Seconds
Continuously Variable Transmission
Extremely compact
High Reliability
Safety through Redundancy
Reduction of engine-out sizing penalty
Low Cooling Drag
Extremely Quiet
No power lapse with altitude or hot day
5-10x lower energy costs
Zero vehicle emissions

Electric Propulsion Penalties

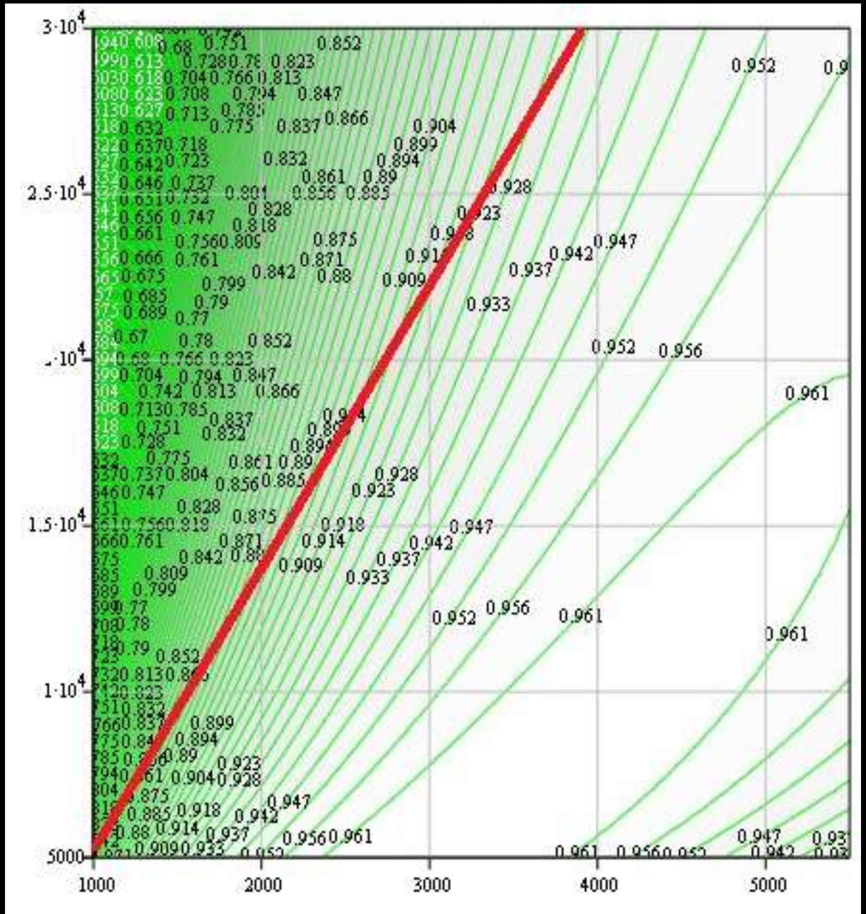
Energy Storage Weight
Energy Storage Cost
Certification/Safety?

Representative Advanced Technology Electric Motor

- NASA Funded Launchpoint Alternator/Motor
  - Halbach Array architecture
  - 8 hp, < 2 lb weight (4 hp/lb)
  - 7.25” diameter with direct drive of 30” diameter propeller
  - 94% at max continuous
  - 97% at part power (~30% power)
  - Low inductance controller

- Turbine/Piston Engines
  - Hydrocarbon/combustion based power (airbreathing)
  - Significant scale effects fundamental to the physics, Reynolds number, manufacturing tolerances, cube-square laws, etc that make smaller engines have lower efficiency, lower specific power, lower reliability.
  - Electric motors offer scale-free integration freedom.

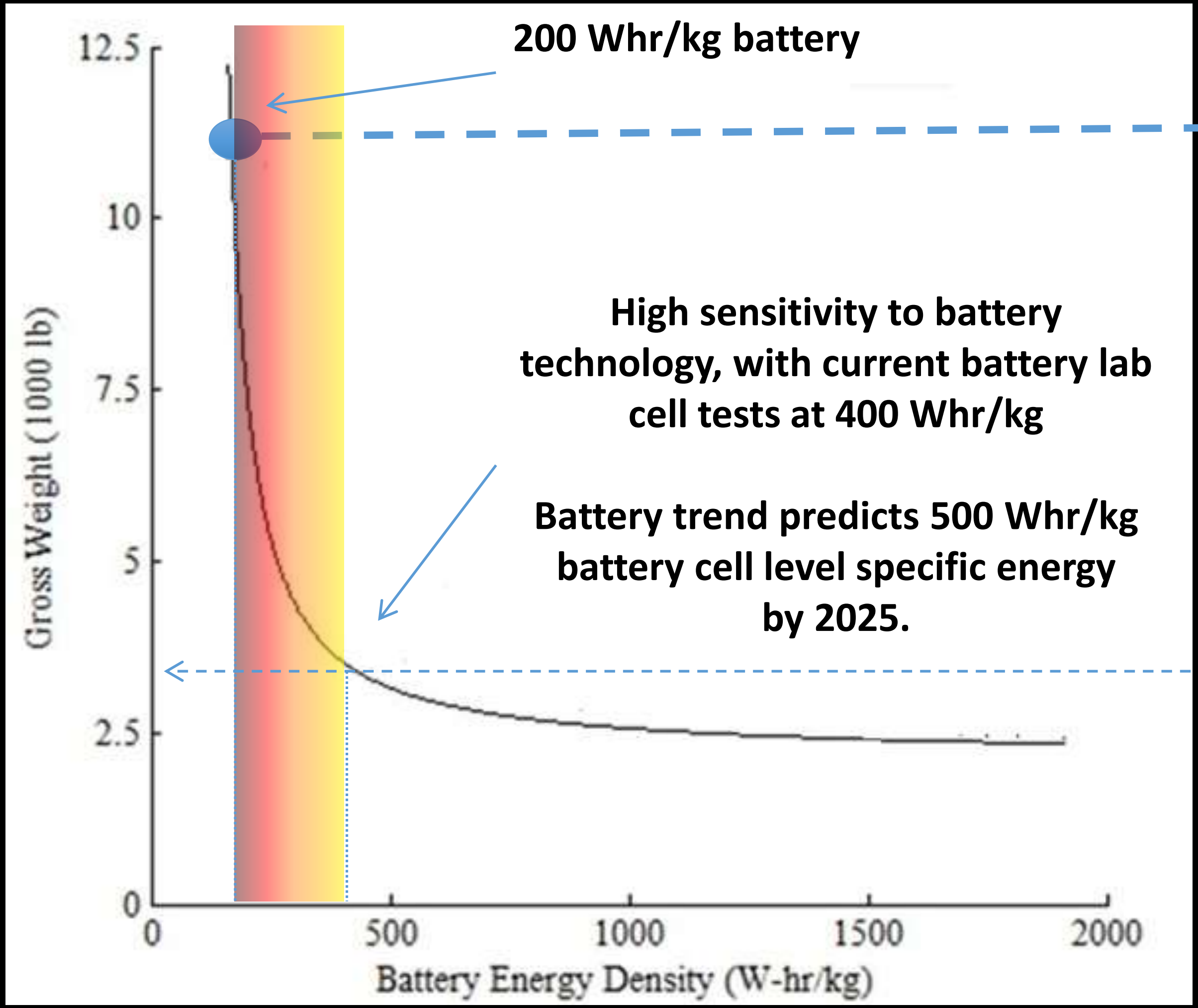
Power



RPM

Battery Specific Energy Penalty

Performance Analysis and Design of On-Demand Electric Aircraft Concepts, M.D. Patterson and B. German, AIAA Aviation 2013.



Cirrus SR-22
with Retrofit Electric Propulsion
200 nm range + reserves
11,300 lb

Cirrus SR-22
General Aviation Aircraft
500 nm range + reserves
3400 lb

NASA Scale-Free Application of DEP to UAS

***DEP Enabling Characteristic*: Scale-free Propulsion**

Electric motors provide hgh power to weight, efficiency, reliability, and compactness at any scale

GL-10 UAS DEP Tilt-Wing Tilt-Tail Vertical Takeoff and Landing (VTOL) Flight Demonstrator

Fully Redundant Digitally Controlled Vehicle Thrust
Robust Control Throughout Forward Flight to Hover (>20 Flight Transitions)
4x Cruise Efficiency (Lift/Drag Ratio) Compared to Helicopters

NASA Scale-Free Application of DEP to UAS

Vibrant EP Flight Demonstrations at Smaller Scale

NASA Green Flight Challenge, 2011
Pipistrel G4 Taurus $1.5M Winner

Rui Xiang RX1E
China

FEATHER
JAXA

Electric Cri-Cri
Airbus

Pipistrel Watts Up
Slovenia
(Ready for Production)

E-Fan
Airbus

DA-36 E-Star
Airbus

E-Genius
Airbus

Electric Aircraft ≠ Slow Efficient Flight

Recent manned electric aircraft have largely focused on low-speed efficiency

Pipistrel WATTsUP, Alpha Electro, Taurus Electro

Airbus E-Fan

EADS/Diamond DA-36 E-Star

Solar Impulse 2

Notable exceptions: Long-ESA (Yates), Cri-Cri "E-Cristaline" (Duval)

Why Low-Speed?

Low Power Required = More Endurance

$P_{required} = T * V / \eta_{propulsive} \approx D * V / \eta_{propulsive}$ (level flight)

BUT, if you're concerned about range, and your efficiency is constant with power production

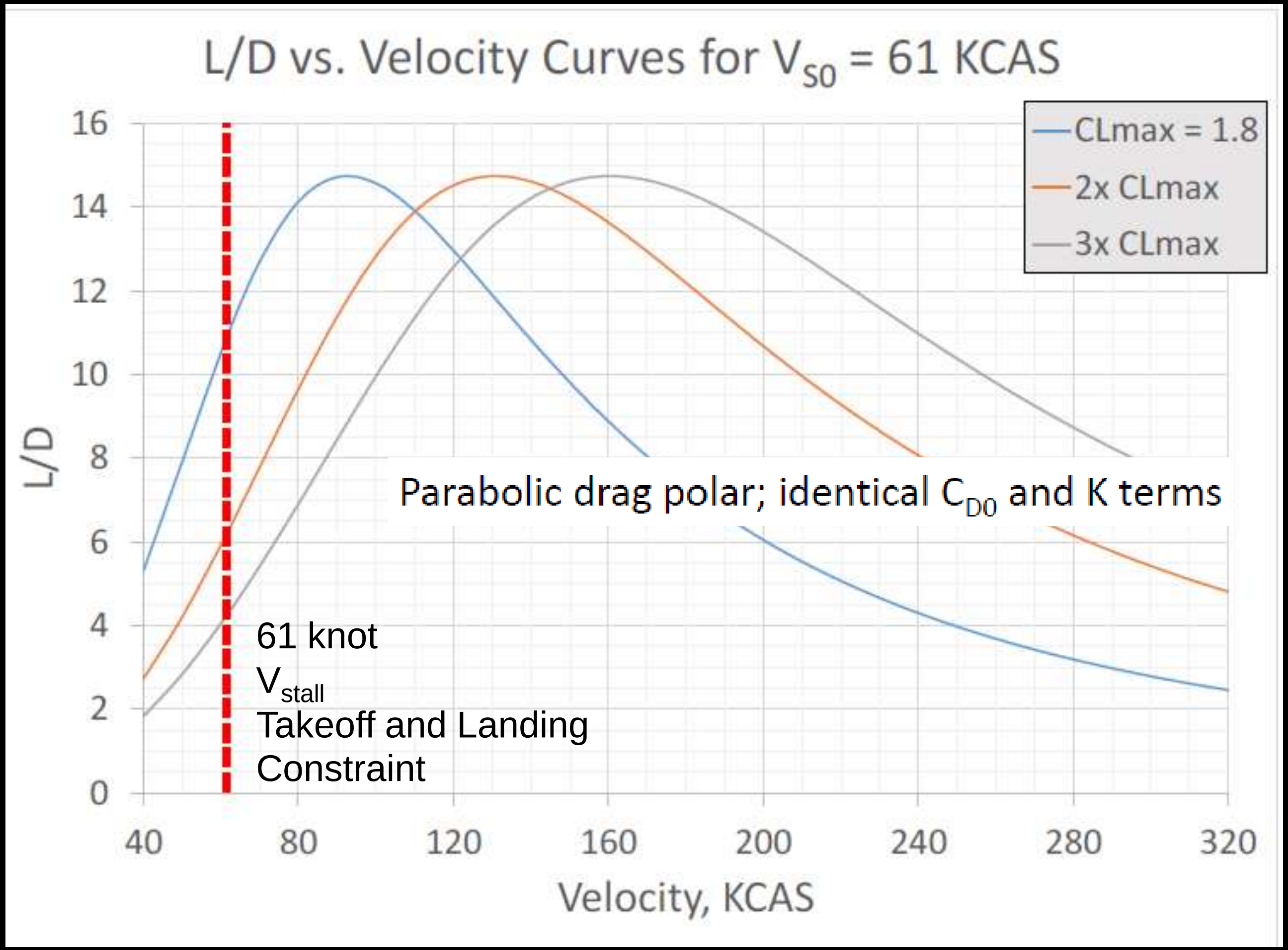
$Range = \eta_{propulsive} * (L/D) * (W_{battery}/W_{gross})$

Range is *independent* of velocity

The aerodynamic design of the aircraft determines peak L/D and at what velocity that peak occurs

Efficient electric flight doesn't need to be slow

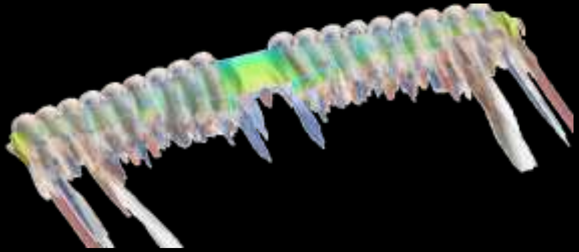
What If You Could Design the Wing for L/D_{max} At the High Speed Cruise Condition?

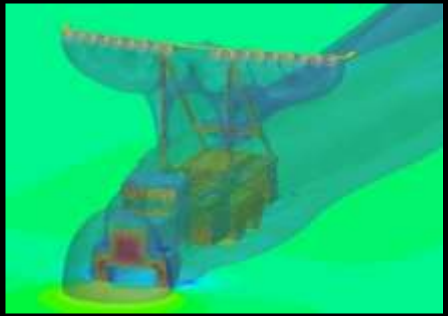


Distributed Electric Propulsion (DEP) enables design not only higher C_{Lmax}

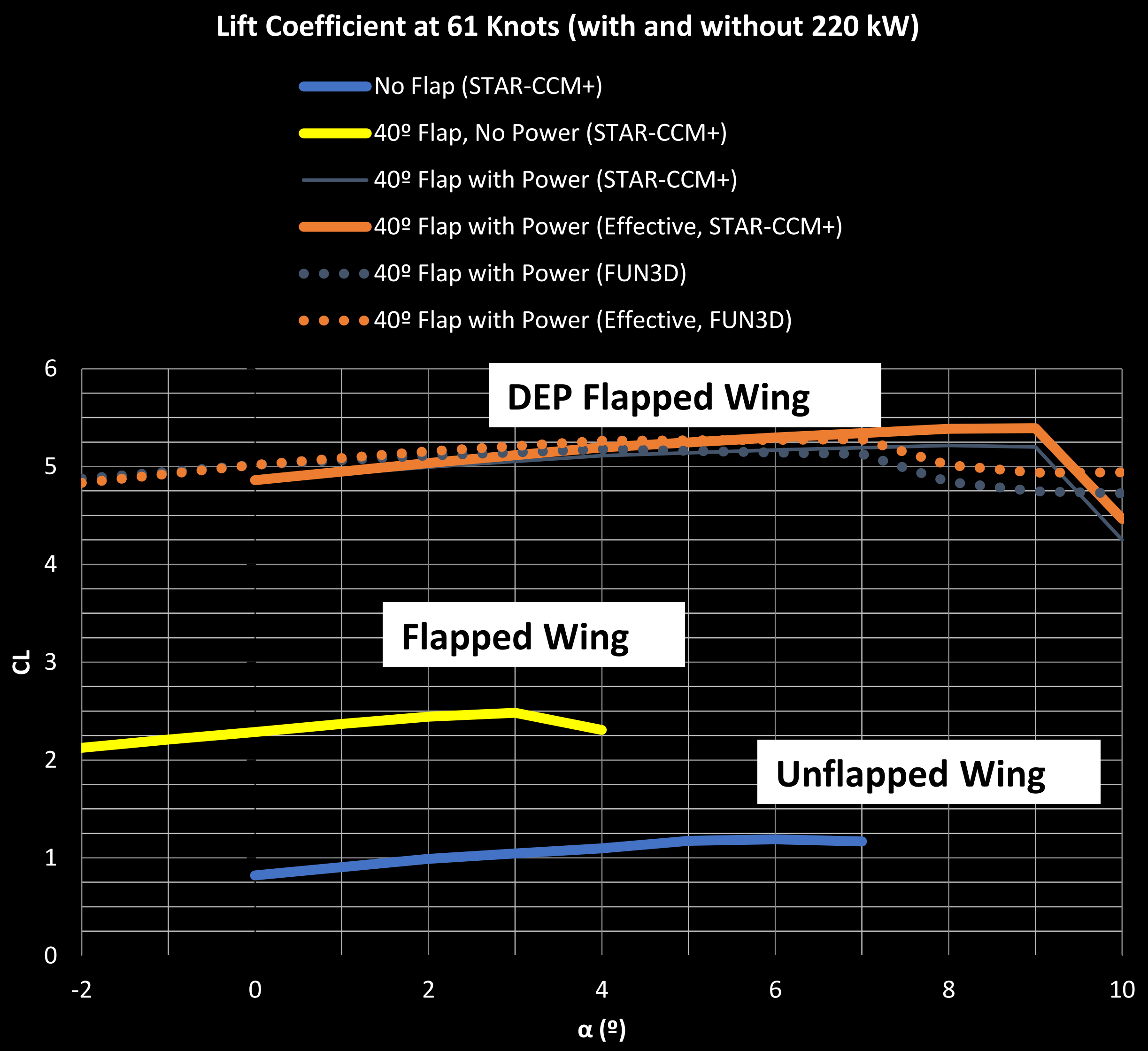
But also higher L/D_{max}, and higher $\eta_{propulsive}$ at high speed

NASA DEP LEAPTech Testing





DEP Aero-Propulsion Highlift Integration



DEP can provide highly coupled aero-propulsive integration to highlift systems to provide significant low speed lift augmentation, without the typical problems such as high pitching moments associated with circulation augmentation due to aft loading of the wing airfoil (or additional noise sources).

Transformational Aeronautic Concepts Program

SCEPTOR X-Plane Project

(Scalable Convergent Electric Propulsion Technology Operations Research)

Tecnam P2006T Light Twin General Aviation Aircraft

NASA Distributed Electric Propulsion (DEP) X-Plane

$15 million, 3-year research project to achieve the first DEP manned flight demonstrator in 2017

Instead of focusing on low speed efficiency, SCEPTOR focuses on how DEP technologies enables cruise efficiency at higher speeds.

SCEPTOR DEP X-Plane

Airbus E-fan: 46 miles in 37 minutes = 74 mph average speed

NASA SCEPTOR Primary Objective

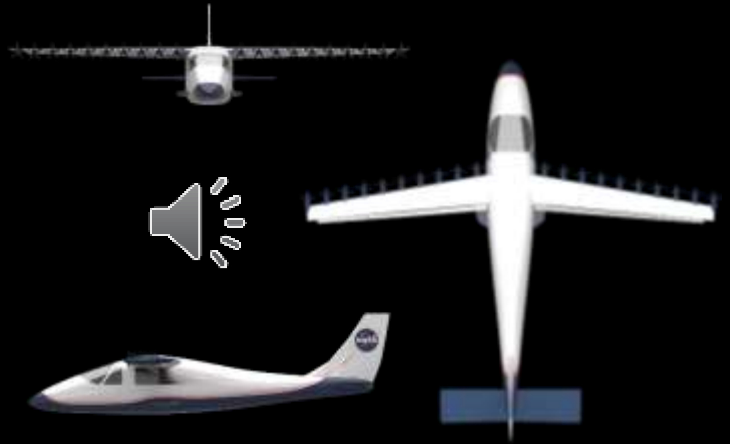
- Goal: 5x Lower Energy Use (Comparative to Retrofit GA Baseline @ 175 mph)
  - Motor/controller/battery conversion efficiency from 28% to 92% (3.3x)
  - Integration benefits of ~1.5x (2.0x likely achievable with non-retrofit)

NASA SCEPTOR Derivative Objectives

- 30% Lower Total Operating Cost (Comparative to Retrofit GA Baseline)
- Zero In-flight Carbon Emissions

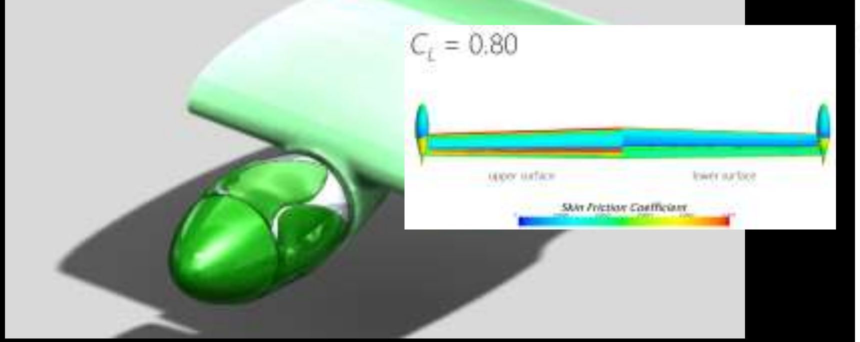
NASA SCEPTOR Secondary Objectives

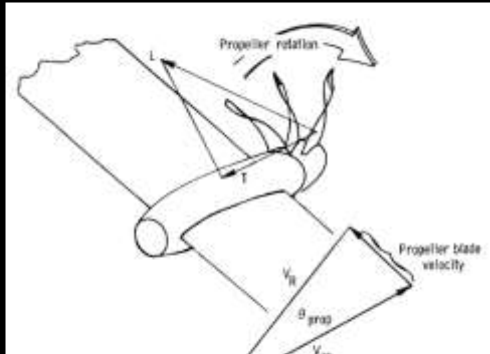
- 15 dB Lower community noise (with even lower true community annoyance) .
- Flight control redundancy, robustness, reliability, with improved ride quality.
- Certification basis for DEP technologies.
- Analytical scaling study to provide a basis for follow-on ARMD Hybrid-Electric Propulsion (HEP) commuter and regional turbo-prop research investments.



Compact/Synergistic DEP Integration New DoF

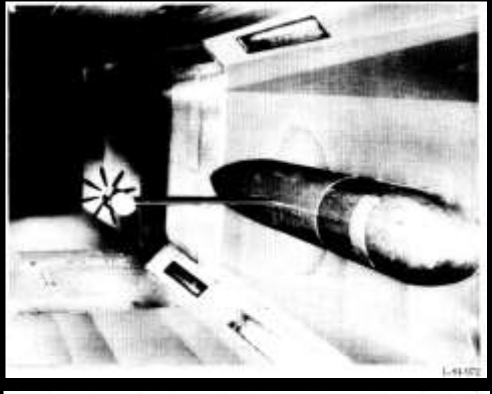
Folding LEAPTech Low Tip Speed Propeller



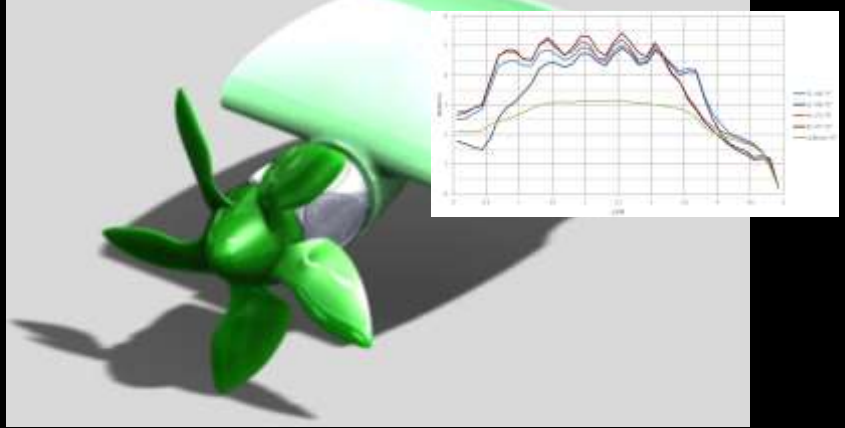


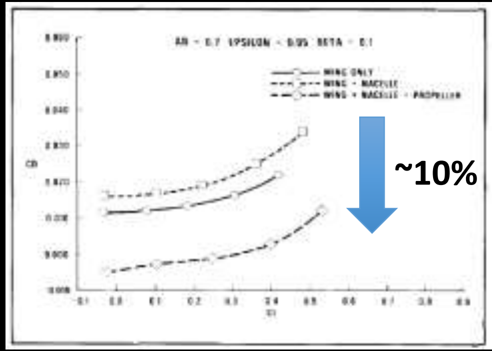
Wingtip Vortex Integration

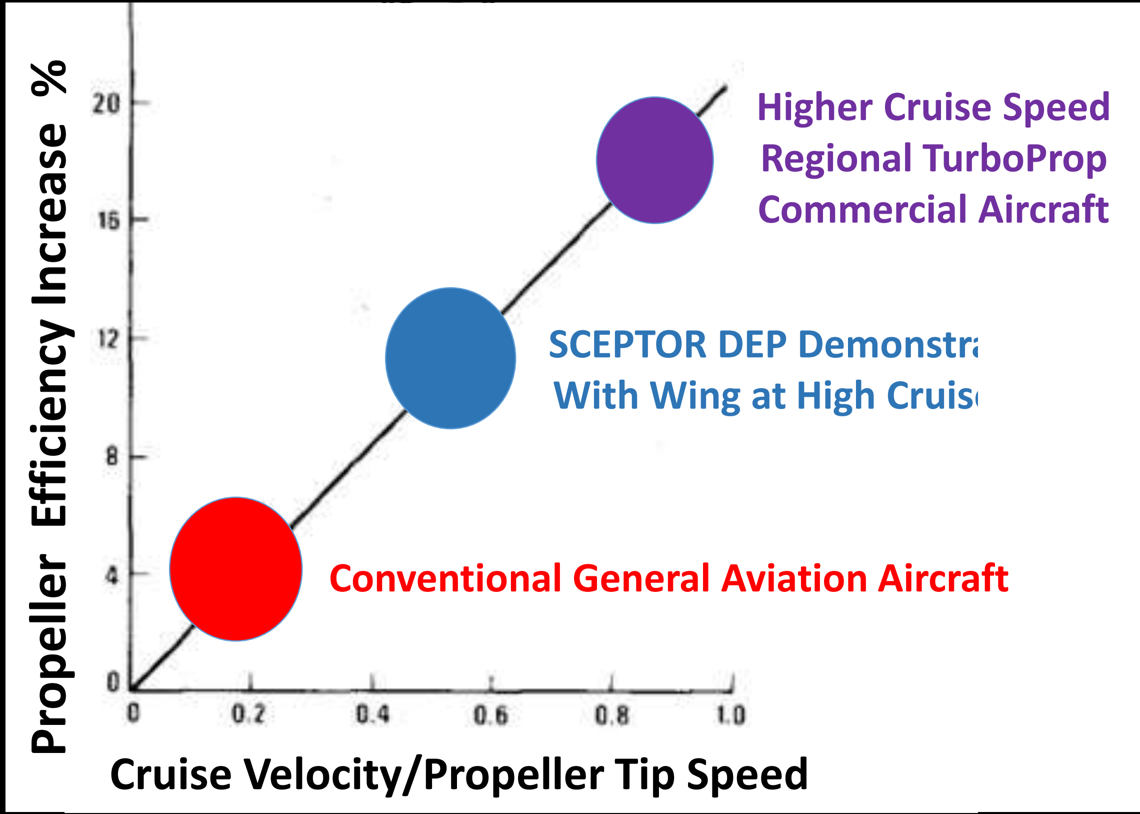
Alisport Slient-2 Motorglider



Folding LEAPTech Low Tip Speed Propeller





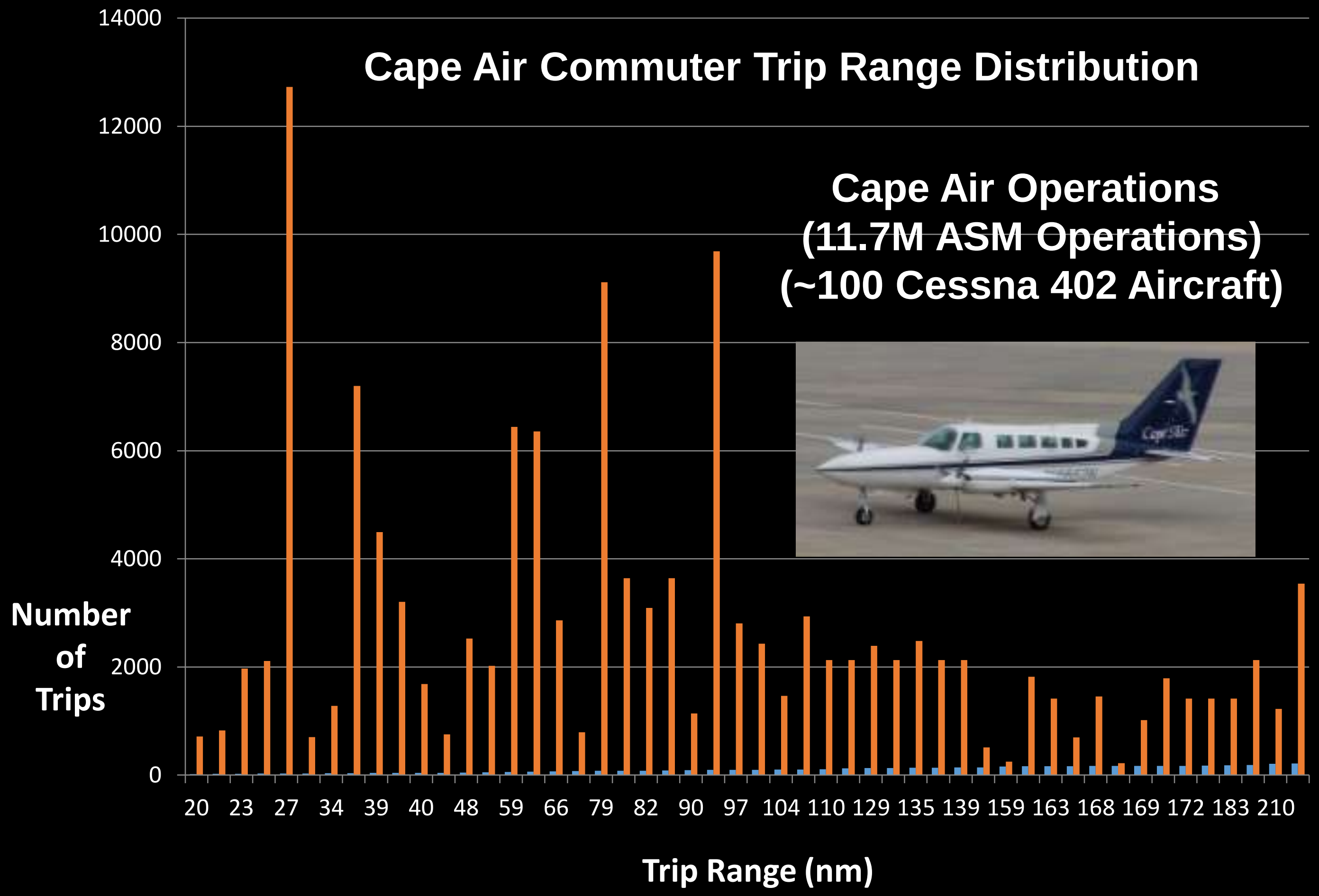


Aerodynamic Effects of Wing Tip Mounted Propellers and Turbines, L. R. Miranda, AIAA Paper 86-1802, 1986.

Evaluation of Installed Performance of a Wing Tip Mounted Pusher TurboProp, J.C. Patterson, NASA TP 2739, August 1987.

EP Early Adopter Opportunities

Pathfinder markets are already feasible to establish renewable based, ultra low carbon aviation solutions; while establishing early certification and technology experience.



Cape Air Northeast Operations

Hyannis Airport, MA
1.4 MW solar farm

DEP 9 pax
Thin-Haul Commuter

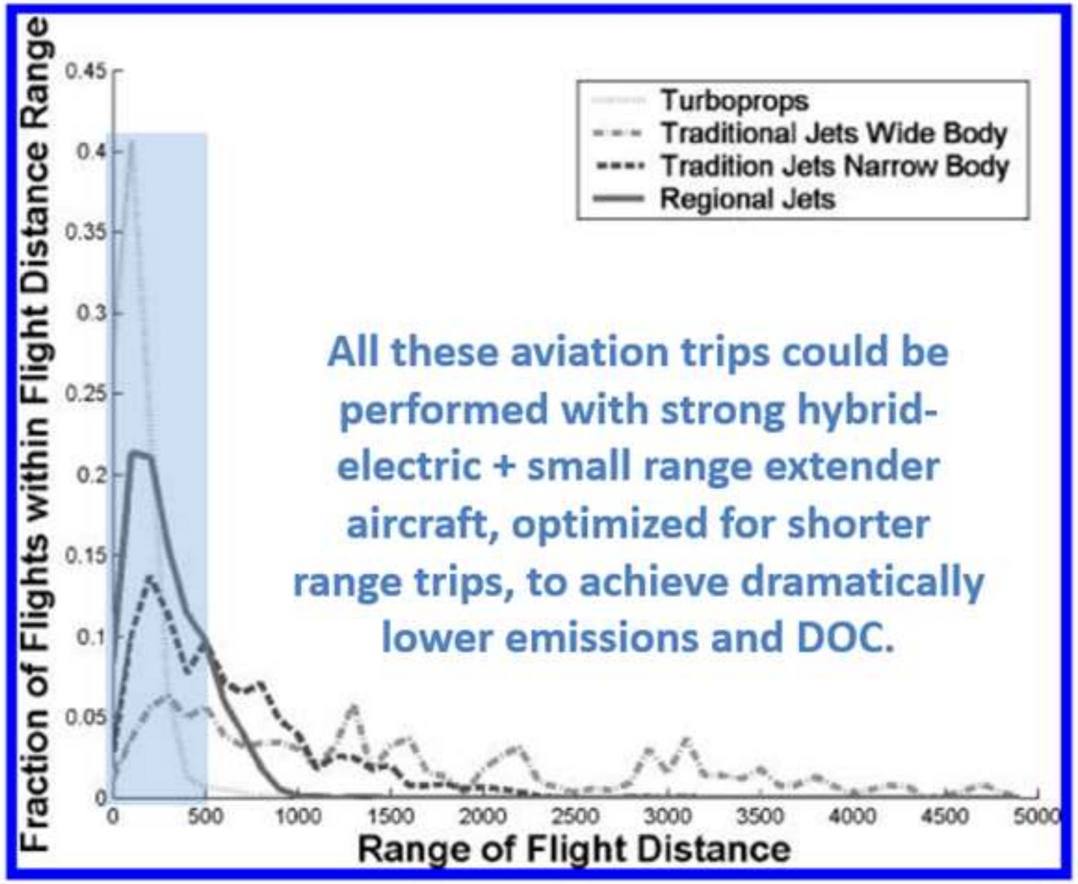
EP Evolutionary Technology Path

Small aircraft EP research enables faster tech development.

Large battery mass fraction aircraft @ 400 Whr/kg pack level specific energy enable ranges to >300 nm + reserves, with 60-90% reduction in life cycle carbon @ ~30% lower operating costs.

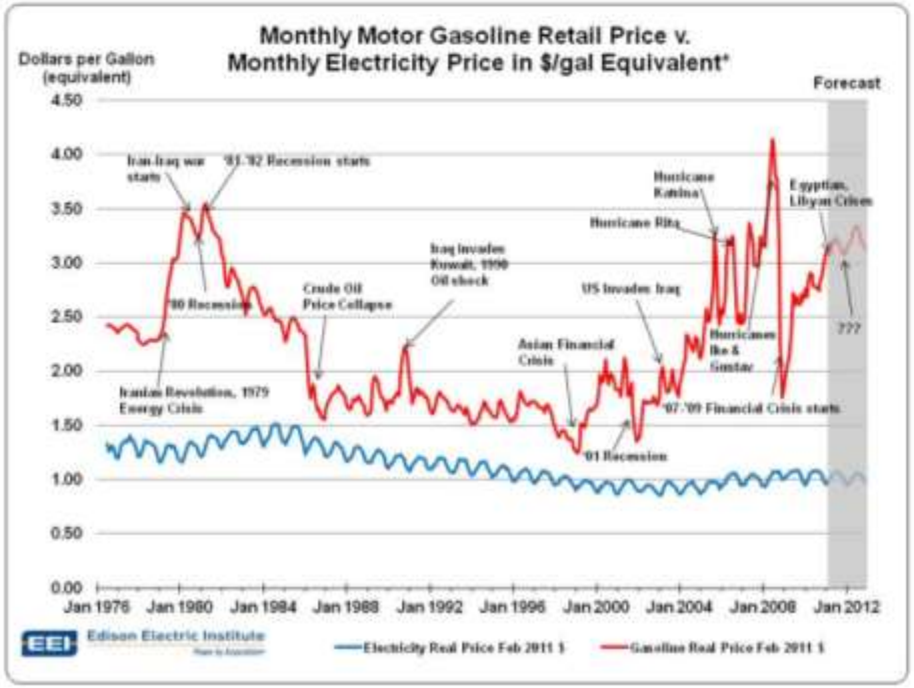
Small range extenders sized for ~50% of cruise power enable ranges to >600 nm + reserves.

Ability to incentivize >50% of aviation operations and >13% of carbon emissions for a quick start sustainable carbon path.

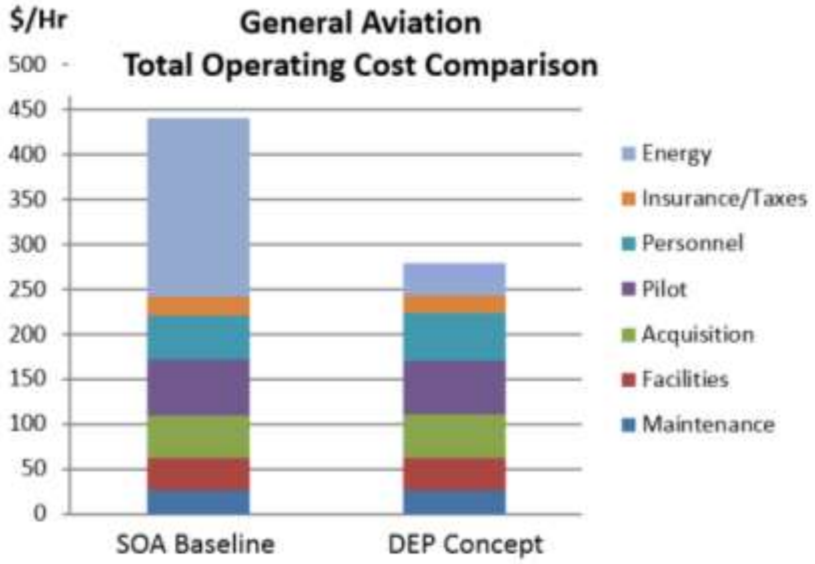


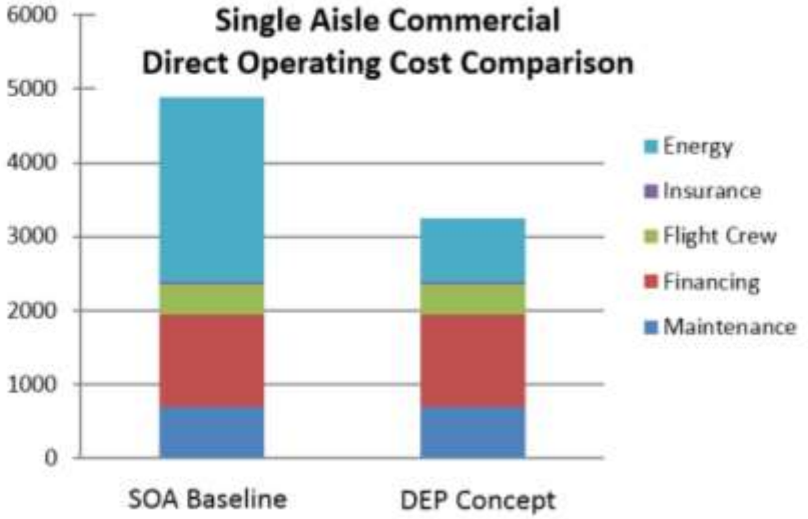
Aviation Trip Range Distribution
Across all commercial aviation sectors
(Number of trips vs distance nm)

Electricity Based Operating Cost Value Proposition



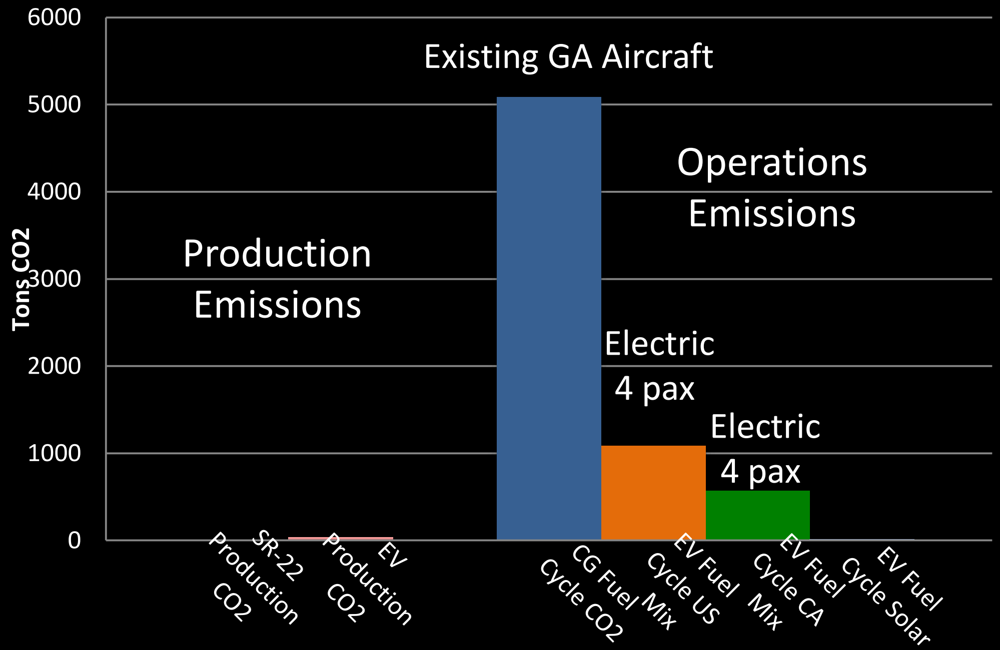
Electricity based aircraft energy provide a decrease in price variability and cost risk as well as a true renewable energy path (100LL fuel is ~2x higher cost than auto gas)





Life Cycle Carbon Emissions of Small Aircraft

Production versus Operation emissions GREET analysis over the lifetime of the aircraft, including 8 batteries swaps over aircraft lifetime.

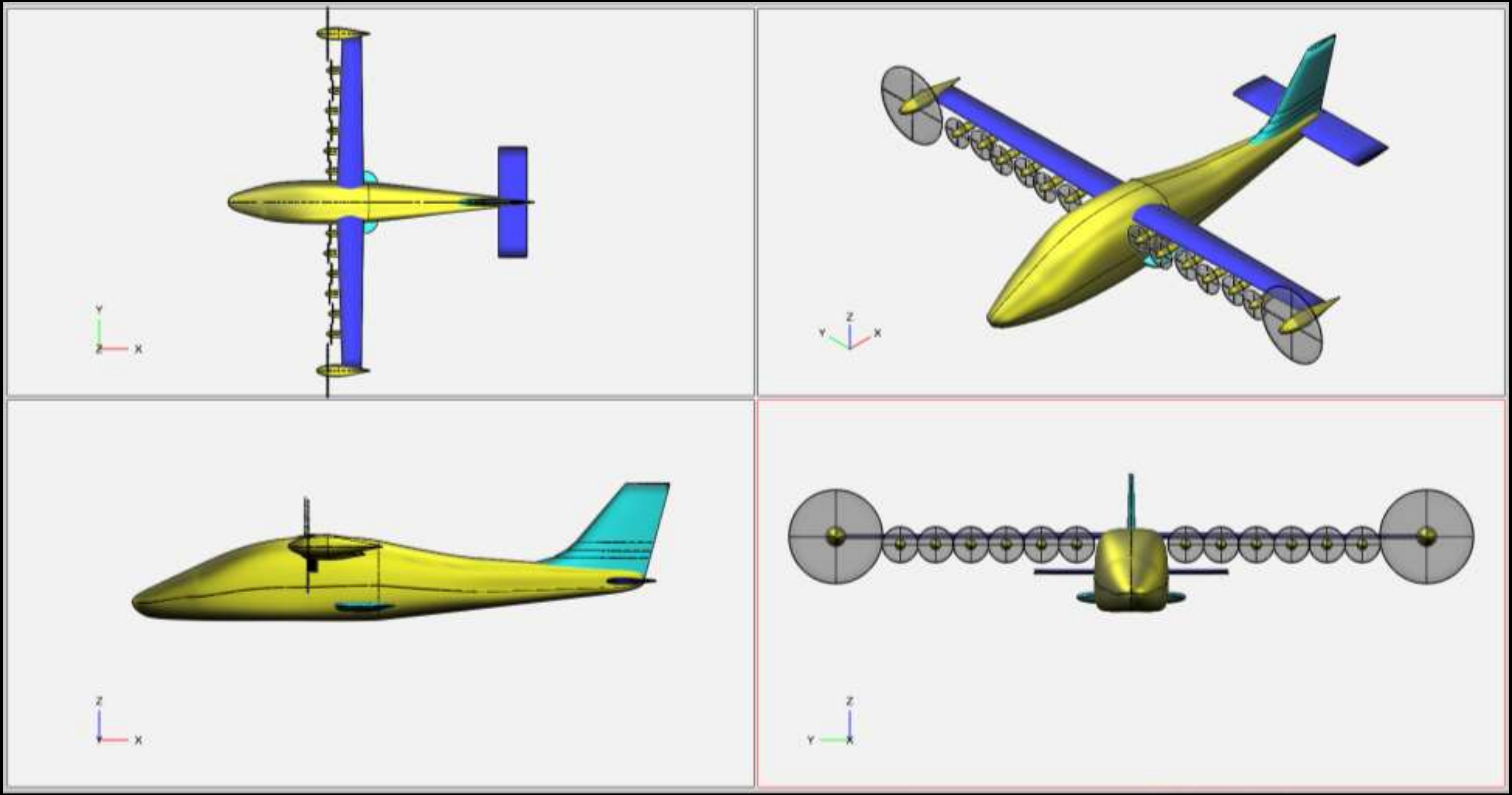


Zip Aviation Life Cycle Emissions, Jonathan Baraclough, NASA AFRC, September 2012.

Zip Aviation, Electric, Autonomous, On-Demand High Speed Regional Mobility, M.D. Moore, AIAA Aviation 2013.

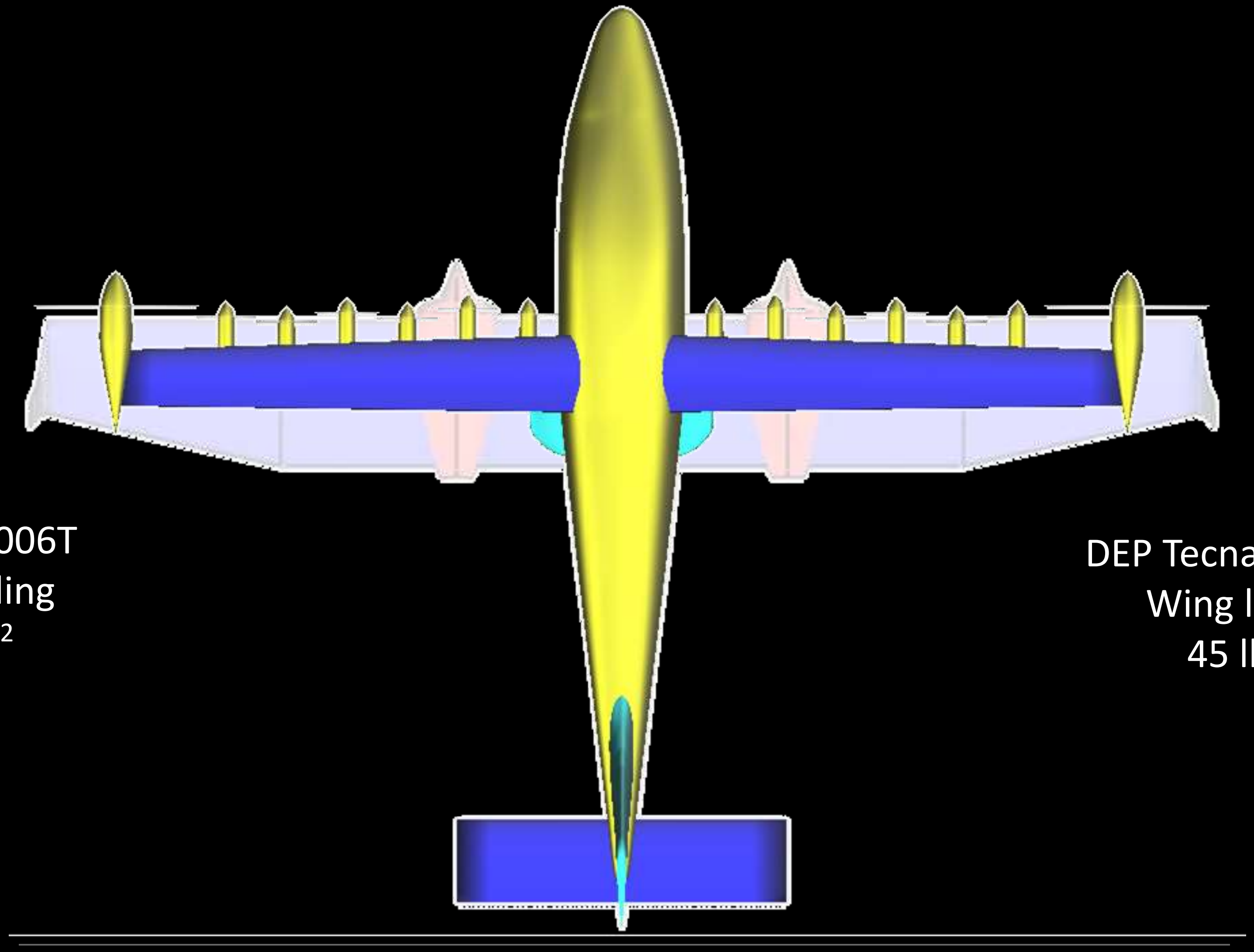
Electric Propulsion not only provides 5 to 10 times reduction in greenhouse gas emissions with current electricity, and essentially zero emissions with renewable based electricity; it also provides a technology path for small aircraft to eliminate 100 Low Lead AvGas, which is the #1 contributor to current lead environmental emissions.

Current SCEPTOR Configuration



Open Vehicle Sketch Pad (OpenVSP) Models

Comparison to Baseline Tecnam P2006T



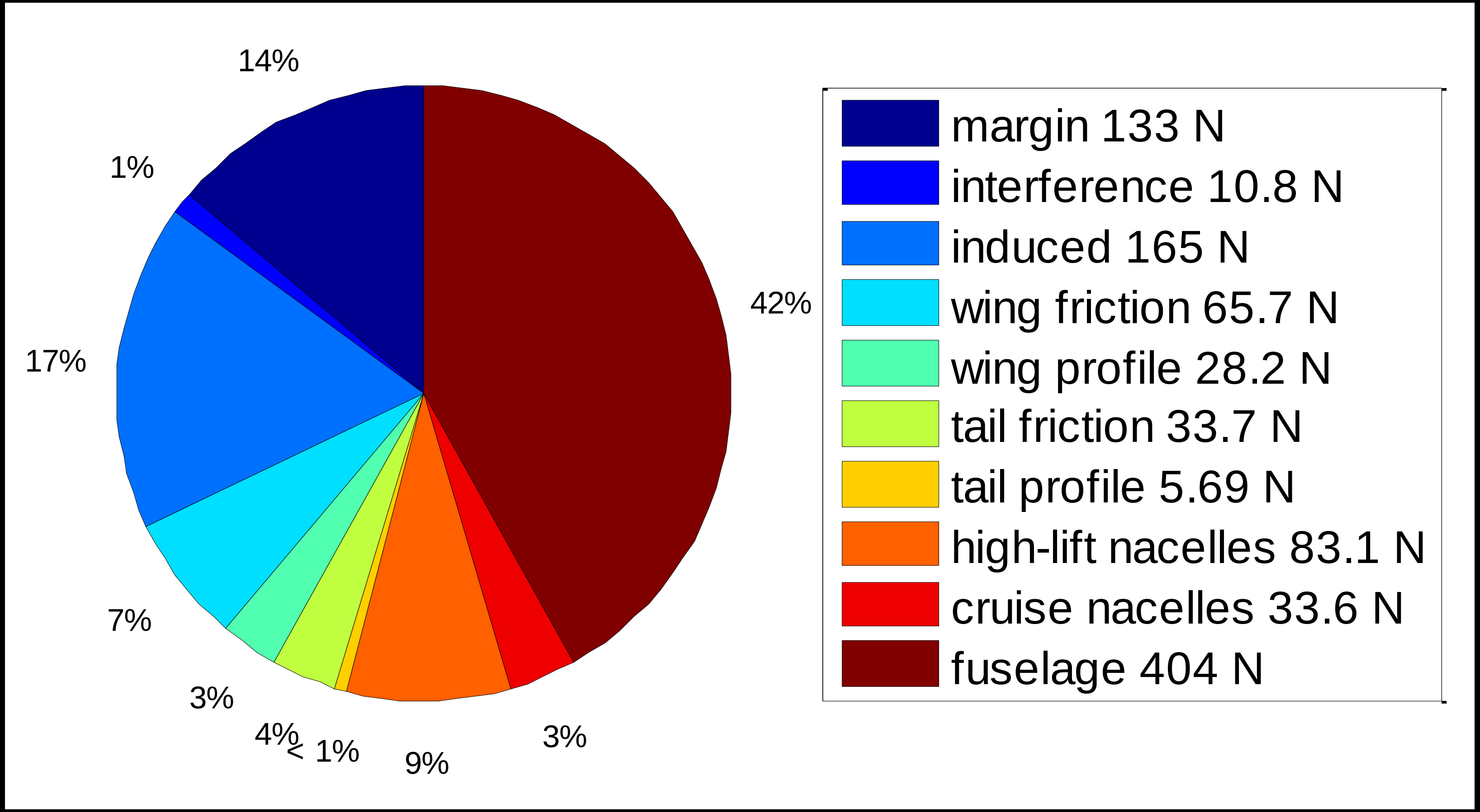
Tecnam P2006T
Wing loading
17 lb/ft^2

DEP Tecnam P2006T
Wing loading
45 lb/ft^2

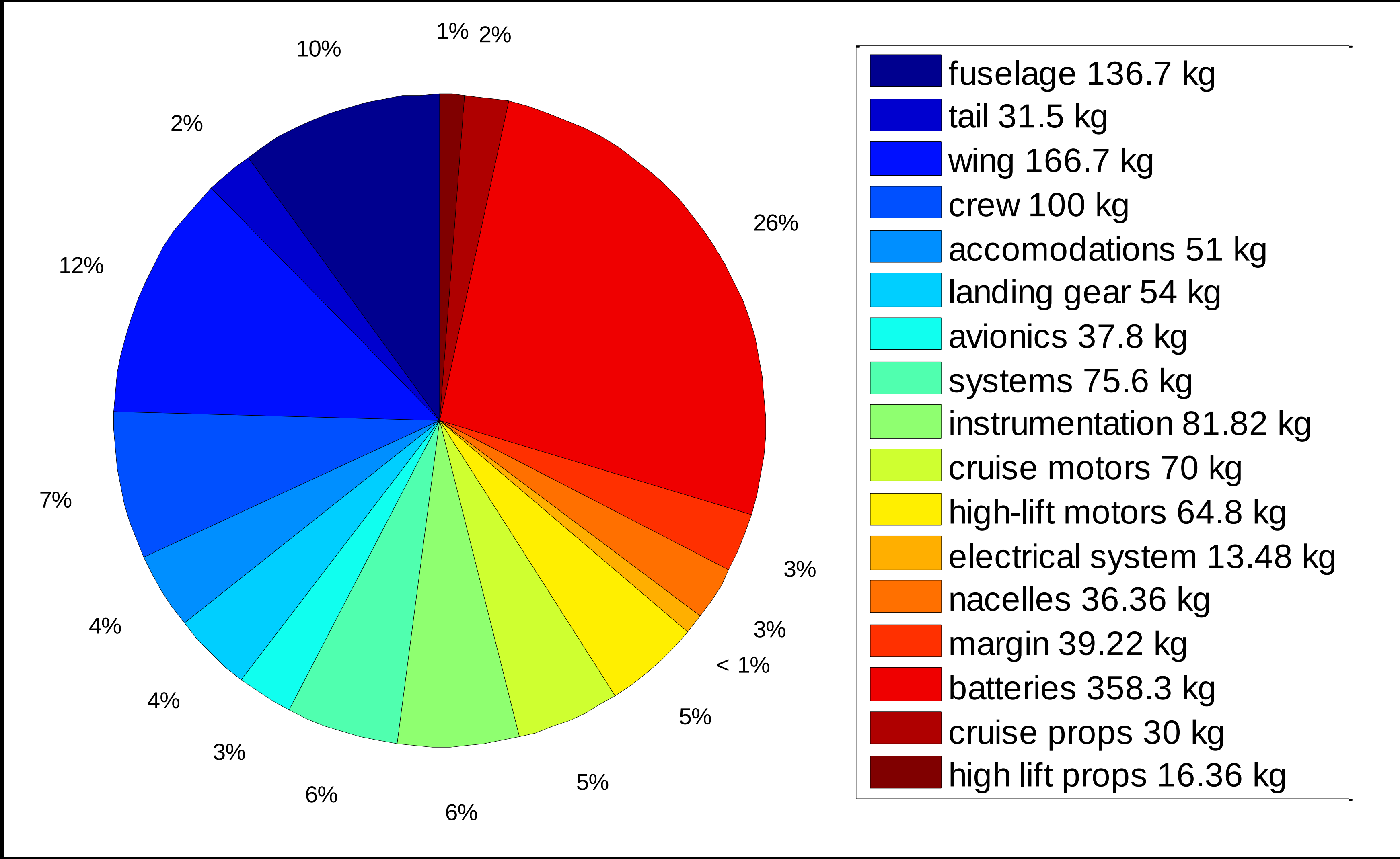
SCEPTOR Characteristics

- Wing
  - Span: 9.639m (31.62ft)
  - Root chord: 0.756m (2.48ft)
  - Tip chord: 0.529m (1.74ft)
  - LE sweep: 1.887 deg
  - Sweep @ 0.7c: 0 deg
  - Airfoil: gnew5bp93 (15%)
  - Area: 6.194m^2 (66.67ft^2)
  - Aspect ratio: 15
  - Washout: 2 deg
  - Root incidence: 2 deg
  - Wing loading: 2153 N/m^2 (45.0 lbf/ft^2) (@3000 lbf)
- Cruise Props
  - Number: 2
  - Diameter: 1.524m (5ft)
  - Blades: 3
  - Airfoil: MH117
  - Power @ 3000 lbf, 150KTAS, 8000ft: 42kW @ 2250 RPM
- High Lift Props
  - Number: 12
  - Diameter: 0.576m (1.89ft)
  - Blades: 5
  - Airfoil: MH114
  - Power @ 55KTAS, SL: 12kW @ 4548 RPM

SCEPTOR Drag Breakdown

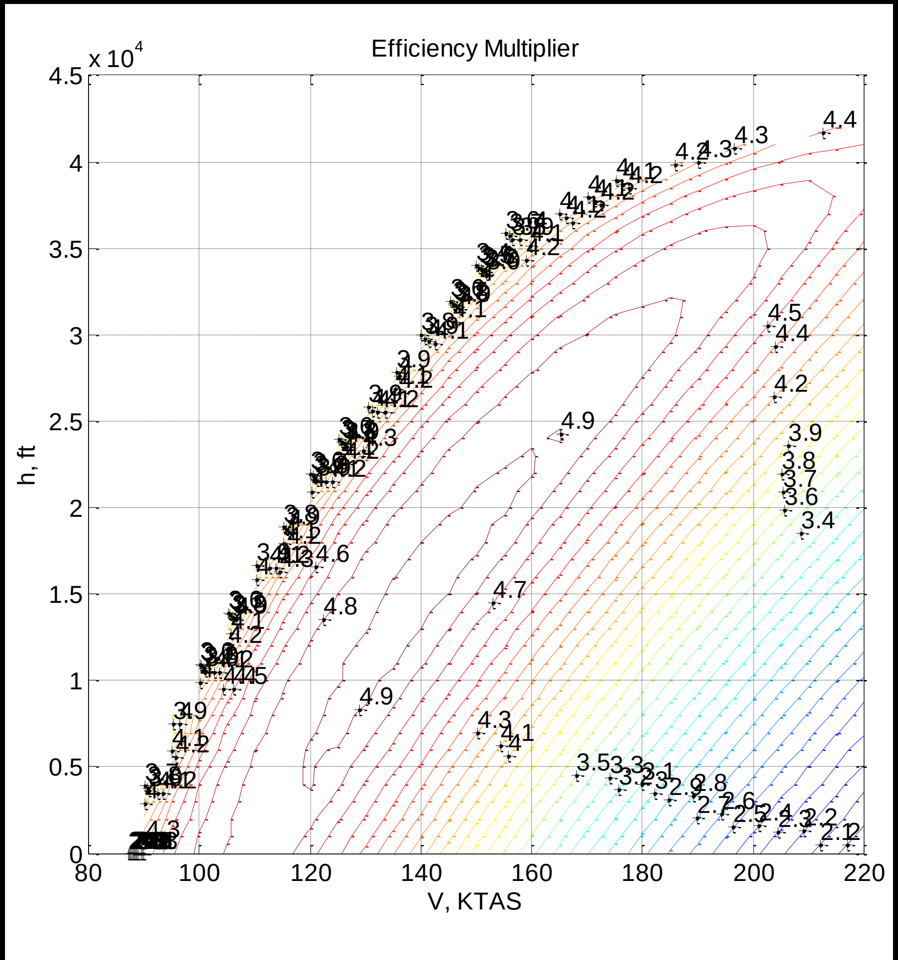


SCEPTOR Mass Breakdown

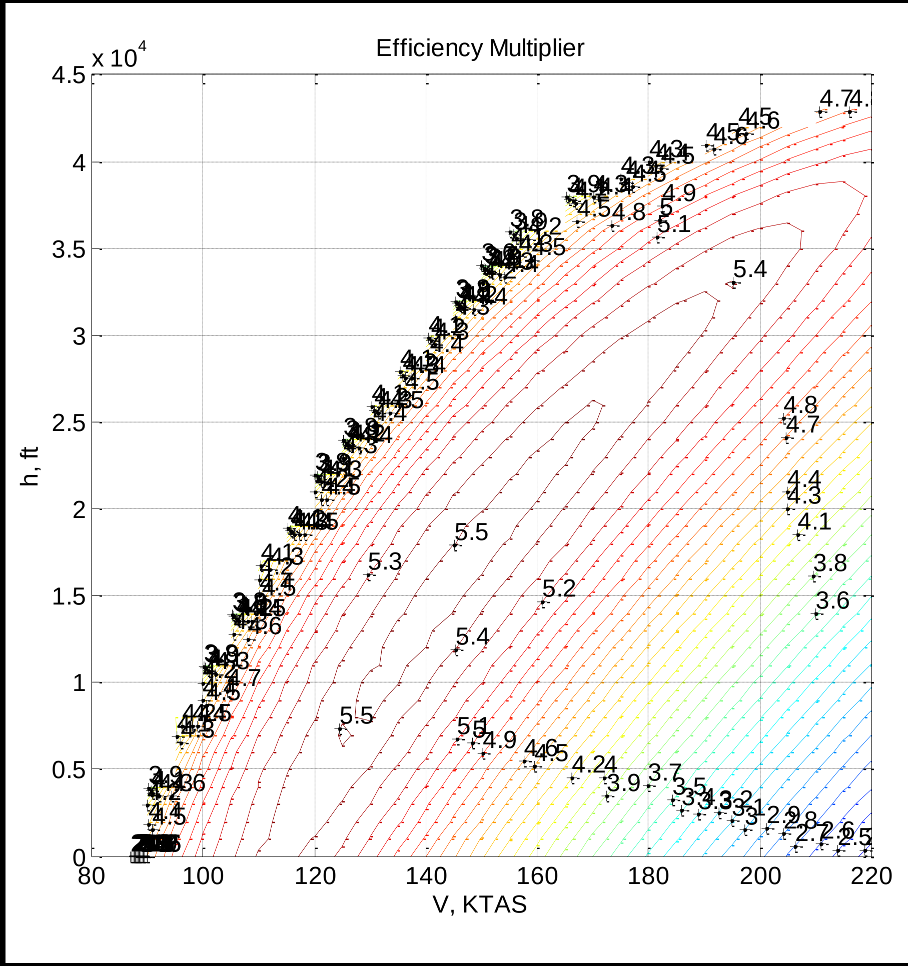


SCEPTOR Primary Objective Metric

With 0.5 D/q margin



No D/q margin added



Conclusions

Technology evolutionary strategy is as important as the technology itself if a strong market goal-focus exists (such as to achieve dramatic reductions in aviation carbon emissions).

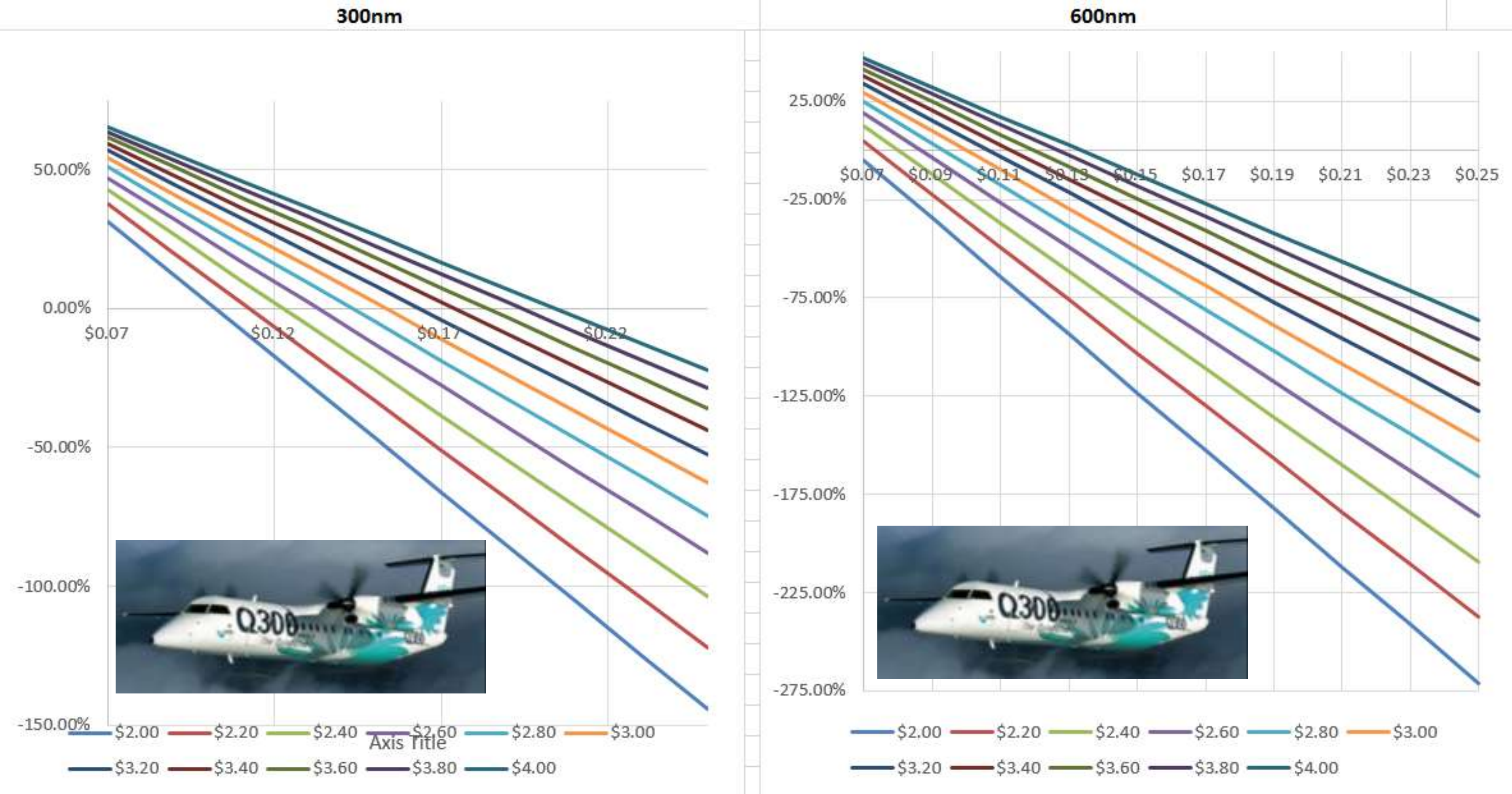
Research focusing on rapid, spiral development of EP technologies can achieve early success in reducing in-flight carbon emissions for shorter range aircraft – relatively quickly.

Shorter range aircraft designed to achieve low operating costs will almost certainly be designed as large battery, series hybrid with small range extenders for operations flexibility.

High utilization is a key ingredient for the economics of electric vehicles to make sense, with rapid/efficient/high life cycle battery charging systems a critical operational element.

Incentivizing low carbon aviation through dramatic improvements in operating costs has a higher probability of success than being dependent on carbon taxing.

Current NASA Cost-Emission Trade Studies



Q400 Regional
<u>Turbo-Prop</u>

Battery Pack Level
Specific Energy
500 Watt Hour/ KG

100% Electric
(No Hybrid Engine)

Energy Cost Only
(No Battery Amort.)

Variation in Comparative Direct Operating Cost at Various JP fuel vs Electricity Rates
(Kevin Antcliff and Mark Guynn, NASA LaRC)