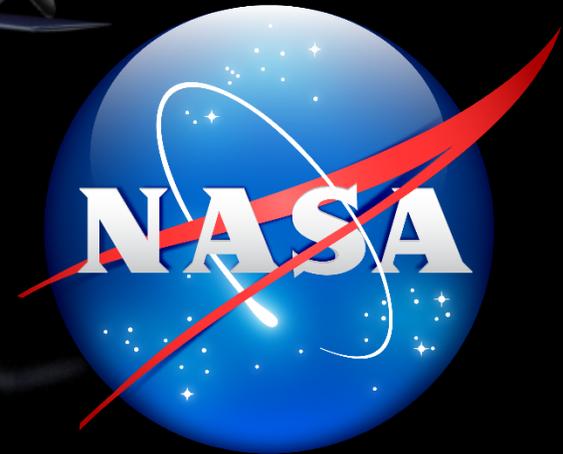
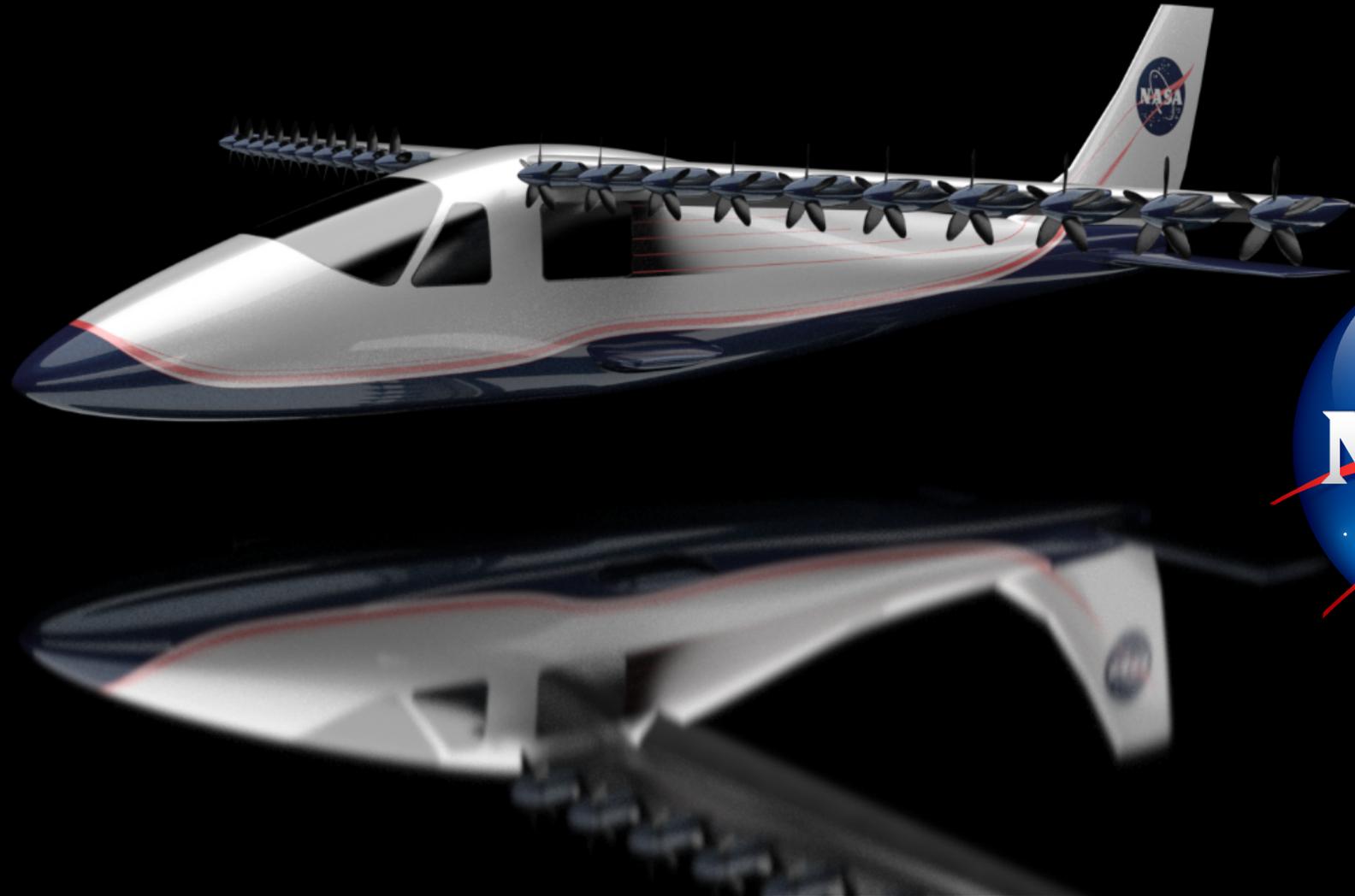


# *Distributed Electric Propulsion (DEP) Aircraft*



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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

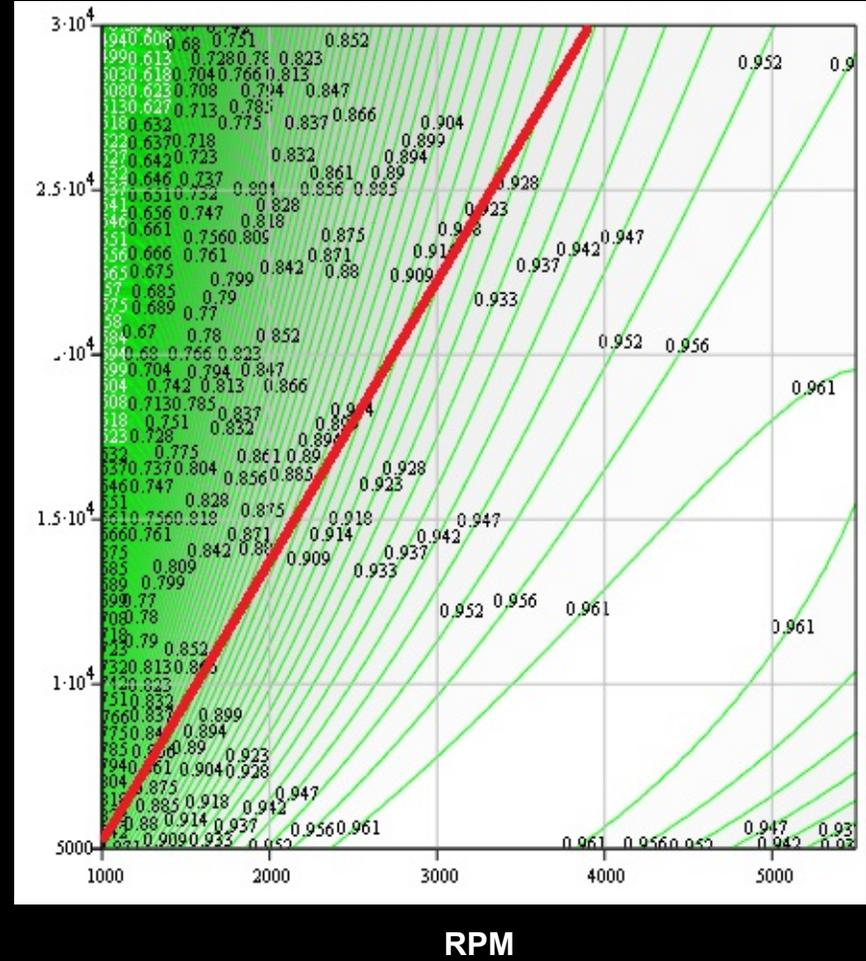
- **NASA Funded Launchpoint Alternator/Motor**



- 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.





# ***NASA Scale-Free Application of DEP to UAS***

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

***Electric motors provide high 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**

# Vibrant EP Flight Demonstrations at Smaller Scale



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



Rui Xiang RX1E  
China



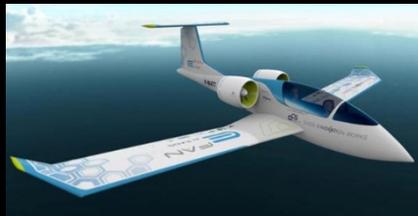
FEATHER  
JAXA



Electric Cri-Cri  
Airbus



Pipistrel Watts Up  
Slovenia  
(Ready for Production)



E-Fan  
Airbus

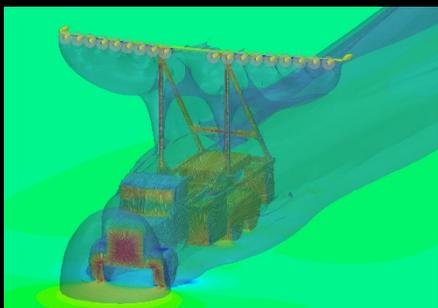
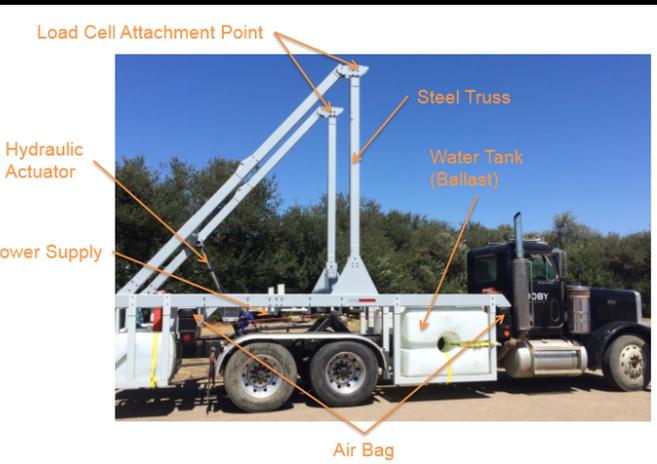
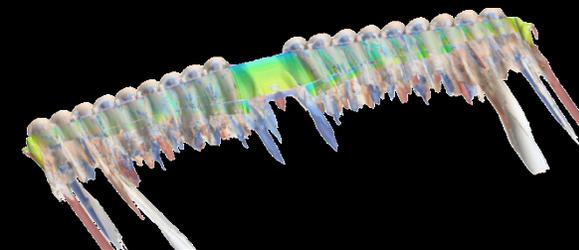
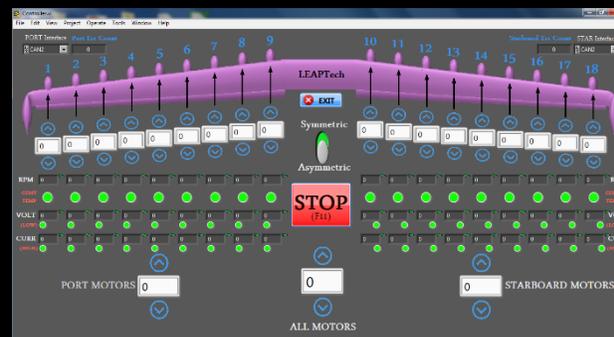


DA-36 E-Star  
Airbus



E-Genius  
Airbus

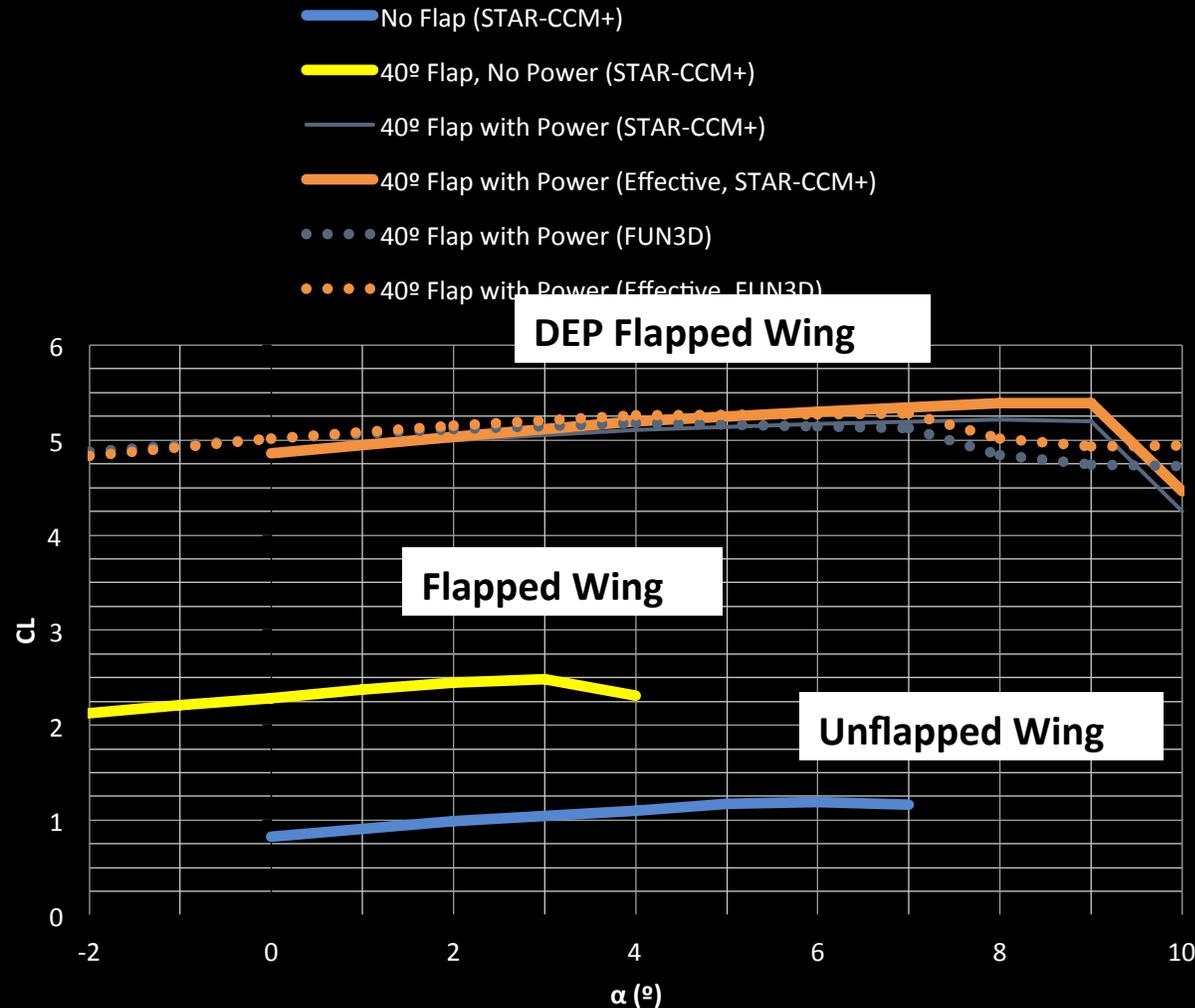
# NASA DEP LEAPTech Testing



# DEP Aero-Propulsion Highlift Integration



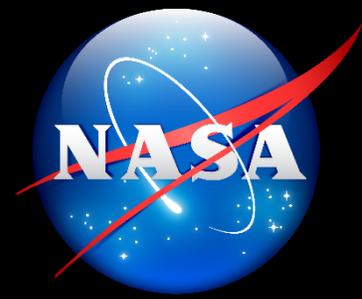
Lift Coefficient at 61 Knots (with and without 220 kW)



***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**

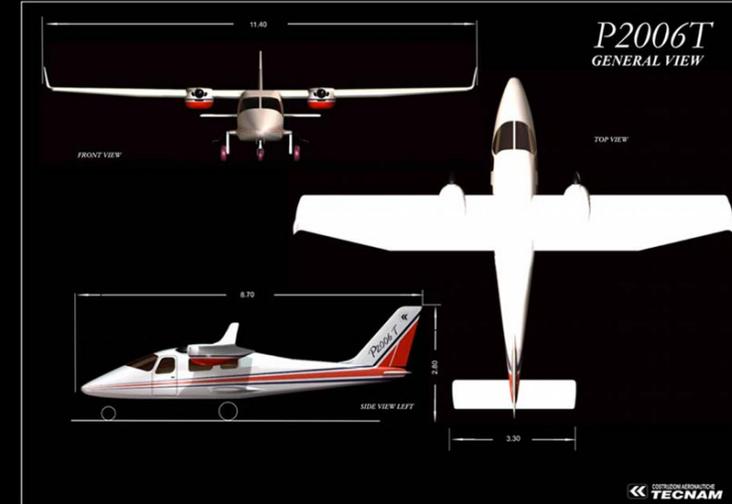
**Instead of focusing on low speed efficiency, SCEPTOR focuses on how DEP technologies enables cruise efficiency at higher speeds.**



# 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

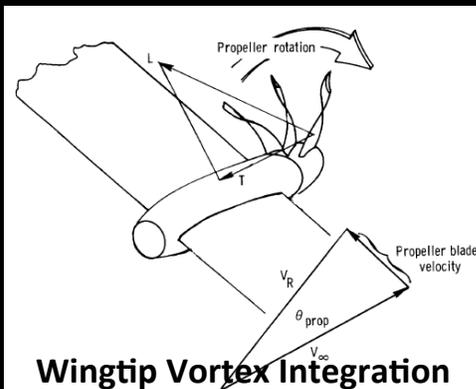
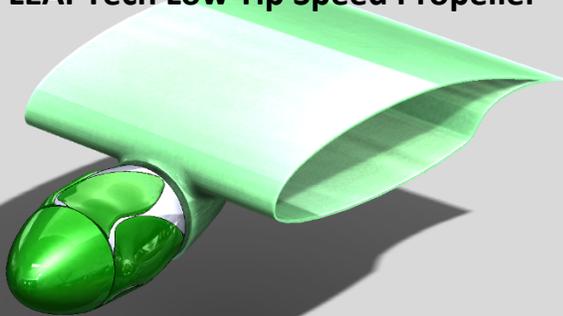
- 15 dB Lower community noise (with even lower true community annoyance) .
- Flight control redundancy, robustness, reliability, with improved ride quality.
- Certification basis for DEP technologies.
- Analytical scaling study to provide a basis for follow-on ARMD Hybrid-Electric Propulsion (HEP) commuter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





# Compact/Synergistic DEP Integration New DoF

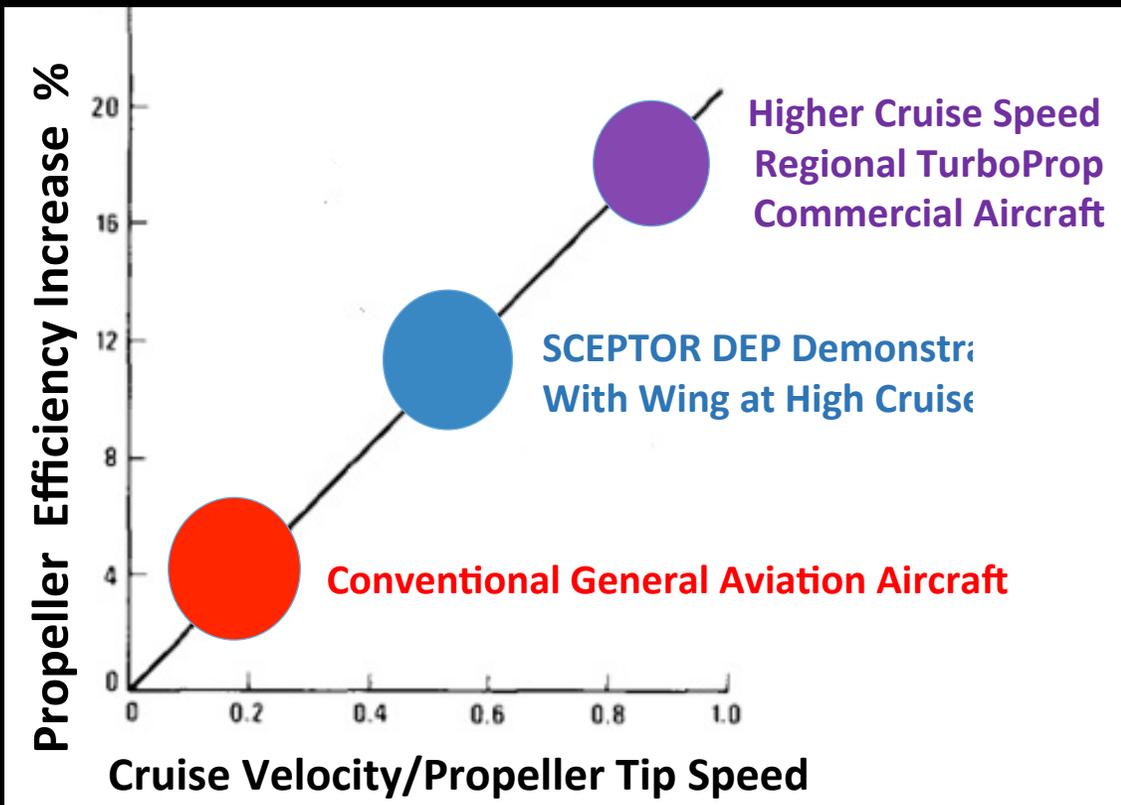
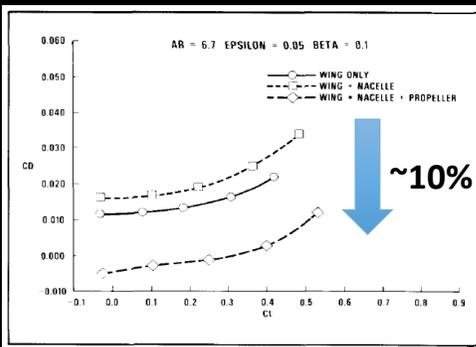
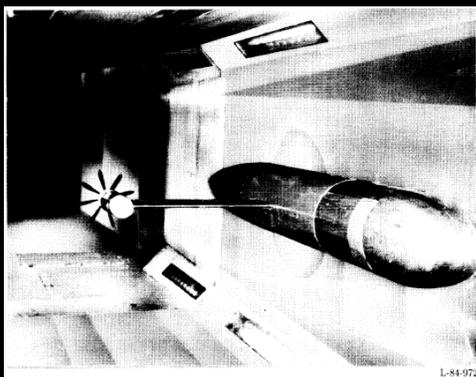
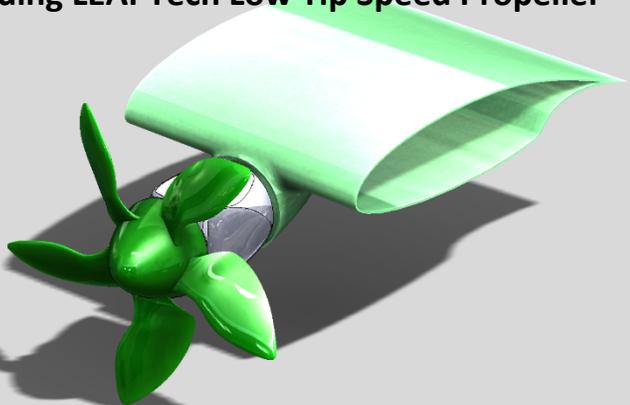
Folding LEAPTech Low Tip Speed Propeller



Alisport Slient-2 Motorglider



Folding LEAPTech Low Tip Speed Propeller



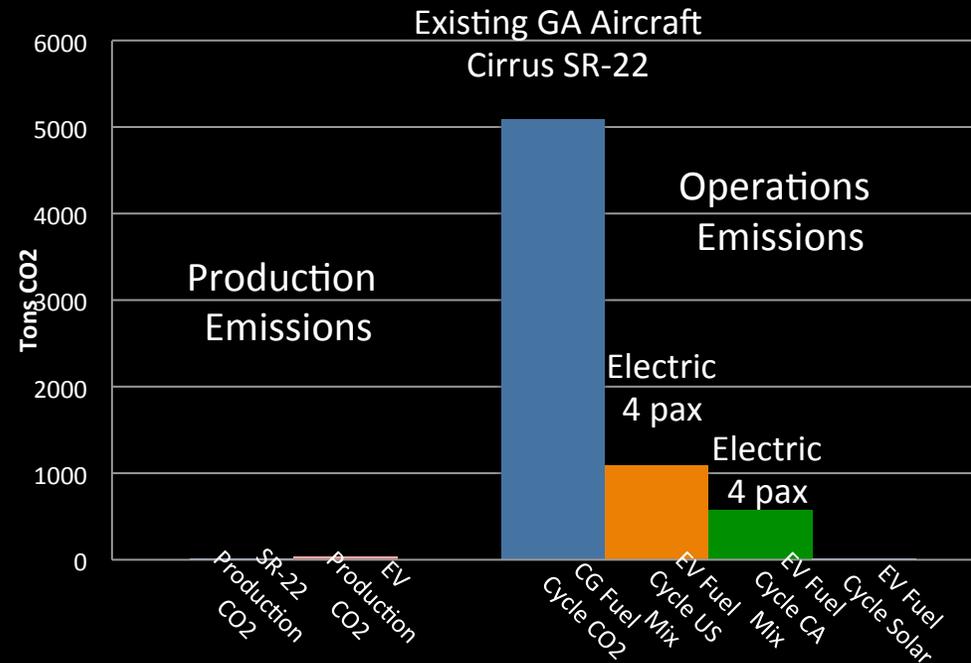
Aerodynamic Effects of Wing Tip Mounted Propellers and Turbines, L. R. Miranda, AIAA Paper 86-1802, 1986.

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



# 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.

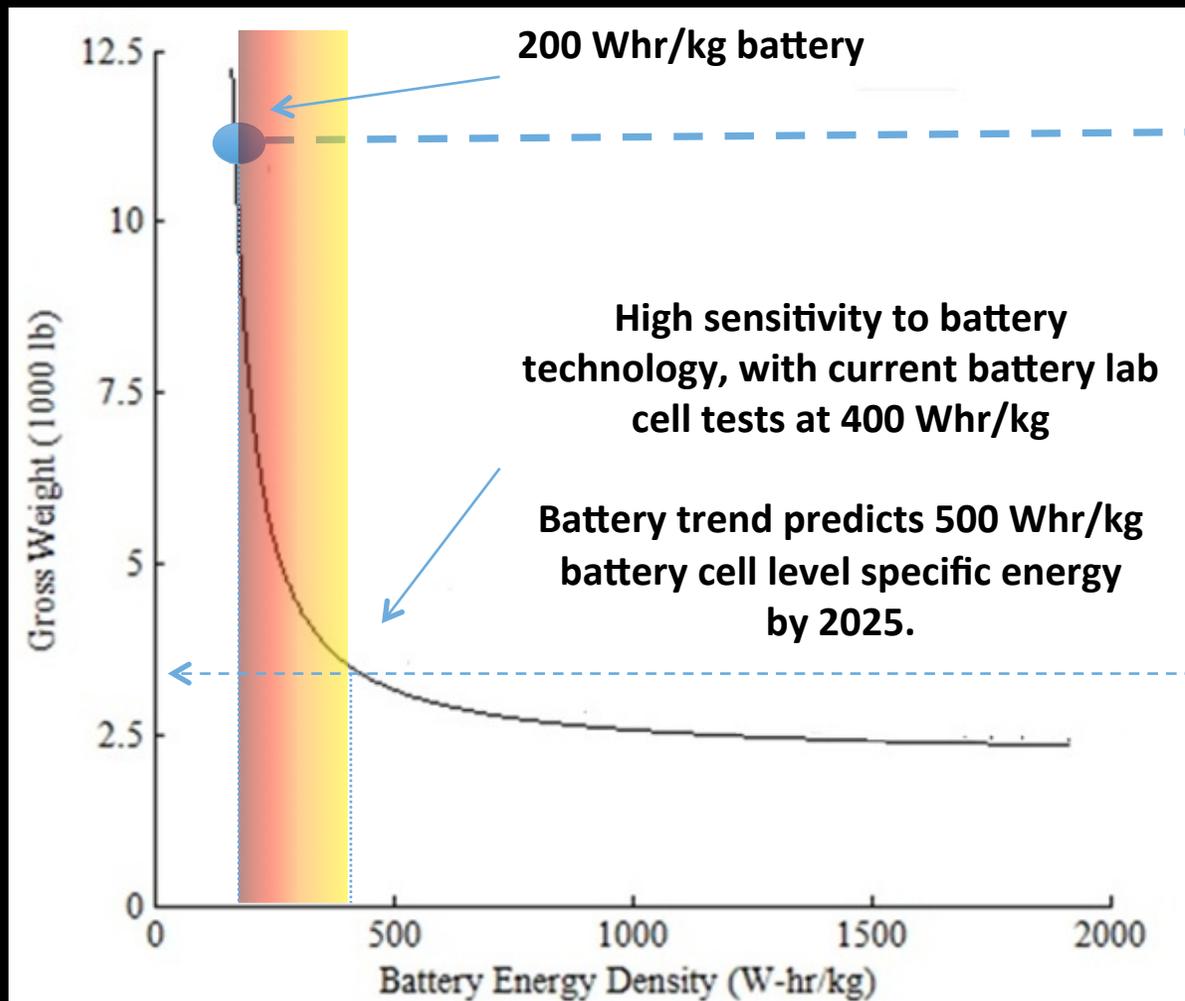
Zip Aviation, Electric, Autonomous, On-Demand High Speed Regional Mobility, M.D. Moore, AIAA Aviation 2013.

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.



# 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

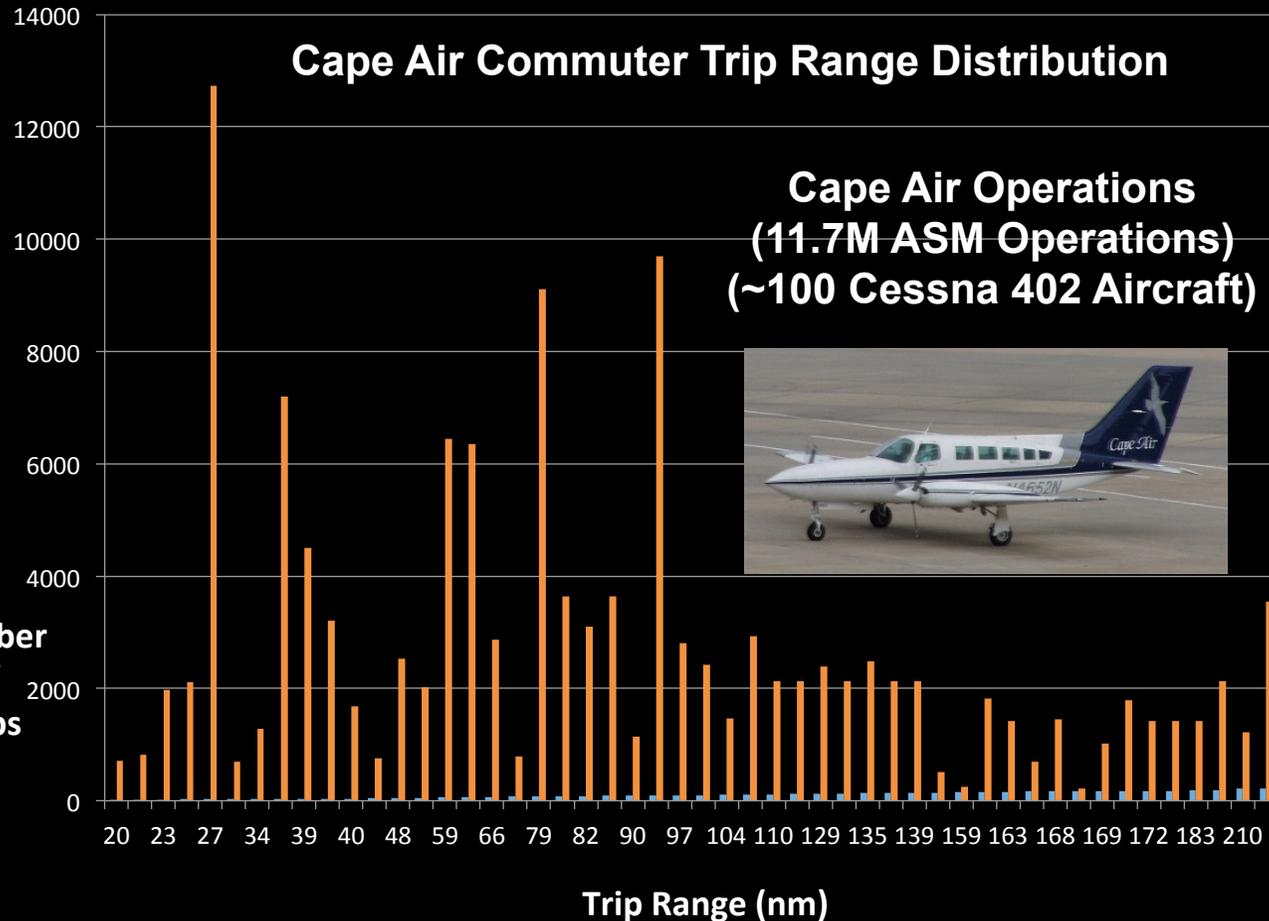


**Cirrus SR-22  
General Aviation Aircraft**  
500 nm range + reserves  
3400 lb



# 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

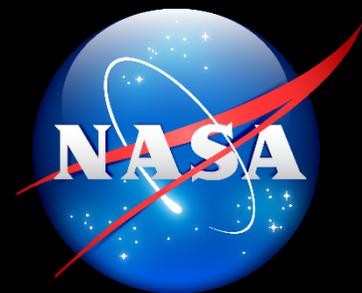


### Hyannis Airport, MA 1.4 MW solar farm



DEP 9 pax  
Thin-Haul Commuter





# EP Evolutionary Technology Path



**Small aircraft EP research enables faster tech development.**

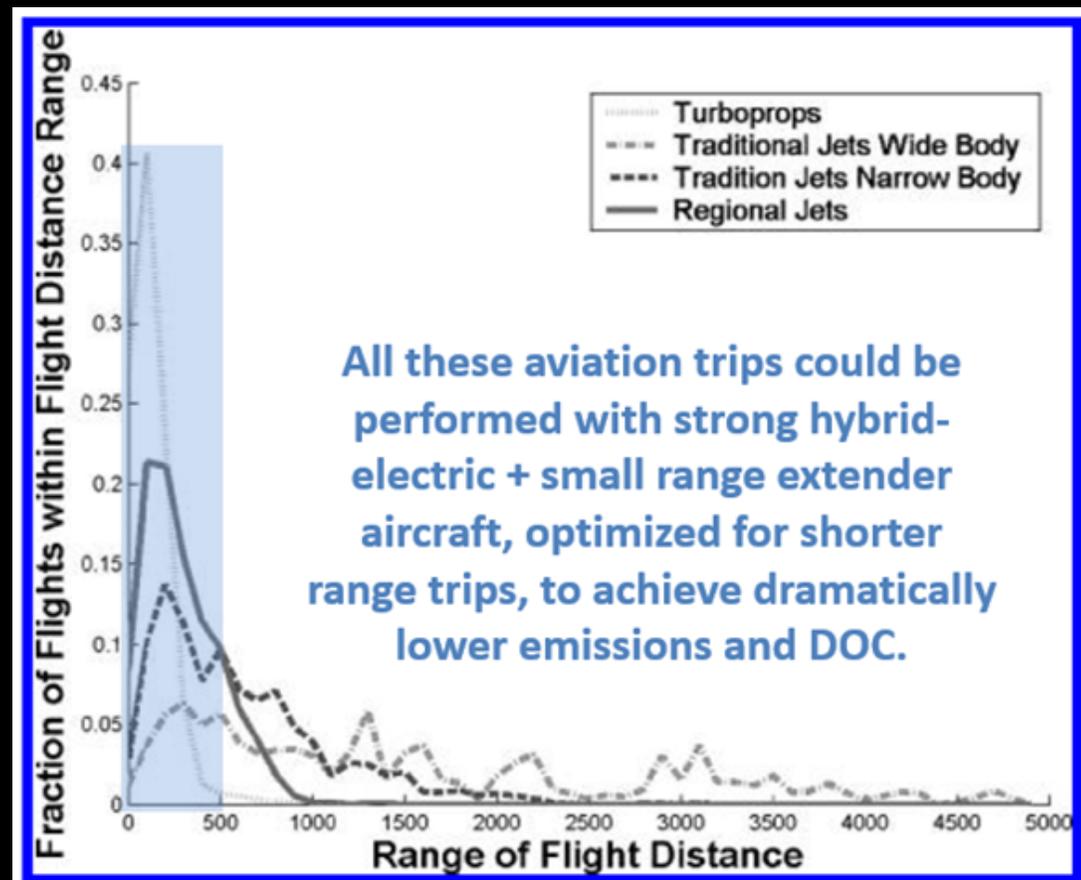
**Large battery mass fraction aircraft @ 400 Whr/kg pack level specific energy enable ranges to >300 nm + reserves, with 60-90% reduction in carbon @ ~30% lower operating costs.**



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

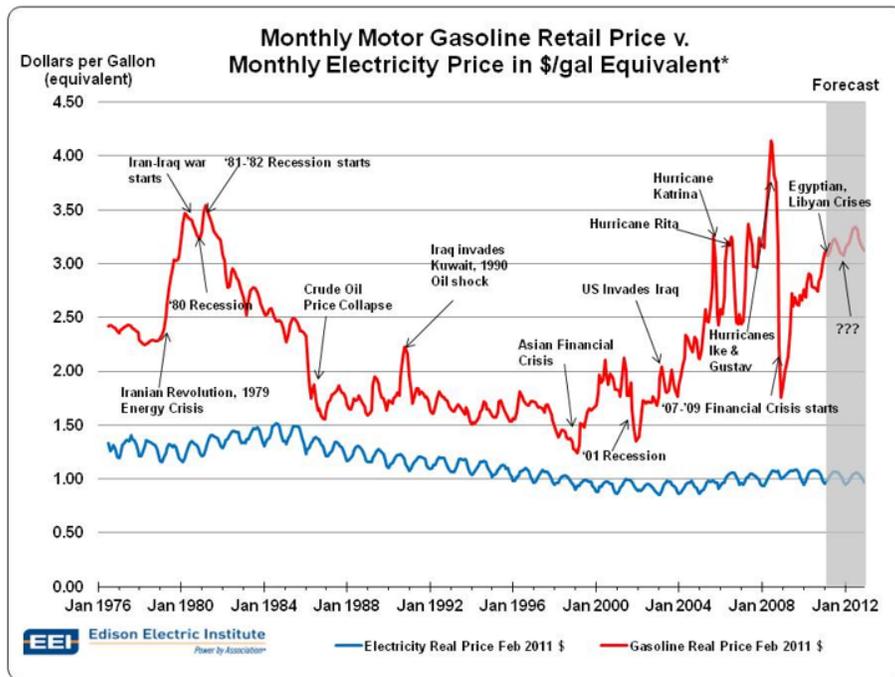


**Ability to incentivize >50% of aviation operations and >13% of carbon emissions for a quick start sustainable carbon path.**



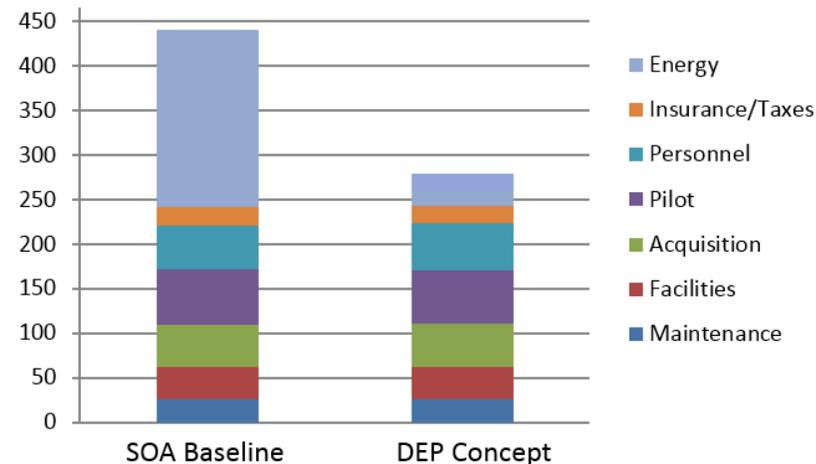
**Aviation Trip Range Distribution  
Across all commercial aviation sectors  
(Number of trips vs distance nm)**

# Electricity Based Operating Cost Value Proposition

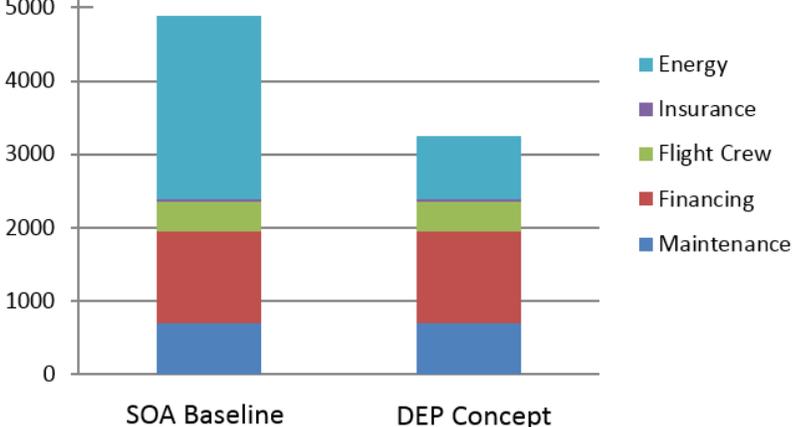


**Electricity based aircraft energy provide a decrease in price variability and cost risk as well as a true renewable energy path (100LL fuel is ~2x higher cost than auto gas)**

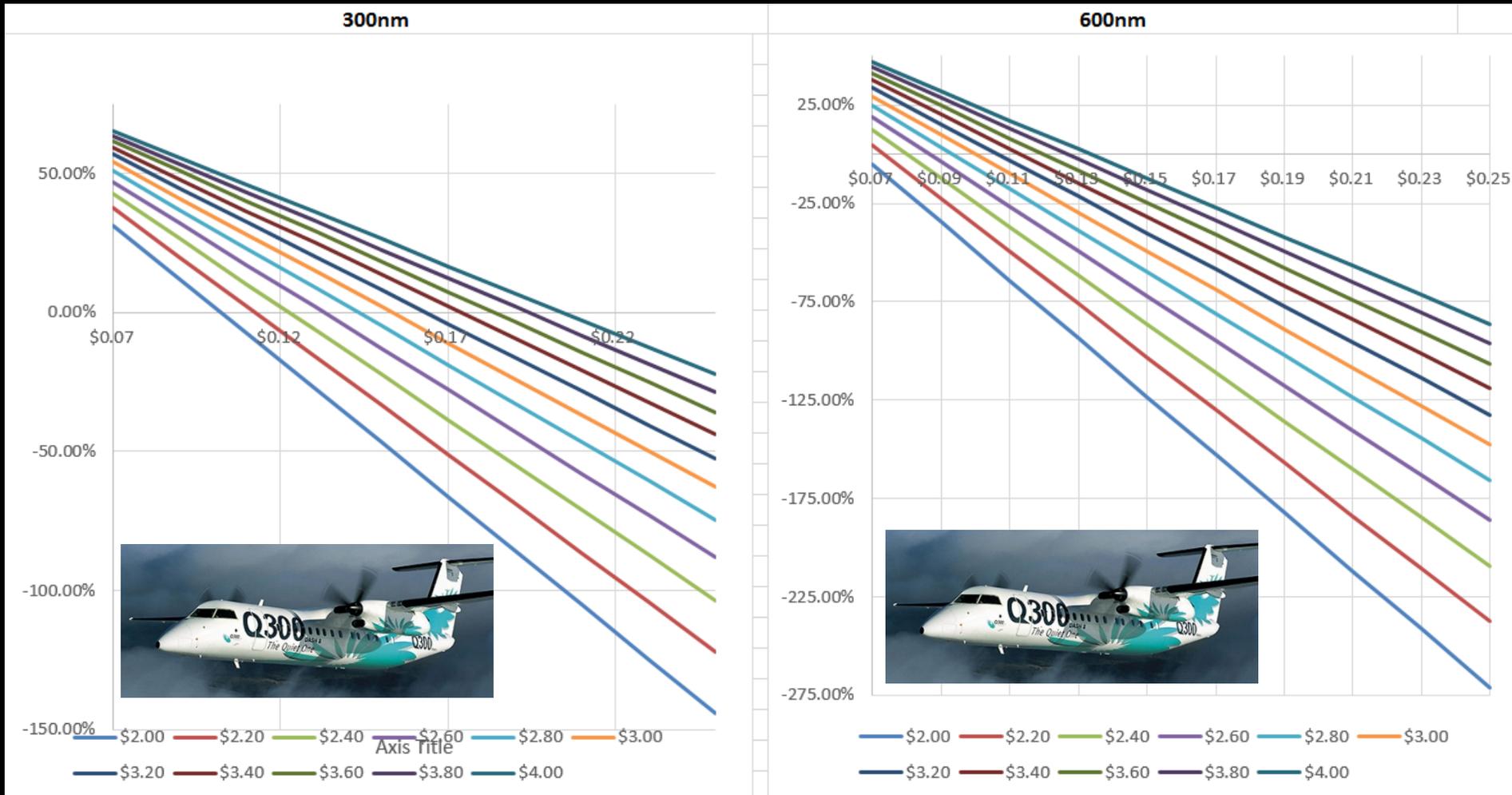
**General Aviation Total Operating Cost Comparison**



**Single Aisle Commercial Direct Operating Cost Comparison**



# Current NASA Cost-Emission Trade Studies



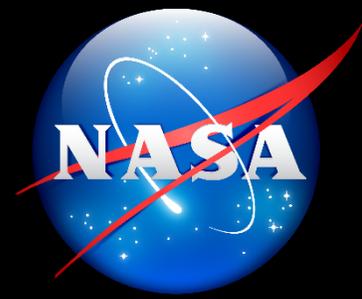
**Q400 Regional Turbo-Prop**

**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)**



# Conclusions

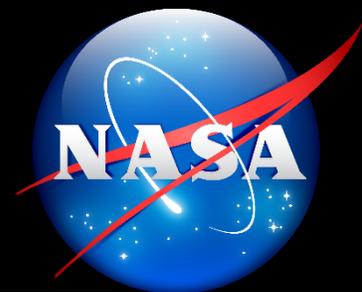
***Technology evolutionary strategy is as important as the technology itself if a strong market goal-focus exists (such as to achieve dramatic reductions in aviation carbon emissions).***

***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.***

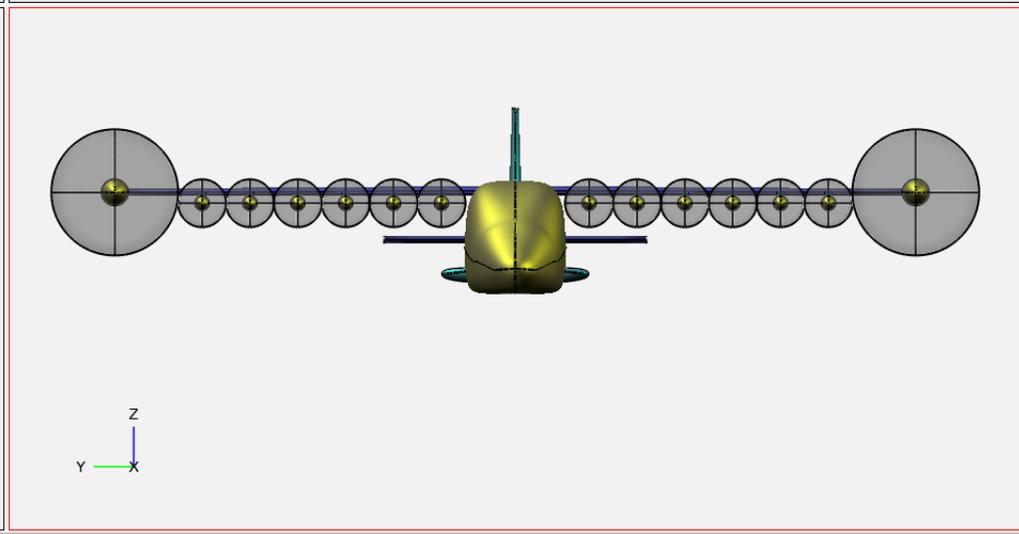
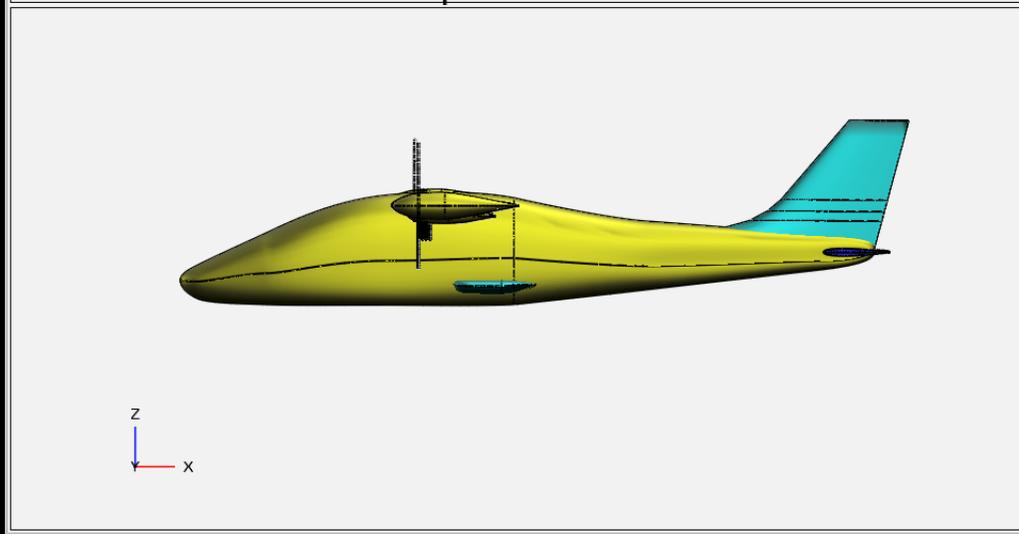
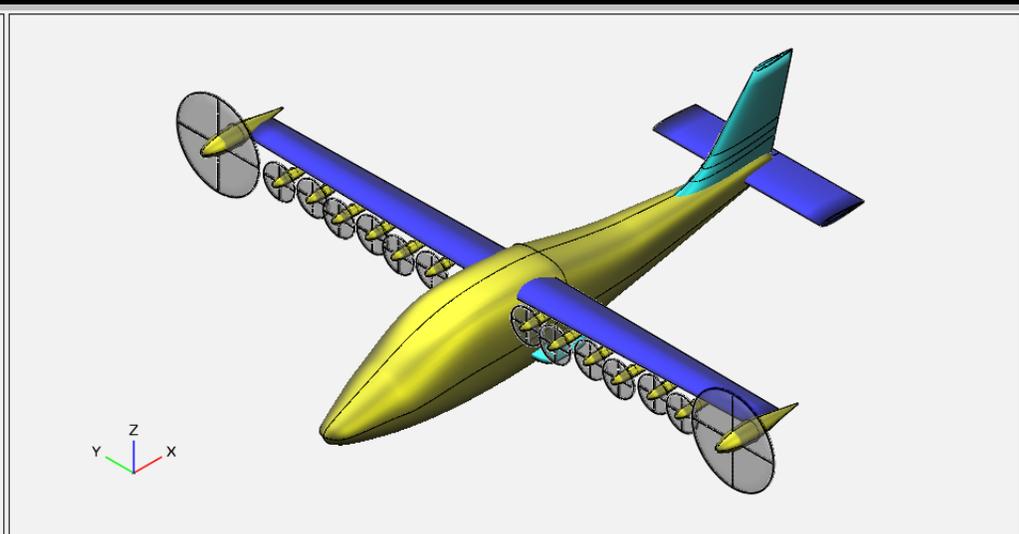
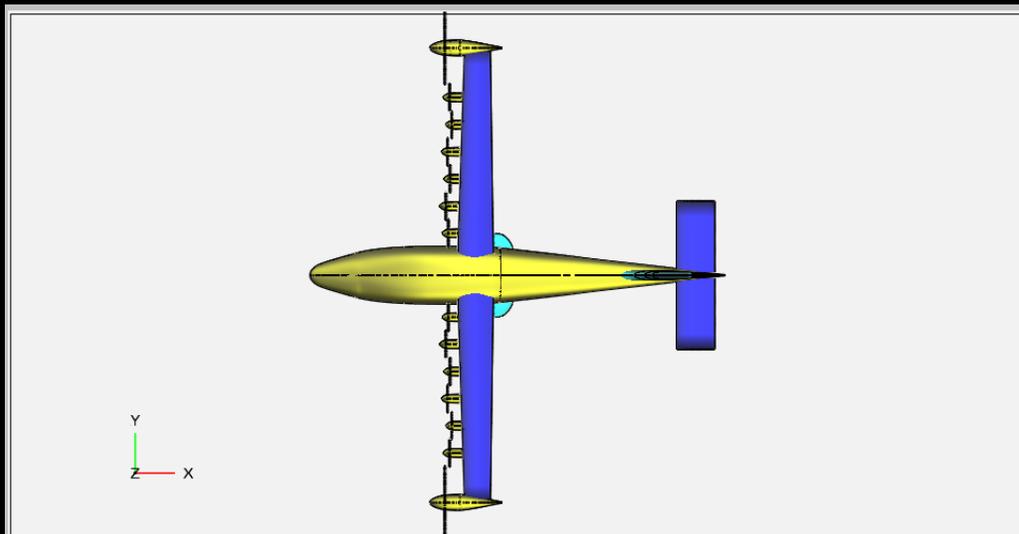
***Shorter range aircraft designed to achieve low operating costs will almost certainly be designed as large battery, series hybrid with small range extenders for operations flexibility.***

***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.***

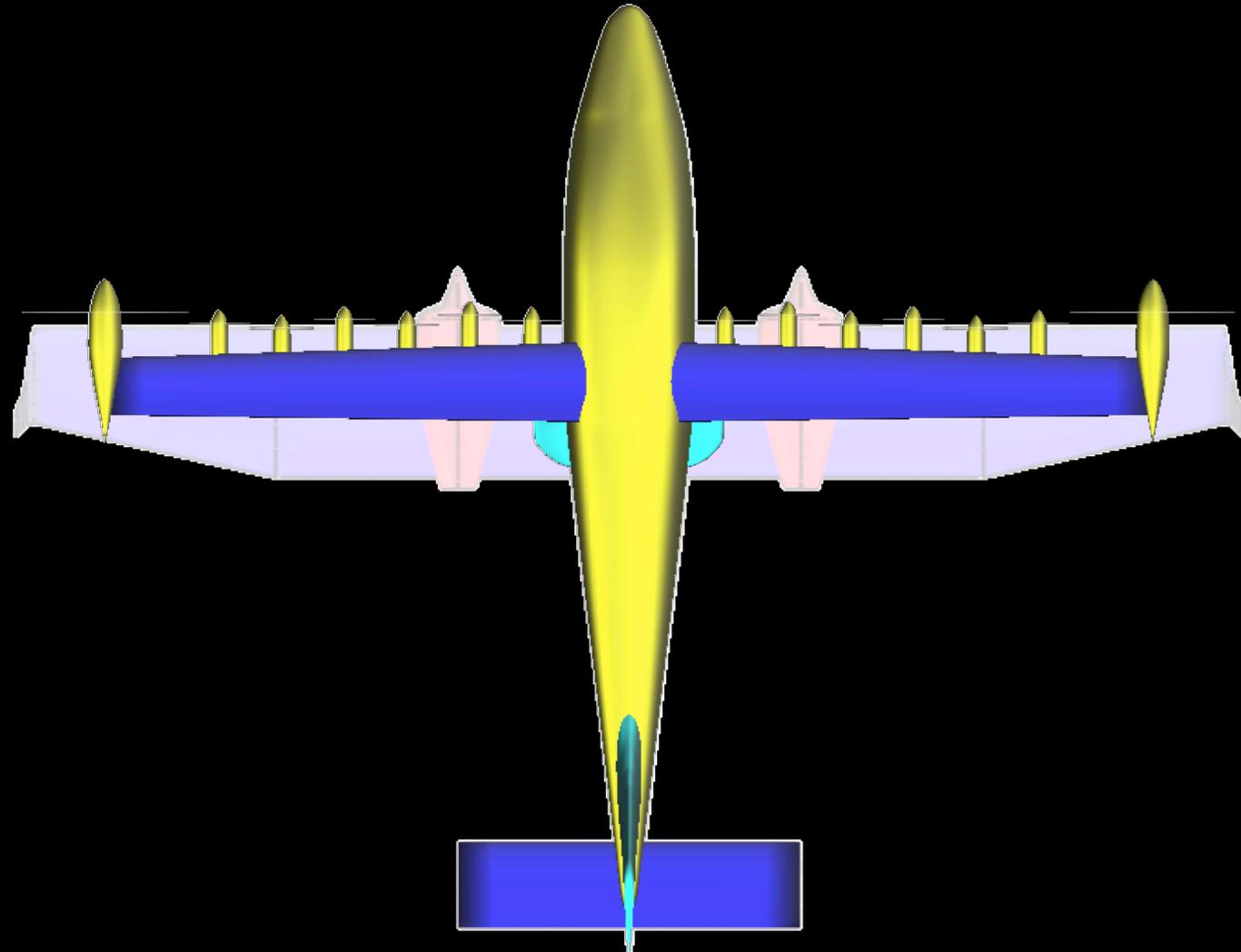
***Incentivizing low carbon aviation through dramatic improvements through natural market economic forces has a higher probability of success than being dependent on carbon taxing.***



# Current SCEPTOR Configuration



# *Comparison to Baseline Tecnam P2006T*



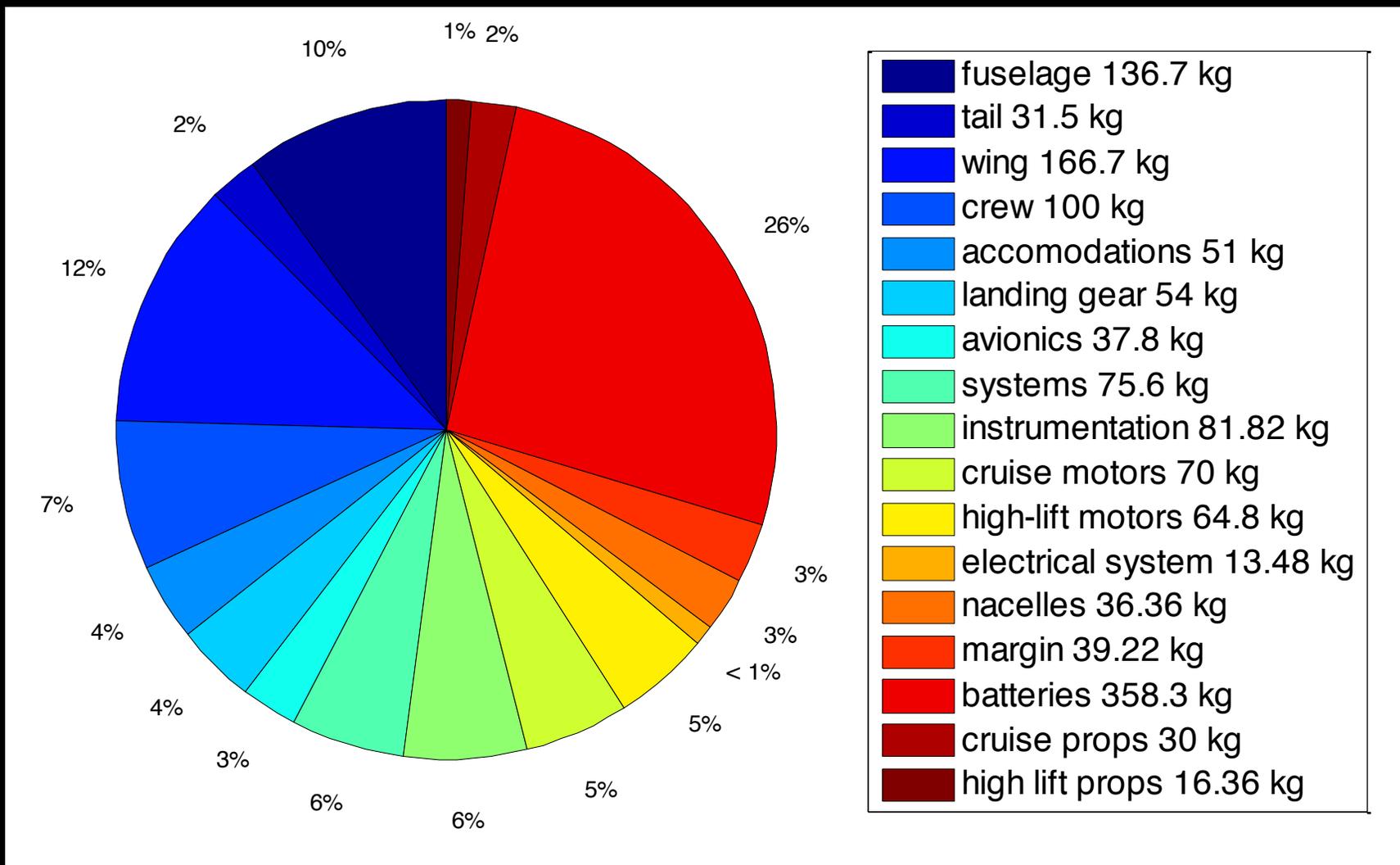


# *SCEPTOR Characteristics*

- **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<sup>2</sup> (66.67ft<sup>2</sup>)
  - Aspect ratio: 15
  - Washout: 2 deg
  - Root incidence: 2 deg
  - Wing loading: 2153 N/m<sup>2</sup> (45.0 lbf/ft<sup>2</sup>) (@3000 lbf)
- **Cruise Props**
  - Number: 2
  - Diameter: 1.524m (5ft)
  - Blades: 3
  - Airfoil: MH117
  - Power @ 3000 lbf, 150KTAS, 8000ft: 48.12kW @ 2250 RPM
- **High Lift Props**
  - Number: 12
  - Diameter: 0.576m (1.89ft)
  - Blades: 5
  - Airfoil: MH114
  - Power @ 55KTAS, SL: 14.4kW @ 4548 RPM

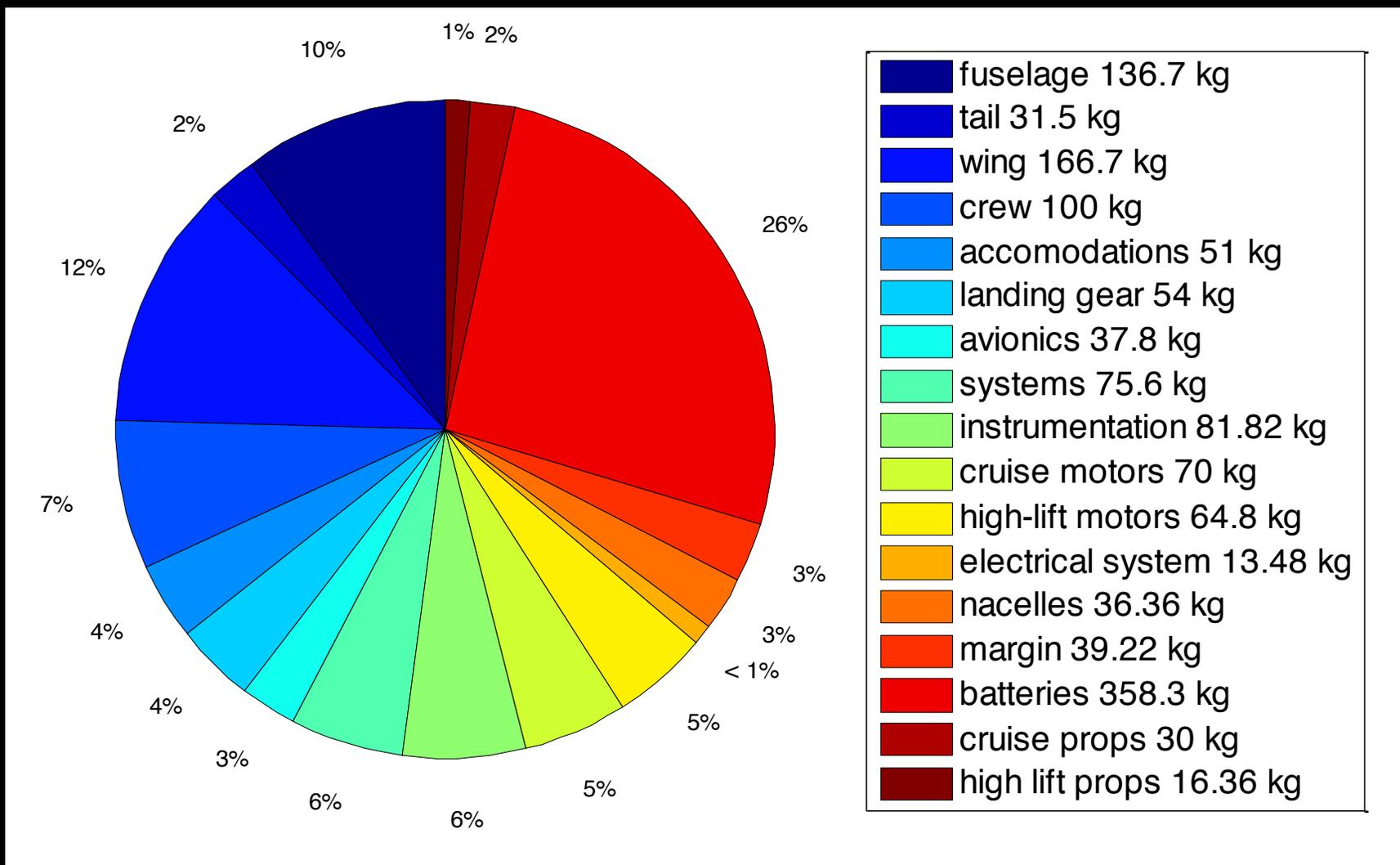


# SCEPTOR Drag Breakdown





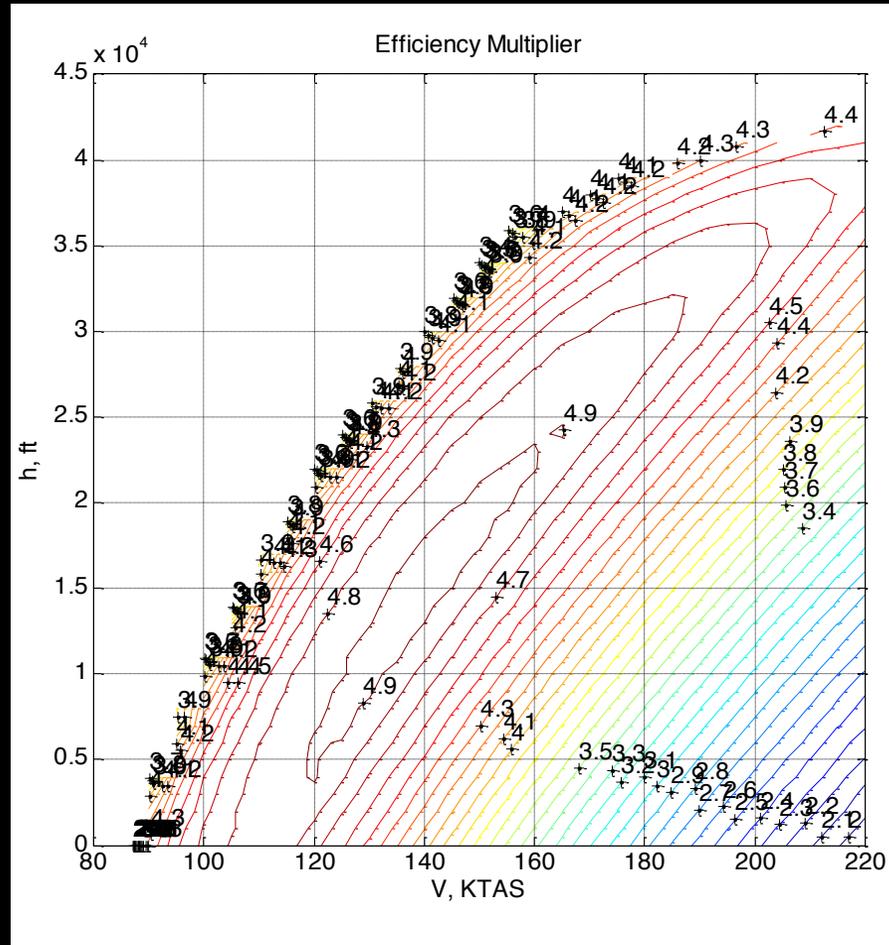
# SCEPTOR Mass Breakdown





# SCEPTOR Primary Objective Metric

With 0.5 D/q margin



No D/q margin added

