Electric Propulsion (EP) Example Roadmap Decomposition

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Top-Level ODM Barriers & EP

➢ **Current General Aviation (GA) Aircraft compared to Commercial Airliners**

- **Poor Aerodynamic and Propulsive Efficiencies**
  - Aerodynamic efficiency measured as Lift/Drag ratio is 9-11 compared to 17-20.
  - (Thermal) x (propulsive efficiency) of 20-24% compared to 36-40%.
- **Poor Emissions**
  - High Hydrocarbon, Green House Gas emissions, particulates and lead pollution.
- **Poor Community Noise**
  - Similar levels and certification compliance with few improvements for the past 50 years.
- **Poor Comparative Safety**
  - **Accident rate 56x worse than airlines, 15x worse than autos per 100 million vehicle miles traveled**.
- **Poor Ride Quality**
  - Low wing loading leads to bumpy ride along with gust sensitivity. (Note, technology needed for SVO also applicable to active gust alleviation)
- **Poor Dispatch Reliability Rate**
  - Maintenance and weather sensitivity result in <70% rate for trip completion.
- **Substantially Higher Operating Costs**
  - Compared to all other transportation options (car, airline, train).
- **Onerous Training Requirements**
  - Currently only 0.18% of the U.S. population is capable of flying GA aircraft compared to 69% who have a driver's license.

Retrofit EP Approach

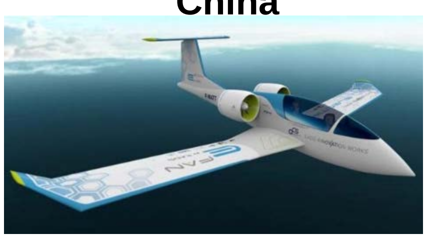
EP demonstrators have focused on achieving high efficiency, in energy constrained aircraft at low cruise speeds.

Pipistrel Watts Up
Slovenia

Rui Xiang RX1E
China

FEATHER
JAXA

Electric Cri-Cri
Airbus



E-Fan
Airbus

DA-36 E-Star
Airbus

E-Genius
Airbus

Top-Level ODM Barriers & Retrofit EP

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Retrofit EP Roadmap: Goals

- **Propulsive Efficiency**
  - Powertrain Efficiency > 90% (3.2x existing reciprocating engines)
- **Emissions**
  - Zero in-flight carbon, 3-5x lower life cycle carbon, elimination of lead
- **Direct Operating Cost**
  - Energy/gal cost reduction of 0 to 30%, with 3.2x less energy = 3.2 to 4.2x lower energy cost
  - Including battery amortization, 1.5 to 2.0x lower energy cost
- **EP aircraft ranges of ~100 nm + reserves within 3 years**

Top-Level ODM Barriers & Clean Sheet EP

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NASA SCEPTOR Clean Sheet EP Approach

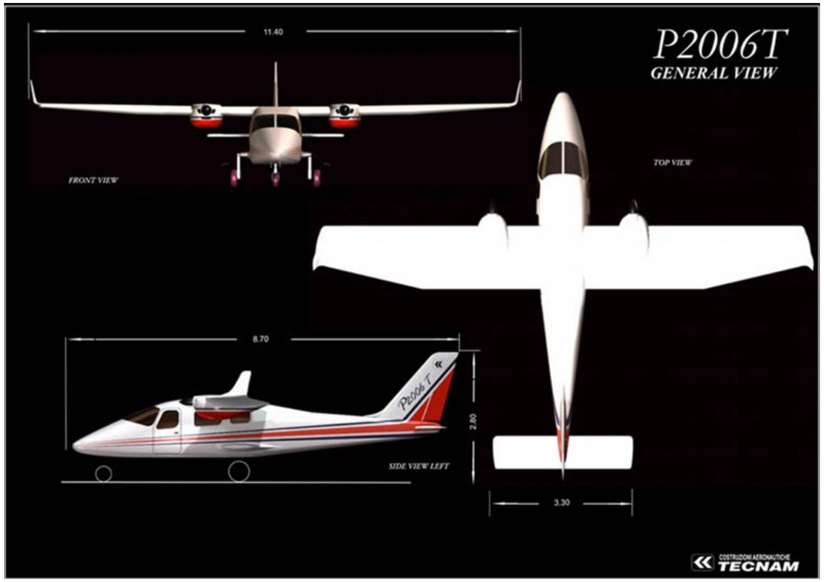
Tecnam P2006T Light Twin General Aviation Aircraft

NASA Distributed Electric Propulsion (DEP) X-Plane

~$16 million (from CAS), 3-year research project to achieve the first Distributed Electric Propulsion (DEP) manned flight demonstrator in 2017.

Instead of focusing on low speed efficiency, SCEPTOR focuses on how DEP technologies enables high-speed cruise efficiency through tight integration of propulsion and aerodynamics.

NASA SCEPTOR Clean Sheet EP Approach



NASA SCEPTOR X-Plane

NASA SCEPTOR Primary Objective

- Goal: 5x Lower Energy Use (Comparative to Retrofit GA Baseline @ 175 mph)
  - Motor/controller/battery conversion efficiency from 28% to >90% (3.2x)
  - Integration benefits of ~1.5x (2.0x achievable with fuselage clean sheet)

NASA SCEPTOR Derivative Objectives

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

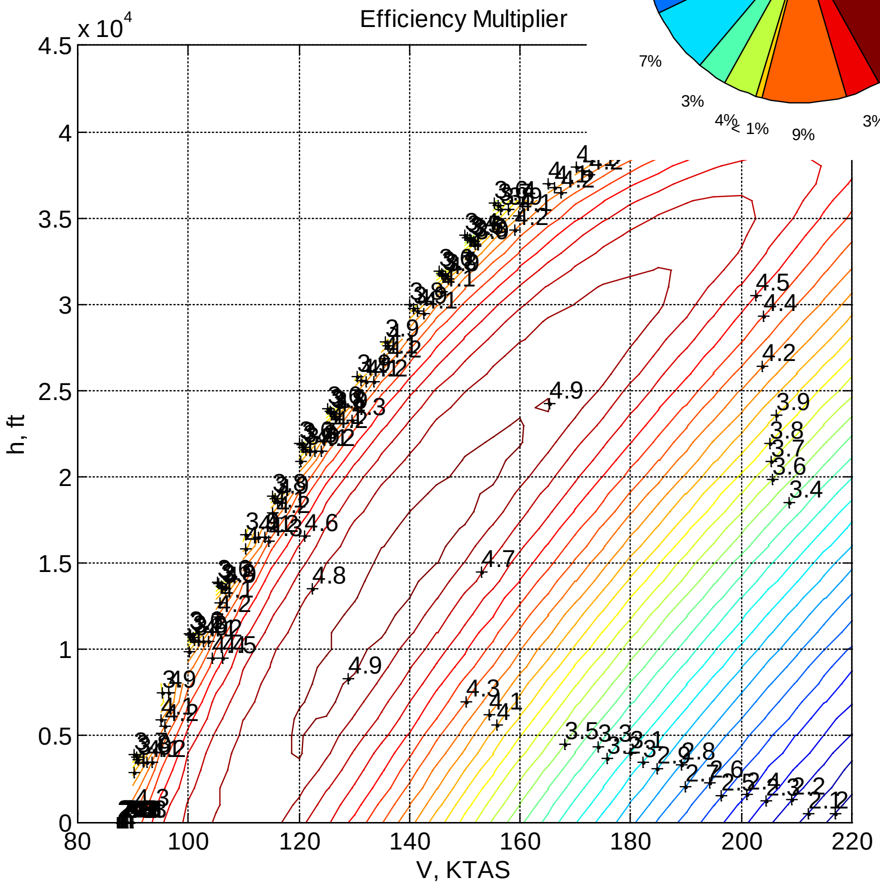
Clean Sheet EP Roadmap: Goals

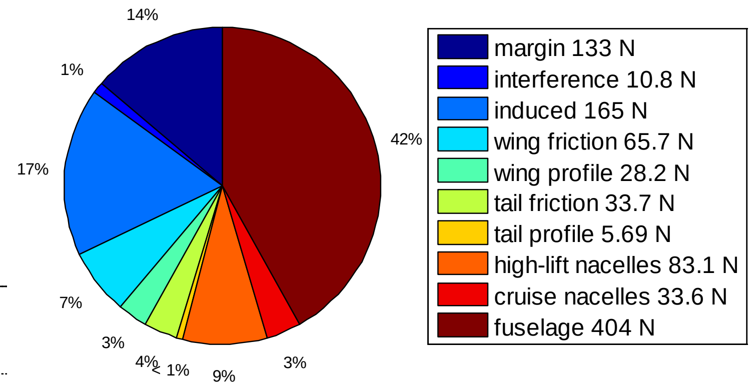
- **Aerodynamic Efficiency**
  - Wing area decrease, cooling/scrubbing/blockage drag, spanwise loading
- **Propulsive Efficiency**
  - Wingtip integration improvement of 5-13%
- **Community Noise**
  - Lower tip speed propellers, variable rpm frequency spreading = 15 dB lower
- **Safety**
  - Propulsion system redundancy, propulsion enhanced control at low speed
- **Ride Quality**
  - Wing loading increase from 17 to 45 lb/ft^2
- **Direct Operating Cost**
  - 3 to 4x lower energy cost (including battery amortization)
- **DEP aircraft ranges of ~200 nm + reserves within 3 years**

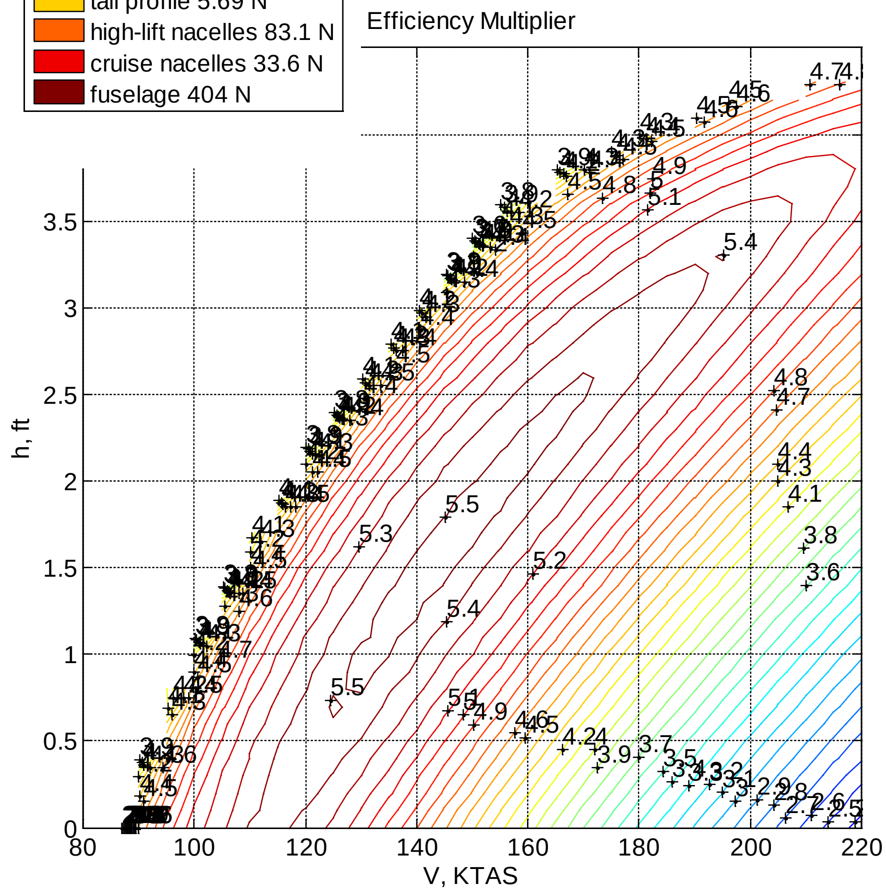
SCEPTOR EP Approach: Efficiency

With 0.5 D/q Margin

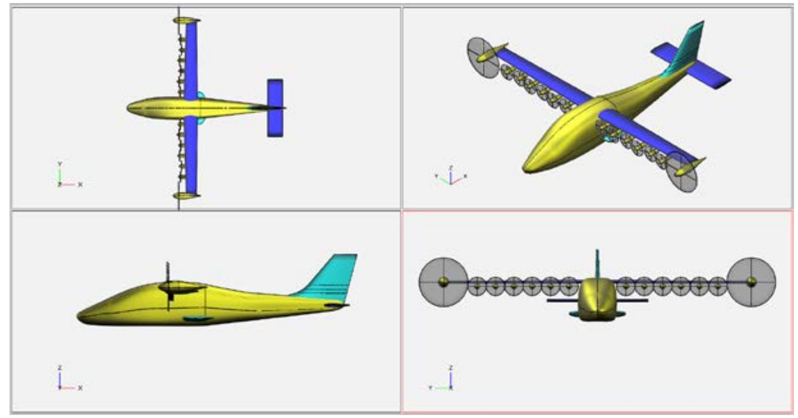
No D/q Margin

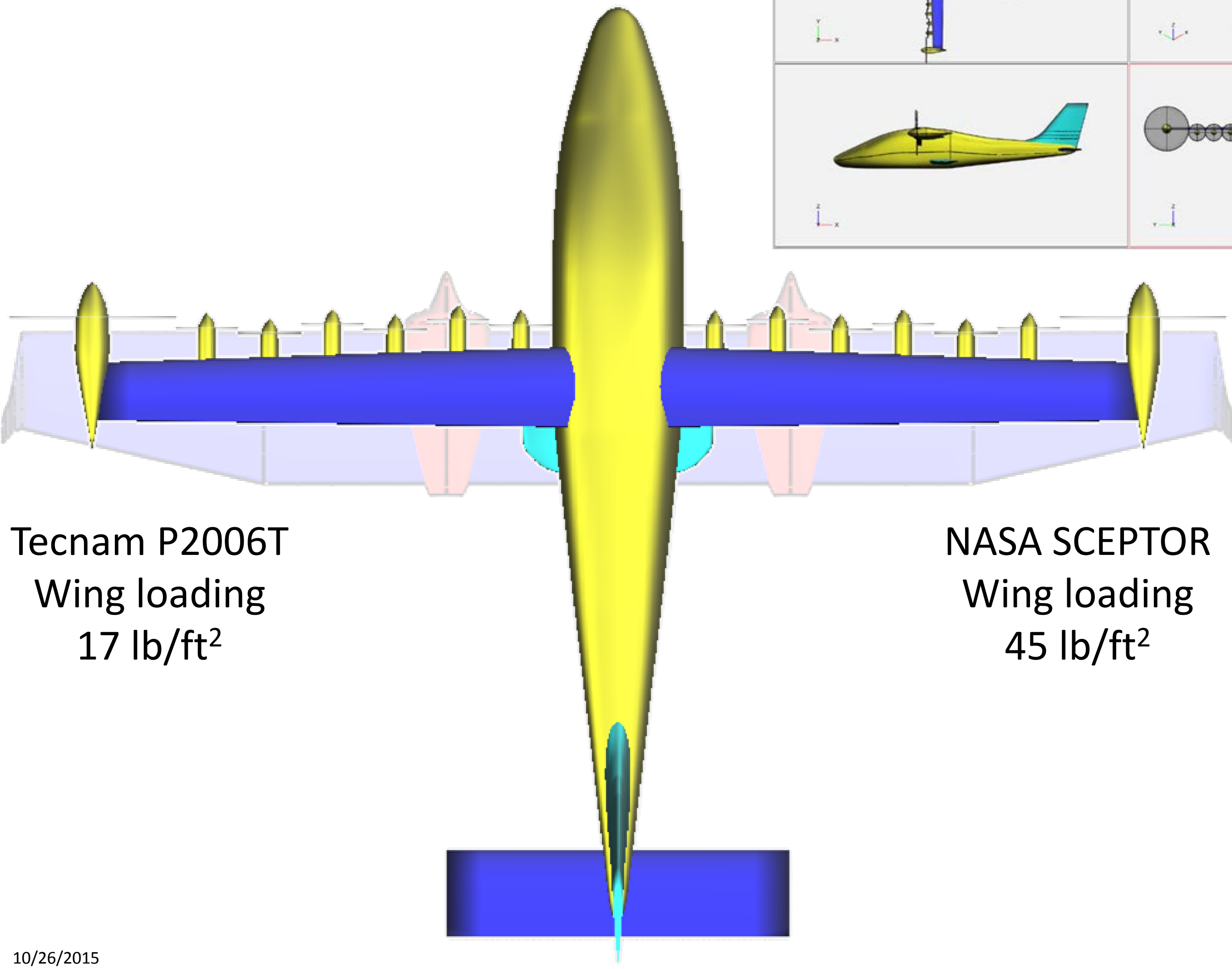




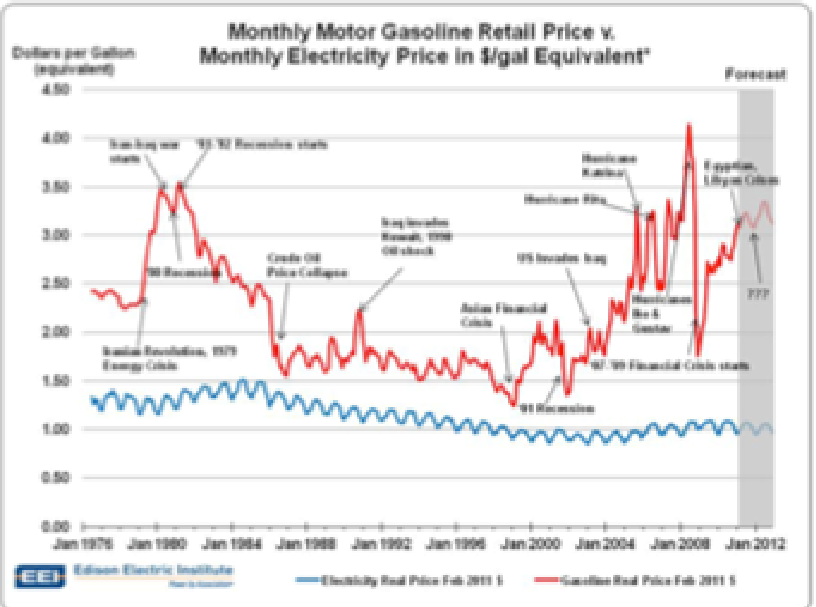


SCEPTOR EP Approach: Ride Quality

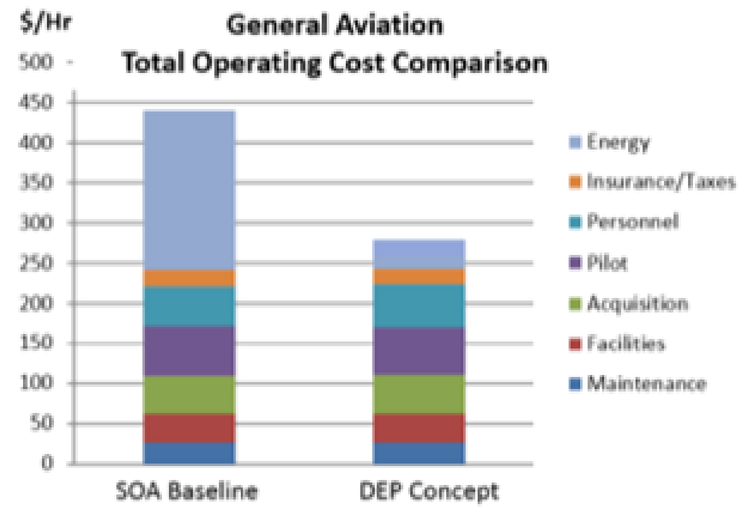


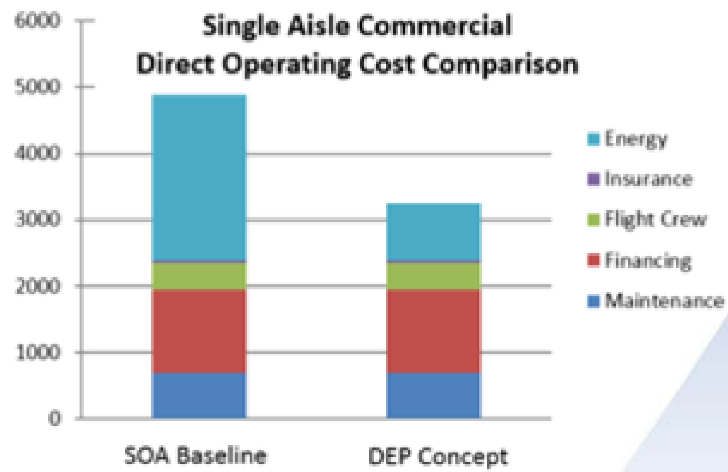


SCEPTOR EP Approach: Operating Cost



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)





ODM Technical Challenge Decomposition

Societal Acceptability Criteria
Ranked by NASA Perceived Importance

Economically Feasibility

Metric
Total Operating Cost/Mile

Safety

Metric
Accident Rate

Ease of Use

Metric
Training In-flight workload

Community Noise

Metric
Perceived Annoyance @ Community Stand-off Distance

Close Proximity Accessible Infrastructure

Metric
Field Length Required

Reliability

Metric
Trip Completion Rate

Ride Quality

Metric
Equivalent Wing loading

Low Carbon Emissions

Metric
Full life cycle GHG

Low Operating Cost

Approach
Electric DEP decreases Energy Cost by >5x

Low Acquisition Cost

Approach
Robotic automotive composites manufacturing

EP Roadmap: Possible Pre-Competitive Goals

- **Certification standards that encapsulate both the isolated engine (Part 33) and fully integrated propulsion differences.**

- **Best practices handbooks for this new technology as an industry guide and lessons learned (similar to Composite Lightning Protection and Crashworthiness Design Guides).**

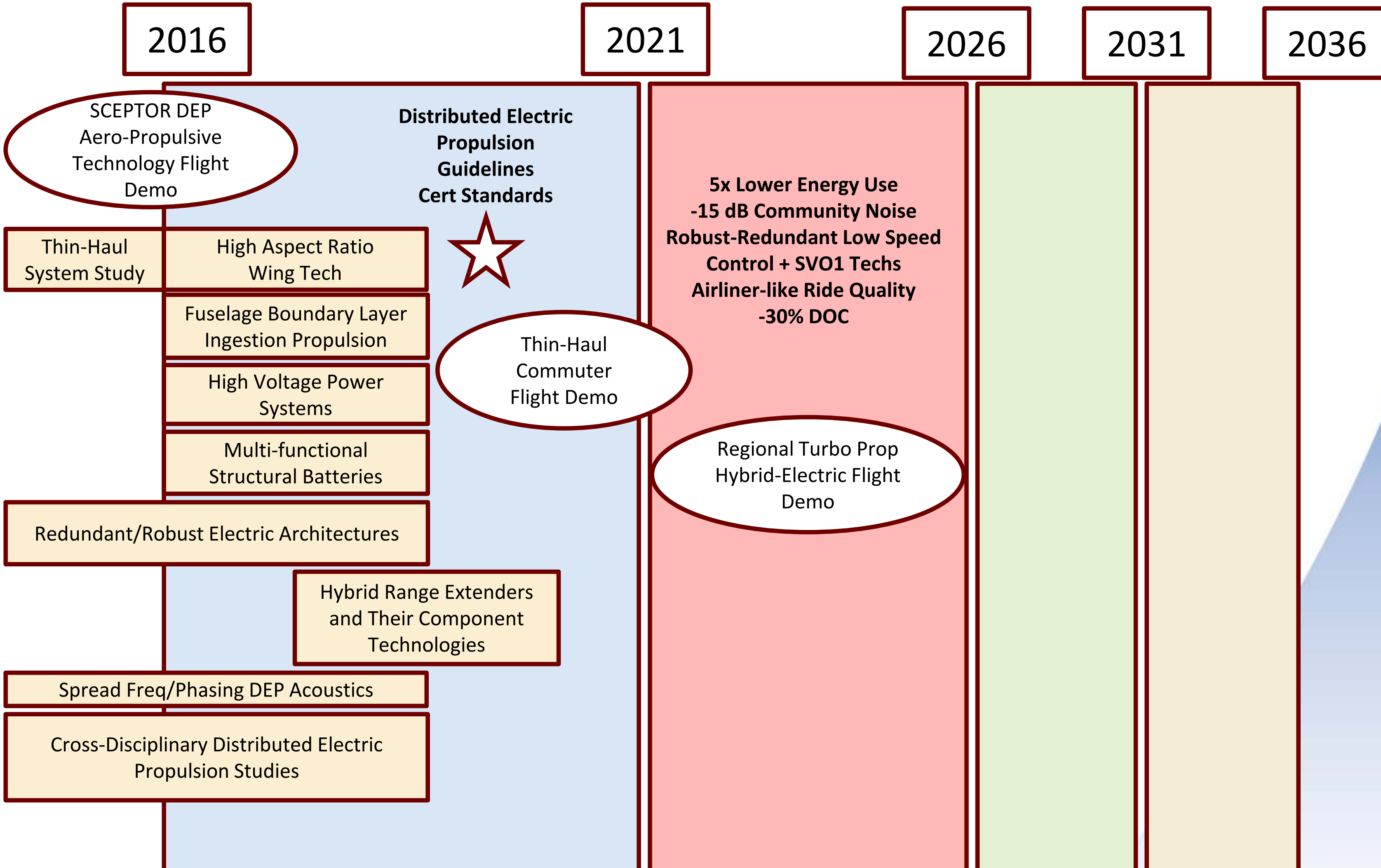
- **Battery and controller bus standards, connectors, energy state and reserve requirements determination.**

- **Investment to push cross-disciplinary integration benefits and EP component technologies, and pull from other industries into General Aviation for EP incubation and advanced technology learning with minimum consequence.**

Possible Outcomes from EP Roadmap

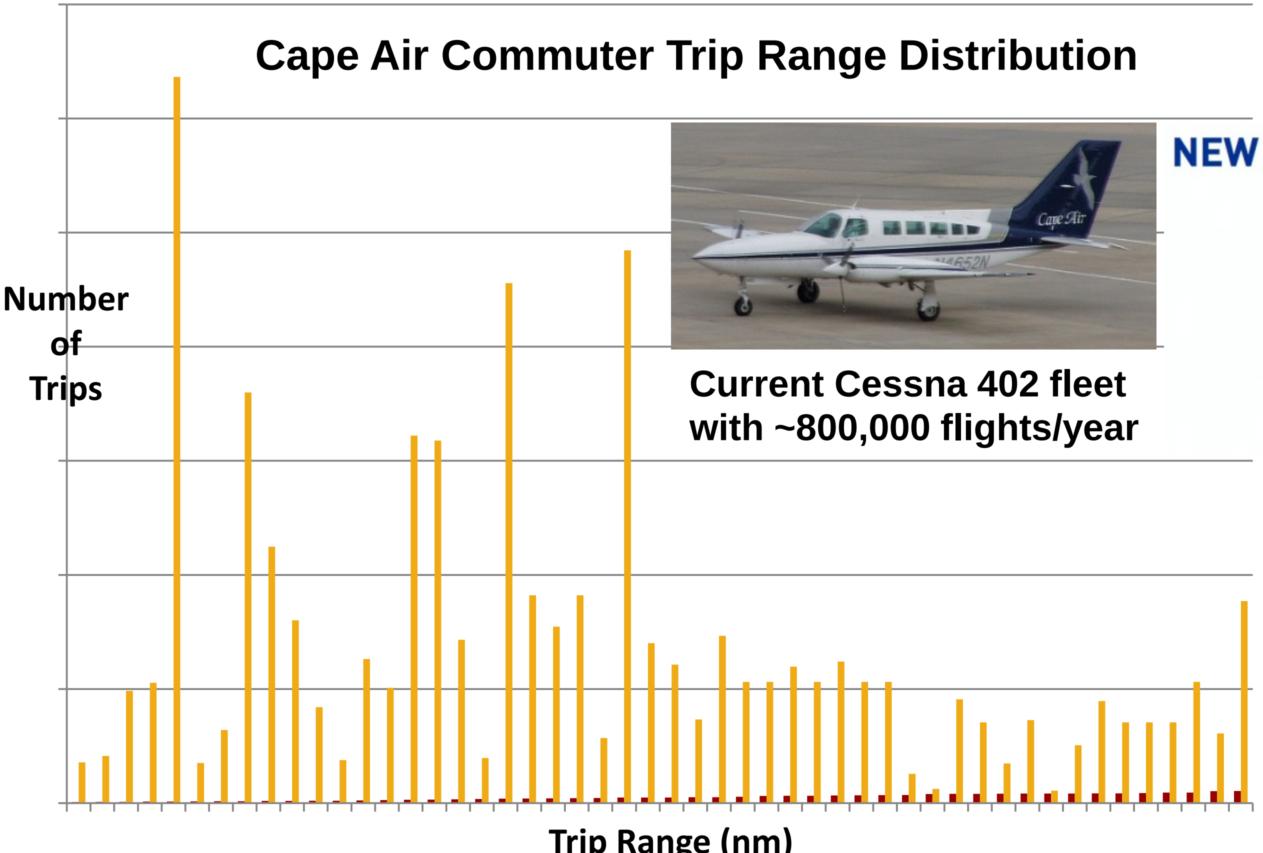
- **Electric propulsion provides a method of addressing multiple barriers with a single technology that integrates across many disciplines**
  - Propulsive and aerodynamic efficiency, emissions, community noise, control, and ride quality characteristics can be significantly improved through tight coupling of distributed electric propulsion.
- **New integration strategies require advanced design tools that maximize cross-disciplinary coupling benefits to achieve optimal system solutions**
- **Advanced electric motors and controllers**
- **Redundant and robust high voltage (>400 volts) architecture standards**
- **Advanced batteries and integration solutions**
  - Electric propulsion design guide handbook across battery chemistries, BMS, integration concerns (EMI, heating, structural casings), etc.
- **Hybrid-electric range extenders**
  - Practical ranges increasing from 200 to 400 nm in the near-term require hybrid-electric systems with small APUs to augment energy storage.

Electric Propulsion Technologies Roadmap



EP Market Evolution Strategy

EP aviation markets are already feasible to establish ultra low carbon aviation solutions with significantly lower operating costs; while providing early technology certification and lessons learned, before introducing to larger aircraft.



Current Cessna 402 fleet with ~800,000 flights/year

2025 EP Market Outcome

9 Pax payload
<10,000 lbs gross weight
200 mile electric range
Near-all weather
Propulsion redundancy
High wing loading ride quality
Ultra low community noise

<2000 ft field length capable
>200 mph cruise speed at high efficiency
400 mile range with hybrid-electric range extender
Single-pilot with Part 121-like safety
Robust low speed propulsion enhanced control
Low gust sensitivity
<$3.00/mile operating cost

Dramatic reductions in life cycle carbon emissions promoting a path towards the use of renewable energy sources (wind, solar, etc)