“The engineers had the firm belief that the hybrid was the answer to all these questions -- oil depletion, emissions, and the long-term future of the automobile society -- but the business people weren't in agreement.”
Worldwide Sales of Toyota Hybrids as of July 2015

8,000,000
Mission Analysis and Aircraft Sizing of a Hybrid-Electric Regional Aircraft

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Outline

1. Background & Introduction
2. Approach
3. Results
4. Conclusions
5. Future Work

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1. Background & Introduction

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Short Haul Revitalization Study

MOBILITY THROUGH THE AIR IS VITAL TO ECONOMIC STABILITY, GROWTH, AND SECURITY AS A NATION

National Plan for Aeronautics R&D and Related Infrastructure

U.S. leadership for a new era of flight

6 Strategic Thrusts

- Safe, Efficient Growth in Global Operations
- Transition to Low-Carbon Propulsion
- Innovation in Commercial Supersonic Aircraft
- Real-Time System-Wide Safety Assurance
- Ultra-Efficient Commercial Vehicles
- Assured Autonomy for Aviation Transformation

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Many Experimental Aircraft...  
...Even More to Come

Top-Left: Adambro, available at https://commons.wikimedia.org/wiki/File:Boeing_Fuel_Cell_Demonstrator_AB1.JPG, licensed under CC BY-SA 3.0.

Middle-Left: Bernd Sieker, available at https://commons.wikimedia.org/wiki/File:Airbus_E-Fan_%281408845198%29.jpg, licensed under CC BY-SA 2.0.

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Objective

• Would a parallel hybrid-electric aircraft introduced in the 2030 time frame be competitive with conventional aircraft for a regional, short-haul mission?

Output

• Total energy consumption
• Total projected energy cost
• TOGW, OEW, Battery Weight, etc.

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2. Approach

Background Credit: Sefjo, available at https://commons.wikimedia.org/wiki/File:Czech_Airlines_ATR_42-500_OK-KFO.jpg, licensed under CC BY-SA 3.0.
Study Decisions and Assumptions

- Year 2030 technology
- Parallel hybrid-electric propulsion
- Various levels of battery specific energy
- No deviation from propulsion airframe integration of baseline aircraft
- No change to airframe design parameters
- Fixed level of electrification for full mission
- Tools used include: OpenVSP, FLOPS, NPSS, WATE++, and ModelCenter

Background Credit: Sefjo, available at https://commons.wikimedia.org/wiki/File:Czech_Airlines_ATR_42-500_OK-KFO.jpg, licensed under CC BY-SA 3.0.
Parallel Hybrid-Electric Propulsion and Percent Electrification

Battery or Equivalent → Power Conditioning → Motor → Turbine → Engine

1. 0% Electric
2. 25% Electric
3. 50% Electric
4. 75% Electric

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Baseline Aircraft

ATR 42-500

48 pax

840 nm

Mach 0.475

5% Reserve

87 nm Alternate Airport

45 min. hold

Ty V. Marien. Seat Capacity Selection for an Advanced Short-Haul Aircraft Design 3:30 – 4:00pm Today
Advanced Aircraft (Year 2030)

1. Baseline aircraft modeled
2. Calibrated to match ATR 42-500
3. Decreased to the study mission range of 600 nm
4. Advanced technology factors introduced
5. Advanced aircraft sized for minimum gross weight to meet study mission
6. Hybrid-electric engine deck introduced
7. Optimized with hybrid-electric propulsion and additional battery weight
Multi-Disciplinary Optimization Framework

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3. Results

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Modified NASA PW127E-like Performance: Current and Advanced

| Units          | 2015   | 2030   |
|----------------|--------|--------|
| Mach           | 0      | 0      |
| Altitude       | 0      | 0      |
| Throttle       | 100    | 100    |
| Power          | 2,400  | 2,400  |
| Jet Thrust     | 287    | 287    |
| SFC            | 0.474  | 0.427  |
| Mass Flow      | 12.15  | 10.65  |
| OPR            | 14.7   | 14.7   |

Background Credit: Sefjo, available at [https://commons.wikimedia.org/wiki/File:Czech_Airlines_ATR_42-500_OK-KFO.jpg](https://commons.wikimedia.org/wiki/File:Czech_Airlines_ATR_42-500_OK-KFO.jpg), licensed under [CC BY-SA 3.0](https://creativecommons.org/licenses/by-sa/3.0/).
## Modified NASA PW127E-like Weights: Current and Advanced

| Component Weights (lb) | Current 2400 SHP | Advanced 2400 SHP | Advanced Hybrid-Electric Gas Turbine + Electric Motor |
|------------------------|------------------|-------------------|-------------------------------------------------------|
|                        |                  |                   | 1800 + 600 SHP | 1200 + 1200 SHP | 600 + 1800 SHP |
| Turbine Engine + Gearbox | 1054             | 1010              | 819          | 626          | 410          |
| Propeller System + Nacelle | 782             | 781               | 766          | 752          | 737          |
| Electrical System       | -                | -                 | 135          | 270          | 405          |
| Total System             | 1836             | 1791              | 1720         | 1648         | 1552         |

Background Credit: Sefjo, available at [https://commons.wikimedia.org/wiki/File:Czech_Airlines_ATR_42-500_OK-KFO.jpg], licensed under CC BY-SA 3.0.
### Study Cases at 600 nm

| Percent Electric | Battery Specific Energy |
|------------------|-------------------------|
| 0%               | 500 Wh/kg               |
| 25%              | 750 Wh/kg               |
| 50%              | 1000 Wh/kg              |
| 75%              |                         |

Battery Specific Energy = BSE in the following slides

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Battery, Fuel, and Total Energy versus Percent Electric

- Battery energy and fuel energy are equal at 76% electric.
- At 500 Wh/kg, total energy remains relatively constant.
- At 750 and 1000 Wh/kg, the total energy decreases significantly.

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Comparing our advanced 75% electric to 0% electric:

At 500 Wh/kg:
- 2.3X heavier TOGW

At 750 Wh/kg:
- 63% heavier TOGW

At 1000 Wh/kg:
- 39% heavier TOGW

Background Credit: Sefjo, available at https://commons.wikimedia.org/wiki/File:Czech_Airlines_ATR_42-500_OK-KFO.jpg, licensed under CC BY-SA 3.0.
• $3.33 per gallon for Jet-A
• $0.11 per kWh for elec.
Comparing advanced 75% electric to 0% elec.

At 500 Wh/kg:
• 10% more

At 750 Wh/kg:
• 14% less

At 1000 Wh/kg:
• 23% less
### Design Range Sensitivity (500 Wh/kg)

| %Electric | Units | 0% | 75% | 0% | 75% |
|-----------|-------|----|-----|----|-----|
| Range     | nm    | 300| 300 | 600| 600 |
| Total Fuel Weight | lb    | 2,310| 850 | 3,340| 1,720 |
| Total Batt. Weight | lb    | 0| 15,270 | 0| 39,590 |
| OEW       | lb    | 21,300| 24,200 | 21,800| 30,300 |
| TOGW      | lb    | 34,500| 51,100 | 35,900| 82,400 |
| Elec. Energy Cost | $    | 0| 260 | 0| 660 |
| Fuel Energy Cost | $    | 610| 220 | 1,110| 550 |
| Total Energy Cost | $    | 610| 480 | 1,100| 1,210 |

Background Credit: Sefjo, available at [https://commons.wikimedia.org/wiki/File:Czech_Airlines_ATR_42-500_OK-KFO.jpg](https://commons.wikimedia.org/wiki/File:Czech_Airlines_ATR_42-500_OK-KFO.jpg), licensed under [CC BY-SA 3.0](https://creativecommons.org/licenses/by-sa/3.0/).
Break-Even Energy Cost for the 75% Electric Advanced Turboprop

**Prediction 1:**
- $3.33 per gallon of Jet-A
- $0.11 per kWh for elec.
- 9% increase in total energy cost

**Prediction 2:**
- $3.33 per gallon of Jet-A
- $0.08 per kWh for elec.
- 14% decrease in total energy cost

Background Credit: Sefjo, available at https://commons.wikimedia.org/wiki/File:Czech_Airlines_ATR_42-500_OK-KFO.jpg, licensed under CC BY-SA 3.0.
4. Conclusions

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Conclusions

• At 600 nm, BSE must be greater than 500 Wh/kg to yield energy consumption parity
• At 300 nm, BSE can be less than 500 Wh/kg for energy consumption parity
• The economics for a parallel hybrid vehicle at 600 nm and 500 Wh/kg is less attractive than for a conventional unless the electricity to fuel cost ratio decreases
• The 75% electric advanced turboprop needs a BSE of 600 Wh/kg to operate in total energy cost parity

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5. Future Work

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Future Work

- Explore additional comparison metrics (life cycle emissions, noise, etc.) for hybrid and conventional aircraft
- Determining the BSE needed at a given design range to achieve a given objective
- Alternative propulsion-airframe integration that takes advantage of additional flexibilities provided by electric propulsion (distributed electric propulsion, series-hybrid, etc.)
- Optimize additional airframe design parameters to ensure a match between airframe and propulsion
Thanks!

Any questions?

Acknowledgements:
This work was funded by NASA’s Advanced Air Transport Technologies project.

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