# Total Cost of Ownership (TCO) Analysis of Hydrogen Fuel Cells in Aviation – Preliminary Results

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# Fuel Cells for Aviation

**Total Cost of Ownership Analysis**

1. Unmanned Air Vehicles (UAVs): Piston engines, batteries, fuel cells
2. Urban Air Mobility (UAM) for Air Taxis: Batteries, fuel cells
3. UAM Helicopters: Piston engines, fuel cells
4. Regional Airplanes: Piston engines, fuel cells

**Hydrogen and Fuel Cells for Aviation: Study Parameters for Cost and Performance**

- Fuel cell system (FCS) cost: $250/kW
- FCS lifetime: 3,000 h
- FCS specific power: 1000 W/kg
- $LH_2$ storage system gravimetric capacity: 18%
- $LH_2$ cost: $5/kg
- Battery cost: $200/kWh
- Battery specific energy: 200 Wh/kg
- Battery lifetime without loss of range: 300 cycles

> Baseline cost and performance parameters for fuel cells, $H_2$ cost, $H_2$ storage, and batteries derived or projected from HFTO data for automotive light-duty and heavy-duty vehicles

**Hydrogen and Fuel Cells for Aviation: Single Variable Sensitivity Analysis**

- Identify performance and cost attributes for hydrogen and fuel cells to be competitive with the incumbent technology
- Develop metrics for DOE targets for promising applications

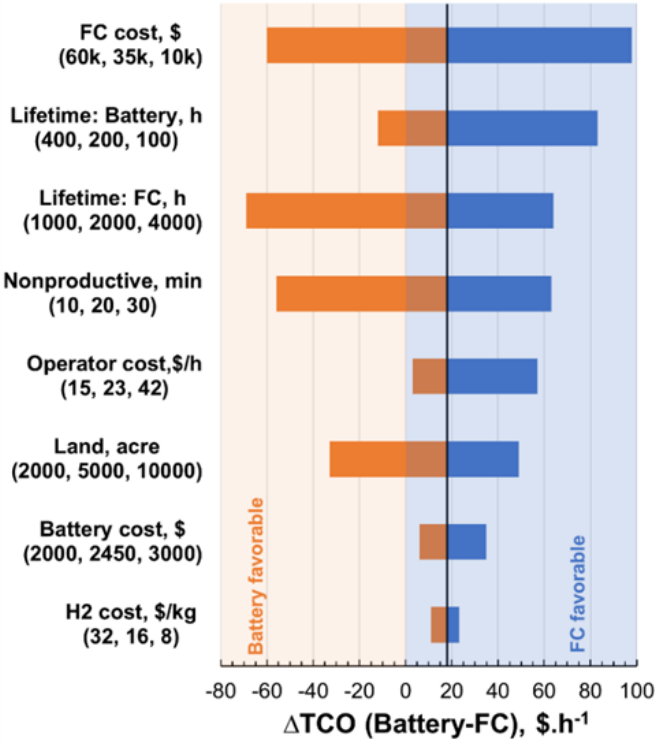
# 1a. Multi-Rotor Hexa-Copter UAV: Total Cost of Ownership

## Gas Drilling Area Aerial Inspection

- Payload: HDL-32E Lidar, $85k
- PEMFC Module: 2.2 kW, $39k*, 2000 h lifetime
- $H_2$ Tank: 3.9 kg, 6000 psi, 0.24 kg-$H_2$
- Li-Po Battery Pack: 1400 Wh, $12.6k**, 200 h lifetime

| Assumptions | Battery | Fuel Cell |
|---|---|---|
| Analysis time, year | 10 | 10 |
| Land size, acre | 5,000 | 5,000 |
| Daily mission time, h | 6 | 6 |
| Number of required swap batteries | 4 | |
| Nonproductive time, min | 20 | 20 |
| Endurance, min | 37 | 110 |
| UAV scanning speed, acre/h | 180 | 180 |
| Fleet size | 8 | 6 |
| Operator labor rate, $/h | $23 | $23 |
| Energy/Fuel cost, $/kWh, $/kg-H2 | $0.13 | $16 |

## Sensitivity Analysis




**$18/h Saving in TCO with Fuel Cells**

- Higher endurance: Fleet size smaller by 2 drones, $46/h saving in labor cost***
- 2 fewer LIDARs ($85k): $5/h saving in CAPEX fewer LIDARs
- More expensive fuel: $7/h higher cost of $H_2$
- More expensive FCS ($39k): $25/h higher replacement cost.
- TCO most sensitive to FCS cost, battery/FC lifetime, and nonproductive time

Includes $H_2$ tank and pressure booster* Includes swap batteries and charger** FAA requires 1 pilot per drone***

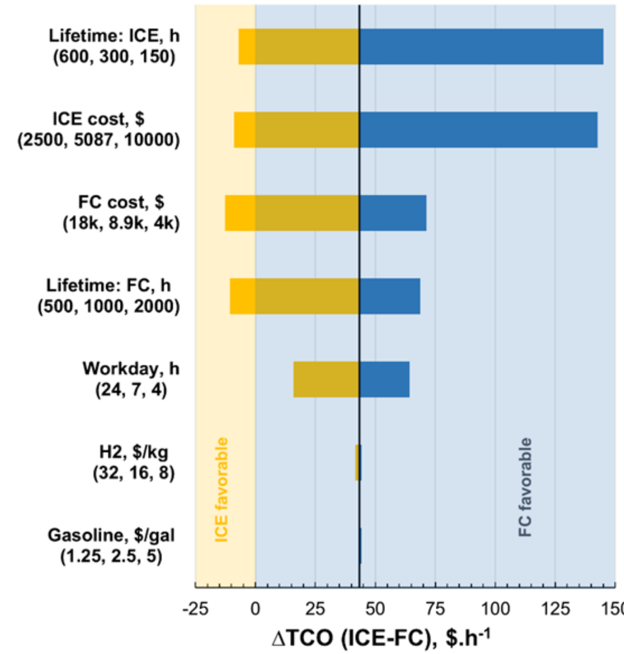
# 1b. Fixed-Wing UAV: Total Cost of Ownership

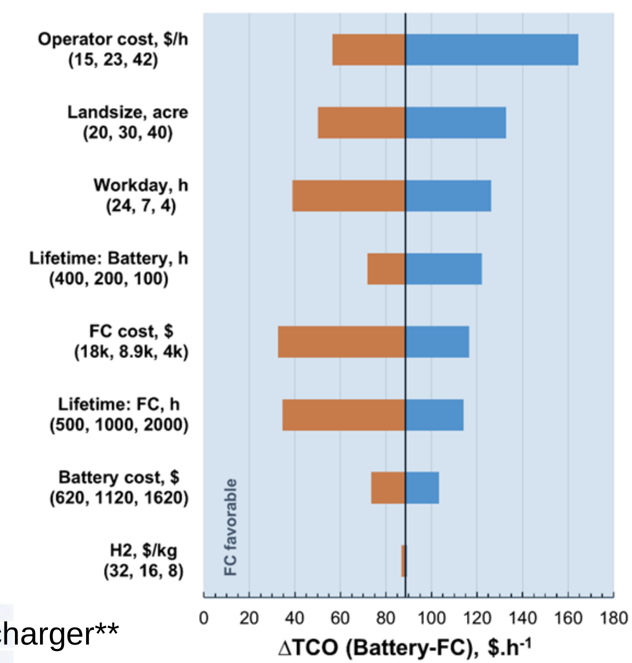
### Gas Drilling Area Aerial Inspection

- Payload: RIEGL Lidar, $100k
- PEMFC Module: 650 W, $13k*, 1000 h lifetime
- $H_2$ Tank: 2.9 kg, 6000 psi, 0.18 kg-$H_2$
- Li-Po Battery Pack: 640 Wh, $2.6k**, 200 h lifetime
- ICE: 2500 W, $5k, 300 h lifetime

| Assumptions | ICE | Battery | Fuel Cell |
| --- | --- | --- | --- |
| Analysis time, year | | 10 | |
| Land size, acre | | 30,000 | |
| Daily mission time, h | | 7 | |
| Number of required swap batteries | | 1 | |
| Endurance, min | 576 | 88 | 450 |
| Nonproductive time, min | 30 | 30 | 30 |
| Area scanning speed, acre/h | 800 | 800 | 800 |
| Fleet size | 6 | 8 | 6 |
| Operator labor rate, $/h | $23 | $23 | $23 |
| Fuel/energy cost, $/gal,$/kWh, $/kg-H2 | $2.5 | $0.13 | $16 |

- Fuel cell vs. ICE: $43/h saving in TCO because of cheaper FCS replacement cost, longer lifetime
- Fuel cell vs. battery: $88/h saving in TCO mainly because of fleet size smaller by 2 drones, 4 fewer operators and spotters




Includes $H_2$ tank and pressure booster*

Includes swap batteries and charger**

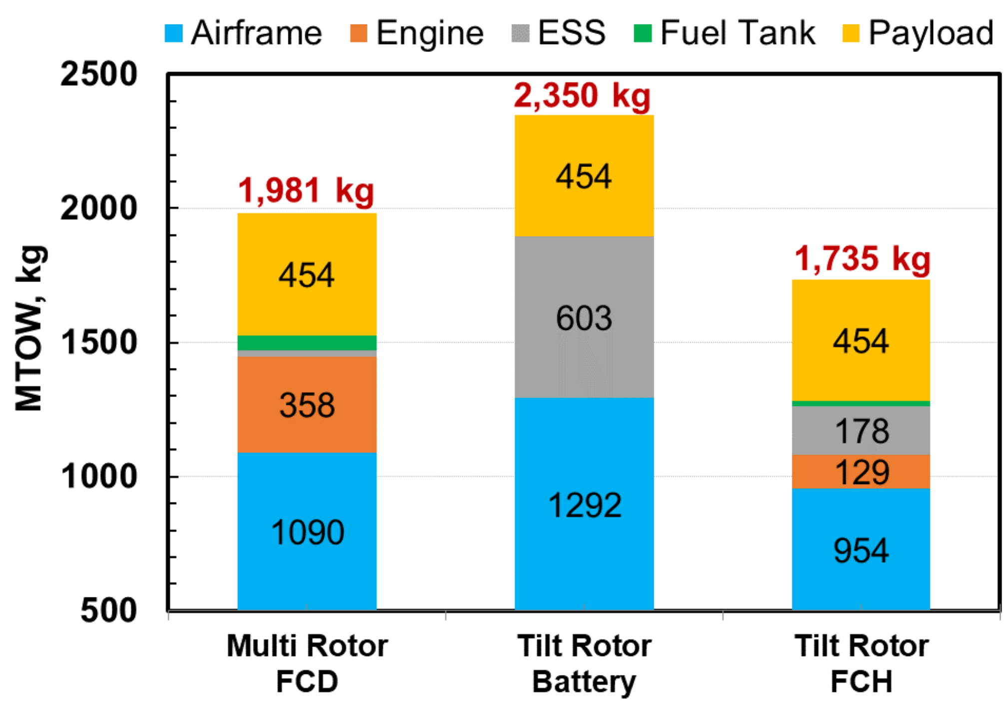
# 2. Urban Air Mobility (eVTOLs) – Air Taxis*

**Objectives**: Identify fuel cell air-taxi platforms that can match the payload (454 kg), range (96 km) and maximum cruise speed (240 km/h) of battery-powered urban air taxis

- Compare performance (MTOW, FCS/ESS size, $LH_2$), initial cost and total cost of ownership (TCO)

**Conclusions**

- Multi-Rotor FCD eVTOL: 358-$kW_e$ FC, 5-kWh battery not required for speeds > 150 mph.
- Fixed-Wing Battery eVTOL: 121-kWh battery, 603 kg battery weight
- Fixed-Wing FCH eVTOL: 129-kW FCS + 36-kWh battery. FCH charges the battery during cruise.
- MTOW: FCH-powered tilt rotor < FCH-powered multi rotor < battery-powered tilt rotor




| | Multi Rotor FCD | Tilt Rotor Battery | Tilt Rotor FCH |
|---|---|---|---|
| Engine Power | 358 kW | | 129 kW |
| Fuel Capacity | 9.9 kg-$H_2$ | | 3.6 kg-$H_2$ |
| ESS Capacity | 4.9 kWh | 120.7 kWh | 35.5 kWh |

Uber Elevate. Fast-Forwarding to a Future of On-Demand Urban Air Transportation. Oct. 27, 2016, www.uber.com/us/en/elevate.
UberAir Vehicle Requirements and Missions. https://s3.amazonaws.com/uber-static/elevate/Summary+Mission+and+Requirements.pdf.

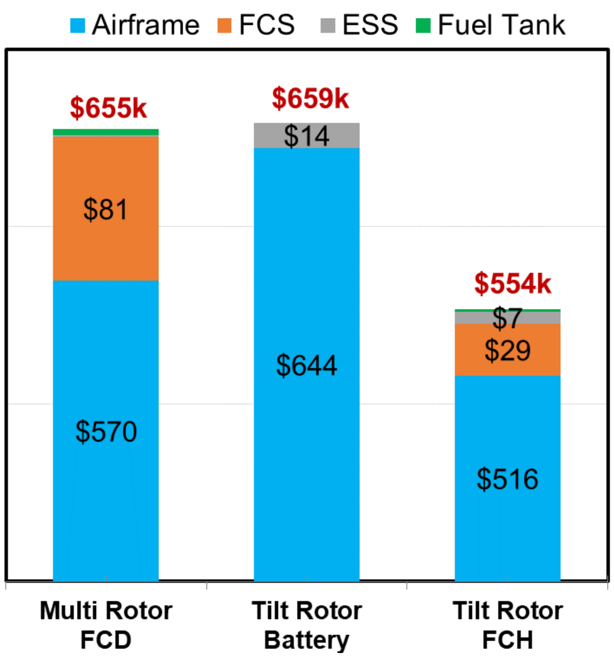
# Total Cost of Ownership of Air Taxis

- **Fuel cells can offer performance and cost advantages over batteries for UAM air taxis, but additional study is needed for evaluating $LH_2$ vs. battery recharging infrastructure**

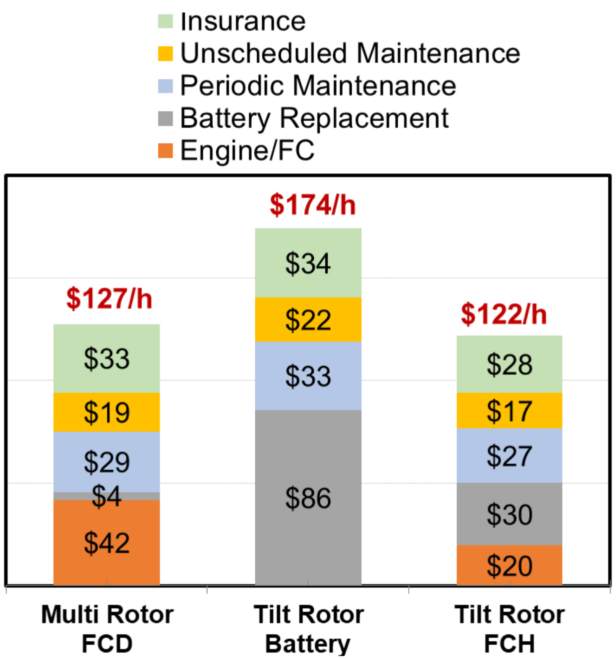
### CAPEX
- Tilt-rotor FCH eVTOL is ~$100k cheaper option
- Cost of $LH_2$ storage system relatively small

### OPEX
FC eVTOLs have ~$50/h lower OPEX than battery eVTOL due to lower replacement costs
- Multi-rotor FCD eVOL: $42/h FCS + $4/h battery
- Tilt-motor battery eVTOL: $86/h
- FCH tilt-motor eVTOL: $20/h FCS + $30/h battery

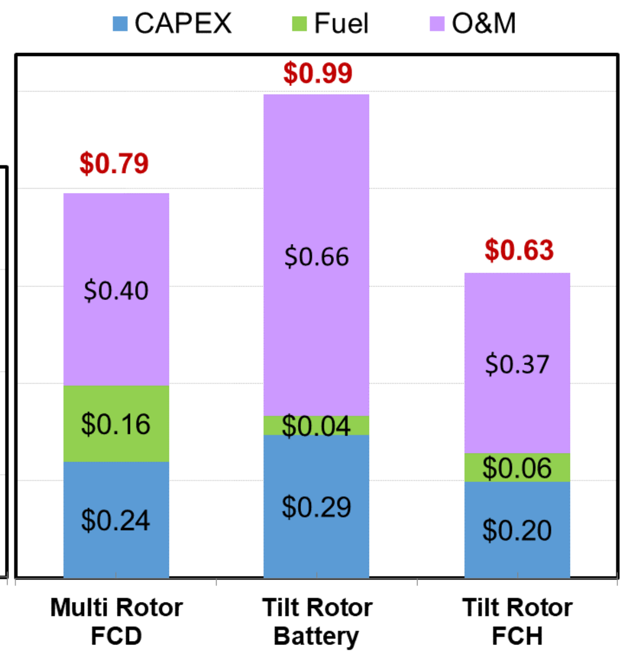
### TCO
- FCH eVTOL << Battery eVTOL
- FCH tilt-rotor eVTOL < FCD multi-rotor eVTOL, but tilt rotors may require additional maintenance cost




**CAPEX, k$**




**OPEX, $/h**




**TCO, $/PAX.mile**

Other annual fixed costs include crew wages, hangar fees, navigation/weather service

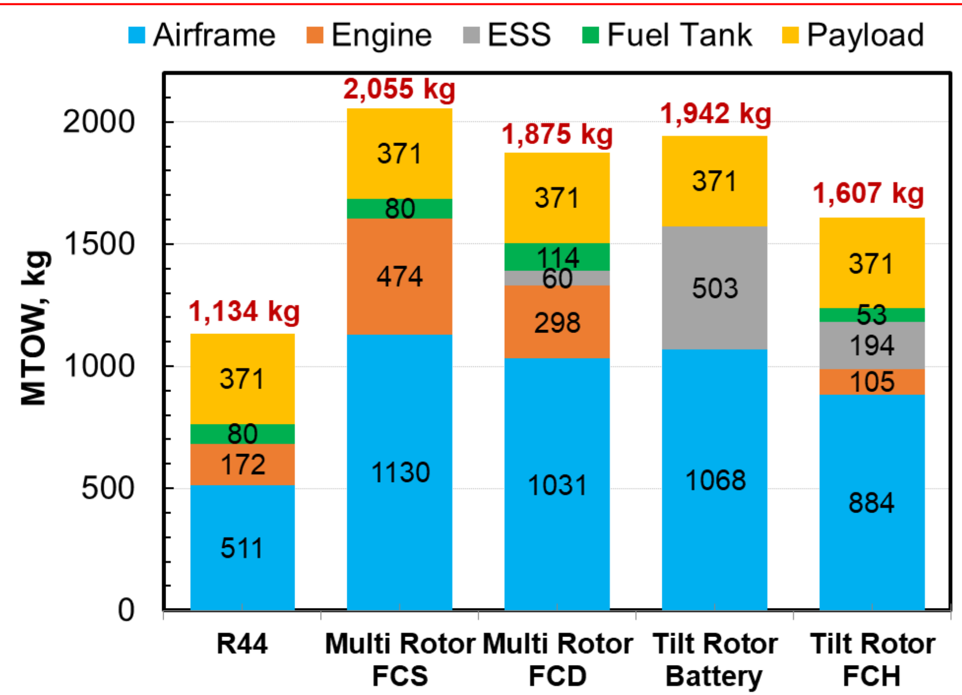
# 3. Hydrogen Fuel Cell Powered Helicopters : Multi-Rotor and Tilt-Rotor Crafts

**Objectives**: Identify battery and fuel cell air-taxi platforms that can match the published payload and maximum cruise speed of a commercial helicopter (Robinson R44 Raven II)

- Compare performance (range, MTOW), initial cost and TCO of promising air taxis

**Conclusions**

- Only FCH tilt-rotor eVTOL can match the range of R44 at 1.4 MTOW
- Batteries are not suitable for the targeted 350-km range
- Hybridizing FCS reduces MTOW and extends the range
- Fuel Cell Size: 426 kW for FC multi rotor, 268 kW for FCD multi rotor, 95 kW for FCH tilt rotor




| | R44 | Multi Rotor FCS | Multi Rotor FCD | Tilt Rotor Battery | Tilt Rotor FCH |
|---|---|---|---|---|---|
| Engine Power | 184 kW | 426 kW | 268 kW | | 95 kW |
| Fuel Capacity | 126 kg | 14 kg-$H_2$ | 21 kg-$H_2$ | | 9 kg-$H_2$ |
| ESS Capacity | | | 12 kWh | 101 kWh | 39 kWh |
| Range | 350 km | 200 km | 250 km | 120 km | 350 km |

# Fuel Cells for Helicopters: Total Cost of Ownership

### CAPEX

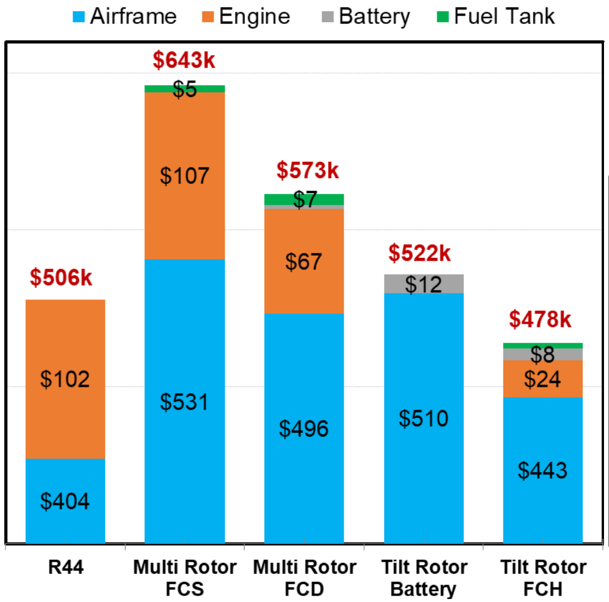
- FCD Multi Rotor: $67k higher because of 1.7X MTOW, but the range is < 350 km
- FCH Tilt Rotor: $28k lower because of less expensive propulsion system, but the range is << 350 km

### OPEX

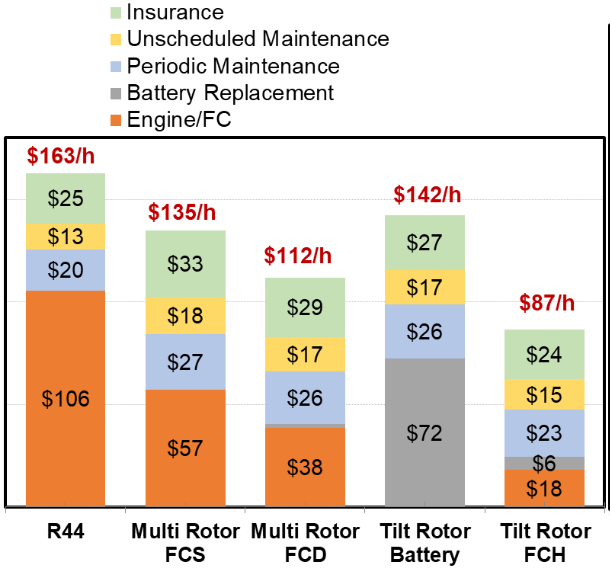
- FCS Replacements: 3
- Battery Replacement: 47 for battery tilt rotor, 5 for multi-rotor FCH, 7 for tilt rotor FCH
- FCS OPEX: $36/h FCH multi rotor
- Battery Replacement Cost: $142/h for battery tilt rotor

### TCO

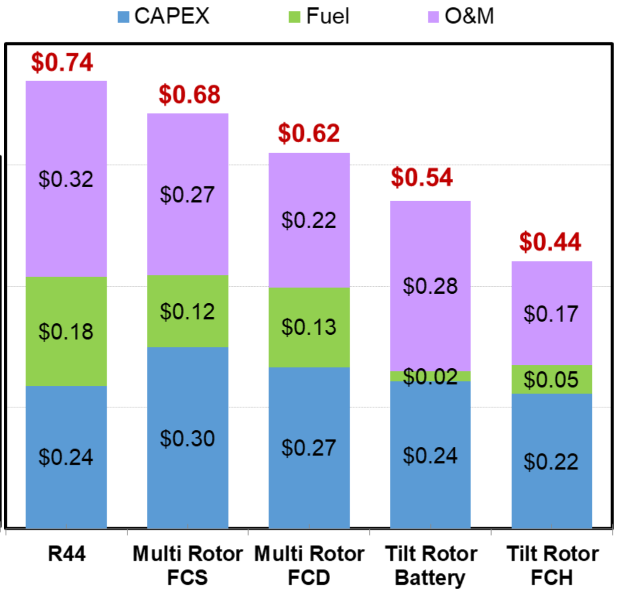
- Hybrid fuel cells and tilt-rotor eVTOL can compete with the incumbent technology
- Fuel cells offer superior range and lower TCO than the batteries




CAPEX, k$




OPEX, $/h

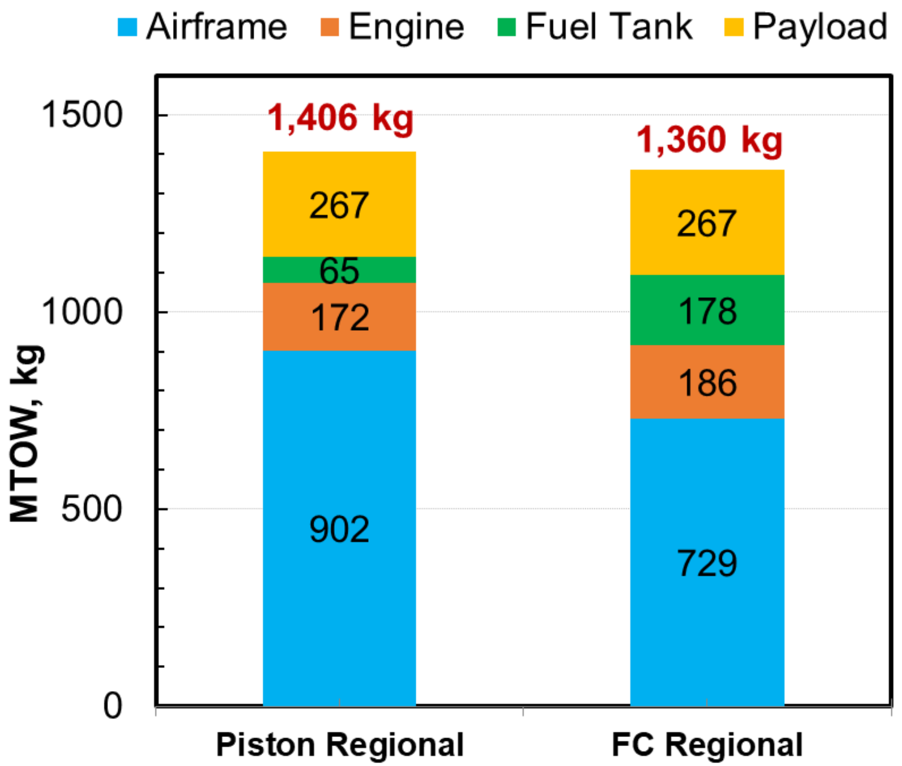



TCO, $/PAX.mile

Other annual fixed costs include crew wages, hangar fees, navigation/weather service

# 4. Hydrogen Fuel Cells for Regional Planes: Feasibility and Performance

- Objective: Verify that a $LH_2$-fueled PEMFCS can replace a turbo-charged, 6-cylinder, aviation gas fueled piston engine in a 4-seat regional plane without sacrificing payload (267 kg), cruise speed (269 km/h) at 18,000 ft elevation, or range (1,695 km)
- Conclusion: Determined FCS rated power (186 kW) and $LH_2$ tank capacity (32 kg) to satisfy the mission requirements, 0.123 kW/kg power-to-weight ratio, allowing for 10% power degradation at ground over lifetime and boil-off losses
- Main FCS Parameters: 50% higher efficiency, 850 W/L power density, 1000 W/kg specific power
- Main Storage Parameters: 18% gravimetric capacity (kg-$H_2$/kg-system)




| | Piston Regional | FC Regional |
|---|---|---|
| Engine Power | 173 kW (230 hp) | 186 kW |
| Fuel Capacity | 235 kg (329 L) | 32 kg (450 L) |

# Fuel Cells for Regional Planes: Total Cost of Ownership

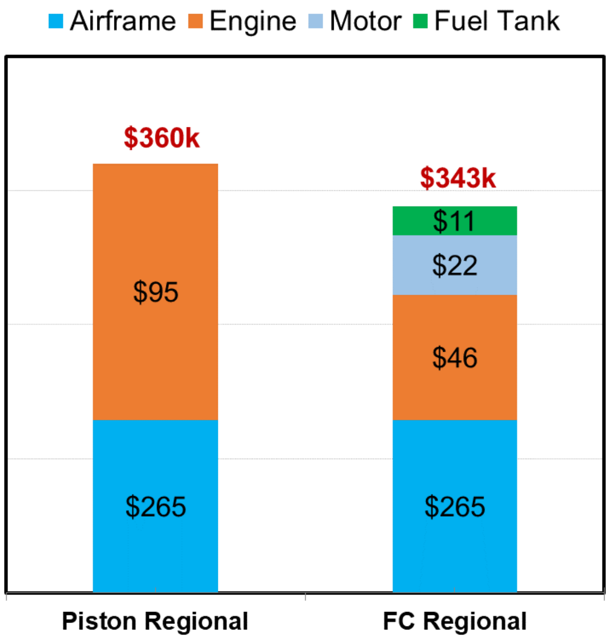
**Hydrogen fuel cells can compete with piston engines in regional planes on performance and cost basis.**

**Allowable Costs for Competitive TCO: Multi-Variable Analysis**

- Delivered Fuel: 1.5X
- FCS: 1.25X
- Storage System: 1.5X
- FCS Replacement: 1.25X
- FCS Lifetime: 3,000 h

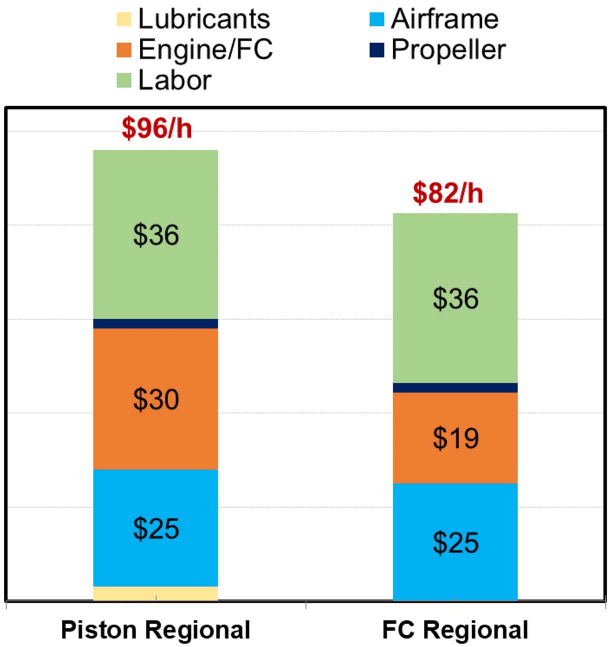
**CAPEX (k$)**

- $17k smaller for FC regional



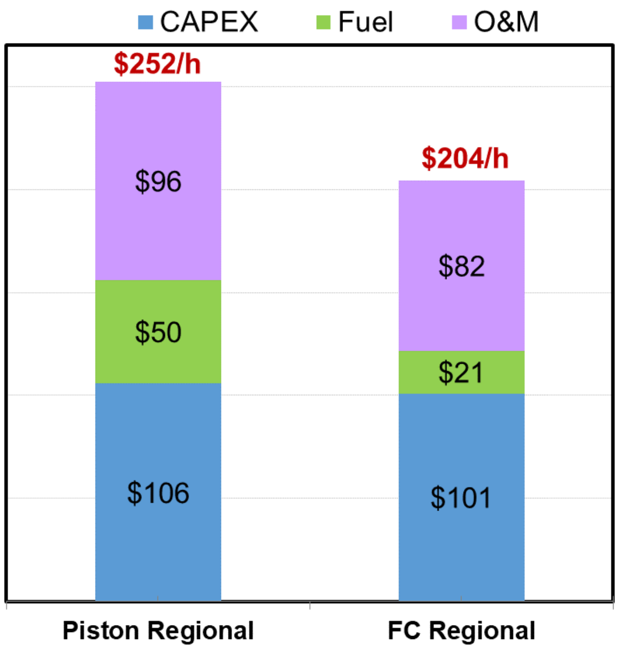

**OPEX ($/h)**

- $14/h lower for FC regional because FCS lifetime (3,000 h) > engine TBO (2,000 h)




**TCO ($/h)**

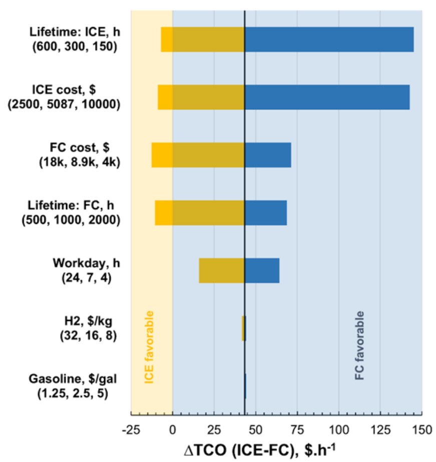
- CAPEX > O&M >> Fuel



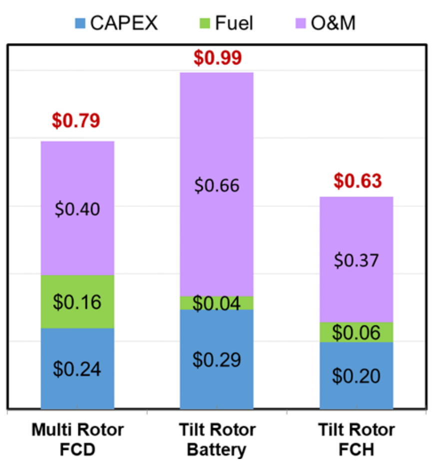

Other annual fixed costs include crew wages, hangar fees, insurance, navigation/weather service

# Fuel Cells for Aviation: Summary and Conclusions

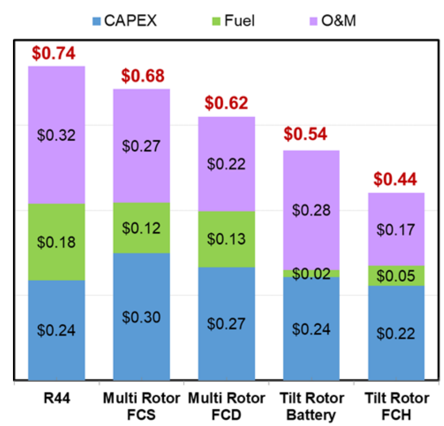
1. Hydrogen fuel cells (HFC) are promising candidates for deployment in commercial UAVs
   - Superior to ICEs because of longer lifetime (1,000 h vs. 300 h), lower maintenance cost
   - Superior to batteries because of longer endurance, smaller fleet
2. HFC are suitable for consideration in UAM - air taxis
   - Main advantages of HFC over batteries: Higher specific power, and longer durability as the duty cycle has rapid charge and discharge rates
   - Because of short range (25-60 miles), fuel cells can be used in multi-rotor and tilt-rotor eVOLs
3. HFC can replace aviation gasoline and piston engines in UAM - helicopters
   - Because of long range (350 km), hybrid FCS powered tilt rotor eVOL is the best candidate
4. HFC can compete with aviation gasoline and piston engines in regional planes
   - Fuel cells not competitive with turbine engines on the basis of specific power (W/kg), but hydrogen may replace aviation gasoline



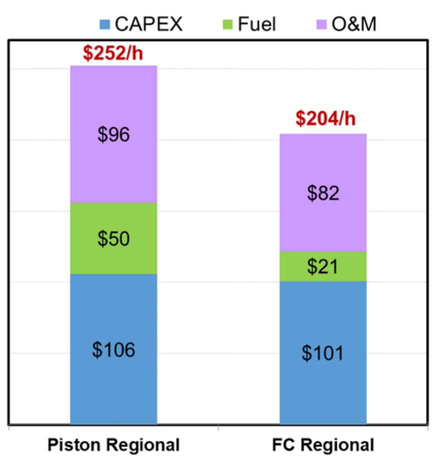

UAV, $/h




UAM – Air Taxi, $/PAX.mile




UAM – Helicopter, $/PAX.mile




Regional Plane, $/mile