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# Physics-Based Prediction of Remaining Useful Life of Lithium-Ion Batteries in Fuel Cell-Battery Hybrid Aircraft Using an Open-Source Modelica Framework

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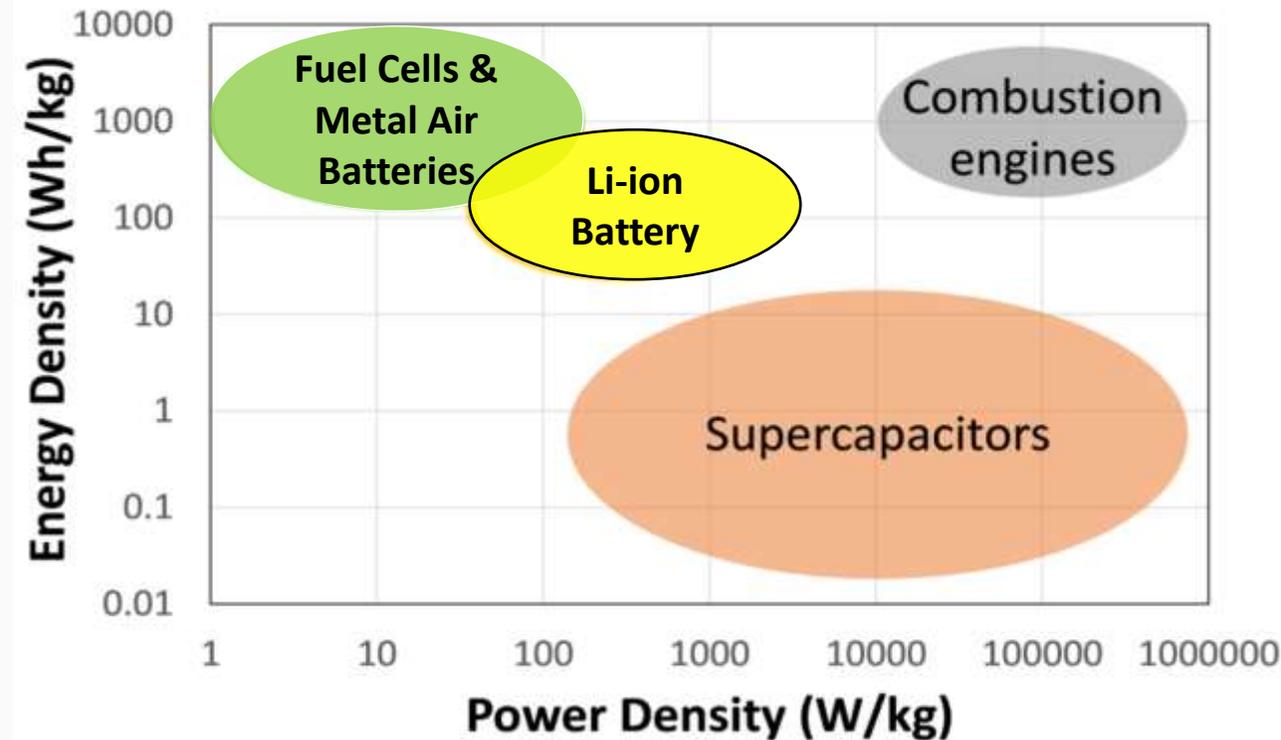
# Introduction



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- Electric aviation offers clear advantages over traditional planes for short distance flights
  - Reduced noise pollution, minimal maintenance, etc.
- Battery lifespan a key factor: fast charge cycles and high power application in-flight degrade stacks quickly
- Fuel/cell hybrid architectures frequently proposed alternative in land-based vehicles
  - Combines high specific energy of fuel cells with superior specific power of battery
  - In principle, easily portable to aircraft

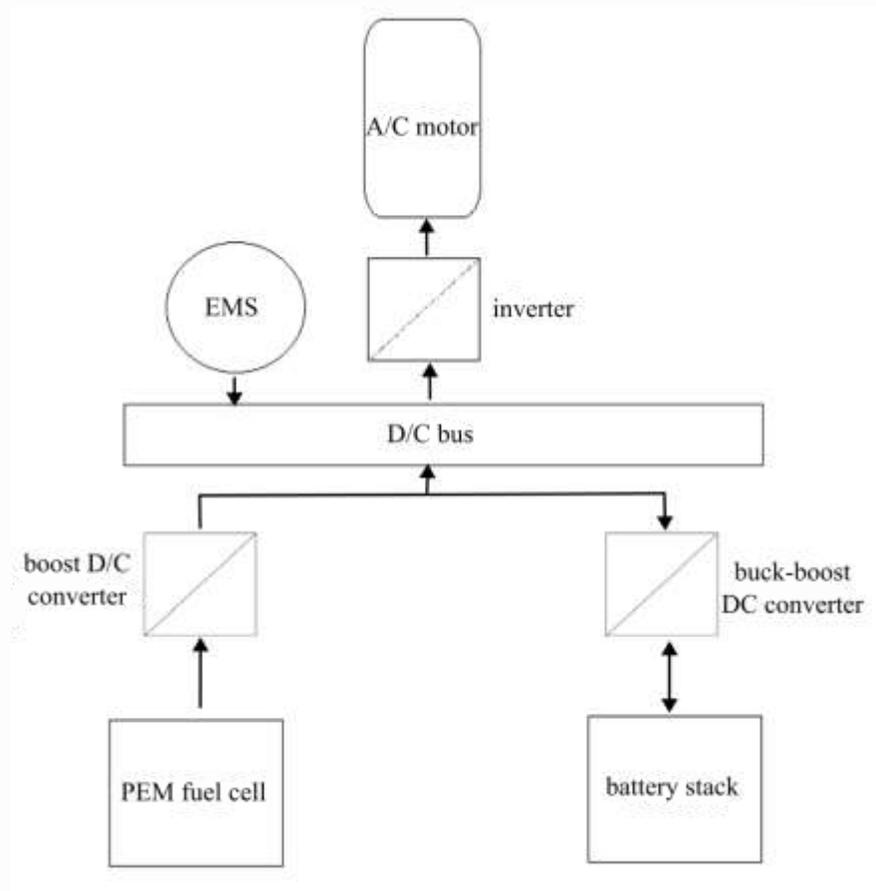


# Introduction



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- Key components are fuel cell, battery stack, power electronics, and energy management system (EMS)
- Fuel cell is primary power supplying, outputting constant load
- Battery supplements output during short-term transients and high-power applications
- Some architectures also include supercapacitor banks
- End Goal: Devise a system that effectively balances load between the two power supplies and weighs **less than or equal to** the motor and fuel in a traditional aircraft

# Objectives



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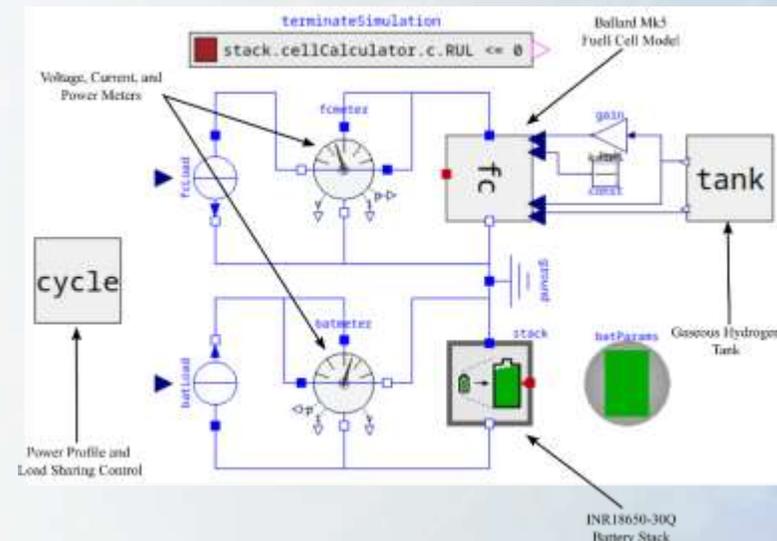
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Image credit: <https://www.github.com/OpenModelica>

- However, the battery stack remains the maintenance bottleneck (est. 500 flight hour lifespan, vs 4000+ for fuel cell); hence **EMS should be optimized to extend battery life**
- Current studies are dominated by simulation space; relatively few examples demonstrating control on physical hardware
  - Of these, the majority depend on proprietary resources such as MATLAB/SIMULINK

- Present work begins the development of an open-source library written for the Modelica language, building upon the standard multi-physics libraries of OpenModelica.
- Key components: fuel cell model, battery stack, simple H<sub>2</sub> tank, “cycle” block for power profile and load sharing



# The Cessna 206



## Key specifications:

- Max Takeoff Weight: 1719 kg
- Usable Fuel Weight: 237 kg
- Basic Empty Weight: 1073 kg
- Maximum Payload: 560 kg
- Max Cruise Speed: 298 km/hr
- Max Range: 1302 km
- Power Plant: 310 hp (230 kW) Lycoming TIO-540-AJ1A



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- 6-seater aircraft primarily used for short-hop passenger flight
- Can be adapted for courier service in rural areas



Image credits: <https://cessna.txtav.com/en/piston/cessna-turbo-stationair-hd>

# Thermal Management & Balance of Plant

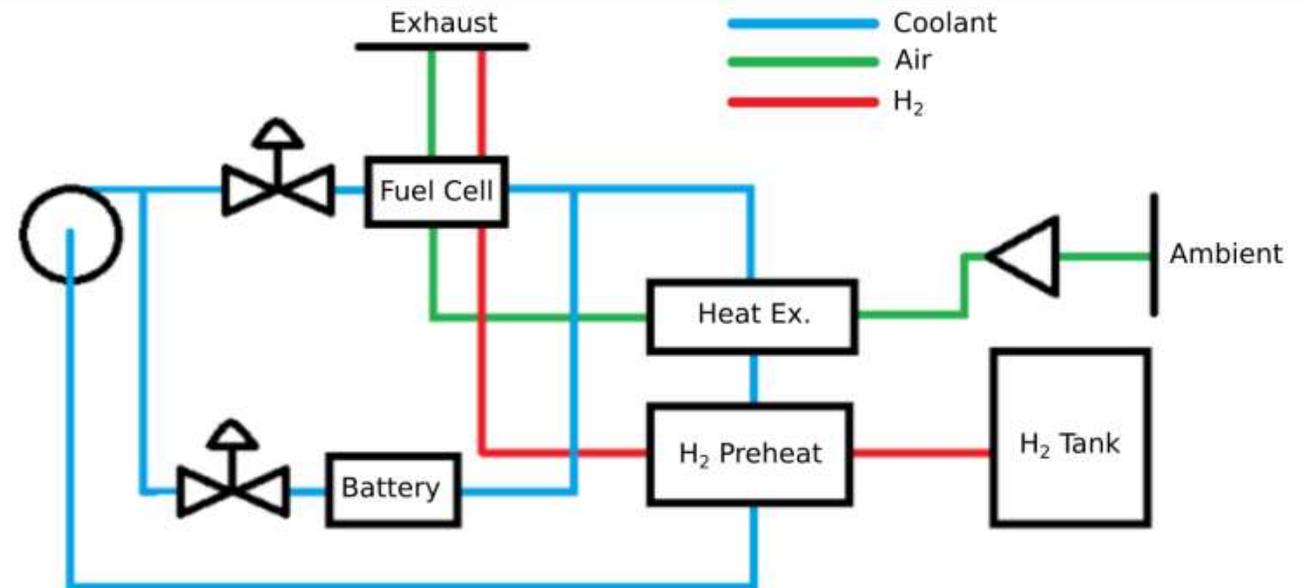


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- Thermal Management and Balance of Plant: Cooling system required to ensure FC and battery stacks maintain safe operational temperatures
- Typically provided by cooling plates and water (or some aqueous solution)
- Heat ultimately rejected from system by via a heat exchanger and ambient air stream

- Coolant pumps and air compressors important to maintain flow rates and BOP
- Creates some parasitic power draw





# Flight Profile & Load Sharing

- Flight profile developed from publicly available data for a Cessna 206 6-seater
- Power demands computed from fuel consumption rates
- Can further be used to roughly estimate the size of the required fuel cell and battery stacks (300 Mk5 cells and 4 168S12P 30Q stacks, respectively)
- Five phases: taxi (before and after flight), takeoff, cruise, descent, and refuel/recharge

- In general, fully customizable; provide maximum, cruise, and taxi power, time at each power, time taken to ramp, etc.
- Noise generator added to cruise to simulate noise observed in the raw data

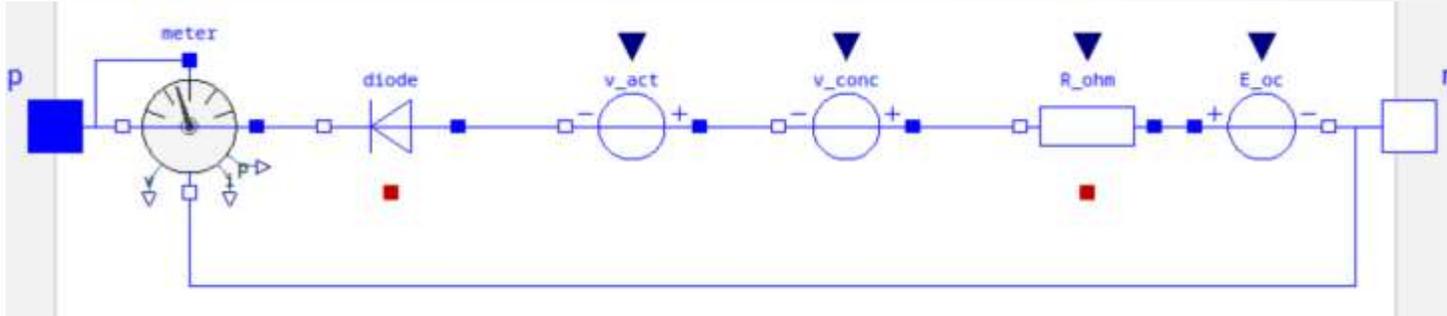
route	$P_{\text{taxi}}$ (kW)	$t_{\text{taxi}}$ (min)	$P_{\text{max}}$ (kW)	$t_{\text{max}}$ (min)	$P_{\text{cruise}}$ (kW)	$t_{\text{cruise}}$ (min)
Charlotte/Myrtle Beach	30	12	190	12	160	47
Columbia/Richmond 1	55	14	230	2	170	104
Columbia/Richmond 2	40	7.3	200	20	125	120
Columbia/Richmond 3	30	6	225	2	165	110
Greenville/Augusta	50	10	215	3	150	45
average	41	9.86	212	7.8	154	85.2

# Fuel Cell Model



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Characterization data for a Ballard Mk5 fuel cell (active area 232 cm<sup>2</sup>) taken from Laurencelle, 2001

Total Voltage:  $E = N N_m (E_{OC} + V_{act} + V_{conc} + V_{ohm})$

Open Circuit Voltage:  $E_{OC} = \frac{1}{nF} \left( \Delta G_{reac}^{\circ} + RT \ln \left( \frac{P_{H_2} P_{O_2}^{0.5}}{P_{H_2O}} \right) \right)$

Activation Losses:  $V_{act} = a \ln i$

Concentration Losses:  $V_{conc} = m e^{bi}$

Ohmic Losses:  $V_{ohm} = ri$

Parameter	Expression
$a$ (V)	$4.01 \times 10^{-2} - 1.40 \times 10^{-4} T$
$m$ (V)	$3.30 \times 10^{-3} - 8.2 \times 10^{-5} T$
$b$ (cm <sup>2</sup> -mA <sup>-1</sup> )	$8.00 \times 10^{-3}$
$r$ (kΩ-cm <sup>2</sup> )	$4.77 \times 10^{-4} - 3.32 \times 10^{-6} T$

# H<sub>2</sub> Supply System



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Gas partial pressures given by:

$$P_{H_2} = (1 - U_{H_2})x_{H_2}P_{fuel}$$

$$P_{O_2} = (1 - U_{O_2})x_{O_2}P_{air}$$

$$P_{H_2O} = (x_{H_2O} + 2x_{H_2O}U_{O_2})P_{air}$$

Utilization rates given by:

$$U_{O_2} = \frac{IRT}{2nFP_{air}Q_{air}x_{O_2}}$$

$$U_{H_2} = \frac{IRT}{2nFP_{fuel}Q_{fuel}x_{H_2}}$$

**Gaseous** hydrogen tank maintained at 160 bar

Outflow maintained by regulator to constant 3 bar:

$$Q_{fuel} = \frac{0.0004734C_vP_{tank}}{\rho_{tank}} \sqrt{\frac{(P_{tank} - P_{fuel})M}{T_{tank}P_{tank}Z}}$$

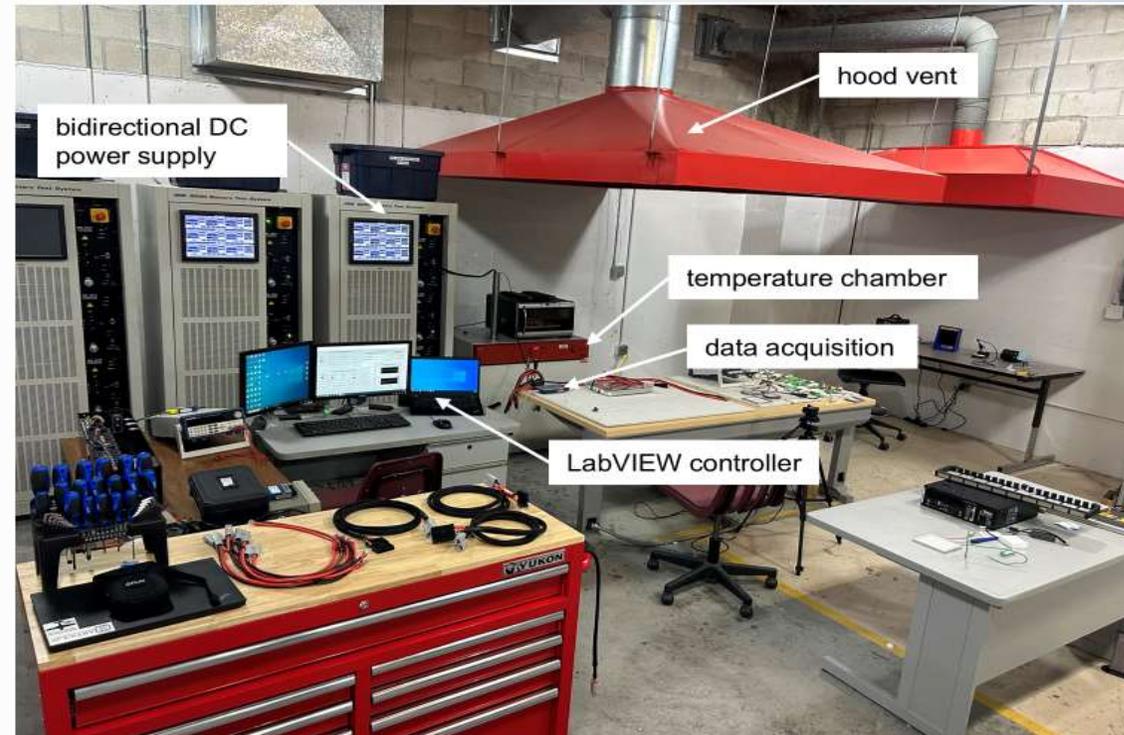
# Battery Stack Characterization



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- Batteries characterized based on discharge test data provided by the University of South Carolina Adaptive Real-Time Systems (ARTS) Laboratory
- Tested via NHR 9200 Battery Test system controlled by LabView
- Cells kept in temperature chamber; maintained constant 20C ambient



# Battery Stack Characterization

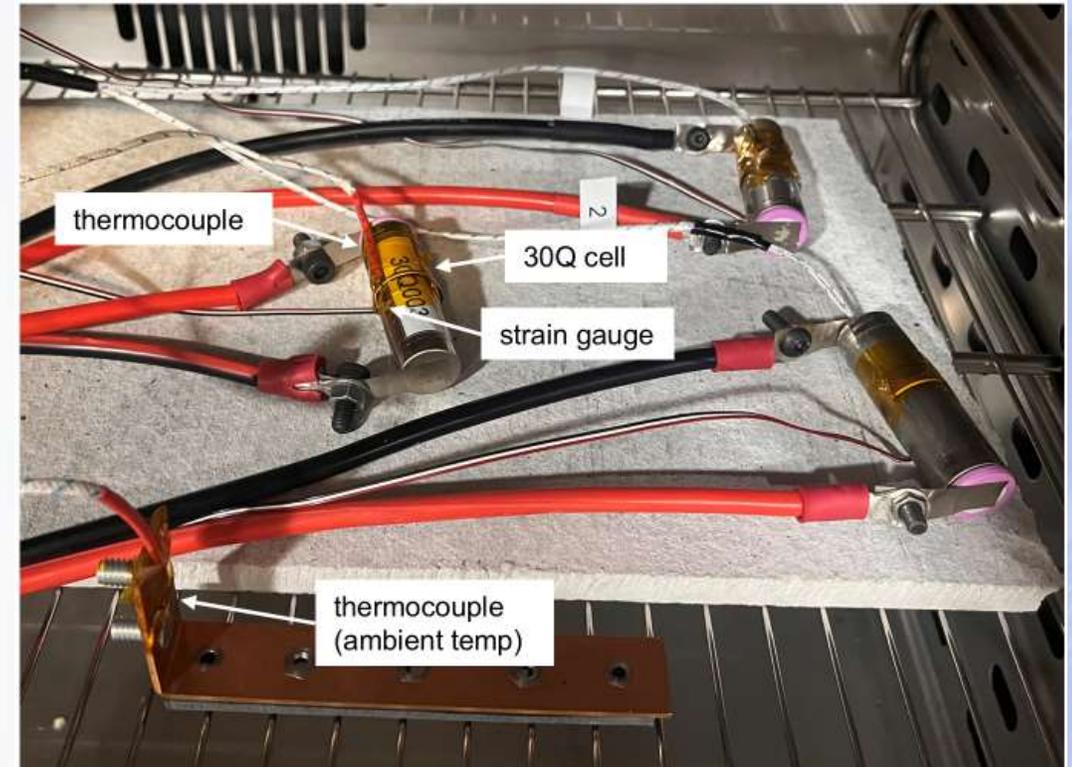


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- Samsung INR 18650-30Q utilized
  - LiCoO<sub>2</sub> cell with nominal 3.15 A-hr capacity
- Tested in temperature control chamber maintained at 20°C

Specification	Samsung 33G	Samsung 30Q
Diameter, mm	18.40	18.33
Length, mm	65.2	64.85
Weight, g	48.0	48.0
Cell Capacity, A-hr	3.15	3.0
Nominal Voltage, V	3.600	3.600
Standard Charge Method	CCCV	CCCV
Standard Charge Current, A	0.975	1.5
Standard Charge Voltage, V	4.2	4.2
Standard Charge Cutoff, mA	60	150
Maximum Charge Current, A	3.250	4.000
Standard Discharge Cutoff Voltage, V	2.5	2.5
Maximum Continuous Discharge Current, A	6.5	15.0
Operating Temperature, °C	-20 to 60	-20 to 75



# Battery Stack Characterization



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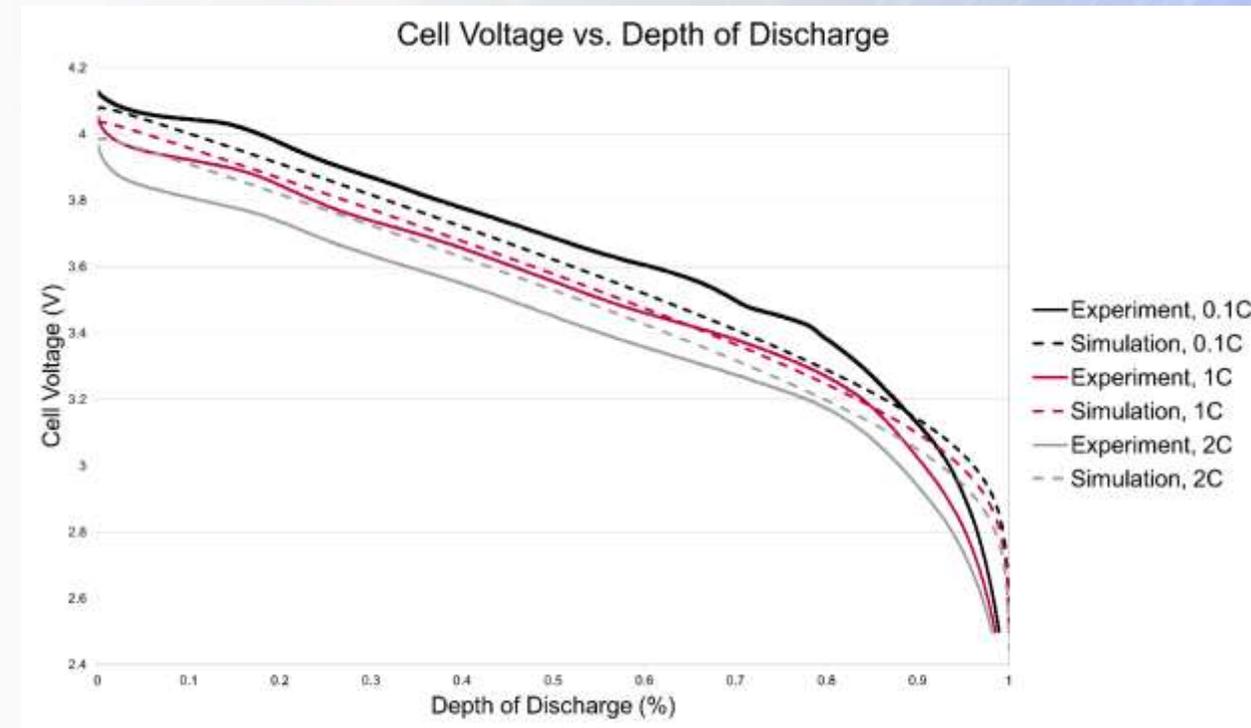
- Each cell discharged in increments of 10% SOC using 6 A pulses
- Resulting data curve-fitted to find the coefficients of the empirical relation:

$$OCV = K_0 + K_1 SOC + K_2 \ln SOC + K_3 \ln(1 - SOC)$$

- Internal resistance calculated from Ohm's Law:  $\sim 0.162 \Omega$
- Degradation model taken from Saxena, 2016:

$$C = \frac{AC_0}{100} \left( \frac{EFC}{100} \right)^b$$

$$A = 3.25 SOC_m (100 + 3.25 DOD - 2.25 DOD^2)$$

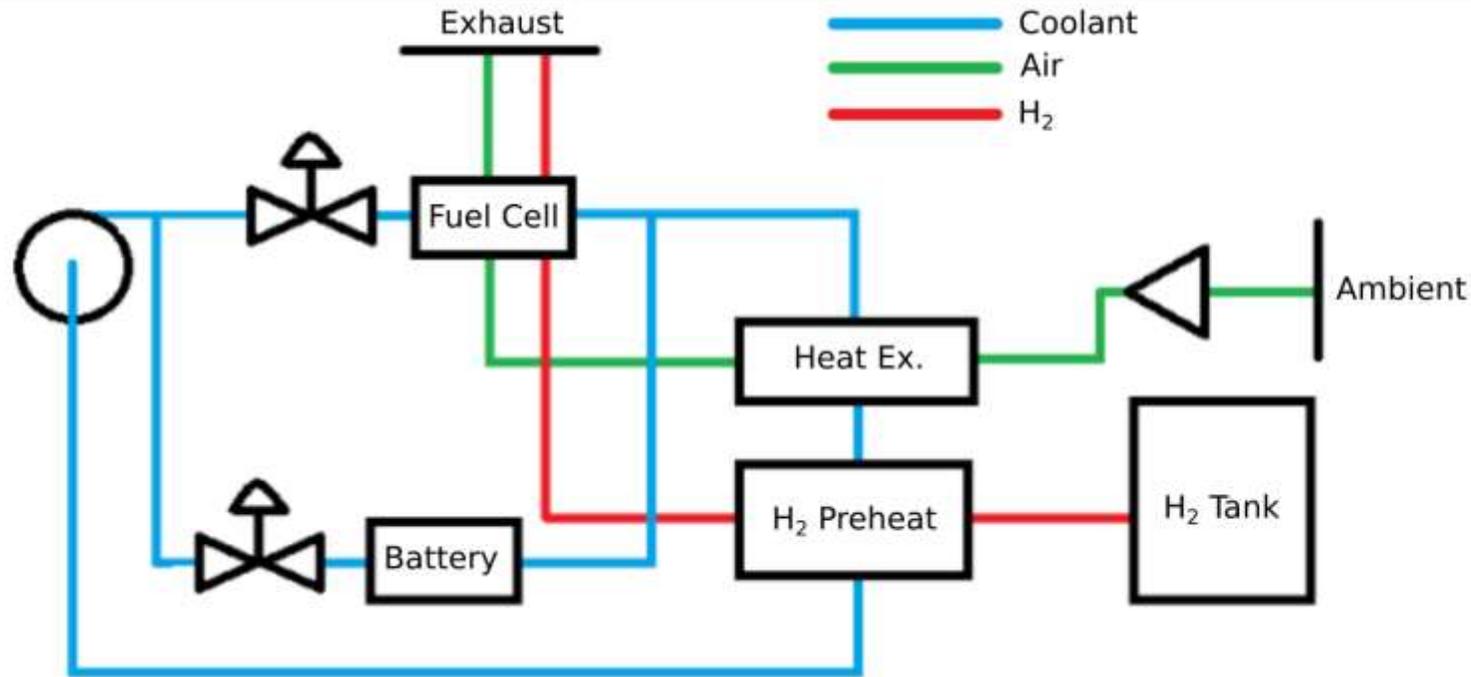


# Additional Considerations



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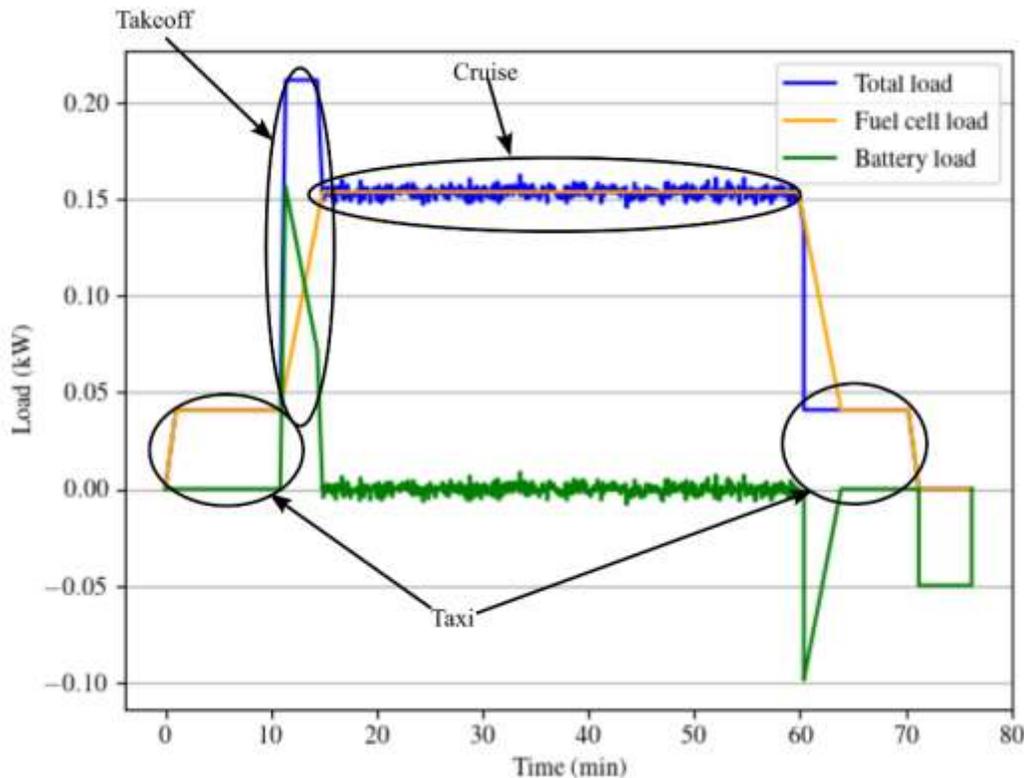
- Weight and volume must be optimized
- Includes coolant and loop components, not just power train
- Must consider impact of air intake on airframe drag
- Also requires detailed models for power converters (DC/DC boosters, inverters, etc.)

# Flight Profile & Load Sharing



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- In general, fuel cell provides the base load; battery discharges (or charges) to make up any difference between FC and demand

**Algorithm 1** SIMPLIFIED LOAD SHARING SCHEME FOR THE CONSIDERED HYBRID AIRCRAFT CONSIDERED.

```

1: for each time step do
2:   if Takeoff then
3:     FuelCellPower ← slowly ramp to CruisePower
4:     BatteryPower ← TotalDemand - FuelCellPower
5:   else if Cruise then
6:     Noise ~ random normal fluctuation
7:     EffectiveDemand ← CruisePower + Noise
8:     if EffectiveDemand > CruisePower then
9:       Battery discharges to meet extra demand
10:    else
11:      Fuel cell charges battery with excess power
12:    end if
13:   else if Landing then
14:     FuelCellPower ← slowly ramp down
15:     BatteryPower ← FuelCellPower - TotalDemand
16:   else
17:     FuelCellPower ← TotalDemand
18:     BatteryPower ← 0
19:   end if
20: end for
    
```

- During takeoff and landing, FC ramps more slowly than total load
  - Battery becomes essential to takeoff
  - Actually charges battery slightly during landing
- Battery and H<sub>2</sub> tank fully recharged/refilled between flights

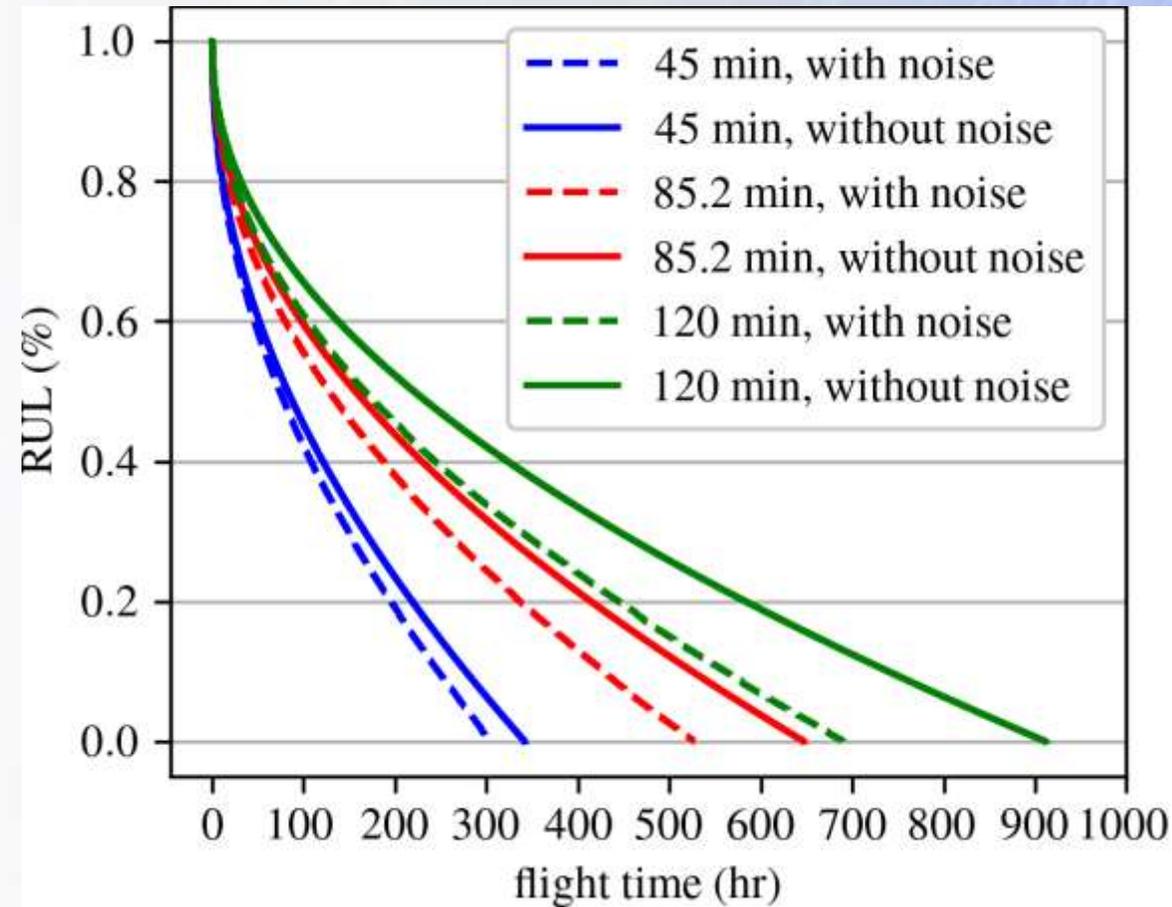
# Results



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- Batteries considered to reach end of life when capacity reaches 80% of nominal (2.4 A-hr for 30Q)
- Remaining useful life (RUL) defined as the percentage of capacity fade remaining
- To estimate life span, repeatedly simulate generic flight profile until RUL reaches zero
  - Between flights, fully recharged battery and refilled H<sub>2</sub> tank
- Largest battery stressor is takeoff; hence repeated short flights, which experience this more often, register fewer flight hours before replacement
- Also note effect of noise in the power profile: can reduce flight hours by up to 20%!



# Conclusions



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- Results indicate two foci for future work with regards to EMS: effective management of take-offs and removing noise from demand profile
  - Addition of capacitor banks may help with the latter; high charge/discharge rates used to smooth the power curve
- Limitations:
  - Thermal management; all work here is considered isothermal
  - Parasitic power draw from smaller components (ex., cool pumps)
  - Converting from gaseous hydrogen to liquid hydrogen tank (preheat can also act as heat sink for coolant)
  - Developing controller to account for non-routine events (ex., aborted takeoffs, minor ascents/descents, etc.)

# Acknowledgements



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# Discussion



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## Open Modelica Modeling of Battery Fuel Cell Electric Aircraft

<https://github.com/ARTS-Laboratory/Open-Modelica-modeling-of-battery-fuel-cell-electric-aircraft>



# The Cessna 208



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- 8-seater aircraft primarily used for short-hop passenger flight
- Can be adapted for courier service in rural areas



Image credits: <https://cessna.txtav.com/en/turboprop/caravan>

## Key specifications:

- Max Takeoff Weight: 3629 kg
- Usable Fuel Weight: 1009 kg
- Basic Empty Weight: 2145 kg
- Maximum Payload: 1393 kg
- Max Cruise Speed: 344 km/hr
- Max Range: 1982 km
- Power Plant: 765 hp (503 kW) Pratt&Whitney PT6A-114A