ASME 2025 International Design Engineering Technical Conferences &
Computers and Information in Engineering Conference
IDETC/CIE 2025
August 17-20, 2025, Anaheim, USA

Hybrid Powertrain Optimization for Regional Aircraft Integrating Hydrogen Fuel Cells and Aluminum Air Batteries

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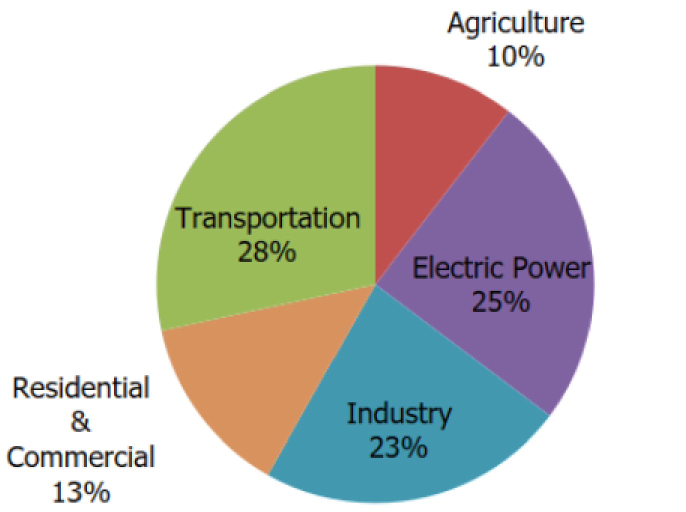
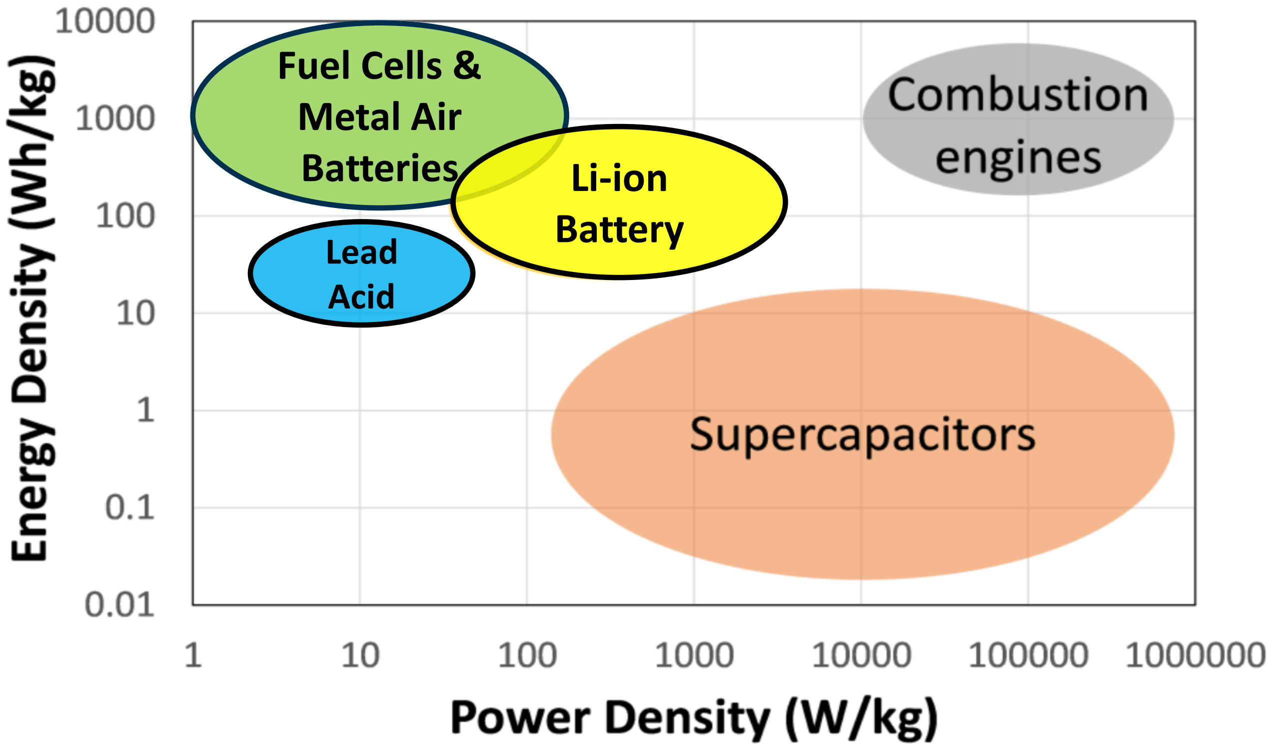
Introduction and Motivation

- Reduce greenhouse emissions in transportation
- Lower ramp rate of the hydrogen fuel cell (slow to react to altering demands).
- Only batteries not sufficient for long range flights (low power/ weight ratio).

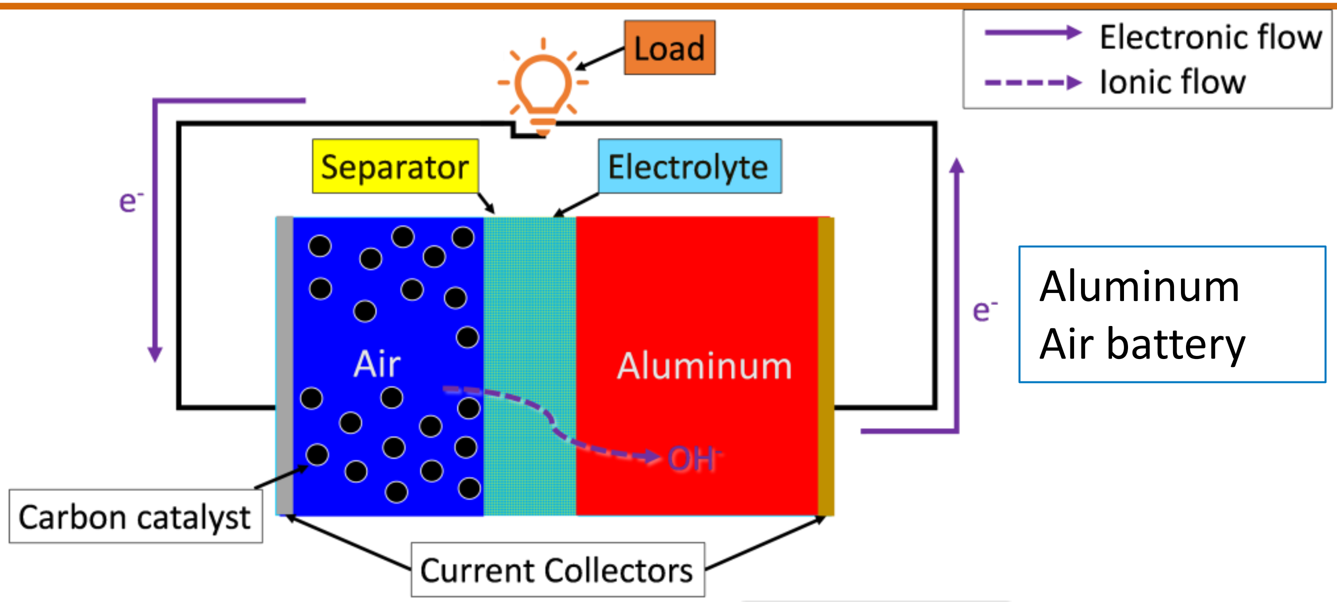


Total U.S. Greenhouse Gas Emissions by Economic Sector

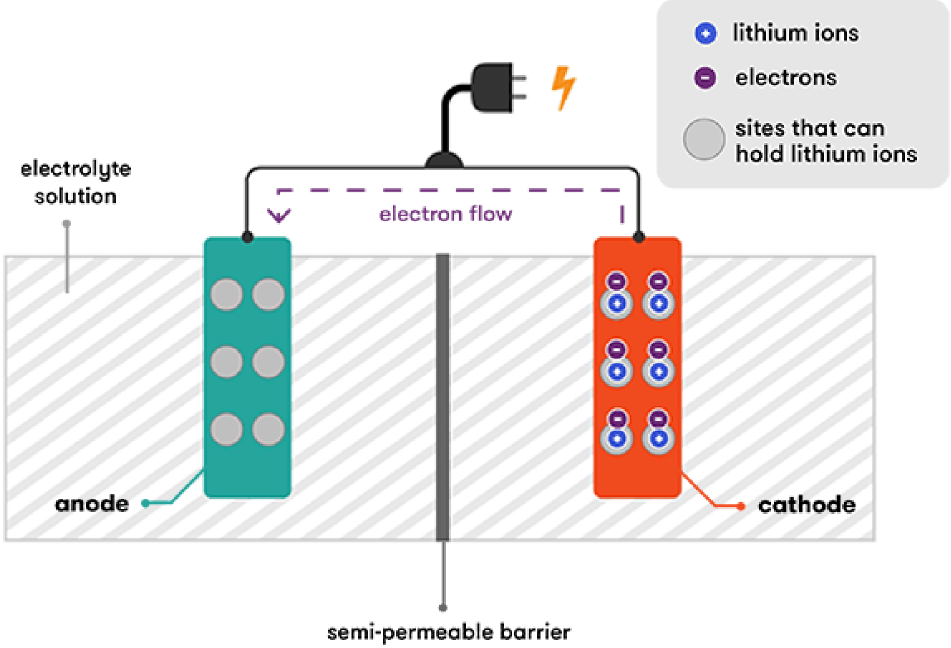


Source: U.S. Department of Energy, "Hydrogen Storage," Office of Energy Efficiency & Renewable Energy. [Online]. Available: https://www.energy.gov/eere/fuelcells/hydrogen-storage.

Introduction: Hybrid Powertrain

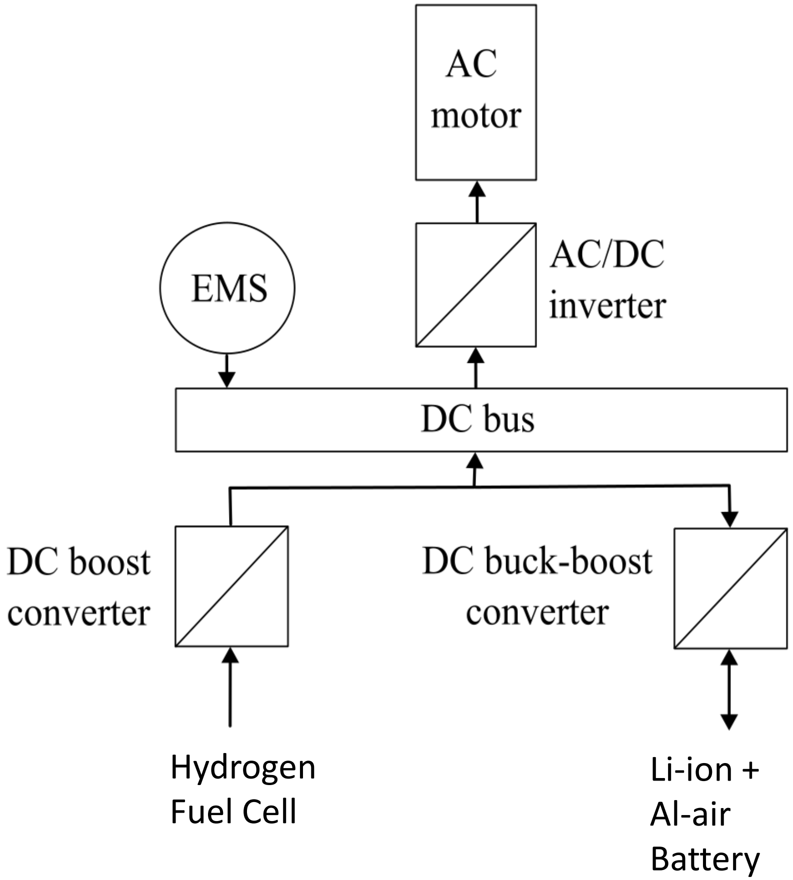


Aluminum Air battery



Li-ion battery

- **Aluminum (Al) Anode** and **Air (Oxygen) Cathode**.
- **High Energy Density**, **Non-Rechargeable**.



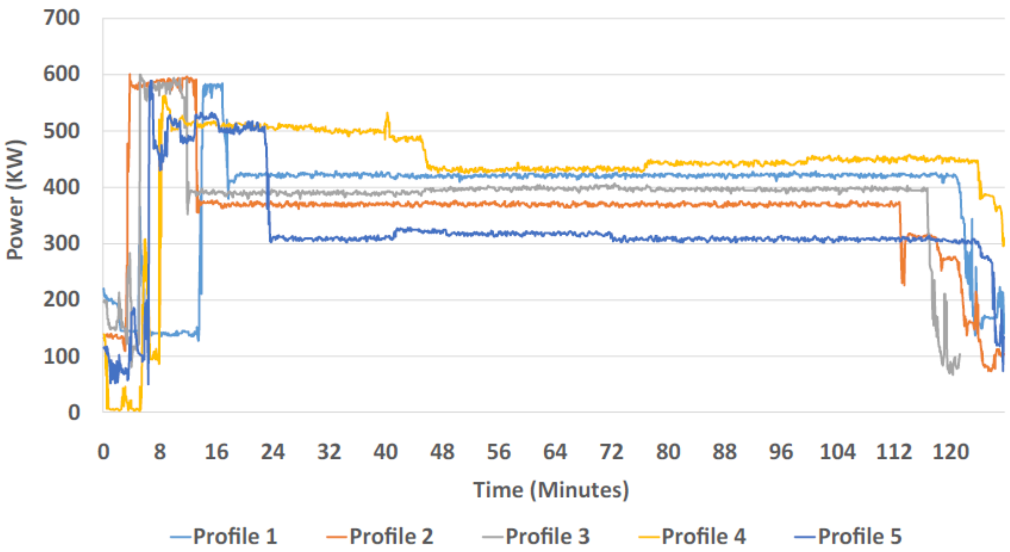
Hybrid Powertrain

Outline

- ➢ Cessna 208 Specifications
- ➢ Mixed Integer Problem Formulation
- ➢ Experimental Set-up and Results
- ➢ Conclusion

Cessna 208

Cessna 208



- Maximum Takeoff Weight: 8,000 lb (3,629 kg)
- Usable Fuel Weight: 2,224 lb (1,009 kg)
- Usable Fuel Volume: 332 gal (1,257 l)
- Basic Empty Weight: 4,730 lb (2,145 kg)
- Useful Load: 3,305 lb (1,499 kg)
- Maximum Payload: 3,070 lb (1,393 kg)
- Maximum Range: ~1,070 nautical miles (1,982 km)
- Maximum Flight Duration: 4-5 hours
- Engine (PT6A-114A) Weight: ~200 kg
- Seating Capacity: 9-14 passengers (plus 1-2 crew)

Power curves from the Cessna 208 for Columbia (South Carolina) to Richmond (North Carolina)

Objective Function and Decision Variables

- Multi-objective optimization: system sizing and power scheduling.
- Decision variables:
  - Hydrogen tank (L)
  - Fuel cell capacity (kWh)
  - Battery capacity (kWh)
  - Al-air capacity (kWh)

$$C_{\mathrm{H}}^{\mathrm{wt}} V_{\mathrm{H}} + C_{\mathrm{FC}}^{\mathrm{wt}} E_{\mathrm{fc}} + C_{\mathrm{Li}}^{\mathrm{wt}} E_{\mathrm{Li}} + C_{\mathrm{Al}}^{\mathrm{wt}} E_{\mathrm{Al}},$$

Weight of hydrogen tank

Weight of fuel cell

Weight of Li-ion battery

Weight of Al-air battery

$$\sum_{t \in T} P_{\mathrm{fc}}^{t} + P_{\mathrm{Li}}^{t} + P_{\mathrm{Al}}^{t}.$$

TABLE 1: WEIGHT COEFFICIENT VALUES

Coefficient	$C_{\mathrm{H}}^{\mathrm{wt}}$ (kg/L)	$C_{\mathrm{fc}}^{\mathrm{wt}}$ (kg/kWh)	$C_{\mathrm{Li}}^{\mathrm{wt}}$ (kg/kWh)	$C_{\mathrm{Al}}^{\mathrm{wt}}$ (kg/kWh)
Value	1/11000	1.5	4	0.1234

Constraint Set

- To comply with payload limitations, the **total installed weight of all propulsion components is bounded** above by 1,200 kg.

$$C_{\mathrm{H}}^{\mathrm{wt}} V_{\mathrm{H}} + C_{\mathrm{FC}}^{\mathrm{wt}} E_{\mathrm{fc}} + C_{\mathrm{Li}}^{\mathrm{wt}} E_{\mathrm{Li}} + C_{\mathrm{Al}}^{\mathrm{wt}} E_{\mathrm{Al}} \leq 1200,$$

TABLE 1: WEIGHT COEFFICIENT VALUES

Coefficient	$C_{\mathrm{H}}^{\mathrm{wt}}$ (kg/L)	$C_{\mathrm{fc}}^{\mathrm{wt}}$ (kg/kWh)	$C_{\mathrm{Li}}^{\mathrm{wt}}$ (kg/kWh)	$C_{\mathrm{Al}}^{\mathrm{wt}}$ (kg/kWh)
Value	1/11000	1.5	4	0.1234

- At every time step, **the total power demand is exactly met** by the combined output from the hydrogen fuel cell, Li-ion battery, and aluminum-air battery.

$$P_{\mathrm{fc}}^{t} + P_{\mathrm{Li}}^{t} + P_{\mathrm{Al}}^{t} = P_{\mathrm{dem}}^{t}, \quad \forall t \in T,$$

Constraint Set

- Available **hydrogen supply is sufficient** to meet the fuel cell energy demand throughout the entire flight.

$$V_{\mathrm{H}}\,\eta_{\mathrm{fc}}\,H_{\mathrm{LHV}}\,H_{\mathrm{mass}} \geq E_{\mathrm{fc}},$$

TABLE 2: HYDROGEN FUEL CELL PROPERTIES

Coefficient	η_{fc}	H_{LHV} (kWh/kg)	H_{mass} (kg/L)
Value	0.55	33.33	0.09

- **Fuel cell ramp rate constraint**: The power output from the hydrogen fuel cell over short periods (between any two timesteps) must **remain within 10% of its rated capacity**.

$$P_{\mathrm{fc}}^{t_1} - P_{\mathrm{fc}}^{t_2} \leq 0.1\,E_{\mathrm{fc}}, \quad \forall t_1, t_2 \in T,$$

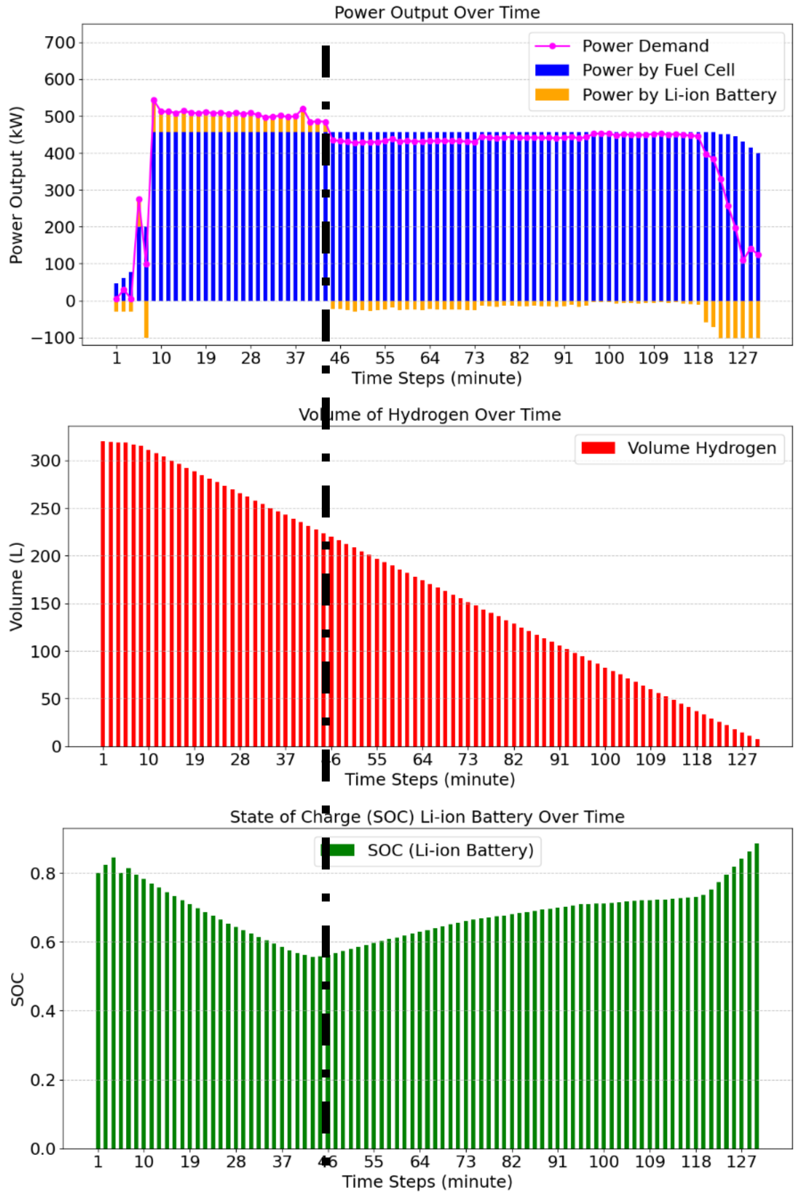
Constraint Set

- The battery's state of charge **(SOC) changes dynamically** based on how much energy is drawn over time.
- At any time t_1, the **stored energy** is updated from time t_2 by **accounting for power consumed** over the interval.

$$SOC_{\mathrm{Li}}^{t_1} E_{\mathrm{Li}} = SOC_{\mathrm{Li}}^{t_2} E_{\mathrm{Li}} - P_{\mathrm{Li}}^{t_1} \Delta t, \quad \forall t_1, t_2 \in T.$$

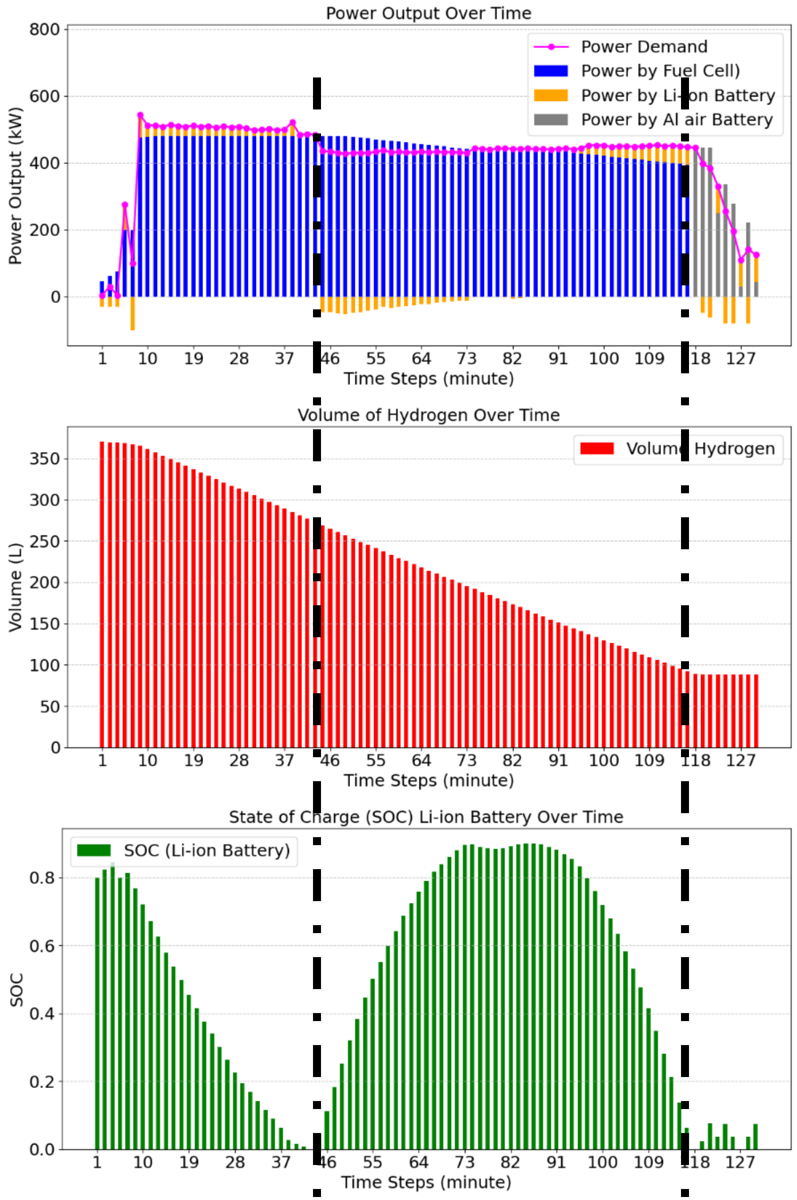
Experiment 1

- **Primary Power Source**: The hydrogen fuel cell serves as the main power provider throughout the flight, with lithium-ion batteries acting as a complementary source.
- **Phase-Specific Optimization**: During the cruise, when power demands are relatively steady, the fuel cell fulfills most of the load.
- **Battery-Assisted Smoothing**: The Li-ion battery steps in to manage transient spikes and dips in power demand, ensuring smooth and stable energy delivery.
- **Hydrogen Usage**: The gradual depletion of hydrogen volume indicates consistent fuel consumption by the fuel cell.
- **Battery State of Charge (SOC)**: The SOC curve confirms that the battery is effectively used to buffer variations and is recharged during low-demand phases.



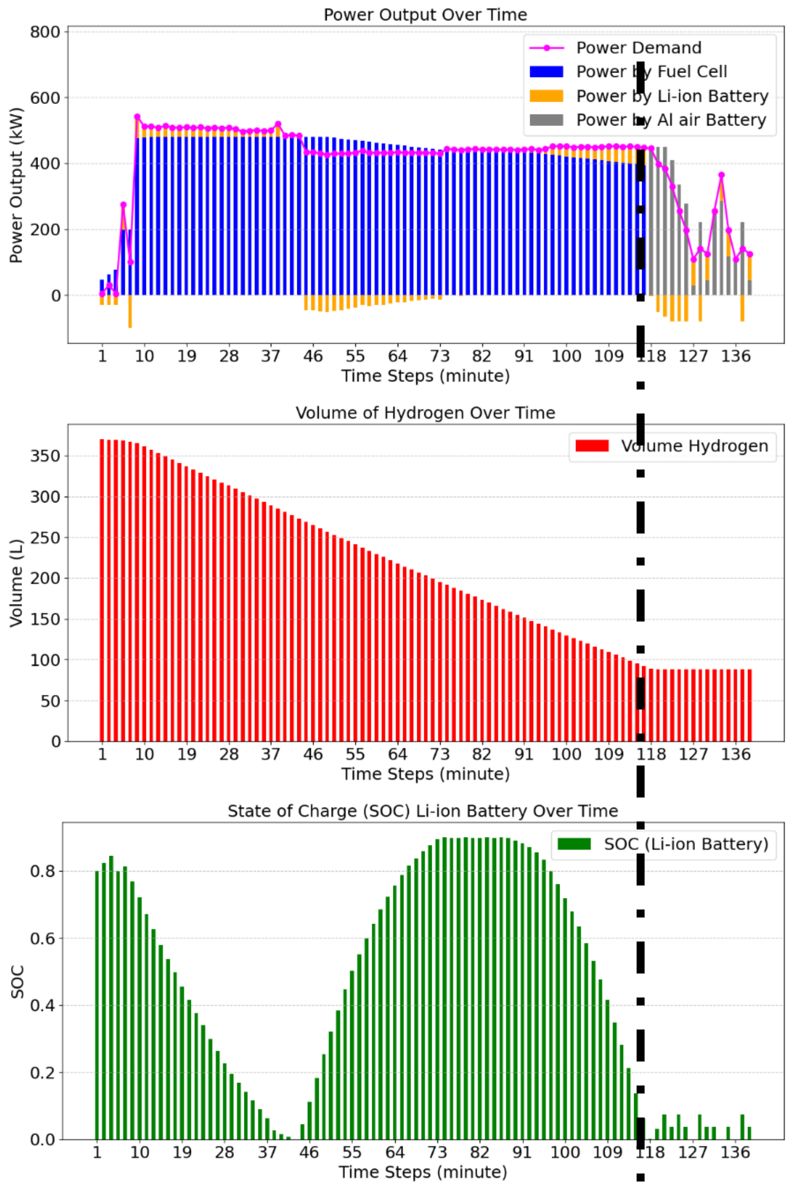
Experiment 2

- **Scenario Setup**: We consider a scenario where hydrogen volume drops below 20% of total capacity, posing safety risks. Aluminum-air battery is activated as a backup.
- **Normal Operation Phase**: Power is supplied by the hydrogen fuel cell and Li-ion battery. The fuel cell handles main power load during climb and cruise, while the battery smooths fluctuations.
- **Critical Transition Phase**: Once hydrogen falls below 20%, the fuel cell shuts down to preserve remaining fuel.
- **Emergency Backup Activation**: Aluminum-air battery takes over as the primary power source to ensure safe flight completion under depleted hydrogen conditions.



Experiment 3

- **Scenario Setup**: A rerouting scenario is considered in which the aircraft must perform a go-around and return to the runway due to events like a missed approach, poor visibility, or adverse weather.
- **Normal Operation Phase**: Initially, the system functions under planned conditions using the hydrogen fuel cell as the primary power source, with the lithium-ion battery assisting during power fluctuations.
- **Critical Transition Phase**: A deviation from the flight plan triggers an extended flight duration, requiring real-time energy management adjustments to handle the additional power and energy demands.



Optimal Sizing Results

TABLE 3: SIZING CONFIGURATIONS FOR HYBRID ENERGY SYSTEM COMPONENTS

Experiment	Fuel Cell capacity (kWh)	Li-ion Battery capacity (kWh)	Aluminum-air battery capacity (kWh)	Hydrogen volume (L)	Powertrain weight (kg)
Experiment 1	458	100	0	320	1200
Experiment 2	480	80	450	370	1142
Experiment 3	480	80	450	370	1142

Experiment 1:

- No aluminum-air battery used; only fuel cell and Li-ion battery components are sized.
- Powertrain reaches maximum allowable weight of 1200 kg, utilizing full design capacity.
- Hydrogen volume is limited to 320 L.

Experiment 2 and 3:

- Aluminum-air battery with 450 kWh capacity to support backup power needs.
- Fuel cell size increases slightly to 480 kWh, while Li-ion battery size decreases to 80 kWh.
- Hydrogen volume increases to 370 L, yet total system weight remains under the limit at 1142 kg.

Conclusion and Future Work

- **Hybrid Powertrain Development**: Designed a multi-source hybrid energy system for the Cessna 208 aircraft, integrating a hydrogen fuel cell, lithium-ion battery, and aluminum-air battery to enhance operational flexibility and safety.
- **Optimization Framework**: Formulated and solved a mixed-integer programming model that jointly optimizes component sizing and power scheduling across mission profiles.
- **Scenario-Based Validation**: Conducted rigorous simulations under nominal, hydrogen-limited, and emergency diversion scenarios using real-world flight data to validate system performance and robustness.
- **Path Forward**:
  - **Stochastic Sizing**: Future work will extend the sizing model to account for uncertainties in energy prices and environmental conditions.
  - **Robust Energy Planning**: Focus on adaptive scheduling policies that generalize across diverse flight profiles and operational contingencies.

Thank You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