Economic Drivers of High-Energy-Density Batteries in Electric Aviation and Their Safety Implications

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The Arts-Lab at USC

We use

foundational science

Day School

to develop essential tools

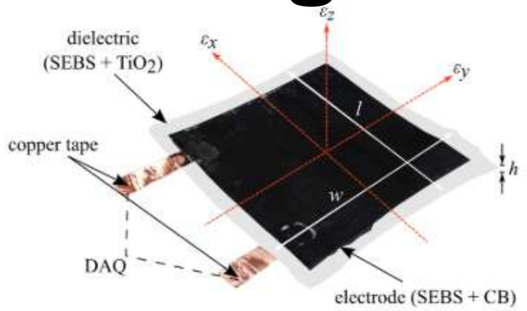
Dan Thompson

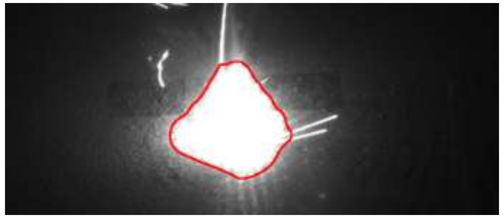
to solve real-world problems

public domain

We are Engineers (mostly)

Sensing





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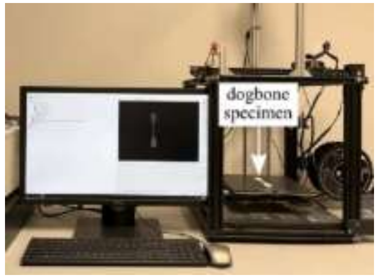
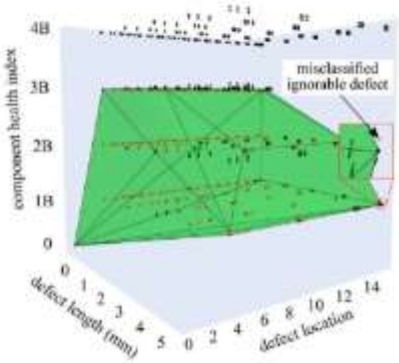
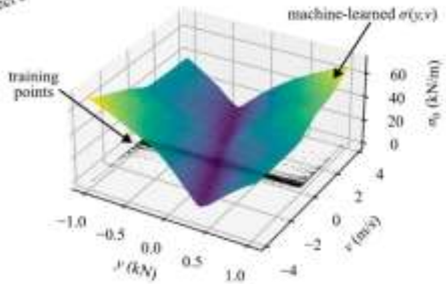
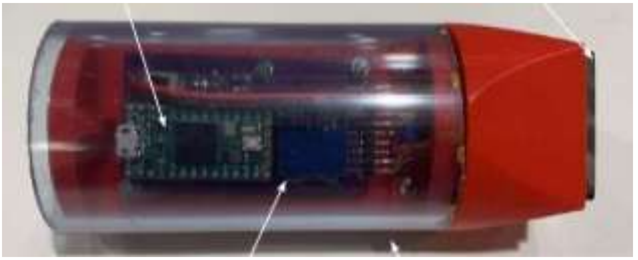






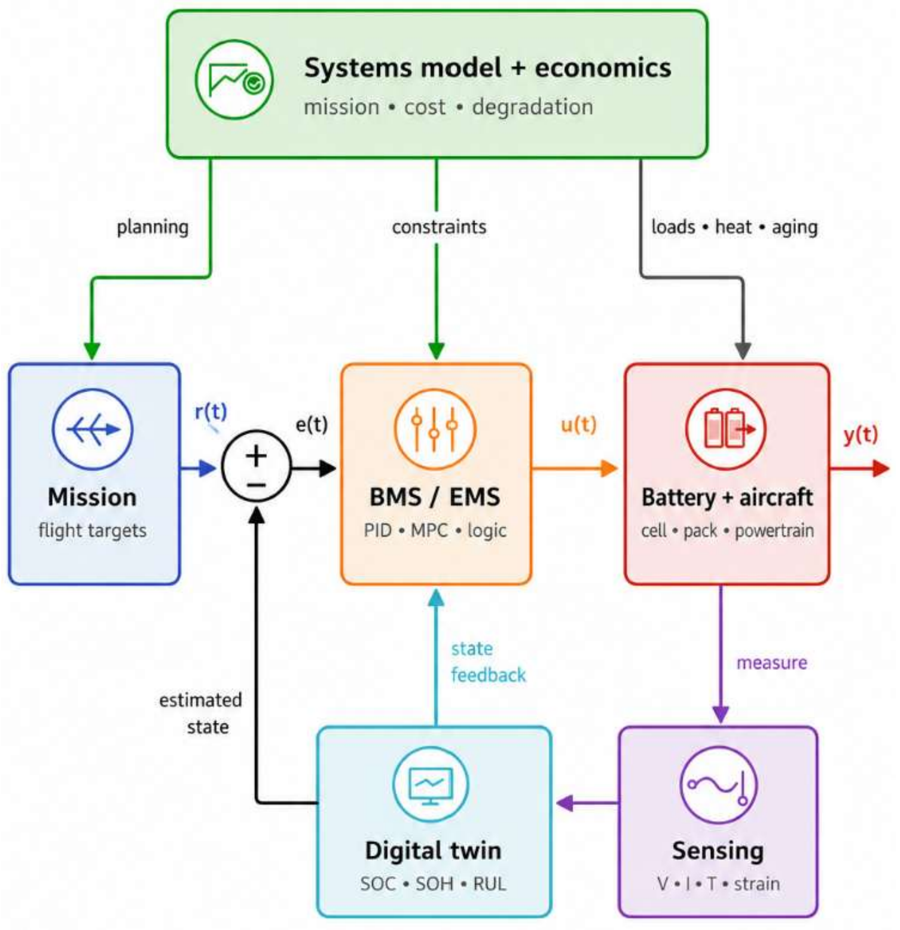


AI/ML

Embedded Systems

Batteries as Controls Problem

- Battery states are hidden
  - SOC, SOH, RUL, temperature, internal resistance, and mechanical damage.
- Operational choices matter
  - Charge rate, SOC window, depth of discharge, cooling, and flight profile.
- Safety is coupled across physics
  - Electrical, thermal, chemical, and mechanical behavior evolve together.
- Packs are distributed systems
  - Cells age differently, share current unevenly, and create local weak points.



Sensing → Models → BMS Decisions → Safer Operations

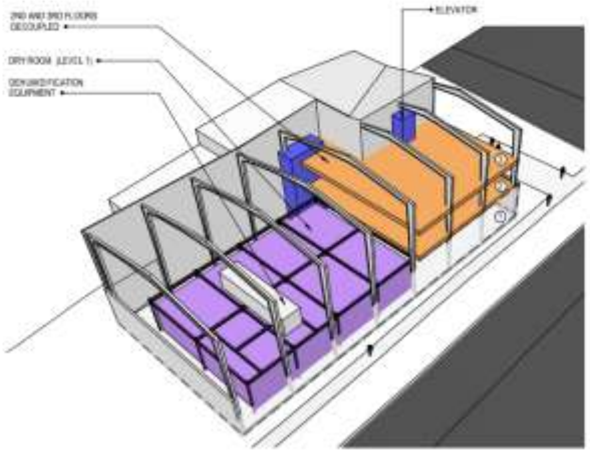
Battery Research at USC

SC NEXUS

- Projects that will enable SC NEXUS to become global leader in bolstering grid resilience through distributed energy resources
- The SC Nexus for Advanced Resilient Energy (SC NEXUS) received $45 million in implementation grant funding through the US Department of Commerce

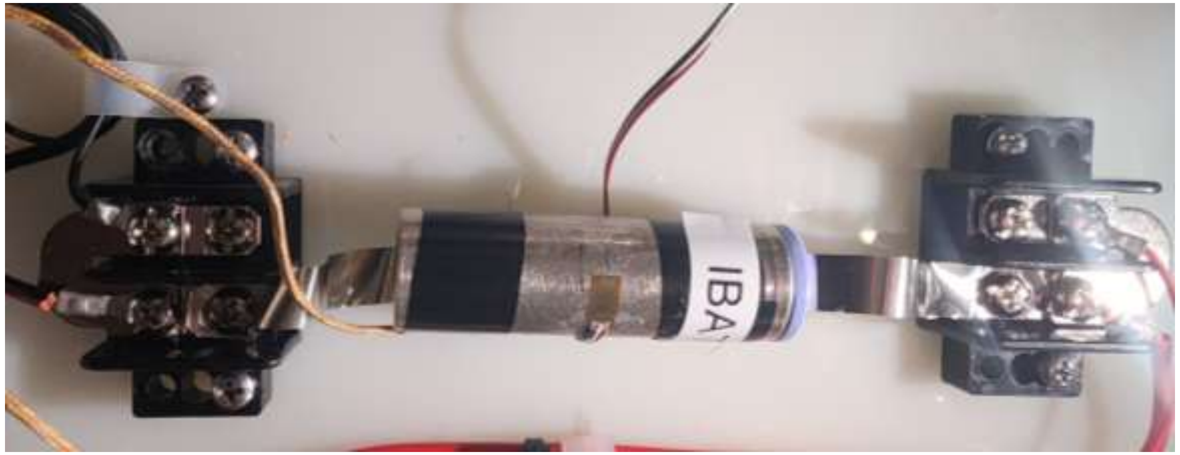
Carolina Institute for Battery Innovation

- $45M U.S. Department of Commerce implementation grant.
- Statewide partnership for resilient energy systems.
- Connects batteries, grid testbeds, workforce, and entrepreneurship.
- Provides the ecosystem for our battery labs and digital-twin work.



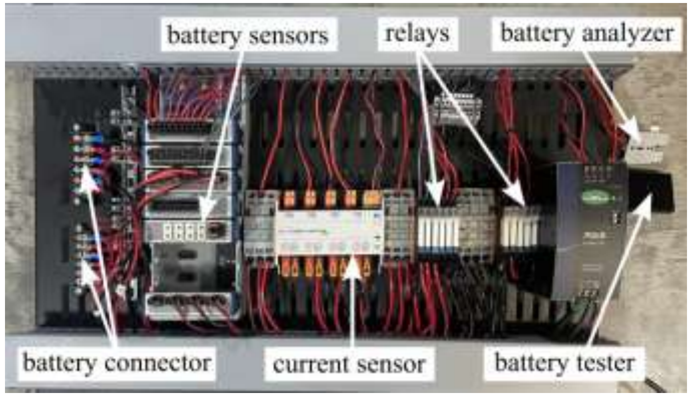
ARTS-Lab Battery Testing Facility

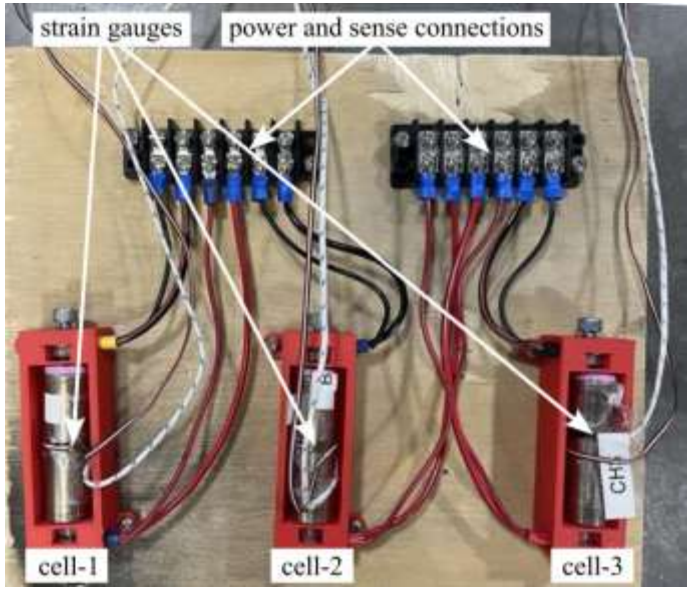
- 12-channel battery cycling and test capability.~100 kW installed cycling capacity.
- Pack/modular cyclers, and custom test rigs.
- Integrated controls and hardware-in-the-loop battery testing.
- Strain sensing for cell health, degradation, and safety diagnostics.



Battery Testbeds for Realistic Conditions

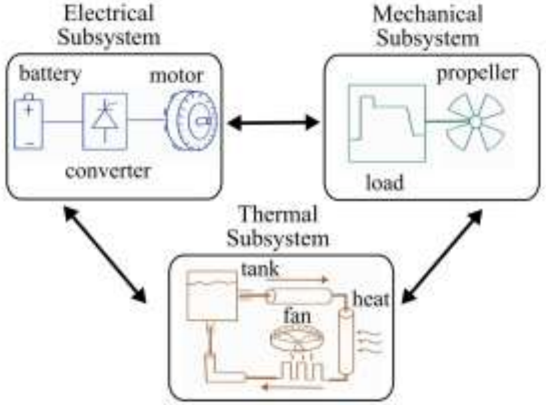
- Integrated temperature, strain, and acoustic emission.
- Cell, module, and parallel-pack testing under controlled environments.
- Moving beyond single-cell cycling to realistic operating profiles.
- Goal: replay flight-like load, thermal, and vibration conditions.

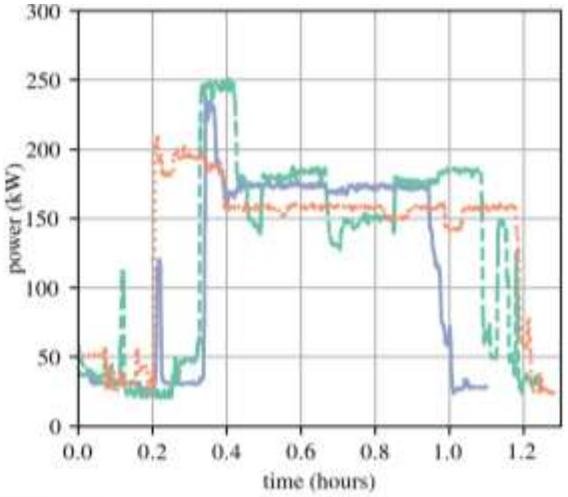




Multi-Physics Models for Electric Aircraft

- Aircraft-scale models across multiple platforms.
- Electrical, thermal, mechanical, and control domains.
- Simulate flight loads, energy use, and battery behavior.
- Built for controls, degradation, and design trade studies.
- Open-source tools for collaboration and validation.





electric-light-sport-aircraft-multiphysics-model Public
Multi-physics modeling of electric light aircraft powertrain
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electric-light-utility-aircraft-multiphysics-model Public
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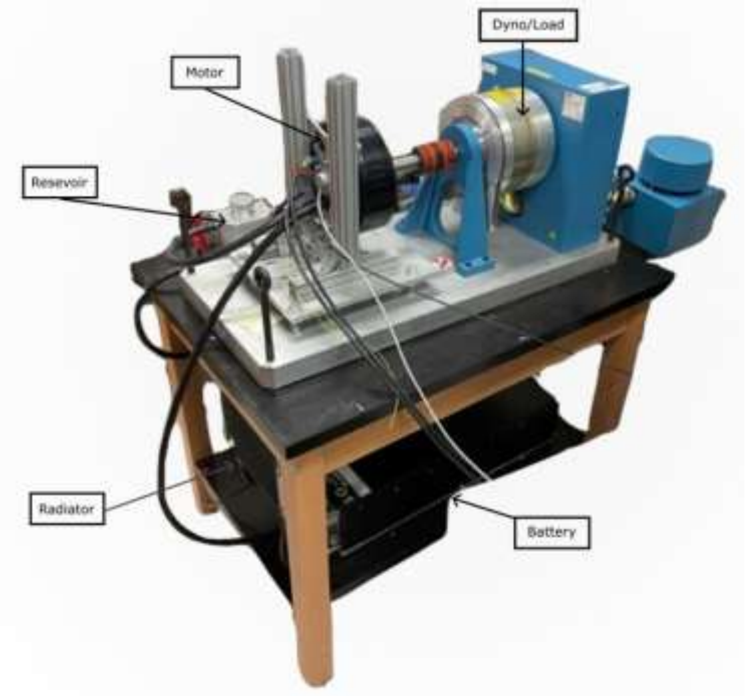
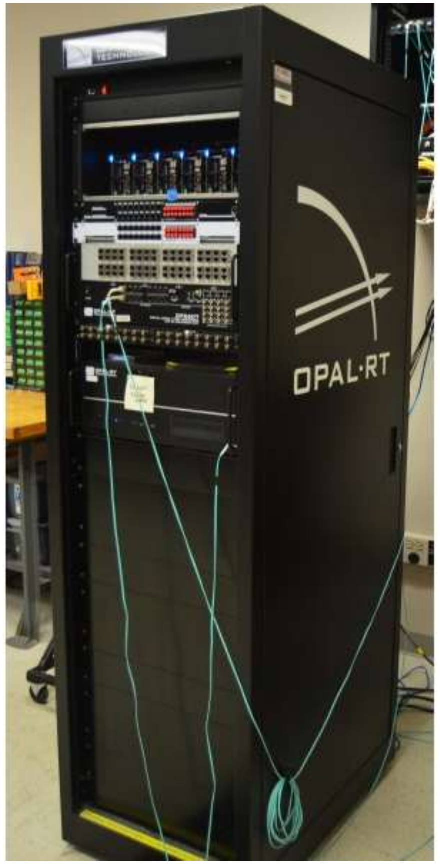
GitHub

Hardware-in-the-Loop Testbed

- Physical motor–dyno testbed for aircraft digital twins.
- OPAL-RT platform for real-time hardware-in-the-loop testing.
- Power electronics, inverters, batteries, and liquid cooling under one roof.
- Experimental hardware to validate models, controls, and safety logic.
- Goal: move from simulation to flight-like laboratory testing.

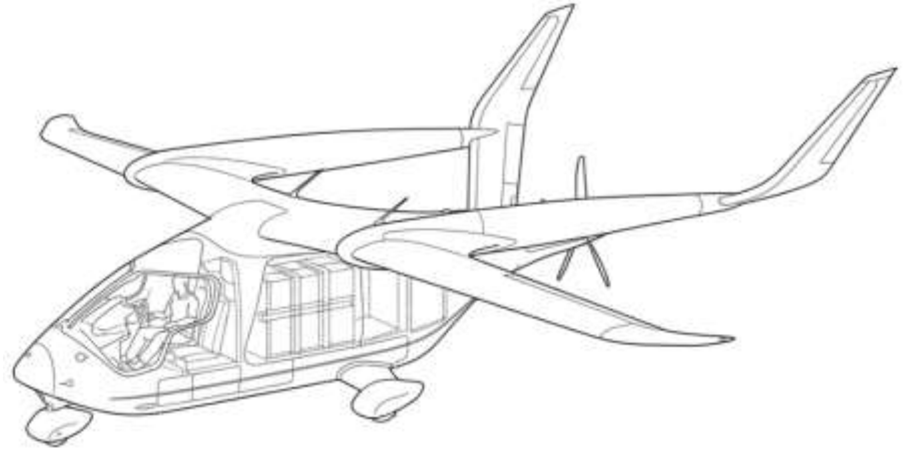




Electric Aviation as a Systems Problem

Short-range Cargo is the Near-term Opportunity

- Current batteries favor short missions.
- Cargo is the easier first autonomy case.
- Autonomy can recover ~225 kg from crew mass.
- Repeatable routes make scheduling easier.
- Economics depend on payload, range, and downtime.

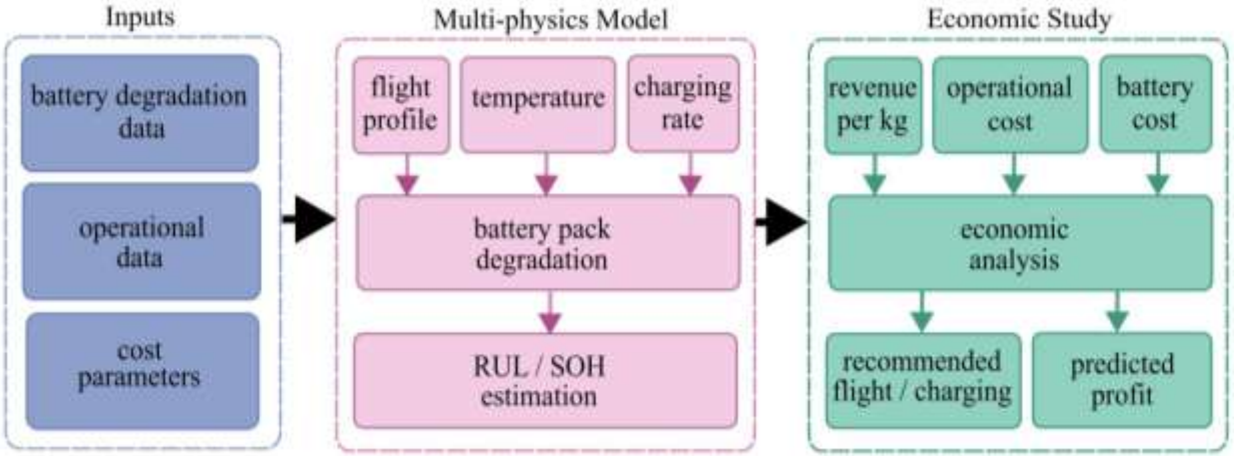


ZLEA, “BETA ALIA CTOL Aircraft (modified),” Wikimedia Commons, 2026. URL https://commons.wikimedia.org, original image licensed under CC BY-SA 4.0. Adapted and modified for this manuscript.

Weii, A. (2026, March 31). China tests 'world's heaviest cargo drone' suited to high-altitude and island operations. South China Morning Post.

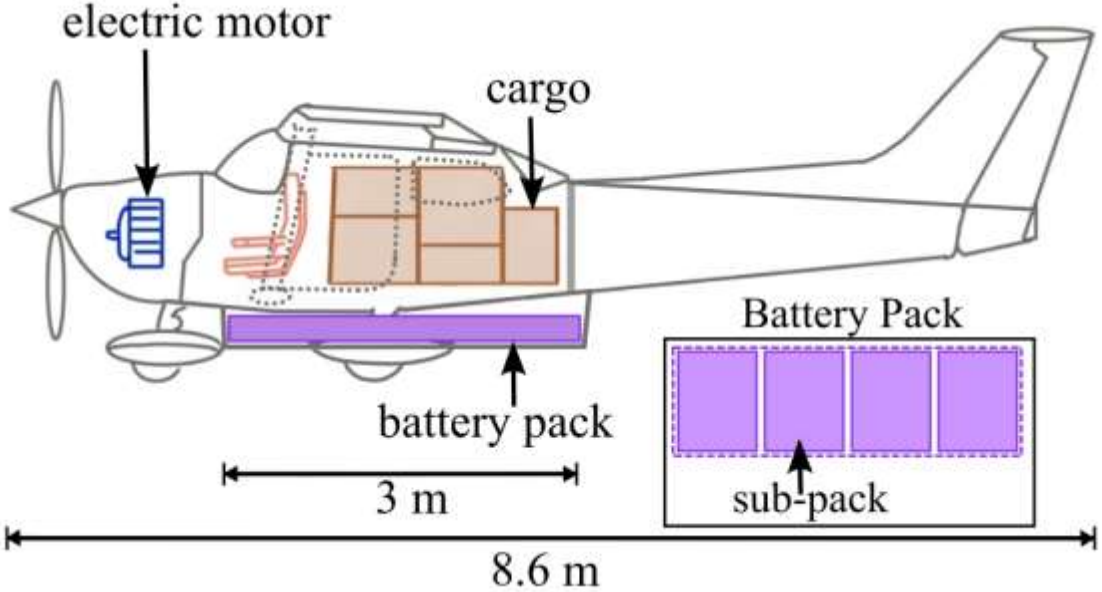
Results from Electric Aviation Studies

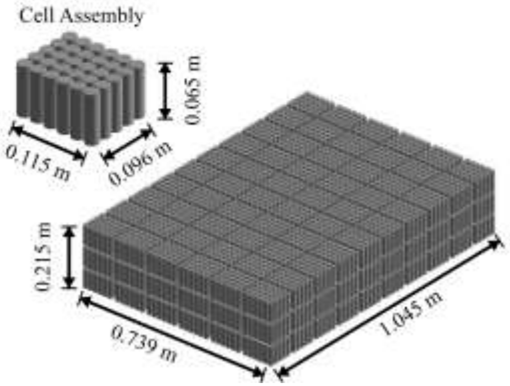
- Our studies connect lab data, degradation models, and aircraft economics.
- I will pull a few key results to show the main trend.
- Aircraft design, routing, charging, and battery aging are closely coupled.



Light Utility Aircraft

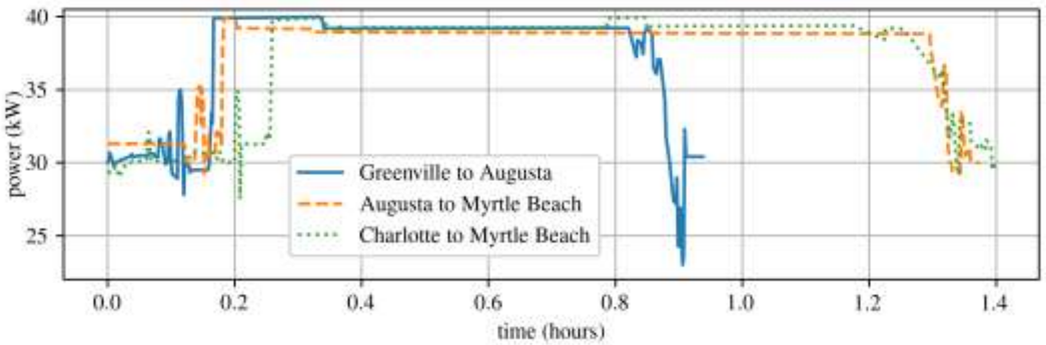
- Cessna 206-class research platform.
- 4–6 seat utility/cargo aircraft.
- Battery-electric powertrain model.
- Electrical, thermal, and mechanical domains.
- Used for routing, degradation, and controls studies.





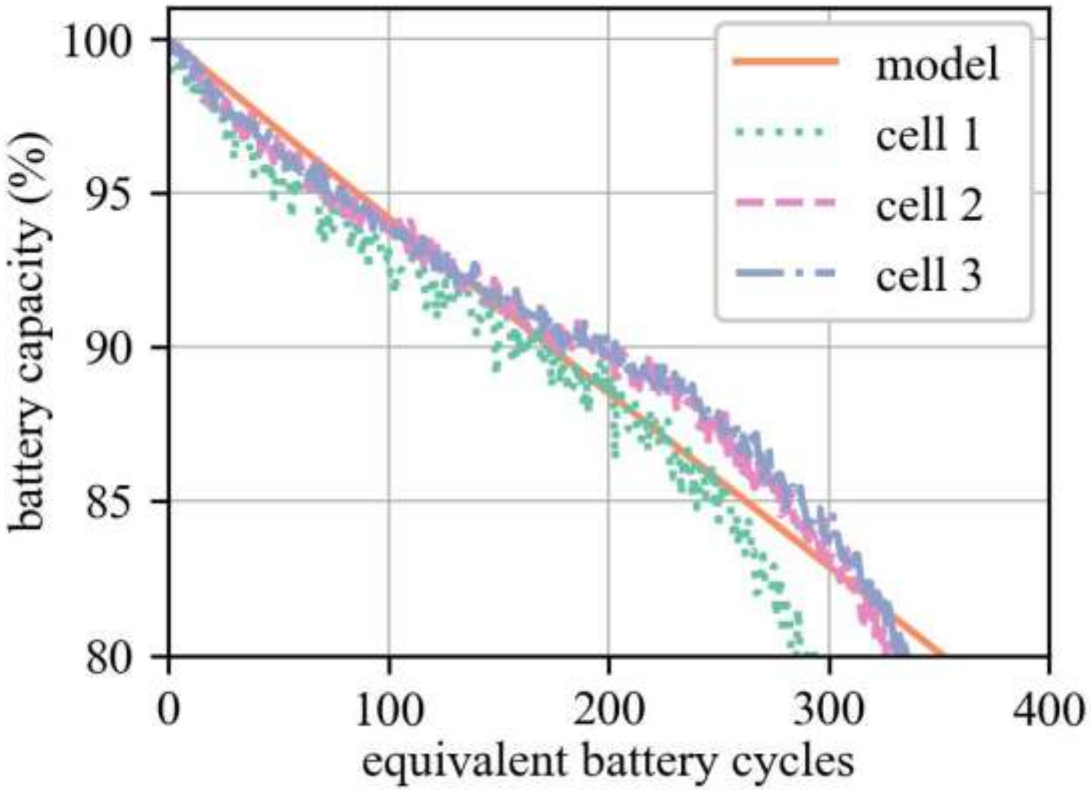
Representative Southeastern Cargo Routes

- Greenville → Augusta: 126 kWh and 161 km (100 miles)
- Augusta → Charleston: 158 kWh and 212 km (132 miles).
- Charlotte → Myrtle Beach: 172 kWh and 253 km (157 miles).
- 54–74% battery use per flight.



Cell Data Grounds the Aircraft Model

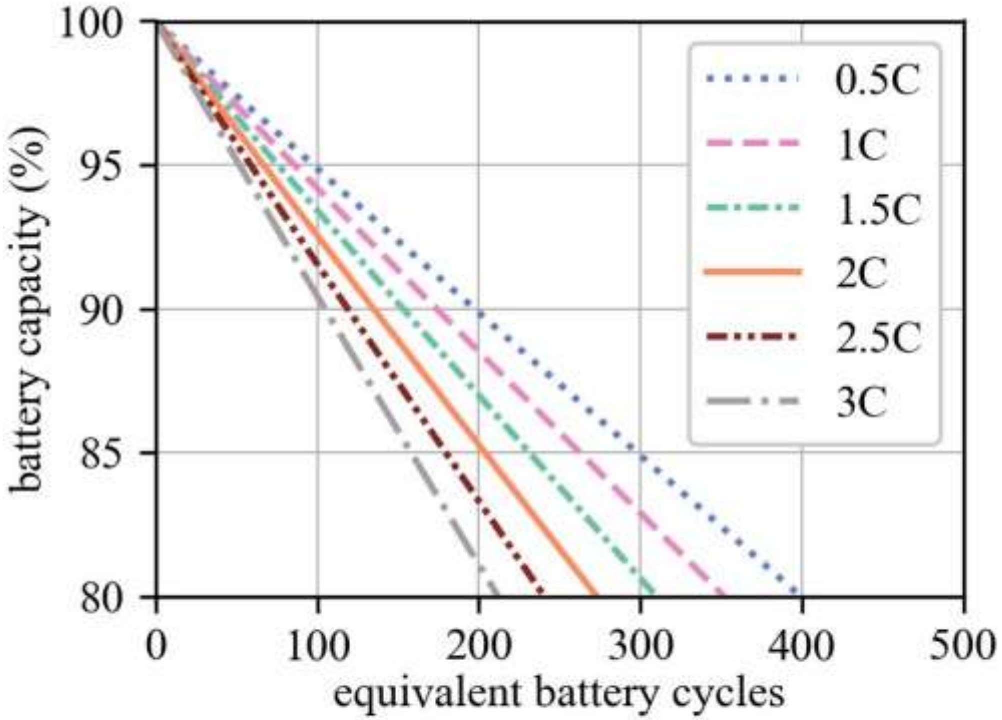
- Semi-empirical SOH model from Olmos et al.
- Stress factors: temperature, DOD, SOC, and C-rate.
- Fit to Samsung 30Q cells tested in our lab.
- Model tracks the three-cell aging trend.
- Main use: extrapolate across charging rates.



Josu Olmos, Iñigo Gandiaga, Andoni Saez de Ibarra, Xabier Larrea, Txomin Nieva, and Iosu Aizpuru. Modelling the cycling degradation of li-ion batteries: Chemistry influenced stress factors. *Journal of Energy Storage*, 40:102765, 2021

Battery Degradation is Mission-dependent

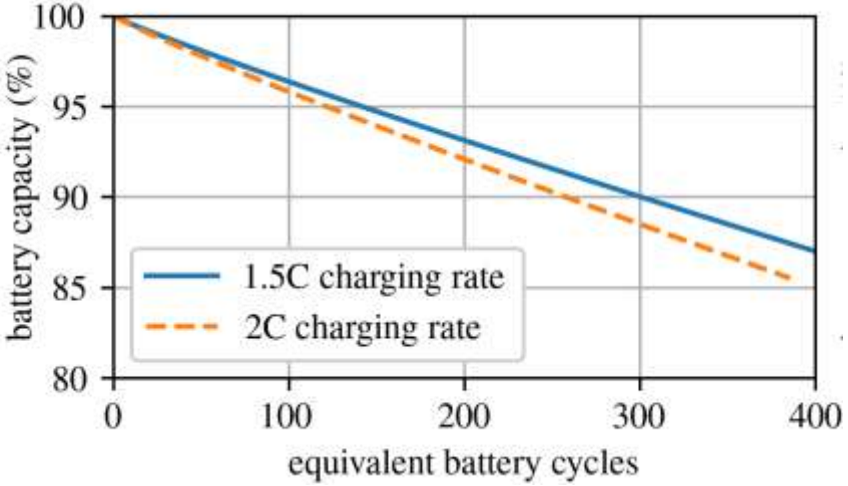
- Faster charging accelerates aging.
- Deeper missions reduce useful life.
- 80% SOH defines replacement.
- Real flight profiles matter.
- Pack-level effects remain the hard part.



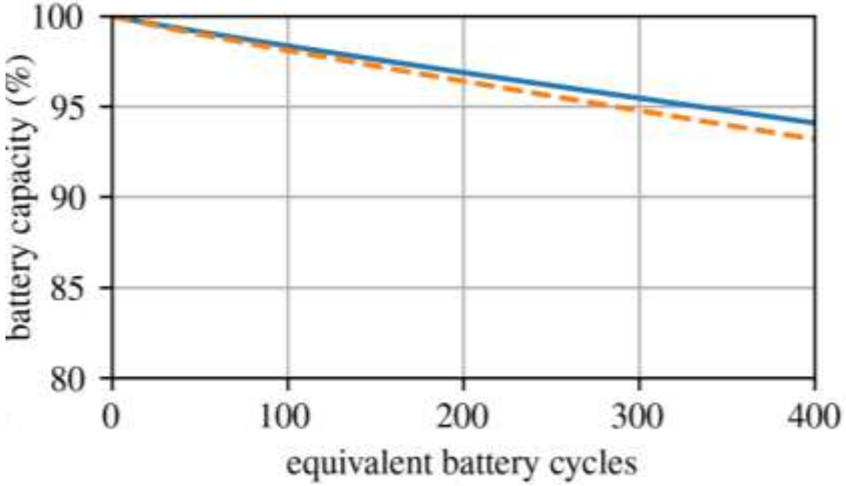
A semi-empirical SOH model fit to our Samsung 30Q cell data was used to simulate repeated flight/charge cycling, showing that higher charging rates accelerate capacity fade.

Electric Aviation is a Systems Problem

- Battery mass changes payload.
- Flight profile changes power demand.
- Thermal behavior changes degradation.
- Charging changes daily utilization.
- Controls connect the whole system.



Battery charged to 100% for each flight



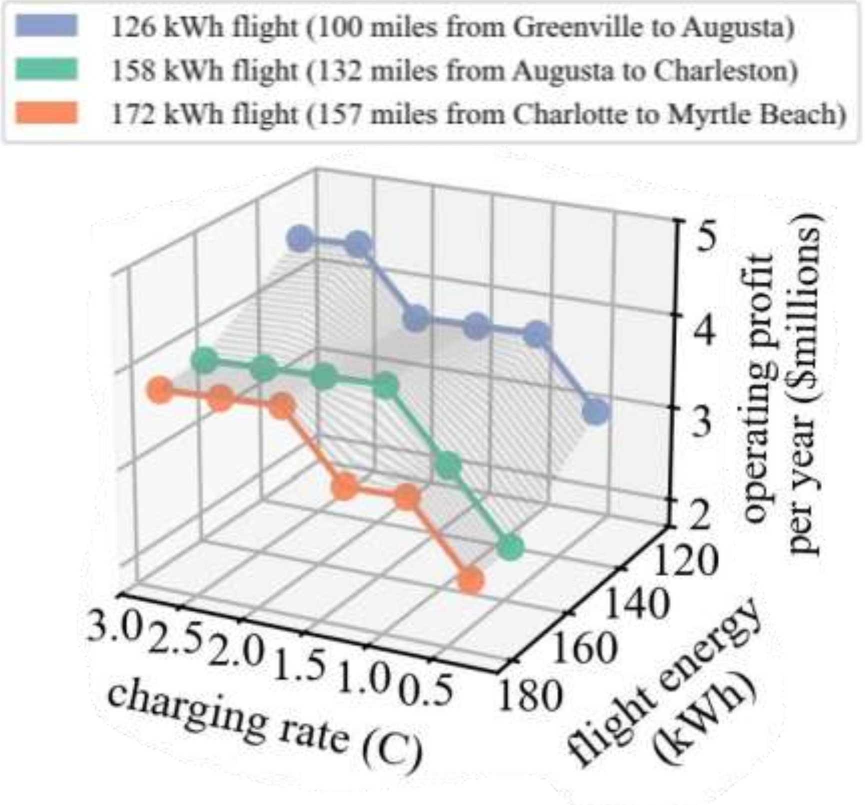
Battery charged to 80% for each flight

Augusta, Georgia to Myrtle Beach, South Carolina

Economics Push the Battery Hard

Aircraft Do Not Make Money Sitting on The Ground

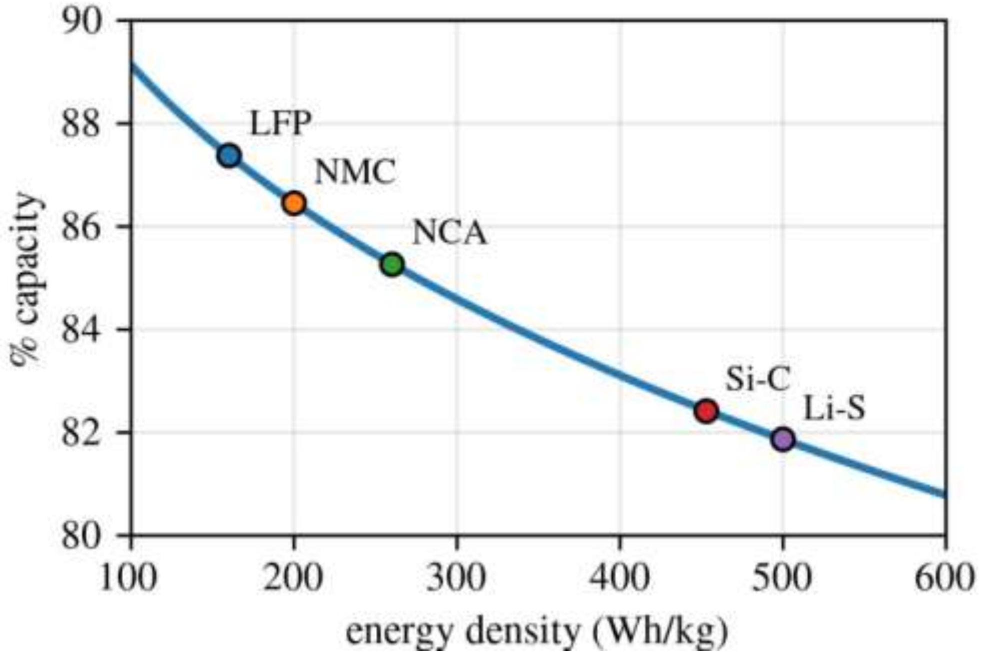
- Revenue comes from completed flights.
- Charging time is lost utilization.
- Faster charging can add flights.
- Battery replacement cost rises.
- The schedule sets the tradeoff.



In an eight-hour operating day, faster charging only improves economics when it creates enough time for an additional flight, producing the step changes.

Energy Density Determines What Missions are Even Possible

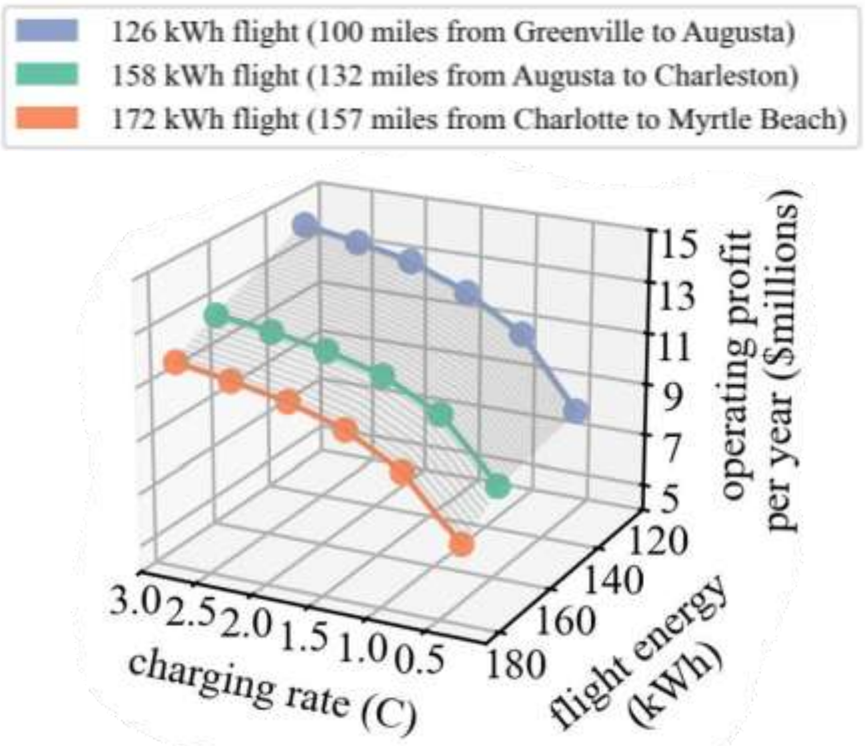
- Battery mass competes directly with payload.
- LFP is safe, but too heavy for this mission.
- NMC is useful for prototypes and early testing.
- NCA starts to approach economic viability.
- Si-C and Li-S are likely needed for profitable cargo flight.



Results from a regional utility cargo aircraft study show that profitable electric flight likely requires moving beyond LFP and NMC toward higher-energy Si-C and Li-S cells, despite shorter life and tighter operating margins.

Rule of Thumb: If It Can Fly, It Should Fly

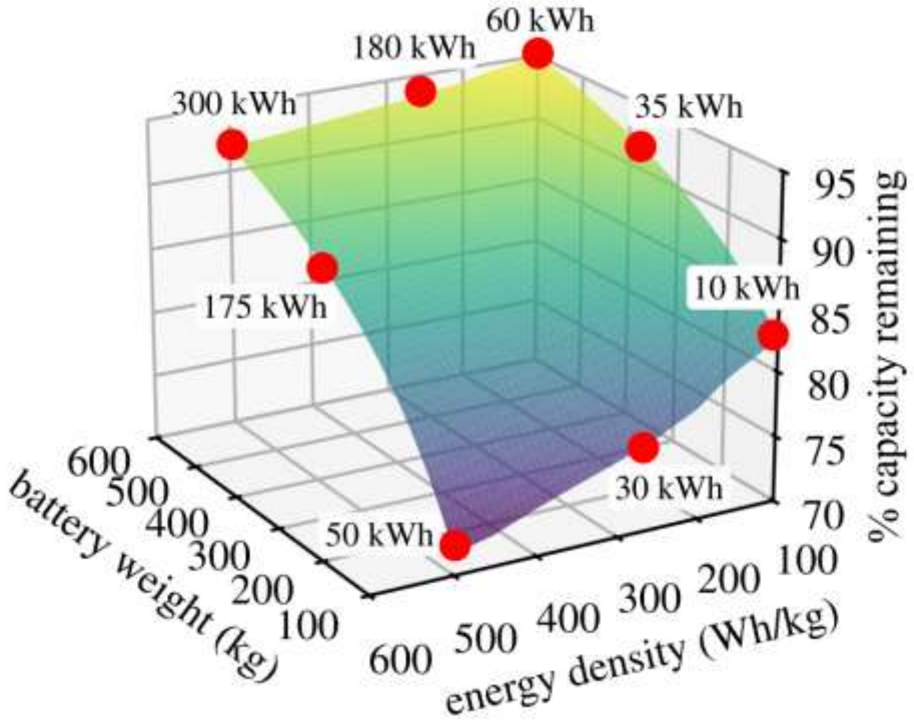
- Profit comes from utilization.
- Charging time is still downtime.
- More demand rewards faster turnaround.
- Battery aging becomes an operating cost.
- Continuous operations push batteries hardest.



For continuous 24-hour operations, the economics keep improving as charging gets faster because the aircraft can immediately return to service, making battery degradation an operating cost rather than the primary limit.

Energy Density Decides the Design Space

- Higher energy density reduces battery mass.
- Larger packs reduce depth of discharge.
- Lower DOD can extend useful life.
- Battery mass directly reduces payload.
- The best design balances weight, range, and aging.

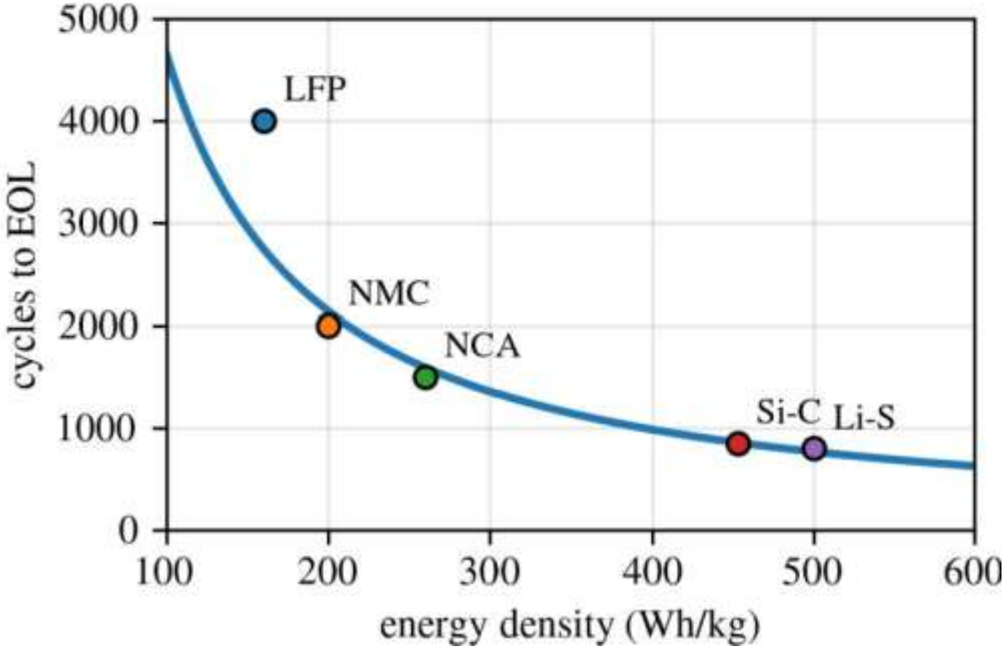


Battery weight, energy density, and pack capacity interact: higher-energy cells reduce the mass needed for a mission, while larger packs reduce depth of discharge and slow aging, but at the cost of available payload.

Economics Drive Safety Considerations

The Useful Batteries may not be the Most Forgiving

- Aviation rewards high energy density.
- Higher-energy cells often cycle less.
- Fewer cycles mean faster replacement.
- Degradation becomes part of the economics.
- Safety margins become harder to manage.



In this fixed-wing cargo aviation model, the chemistries that provide the energy density needed for useful payload and range also tend to have fewer cycles to end-of-life, creating a direct tradeoff between performance, cost, and safety margin..

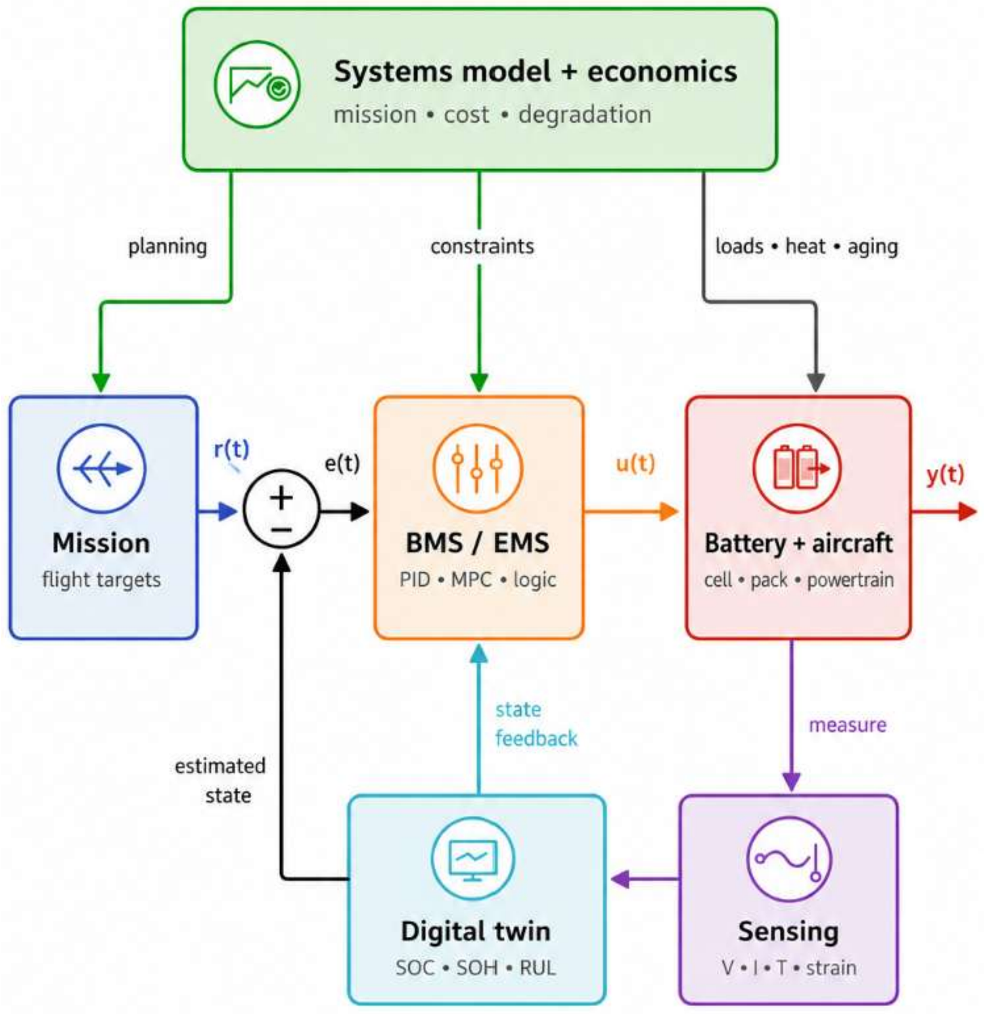
Battery Swapping adds New Failure Points

- More connectors and handling events.
- More packs stored near each other.
- More chances for mismatch or abuse.
- Faster inspection becomes essential.
- Safety becomes an operations problem.

NIO handout via Reuters, “Insight: Inside China's electric drive for swappable car batteries.”

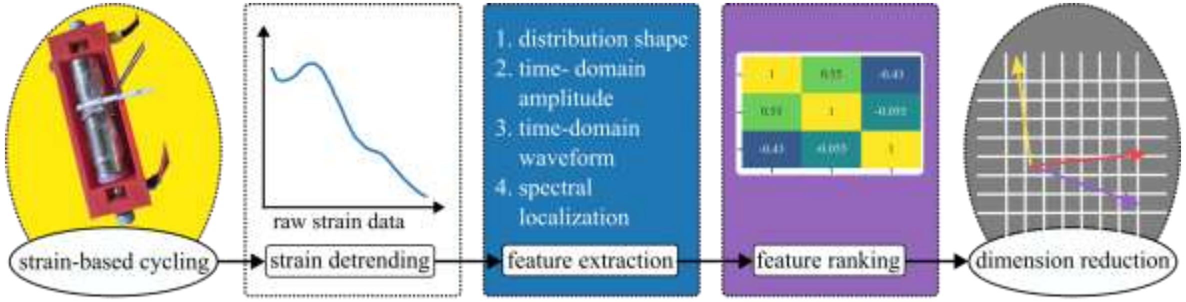
Tighter Margins Require Better Diagnostics

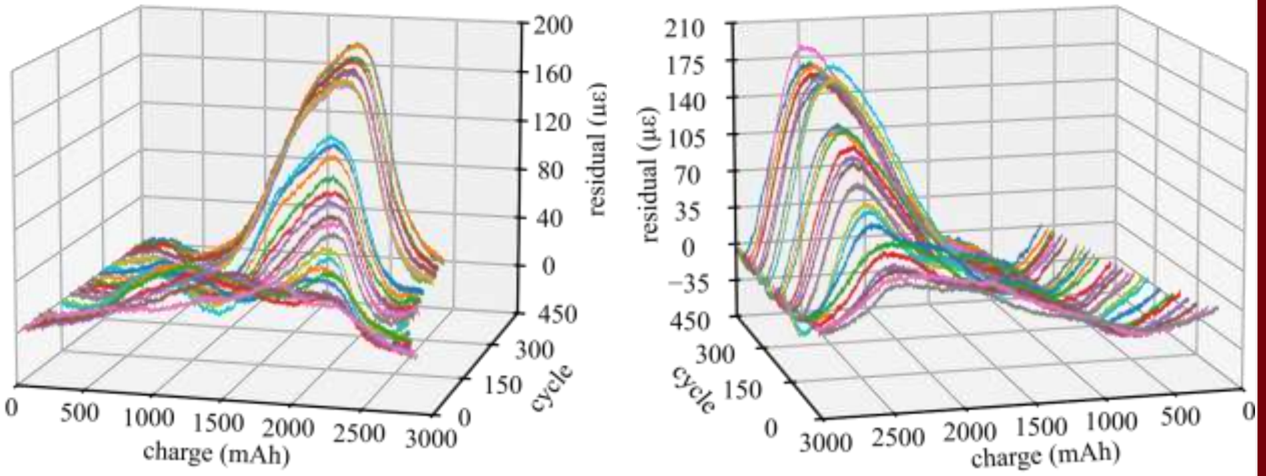
- High-utilization batteries need closer monitoring.
- Voltage and current do not show everything.
- Mechanical response carries hidden health information.
- Strain sensing adds another diagnostic channel.
- Goal: detect aging before it becomes a failure.



Strain Sensing is One Diagnostic Window

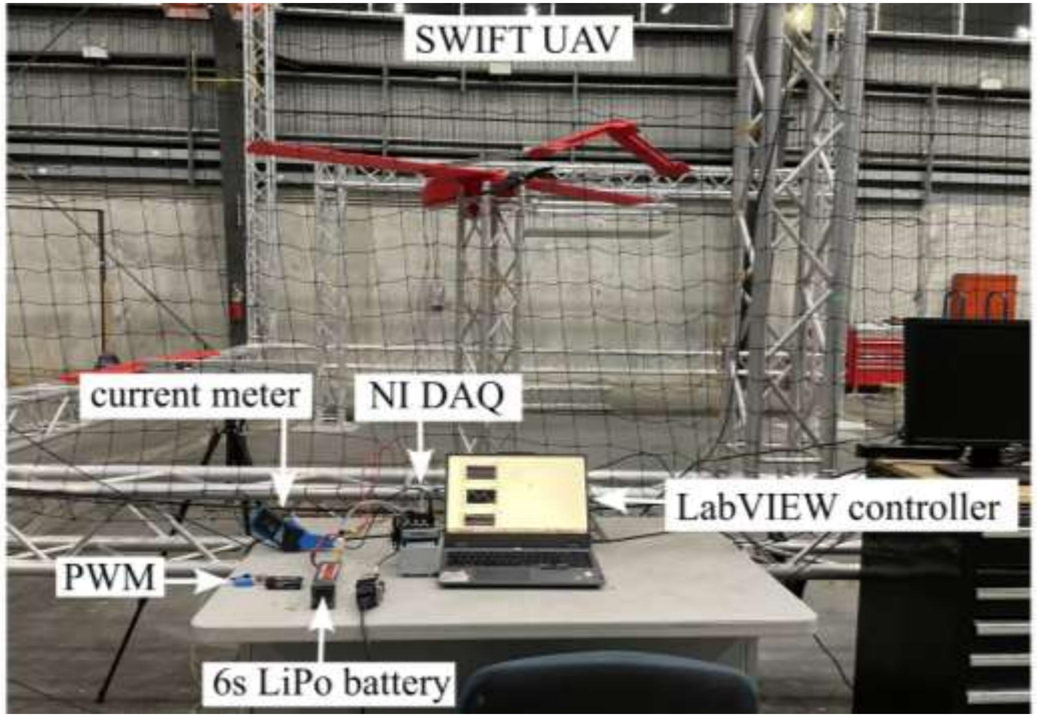
- Measures mechanical response directly.
- Tracks reversible and irreversible expansion.
- Complements voltage, current, and temperature.
- Aging and abuse leave mechanical signatures.
- Goal: diagnostics that inform controls.





Our Answer: The Full Stack

- Cell sensing for hidden states.
- Pack testing under realistic conditions.
- Aircraft models for operational decisions.
- Digital twins for fleet-level scheduling.
- Controls to keep batteries useful and safe.



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Thank You for Your Time

Electric Light Utility Aircraft Multiphysics Model

GitHub

https://github.com/ARTS-Laboratory/electric-light-utility-aircraft-multiphysics-model

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