# Sustainable Electrification of Transportation Systems


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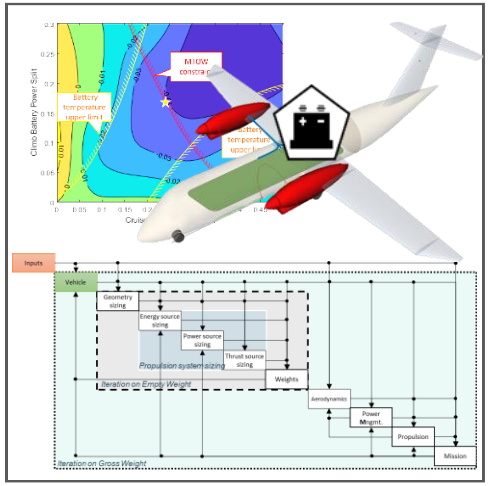
# Integrated Design of Environmentally-friendly Aerospace Systems (IDEAS) Lab

We aim to bring a **holistic approach** that accounts for the **system-level** and **life-cycle** impact of greenhouse gas emissions in the **systems design and operation of future aircraft**

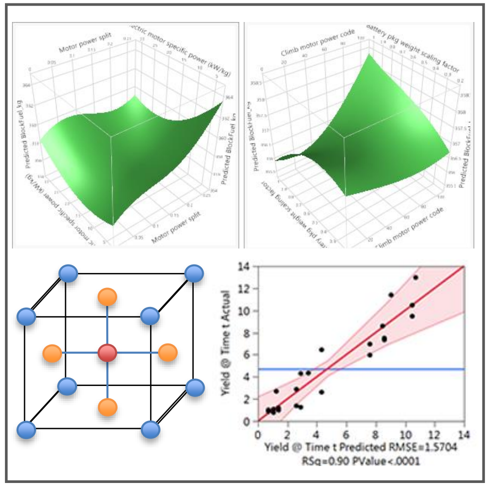
Enablers

### Multi-physics Modeling and Simulation



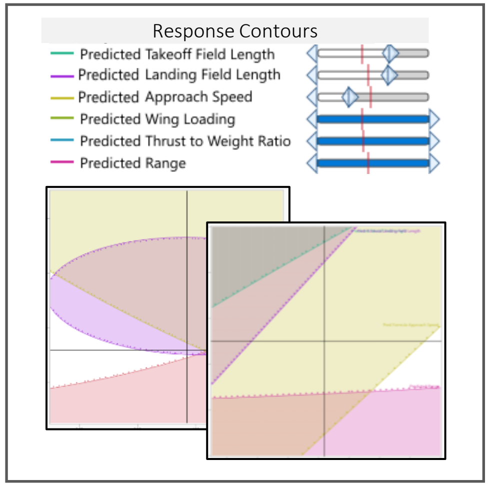
Analyze, understand and design the **complex system behavior** using model-based systems engineering (**MBSE**)

### Statistical Methods and Probabilistic Design



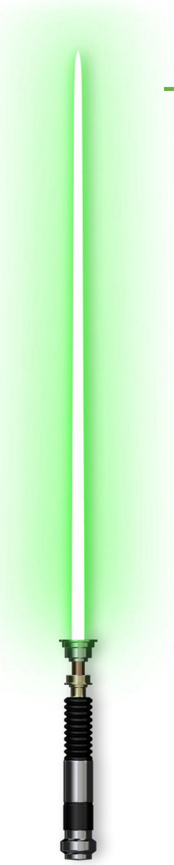
**Reduce the uncertainty** associated with novel concepts in early design phases

### Design Space Exploration and Optimization




Support decision making and explore the vast and uncharted **design space under varying constraints**

# Electrified Aircraft Propulsion



**The Light Side of Electrification**

True zero emissions *(in flight)*

Quieter

Propulsive flexibility

High efficiency

Reliability and maintainability (?)

Cost of electricity (?)


**The Dark Side of Electrification**

Jet A:
**11.9 kWh/kg**

Lithium-Ion Battery:
**0.2 kWh/kg**

**~60 times heavier**

Thermal issues

Safety and certification

Battery life and degradation

Lifecycle cost of $CO_2$

# A simple comparison

*Electrifying a single aisle plane*


**Boeing 737-800**
160 passengers
525 mph (844 km/h)

Conventional (Jet-A)

- Range: 2500 NM (4630 km)
- Fuel mass: 46,000 lb (20,865 kg)

Fully Electric

*Assuming 80% powertrain efficiency*

- For the same mass: 300 Wh/kg battery can only fly **216 NM** ➔ 8.6% of the original range
- For the same range: **3,300 Wh/kg** battery required to fly the original range ➔ 16.5 times of current tech!

# A simple comparison

*Electrifying a regional plane*


**ATR 42-600**
48 passengers
332 mph (535 km/h)

Conventional
(Jet-A)

- Range: 726 NM (1,345 km)
- Fuel mass: 2247 lb (1,019 kg)

Fully Electric

*Assuming 80% powertrain efficiency*

For the same range:

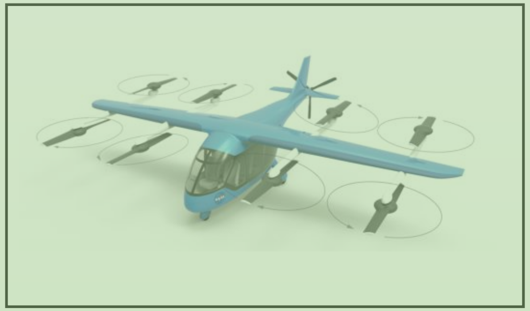
- **~22,000 lbs (10,000 kg)** battery mass at 300 Wh/kg ➔ x10 of fuel mass
- **1,300 Wh/kg** battery required at the same fuel mass ➔ 6.6 times of current tech!

# Electrified Aircraft: A Diverse Design Space

**Electric**

Uber Elevate
Urban Air Mobility
Image Credit: uber.com

Pipistrel Alpha Electro
Electric Propulsion
Image Credit: pipistrel.si

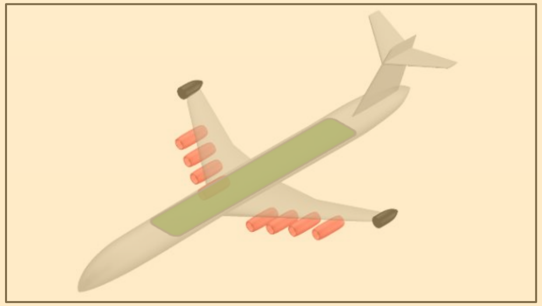


NASA Lift + Cruise eVTOL
Turboelectric Propulsion
Image Credit: nasa.gov

NASA X-57 Mod IV
Distributed Electric Propulsion
Image Credit: nasa.gov

**Hybrid**

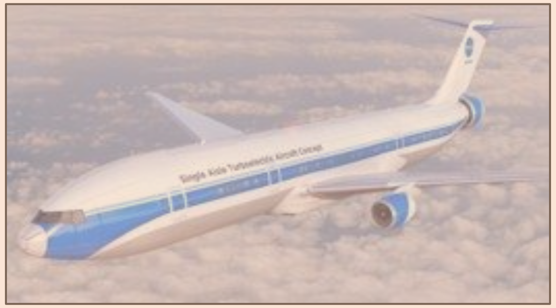
UTC Hybrid-Electric Vehicle
Parallel Hybrid Electric Propulsion
Image Credit: tech.utc.com



NASA Turboelectric ULI
Hybrid Turboelectric Distributed Propulsion

**Turboelectric**

ESAero ECO-150
Turboelectric Distributed Propulsion
Image Credit: nasa.gov



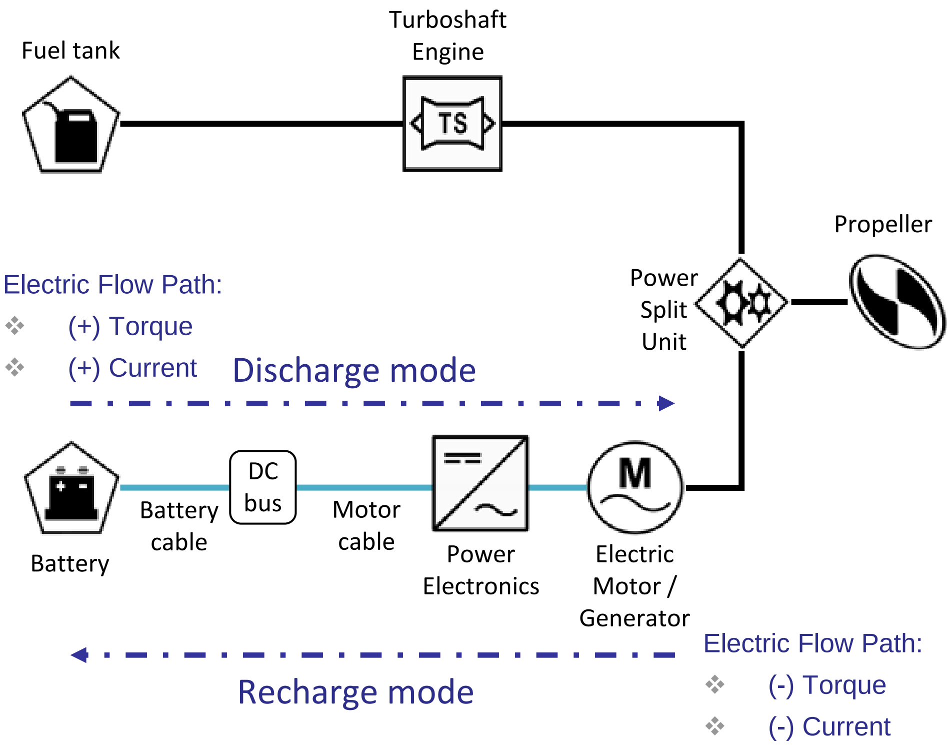
NASA STARC-ABL
Partially Turboelectric Propulsion
Image Credit: nasa.gov

More range and payload

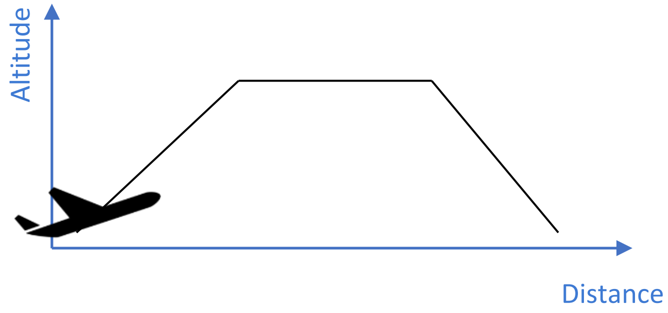
100% More Battery 0%

# Electrified Aircraft Propulsion *and* Operation

## Parallel Hybrid Electric Architecture



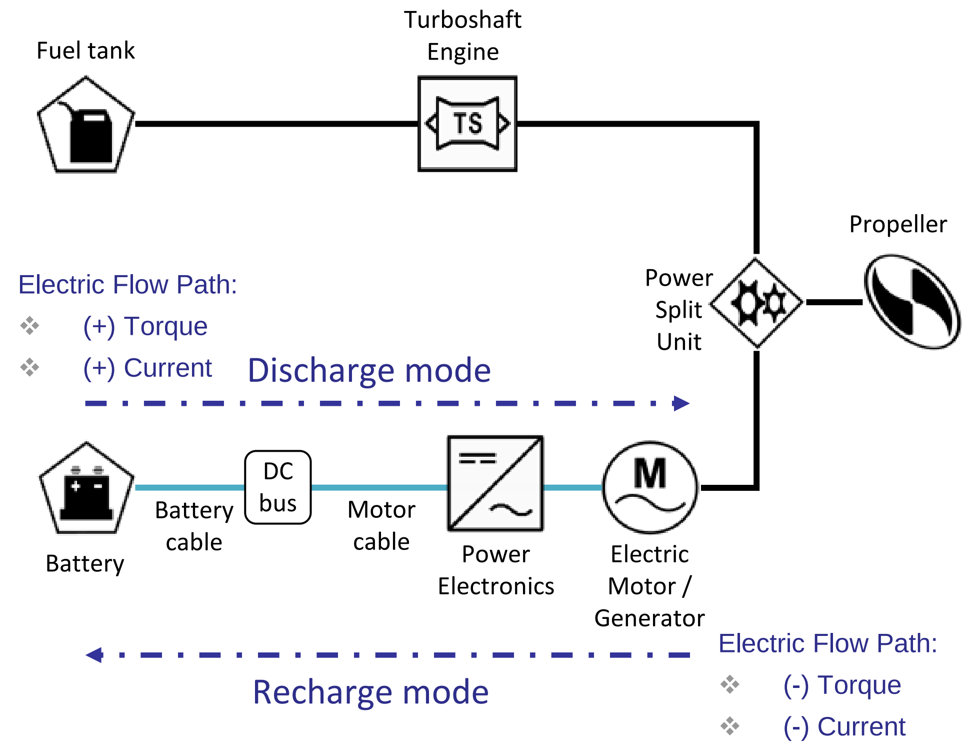

Notional mission profile




- **How much** electric power?
- **When** to electrify?
- **How long** to electrify?

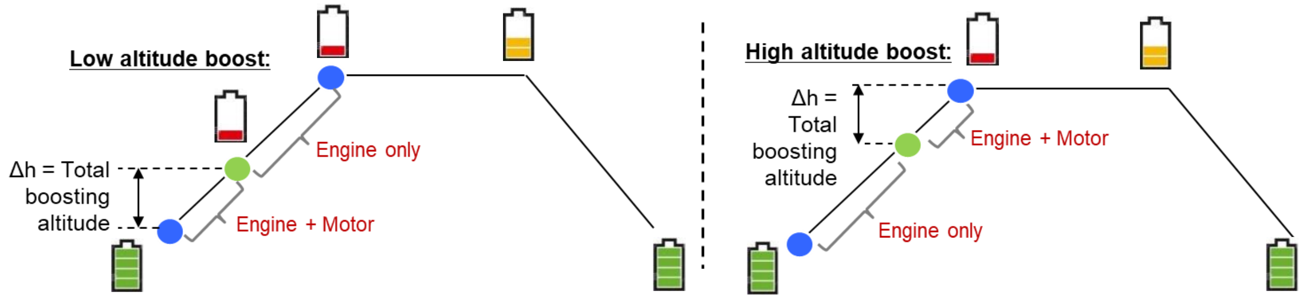
# Electrified Aircraft Propulsion *and* Operation

## Parallel Hybrid Electric Architecture




## Modes of Operation

- Takeoff power shaving
- Climb e-boost
- Electric taxi
- In-flight battery recharge




- **How much** electric power?
- **When** to electrify?
- **How long** to electrify?

*Objective: minimize fuel burn*

G. Cinar, et al. “System Analysis and Design Space Exploration of Regional Aircraft with Electrified Powertrains," Journal of Aircraft, vol. 60, no. 2, pp. 382-409.
DOI: 10.2514/1.C036919

# Benefit Assessments of a 50 pax 2030 Hybrid Electric Aircraft

**50 passenger Electrified Aircraft – Sensitivity Analysis:**

| Scenario | Block fuel (kg) | Cruise avg BSFC (lb/hr/hp) | Engine SLS rated power (kW) | Electric motor rated power (kW) | Battery capacity (kWh) | OEW (kg) | TOGW (kg) |
|---|---|---|---|---|---|---|---|
| S.0 - Advanced Conventional | 1165 | 0.3679 | 1657 | N/A | N/A | 10419 | 16539 |
| S.I - EAP no e-taxi; no charging | 1151 | 0.3684 | 1598 | 84 | 75 | 10494 | 16778 |
| *comparison over S.0* | *-1.17%* | *+0.13%* | *-3.61%* | - | - | *+0.72%* | *+1.45%* |
| S.II - EAP no e-taxi; battery charged | 1150 | 0.3687 | 1586 | 83.4 | 37.8 | 10463 | 16657 |
| *comparison over S.0* | *-1.29%* | *+0.22%* | *-4.28%* | - | - | *+0.42%* | *+0.71%* |
| S.III - EAP with e-taxi; battery charged | 1074 | 0.3697 | 1456 | 237.0 | 133.2 | 10542 | 16895 |
| *comparison over S.0* | *-7.81%* | *+0.49%* | *-12.13%* | - | - | *+1.18%* | *+2.15%* |
| S.IV - EAP with e-taxi; no charging | 1055 | 0.3700 | 1476 | 240.3 | 205.2 | 10612 | 17127 |
| *comparison over S.0* | *-9.37%* | *+0.58%* | *-10.92%* | - | - | *+1.86%* | *+3.55%* |

Corresponds to a roughly equivalent % reduction in in-flight $CO_2$ emissions

Different Operation Scenarios (S):

- S.I: 5% motor power split, full power at takeoff, full climb e-boost at full power
- S.II: 5% motor power split, full power at TKO, low alt. climb e-boost at 25% motor power for 2500 ft
- S.III: 14% motor power split, full power at takeoff, low altitude climb e-boost at full motor power for 12000 ft
- S.IV: **14% motor power split**, full power at takeoff, full climb e-boost at full power

- G. Cinar, et al. (2023) “System Analysis and Design Space Exploration of Regional Aircraft with Electrified Powertrains," Journal of Aircraft, vol. 60, no. 2, pp. 382-409.
- Project funded by NASA

# Michigan Initiative for Sustainable Aviation (MISA)

We aim to **reduce the harmful impact of aviation on the environment** through new practices and radical innovation. Sustainable Aviation has broad implications across disciplines from **engineering to environmental and climate sciences, public policy, business and law**. University and industry partners across disciplines can converge under MISA to bring a **holistic approach that considers the full life-cycle impact of design, development, and operation of aircraft systems on the environment and society.**

**Our research focus addresses:**

- High efficiency airframes
- Propulsion technologies
- Sustainability-driven system design and integration
- Energy generation, storage, and management on- and off-ground
- Thermal and power management
- Advanced multi-functional materials and ecomaterials
- Next-gen air traffic management and operational improvements
- Environmental, economical, and societal impacts

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