OPTIMAL DESIGN AND CONTROL OF BATTERY ENERGY STORAGE SYSTEMS FOR HYBRID PROPULSION AND MULTI-SOURCE SYSTEMS FOR AEROSPACE APPLICATIONS

2019 NASA AEROSPACE BATTERY WORKSHOP

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CENTER FOR AUTOMOTIVE RESEARCH – BATTERY RESEARCH

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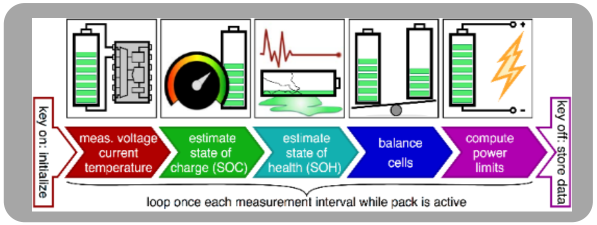
Characterization and **benchmarking** of automotive battery

(Li-ion, beyond Li-ion, lead acid, NMH,…)

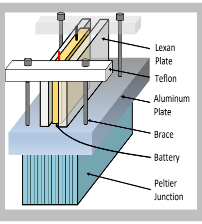


Model and **control development**

(SoC, SOH, SoX)

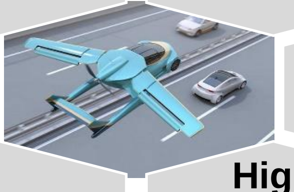
Electro-thermal characterization

Aging characterization



Transit vehicles

Passenger car



Grid connected

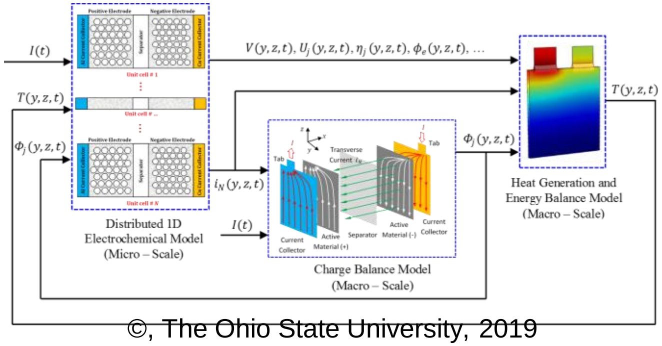
Aerospace

High performance/ racing car

- State of the art battery cyclers (µA to 1000A; up to900V)
- Thermal management testing and design
- HIL/SIL capabilities and BMS testing and calibration;

Testing facilities for cells, module, pack

Modeling, Control, Diagnostics & Prognostics



Prototyping

AGENDA

1. Introduction to the Center for Automotive Research (CAR)
2. Potential benefits and issues of Li-ion batteries in aerospace applications
3. Numerical strategies for co-optimization of design and control for multi-source systems
4. Case study: NASA ULI Electric Propulsion Challenges and Opportunities
    1. Program introduction
    2. Cell characterization and modeling
    3. design and energy management for hybrid turboelectric aircraft for commercial aviation via dynamic programming

POTENTIAL BENEFITS LITHIUM-ION ENERGY STORAGE SYSTEMS

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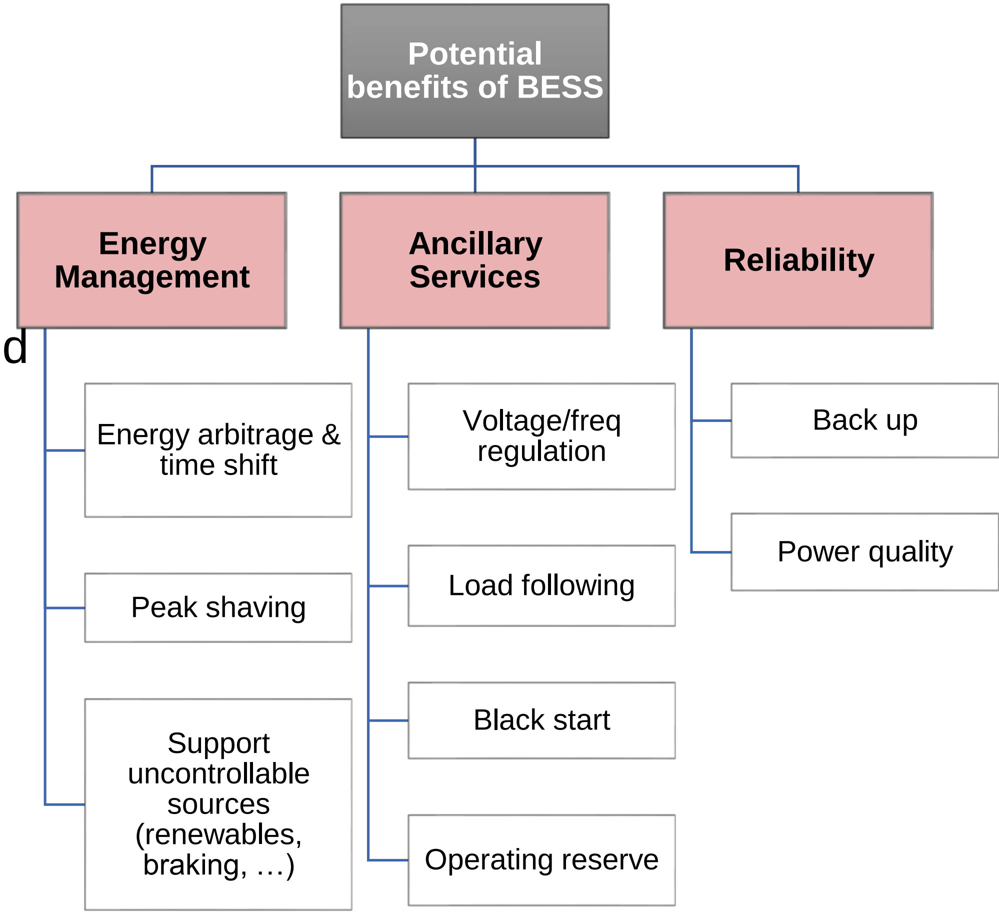
1. **System efficiency -** decoupling the energy generation from the load;
2. **Emissions** - enabling optimal control of fuel-based power generation;
3. **Management of Uncontrollable Sources** - e.g. renewable sources and regenerative braking;
4. **Controllability & Power Quality** – facilitating the management of complex multi-source systems;
5. **Reliability at the System Level** – providing back up;
6. **Weight** - 10 kg weight reduction for a aircraft will result in the saving of 17,000 tonnes of fuel and 54,000 tonnes of carbon dioxide emission per year for all air traffic worldwide (DOI: 10.1049/iet-est.2016.0019)
7. **Delay System Expansion / Investments**;
8. **Flexibility & Modularity**.



Potential benefits of BESS

- **Energy Management**
  - Energy arbitrage & time shift
  - Peak shaving
  - Support uncontrollable sources (renewables, braking, …)
- **Ancillary Services**
  - Voltage/freq regulation
  - Load following
  - Black start
  - Operating reserve
- **Reliability**
  - Back up
  - Power quality

Lithium-ion batteries represents a more sustainable and cost-effective energy solutions when compare to other energy storage devices.

CHALLENGES IN DESIGN OF LITHIUM-ION BATTERY PACKS FOR STATIONARY AND PROPULSIVE APPLICATIONS

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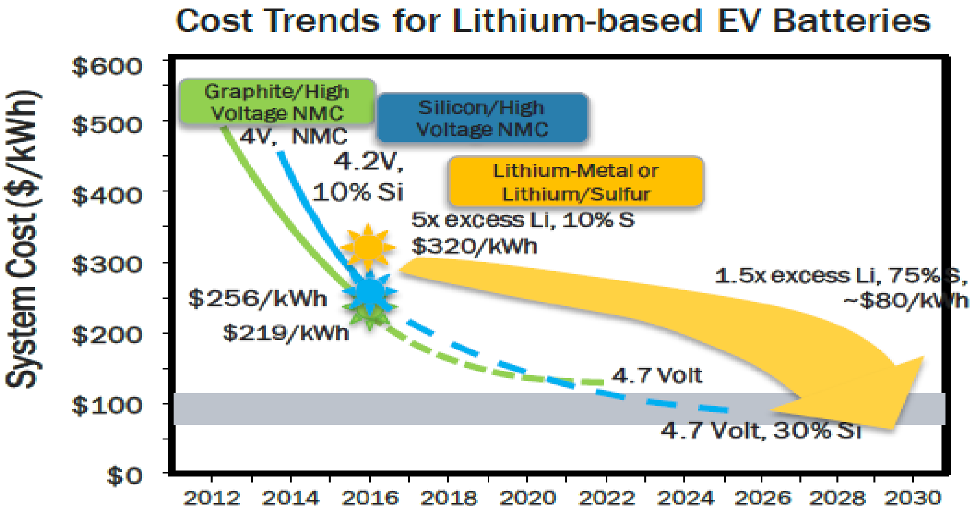
Energy Management Prospective:

1. cost (initial, operational, maintenance, replacement);
2. high energy/power density battery cells (especially for propulsive and space);
3. charging/discharging rate limits (fast charging capabilities);
4. weight overhead of electronics, packaging, and cooling required for operating lithium-ion batteries.



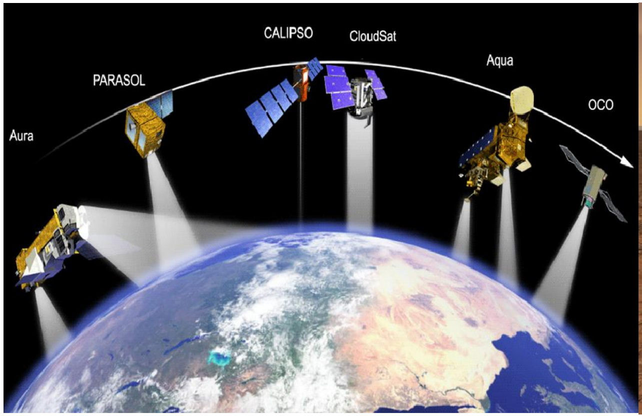
Source: US Department of Energy Vehicle Technology Office Annual Merit Review (2018)

Source: Nasa.gov

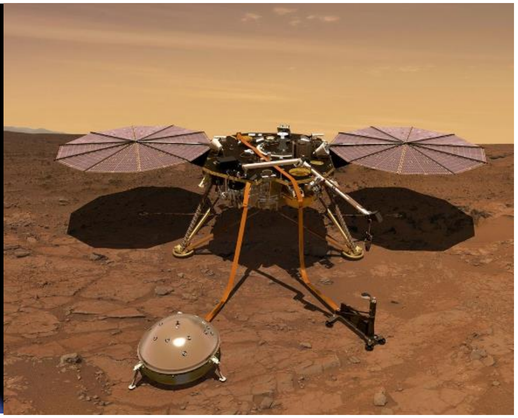
System Integration Prospective:

5. SAFETY;
6. reliability & durability of cell performance over time and capability of prognosis and diagnosis;
7. complexity of large-size high-voltage battery pack (aviation and stationary).

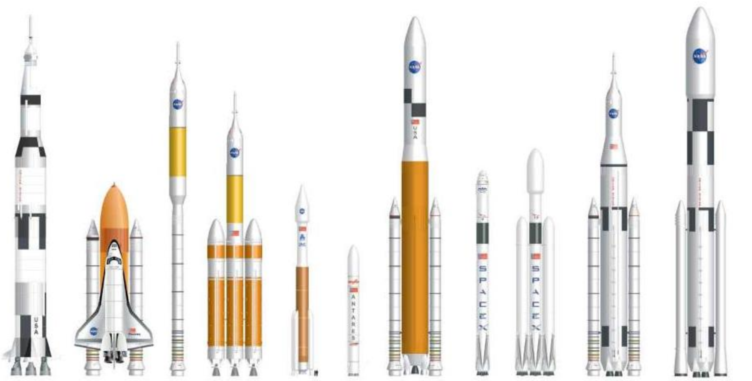
LITHIUM-ION BATTERY IN AEROSPACE APPLICATIONS



Satellites



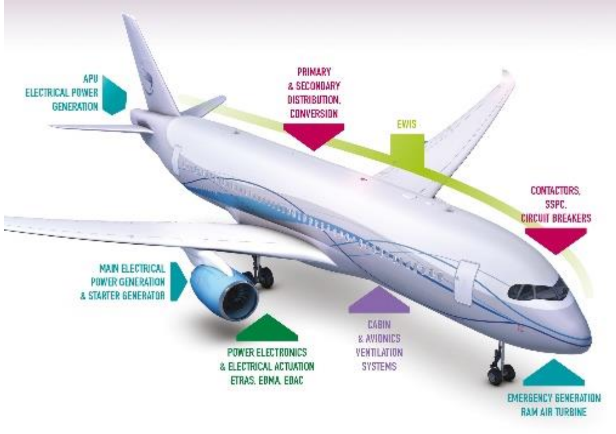
Moon/Mars exploration



Source: NASA; SpaceX; Orbital Sciences

Ken Ellis / Houston Chronicle

Launch vehicles



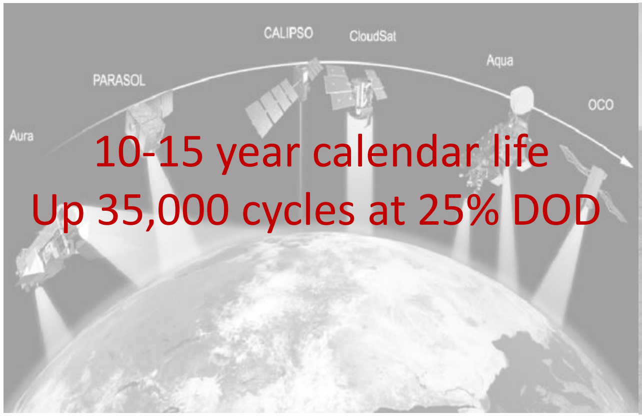
More Electric Aircraft

Electric/Hybrid commercial aviation

UAV

Sources: nasa.gov; safran-group.com

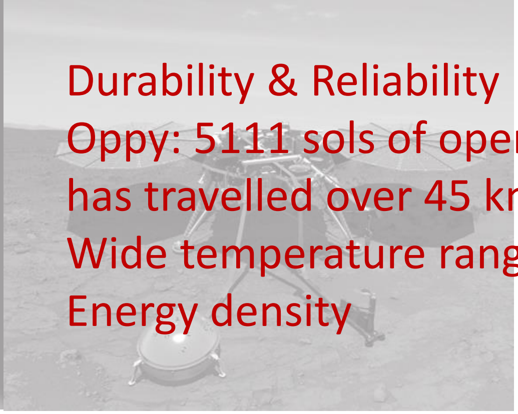
LITHIUM-ION BATTERY IN AEROSPACE APPLICATIONS



10-15 year calendar life

Up 35,000 cycles at 25% DOD

Satellites



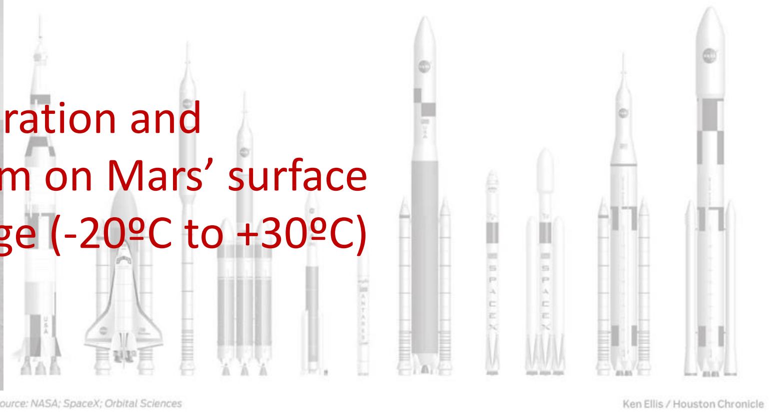
Durability & Reliability

Oppy: 5111 sols of operation and has travelled over 45 km on Mars' surface

Wide temperature range (-20ºC to +30ºC)

Energy density

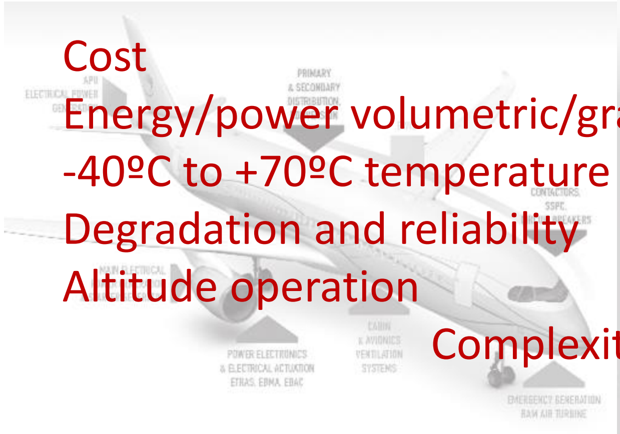
Moon/Mars exploration



Source: NASA; SpaceX; Orbital Sciences

Ken Ellis / Houston Chronicle

Launch vehicles



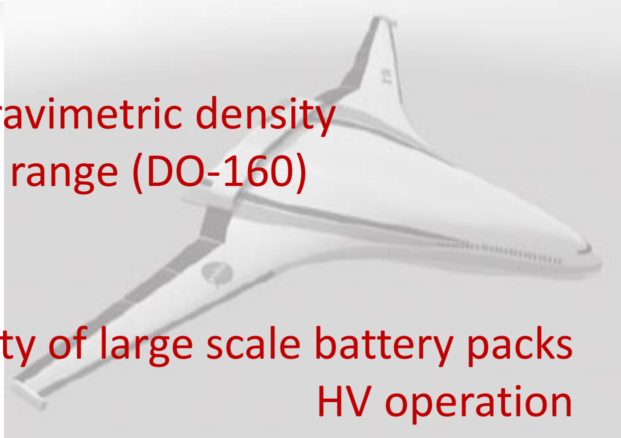
Cost

Energy/power volumetric/gravimetric density

-40ºC to +70ºC temperature range (DO-160)

Degradation and reliability

Altitude operation

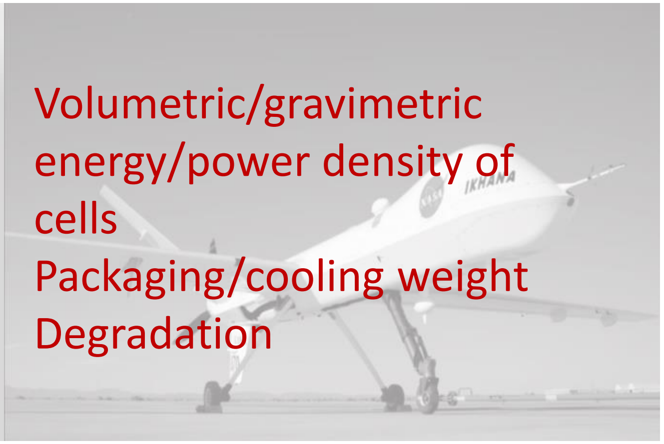


Complexity of large scale battery packs

HV operation

More Electric Aircraft

Electric/Hybrid commercial aviation



Volumetric/gravimetric energy/power density of cells

Packaging/cooling weight

Degradation

UAV

Sources: nasa.gov; safran-group.com

DOI: 10.1109/BCAA.2002.986382
doi.org/10.1016/j.electacta.2018.02.020

LITHIUM ION BATTERY TECHNOLOGIES

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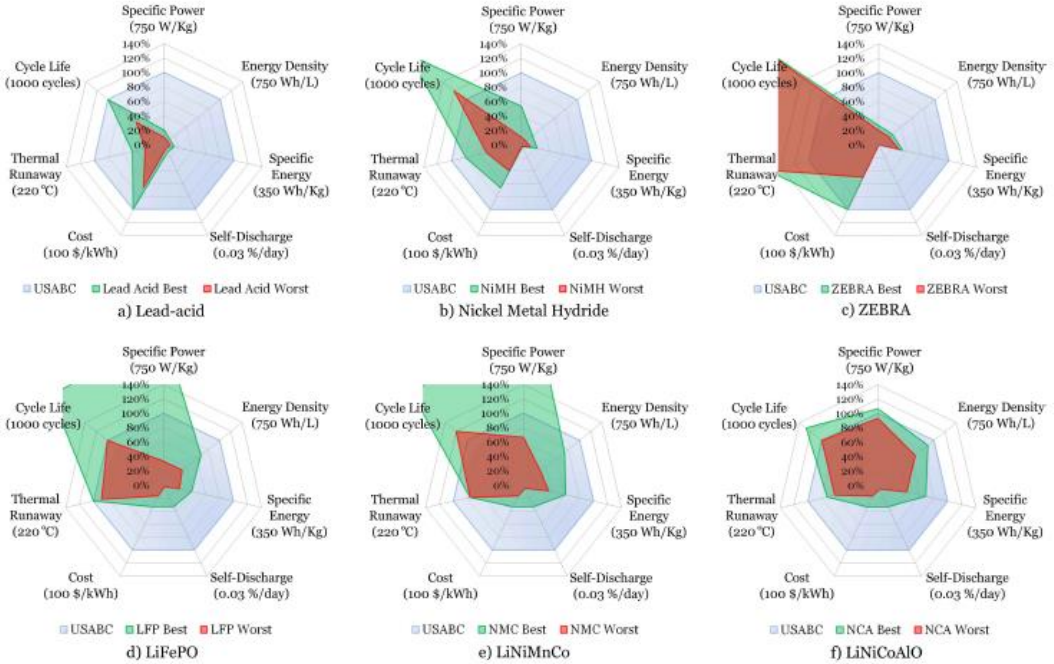


a) Lead-acid

b) Nickel Metal Hydride

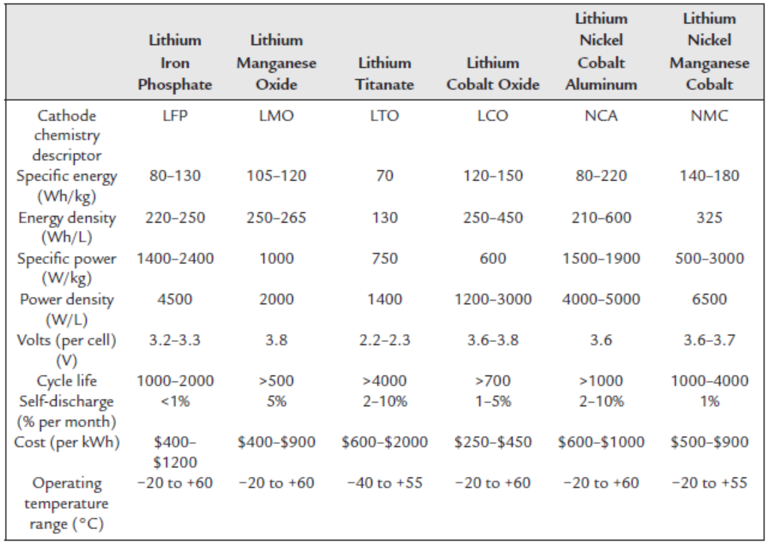
c) ZEBRA

d) LiFePO

e) LiNiMnCo

f) LiNiCoAlO

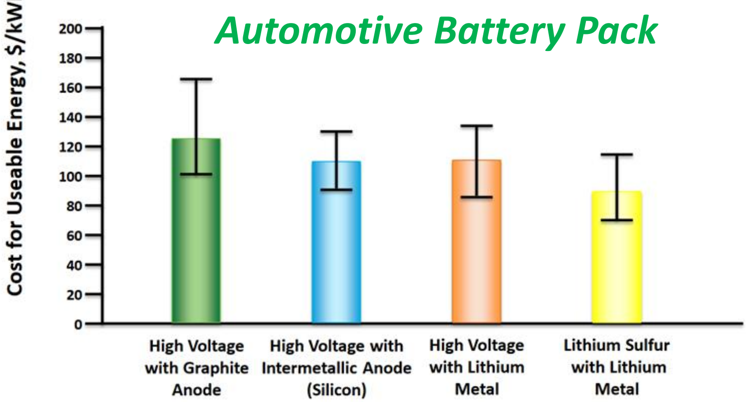
Spider plots of prevalent battery technologies

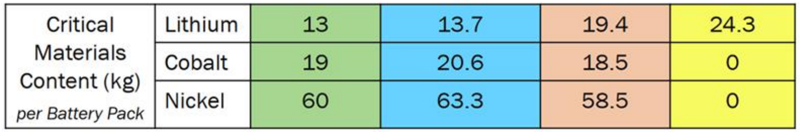


	Lithium Iron Phosphate	Lithium Manganese Oxide	Lithium Titanate	Lithium Cobalt Oxide	Lithium Nickel Cobalt Aluminum	Lithium Nickel Manganese Cobalt
Cathode chemistry descriptor	LFP	LMO	LTO	LCO	NCA	NMC
Specific energy (Wh/kg)	80–130	105–120	70	120–150	80–220	140–180
Energy density (Wh/L)	220–250	250–265	130	250–450	210–600	325
Specific power (W/kg)	1400–2400	1000	750	600	1500–1900	500–3000
Power density (W/L)	4500	2000	1400	1200–3000	4000–5000	6500
Volts (per cell) (V)	3.2–3.3	3.8	2.2–2.3	3.6–3.8	3.6	3.6–3.7
Cycle life	1000–2000	>500	>4000	>700	>1000	1000–4000
Self-discharge (% per month)	<1%	5%	2–10%	1–5%	2–10%	1%
Cost (per kWh)	$400–$1200	$400–$900	$600–$2000	$250–$450	$600–$1000	$500–$900
Operating temperature range (°C)	−20 to +60	−20 to +60	−40 to +55	−20 to +60	−20 to +60	−20 to +55

DOI: 10.1109/JESTPE.2016.2566583

Projected Cost for a 100kWh, 80kW Automotive Battery Pack





Critical Materials Content (kg) *per Battery Pack*					
	Lithium	13	13.7	19.4	24.3
	Cobalt	19	20.6	18.5	0
	Nickel	60	63.3	58.5	0

<u>Note:</u> These are the **best case projections** (all chemistry problems solved, performance is not limiting, high volume manufacturing), and do not include extreme fast charge capability.

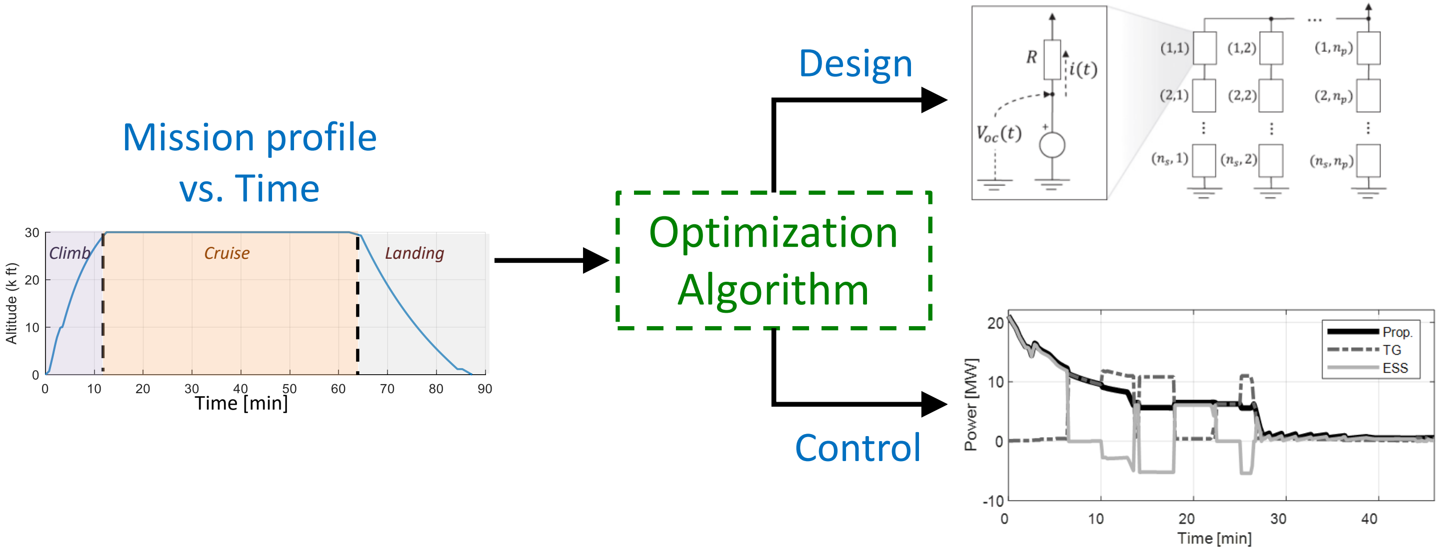
Source: US Department of Energy Vehicle Technology Office Annual Merit Review (2018)

Irena report

ISBN: 978-92-9260-038-9

BATTERY PACK DESIGN STRATEGIES FOR MULTI-SOURCE SYSTEMS

Co-optimize design and control *of* ***battery pack*** *given a mission profile:*



Mission profile vs. Time

Optimization Algorithm

Design

Control

Objective

Minimize: overall weight
capital cost
operating (lifetime) cost
degradation
thermal requirements

Design

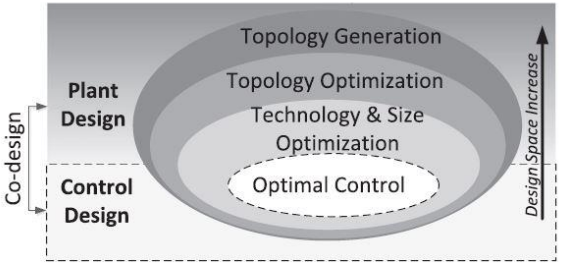
- Chemistry/format selection
- Number of cells and configuration
- Chemistry combination (if hybrid storage)
- Thermal management system
- Current/voltage/power limits

Question: how do we approach this complex coupled design and control optimization problem?

Control

- Power and thermal limits control
- dynamic power split between the different sources
- Power split between different ESS

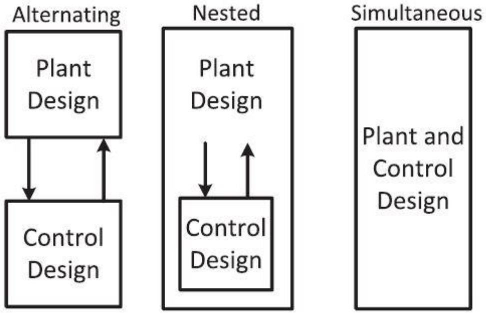
DESIGN AND CONTROL OPTIMIZATION



Design and control optimization for HEV applications results in multi-objective optimization problem with a coupling between the physical system and the control algorithm

Problem complexity increases with size of design space

Coordination architectures to solve system level optimization:

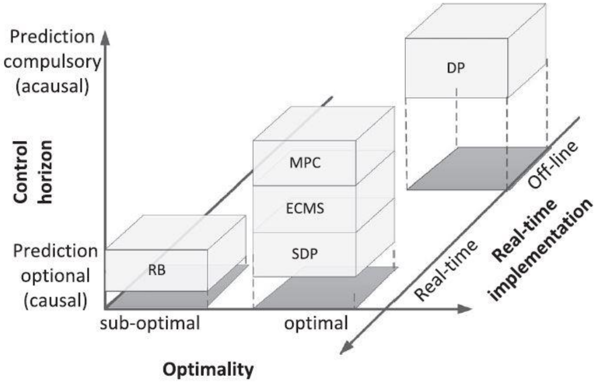


Common objective functions to minimize:

1) Fuel consumption
2) Total cost (capital and lifetime)
3) Vehicle weight

Strong dependence on design and control parameters

1) Alternating: optimize plant first, then control (iterative method, weak/no coupling between parameters)
2) Nested: control design nested within plant design (fully optimize control for every plant configuration, some coupling between parameters)
3) Simultaneous: plant and control optimized in one step (strong coupling between parameters)

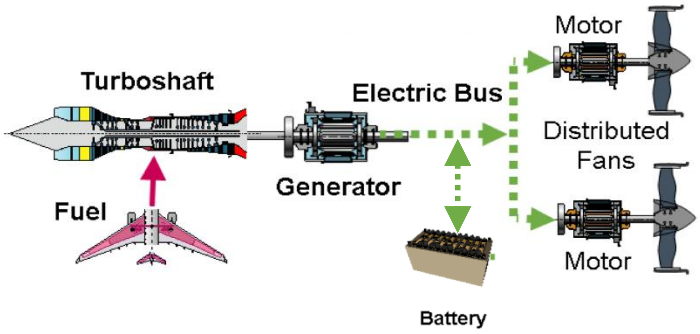


DP typically used as benchmark solution for online control optimization strategies

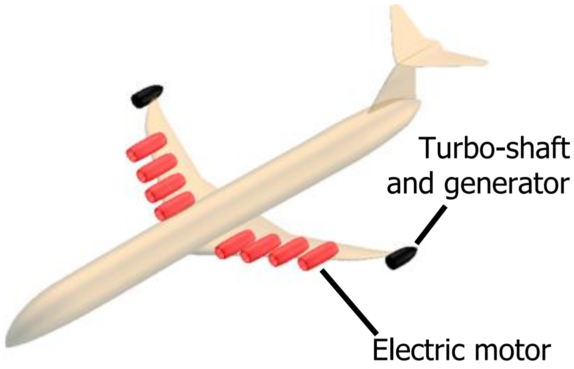
E. Silvas, T. Hofman, N. Murgovski, L. Pascal Etman, and M. Steinbuch, "Review of Optimization Strategies for System-Level Design in Hybrid Electric Vehicles," *IEEE Transactions on Vehicular Technology,* Vol. 66, No. 1, January 2017.

NASA ULI ELECTRIC PROPULSION: CHALLENGES AND OPPORTUNITIES

NASA ULI Electric Propulsion: Challenges and Opportunities



Felder, J.L., NASA Electric Propulsion System Studies, Report No. GRC-E-DAA-TN28410, 2015, Available at www.nasa.gov.



The Ohio State University

NASA

North Carolina A&T State University

Georgia Tech

Wisconsin University of Wisconsin-Madison

University of Maryland 1856

Distributed electric propulsion is a leading architecture for measurable CO_2 reduction on large commercial aircraft - regional, single aisle, and twin aisle.

- Two turbo-generators to supply electrical power to distributed motors
- Eight motors with embedded power electronics
- Integrated thermal management system
- Battery energy management can be charge-depleting or charge-sustaining; battery thermal management system is separate from powertrain

Challenge 1 System Integration

Success Criteria: Vehicle energy and CO_2 >20% improvement over existing solutions

Challenge 2 Ultra-High Power Density Electric Machine and Power Electronics

Success Criteria: Electric machines > 14 kW/kg, power electronics > 25 kW/kg, efficiency > 99%, bus voltage up to 2kV without partial discharge

Challenge 3 Energy Storage

Success Criteria: Power density and reliability (desired 450 Wh/kg)

Challenge 4 Advanced Control of Onboard Electrical Power Systems

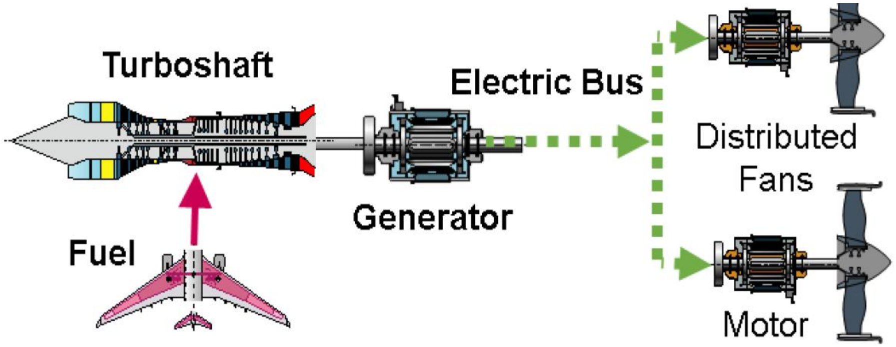
Success Criteria: System remains stable at 20% voltage sag and 200% step load change

Challenge 5 Research Infrastructure for More Electric Aircrafts

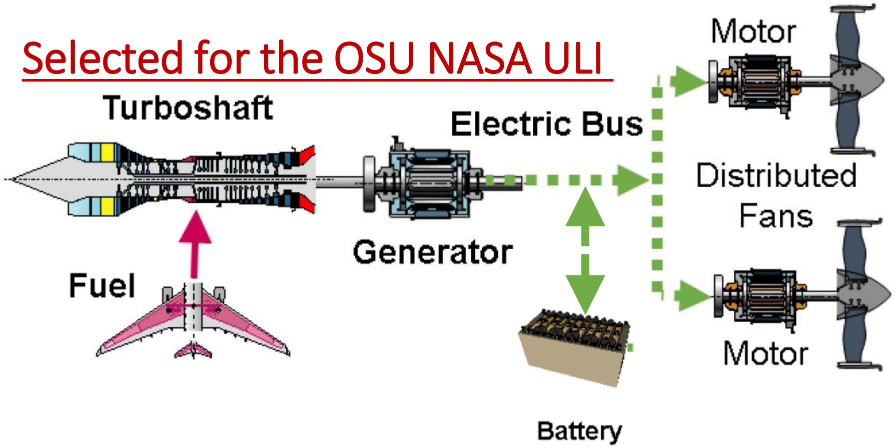
Success Criteria: Sub-system and component prototyping and testing at elevation – 2 kV, 1 MW, 20 kRPM drive tests

Research on thermal management system design is integrated in every aspect of the project.

Benefits of Battery Turboelectric Hybrid Aircrafts



Selected for the OSU NASA ULI



Turboelectric Distributed Propulsion

Benefits:

- Enable new aero efficiencies
- Improve propulsion efficiency
- Freedom in engine design
- Enable Power Sharing between fans
- Degree of freedom in using residual thrust form the turboshaft

Challenges:

- High **efficiency** electric machine and power converters
- **Weight** -> increase energy density of the electric drive
- **System integration**

Distributed Series Hybrid Turboelectric

Benefits:

- As turboeletric solution
- Use battery as buffer ad peak shaving
- Optimize power split battery/turboelectric
- Improve dynamic stability of the electric bus

Challenges:

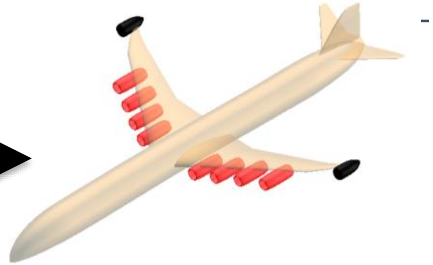
- **System integration**
- Increase system **complexity**
- **Weight** -> increase energy density of the battery packs (cells and system integration
- **Safety, reliability, and lifetime**

Felder, J.L., NASA Electric Propulsion System Studies, Report No. GRC-E-DAA-TN28410, 2015, Available at www.nasa.gov.

Benefits of Battery Turboelectric Hybrid Aircrafts

Baseline Aircraft (CRJ 900)

Next Generation Aircraft (A220)

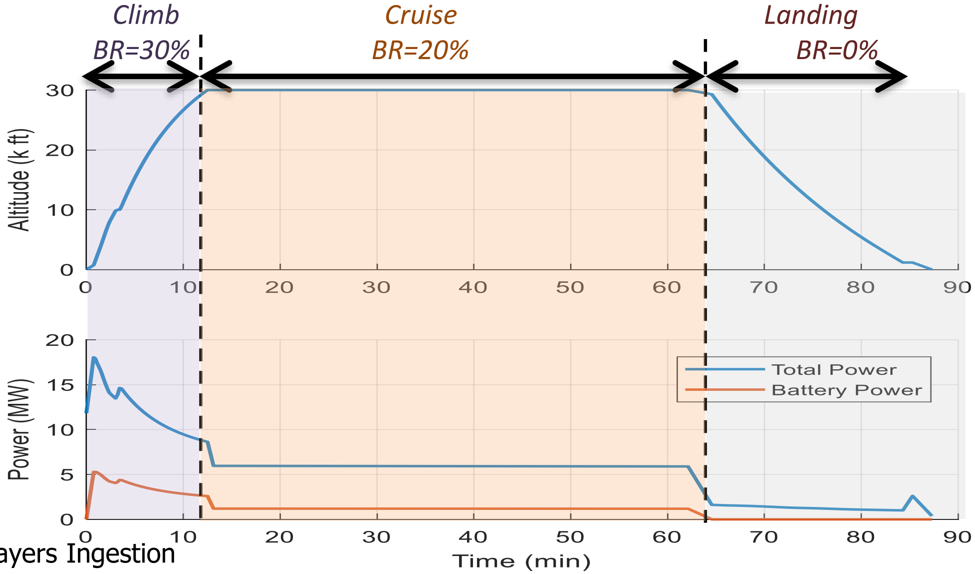


Distributed Hybrid Turbo Electric

15% improvement to Next Gen (A220)

Fuel Burn Reduction at 600 nmi and typical payload

8%



Distributed Propulsion

9%

Use of Hybrid Propulsion

6%*

BLI/Optimized Power management

~5%

BLI = Boundary Layers Ingestion

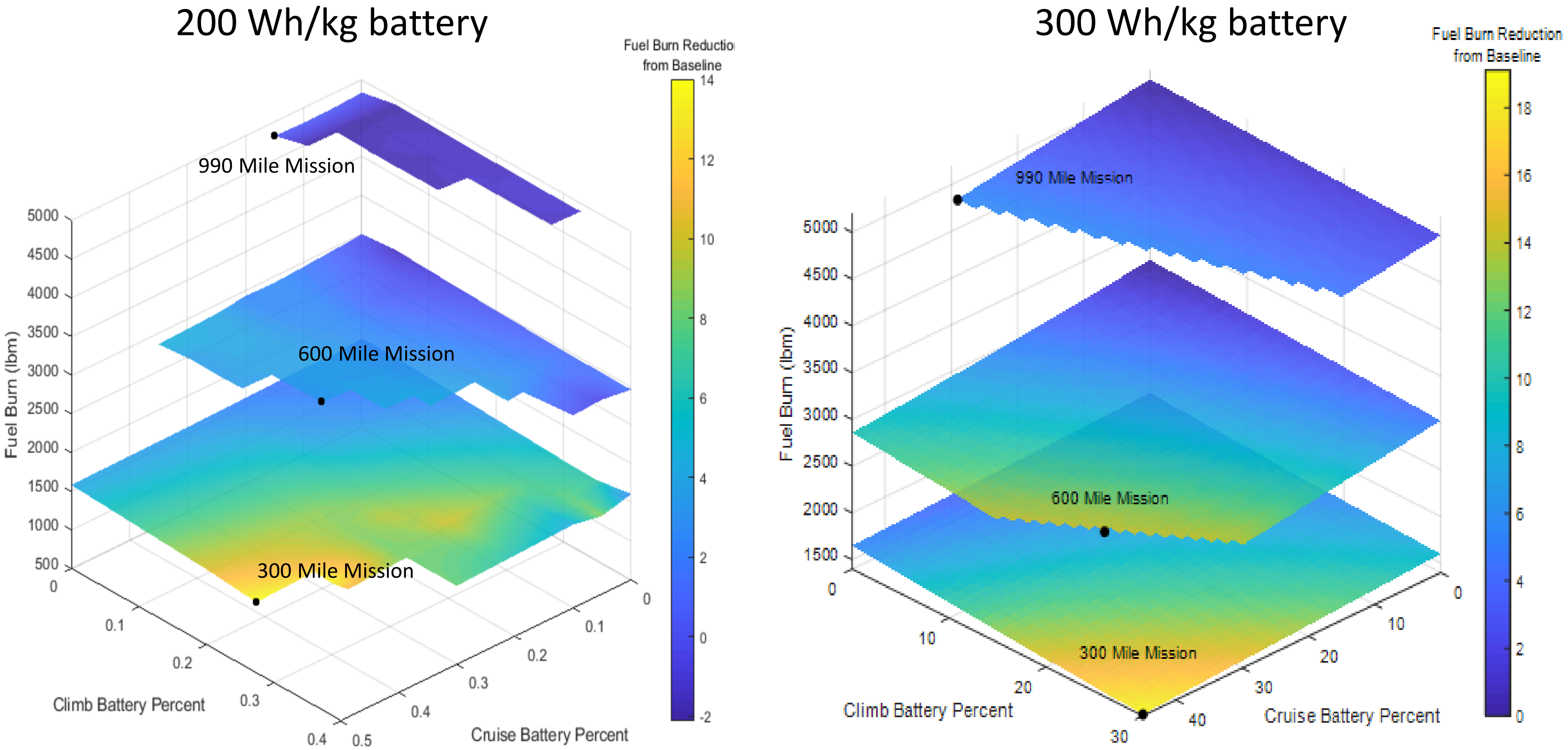
BR = Power split between Batteries and Turboshaft

*Assumes 200 Wh/kg batteries used at rate of 30% of overall propulsive power during climb and 20% during cruise @ 600 nmi.

Perullo, C., Alahmad, A., Wen, J., D'Arpino, M., Canova, M., Mavris, D. N., & Benzakein, M. J. (2019). Sizing and Performance Analysis of a Turbo-Hybrid-Electric Regional Jet for the NASA ULI Program. In *AIAA Propulsion and Energy 2019 Forum* (p. 4490).

Feasibility Analysis

Missions simulated in GT-HEAT with a **93% efficient electric powertrain, no battery power limits, constant power split during climb and cruise**



Fuel burn reduction compared to the Turboelectric solution with Distributed Energy Propulsion

Feasibility Analysis

Design of a 2MWh battery pack for the 600nmi. 30% climb – 20% cruise mission profile.

Cell	Cell 1	Cell 2	Cell 6	Cell 7	Cell 8	Cell 9
Format	18650 Cylindrical		Pouch			
Chemistry	LMO	NMC	NMC	Li-Si	Li-Metal	Li-S
Capacity assessment [Ah] (@1C, $23^{o}C$)	3.25	2.85	10.87	10.24	(19.40)	(14.7)
Energy Density assessment [Wh/kg] (@1C, $23^{o}C$)	237	215	224	336	(478)	(363)
Experimentally Tested?	Yes				No	No
ΔSoC_{avail}	(10-95)%					
$m_e n_e$ *- Total Cell Number*	**176,472 (516s x 342p)**	**196,560 (504s x 390p)**	**51,816 (508s x 102p)**	**54,752 (472s x 116p)**	**27,608 (476s x 58p)**	**66,990 (770s x 87p)**
Max C-rate (discharge)	2.20	2.26	2.16	2.15	2.28	2.06
Heat Generation (kW) (Peak/Average)	672 / 66	357 / 42	438 / 41	330 / 24	74 / 7	-
Efficiency [%] (Min/Average)	88 / 97	90 / 97	92 / 98	94 / 98	94 / 98	-
Pack Weight (Tons)	**8.39**	**9.26**	**8.88**	**5.91**	**4.16**	**5.69**

Design & Control Optimization Problem

Series/Parallel Battery-Hybrid Turboelectric with Distributed Propulsion

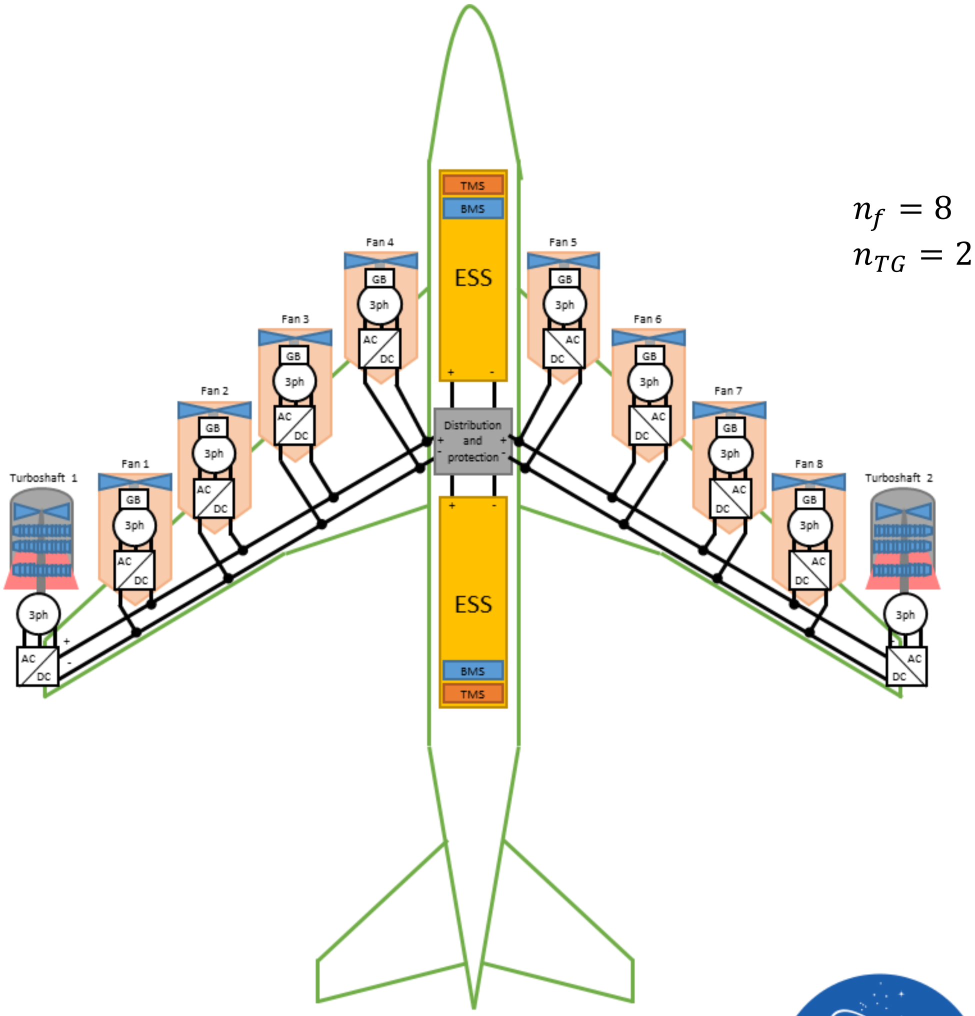
Design Factors:
- Cell chemistry
- Number of cells (S/P)

Control variables:
Electric power split

External Inputs:
- Mission profile (time, MN, altitude)
- Aircraft assembly (mass tracking)

Pack Design Objectives:
- Pack weight and volume
- Pack cost
- Operating costs (degradation and replacement)

Energy Management Objectives:
- Fuel burn over mission / total energy use
- Cost of total energy (fuel+electrical)
- Overall CO2 production



$n_f = 8$
$n_{TG} = 2$

Modeling Overview

PLANT DESIGN

Design: Energy Storage System selection and sizing

Iterate design between different chemistry and weight

Constraint: maximum take off weight

Initial conditions: initial fuel estimation

Optimize initial weight of the aircraft and ensuring the mission serve fuel

Input: Mission Profile

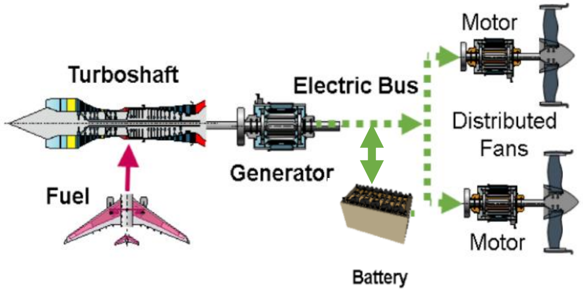
Consider different climb rate with respect to the aircraft weight

CONTROL DESIGN

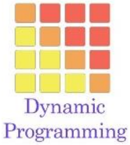
Map-based quasi-static component models

Fan (GT, NPSS) thrust as function of MN, altitude, motor torque, and speed	**Electric Distribution (OSU CAR)** Power losses on wiring and distribution components
Turboshaft (GT, NPSS) fuel burn, shaft power, and thrust as function of MN, altitude, FAR, and electric power slip	**Battery (OSU CAR)** voltage, state of charge, heat generation, aging estimated by equivalent circuit model
Generator (TBD)	**Power Converters (OSU CHPEE)** Conversion efficiency as function of DC link voltage, power request
Motor (UW) Torque-speed curve and efficiency map as function of torque and speed	**Airframe (GT, FLOPS)** Aerodynamic perf., Maximum Take Of Weight (MTOW)

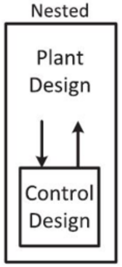
Powertrain architecture & Optimal Power Flow Control



Minimize Fuel Burn & Battery Aging



Constrained by: max battery power, components maximum power, thermal limits

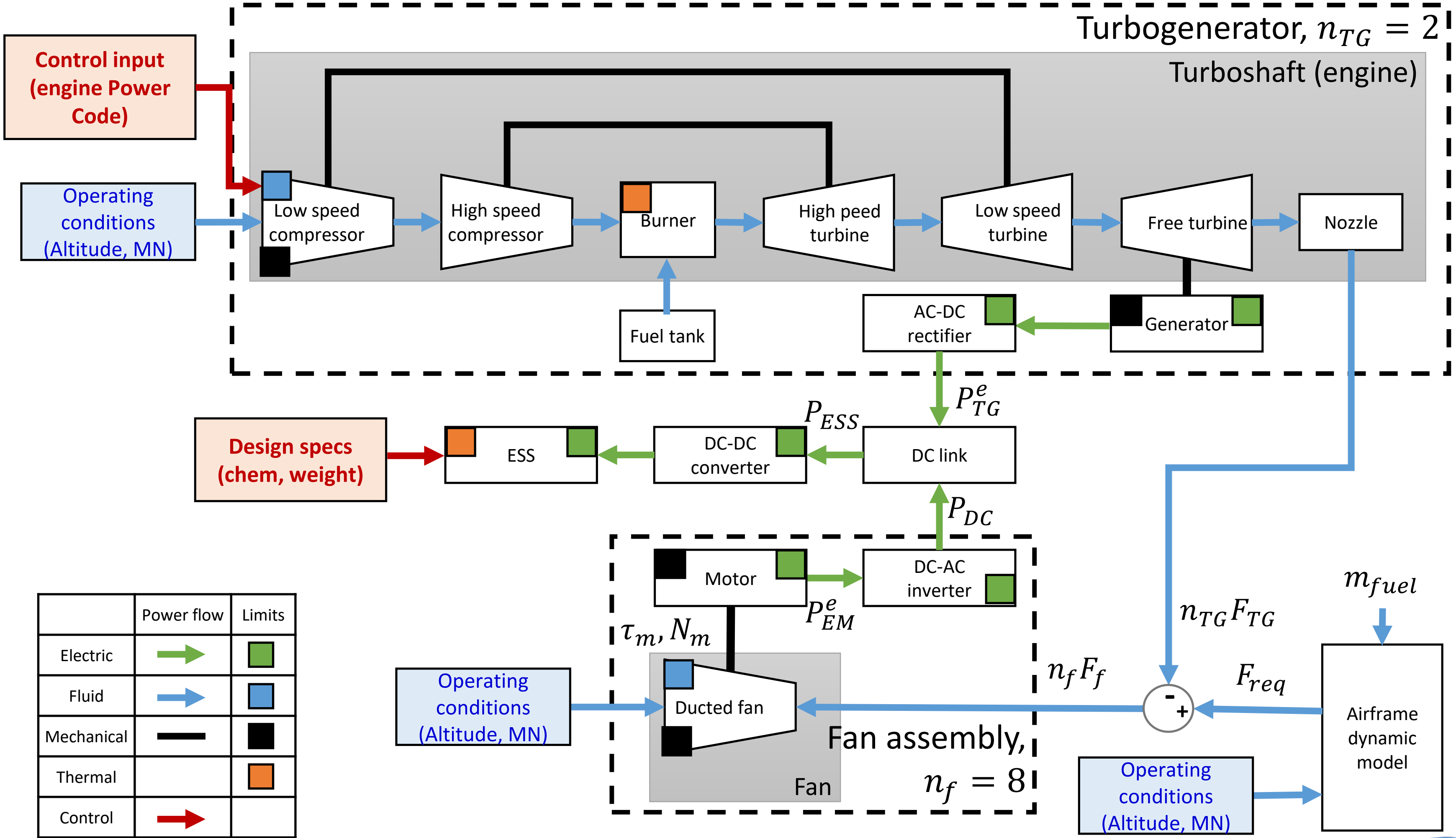


Co-optimization of Design and Control Strategy

Nested approach: control design nested within plant design (fully optimize control for every plant configuration, some coupling between parameters)

Model Architecture

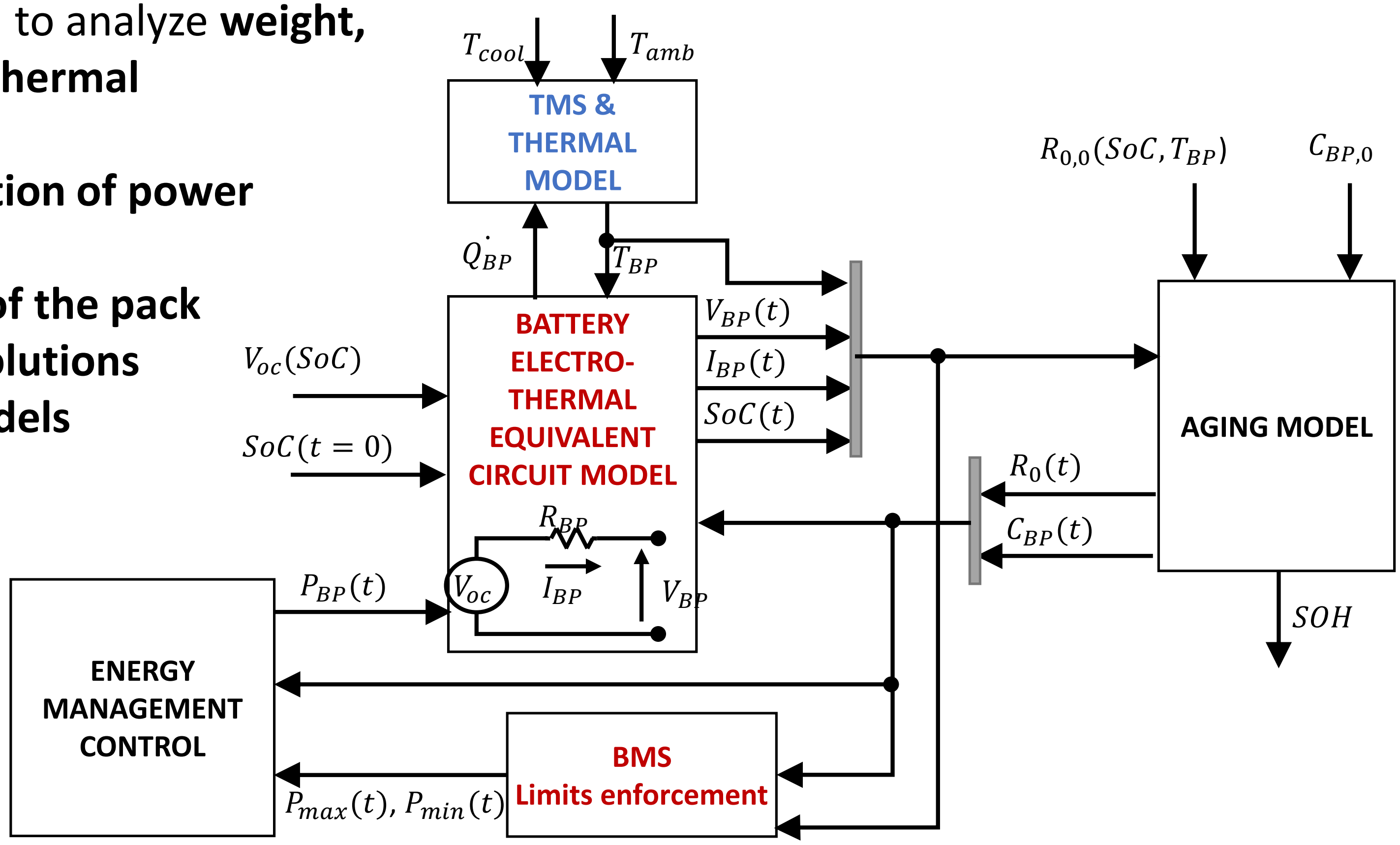
Series/Parallel Battery-Hybrid Turboelectric with Distributed Propulsion



	Power flow	Limits
Electric	→	🟩
Fluid	→	🟦
Mechanical	—	⬛
Thermal		🟧
Control	→	

Battery Cell/Pack Model - Overview

- Prediction model to analyze **weight, battery life** and **thermal requirements**
- **Dynamic estimation of power limits**
- **Thermal model of the pack including TMS solutions**
- **Degradation models**



Calibration for several state of the art (TRL>7) and advanced (low TRL) lithium-ion cells

Experimental Tests:

0, 10, 23 and 50˚C

- Multi-rate capacity - Energy density assessment
- Dynamic Pulse testing - HPPC/RCID
- Performed on multiple samples and cell models for benchmarking

Experimental Tests:

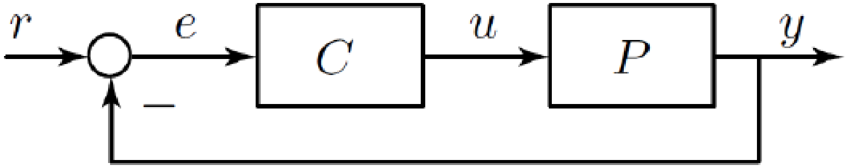
Non-isothermal thermal tests

- Capacity and dynamic profile
- Temperature rise on cell skin is measured for modelling
- Cell to pack analysis

https://doi.org/10.2514/6.2019-4469

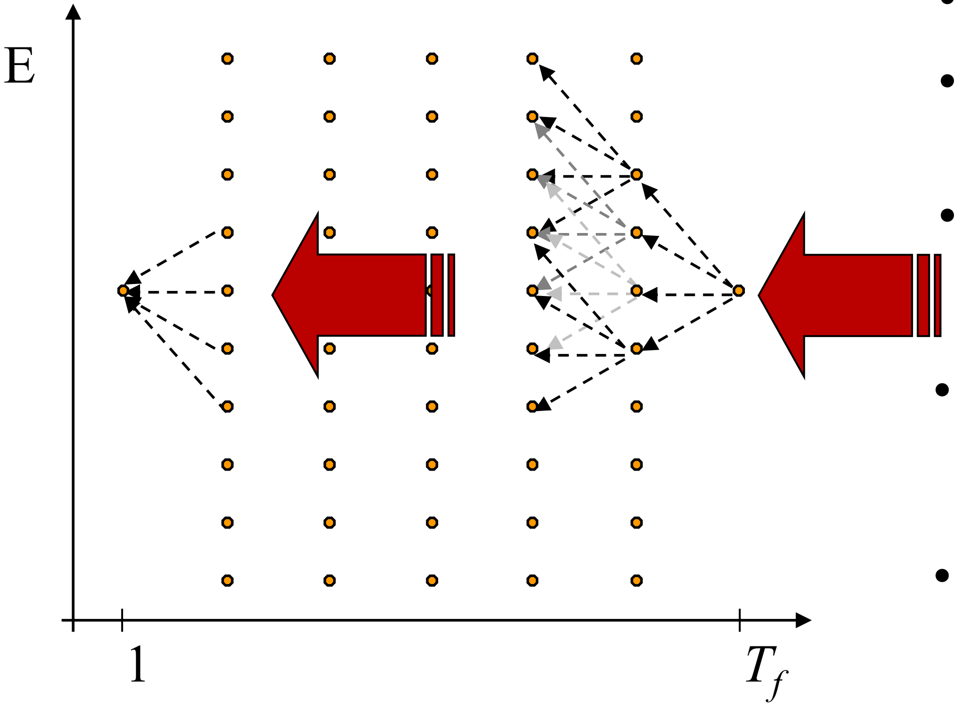
Model-Based Control Design Strategies

- ***Causal energy management strategies:***



- *Use a reference signal and the **current** system output (example, SOC) to make a decision on the control input.*
- *Easy to implement, but suboptimal!*

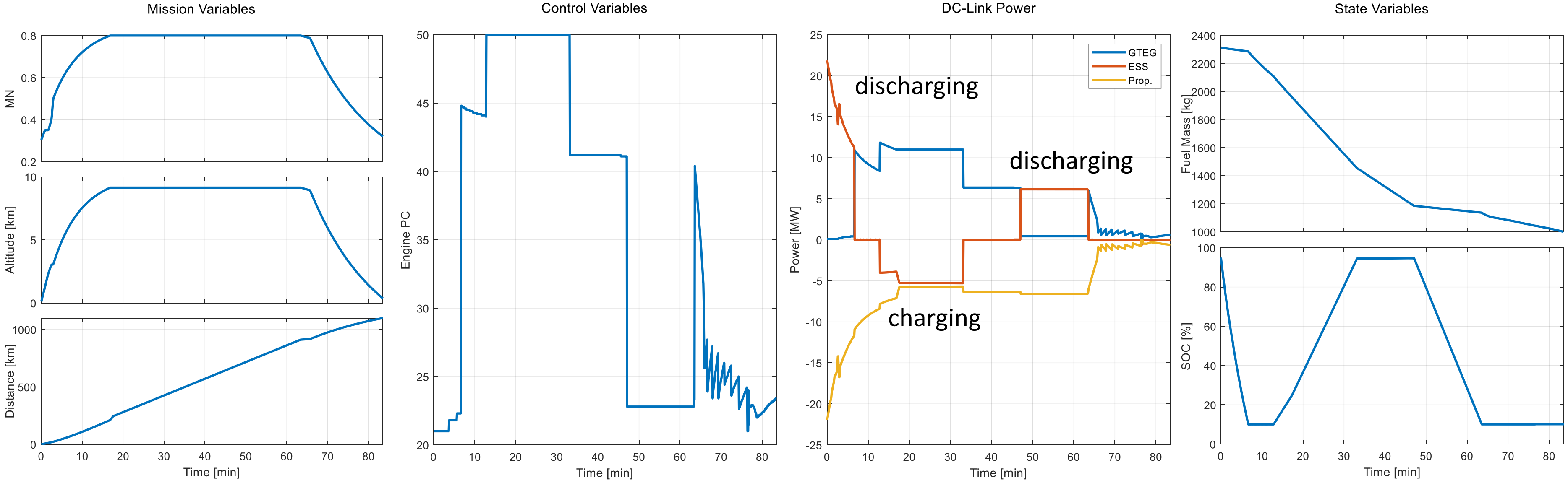
- ***Non-Causal energy management strategies (Dynamic Programming):***

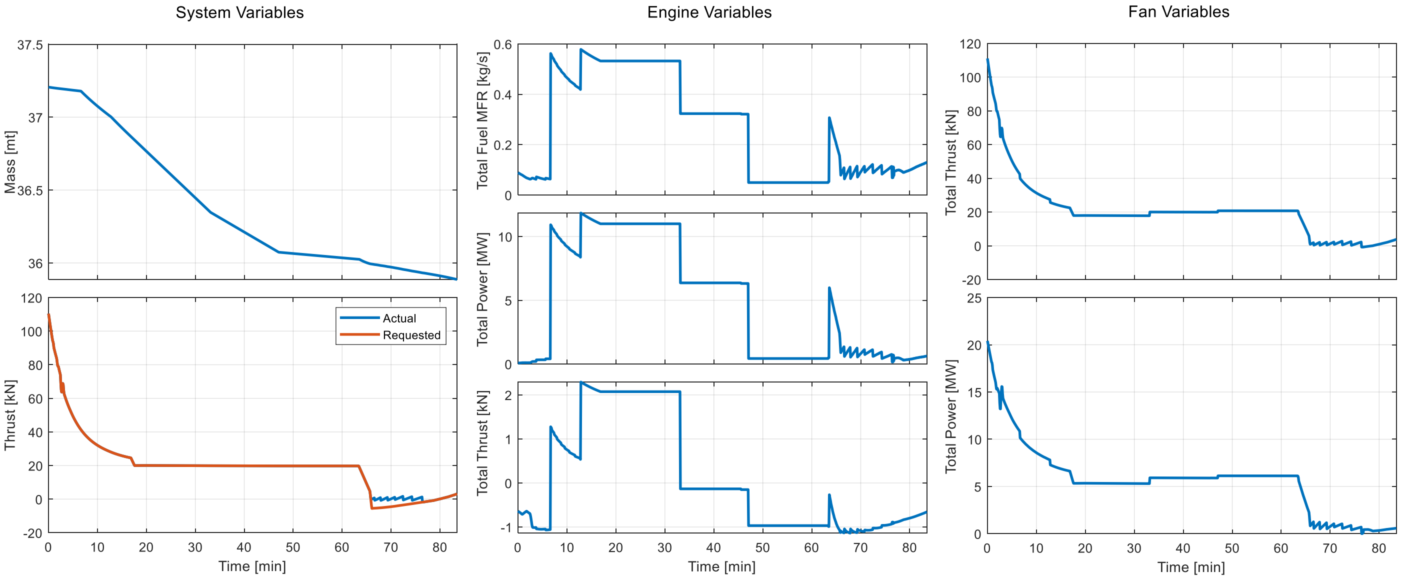


- ***Guaranteed optimal solution!***
- *Require the knowledge of the future (backward algorithm).*
- *Complexity grows exponentially with the number of control inputs and states (e.g., battery SOC).*
- **Dynamic Programming (DP)** is a numerical method based on the Bellman's Optimality Principle
- The algorithm is based on a recursive process that uses a **discretized version of the problem**

DOI: 10.1109/CCA.2009.5281131

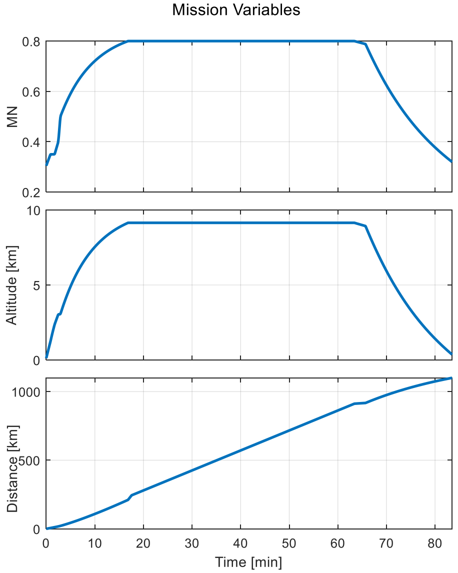
DP Results 600nmi mission
(ESS mass of 10,000kg and GED of 200Wh/kg, No Power Limits)

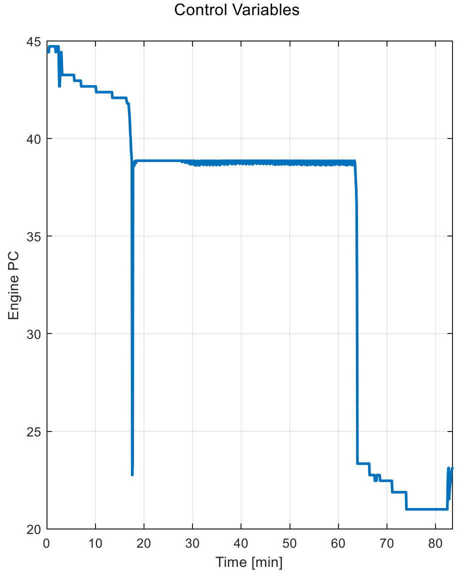


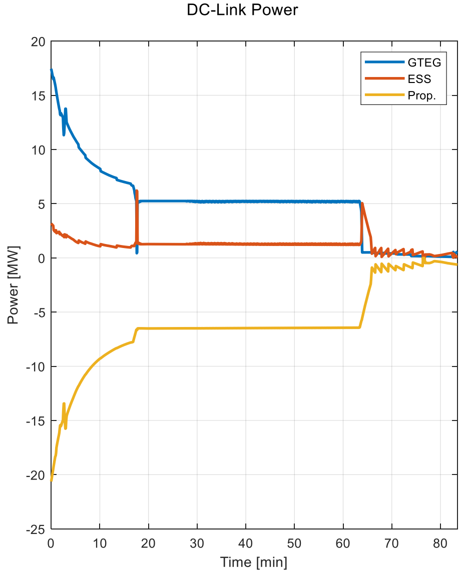


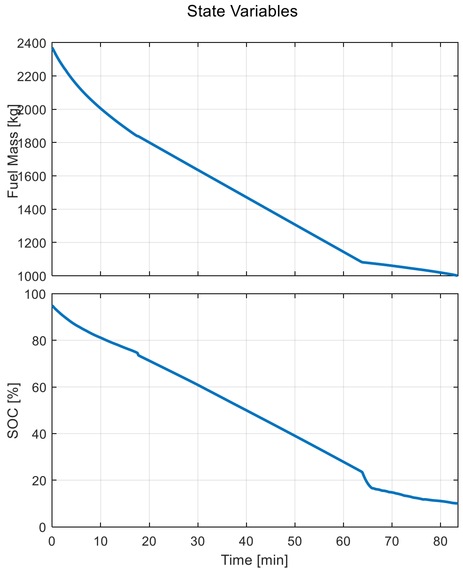
The battery pack is used during climb, charged during part of cruise and then used at the end of cruise. **Peak current of 10C is required during climb.**

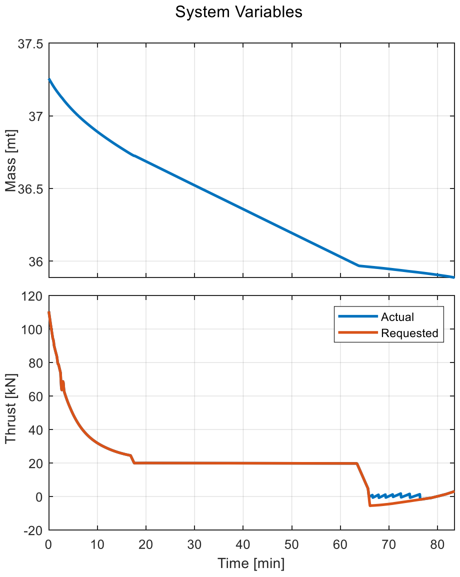
DP Results 600nmi mission
(ESS mass of 10,000kg and GED of 200Wh/kg, with Power Limits)

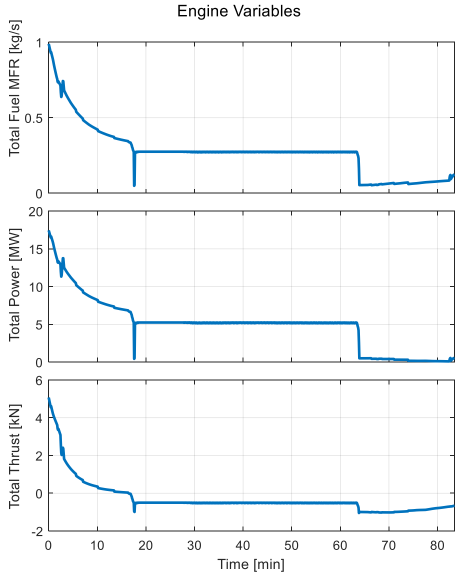


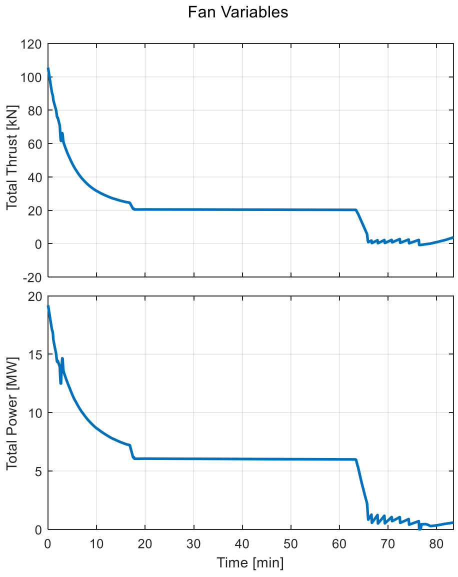


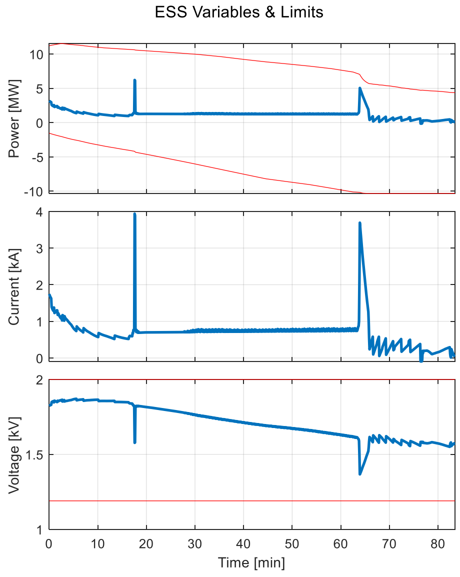












Summary for ESS mass of 10,000kg and GED of 200Wh/kg

Fuel burn reduction compared to the Turboelectric solution with Distributed Energy Propulsion

		Fuel Burn				Battery Energy		
Mission	**Setup**	**Mass [kg]**	**Reduc. [%]**	**$\mathrm{SOC}(t_0)$ [%]**	**$\mathrm{SOC}(t_f)$ [%]**	**Disch. [kWh]**	**Ch. [kWh]**	**Net [kWh]**
Length: 600 nmi **Climb: 13.4 min** **Cruise: 30 kft 0.8 MN**	No ESS	1413	-	-	-	-	-	-
	27 Climb, 18 Cruise Rule based control	1358	**3.9**	95	11	1683	0	1683
	DP w/o Limits Optimal control	1265	**10.5**	95	10	4210	2511	1700
	DP w/ Efest Optimal control	1339	**5.2**	95	10	1634	0	1634*

(*) Difference due to "efficiency" related to when (SOC) / how (magnitude) power is used and corresponding resistance.

Summary for ESS mass of 6,900kg and GED of 300Wh/kg

Fuel burn reduction compared to the Turboelectric solution with Distributed Energy Propulsion

		Fuel Burn				Battery Energy		
Mission	**Setup**	**Mass [kg]**	**Reduc. [%]**	**SOC(t_0) [%]**	**SOC(t_f) [%]**	**Disch. [kWh]**	**Ch. [kWh]**	**Net [kWh]**
Length: 600 nmi **Climb: 13.4 min** **Cruise: 30 kft 0.8 MN**	No ESS	1413	-	-	-	-	-	-
	30 Climb, 20 Cruise Rule based control	1273	9.9	95	10	1758	0	1758
	DP w/o Limits Optimal control	1176	16.8	95	10	4275	2517	1758
	DPM w/ Efest Optimal control	1258	11.0	95	10	1657	0	1657*

(*) Difference due to “efficiency” related to when (SOC) / how (magnitude) power is used and corresponding resistance.

Design/Control Optimization of Hybrid Turboelectric Generator System - Next Steps

- Perform analysis considering multiple factors:
  1. Evaluate impact of different cell **chemistries**
  2. Evaluate impact of battery thermal model for dynamic evaluation of the **power limits**, **thermal management** analysis and **degradation** estimation
  3. Consider different **climb rate** and mission profiles
  4. Consider impact of **electric driveline efficiency**
  5. Extend **weight** analysis
- Analyze different Objective Functions:
  1. *Include battery operating cost due to degradation*
  2. *Include cost-to-cool for the energy storage*

- Develop “online” energy management strategy to implement in HIL for prototype testing.

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Thank You for Your Kind Attention!

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