Electrification for Aircraft Propulsion: Modeling and Potential Benefits

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Alejandra Uranga
Gabilan Assistant Professor
University of Southern California

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USC Viterbi School of Engineering
Department of Aerospace and Mechanical Engineering

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USC PhD students

Saakar Byahut

Michael Kruger

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PI: E. Greitzer (MIT)

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USC

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Summary

- Propulsion system electrification may help reduce aviation's emissions
- Electrification is synergistic with distributed propulsion (DP) and boundary layer ingestion (BLI)
- Improvements in battery technology are crucial to making electrification viable and beneficial (other electrical component tech already sufficient)
- Each electrified propulsion architecture has its sweet spot
  - Fully electric aircraft best for short ranges and small payloads
  - Turbo-electric seems better suited for high ranges
  - Hybrid-electric has niche at intermediate ranges
- Electrification can reduce **on-board energy requirements**

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Outline

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Demand for Air Transportation

- Aviation represents ~3% of global emissions
- Heavily reliant on fossil fuels
- Air transportation projected to grow 4–5% annually for next 20 years
  doubles every 15 years *FAA, Airbus, Boeing*

Annual Traffic (RPK)

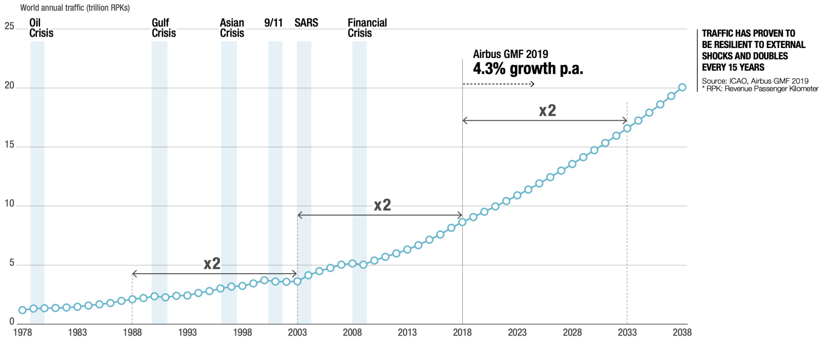

Image source: Airbus Current Market Forecast 2019

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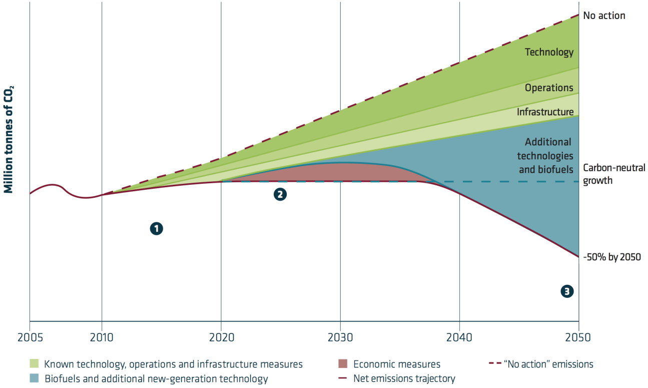
Controlling Emissions from Aviation Requires Radical Changes

2010 ICAO Assembly Commitments

❶ improve fleet fuel efficiency by 1.5% per year from now until 2020

❷ cap net emissions from 2020 through carbon neutral growth

❸ by 2050, net aviation carbon emissions will be half of what they were in 2005.



(Schematic, indicative diagram only)

Source: "The Right Flightpath to Reduce Aviation Emissions", position paper, Air Transportation Action Group, UNFCCC Climate Talks, Cancun, Mexico, 2010

Candidate Technology: Propulsion System Electrification

Aircraft electrification

(= *use electrical components as major elements in propulsion system*)

can help reduce emissions from aviation

- Alleviate dependence on fossil fuels: batteries carry electrical energy
- Electricity production from variety of sources (some low-emissions)
- Leverage high efficiency levels of electrical components
- Can facilitate use of beneficial technologies:
  distributed propulsion (DP) and boundary layer ingestion (BLI)

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Electrification Benefit: Higher Conversion Efficiency

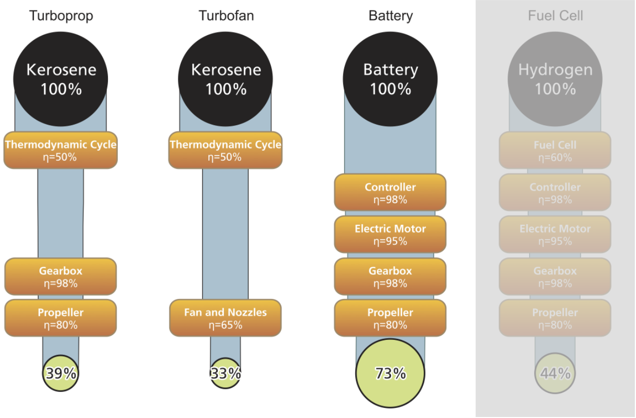

Image source: Hepperle 2012

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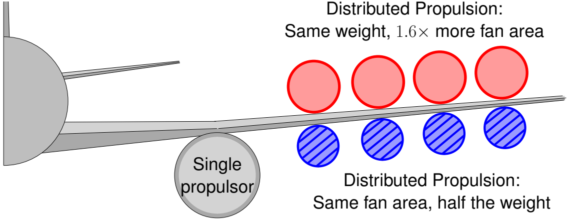
Electrification Benefit: Distributed Propulsion (DP)

DP provides potential weight reduction or larger fan area

(cube-squared scaling: $m_{\text{prop}} \sim \dot{m}_{\text{prop}}^{3/2}$)



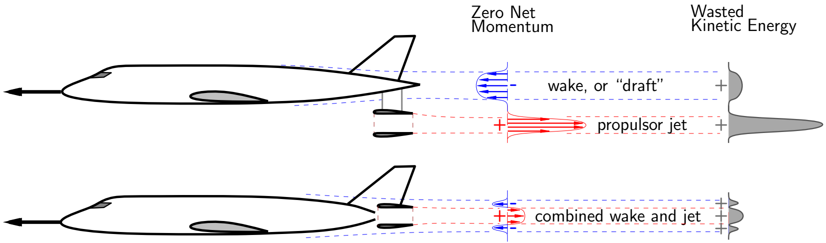
Assumption: Electrification facilitates DP

Kruger et al., AIAA 2018-4227, AIAA Aviation Forum 2018

Electrification Benefit: Boundary Layer Ingestion (BLI)

BLI reduces wasted kinetic energy in combined wake+jet

⇒ Lower power requirement for a given forward force



Assumption: Electrification facilitates BLI

Uranga et al., AIAA Journal 2017

Electrification Challenges

The weight of energy

- Battery specific energy is $\sim$2 orders of magnitude lower than hydrocarbon fuel
  $$e_{\text{fuel}} \simeq 12\,000\,\text{W·h/kg} \quad \text{versus} \quad e_{\text{bat}} \simeq 175-250\,\text{W·h/kgtoday}$$

Aircraft re-design needed

- Electrified propulsion not beneficial if just swapped in place of conventional systems

Nascent technologies

- Low TRLs not "aerospace-ready"
- Operational and safety challenges
- Well-to-wake analysis may not yield emissions benefit for electrified aircraft, but trends are promising and electicity generation is becoming greener (oil is not)

Terminology

- Conventional: propulsion achieved with hydrocarbon fuel as sole energy source and mechanically-driven fans
- Turbo-electric: powered **only from gas turbines** burning fuel
  - Fully turbo-electric: all fans electrically driven
  - Partial turbo-electric: fans both electrically- and mechanically-driven
- Hybrid-electric: propulsion energy comes from both **fuel** via gas turbines and a **battery**
- All-electric: all propulsion energy provided by a battery

Electrified $\equiv$ using electrical components as major elements in propulsion system (electric motors, maybe batteries, . . .)

Performance Metric: On-Board Energy Usage

On-board energy required to bring passengers from point A to point B

Mission energy: **Productivity-Specific Energy Consumption**

$$PSEC = \frac{\text{[total on-board energy]}}{\text{[payload mass]} \times \text{[range]}} = \frac{E_{tot}}{m_{\text{PL}} \times R} \quad [\,\text{kJ/kg}\cdot\text{km}\,]$$

where on-board energy

$$E_{tot} = \underbrace{m_{\text{fuel}}\; e_{\text{fuel}}}_{\text{fuel energy}} + \underbrace{m_{\text{bat}}\; BSE}_{\text{battery energy}}$$

Considerations related to production of electrical energy to charge batteries on the ground and corresponding chain for kerosene fuel delivery are outside the scope

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Electrified Propulsion System Architectures

Many flavors...

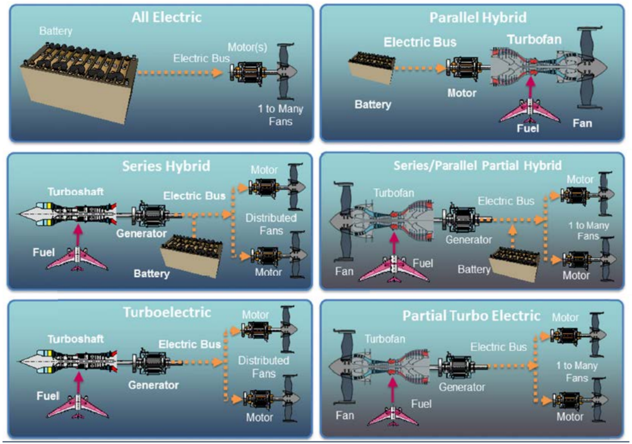
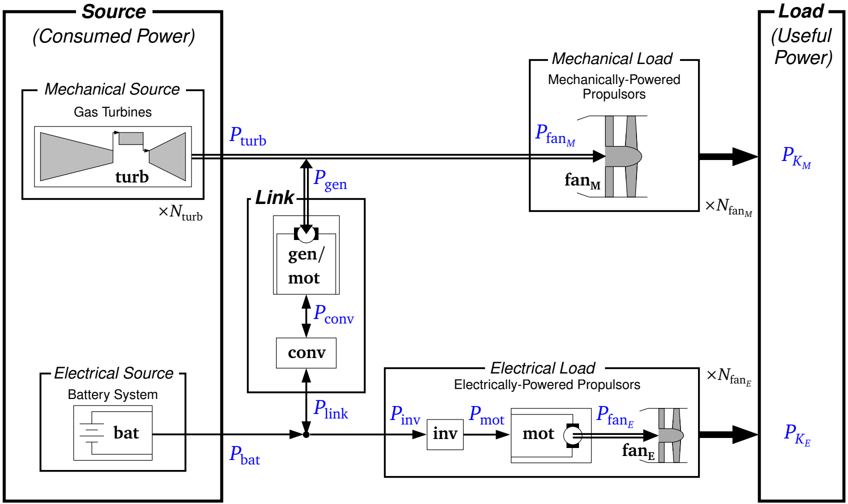


Image source: NAE report 2016

Unified Propulsion System Model



$$f_S \equiv \frac{P_{bat}}{P_{bat} + P_{turb}}$$

$$f_L \equiv \frac{P_{K_E}}{P_{K_E} + P_{K_M}}$$

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Unified Propulsion System Model: Electrification Metrics

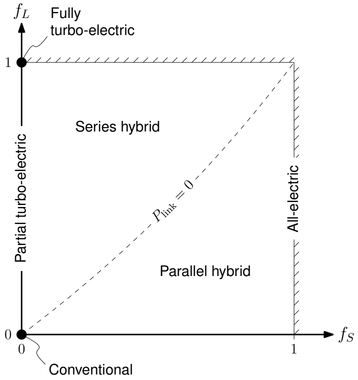
Level of electrification defined based on propulsion-system **power splits**

At the source: Power supplied by gas turbine(s) (mechanical source) and/or battery (electrical source)

Source electrification factor $f_S \equiv \dfrac{P_{\text{bat}}}{P_{\text{bat}} + P_{\text{turb}}}$

At the load: Flow power delivered via mechanically-driven propulsors and/or electrically-driven props.

Load electrification factor $f_L \equiv \dfrac{P_{K_E}}{P_{K_E} + P_{K_M}}$



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Methodology: LUCAS Framework

LUCAS : Library for Unified Conceptual Aircraft Synthesis

- General framework for analysis and design of conventional and novel aircraft
- Power-balance approach for aero-propulsive performance estimation
- Unified propulsion system model
- Models for wide variety of aircraft configurations,
  propulsion system architectures
  technologies (DP, BLI)
- Relies on SUAVE (mission analysis, aerodynamics, weights) and pyOptSparse for optimization

SUAVE references: Lukaczyk et al. AIAA 2015-3087, 2015; Botero et al. AIAA 2016-1275, 2016

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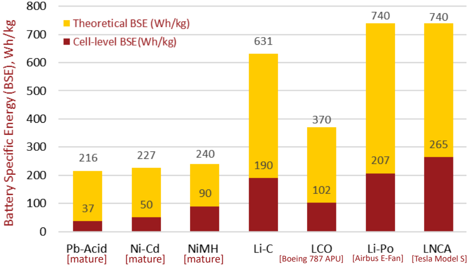
Battery Specific Energy

Theoretical	Cell-level	Pack-level
BSE_{th}	$BSE_{\text{cell}} = \eta_{\text{cell}}\, BSE_{\text{th}}$	$BSE_{\text{pack}} = \eta_{\text{pack}}\, BSE_{\text{cell}} = \eta_{\text{cell}}\eta_{\text{pack}}\, BSE_{\text{th}}$
electrochemical reactants	electrodes, electrolyte, separator, collectors, cell structure	cells, wiring, casing, thermal management

Theoretical → Cell-level: $\eta_{\text{cell}} \sim 30\%$

Cell-level → Pack-level: η_{pack} $60-80\%$

Theoretical and cell-level BSE



- Cell-level BSE is too often quoted in literature and sales pitches
- Specific energy at **pack level** is the relevant parameter for aircraft-level performance

$$BSE_{\text{pack}} \approx 0.2\, BSE_{\text{th}}$$

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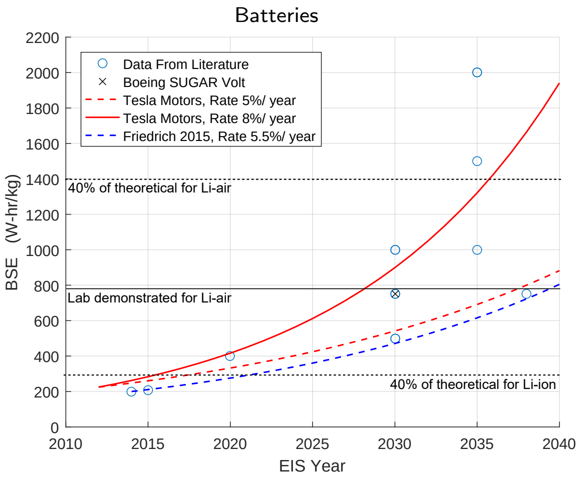
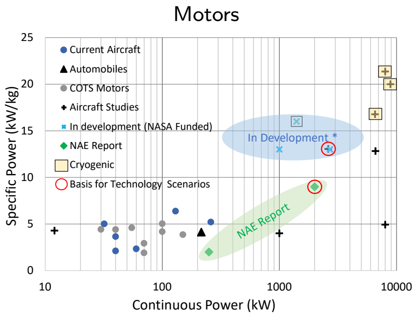
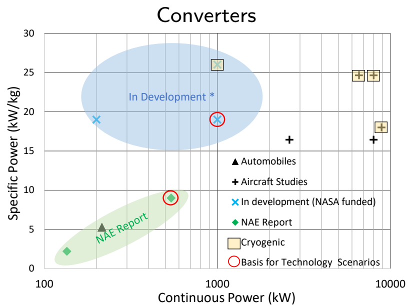
Electric Component Technology Trends







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Cruise-Only Approximation
Full-Mission Commuter
Modeling Lessons
Open Questions

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Technology Scenarios

		Current	Conser-vative 2035	Interme-diate 2035	Optimistic 2035
Battery specific energy (pack)	[W·h/kg]	**175**	**250***	**575**	**900****
Battery specific power	[kW/kg]	0.52	0.745	1.7	2.7
Electrical machines s.p.	[kW/kg]	2	9	12	16
Power electronics s.p.	[kW/kg]	2.3	9	14	19
Thermal management syst. s.p.	[kW/kg]	13.2	13.2	13.2	13.2
Electrical component efficiencies	[-]	0.95	0.98	0.99	0.99

s.p. = specific power
* Current Li-ion chemistries
** Novel Li-ion (Li-S or Li-air) chemistries

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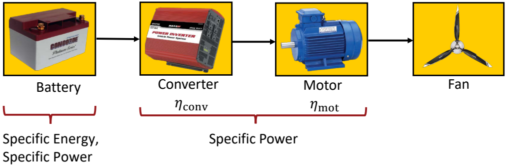
Electric Propulsion System Components



Component	Low Fidelity	Higher Fidelity
Battery	Energy, power, mass $\Rightarrow$ specific energy/power	Capacity, discharge behavior (current, voltage, power)
Motor	Power, mass, efficiency $\Rightarrow$ specific power	Angular speed, voltage, current, physical dimensions, magnetic properties
Power Distribution	Lumped	Safe operating voltages
Converter	Power, mass, efficiency $\Rightarrow$ specific power	Switching topologies, resistances, voltage, current
Wiring	Lumped	Length, cross-sectional area voltage, current, efficiency
Thermal management system (TMS)	Energy flow rate, mass $\Rightarrow$ specific power	Temperature, heat exchanger (density, thermal properties)

Component masses calculated based on specific energy/power

Battery Model

Capture non-linear battery discharge dynamics under variable power loads

- Constant current model:

$$V = V_0 - KQ - RI - GIQ$$

- Calculate V_0, K, R, G from curves
- But flight segments discharge at (piecewise) constant power $\Rightarrow$ constant-power model ($P = IV$)

$$V = V_0 - KQ - RP/V - GQP/V$$

$$V = V_n - \tilde{K}\left(Q - Q_n\right)$$

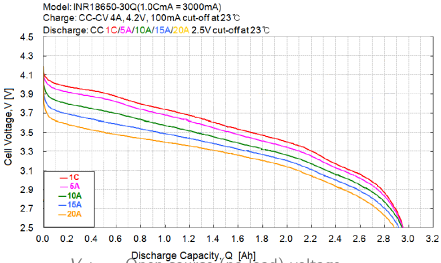
$$\tilde{K} = \frac{K + GP/V_n}{1 - RP/V_n^2 - GPQ_n/V_n^2}$$

$$V_n = \frac{1}{2}\left[(V_0 - KQ_n) + \sqrt{(V_0 - KQ_n)^2 - 4(RP + GPQ_n)}\right]$$

- Energy ($dE = V\,dQ$): area under the V vs. Q line
  - Use initial & final points: (Q_i, V_i) & (Q_f, V_f)

$$\Delta E = \left[V_n - \tilde{K}\left(\frac{Q_i + Q_f}{2} - Q_n\right)\right](Q_f - Q_i)$$

NASA X-57 Maxwell Cell Discharge Profile



V_0:	Open source (no load) voltage
K:	Defines primary dependency of voltage and capacity discharged
R:	Internal resistance
G:	Change in slope of discharge curve due to current
V:	Voltage under load
I:	Current
Q:	Discharge capacity

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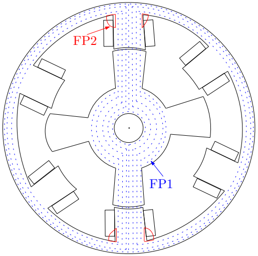
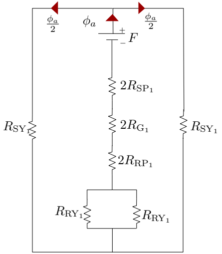
Motor Model: Switched-Reluctance Motor

Model changes in efficiency at different power levels in various flight segments





- Represent magnetic flux ϕ paths as a network of reluctances R and magnetomotive forces F
- Use total flux to calculate motor inductance L ($\Rightarrow$ average torque $\mathscr{T}_{\text{avg}}$)
- Output power: $P_{\text{out,mot}} = \mathscr{T}_{\text{avg}}\,\omega_{\text{mot}}$
- *Copper losses* due to resistance of the stator winding wire: $P_{\text{Cu}} = I^2 R_{\text{coil}}$
- *Core losses* due to hysteresis, eddy-current, excess losses

$$P_{\text{core}} = \sum \mathscr{P}_{\text{k}}\, m_{\text{k}} = \sum \left(\mathscr{P}_{\text{hys,k}} + \mathscr{P}_{\text{eddy,k}} + \mathscr{P}_{\text{exs,k}} \right) \rho_{\text{k}} \mathscr{V}_{\text{k}}$$

- Motor input power: $P_{\text{mot,in}} = P_{\text{mot,out}} + P_{\text{Cu}} + P_{\text{core}}$
- Motor efficiency: $\eta_{\text{mot}} = P_{\text{mot,out}} / P_{\text{mot,in}}$

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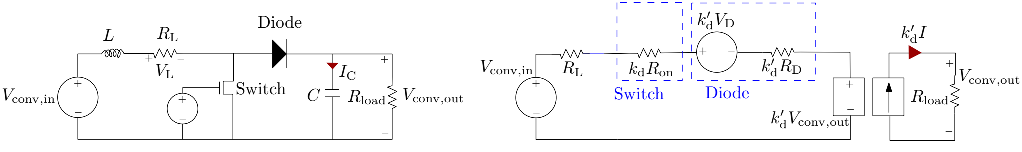
Converter Model

Model changes in efficiency at different power levels in various flight segments
(Can be replaced with low-fidelity model with minimal loss in accuracy)



- Use equivalent circuit model to find relationship between input and output voltage ($\Rightarrow$ power)

$$V_{\text{conv,out}} = \frac{1}{k'_d}\left(V_{\text{conv,in}} - k'_d V_D\right)\left[\frac{k'^2_d R_{\text{load}}}{k'^2_d R_{\text{load}} + R_L + k_d R_{\text{on}} + k'_d R_D}\right]$$

- Duty cycle: $k'_d = 1 - k_d$
- Input and output power: $P_{\text{conv,in}} = V_{\text{conv,in}}\, I$, $P_{\text{conv,out}} = V_{\text{conv,out}}\, k'_d\, I$
- Efficiency $\eta_{\text{conv}} = \frac{P_{\text{conv,out}}}{P_{\text{conv,in}}}$

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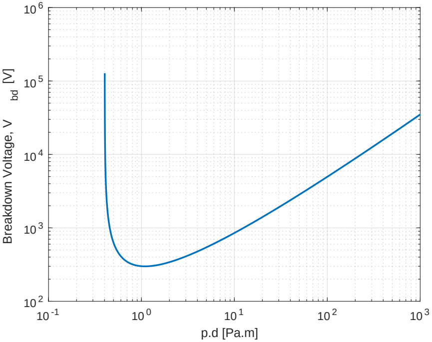
Power Distribution and Paschen's Law

Set a safe operating voltage based on physical limits

- Breakdown voltage: voltage required to create discharge or electric arc between electrodes

$$V_{\text{bd}} = \frac{B\,pd}{\ln\left[\dfrac{A\,pd}{\ln\left(1+\frac{1}{\gamma}\right)}\right]}$$

  - Absolute worst case for air: $V_{\text{bd}} = 327\,\text{V}$ at $pd = 0.760\,\text{Pa.m}$
  - Current aircraft voltages fall below this
- For insulated conductors
  - Fraction of voltage across air gap: $f_V = \dfrac{d}{d + \frac{t_i}{\varepsilon_r}}$
  - Safe operating voltage: $\text{SOV} = \dfrac{V_{\text{bd}}}{f_V}$
- SOV can be much higher than breakdown voltages both at ground-level and at cruise



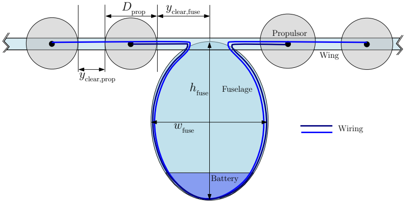
V_{bd}:	Breakdown voltage
p:	Ambient pressure
d:	Separation between electrodes
A, B, γ:	Constants specific to air
t_i:	Insulation thickness
ε_r:	Dielectric constant of insulation

Cables and Wiring

Determine if wiring mass is important in propulsion system modeling

$\Rightarrow$ Wiring mass not significant with distributed propulsion

- Wires supply power to the motors: $P_{\text{mot,in}} = I\,V = I \cdot \text{SOV}$
- Select diameters from American Wire Gauge (AWG) based on current needed
- Cable resistance: $R_{\text{cable}} = \dfrac{L_{\text{cable}}}{\sigma\,A_{\text{cond}}}$
- Cable length calculated from aircraft geometry
- Power dissipated in the cable: $P_{\text{cable}} = I^2 R_{\text{cable}}$
- Wiring mass: mass of conductors + insulation



$$m_{\text{wiring}} = 1.2\left(\frac{\pi}{4}\,\rho_{\text{cond}}\,D_{\text{cond}}^2\,L_{\text{cable}} + \frac{\pi}{4}\,\rho_{\text{ins}}\left[(2\,t_i + D_{\text{cond}})^2 - D_{\text{cond}}^2\right]L_{\text{cable}}\right)$$

- Factor of 1.2 for mass of fixing components (clamps, mounts, ...)

I:	Current
SOV:	Safe operating voltage
L_{cable}:	Cable length
D_{cond}:	Conductor diameter
ρ:	Density
σ:	Conductivity
t_i:	Insulation thickness

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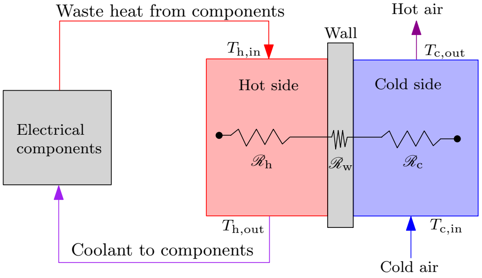
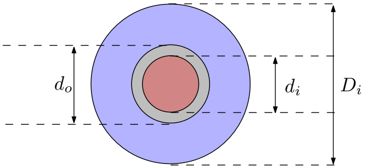
Thermal Management System (TMS)

Size heat exchanger to reject wasted heat from electrical components

- Energy wasted from electrical components:
  $\dot{Q}_{\text{comp}} = (1 - \eta_{\text{comp}})\, P_{\text{comp,in}}$
- Total heat to be rejected: $\dot{Q} = \sum_i \dot{Q}_{\text{comp},i}$
- TMS: heat exchanger with hot side and cold side
- Modeled with number of thermal units (NTU) approach

η:	Efficiency
$P_{\text{comp,in}}$:	Input power to component





Cross section for double pipe heat exchanger

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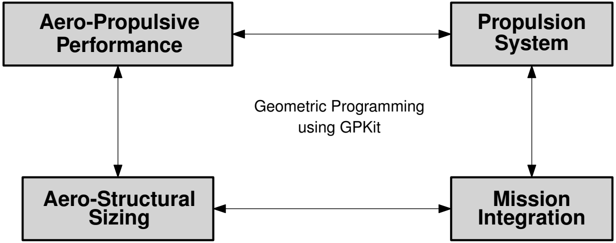
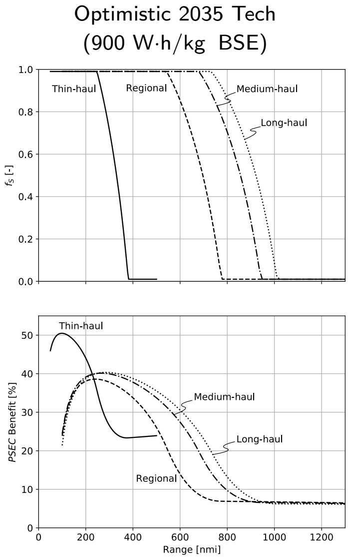
Low-Fidelity Framework Overview

- Generalized range equation for cruise-only mission
- Energy- and power-to-mass scalings for propulsion system components
- Structural sizing based on correlations



GPKit: Burnell, Damen, and Hoburg, "GPkit: A Human-Centered Approach to Convex Optimization in Engineering Design", 2020 CHI Conference on Human Factors in Computing Systems

Mission Determines Optimal Architecture



- All-electric best for very short ranges ($\sim$ 200 nmi)
- Turbo-electric seems best for long ranges (>400 nmi)
  … *but higher-fidelity results may show otherwise*
- Hybrid-electric may have a niche at intermediate ranges, e.g. to extend range of otherwise all-electric option
- All-electric for thin-haul missions is unfeasible with current and conservative 2035 tech

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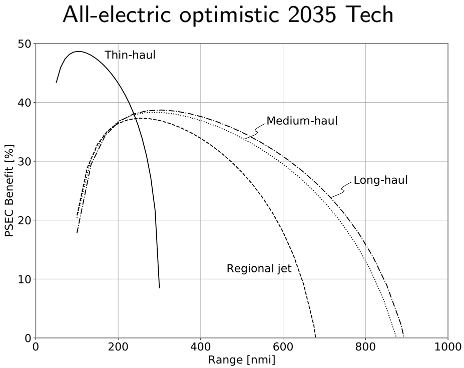
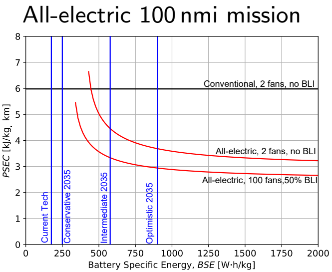
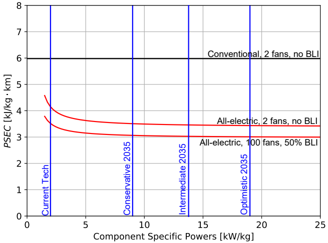
Range Limitations of All-Electric Architectures



- Large sensitivity to range
- All-electric could give large benefits at low ranges,
  but advantage quickly drops with range due to battery mass growth

Electrification Benefits: Technology Effects





- BSE improvements crucial to making all-electric feasible
- Diminishing returns past 900 W·h/kg BSE
- Component powers less limiting than BSE with diminishing returns past 5 kW/kg
- DP beneficial, but diminishing returns past ∼6–8 propulsors
- DP and BLI facilitate electrification: larger missions become feasible

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Commuter Aircraft Mission: 19 Pax, 250nmi range

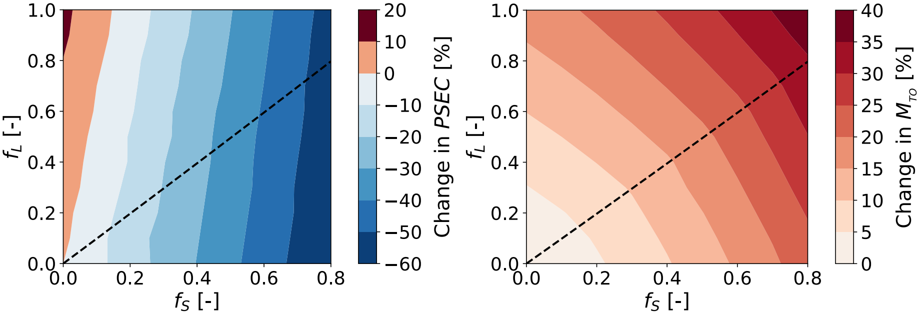
Baseline for comparisons: advanced* technology version of DHC-6 Twin Otter

* (-15% empty mass; -20% in engine SFC and power-to-mass ratio)

Number of passengers	N_{pax}	19
Payload	m_{pay}	1 842 kg (3 979 lb)
Mission range	R	250 nmi (463 km)
Cruise speed	V_{cruise}	94 m/s
Takeoff mass	m_{init}	5 670 kg
Cruise altitude	h_{cruise}	10 000 ft (3 050 m)

Image ©Viking Air

Electrification Design Space - Optimistic Tech Assumptions



- Energy requirement drops quickly as source electrification (f_s) increases (more energy in battery vs fuel)
- Parallel hybrids slightly more efficient than series hybrids
- Aircraft weight grows rapidly as electrification increases

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Hybrid-Electric: 500 nmi Extended Range Mission

Mission-fixed hybrid: Constant electrification throughout mission.

Mission-varying hybrid: Different electrification levels for different mission segments.

Configuration	Tech	Climb f_s	Cruise f_s	ΔM_{TO}	ΔPSEC
Fixed hybrid	Interm.	0.55	0.55	+59%	-27%
	Opt.	0.9	0.9	+52%	-63%
Varying hybrid	Opt.	1	0	+15%	-3.7%

- Potential energy benefits even at intermediate technology
- Fixed hybrid leads to largest energy benefits, but with large weight gains
- Varying hybrids mitigate weight gains at the expense of energy benefits

Conclusions of Full Mission Commuter Study

All-electrics are fundamentally range limited and best suited for very short missions while hybrids can be more versatile

If battery specific energy improves to intermediate tech levels (BSE$\sim$600 W·h/kg)

- All-electric architectures could lead to large energy reductions **for very short range missions** (100 nmi) but with big aircraft weight gains
- Hybrid-electric architectures
  - Give large energy reductions with high electrification levels
  - Can significantly increasing feasible mission range compared to all-electrics
  - Keep aircraft weight gains relatively low

Electrification benefits are primarily due to high efficiency of electrical components
$\Rightarrow$ higher electrification is more beneficial at the expense of weight gains

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Fidelity Levels

- Level 1: Range equation
  - One-liner, hand calculations
  - Order of magnitude checks with minimal info
- Level 2: Cruise-only with low-fidelity models (specific powers and efficiencies)
  - Need to determine appropriate 'full-mission average' values a priori
  - Missing sizing effects (since components not always sized for cruise)
- Level 3: All mission segments with low-fidelity models
  - Realistic sizing and constraints
  - No need to define 'mission average' values
  - Relies on a priori values for component characteristics
- Level 4: All mission segments and detailed component models
  - No need to guess component characteristics
  - Reduces uncertainty in final answers
  - Helps ensure resulting aircraft are realistic

Modeling Lessons

Higher-fidelity mission analysis (Level 3) is needed

for proper sizing (i.e. components meet the full mission requirements)

... otherwise propulsion system size may be underestimated

... snow-balls into significantly undersized airplane

... and conclusions on feasibility and benefits may be way off

Higher-fidelity component models teach us that

- Battery dominates propulsion system mass for all electrics ($\sim$60%)
- Higher safe operating voltages may be possible than currently certified
- Non-battery component efficiencies matter mostly as they affect battery mass

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Open Questions

Aircraft electrification can definitely reduce **on-board energy** requirements but whether it is **environmentally beneficial** or not ultimately depends on

- Electricity production and distribution: strongly dependent on how/where
  e.g. electric flight from Seattle to Indianapolis may be green,
  but return flight might pollute more than on conventional aircraft
- Environmental impact of battery and other electronics production, disposal
- Battery life-cycle considerations e.g. replace every 100 versus 1000 flights
- ... etc ...

Analysis of broader life-cycle emissions impact is crucial
and ultimately needs to be entered into the design equation

(well-to-wake emissions modeling in progress)

References

Downloads available from the ADRL's site at https://adrl.usc.edu/publications/

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Contact

Alejandra Uranga, Ph.D.

Gabilan Assistant Professor
Aerospace & Mechanical Engineering Dept.
University of Southern California

Email: auranga@usc.edu
Phone: (213) 821 - 0846
Web: uranga.usc.edu

Lab site: adrl.usc.edu

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