Turboelectric and Hybrid Electric Aircraft Drive Key Perfomance Parameters

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Background

Hybrid Electric and Turboelectric Aircraft Propulsion

Fully Turboelectric
NASA N3-X

Partially Turboelectric
NASA STARC-ABL

Hybrid Electric – NASA PEGASUS

Electrified Aircraft Propulsion Benefits

$$\text{Benefits} \sim \frac{\left(\frac{L}{D}\eta_{\text{prop}}\right)_{\text{E}}}{\left(\frac{L}{D}\eta_{\text{prop}}\right)_{\text{AC}}}$$

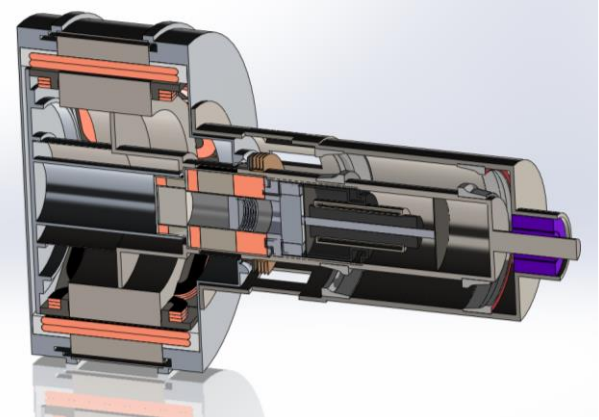
- High Bypass Ratio (BPR)
  - Enabled by de-coupling the shaft speeds and inlet/outlet areas
  - 4-8% improvement in propulsive efficiency expected for fully turboelectric propulsion (Felder, Brown)
- Boundary Layer Ingestion (BLI)
  - Reduces drag by reenergizing the wake
  - 3-8% improvement in propulsive efficiency expected for fully turboelectric propulsion (Felder, Brown)

$$\eta_{\text{prop}}$$

- Lift-to-Drag (L/D) Improvements
  - Distributed propulsion improves wing flow circulation control
  - Up to 8% improvement expected (Wick)

$$\frac{L}{D}$$

Electrified Aircraft Propulsion Costs



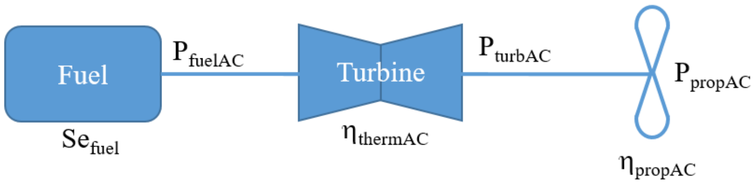
NASA HEMM Motor Concept
with $\eta > 98\%$ (Jansen et al. 2018)

- Electric Drive System
  - Electric machines
    - Generators
    - Motors
  - Power management and distribution
    - Rectifiers
    - Inverters
    - Distribution wiring
    - Fault protection
  - Thermal system
    - *Related to electric drive system losses*
- Performance – STARC-ABL assumptions
  - MW-class motor and generator with at least 13 kW/kg and $\eta = 96\%$
  - Rectifiers and inverters with 19 kW/kg and $\eta = 99\%$
  - Stackup yields overall values of 2 kW/kg and $\eta = 90\%$
- Input energy
  - Fuel energy density ~12,000 Wh/kg
  - Li-ion specific energy on the cell level of up to 200 Wh/kg
  - New battery technologies (Li-sulfur, Li-air) projected to be up to 750-1000 Wh/kg
  - Need to be de-rated from cell level to battery pack specific energy

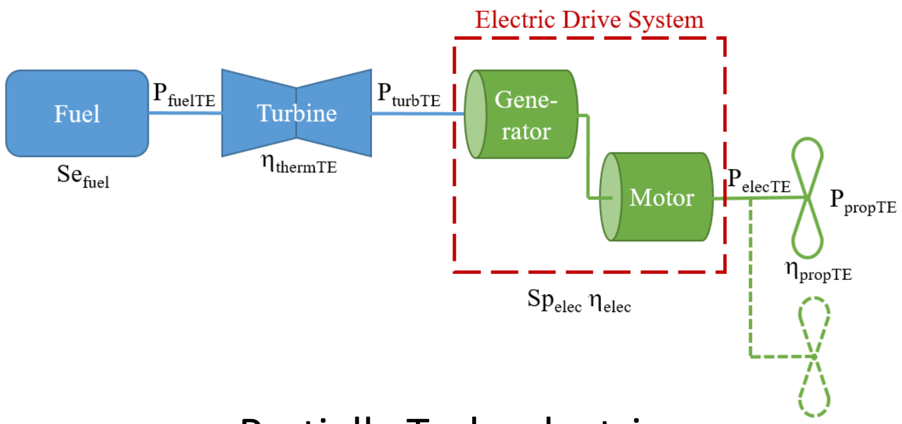
Background

Electrified Aircraft Propulsion Systems

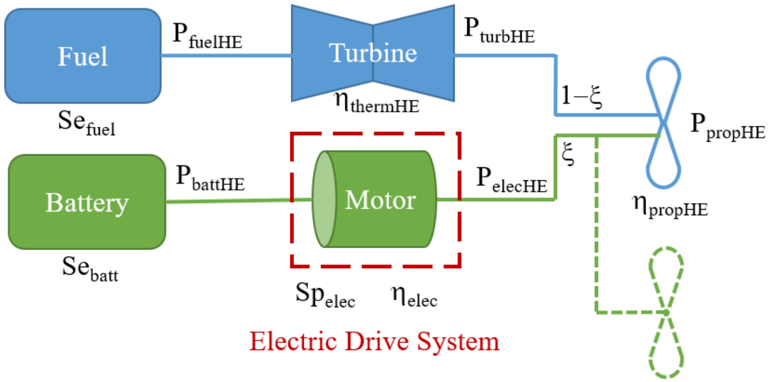
Baseline Turbofan



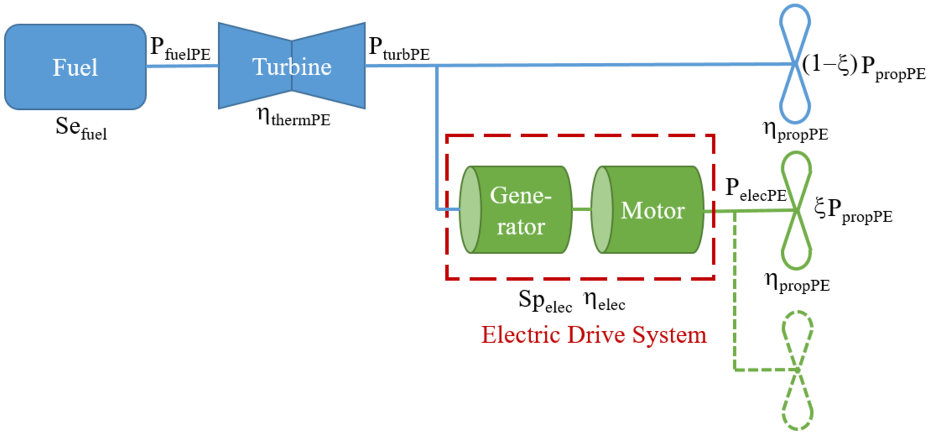
Fully Turboelectric



Parallel Hybrid Electric



Partially Turboelectric



KPPs and Assumptions

- Key Performance Parameters
  - Electric propulsion fraction ξ
  - Electric drive efficiency η_{elec}
  - Electric drive specific power $\mathrm{Sp}_{\mathrm{elec}}$
  - Battery specific energy $\mathrm{Se}_{\mathrm{batt}}$
- Breakeven assumptions
  - Range is the same
  - The input energy is the same
- Other assumptions
  - Payload weight is the same
  - OEW/Initial weight is the same (OEW does not include electric drive system or battery weight)

Range Equation

Set range of conventional aircraft and electrified aircraft equal

$$R_{\text{fuel}} = \frac{Se_{\text{fuel}}}{g}\frac{L}{D}\eta_o \ln\left(\frac{W_{\text{i}}}{W_{\text{f}}}\right)$$

$$R_{\text{batt}} = \frac{Se_{\text{batt}}}{g}\frac{L}{D}\eta_o\left(\frac{W_{\text{batt}}}{W_{\text{i}}}\right)$$

Range Equation

Set range of conventional aircraft and electrified aircraft equal

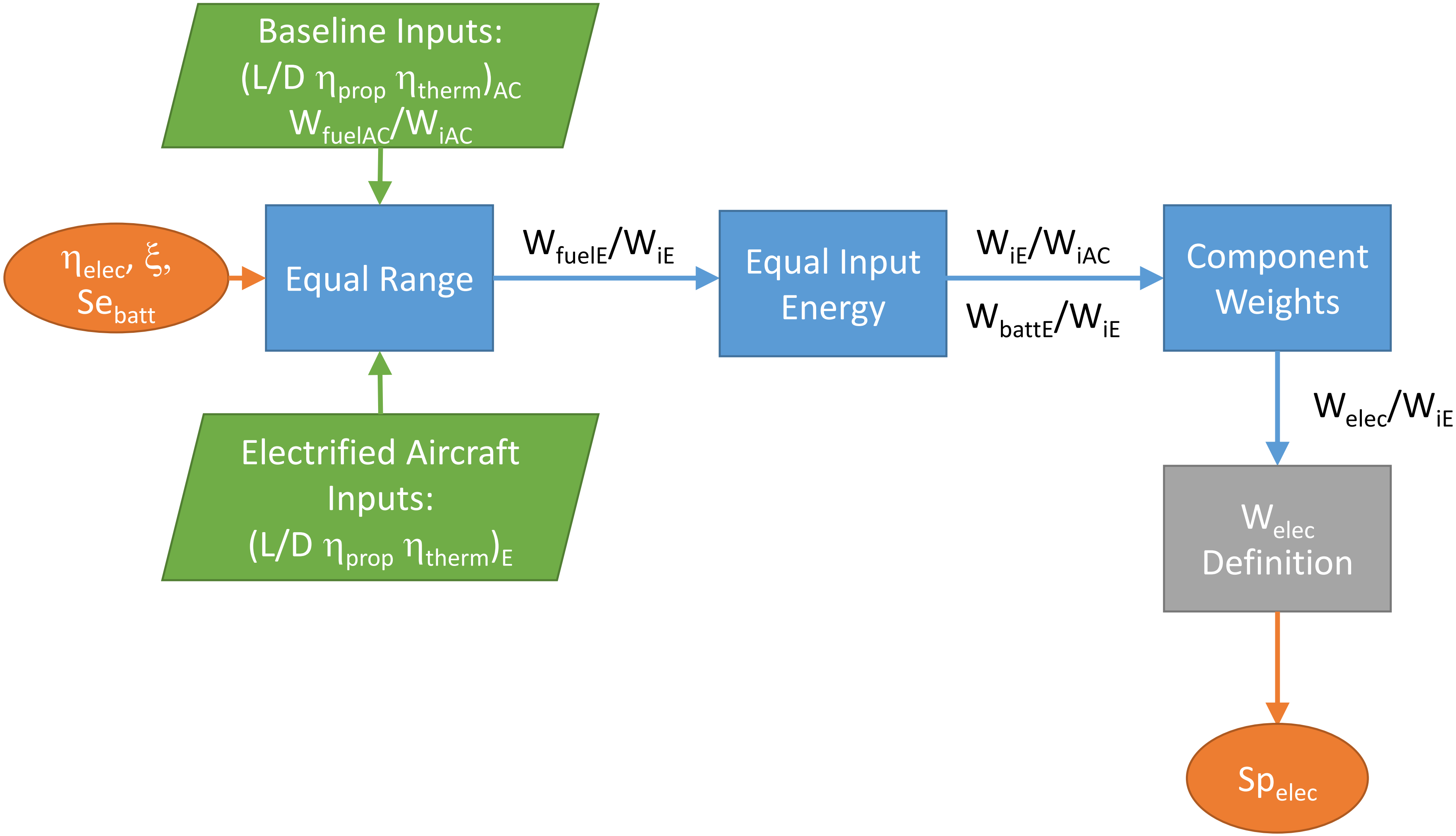
$$R_{\text{fuel}} = \frac{Se_{\text{fuel}}}{g}\frac{L}{D}\eta_o \boxed{\ln\left(\frac{W_{\text{i}}}{W_{\text{f}}}\right)}$$

For small $W_{\text{fuel}}/W_{\text{i}}$:

$$\sim \left(\frac{W_{\text{fuel}}}{W_{\text{i}}}\right)$$

$$R_{\text{batt}} = \frac{Se_{\text{batt}}}{g}\frac{L}{D}\eta_o \left(\frac{W_{\text{batt}}}{W_{\text{i}}}\right)$$

Breakeven Analysis



Baseline Inputs:
$(L/D\ \eta_{prop}\ \eta_{therm})_{AC}$
W_{fuelAC}/W_{iAC}

η_{elec}, ξ,
Se_{batt}

Equal Range

W_{fuelE}/W_{iE}

Equal Input Energy

W_{iE}/W_{iAC}

W_{battE}/W_{iE}

Component Weights

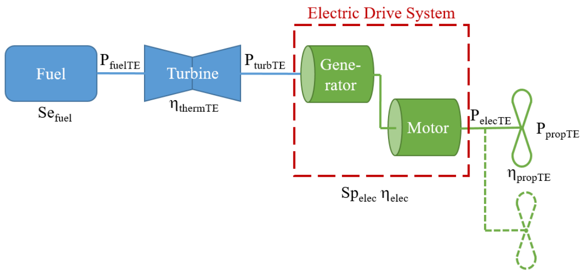
W_{elec}/W_{iE}

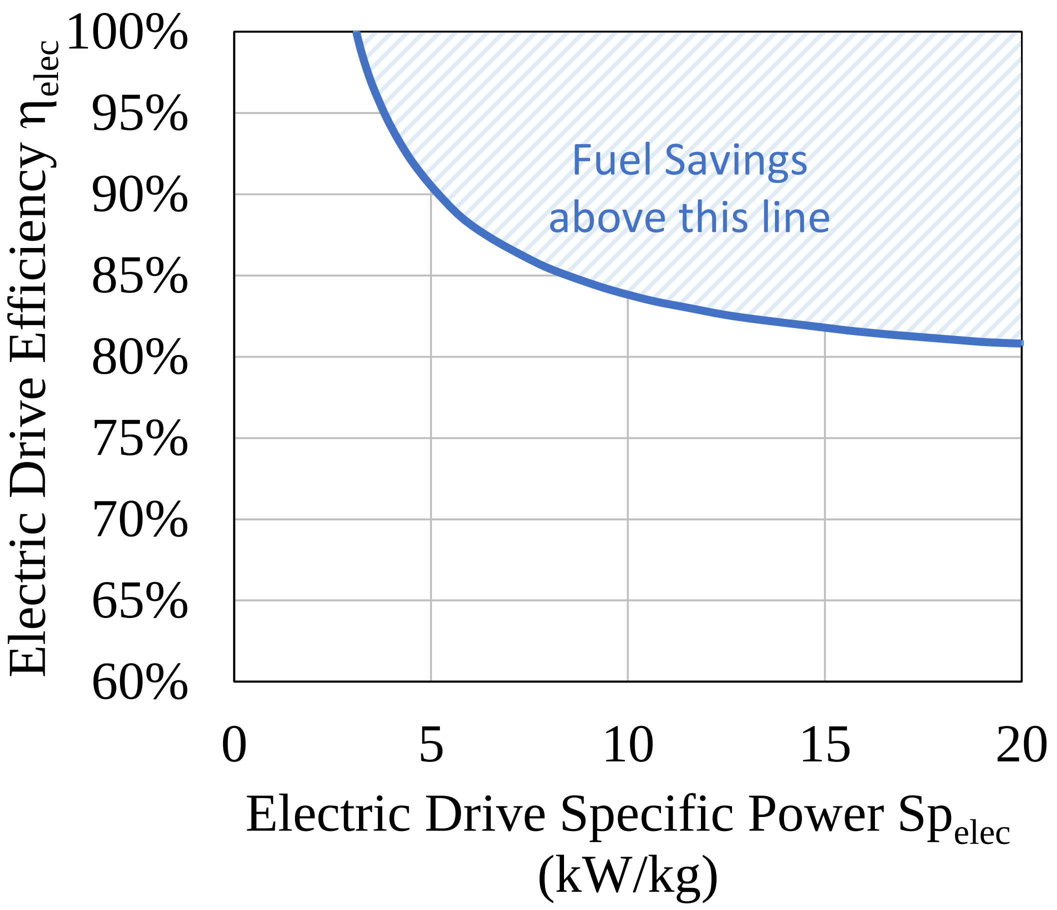
W_{elec} Definition

Sp_{elec}

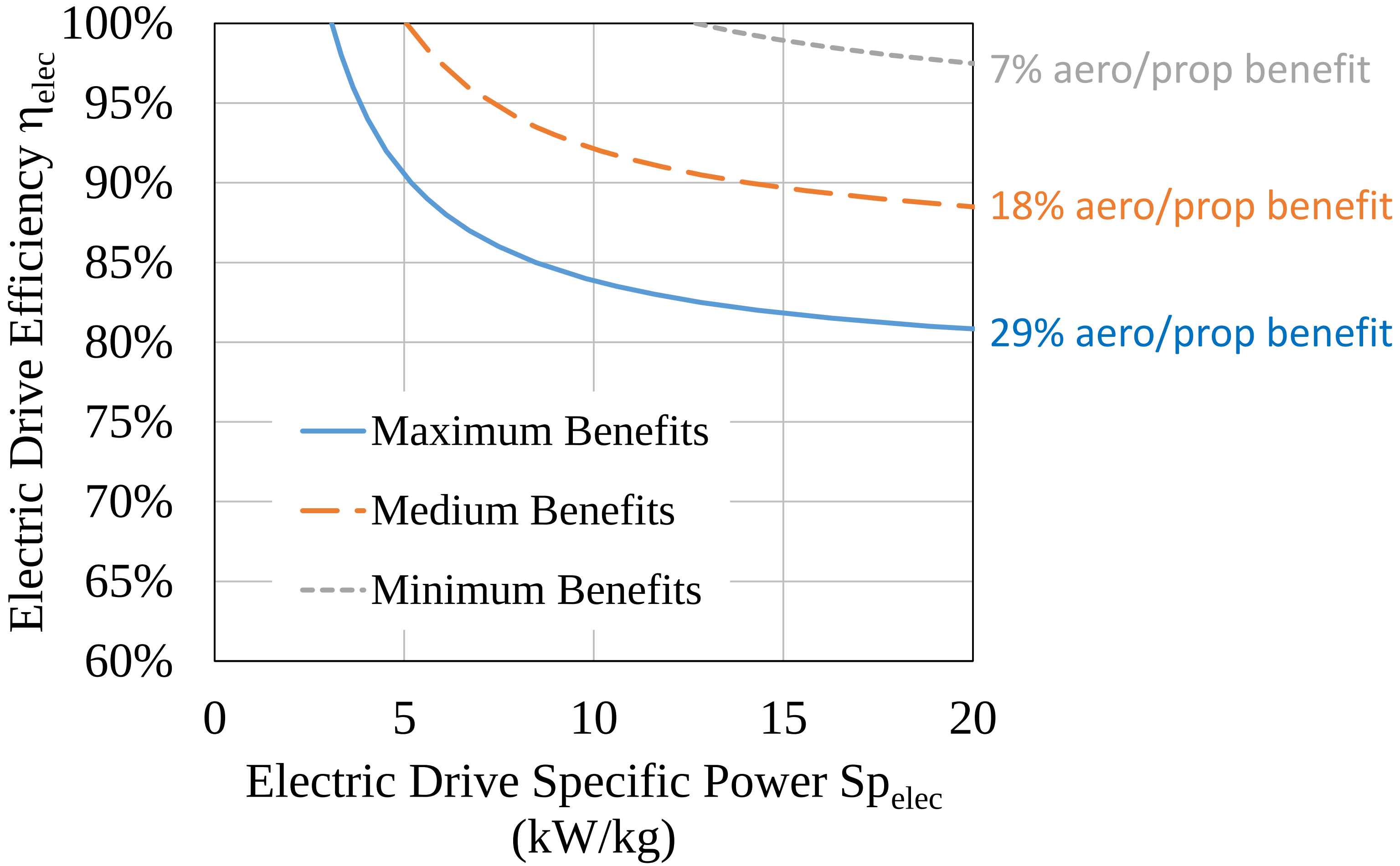
Electrified Aircraft Inputs:
$(L/D\ \eta_{prop}\ \eta_{therm})_{E}$

Turboelectric Aircraft




Fuel Savings above this line

Turboelectric Aircraft

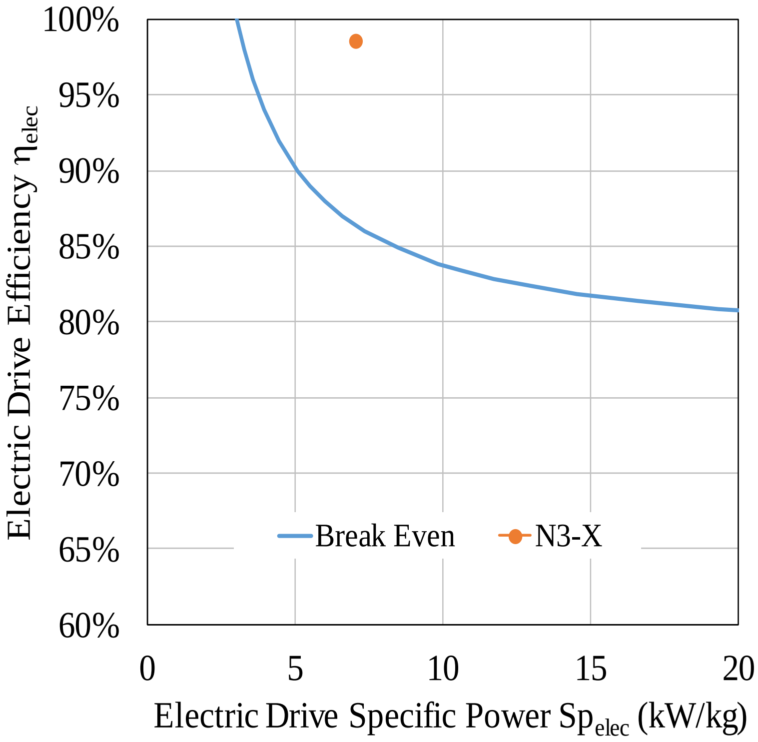


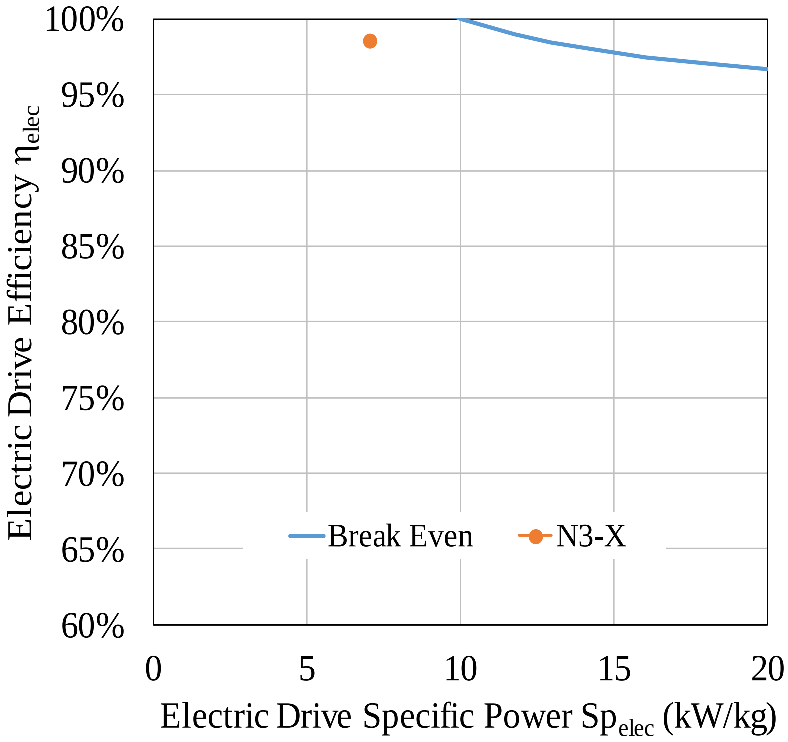
NASA N3-X Turboelectric Example

Parameter	Baseline 777 (tube and wing)	Baseline N3A (HWB)	Turboelectric N3-X (HWB)
L/D	19	22	22
η_{prop}	69.6%	72.2%	77.1%
Sp_{elec} (kW/kg)			7.1
η_{elec}			98.54%

Ref: Felder, Brown, Kim, and Chu, "Turboelectric distributed propulsion in a hybrid wing body aircraft" 2011

NASA N3-X Turboelectric Example


Baseline 777
vs Turboelectric N3-X

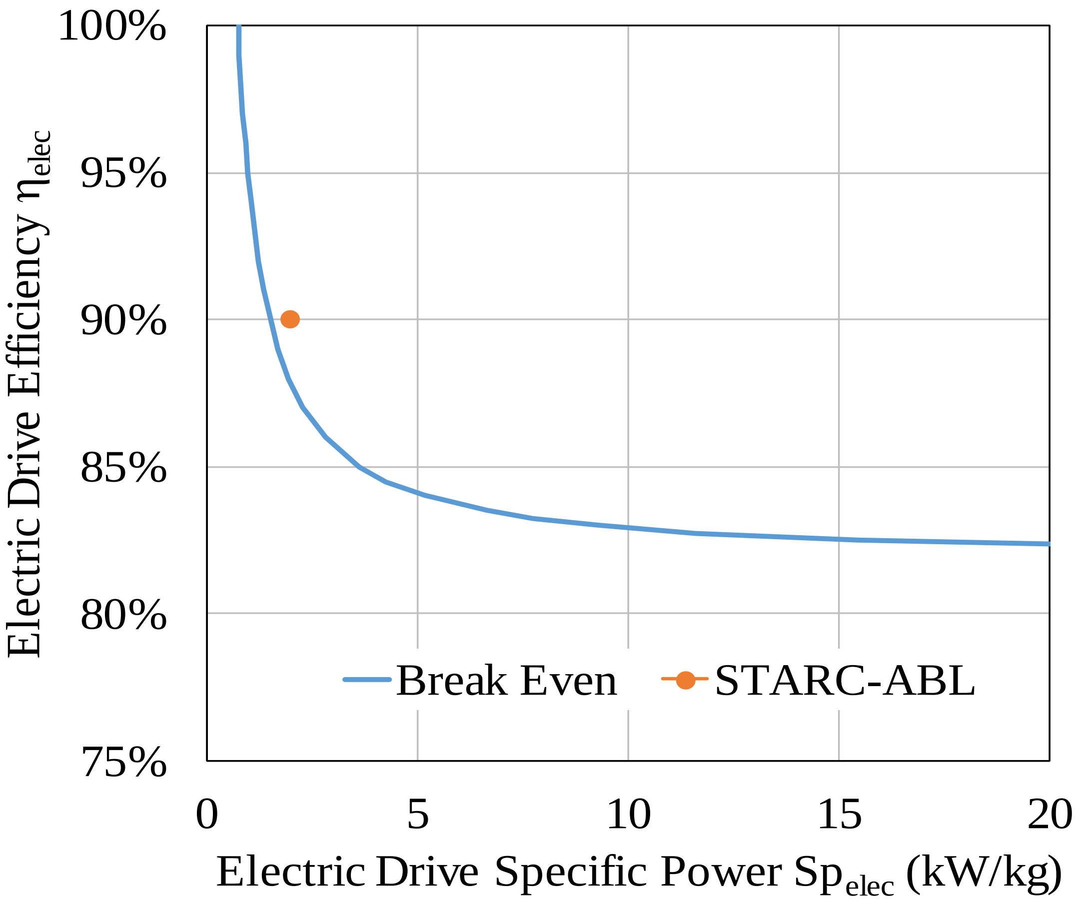

Baseline N3A HWB
vs Turboelectric N3-X

Partially Turboelectric STARC-ABL Example

Parameter	Baseline N3CC	Partially Turboelectric STARC-ABL
ξ		45%
L/D	21.4	22.3
η_{prop}	64%	75.1%
Sp_{elec} (kW/kg)		2.0 kW/kg
η_{elec}		90%

Ref: Welstead and Felder, "Conceptual design of a single-aisle turboelectric commercial transport with fuselage boundary layer ingestion"

Partially Turboelectric STARC-ABL Example



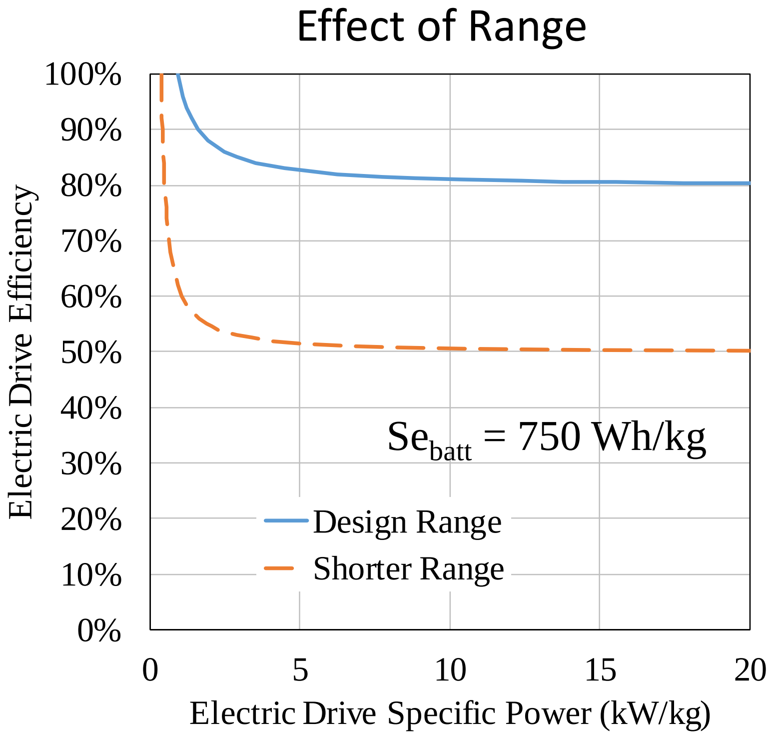
Parallel Hybrid Electric PEGASUS Example

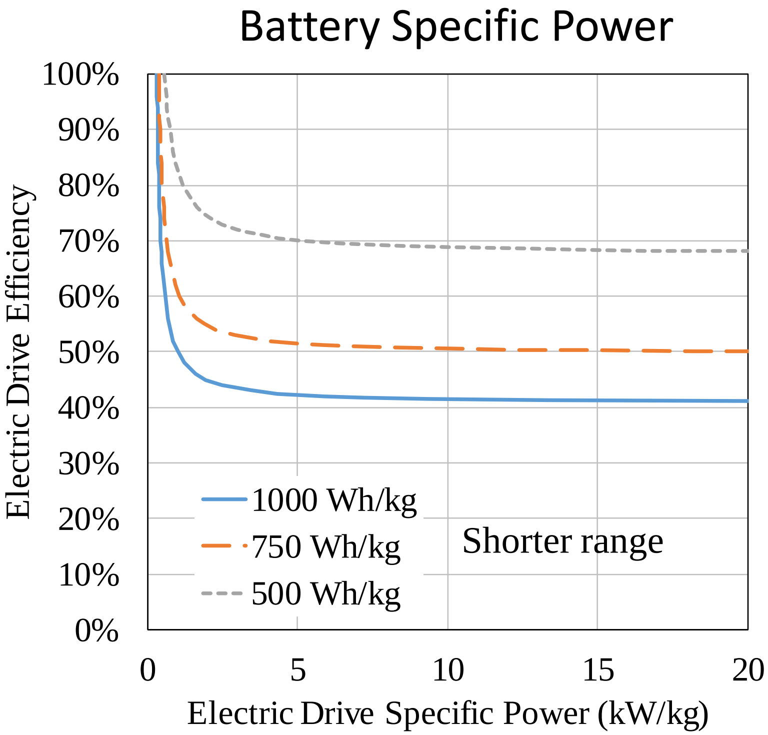
Parameter	Baseline Turboprop	Parallel Hybrid Electric
ξ		25%, 50%, 75%
L/D	11	15
η_{prop}	60%	72%
Se_{batt} (Wh/kg)		500, 750, 1000
Sp_{elec} (kW/kg)		7.3
η_{elec}		90%

Ref: Antcliff et al., “Mission analysis and aircraft sizing of a hybrid-electric regional aircraft,” 2016

Parallel Hybrid Electric

Electric Propulsion Fraction ξ = 25%

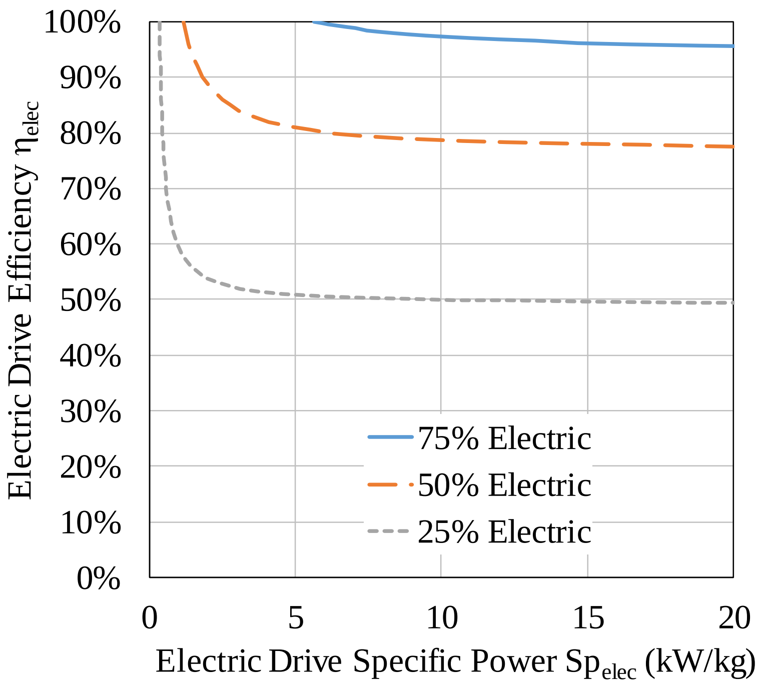




Parallel Hybrid Electric

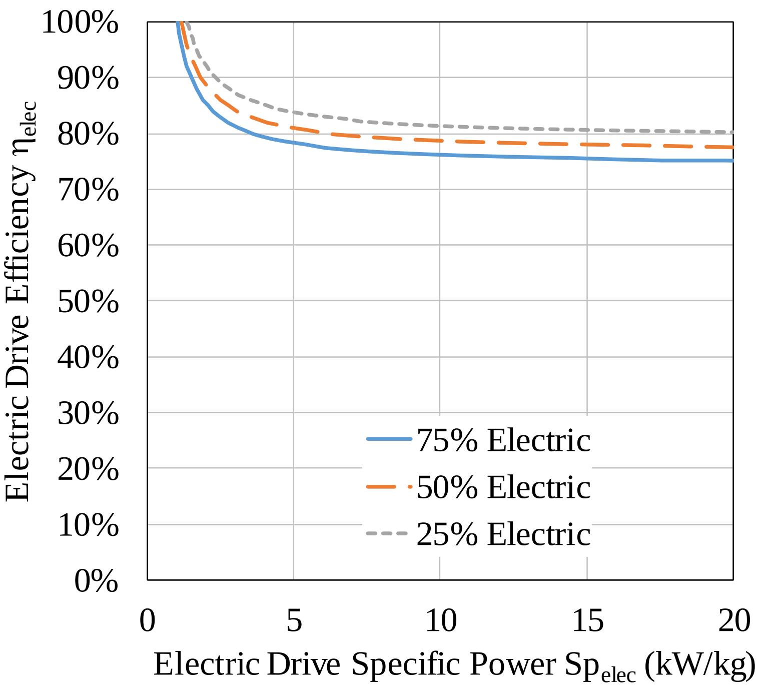
Constant Benefits:

$$\frac{\left(\frac{L}{D}\eta_{prop}\right)_{HE}}{\left(\frac{L}{D}\eta_{prop}\right)_{AC}} = \text{constant with } \xi$$



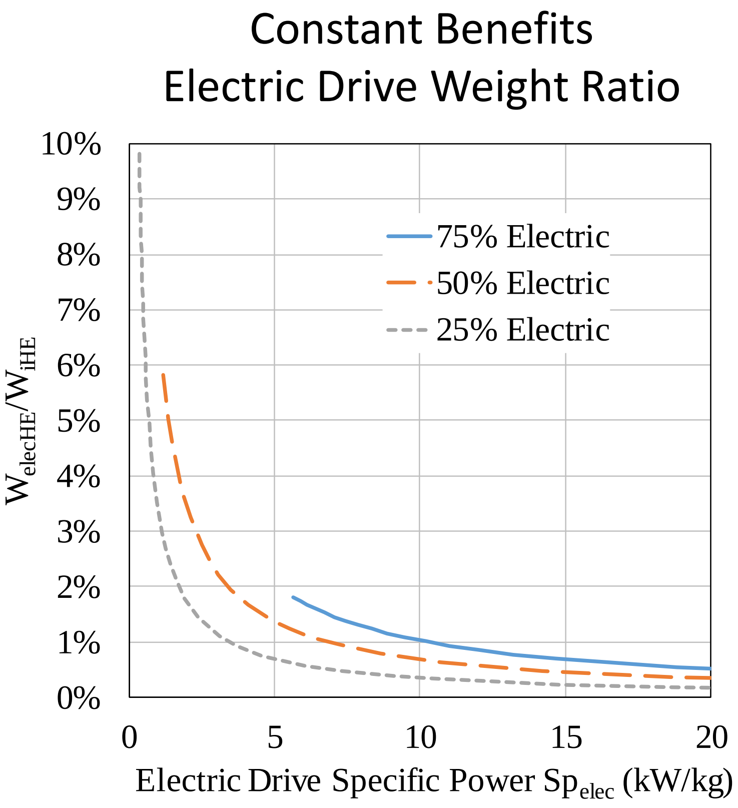
Benefits Scale with ξ:

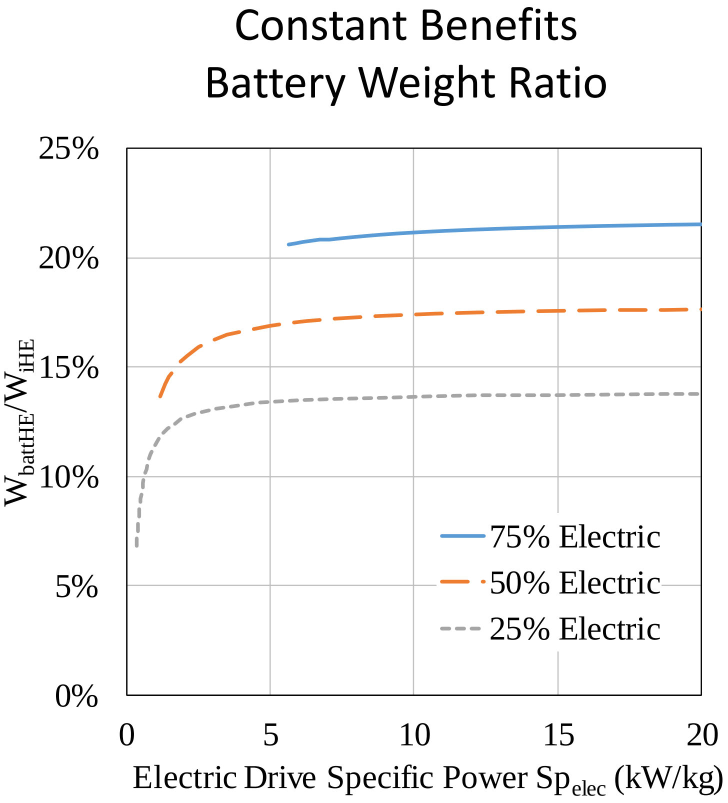
$$\frac{\left(\frac{L}{D}\eta_{prop}\right)_{HE}}{\left(\frac{L}{D}\eta_{prop}\right)_{AC}} \propto \xi$$



Shorter Range, Se_{batt} = 750 Wh/kg

Parallel Hybrid Electric



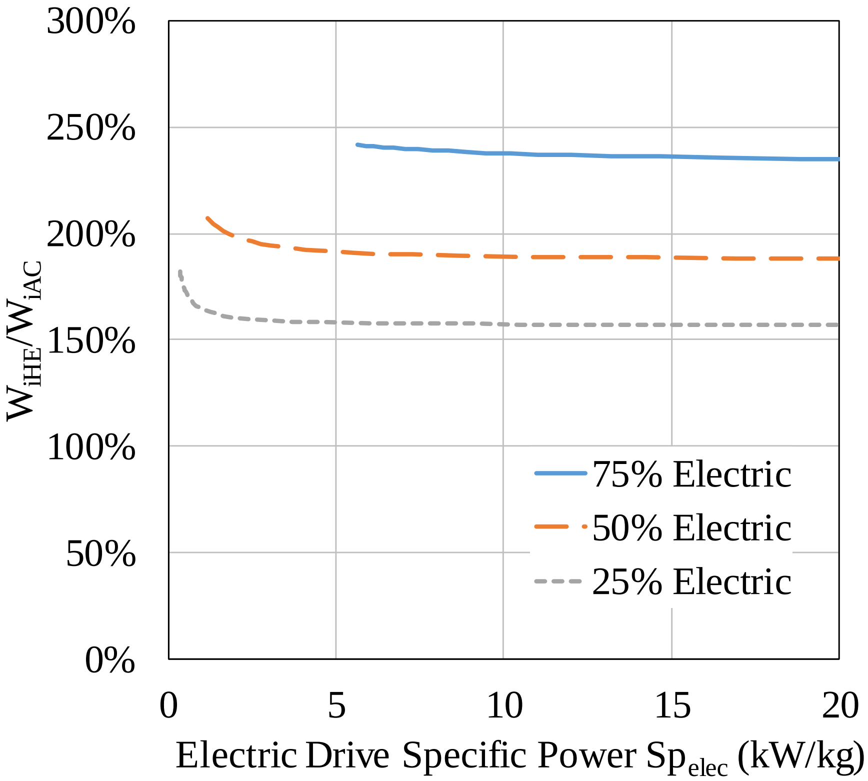


Shorter Range, Se_{batt} = 750 Wh/kg

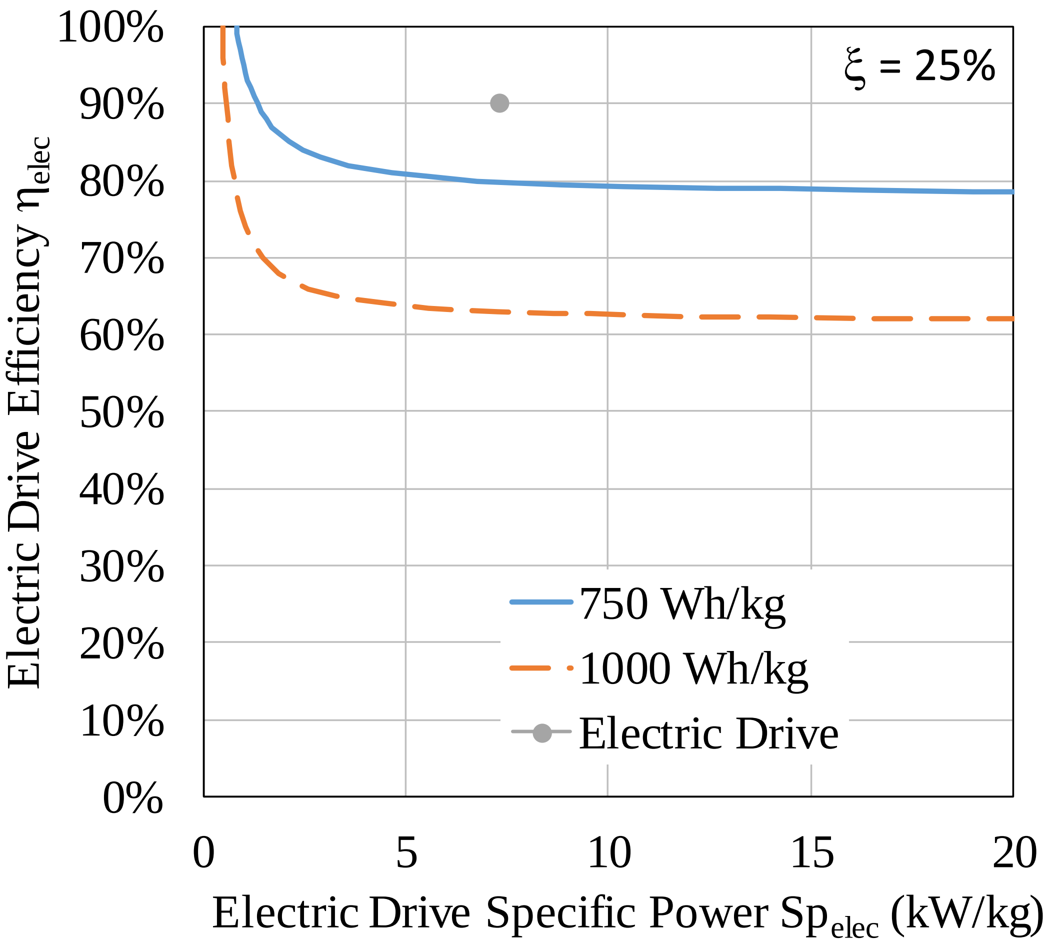
Parallel Hybrid Electric

Shorter Range

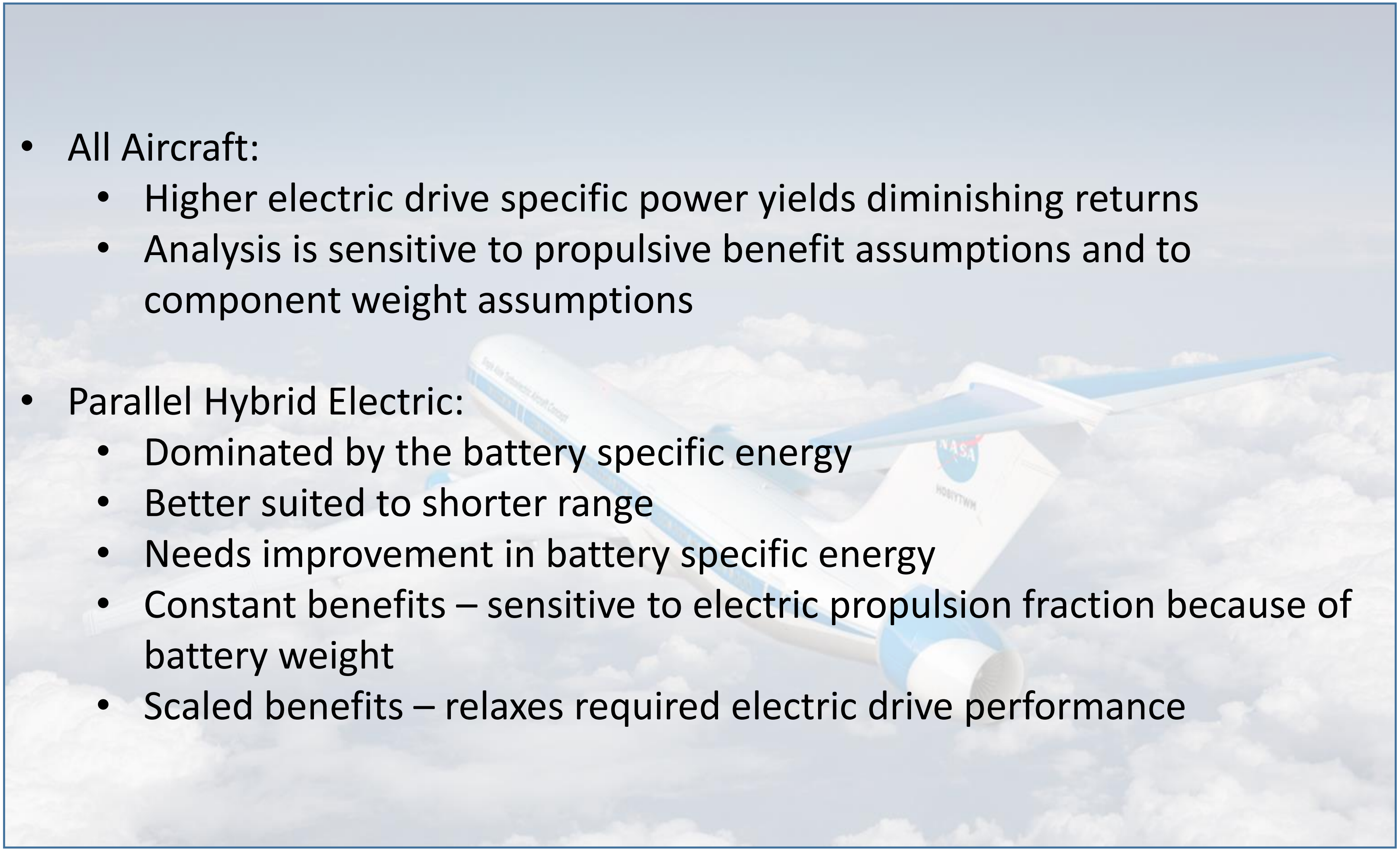
Constant Benefits
Hybrid Electric to Baseline Weight Ratio



Parallel Hybrid Electric



Conclusions



- All Aircraft:
  - Higher electric drive specific power yields diminishing returns
  - Analysis is sensitive to propulsive benefit assumptions and to component weight assumptions

- Parallel Hybrid Electric:
  - Dominated by the battery specific energy
  - Better suited to shorter range
  - Needs improvement in battery specific energy
  - Constant benefits – sensitive to electric propulsion fraction because of battery weight
  - Scaled benefits – relaxes required electric drive performance

Acknowledgments

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