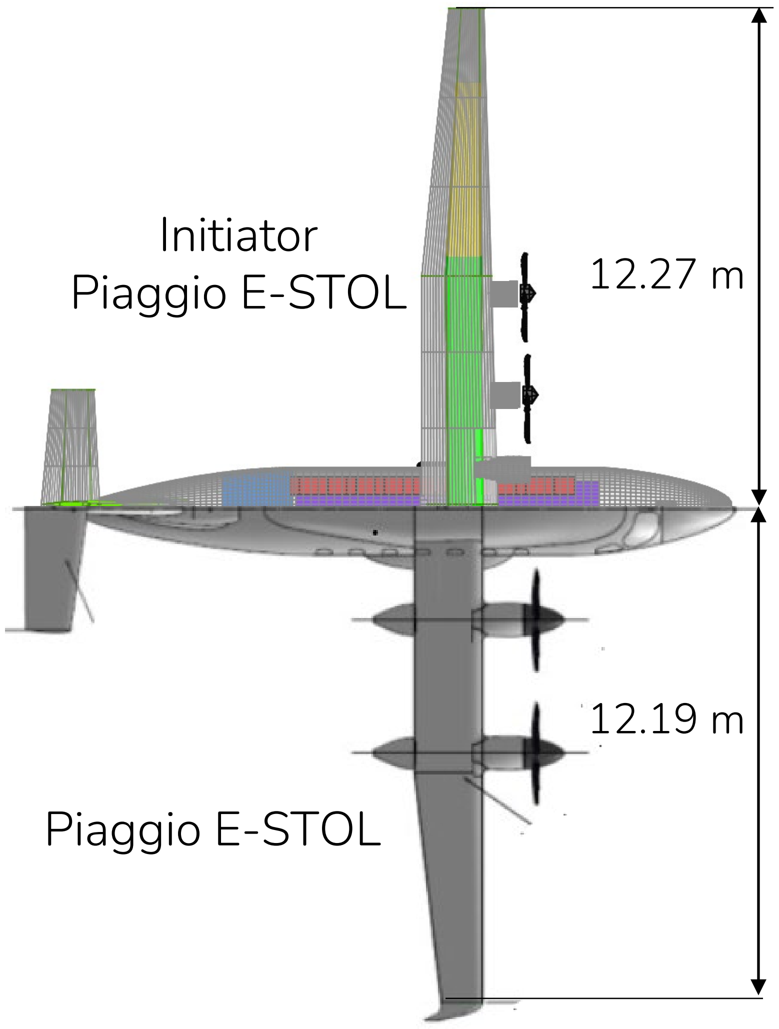
Sensitivity study & MDO results

CHYLA PROJECT WORKSHOP

SOUTHAMPTON, 15TH FEBRUARY 2023

CREDIBLE HYBRID ELECTRIC AIRCRAFT

Sensitivity study: cross-check with Piaggio E-STOL



		$\phi_{cruise} = 10\%$		$\phi_{cruise} = 9\%$
		Piaggio E-STOL	Initiator Piaggio E-STOL	Initiator Piaggio E-STOL
MTOM	[tons]	12.8	12.96	12.5
OEM (inc. battery)	[tons]	9.92	10.47	10.0
Installed Power EM2 (all 4)	[MW]	2.0	2.39	2.30
Installed Power GT	[MW]	1.1	1.12	1.08
Installed Ebat	[GJ]	4.90	5.83	5.43

Analysis should only consider relative comparison between aircraft rather than absolute numbers.

Results are highly sensitive to the battery supplied power ratio

Sensitivity study: approach

CONVENTIONAL

REFERENCE AIRCRAFT	
"Ref_Reg"	
TLARs	range
	pax
	payload
	cruise alt
	cruise Mach
	…
Config	wing AR
	wing location
	airfoils
	…

TLAR exploration →

CONTROL AIRCRAFT	
"Control_Reg_rangeXX"	
TLARs	rangeXX
	pax
	payload
	cruise alt
	cruise Mach
	…
Config	wing AR
	wing location
	airfoils
	…

KPI comparison

KPI comparison

RADICAL AIRCRFAT

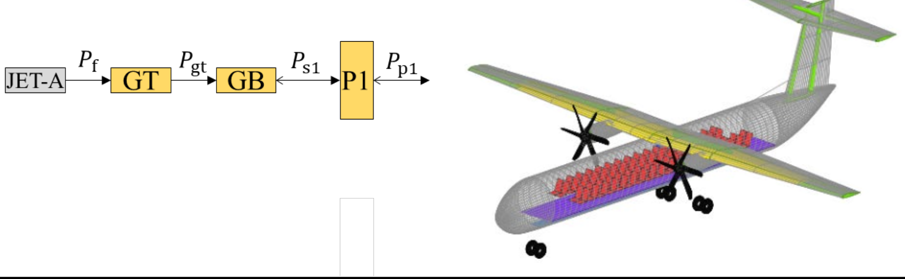
INITIAL RADICAL DESIGN	
"InitRad_Reg_H2_PTE_LEDP"	
TLARs	range
	pax
	payload
	cruise alt
	cruise Mach
	…
Config	wing AR
	wing location
	airfoils
	…
	Jet-A
	Partial Turbo Electric
	Boundary Layer Ingestion

RADICAL DESIGN	
"Rad_Reg_H2_PTE_LEDP_rangeXX"	
TLARs	rangeXX
	pax
	payload
	cruise alt
	cruise Mach
	…
Config	wing AR
	wing location
	airfoils
	…
	Jet-A
	Partial Turbo Electric
	Boundary Layer Ingestion

Sensitivity study: Regional

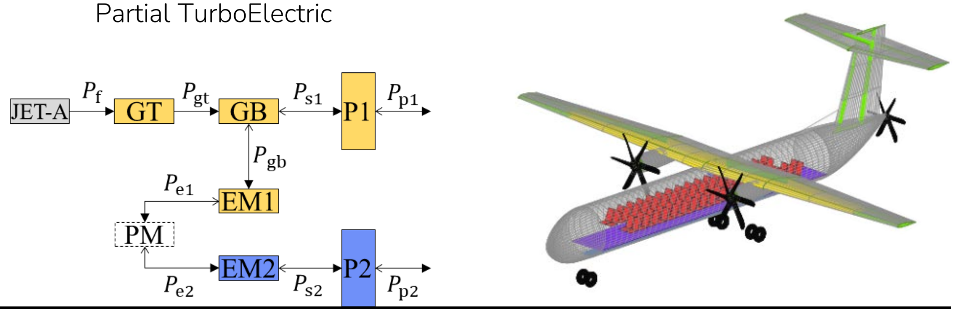
conventional

REG-baseline



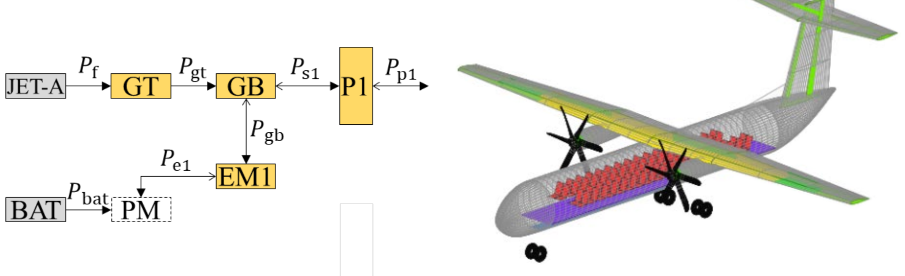
Partial TurboElectric

REG-PTE-BLI



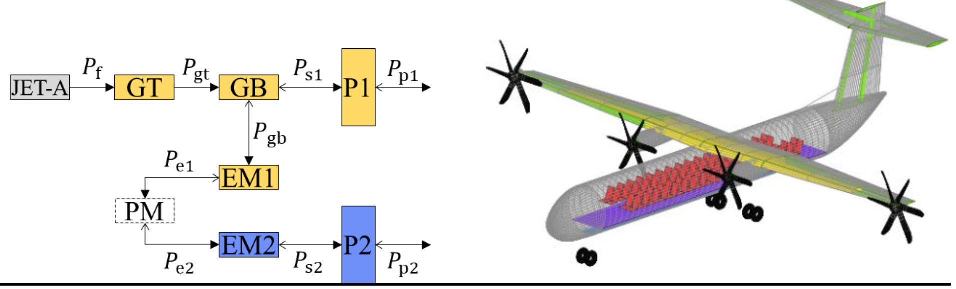
Parallel

REG-boostedTP



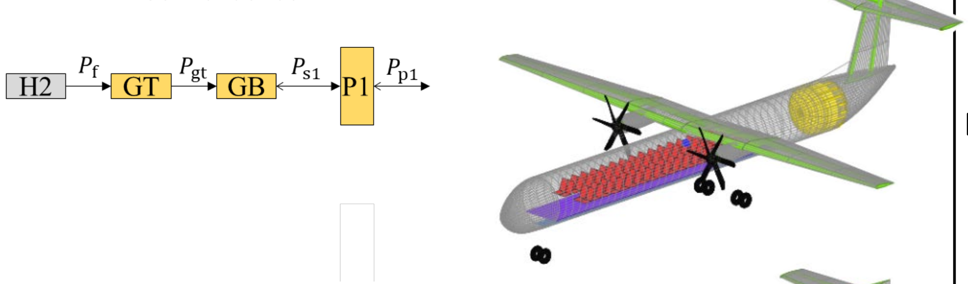
Partial TurboElectric

REG-PTE-WtipMP



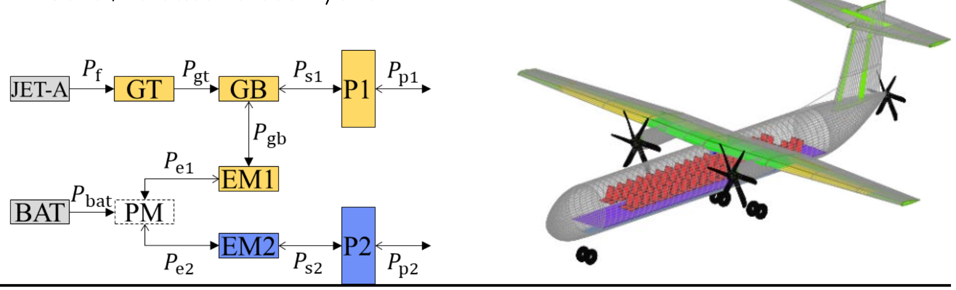
Conventional

REG-LH2



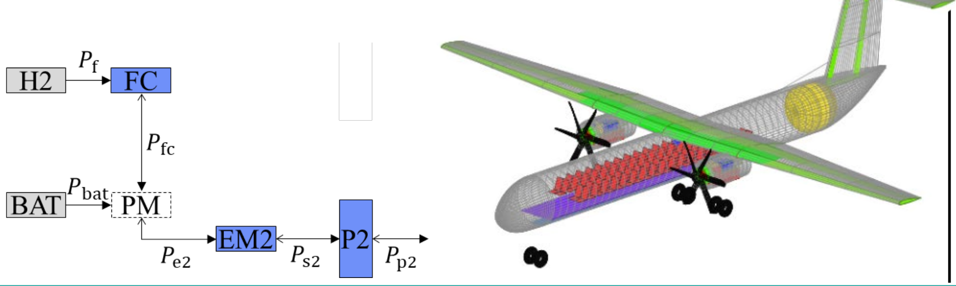
Serial/Parallel Partial Hybrid

REG-SPPH-BLI



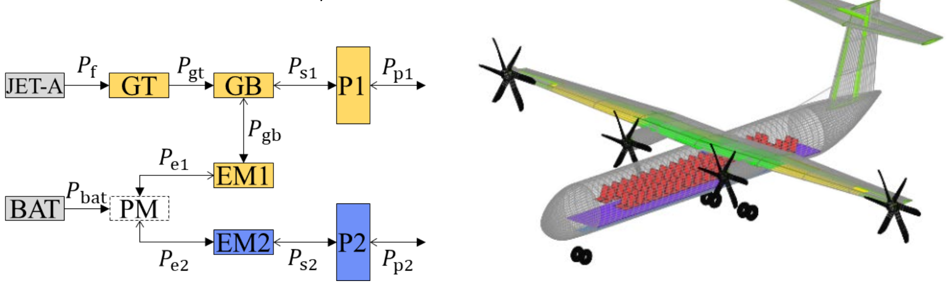
Serial

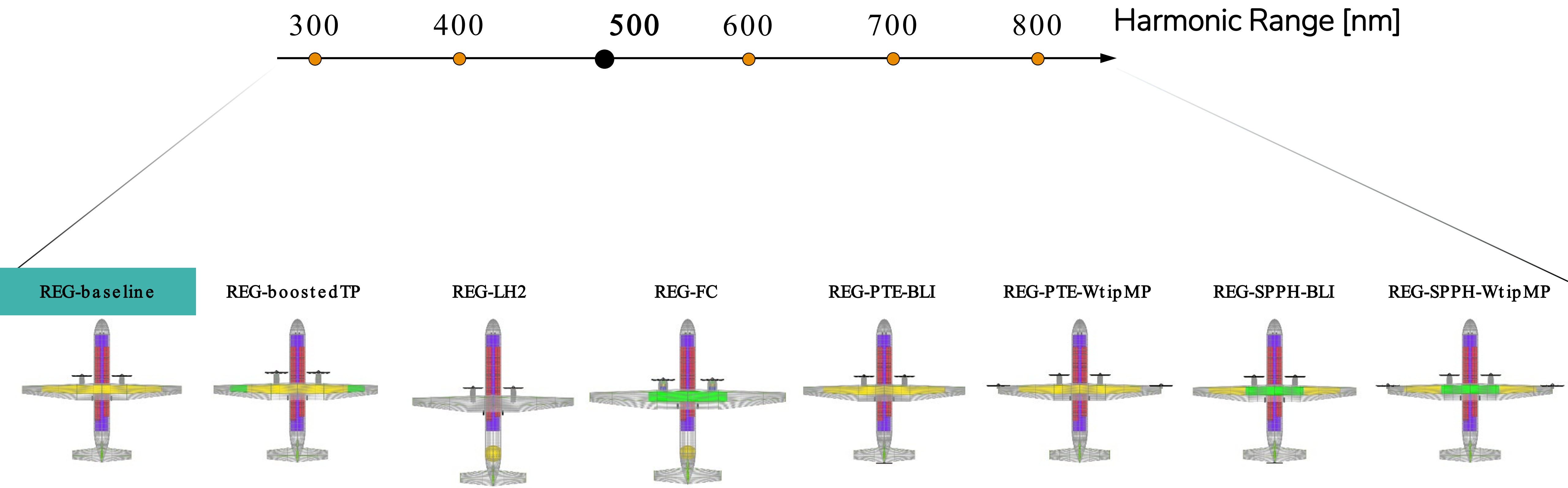
REG-FC



Serial/Parallel Partial Hybrid

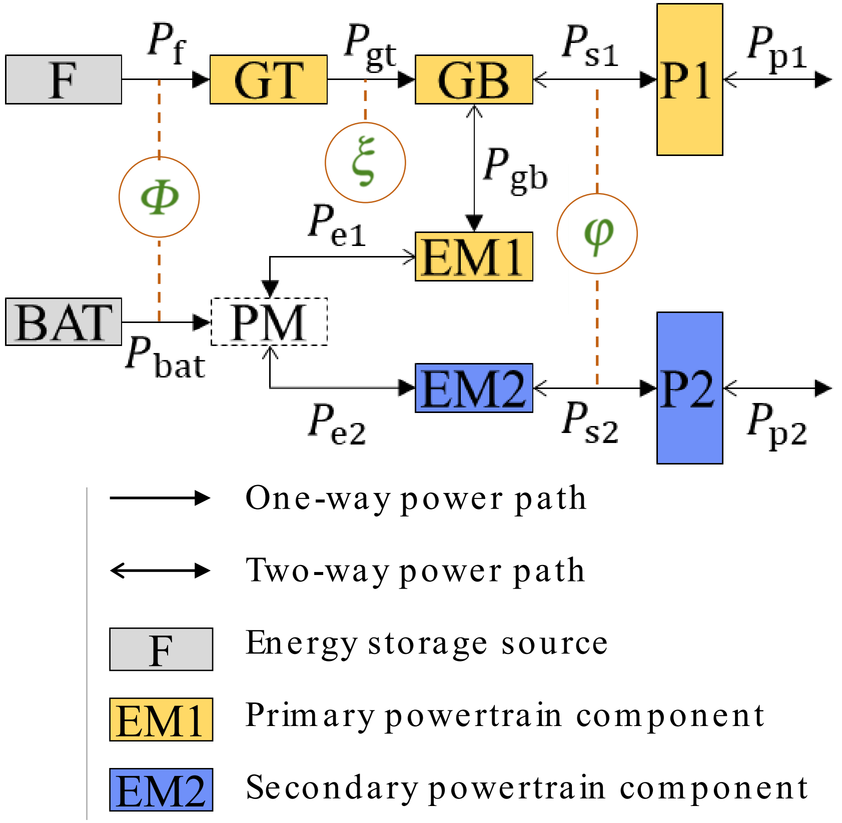
REG-SPPH-WtipMP



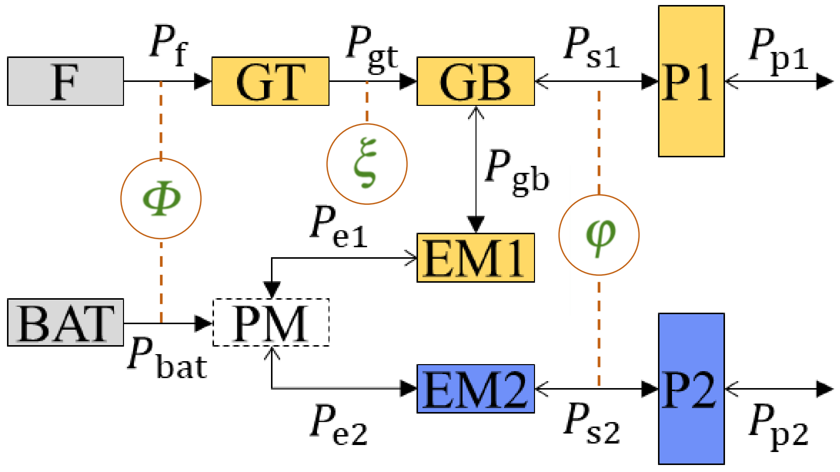

300
400
500
600
700
800
Harmonic Range [nm]
REG-baseline
REG-boostedTP
REG-LH2
REG-FC
REG-PTE-BLI
REG-PTE-WtipMP
REG-SPPH-BLI
REG-SPPH-WtipMP

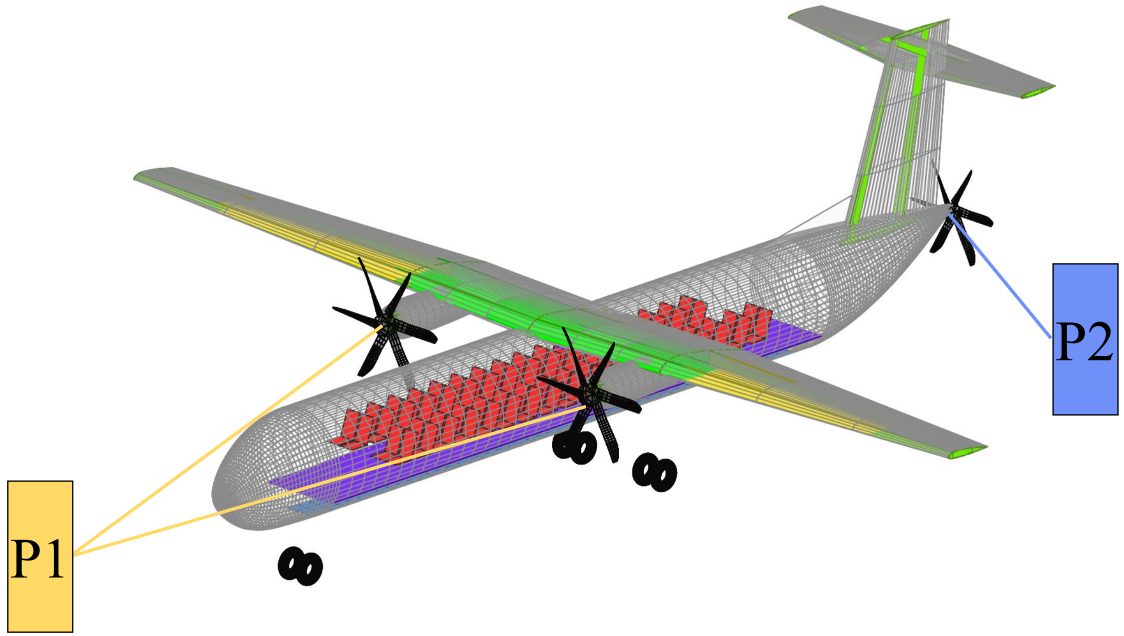
Sensitivity study: Power Control Parameters

Aircraft	MA flight phase	GT throttle ξ	Supplied Power Ratio Φ	Shaft Power Ratio φ
		$\xi = \frac{P_{GT}}{P_{GT max}}$	$\Phi = \frac{P_{bat}}{P_{bat} + P_f}$	$\varphi = \frac{P_{s2}}{P_{s1} + P_{s2}}$
REG-baseline	Climb	0.70-0.95		
	Cruise	0.90-0.90		
	Descent	0.035-0.035		
REG-boostedTP	Climb	0.90-0.90	0.00-0.05	
	Cruise	0.85-0.85	TBD-TBD	
	Descent	0.25-0.10	0.00-0.00	
REG-PTE-BLI	Climb	0.70-0.95		0.00-0.00
	Cruise	TBD-TBD		0.08-0.08
	Descent	0.035-0.035		0.00-0.00
REG-PTE-WtMP	Climb	0.70-1.00		0.10-0.14
	Cruise	TBD-TBD		0.20-0.20
	Descent	0.035-0.035		0.00-0.00
REG-SPPH-BLI	Climb	0.90-0.90	0.01-0.05	0.07-0.05
	Cruise	0.90-0.90	TBD-TBD	0.05-0.05
	Descent	0.05-0.05	0.00-0.00	0.05-0.05
REG-SPPH-WtMP	Climb	0.90-0.90	0.01-0.05	0.08-0.18
	Cruise	0.90-0.90	TBD-TBD	0.20-0.20
	Descent	0.05-0.05	0.00-0.00	0.00-0.00

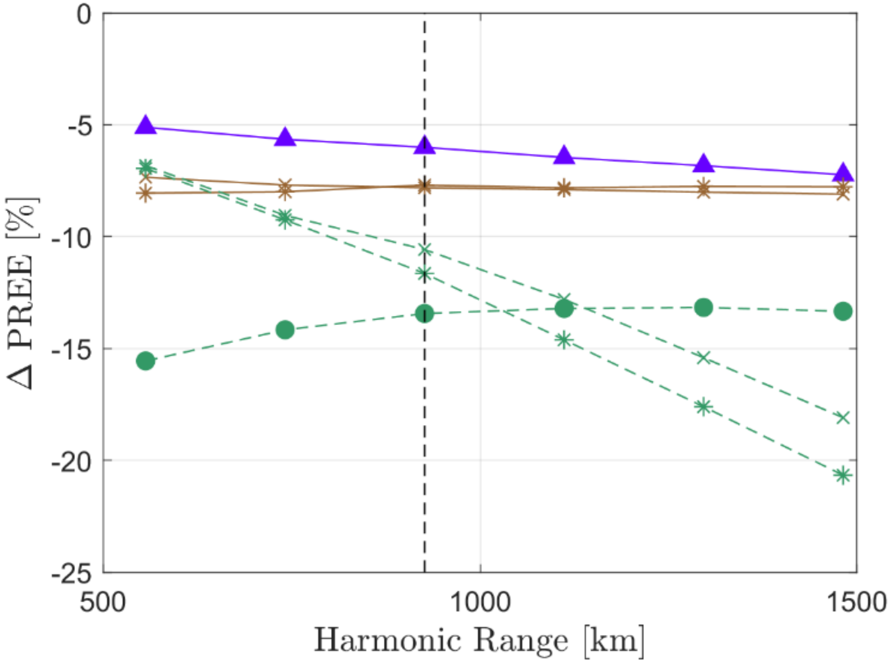


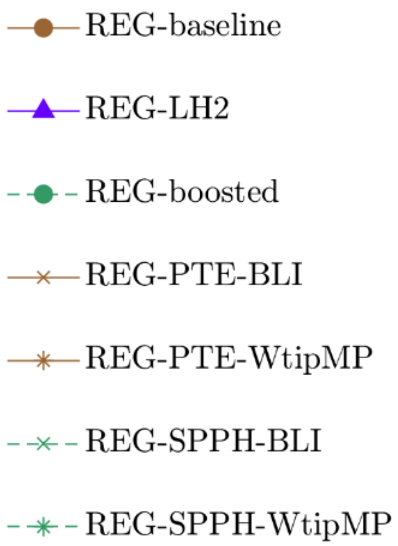
Aircraft	MA flight phase	GT throttle ξ	Supplied Power Ratio Φ	Shaft Power Ratio φ
		$\xi = \frac{P_{GT}}{P_{GTmax}}$	$\Phi = \frac{P_{bat}}{P_{bat} + P_f}$	$\varphi = \frac{P_{s2}}{P_{s1} + P_{s2}}$
REG-SPPH-BLI	Climb	0.90-0.90	0.01-0.05	0.07-0.05
	Cruise	0.90-0.90	TBD-TBD	0.05-0.05
	Descent	0.05-0.05	0.00-0.00	0.05-0.05



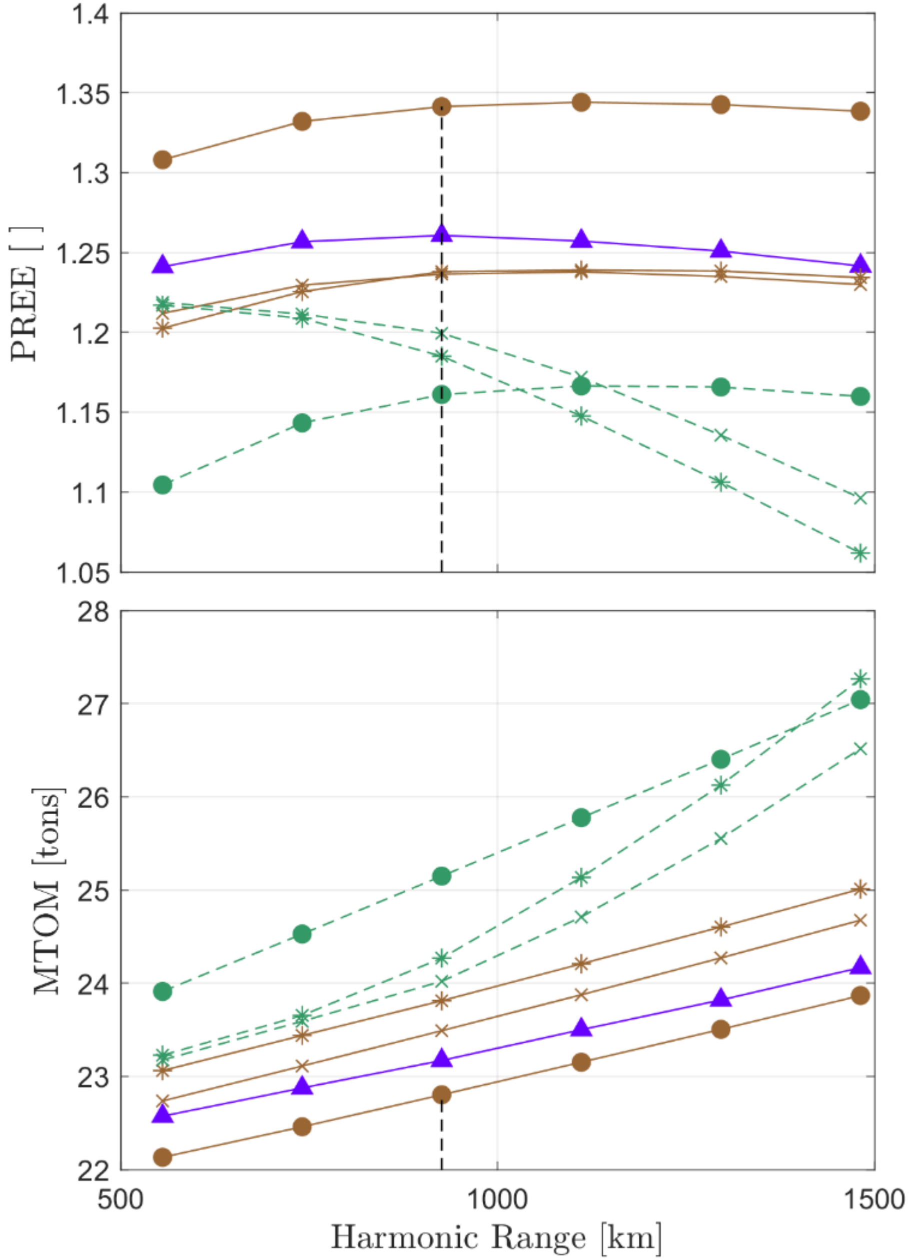


Sensitivity study: Range exploration



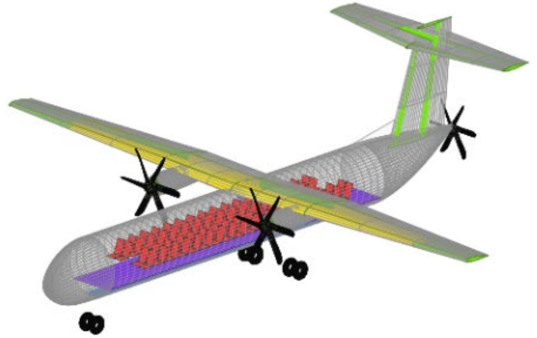


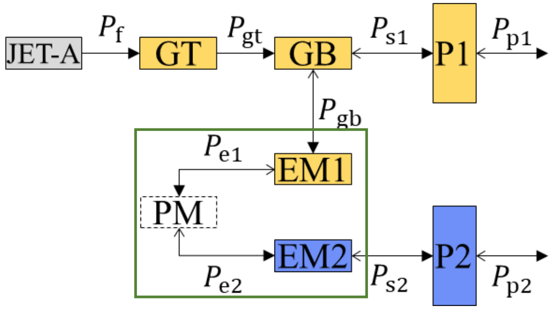
$$PREE = \frac{W_{PL}\,.Range}{E_f + E_{bat}}$$



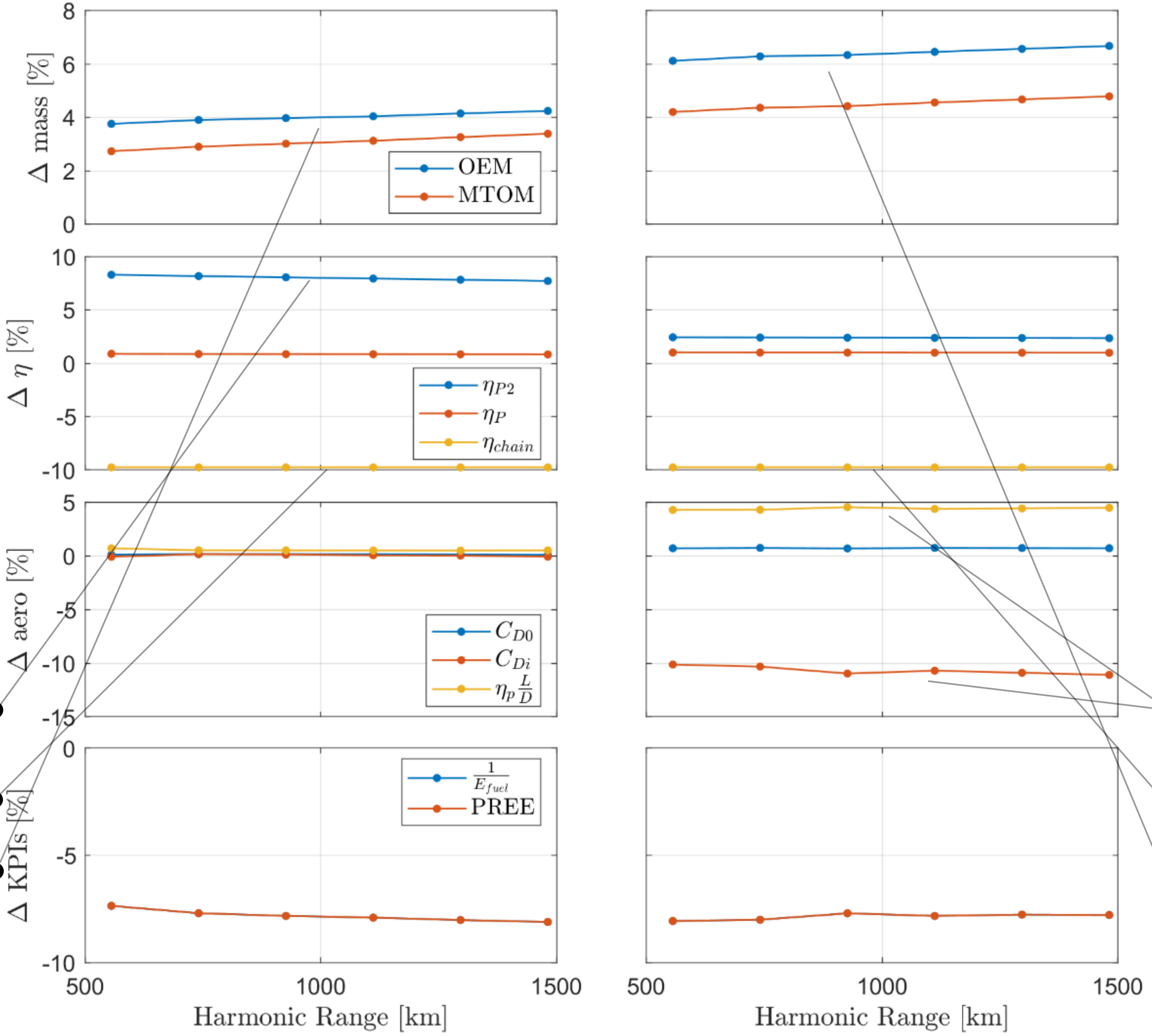
Sensitivity study: Range exploration

REG-PTE-BLI

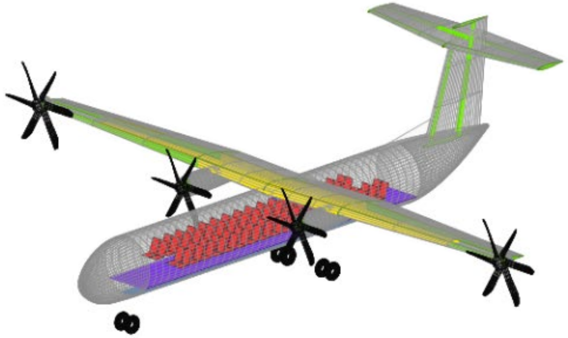


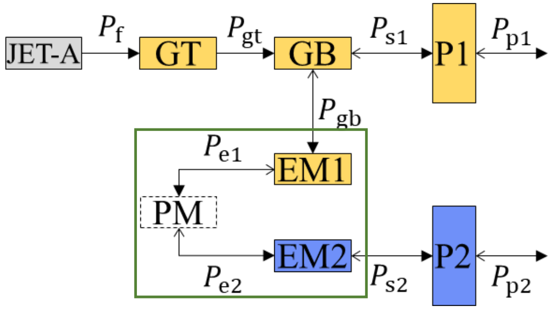


- Higher efficiency of secondary propulsion layout
- 10% extra power losses to P2
- Increased OEM



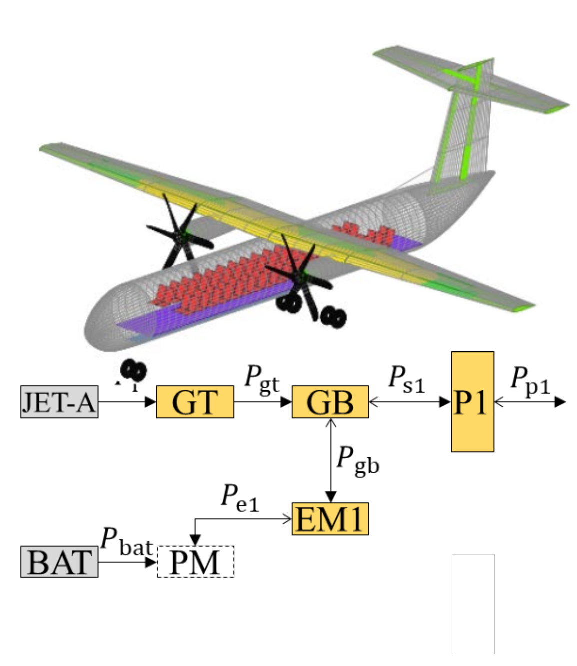
REG-PTE-WtipMP

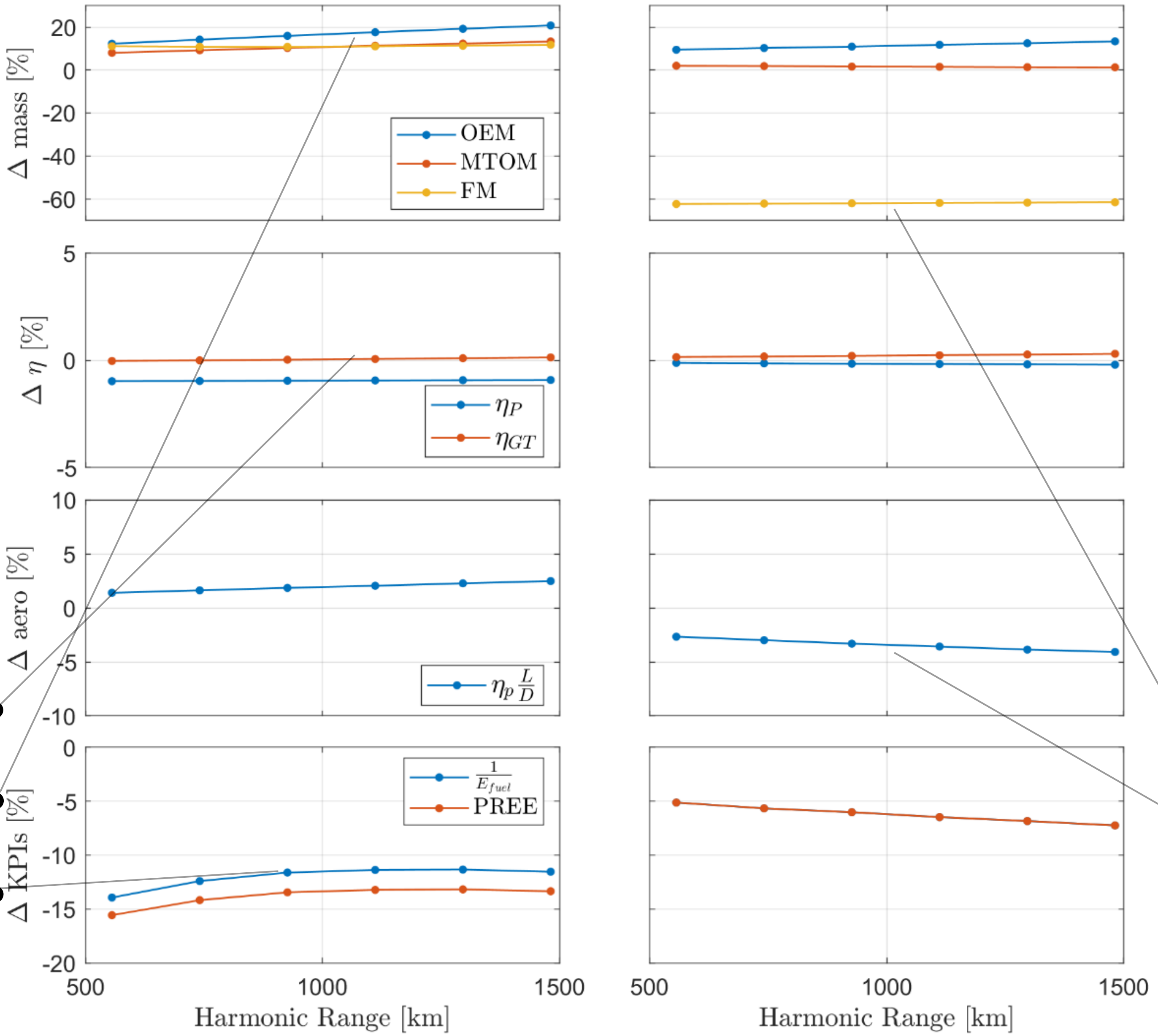




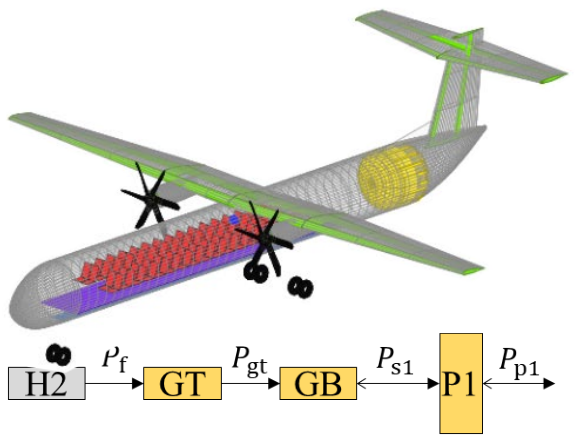
- 10% reduced C_{DI} & 5% improved aero-propulsive efficiency.
- 10% extra power losses to P2
- Increased OEM

REG-boosted TP





REG-LH2



- No significant effect on GT efficiency
- Increased OEM
- Higher fuel despite battery usage.

- Reduced fuel mass such that overall MTOM is rather similar.
- Deteriorated aero-propulsive efficiency (increased C_{D0})

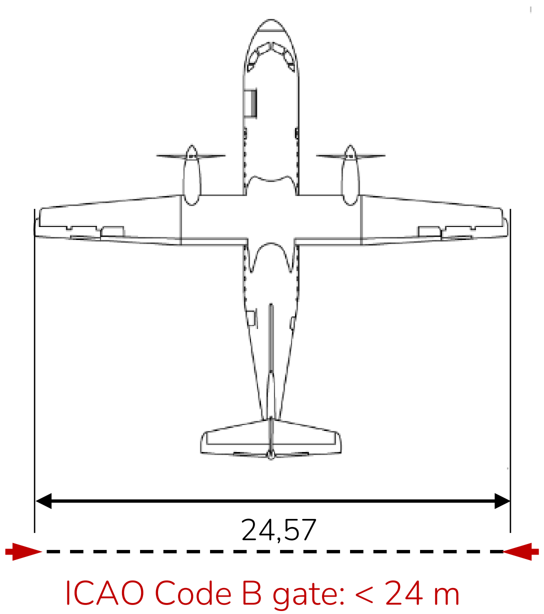
Takeaways

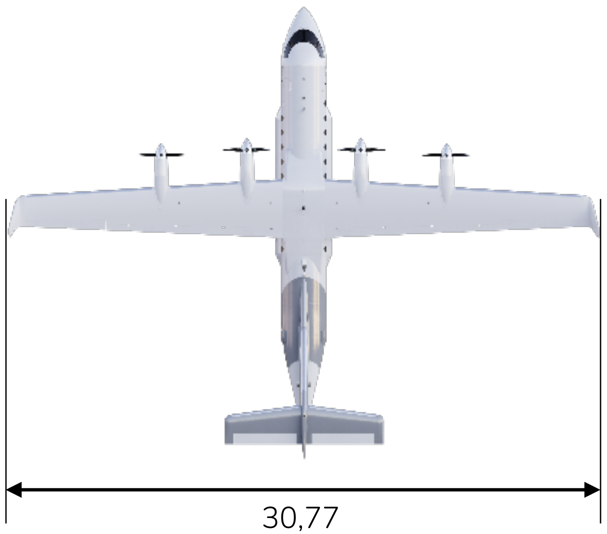
- ✓ Benefits of distributed propulsion at system-level are overcome by power conversion losses and mass penalties.
- ✓ Performance of battery-assisted aircraft is highly dependant on the set power control parameters selected for component sizing and energy usage.
- ✓ When used for temporary phases at high power output, battery usage has a debilitating impact on aircraft-level energy consumption, as well as on fuel consumption.
- ✓ The MTOM achieved by LH2 regional aircraft is comparable to baseline, but performance penalty caused by excess parasite drag due to lengthened fuselage and larger HT.

Outlooks

- ➢ Can distributed propulsion provide some benefits?
- ➢ Can a larger usage of battery energy be beneficial and what would limit the degree of hybridization ?

Radical new aircraft within existing infrastructures

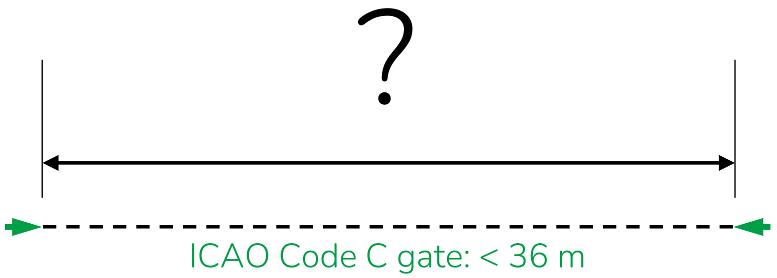




		ATR 42-500		Heart ES-30
pax capacity	[-]	48	>	30
range @ pax	[km]	1555	>	200 (elec) – 400(hybrid)
MTOM	[tons]	18.60	<	20-21
Wing span	[m]	24,57	<	30,77

The increased MTOM of battery-powered aircraft induces a larger wingspan

How restrictive is the 36 meter-span-limit on the degree of hybridization of regional aircraft?



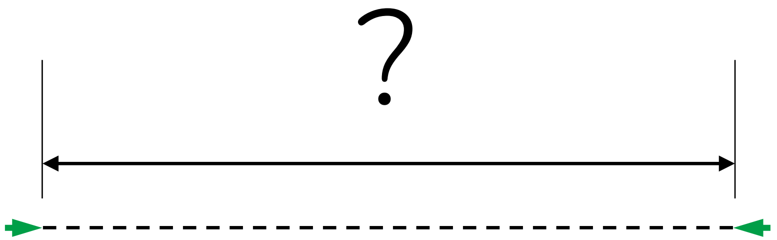
Interest of HEA vs full-electric:

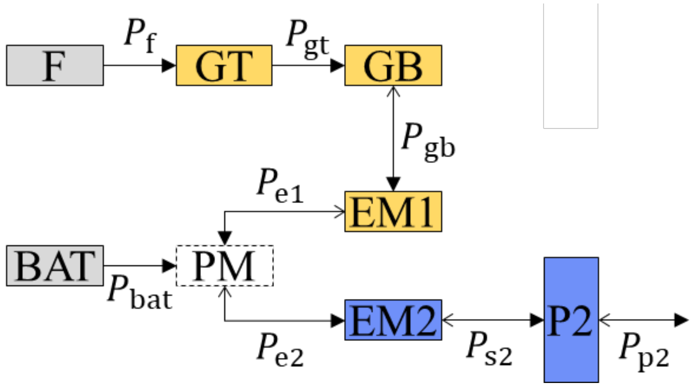
- Approach the span-constraint impact without having to adapt the PL/range requirements from their references within the aircraft class.
- Sets a minimum DoH for the harmonic mission that can then be exceeded for less restrictive missions. (same battery capacity with lower fuel consumption)
- Any electric aircraft with a range-extender is conceptually a HEA that must be sized by its harmonic mission

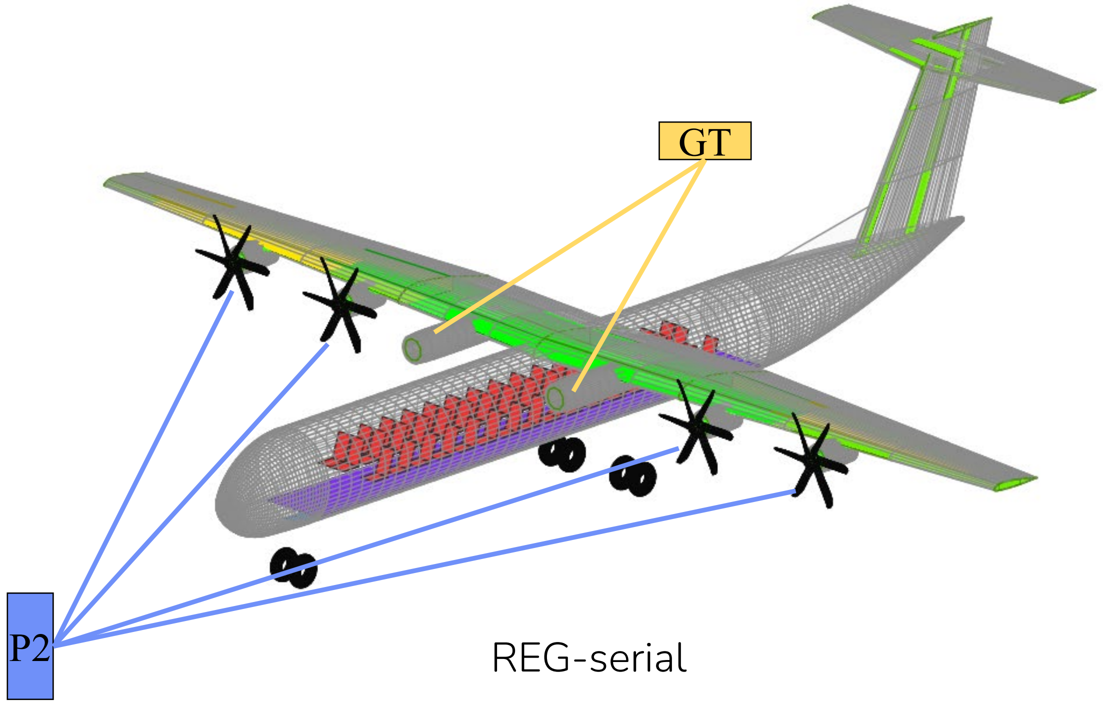
Top Level Aircraft Requirements		
Pax capacity	[-]	48 @ 30'' pitch
Max payload	[kg]	5450
Range at max payload	[nm]	500
Cruise Mach number	[-]	0,4
Cruise altitude - ISA	[ft]	23,000
Landing distance - ISA - SL	[m]	1006
Takeoff distance - ISA - SL	[m]	1372
Diversion Mach number	[-]	0,2785
Diversion altitude	[ft]	4920
Diversion range	[nm]	100
Time-to-climb at cruise altitude at cruise speed on full payload	[min]	22

Aircraft Design Parameters		
Abreast seating	[-]	2 - 1
Wing aspect ratio	[-]	12
Taper ratio	[-]	0,47
Spanwise kink location	[%]	31,5
Tickness-to-chord ratio [root, kink, tip]	[%]	[18, 16, 13]
HT volume coefficient	[-]	1,00
VT volume coefficient	[-]	0,08
VT sweep	[deg]	30
Battery location	[-]	*wing*

How restrictive is the 36 meter-span-limit on the degree of hybridization of regional aircraft?

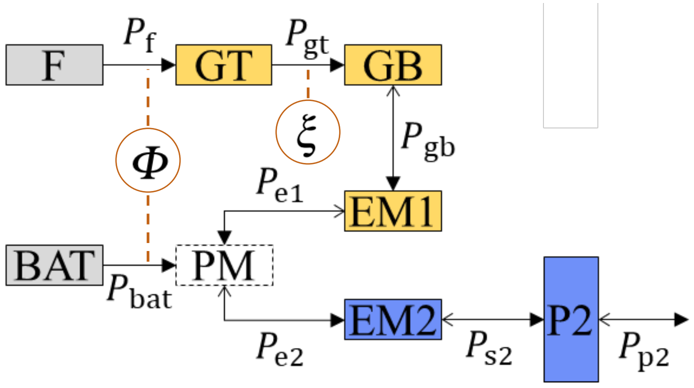






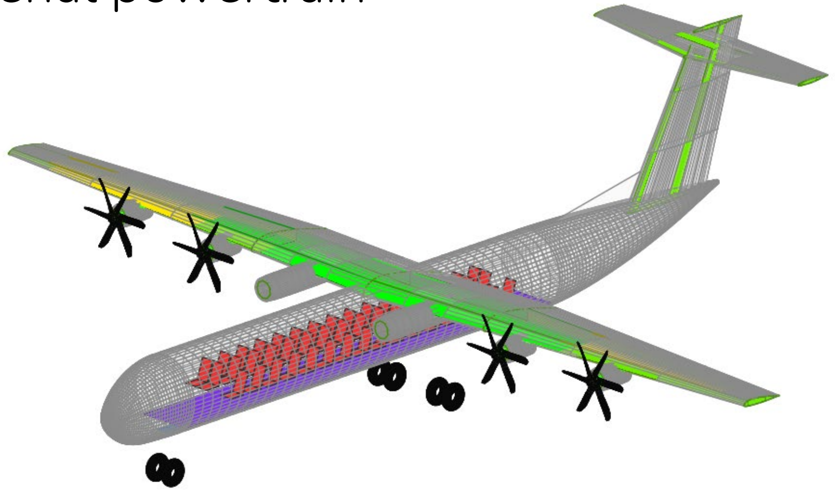
REG-serial

Power Control Parameters for serial powertrain

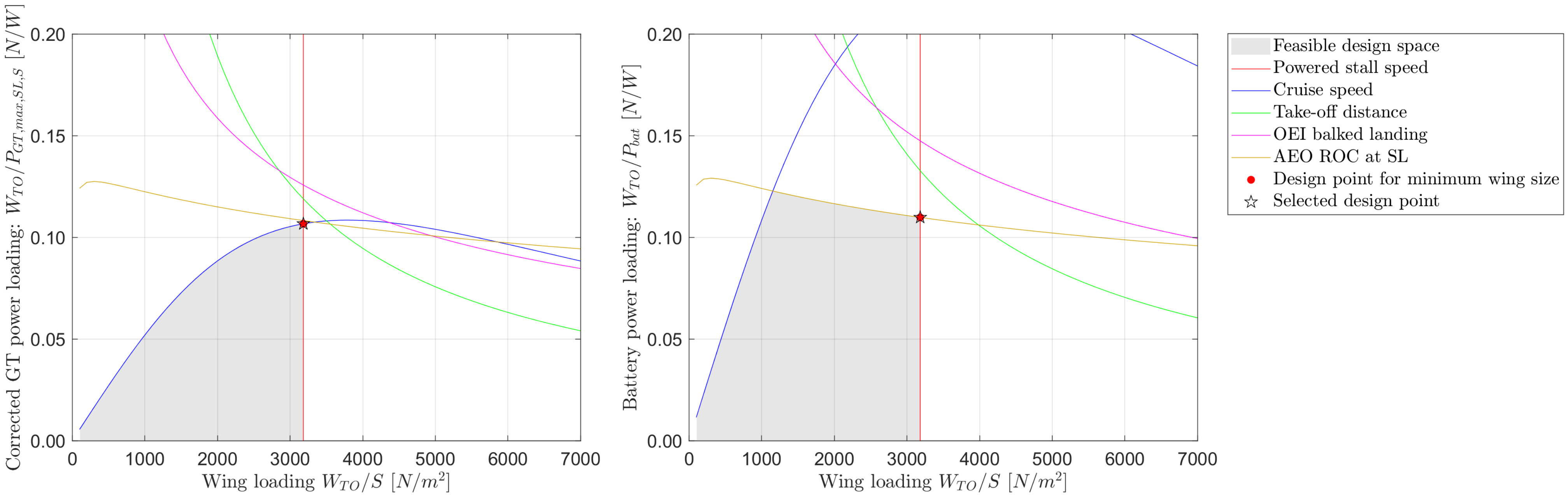


$$\xi = \frac{P_{GT}}{P_{GTmax}}$$

$$\Phi = \frac{P_{bat}}{P_{bat} + P_f}$$



Size the GT for cruise $(\xi_{cruise} = 0.9;\ \phi_{cruise})$ and adapt battery power output to other constraints.

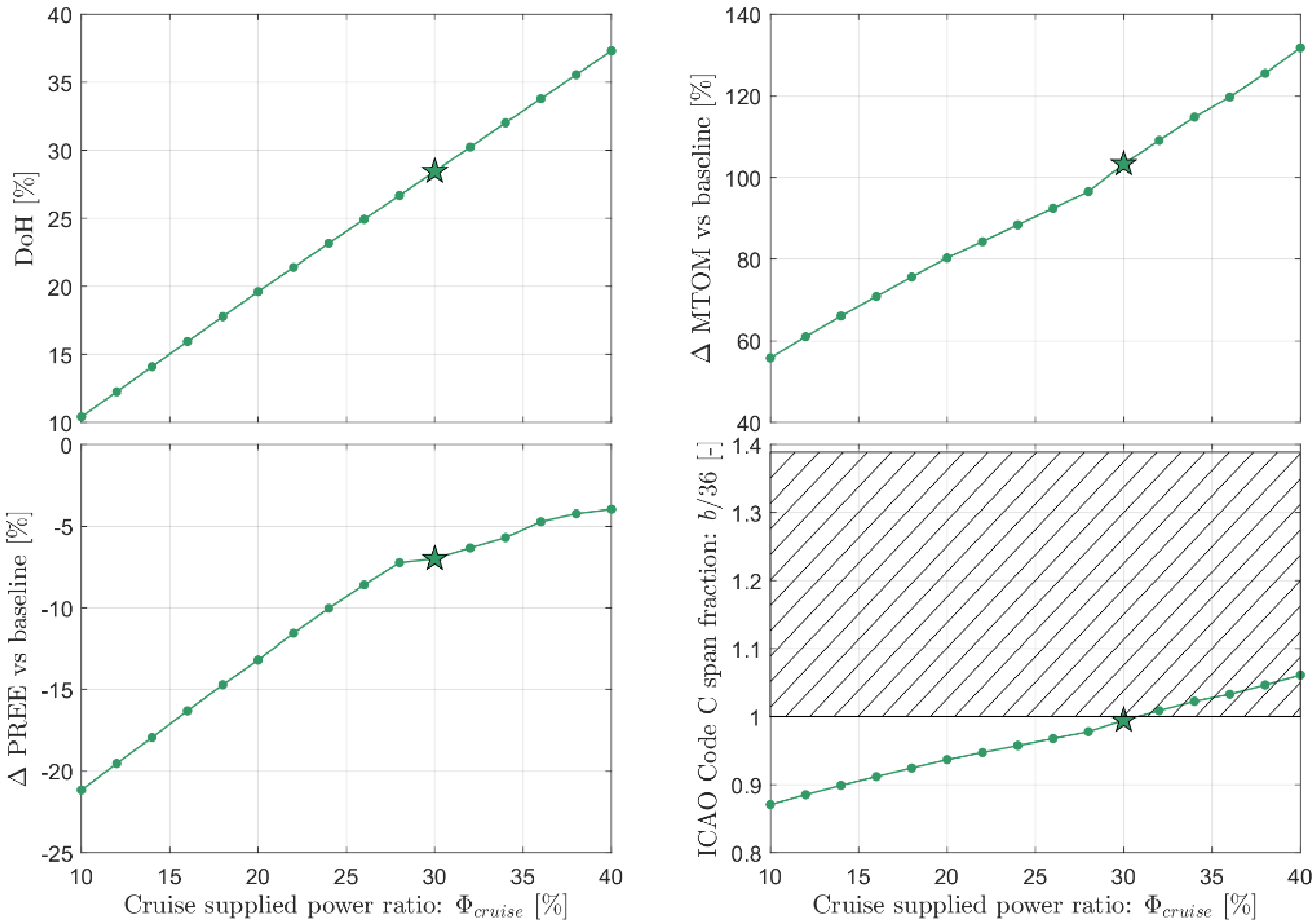


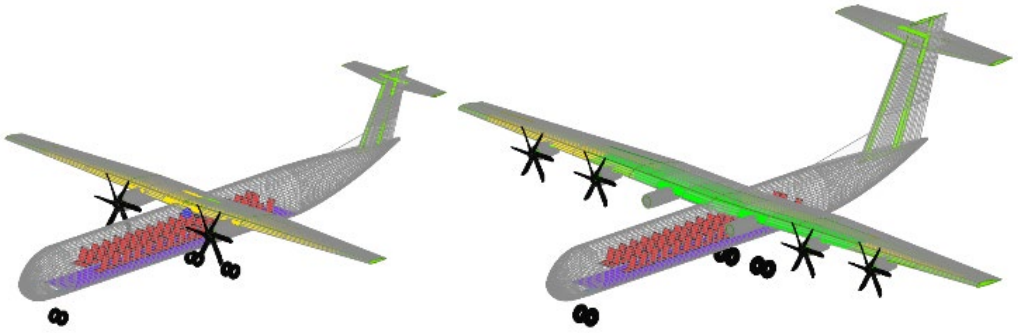
Sensitivity study: finding the 36 m span limit

$$DoH = \frac{E_{bat}}{E_f + E_{bat}}$$

$$PREE = \frac{W_{PL}\,.Range}{E_f + E_{bat}}$$

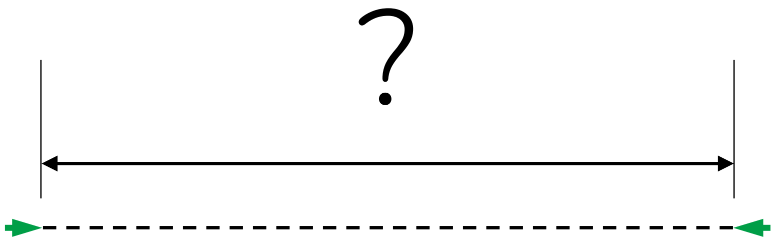
Serial hybrid electric aircraft: high-level results



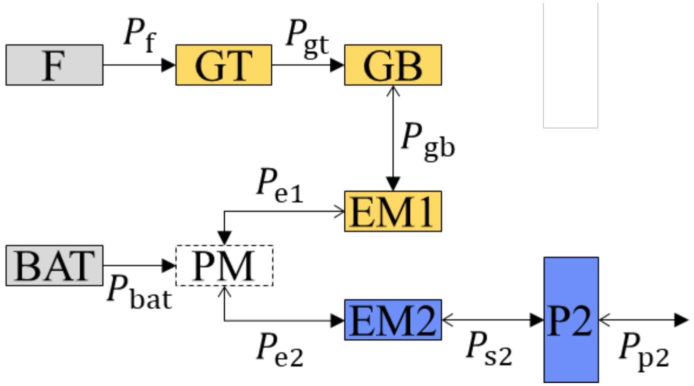


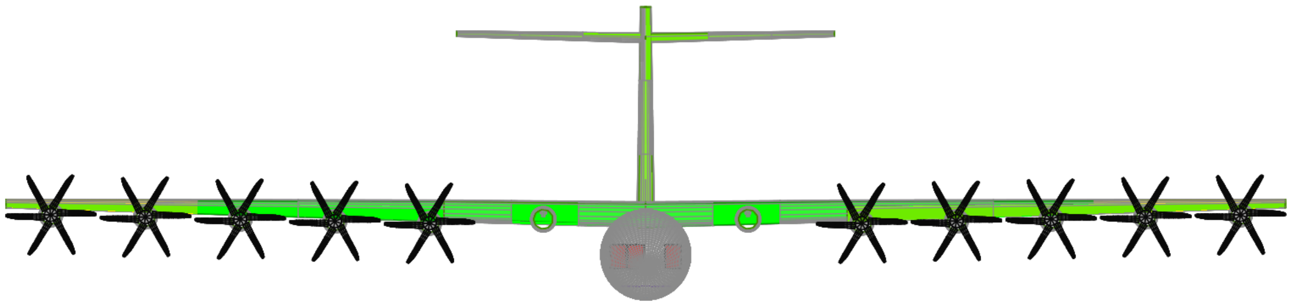
			REG-baseline	REG-serial	Δ [%]
Design Selection Variables	ϕ_{cruise}	$[-]$	N.A.	0,30	N.A.
	GT power loading $W_{TO}/P_{GT,max,SLS}$	$[N/W]$	0,054	0,16	+205
	Battery power loading $W_{TO}/P_{GT,max,SLS}$	$[N/W]$	N.A.	0,103	N.A.
	Take-off wing loading W_{TO}/S_w	$[kN/m^2]$	3,18	3,18	0,0
Masses & Dimensions	MTOM	$[tons]$	17,07	34,71	+103
	OEM	$[tons]$	10,27	27,95	+172
	Fuel mass	$[tons]$	1,35	1,30	-3,8
	Battery mass	$[tons]$	N.A.	11,55	N.A.
	Wing span	$[m]$	25,14	35,80	+42
	Wing area	$[m^2]$	52,65	106,8	+102,9
KPIs nominal mission	Degree of Hybridization	$[-]$	N.A.	28,4	N.A.
	Fuel energy consumption, E_f	$[GJ]$	38,2	29,4	-23,1
	Electric energy consumption, E_{bat}	$[GJ]$	N.A.	11,7	N.A.
	PREE	$[-]$	1,296	1,205	-7,0

Lower the wing span by increasing the wing loading



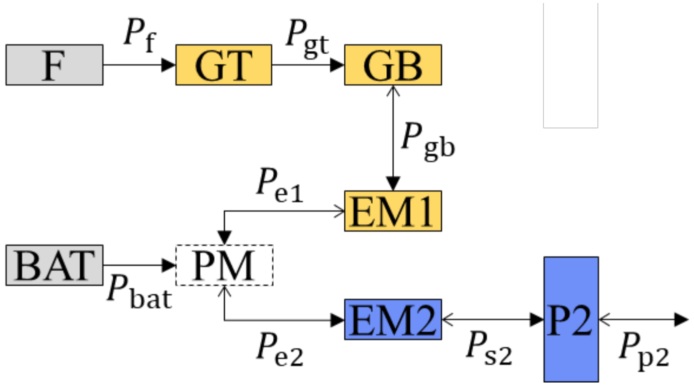
‘Serial’ powertrain architecture, with Leading Edge Distributed Propulsion (LEDP)

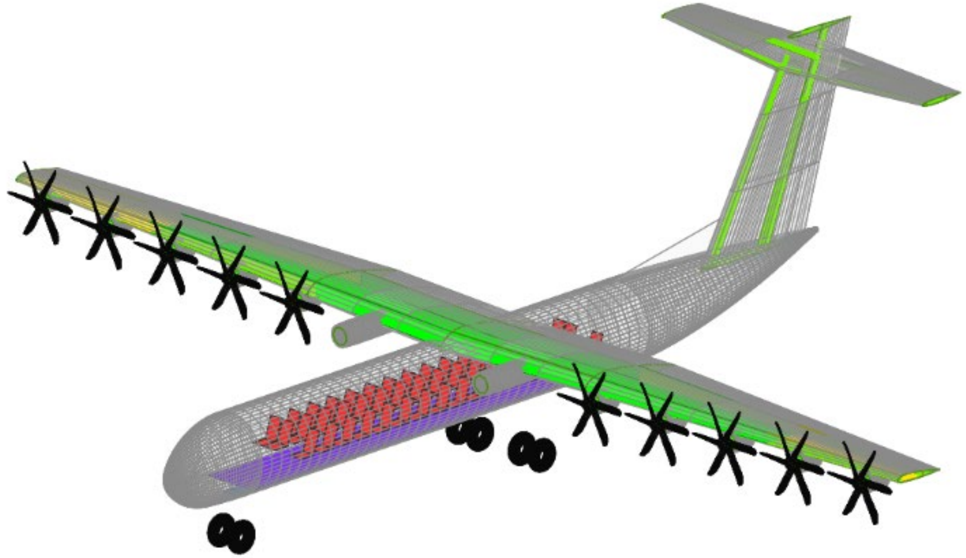




REG-serial-LEDP

'Serial' powertrain architecture, with Leading Edge Distributed Propulsion (LEDP)





REG-serial-LEDP

First try, max wing loading = 5,01 kN/m2. ⇒ not enough wing volume for {fuel + battery}

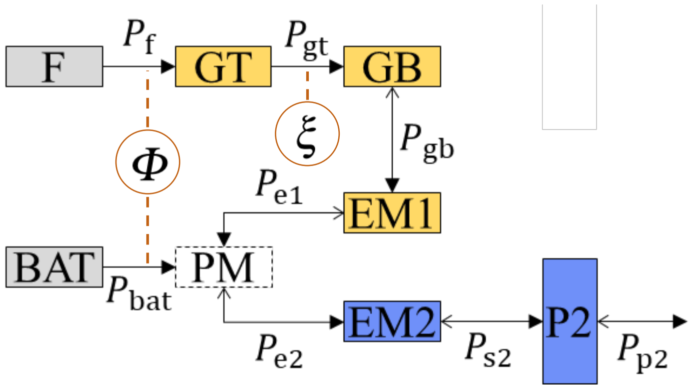
$$b = \sqrt{AR.S}$$

Wing span scales with $S^{1/2}$

$$V_{wing,available} = k \frac{S^{3/2}}{\sqrt{AR}}$$

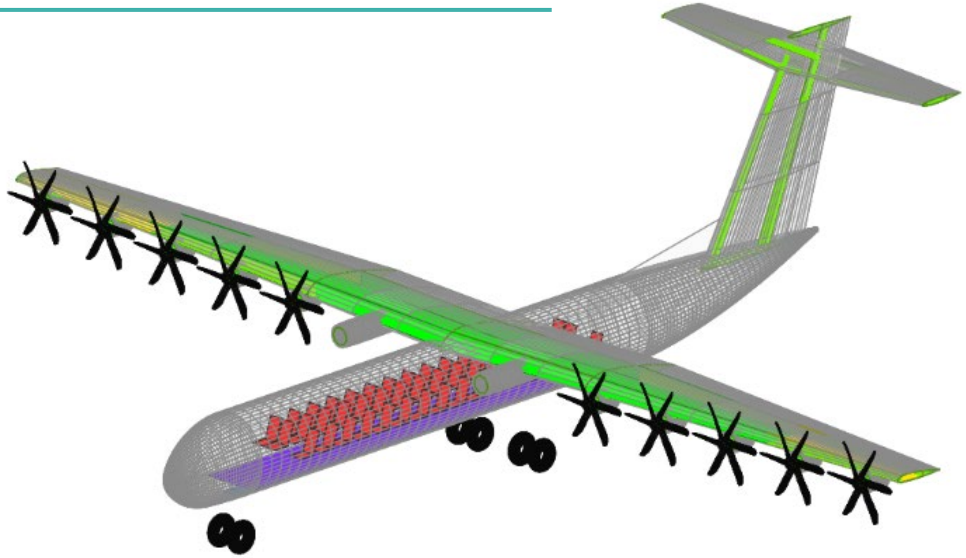
Internal wing volume scales with $S^{3/2}$

⇒ An increase in wing loading would decrease the wing internal volume faster than the wing span

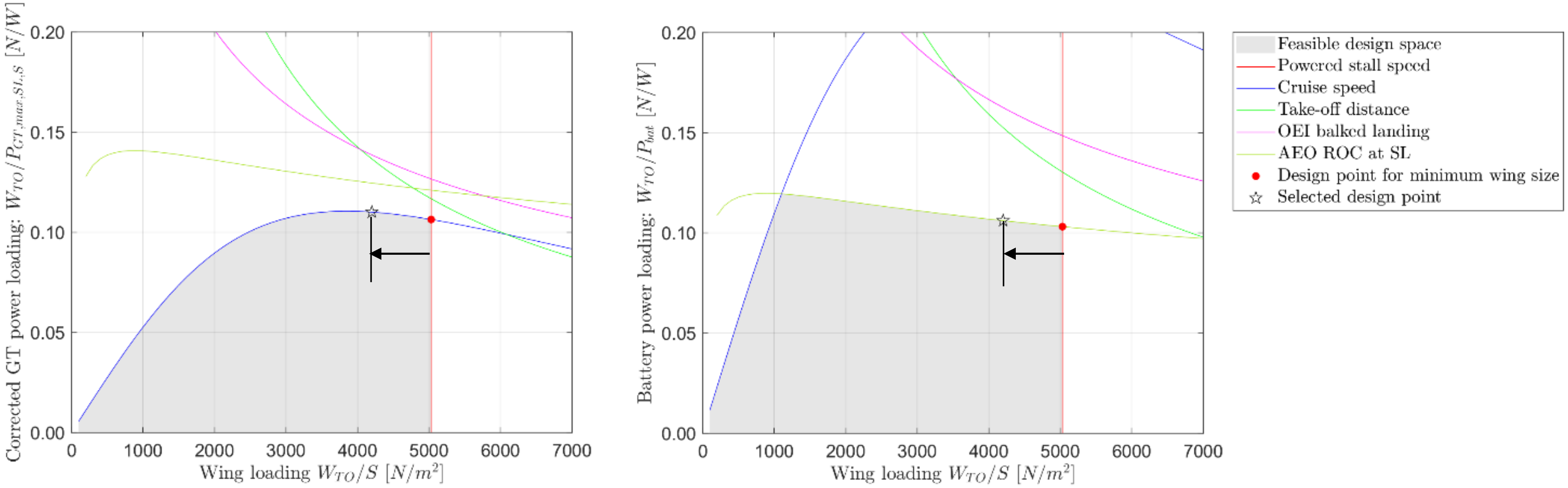


$$\xi = \frac{P_{GT}}{P_{GTmax}}$$

$$\Phi = \frac{P_{bat}}{P_{bat} + P_f}$$



Size the GT for cruise $(\xi_{cruise} = 0.9;\ \phi_{cruise})$ and adapt battery power output to other constraints.

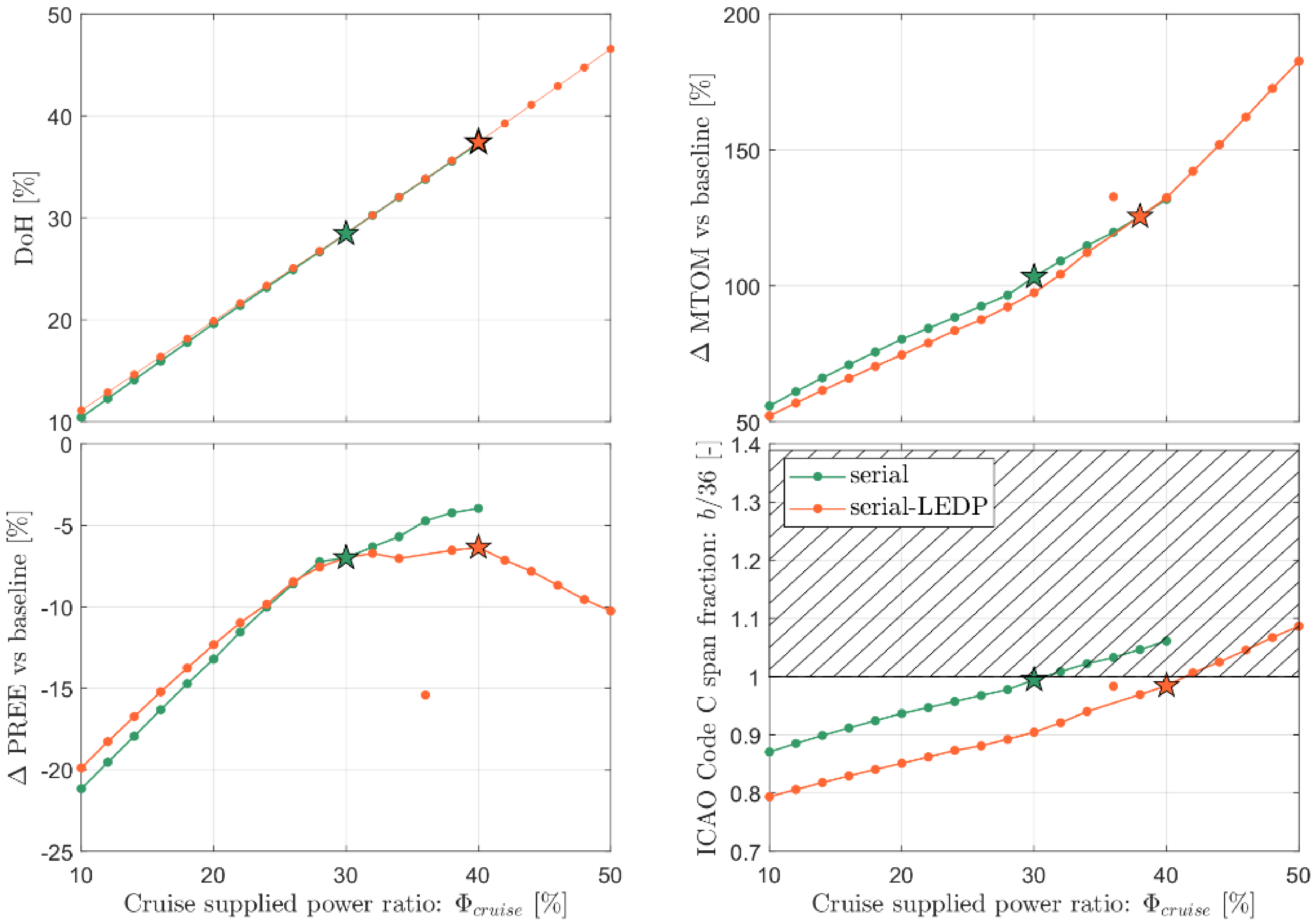


Sensitivity study: finding the 36 m span limit

$$DoH = \frac{E_{bat}}{E_f + E_{bat}}$$

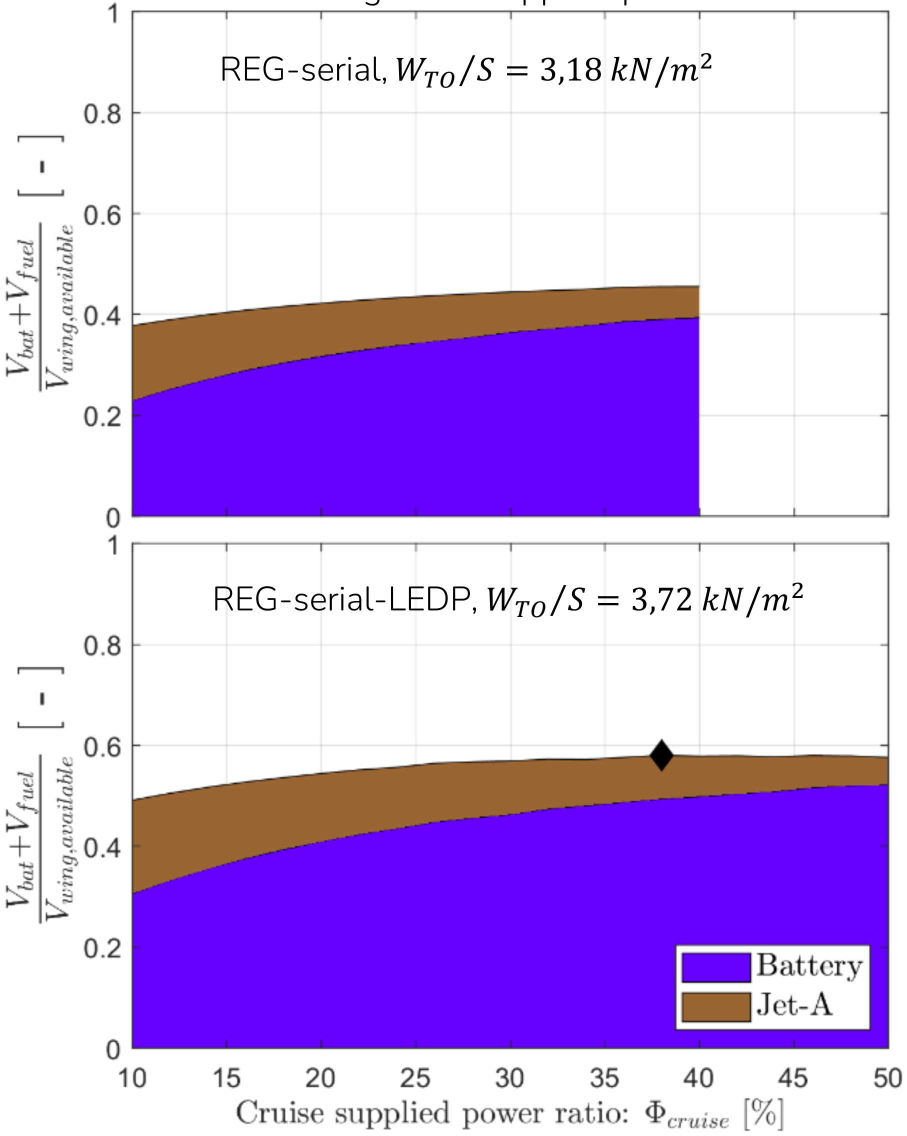
$$PREE = \frac{W_{PL}\,.Range}{E_f + E_{bat}}$$

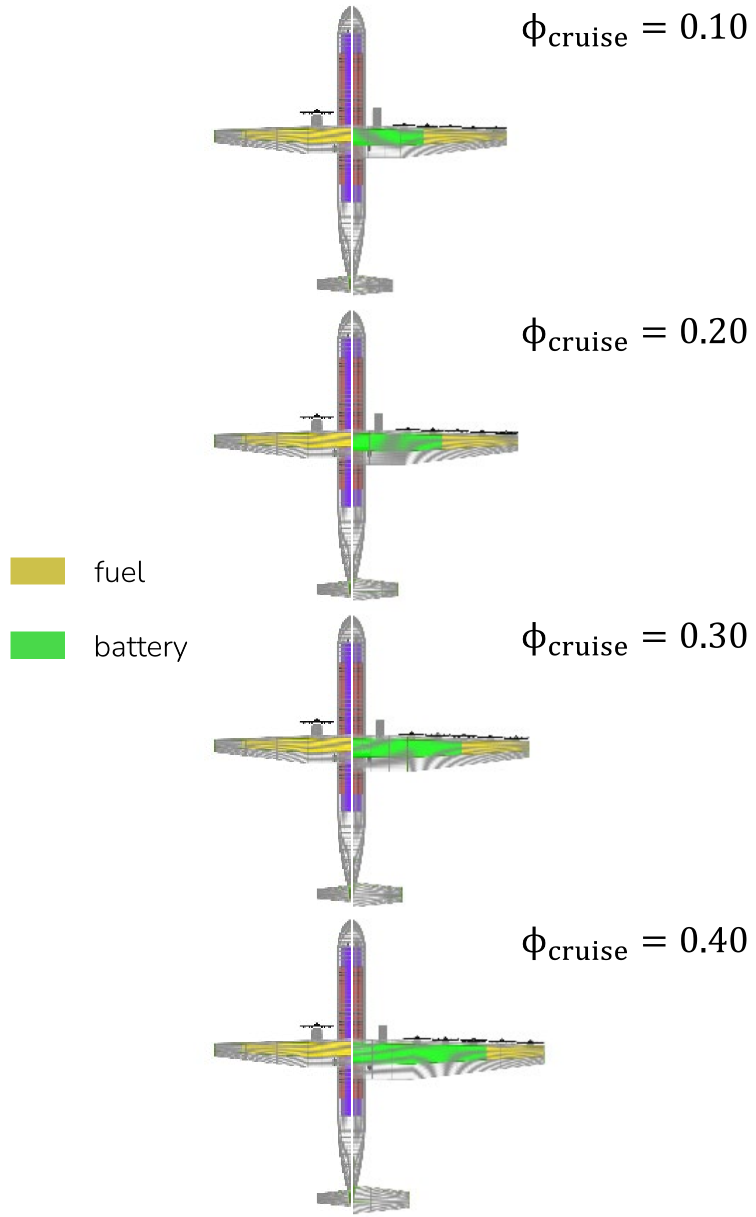
Serial hybrid electric aircraft: high-level results



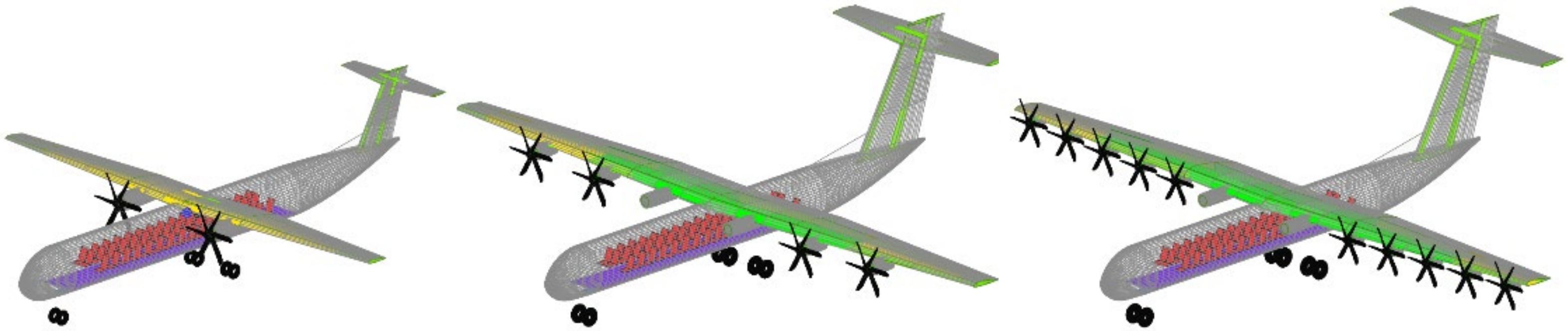
Sensitivity study: internal wing volume constraint

Evolution of wing volume constraint with increasing cruise supplied power ratio





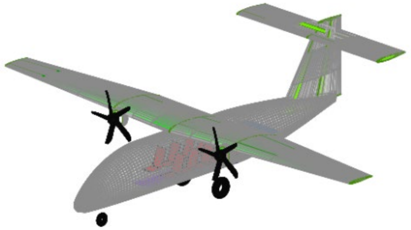
Sensitivity study: span limited regional hybrid electric aircraft



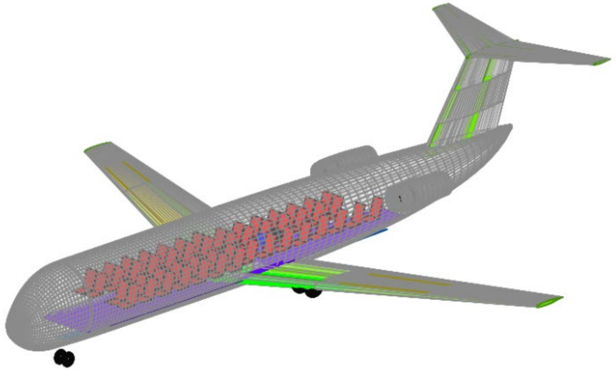
Group	Parameter	Unit	REG-baseline	REG-serial	Δ [%]	REG-serial-LEDP	Δ [%]
Design Selection Variables	ϕ_{cruise}	$[-]$	N.A.	0,30	N.A.	0,40	N.A.
	GT power loading $W_{TO}/P_{GT,max,SLS}$	$[N/W]$	0,054	0,16	+205	0,23	+324
	Battery power loading $W_{TO}/P_{GT,max,SLS}$	$[N/W]$	N.A.	0,103	N.A.	0,09	N.A.
	Take-off wing loading W_{TO}/S_w	$[kN/m^2]$	3,18	3,18	0,0	3,72	+17
Masses & Dimensions	MTOM	$[tons]$	17,07	34,71	+103	39,67	+132
	OEM	$[tons]$	10,27	27,95	+172	33,00	+221
	Fuel mass	$[tons]$	1,35	1,30	-3,8	1,23	-9,3
	Battery mass	$[tons]$	N.A.	11,55	N.A.	16,00	N.A.
	Wing span	$[m]$	25,14	35,80	+42	35,44	+41
	Wing area	$[m^2]$	52,65	106,8	+102,9	104,7	+98,8
KPIs nominal mission	Degree of Hybridization	$[-]$	N.A.	28,4	N.A.	37,4	N.A.
	Fuel energy consumption, E_f	$[GJ]$	38,2	29,4	-23,1	25,5	-33,2
	Electric energy consumption, E_{bat}	$[GJ]$	N.A.	11,7	N.A.	15,3	N.A.
	PREE	$[-]$	1,296	1,205	-7,0	1,213	-6,4

Takeaways

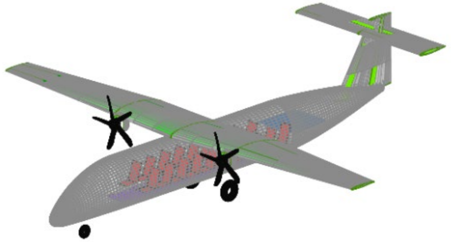
- ✓ For an aircraft sized based on the same TLARs as the ATR-42, the ICAO code C 36 meters span limit is reached for a relatively low DoH ~30%.
- ✓ An increase in wing loading can enable a larger DoH, around 40%
- ✓ Trends indicate that a higher DoH does not necessarily induce a lower fuel consumption.
- ✓ A combination of high wing loading and of low volumetric energy density for batteries compared to jet fuel can lead to the available wing volume being too small for the required volume of the energy carriers.



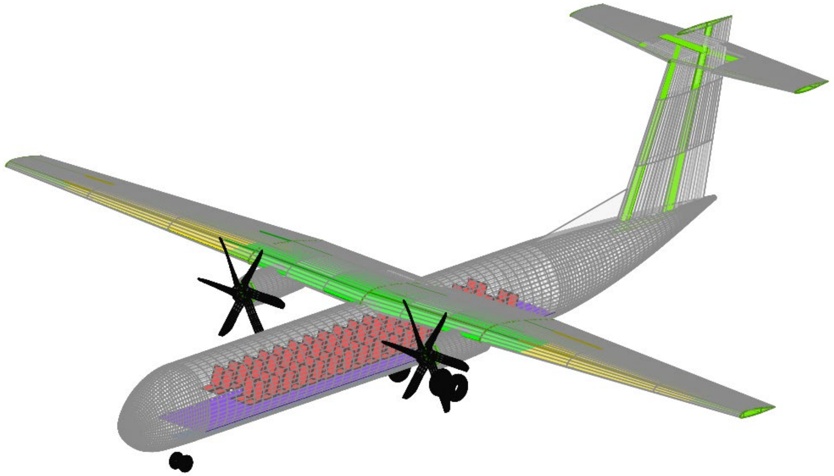
fullE-10pax	
M_{cruise}	0.35
Pax	10



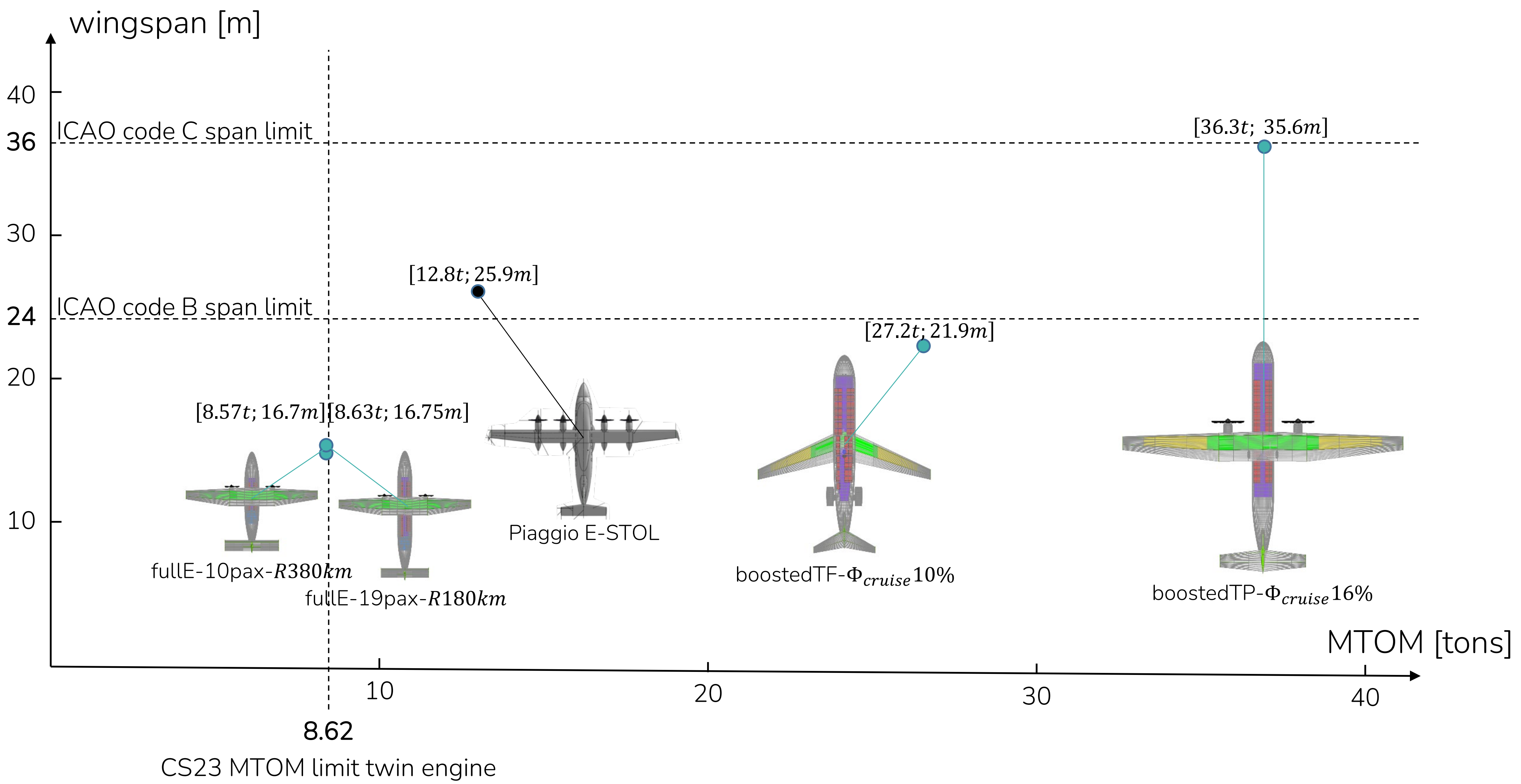
boostedTF	
M_{cruise}	0.7
Pax	50
Range	926km



fullE-19pax	
M_{cruise}	0.35
Pax	19



boostedTP	
M_{cruise}	0.4
Pax	72
Range	926km


wingspan [m]
40
36
30
24
20
10
ICAO code C span limit
ICAO code B span limit
[36.3t; 35.6m]
[12.8t; 25.9m]
[27.2t; 21.9m]
[8.57t; 16.7m]
[8.63t; 16.75m]
Piaggio E-STOL
fullE-10pax-R380km
fullE-19pax-R180km
boostedTF-Φ_{cruise}10%
boostedTP-Φ_{cruise}16%
MTOM [tons]
10
20
30
40
8.62
CS23 MTOM limit twin engine