



**E2. Conceptual design of regional
hybrid-electric aircraft**

**11. HEA TLARs
and
Matching Chart**

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HEA - Top Level Aircraft Requirements



TLARs and Mission

Matching chart

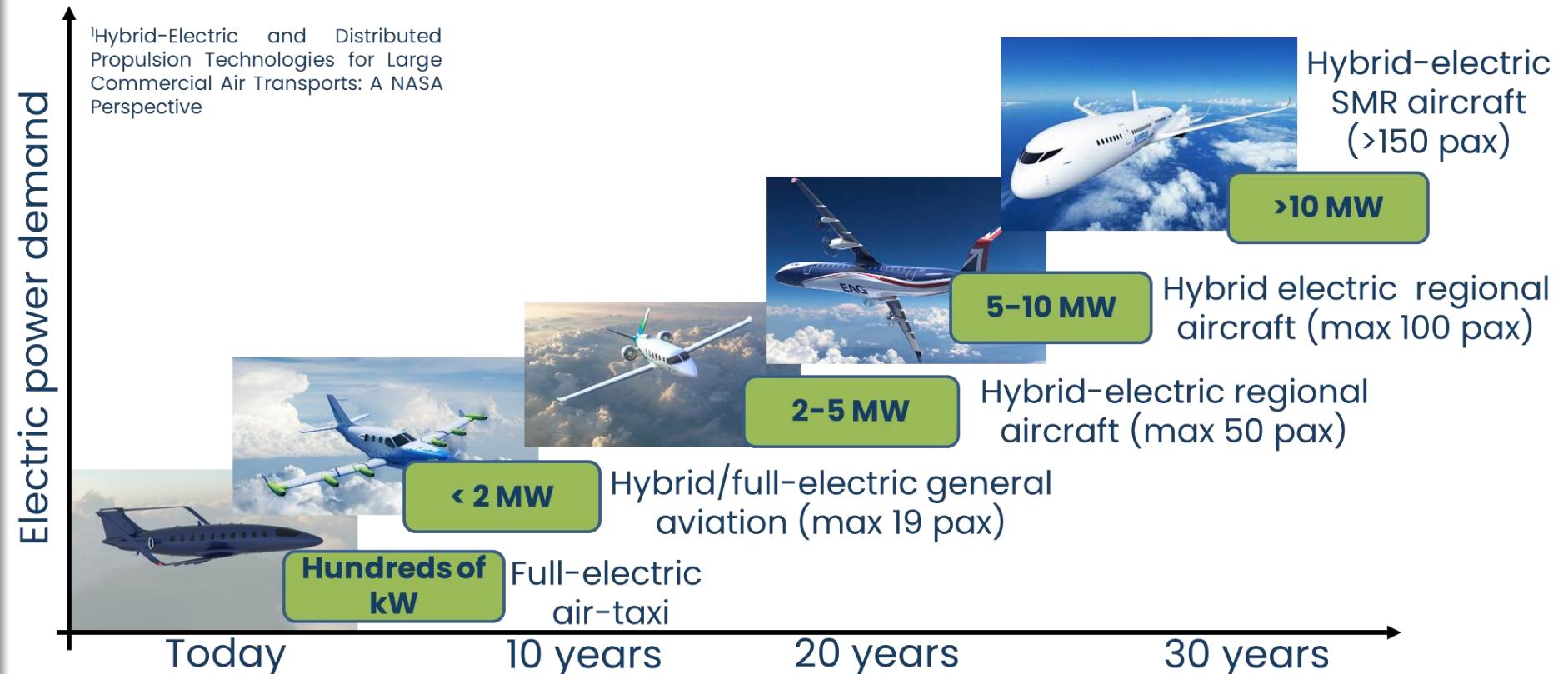
Landing
Equation

Take-off
Equation

Climb
1st, 2nd and final segment
Approach climb

Cruise
Equation

Powertrain architecture
Serial
Parallel



HEA - Top Level Aircraft Requirements



TLARs and Mission

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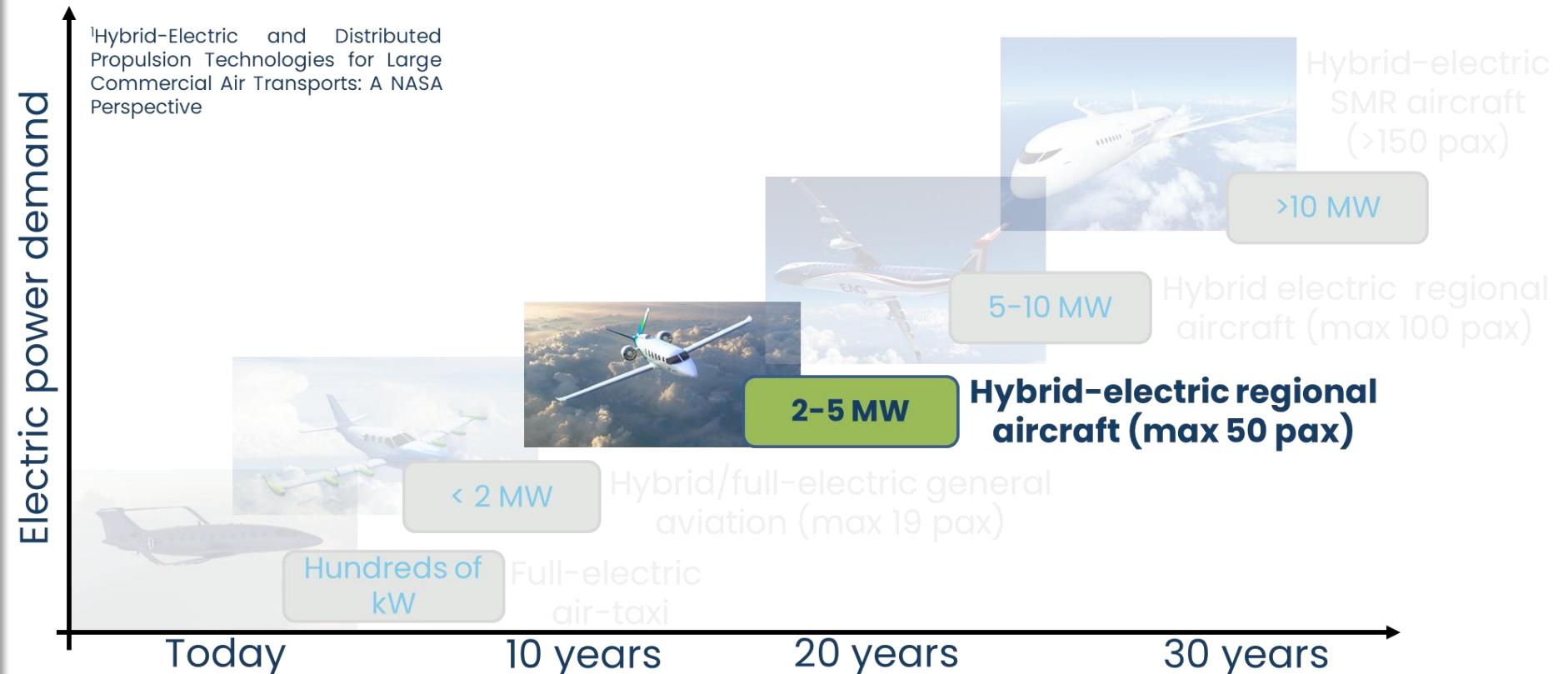
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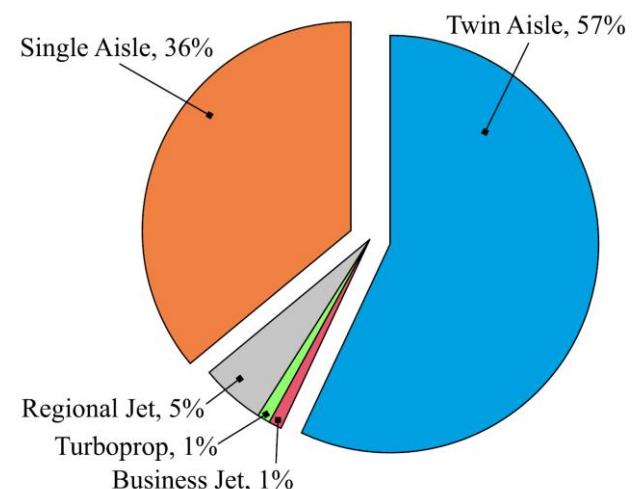
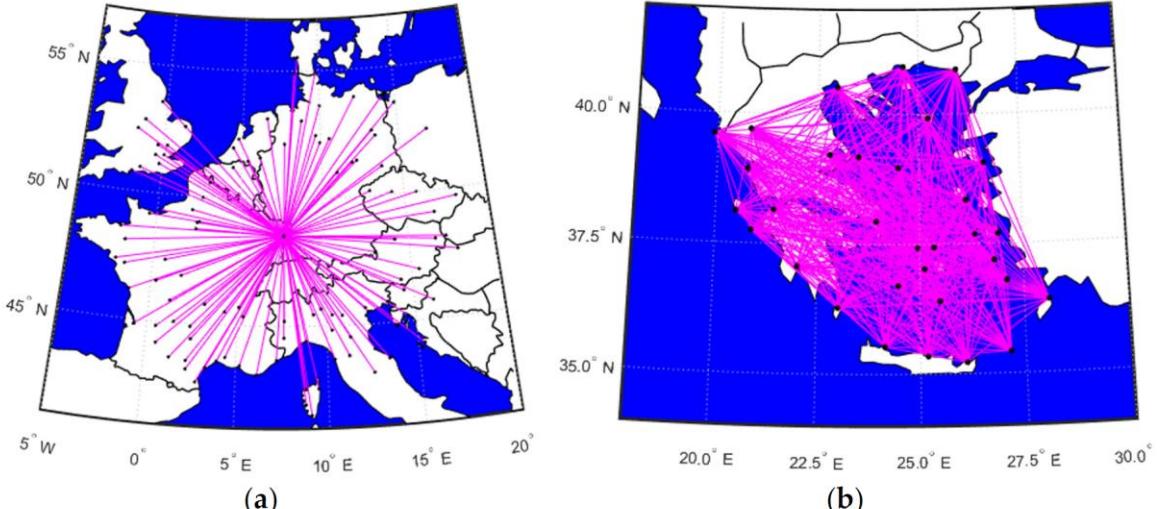
HEA - Top Level Aircraft Requirements



Sector: Regional

Top Level Aircraft Requirements:

- **Number of seats:** up to 40
- **Mission range:** up to 600 nm
- **BFL:** max 1100 m
- **Cruise Mach:** 0.40
- **Cruise altitude:** 20000 ft
- **Maximum wingspan:** 36 m
- **Entry into service:** 2035



HEA - Top Level Aircraft Requirements

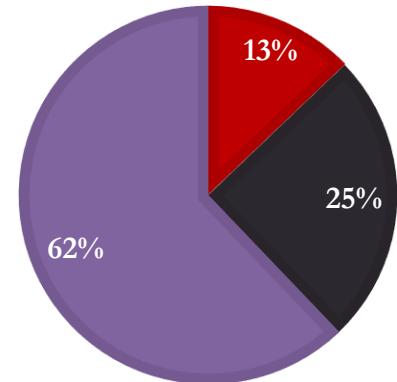


Reference full-thermal regional aircraft

ATR 42-500



■ Mfuel ■ Mpax ■ OEW



Reference data			
Wingspan	24.7 m	Fuselage diameter	2.88 m
Length	22.7 m	Fuel (+reserve)	2336 kg
Wing surface	55.2 m ²	Block Fuel	1753 kg
MTOW	18204 kg	ICE power	2x 1757 kW
N. Passengers	48	Mach cruise	0.47
Range	750 nm	Block Fuel/pax/nm	0.049



HEA - Top Level Aircraft Requirements

Reference full-thermal regional aircraft

ATR 42-500



Design Point data			
Wingspan	24.7 m	Fuselage diameter	2.88 m
Length	22.7 m	Fuel (+reserve)	1384 kg
Wing surface	55.2 m ²	Block Fuel	1084 kg
TOW	16500 kg	ICE power	2x 1757 kW
N. Passengers	40	Mach cruise	0.40
Range	600 nm	Block Fuel/pax/nm	0.045



HEA - Top Level Aircraft Requirements

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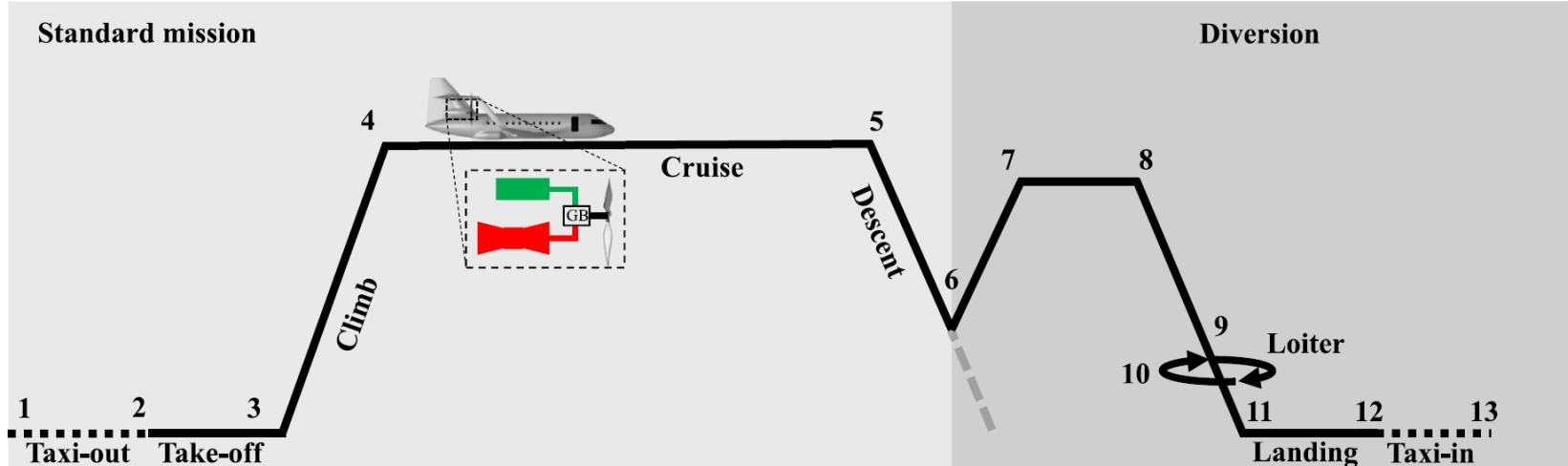
Cruise
Equation

Powertrain architecture
Serial
Parallel

Some reference papers:

1. Abu Salem K. et al. «Review of hybrid-electric aircraft technologies and designs: Critical analysis and novel solutions». *Progress in Aerospace Science*, 2023.
2. Eisenhut D. et al. «Aircraft Requirements for Sustainable Regional Aviation». *Aerospace* 2021, 8, 61.
3. Brdnik A.P. et al. «Market and Technological Perspectives for the New Generation of Regional Passenger Aircraft». *Energies* 2019, 12, 1864.
4. Palaia G. et al. «Mission Performance Analysis of Hybrid-Electric Regional Aircraft». *Aerospace* 2023.
5. Marciello V. et al. «Market analysis, tlars selection and preliminary design investigations for a regional hybrid-electric aircraft». *33º ICAS Congress*, Sweden, 2022.

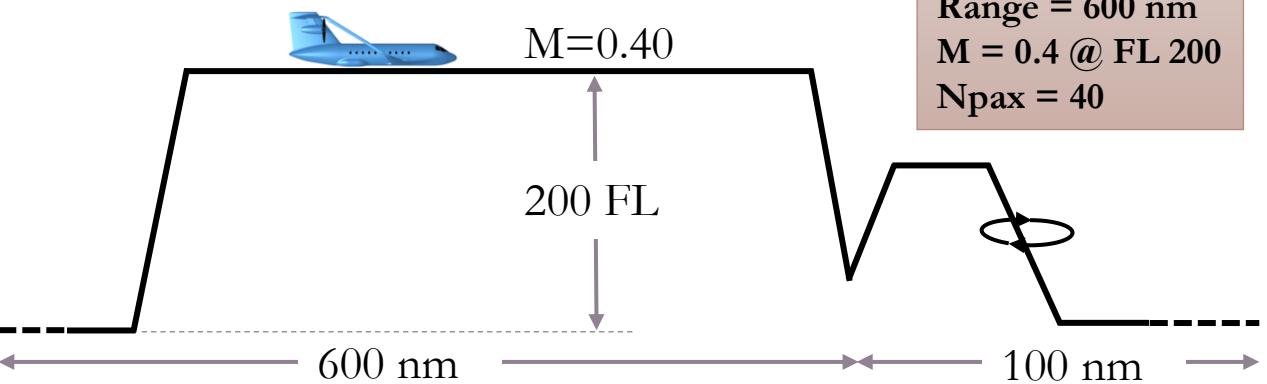
HEA - Mission definition



Main assumptions of the design mission profile.

Phase	Name	Assumptions
1 → 2 & 12 → 13	Taxi-in/out	7% of the maximum power for 240 s
2 → 3	Take-off	100% of power for 45 s
3 → 4	Climb	Constant IAS (170 kn) and RoC (900 ft/min)
4 → 5	Cruise	Constant Mach (0.4) and altitude (200 FL)
5 → 6	Descent	Constant IAS (220 kn) and RoD (-1100 ft/min)
6 → 7	Climb (div)	Constant IAS (150 kn) and RoC (600 ft/min)
7 → 8	Cruise (div)	Constant Mach (0.27) and altitude (100 FL)
8 → 9	Descent (div)	Constant IAS (150 kn) and RoD (-1100 ft/min)
9 → 10	Loiter	30 min @ L/D_{max}
10 → 11	Approach	Constant RoD (-500 ft/min)
11 → 12	Landing	Neglected

Design mission & TLARs



HEA - Mission definition



Standard Mission

Taxiing: ?????

Take-off: ??????

Climb: ?????

Cruise: ?????

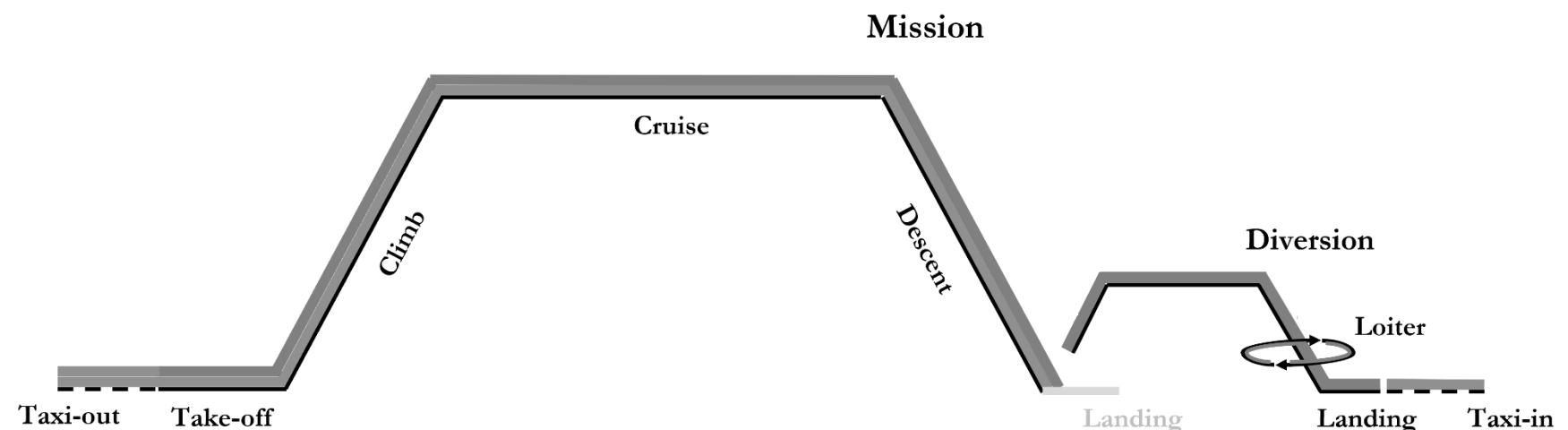
Descent: ?????

Diversion

Climb: ?????

Cruise: ?????

Descent: ?????



HEA - Mission definition



Standard Mission

Taxiing: *Full electric*

Take-off: *Max available power*

Climb: *Thermal/Electric*

Cruise: *Thermal/Electric*

Descent: *Thermal/Electric*

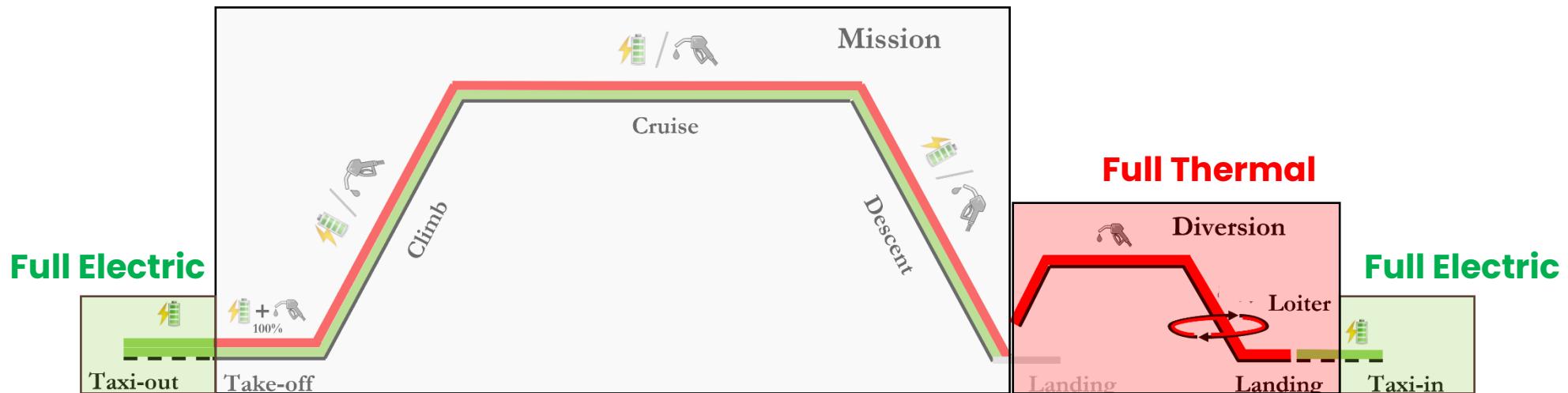
Diversion

Climb: *Thermal*

Cruise: *Thermal*

Descent: *Thermal*

Hybrid power supply

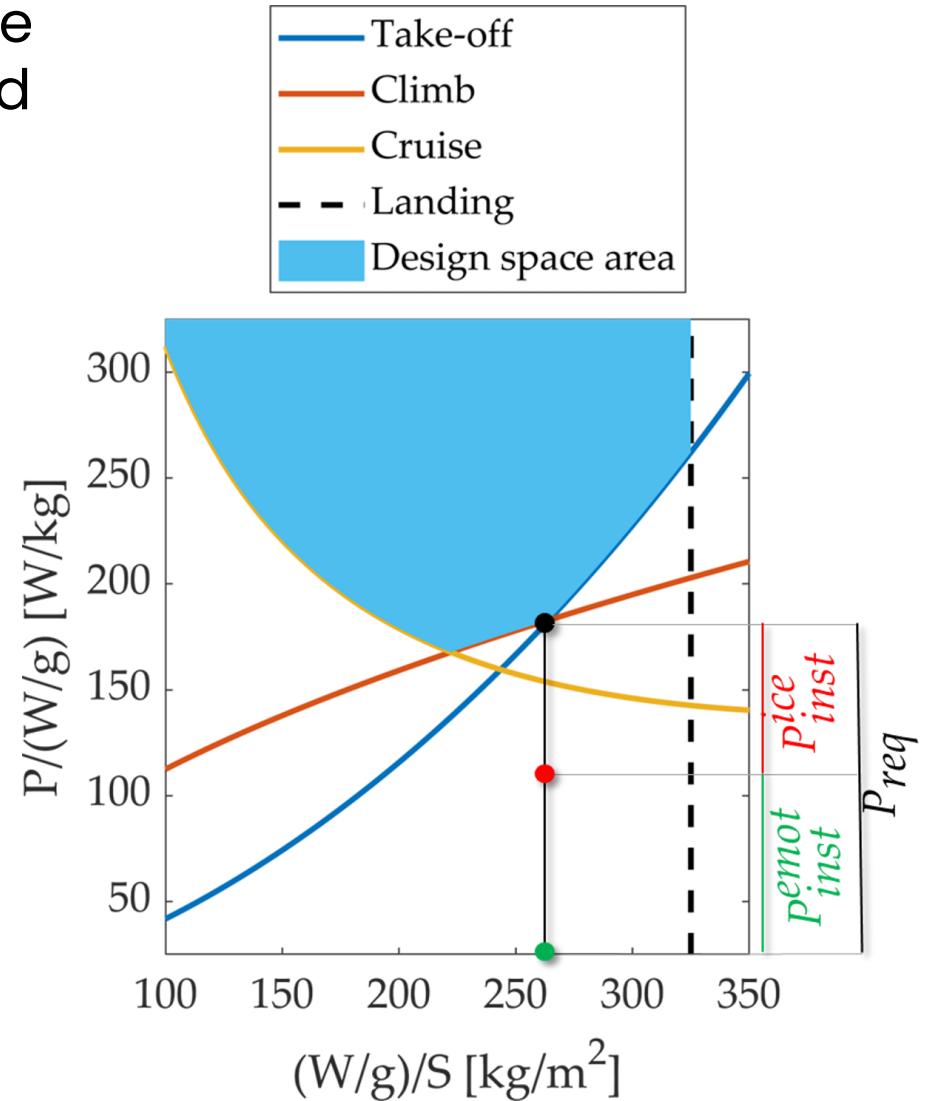
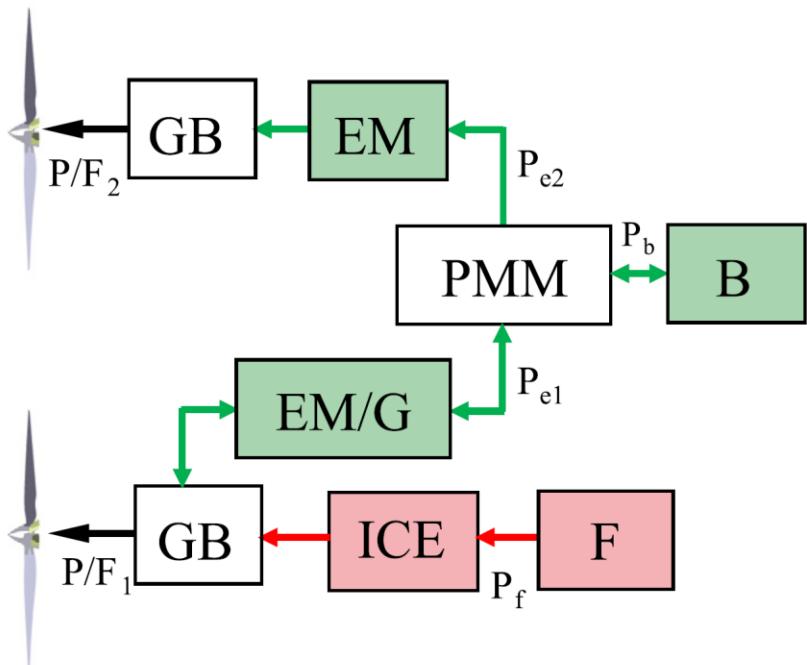




HEA - Powertrain sizing

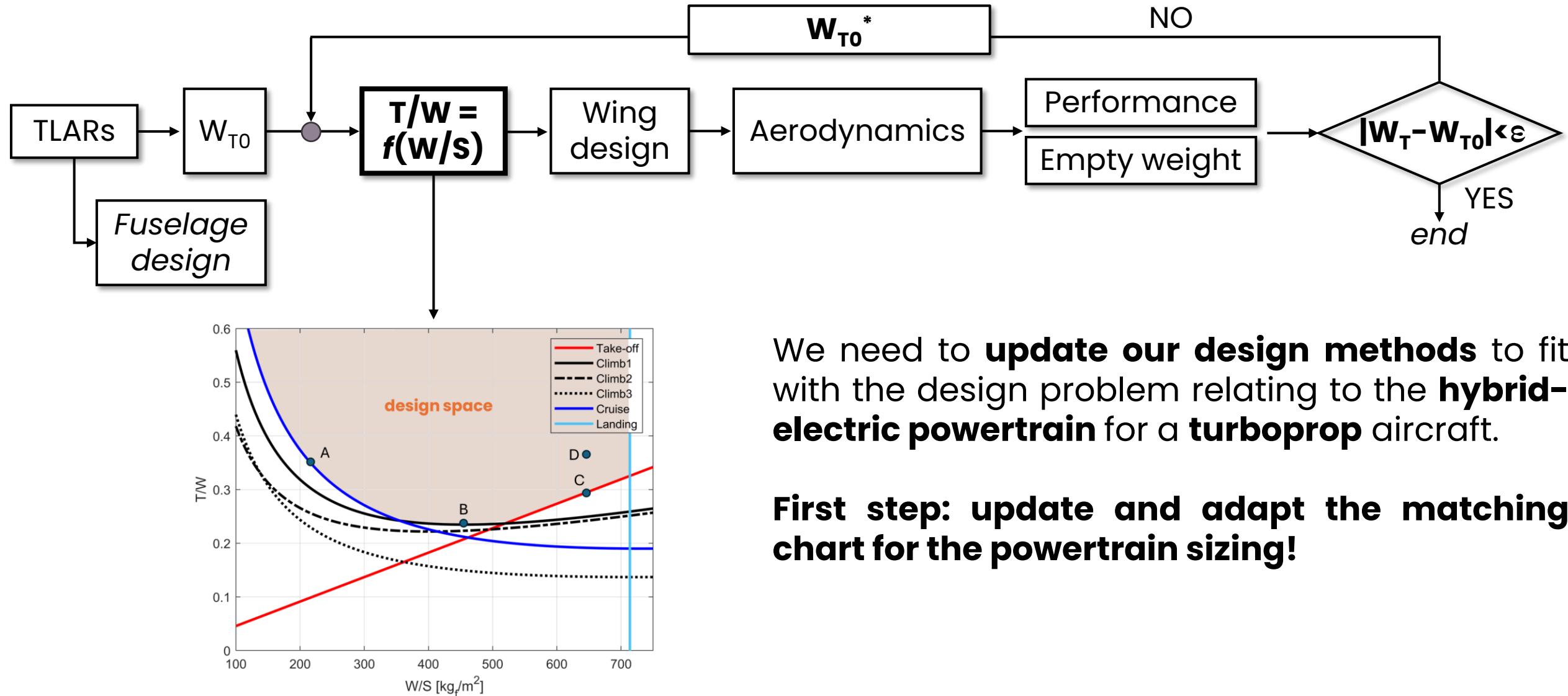
Degree of electric power hybridization defines the amount of electric and thermal power installed on board

$$H_P = \frac{P_{inst}^{emot}}{P_{inst}^{ice} + P_{inst}^{emot}}$$



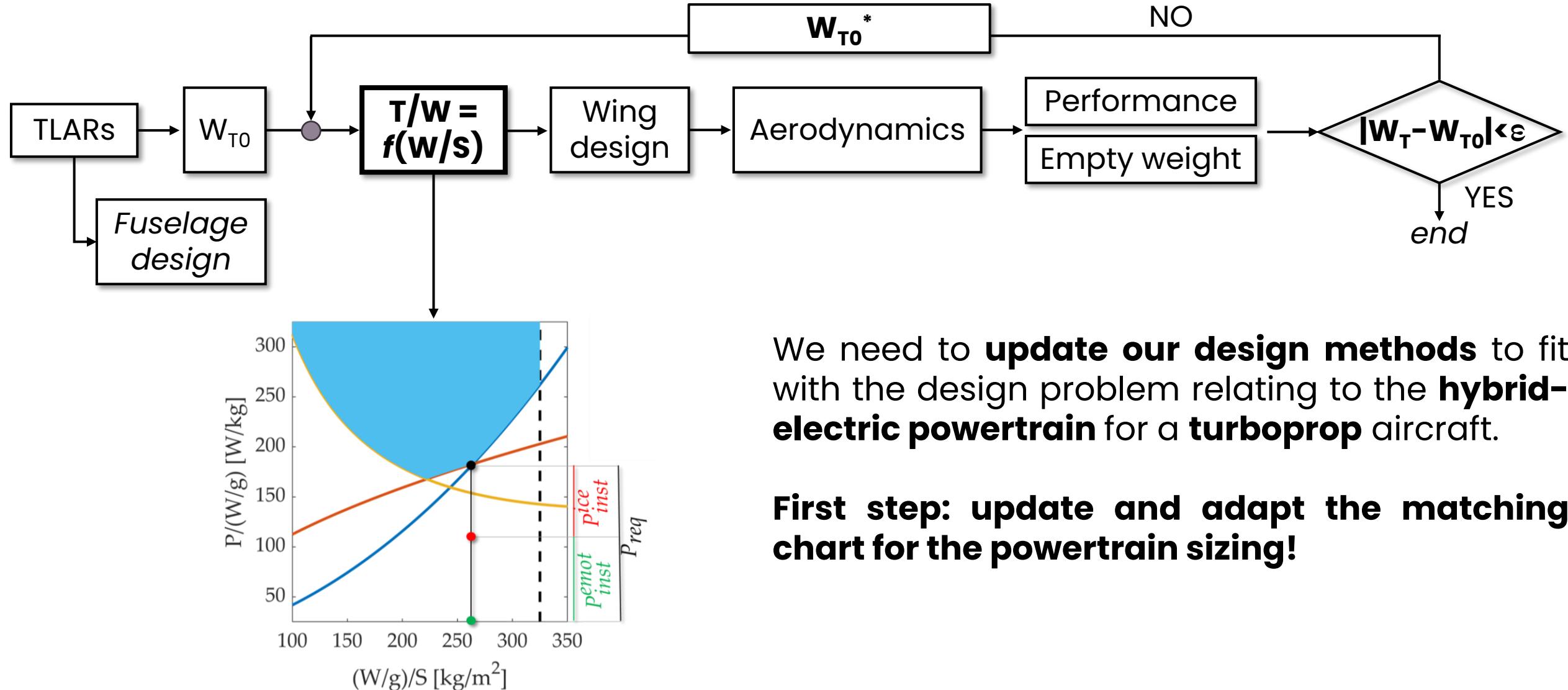


The Aircraft Design Process





The Aircraft Design Process





Matching chart

TLARs and Mission

Matching chart

Landing
Equation

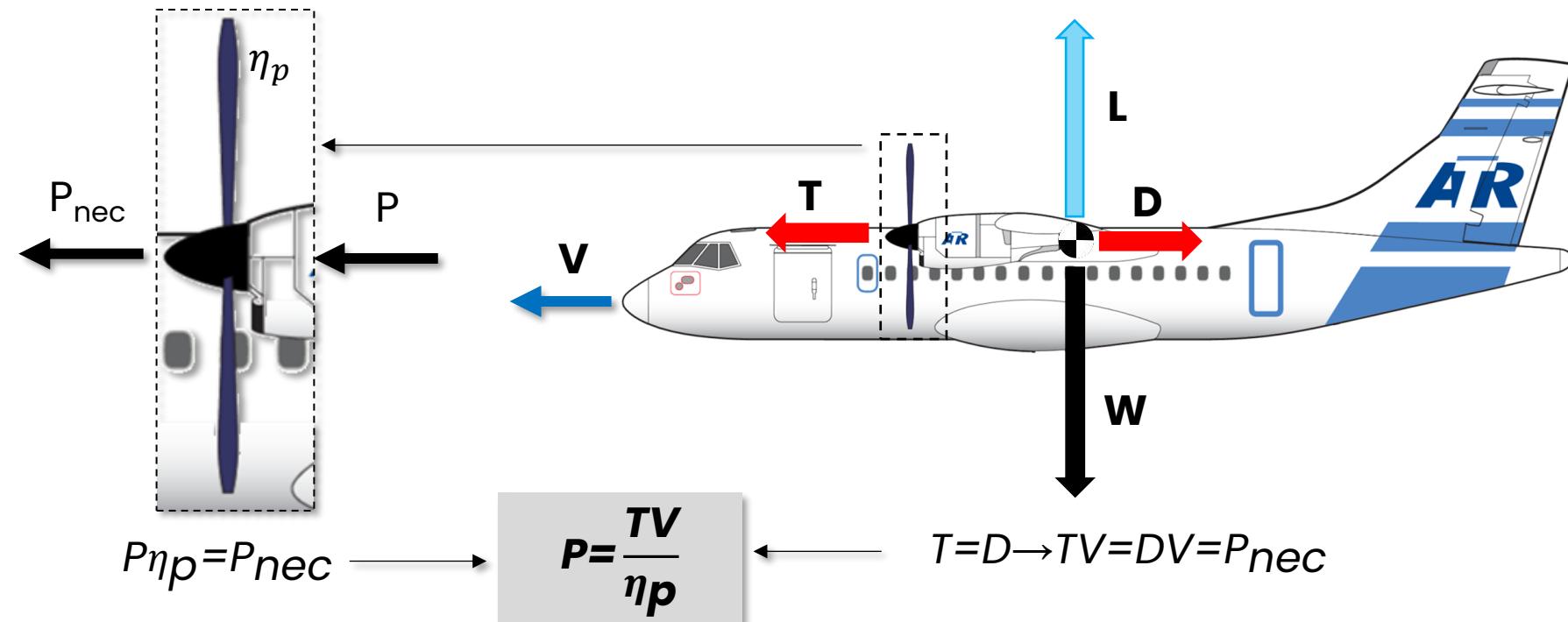
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We need to **update the matching chart equations** by assessing the **power request** to accomplish a specific flight phase



P = power supplied to the propeller shaft by the propulsion system
 P_{nec} = power requested to fly
 ηp = propeller efficiency



Matching chart - Landing

TLARs and Mission

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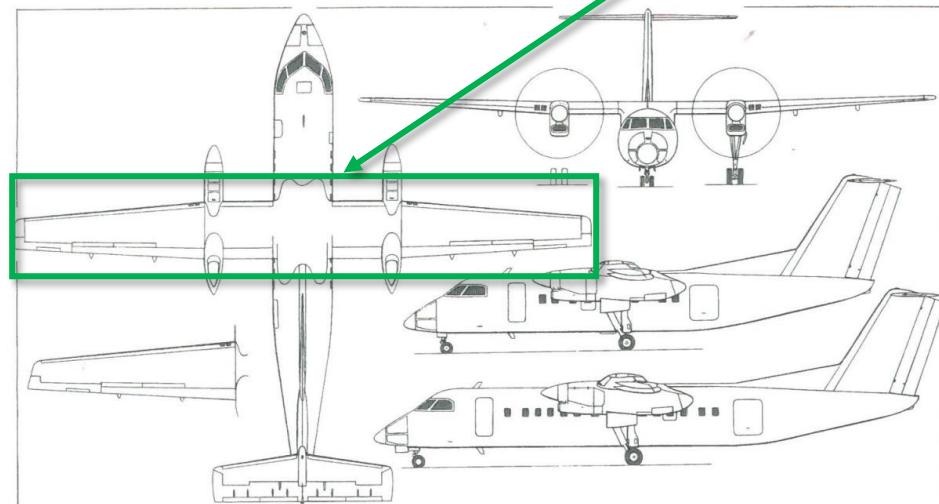
Cruise
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$$\frac{W}{S} \leq \frac{1}{2} \rho V_s^2 C_{Lmax}$$

Step 1: Assessment of C_{Lmax} of clean wing (no flap/slat)

$$C_{Lmax}^{wing3D} = 0.9 \cdot C_{Lmax}^{2D} \cdot \cos(\Lambda_{25})$$



Bombardier Dash 8 Q100, with additional side view (bottom) and wingtip of Q300 (Jane's/Dennis Punnett)

	C_{Lmax}	ΔC_{Lmax}
Clean Airfoil	1,45	-
Plain Flap	2,25	0,80
Single-Slotted Flap	2,60	1,15
Double-Slotted Flap	2,80	1,35
Split Flap	2,40	0,95
Double-Wing (Junkers)	2,25	0,80
Fowler Flap	2,80	1,35
Slat	2,00	0,55
Combinations:		
Plain Flap and Slat	2,45	1,00
Single-Slotted Flap and Slat	2,70	1,25
Double-Slotted Flap and Slat	2,90	1,45
Fowler Flap and Slat	3,00	1,55



Matching chart - Landing

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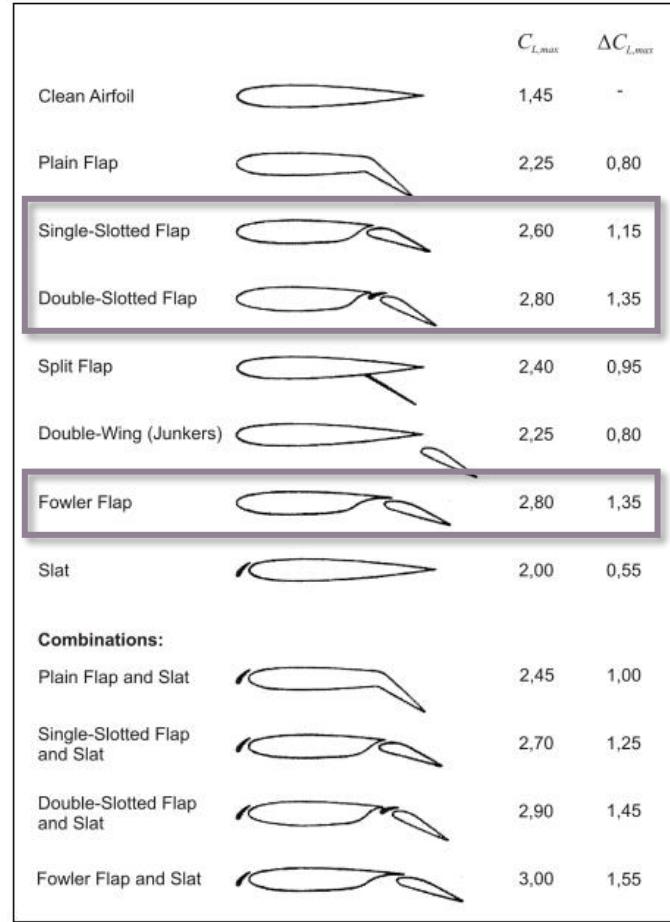
$$\frac{W}{S} \leq \frac{1}{2} \rho V_s^2 C_{Lmax}$$

Step 2: Assessment of ΔC_{Lmax} due to flap/slat

$$\Delta C_{Lmax}^{flap} = 0.92 \cdot \frac{\Delta C_{lmax}^{flap}}{3D} \cdot \frac{S_{flapped}}{2D} \cos(\Lambda_{25})$$

Table 5.16 Characteristics of high-lift devices for several aircraft

No.	Aircraft	Engine	HLD	C_f/C	b_f/b	δ_{fmax}	
						TO	Landing
1	Cessna 172	Piston	Single-slotted	0.33	0.46	20	40
2	Piper Cherokee	Piston	Single-slotted	0.17	0.57	25	50
3	Lake LA-250	Piston	Single-slotted	0.22	0.57	20	40
4	Short Skyvan 3	Turboprop	Double-slotted	0.3	0.69	18	45
5	Fokker 27	Turboprop	Single-slotted	0.313	0.69	16	40
6	Lockheed L-100	Turboprop	Fowler	0.3	0.7	18	36
7	Jetstream 41	Turboprop	Double-slotted	0.35	0.55	24	45





Matching chart - Landing

TLARs and Mission

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$$\frac{W}{S} \leq \frac{1}{2} \rho V_s^2 C_{Lmax}$$

Step 2: Assessment of ΔC_{Lmax} due to flap/slat

$$\Delta C_{Lmax}^{flap} = 0.92 \cdot \Delta C_{l_{max}}^{flap} \cdot \frac{S_{flapped}}{S} \cos(\Lambda_{25})$$

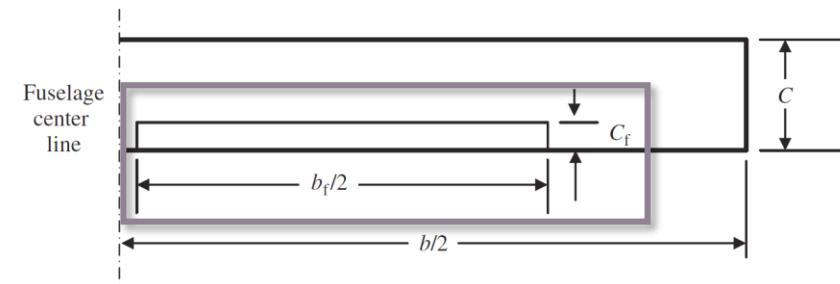
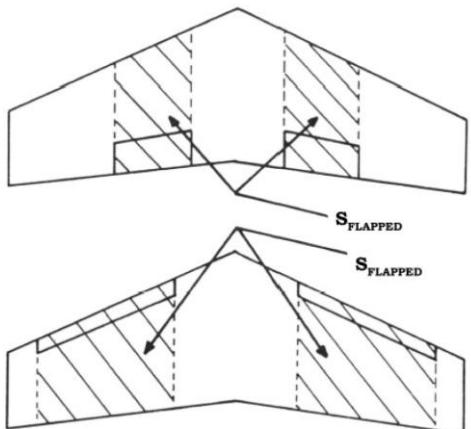


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7	Jetstream 41	Turboprop	Double-slotted	0.35	0.55	24	45



Superficie 'flappata'



Matching chart - Landing

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Equation

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$$\frac{W}{S} \leq \frac{1}{2} \rho V_s^2 C_{Lmax}$$

Step 3: Assessment of C_{Lmax} of flapped wing

$$C_{Lmax}^{flapped} = C_{Lmax}^{clean} + \Delta C_{Lmax}$$



Matching chart - Landing

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$$\frac{W}{S} \leq \frac{1}{2} \rho V_s^2 C_{Lmax}$$

Aircraft model	Landing speed (km/h)
ATR42	193
ATR72	210
Dash 8 Q200	134
L610G	141
ILYUSHIN II-114	160
Embraer EMB 120 Brasilia	165

Fonte: Janes All The Worlds Aircraft 2004-2005 + datasheet



Matching chart – Take-off

TLARs and Mission

Matching chart

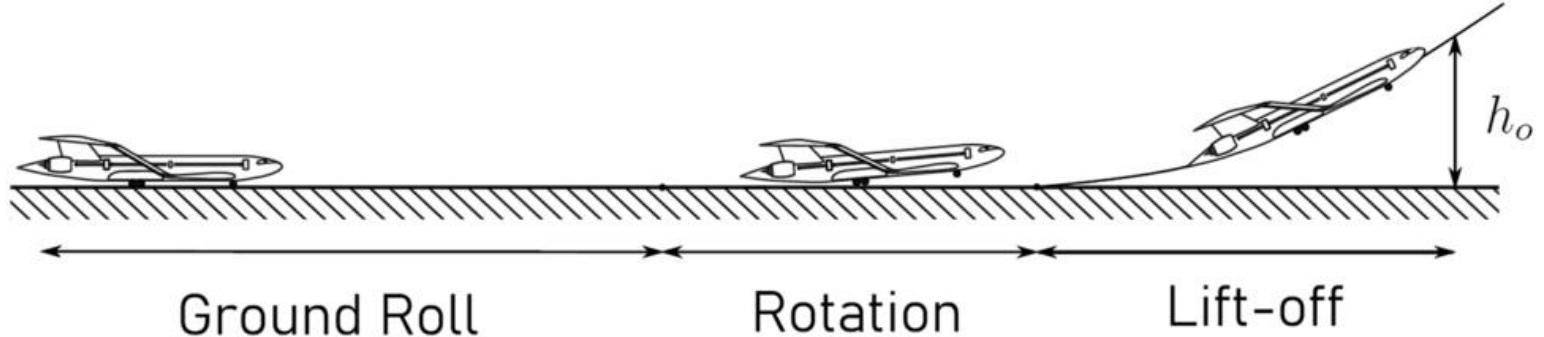
Landing
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Parallel



$$\frac{P}{W} = a_1 \frac{W}{S} + a_2 \left(\frac{W}{S} \right)^2$$

$$a_1 = b_{10} + b_{11} C_{Lmax} + b_{12} C_{Lmax}^2$$

$$a_2 = b_{20} + b_{21} C_{Lmax} + b_{22} C_{Lmax}^2$$

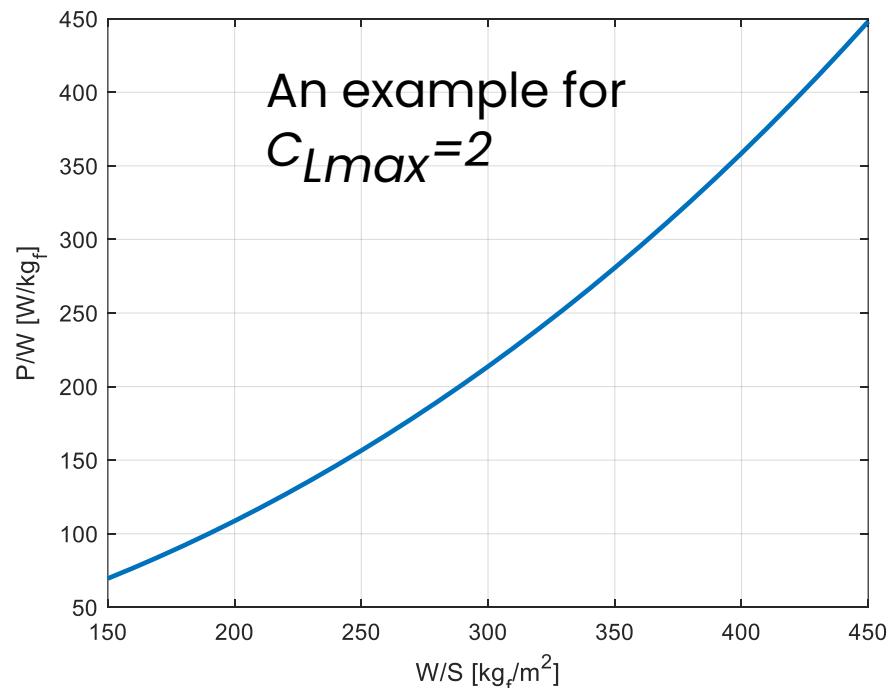
$$b_{10} = 0.2792, b_{11} = -0.03285, b_{12} = -0.007541$$

$$b_{20} = 0.01076, b_{21} = -0.007067, b_{22} = 0.001276$$

$$BFL = 1100 \text{ m}$$

$$1.8 \leq C_{Lmax} \leq 2.5$$

$$150 \text{ kg}_f/\text{m}^2 \leq W/S \leq 450 \text{ kg}_f/\text{m}^2$$





Matching chart – Climb segments

TLARs and Mission

Matching chart

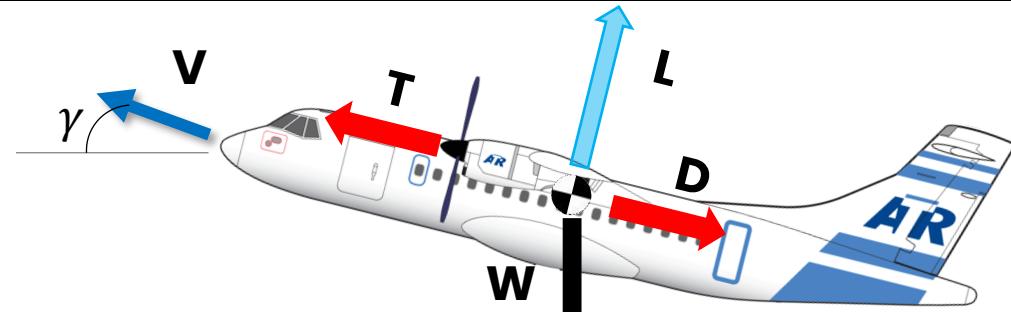
Landing
Equation

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Equation

Powertrain architecture
Serial
Parallel



Thrust must satisfy the steady state climb condition with one engine inoperative, in three different segments

$$\frac{T}{W} = \frac{1}{k_{OEI}} \frac{\frac{1}{2} \rho V^2 (C_{D0} + C_{D0,flap} + C_{D0,gear})}{\frac{W}{S}} + \frac{1}{k_{OEI}} \frac{k}{\frac{1}{2} \rho V^2} \frac{W}{S} \cos^2(\gamma) + \frac{1}{k_{OEI}} \sin(\gamma)$$

$$\frac{P}{W} = \frac{T}{W} \frac{V}{\eta p}$$

$$\frac{P}{W} = \frac{1}{\eta_p k_{OEI}} \frac{\frac{1}{2} \rho V^3 (C_{D0} + C_{D0,flap} + C_{D0,gear})}{\frac{W}{S}} + \frac{1}{\eta_p k_{OEI}} \frac{k}{\frac{1}{2} \rho V} \frac{W}{S} \cos^2(\gamma) + \frac{V}{\eta_p k_{OEI}} \sin(\gamma)$$

$\rho = \rho_{SL}, \eta p = 0.75$



Matching chart – Climb segments

TLARs and Mission

Matching chart

Landing
Equation

Take-off
Equation

Climb

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Cruise
Equation

Powertrain architecture
Serial
Parallel

$$\frac{P}{W} = \frac{1}{\eta_p k_{OEI}} \frac{\frac{1}{2} \rho v^3 (C_{D0} + C_{D0,flap} + C_{D0,gear})}{\frac{W}{S}} + \frac{1}{\eta_p k_{OEI}} \frac{k}{\frac{1}{2} \rho V} \frac{W}{S} \cos^2(\gamma) + \frac{V}{\eta_p k_{OEI}} \sin(\gamma)$$

$\rho = \rho_{SL}, \eta_p = 0.75$

	1 st segment	2 nd segment	3 rd segment
γ - two engines	0%	2.4%	1.2%
γ - four engines	0.5%	3%	1.7%
Slat/flap	On	On	Off
Landing gears	On	Off	Off
Speed	v_2	v_2	$\sim 2v_{st}$



Matching chart – Approach and landing climb

TLARs and Mission

Matching chart

Landing
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Equation

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Equation

Powertrain architecture
Serial
Parallel

$$\frac{P}{W} = \frac{1}{\eta_p k_{OEI}} \frac{\frac{1}{2} \rho v^3 (C_{D0} + C_{D0,flap} + C_{D0,gear})}{\frac{W}{S}} + \frac{1}{\eta_p k_{OEI}} \frac{k}{\frac{1}{2} \rho V} \frac{W}{S} \cos^2(\gamma) + \frac{V}{\eta_p k_{OEI}} \sin(\gamma)$$

$\rho = \rho_{SL}, \eta_p = 0.75$

	Approach climb	Landing Climb
OEI	YES	No
V	$1.23V_{st} \leq V \leq 1.41V_{st}$	$1.13V_{st} \leq V \leq 1.23V_{st}$
Landing gear	Off	On
Flap e slat	On	On
γ - two engines	2.1%	3.2%
γ - four engines	2.7%	3.2%



Matching chart - Cruise

TLARs and Mission

Matching chart

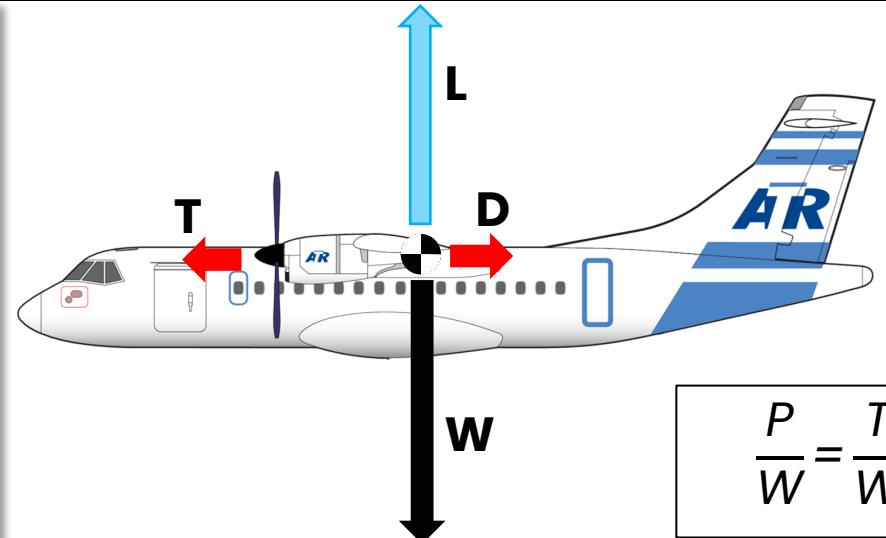
Landing
Equation

Take-off
Equation

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Cruise
Equation

Powertrain architecture
Serial
Parallel



Thrust must equilibrate the aircraft drag ($\gamma = 0^\circ$). The aircraft thrust, calculated at cruise altitude, has to be assessed at sea level

$$\frac{P}{W} = \frac{T}{W} \frac{V}{\eta p}$$

$$\eta p = 0.85$$



$$\left\{ \begin{array}{l} \frac{P_{CR}}{W} = \frac{1}{\eta p} \frac{\rho V^2 C_{DO}}{W/S} + \frac{1}{\eta p} \frac{k}{2} \frac{W}{\rho_{CR} V S} \\ \left(\frac{P_{CR}}{W} \right) = \left(\frac{P}{W} \right)_{SL} \left(\frac{\rho}{\rho_{SL}} \right)^{0.75} \end{array} \right.$$

$$\left(\frac{P}{W} \right)_{SL} = \frac{\frac{1}{\eta p} \frac{\rho V^2 C_{DO}}{W/S} + \frac{1}{\eta p} \frac{k}{2} \frac{W}{\rho_{CR} V S}}{\left(\frac{\rho}{\rho_{SL}} \right)^{0.75}}$$



Matching chart

TLARs and Mission

Matching chart

Landing
Equation

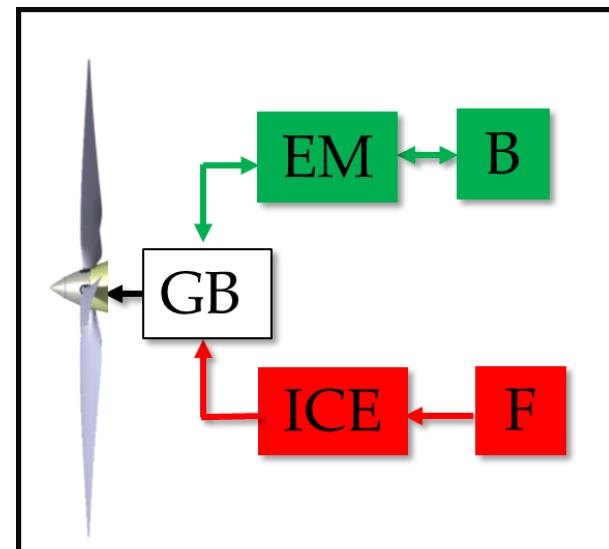
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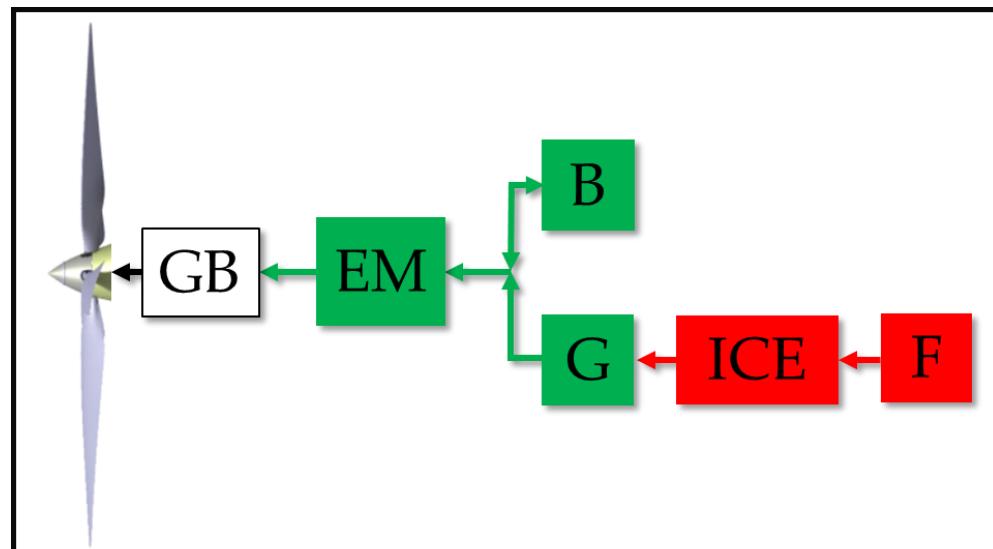
Powertrain architecture
Serial
Parallel

Parallel

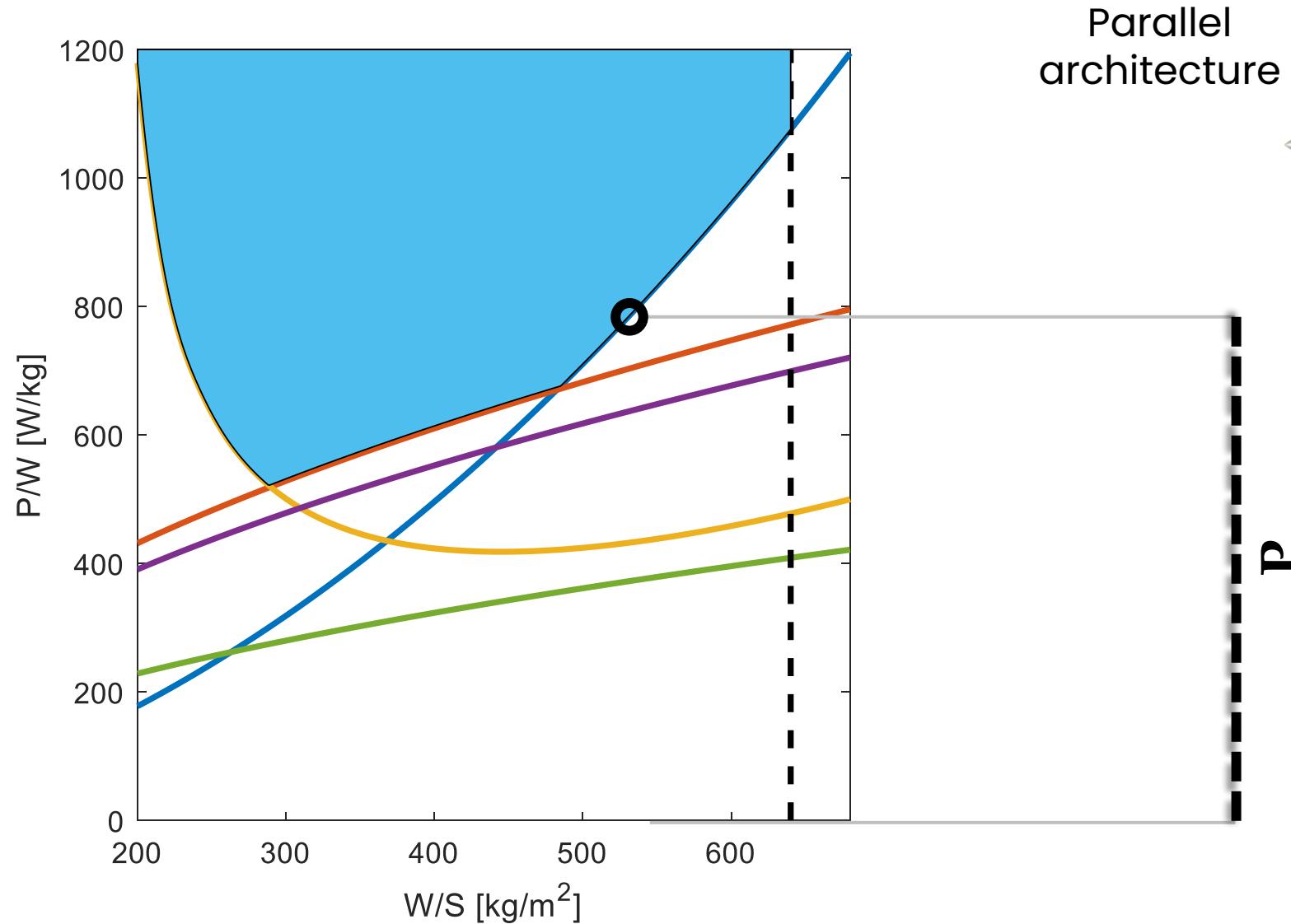


vs

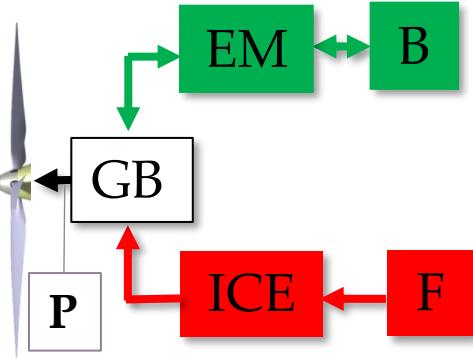
Serial



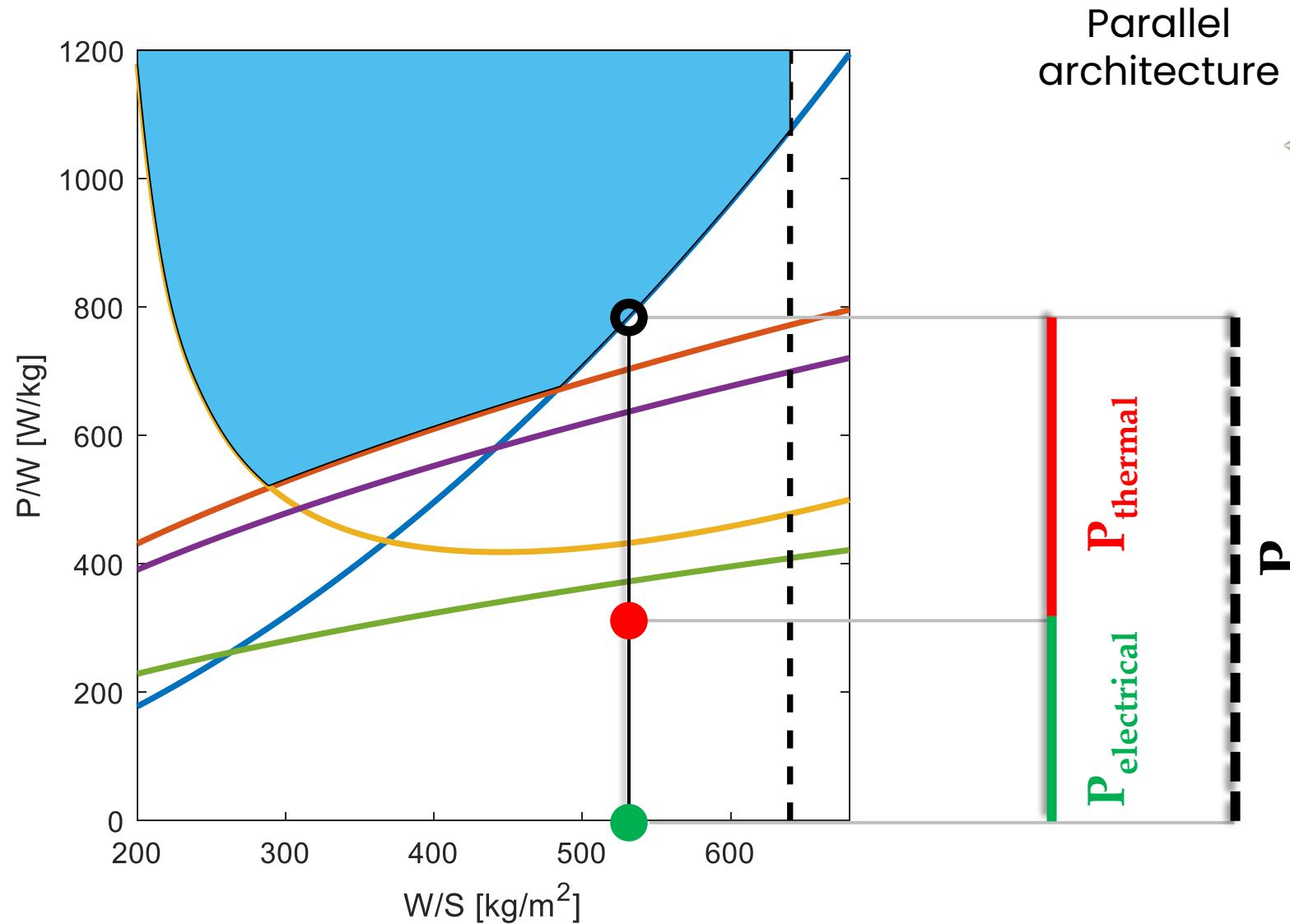
HEA - Powertrain sizing: Parallel



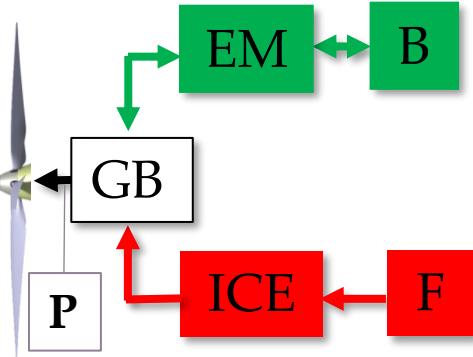
Parallel architecture



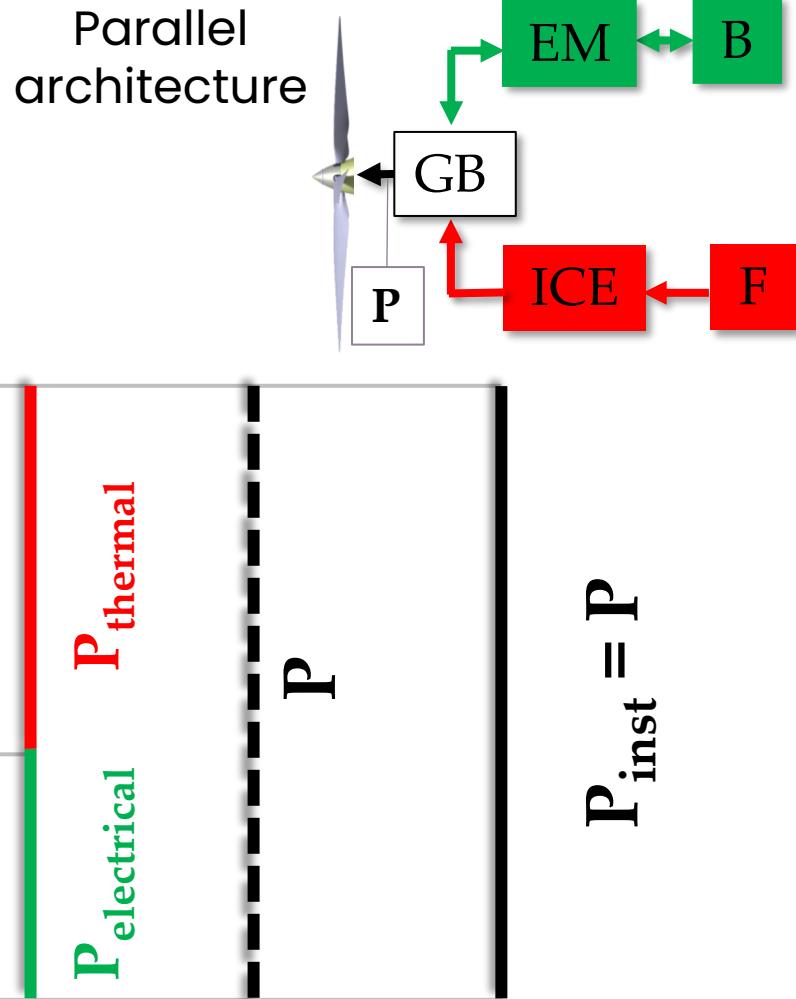
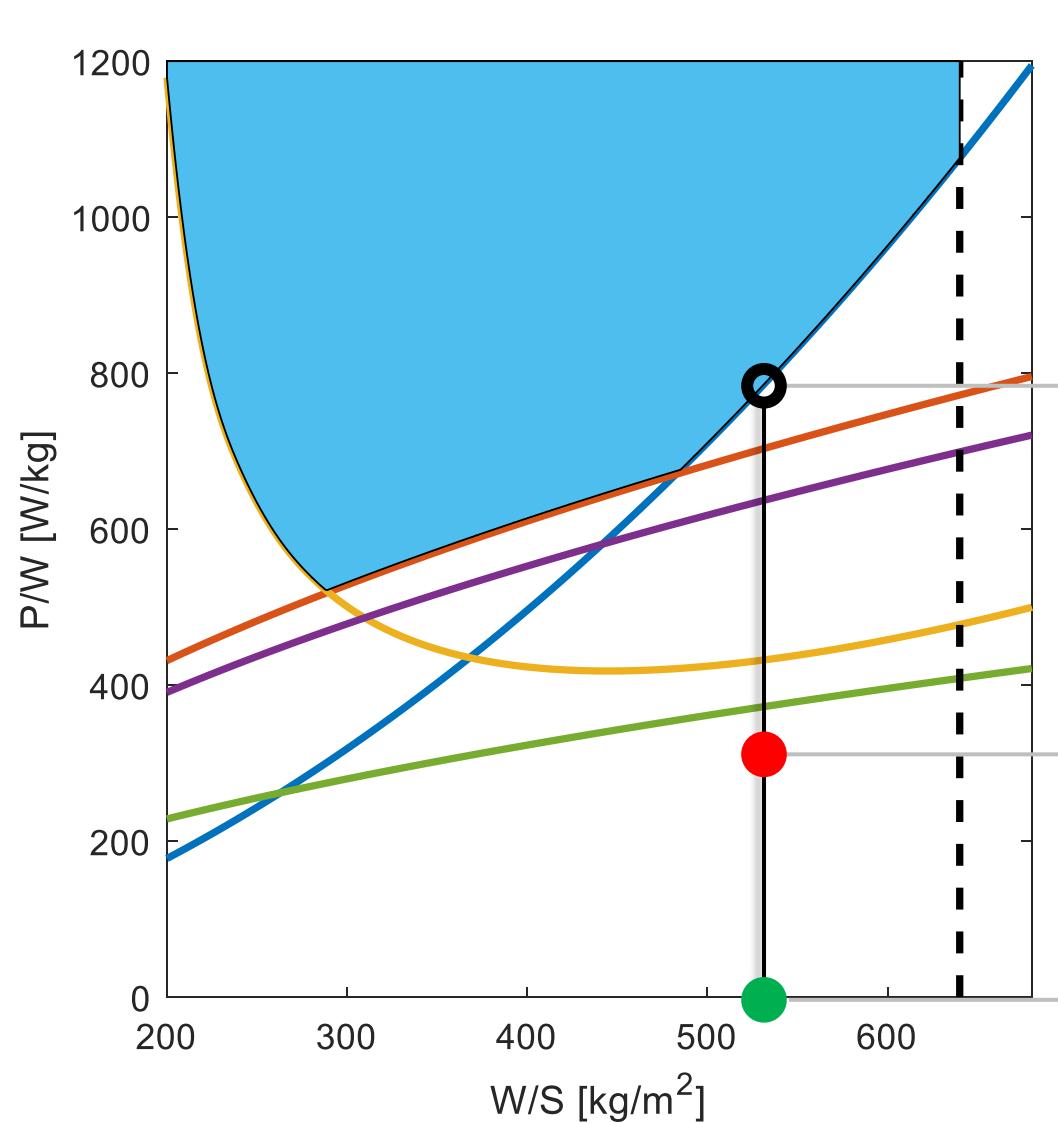
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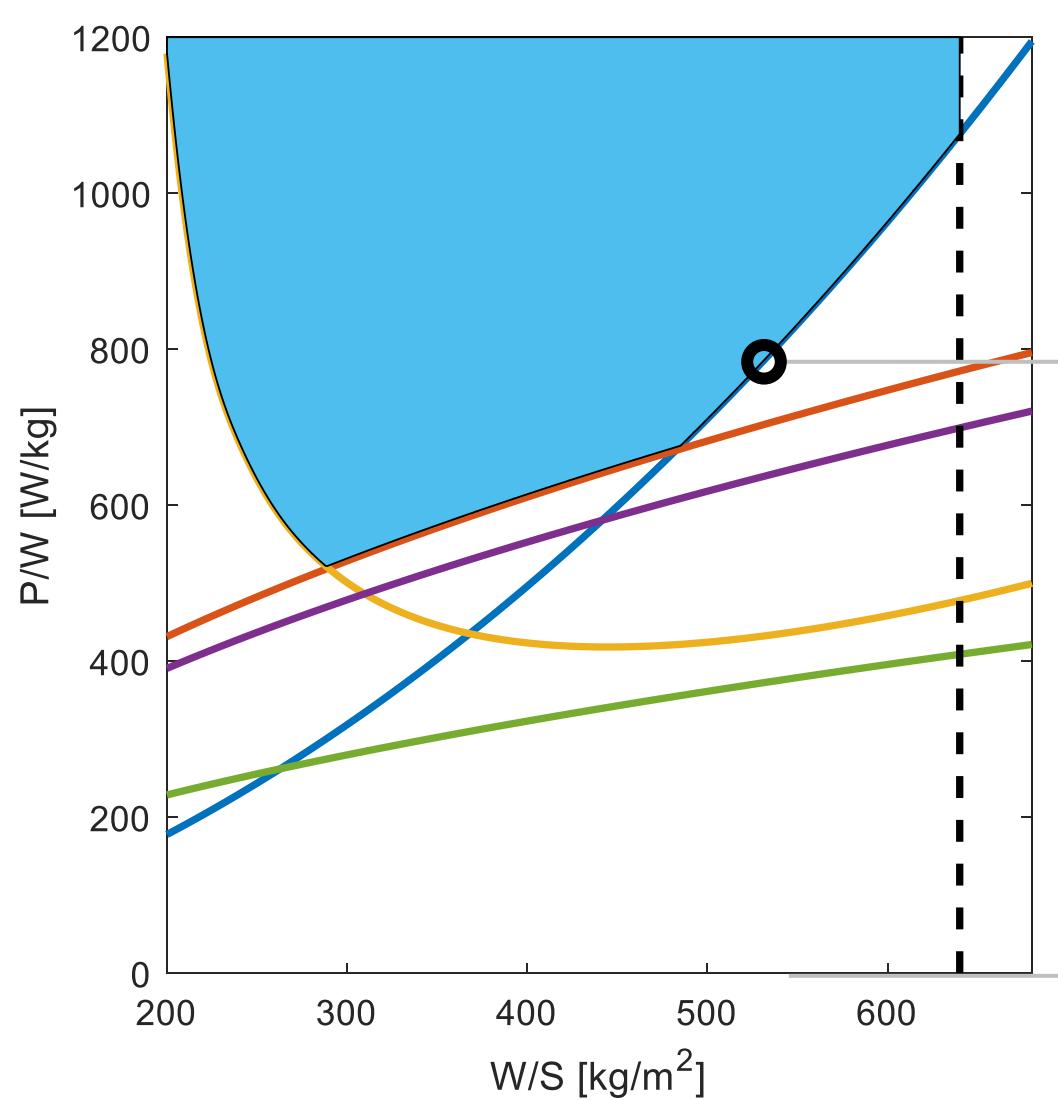
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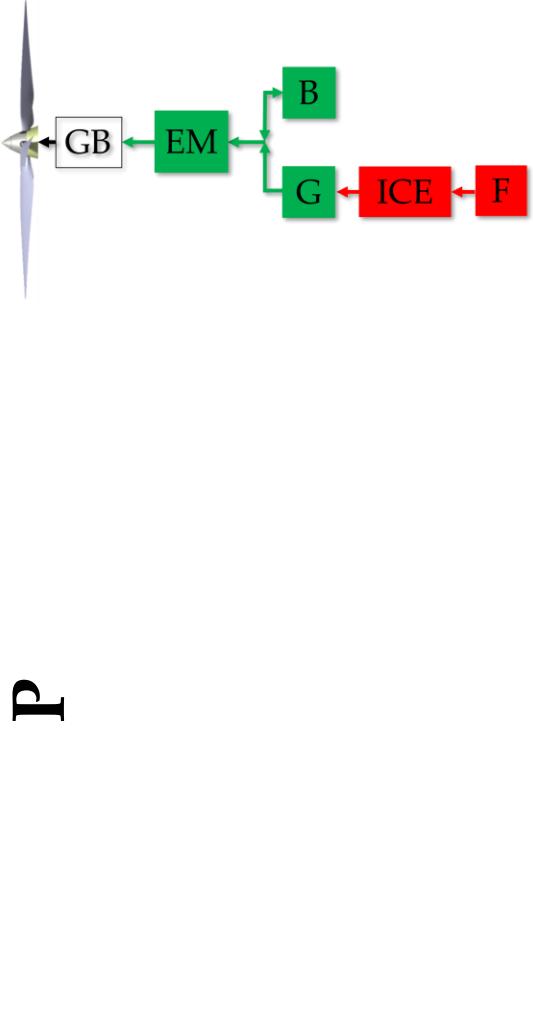
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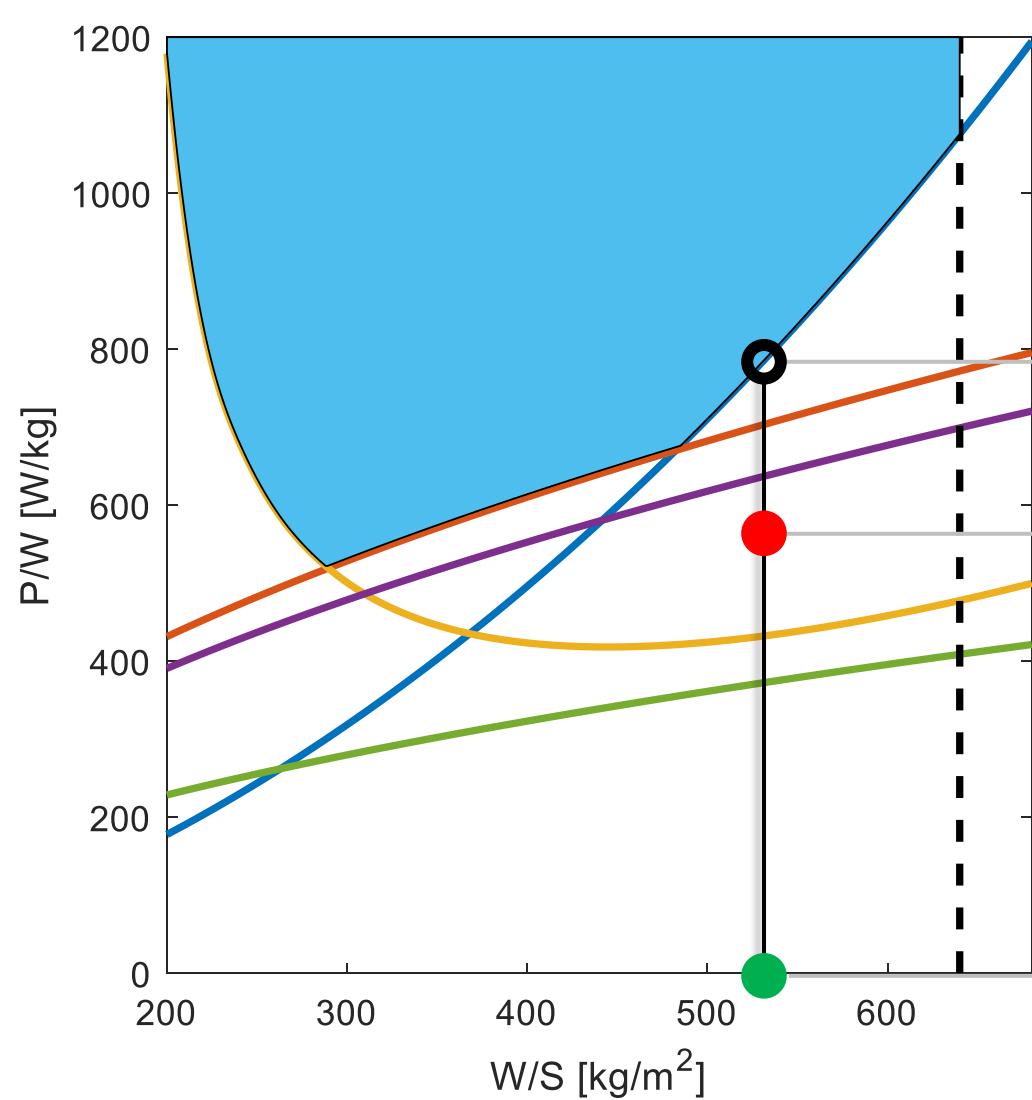
HEA - Powertrain sizing: Serial



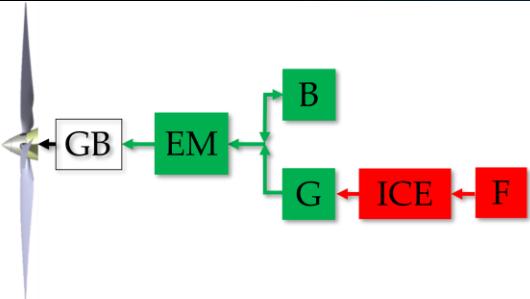
Serial architecture



HEA - Powertrain sizing: Serial



Serial
architecture

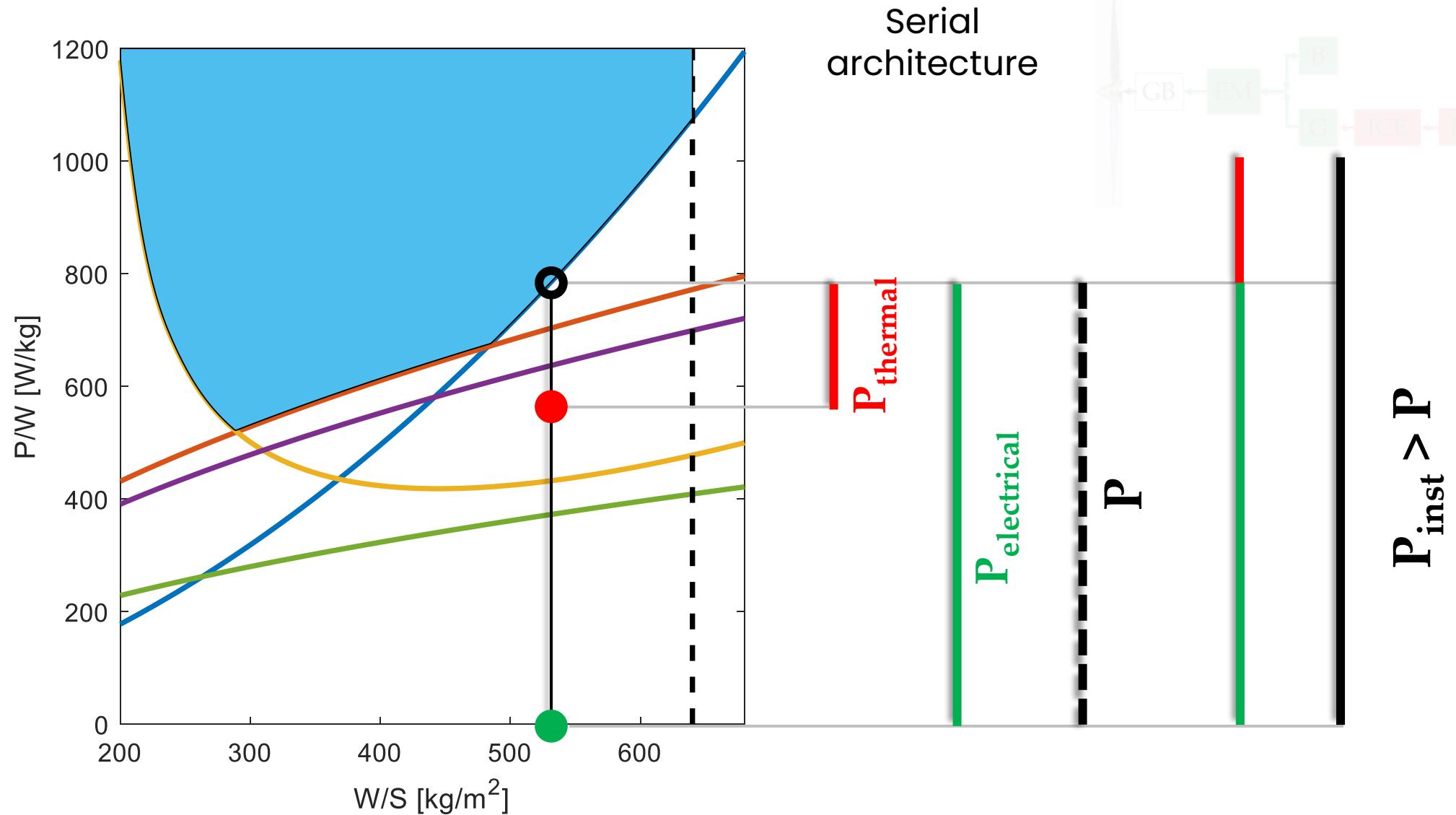


P_{thermal}

$P_{\text{electrical}}$

P

HEA - Powertrain sizing: Serial





End