Progettazione di veicoli aerospaziali (AA-LZ)

E1. Conceptual Design of subsonic commercial aircraft

11. TLARs and Matching chart

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HEA - Top Level Aircraft Requirements

TLARs and Mission

Matching chart

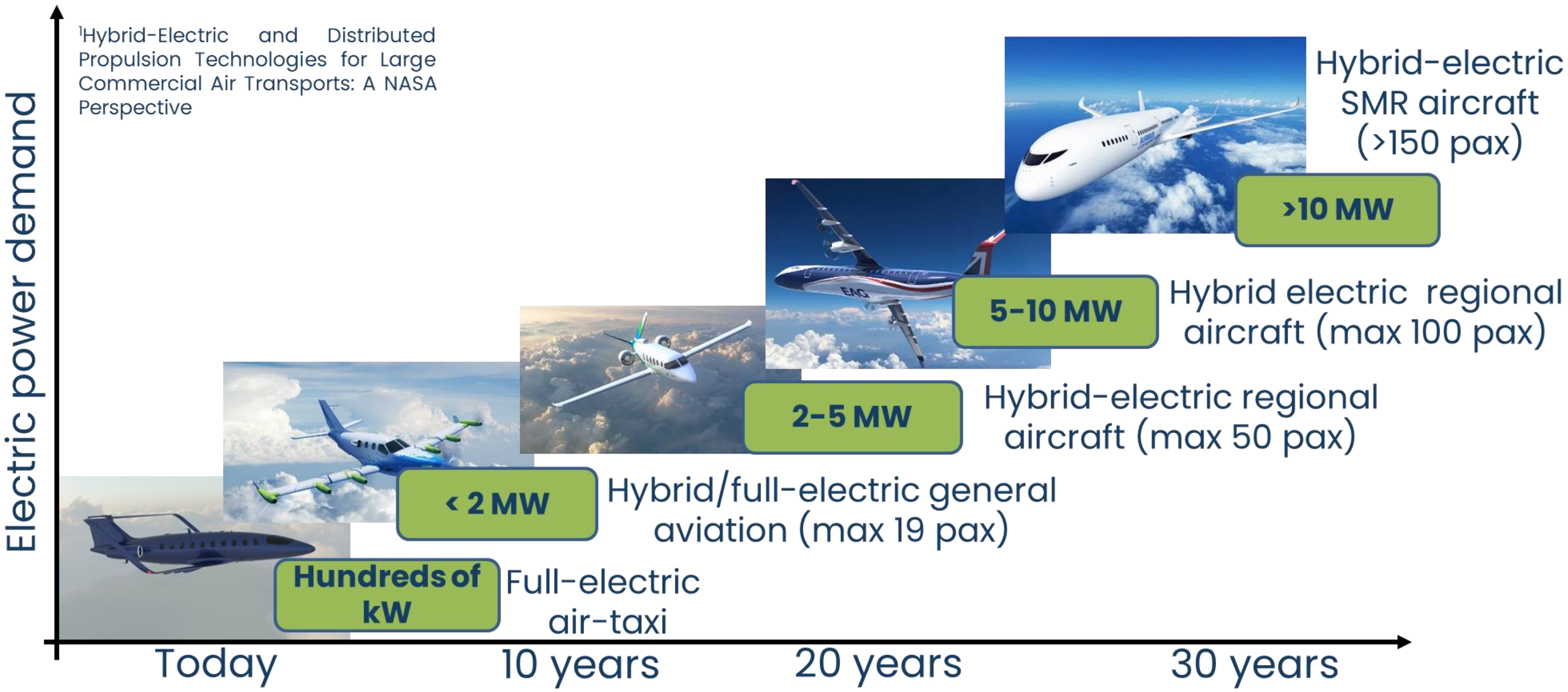
Landing
Equation

Take-off
Equation

Climb
1st, 2nd and final segment
Approach climb

Cruise
Equation

Powertrain architecture
Serial
Parallel



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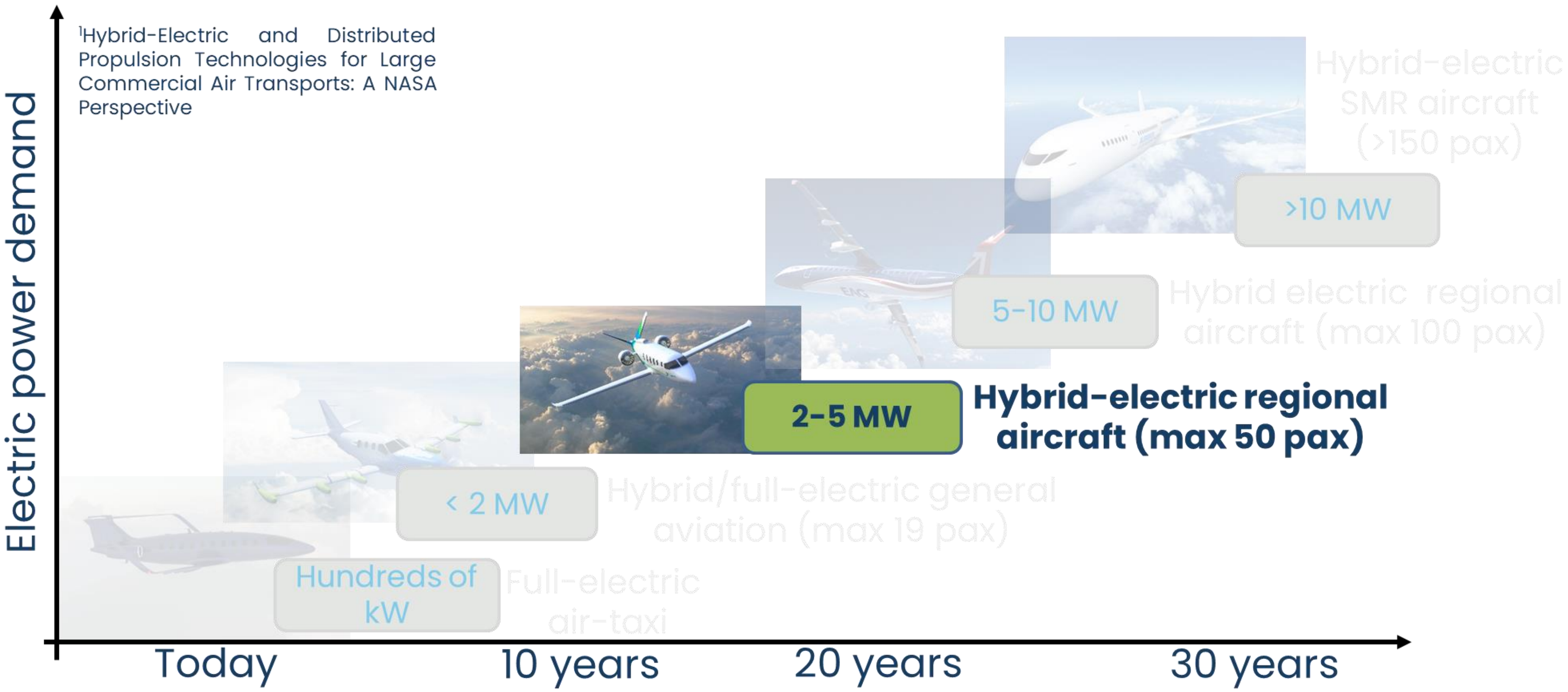
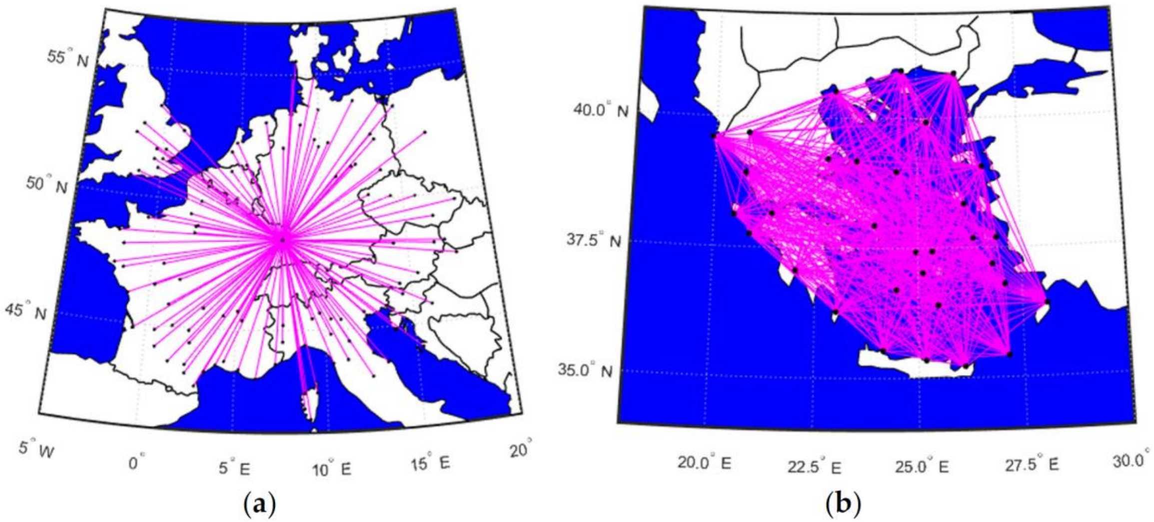


HEA - Top Level Aircraft Requirements

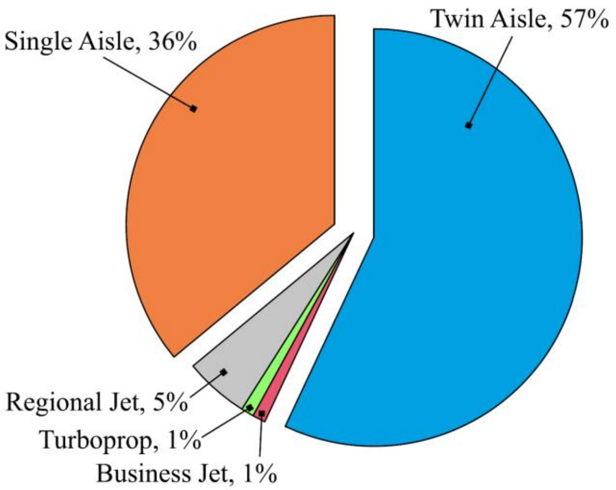
Sector: Regional

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



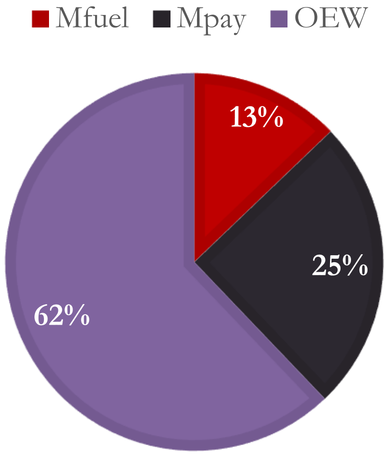
(a) Connections from Strasbourg (SXB) between 350–800 km
(b) Feasible domestic flight routes Greece between 150–800 km



HEA - Top Level Aircraft Requirements

Reference full-thermal regional aircraft

ATR 42-500



Reference data			
Wingspan	24.7 m	**Fuselage diameter**	2.88 m
Length	22.7 m	**Fuel (+reserve)**	2336 kg
Wing surface	55.2 m²	**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

TLARs and Mission

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Landing
Equation

Take-off
Equation

Climb
1st, 2nd and final segment
Approach climb

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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.

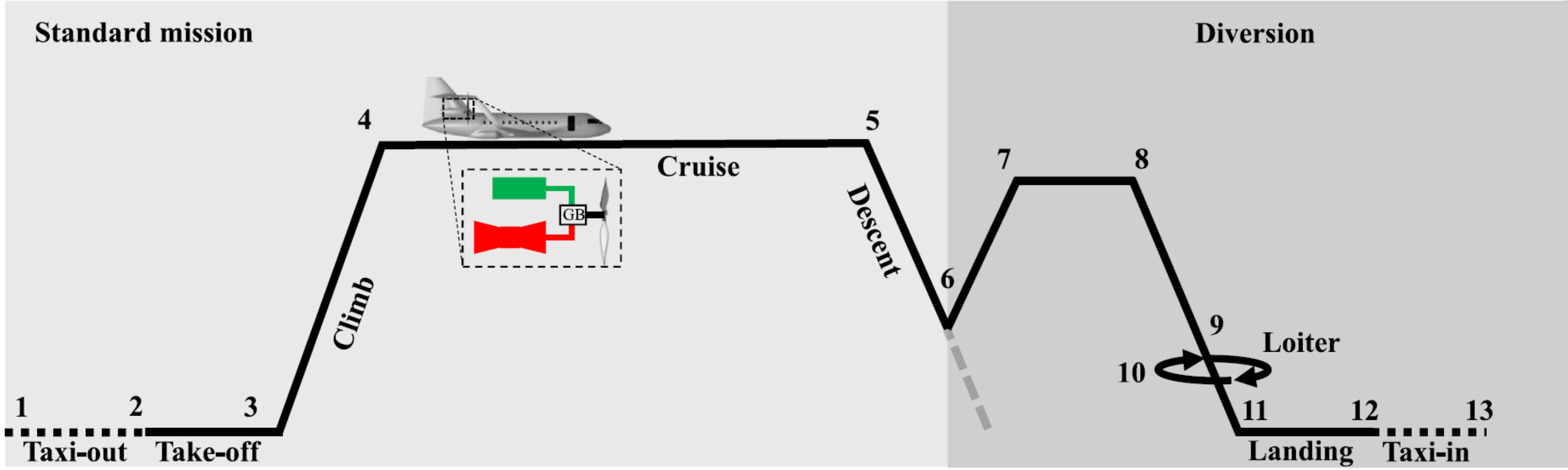
2. Eisenhut D. et al. «Aircraft Requirements for Sustainable Regional Aviation». *Aerospace* 2021, 8, 61.

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». 33° ICAS Congress, Sweden, 2022.

HEA - Mission definition

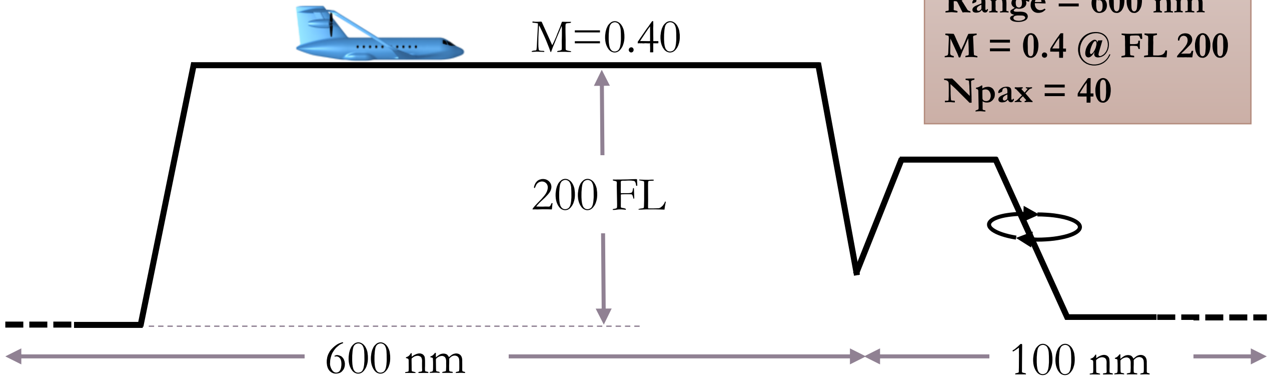


Main assumptions of the design mission profile.

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

Range = 600 nm
M = 0.4 @ FL 200
Npax = 40



HEA - Mission definition

Standard Mission

Taxiing: *?????*

Take-off: *?????*

Climb: *?????*

Cruise: *?????*

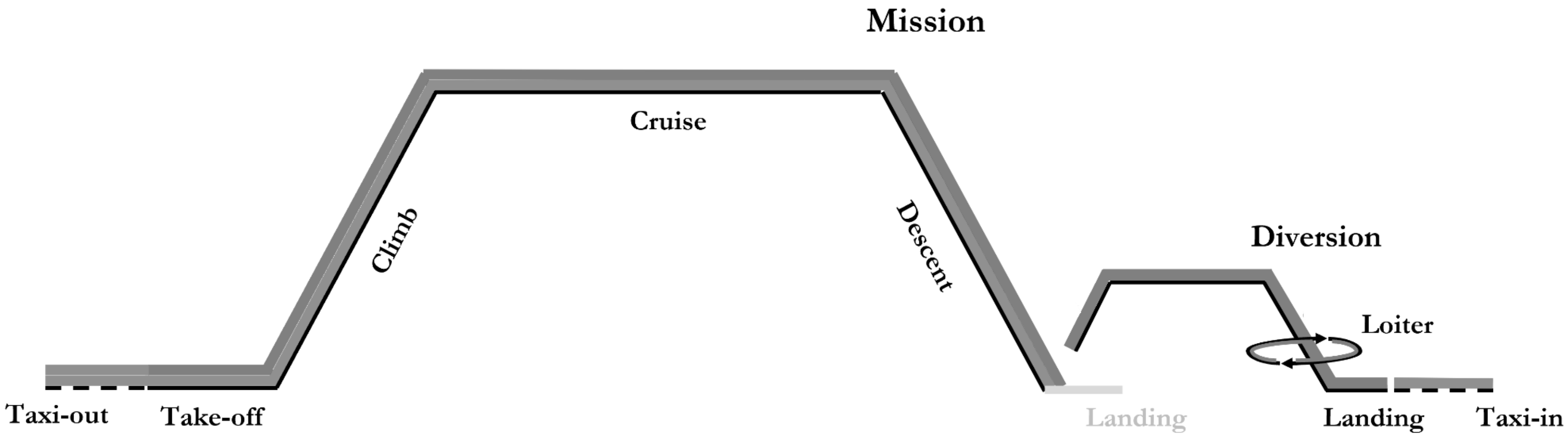
Descent: *?????*

Diversion

Climb: *?????*

Cruise: *?????*

Descent: *?????*



HEA - Mission definition

Standard Mission

Taxiing: *Full electric*

Take-off: *Max available power*

Climb: *Thermal/Electric*

Cruise: *Thermal/Electric*

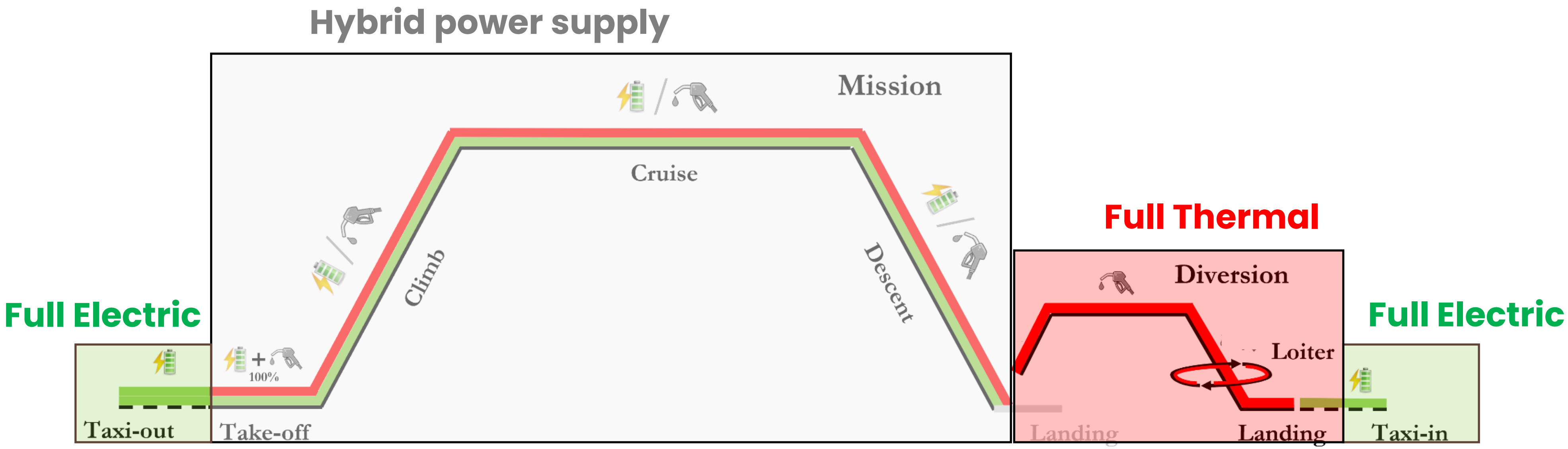
Descent: *Thermal/Electric*

Diversion

Climb: *Thermal*

Cruise: *Thermal*

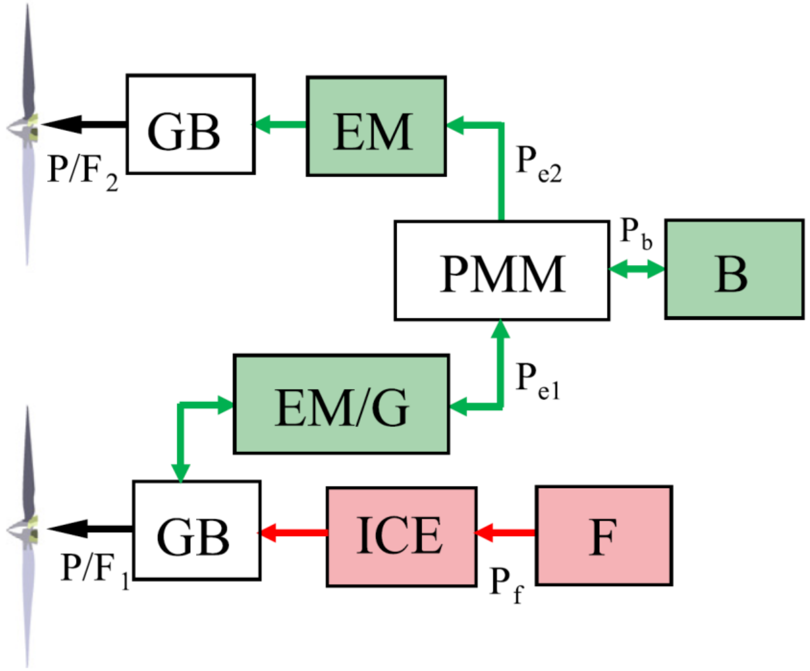
Descent: *Thermal*

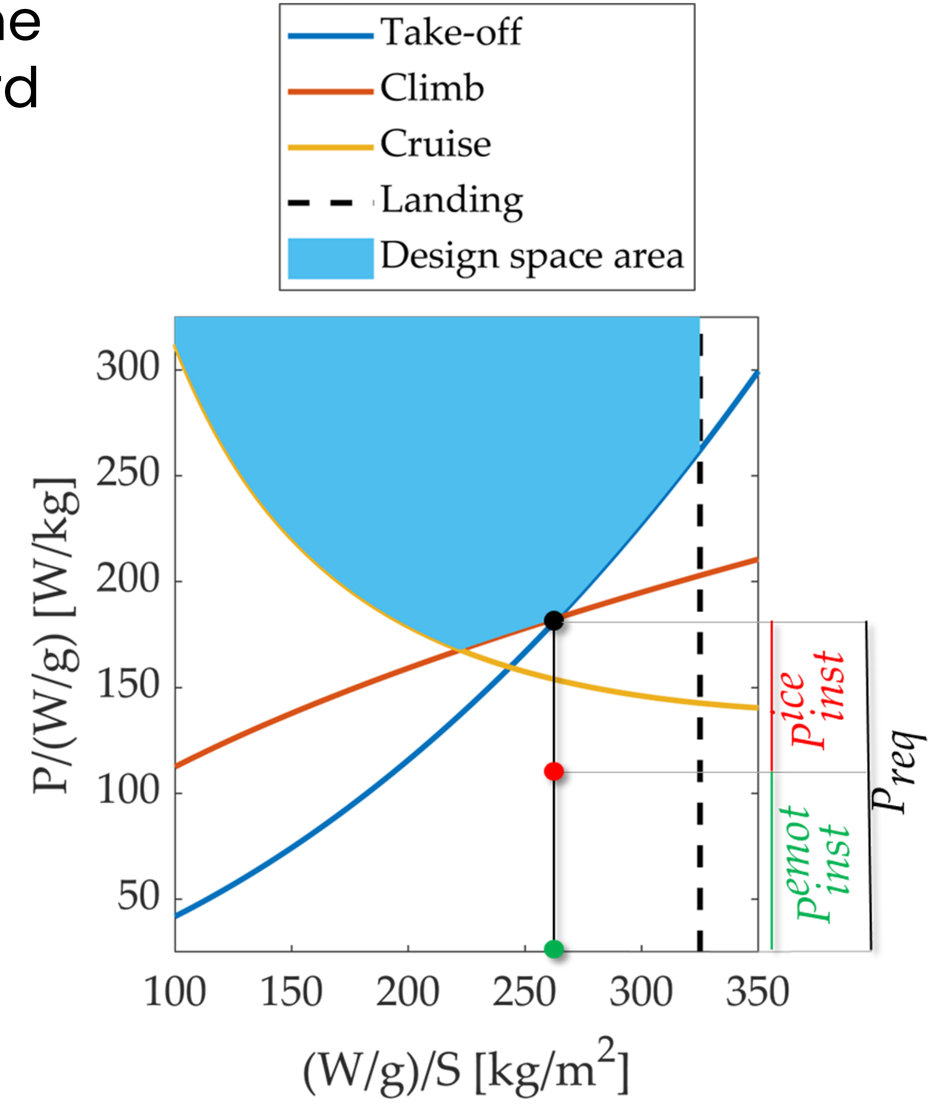


HEA - Powertrain sizing

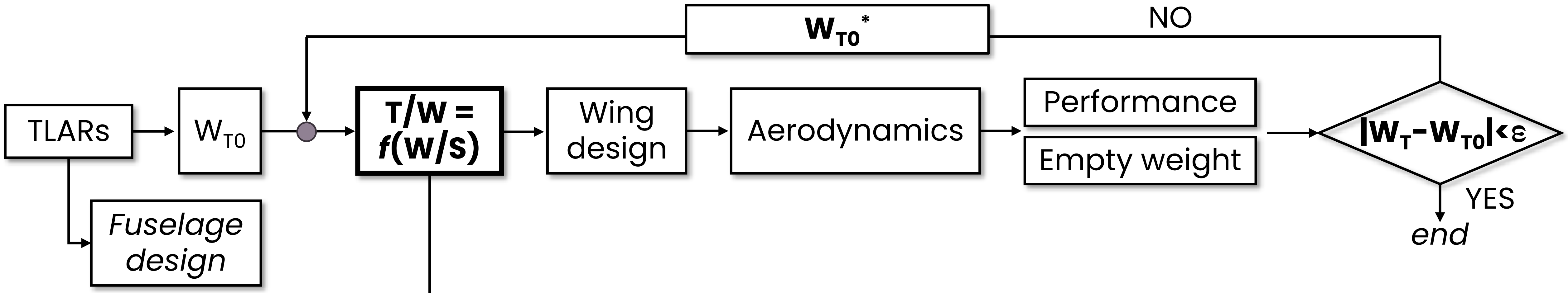
Degree of electric power hybridization defines the amount of electric and thermal power installed on board

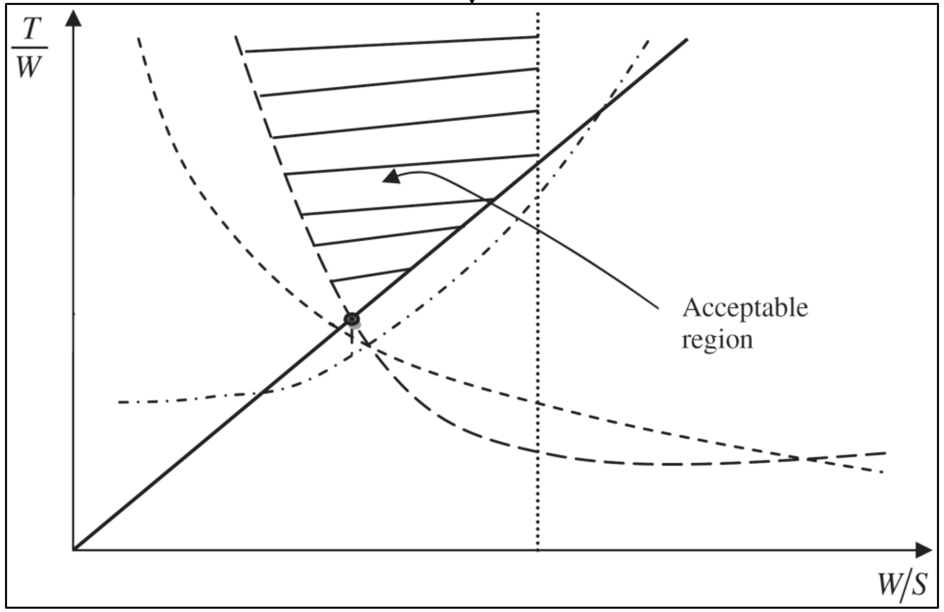
$$H_P = \frac{P_{inst}^{emot}}{P_{inst}^{ice} + P_{inst}^{emot}}$$





The Aircraft Design Process

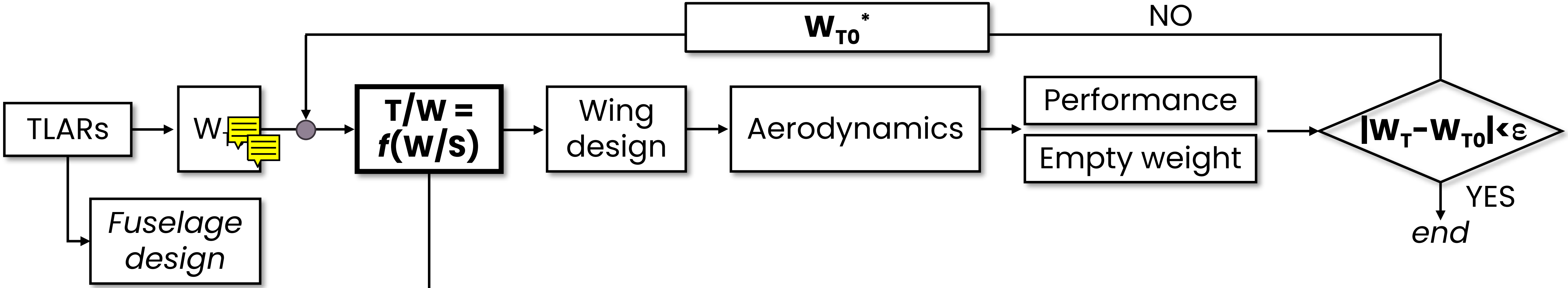


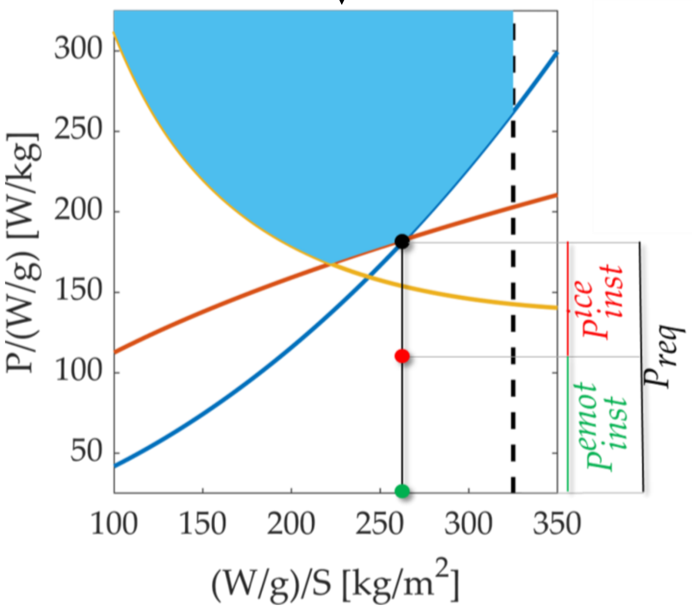


We need to **update our design methods** to fit with the design problem relating to the **hybrid-electric powertrain** for a **turboprop** aircraft.

First step: update and adapt the matching chart for the powertrain sizing!

The Aircraft Design Process





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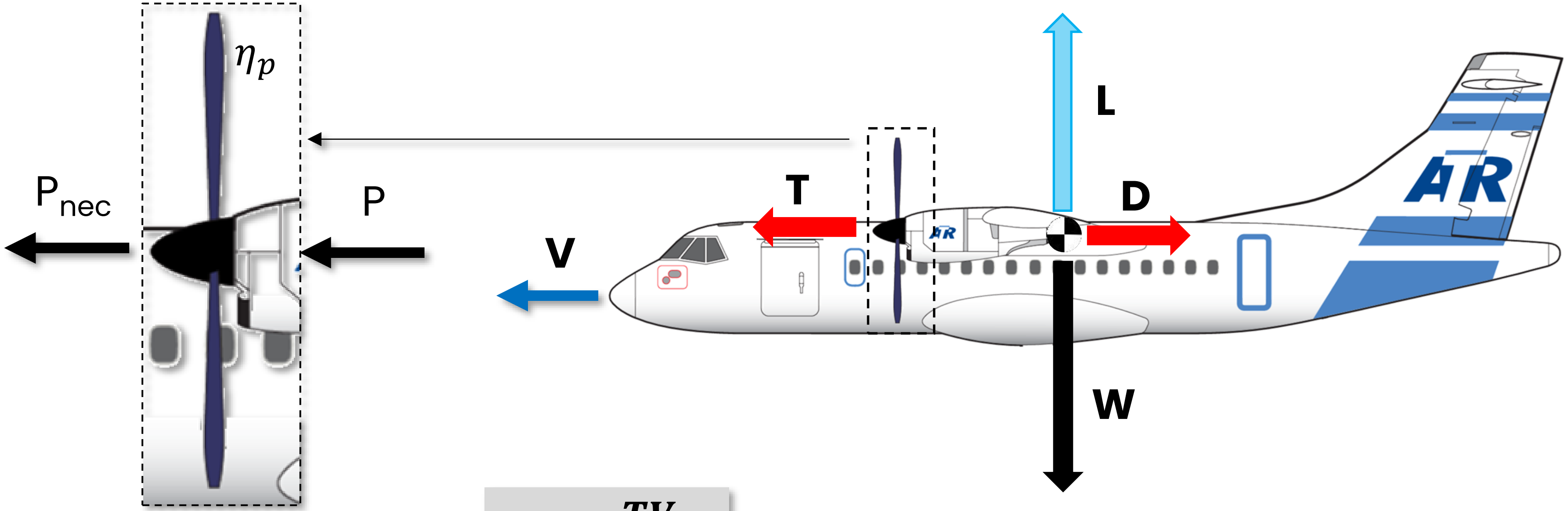
First step: update and adapt the matching chart for the powertrain sizing!

Matching chart

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



$P\eta_p = P_{nec}$ → $\boxed{P = \frac{TV}{\eta_p}}$ ← $T = D \rightarrow TV = DV = P_{nec}$

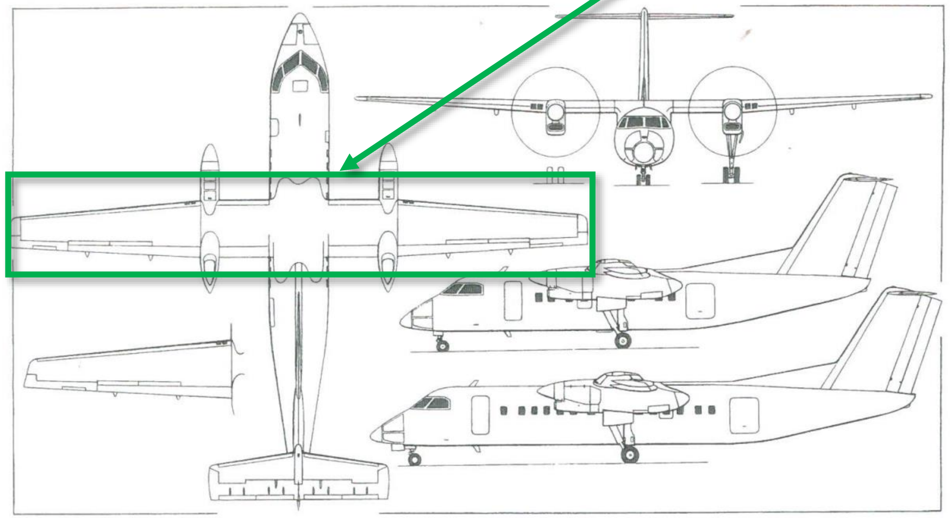
P = *power supplied to the propeller shaft by the propulsion system*
P_{nec} = power requested to fly
η_p = propeller efficiency

Matching chart - Landing

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

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

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



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

	$C_{L,max}$	$\Delta C_{L,max}$
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

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

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

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

Table 5.16 Characteristics of high-lift devices for several aircraft

No.	Aircraft	Engine	HLD	C_f/C	b_f/b	$\delta_{f_{max}}$ TO	$\delta_{f_{max}}$ 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

	$C_{L,max}$	$\Delta C_{L,max}$
Clean Airfoil	1,45	-
Plain Flap	2,25	0,80
Single-Slotted Flap	2,60	1,15
Double-Slotted Flap	2,80	1,35
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Matching chart - Landing

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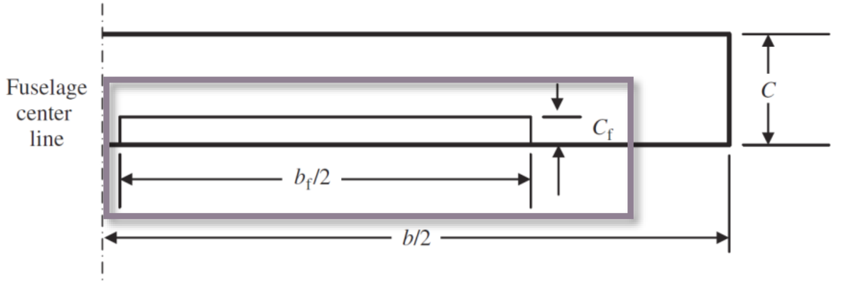

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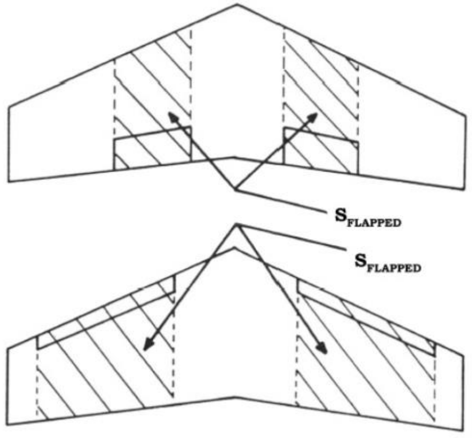

Superficie 'flappata'

Matching chart - Landing

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

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

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

Matching chart - Landing

TLARs and Mission

Matching chart

Landing
Equation

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1st, 2nd and final segment
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Cruise
Equation

Powertrain architecture
Serial
Parallel

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

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

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

Matching chart – Take-off

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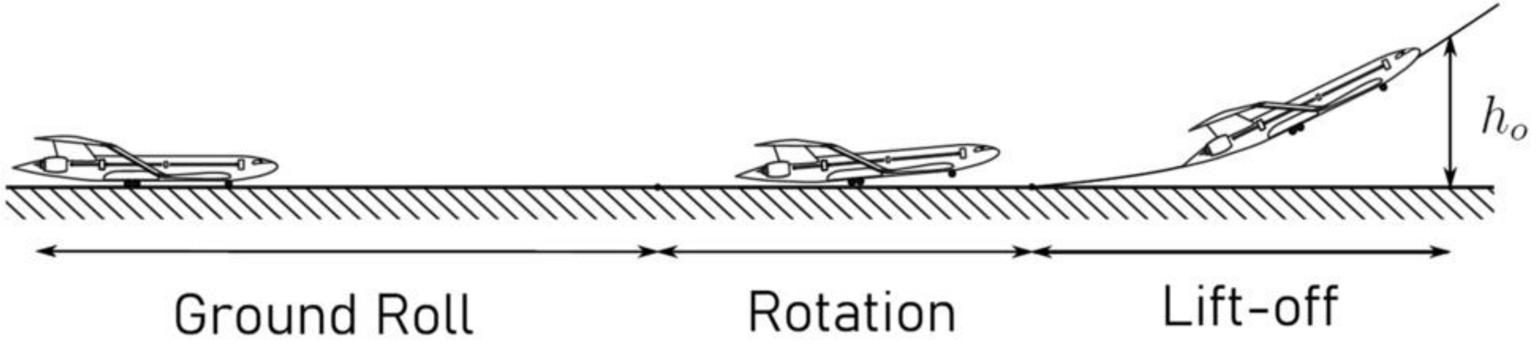
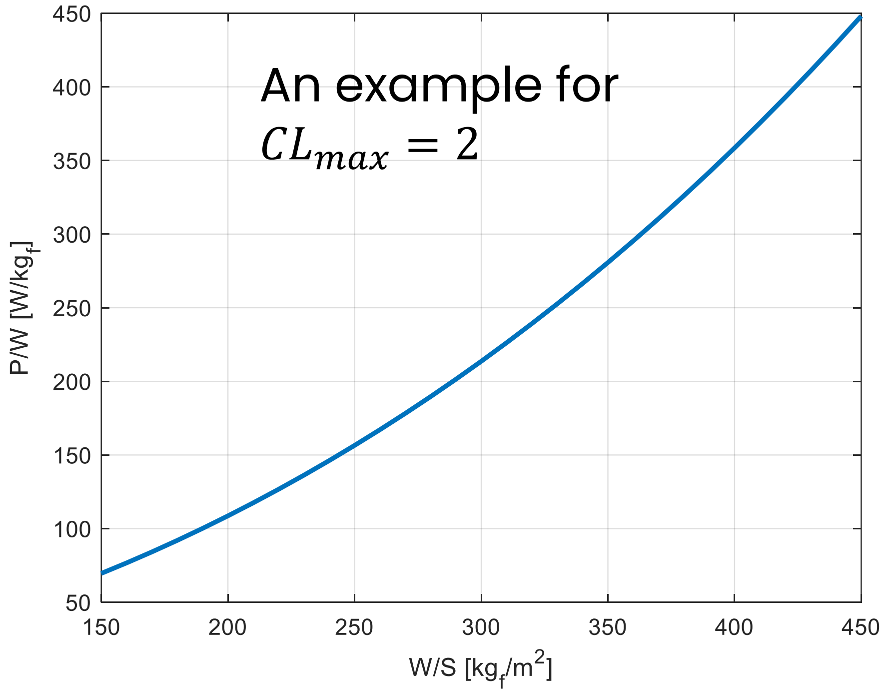


$$\frac{\boldsymbol{P}}{\boldsymbol{W}} = \boldsymbol{a_1}\frac{\boldsymbol{W}}{\boldsymbol{S}} + \boldsymbol{a_2}\left(\frac{\boldsymbol{W}}{\boldsymbol{S}}\right)^{\boldsymbol{2}}$$

$$a_1 = b_{10} + b_{11}CL_{max} + b_{12}CL_{max}^2$$
$$a_2 = b_{20} + b_{21}CL_{max} + b_{22}CL_{max}^2$$

$$b_{10} = 0.2792, b_{11} = -0.03285, b_{12} = -0.007541$$
$$b_{20} = 0.01076, b_{11} = -0.007067, b_{12} = 0.001276$$

$$BFL = 1100\ m$$
$$\mathbf{1.8 \leq CL_{max} \leq 2.5}$$
$$\mathbf{150\ kg_f/m^2 \leq W/S \leq 450\ kg_f/m^2}$$



Matching chart – Climb segments

TLARs and Mission

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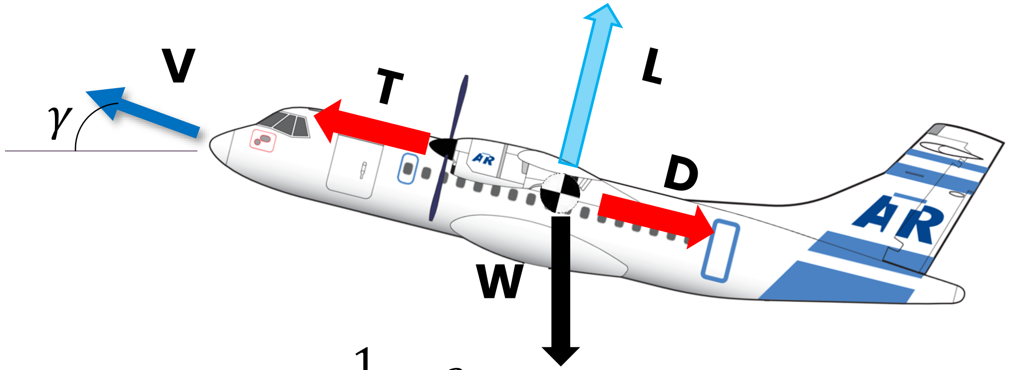


Thrust must satisfy the steady state climb condition with one engine inoperative, in three different segments

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

$$\boxed{\frac{P}{W} = \frac{T}{W}\frac{V}{\eta_p}}$$

$\eta_p = 0.75$

$$\boxed{\frac{P}{W} = \frac{1}{k_{OEI}\eta_p} \frac{\frac{1}{2}\rho V^3 C_{D0}}{W/S} + \frac{1}{k_{OEI}\eta_p} \frac{1}{2} \frac{\rho V^3 k}{W/S} \left(\frac{2W/S}{\rho V^2}\cos(\gamma)\right)^2 + \frac{V}{k_{OEI}\eta_p}\sin(\gamma)}$$

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

Matching chart – Climb segments

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

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

		FIRST SEGMENT	SECOND SEGMENT	FINAL SEGMENT
Minimum climb gradient (N-1) engines	Twin	0.0%	2.4%	1.2%
	Quad	0.5%	3.0%	1.7%
Slats / Flaps Configuration		Takeoff	Takeoff	Clean
Speed reference		V2	V2	1.25 Vs
Landing gear		Retraction	Retracted	Retracted

Matching chart – Approach climb

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

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

3.3.1. Approach Climb

JAR 25.121 Subpart B *FAR 25.121 Subpart B*

This corresponds to an aircraft's climb capability, assuming that one engine is inoperative. The "approach climb" wording comes from the fact that go-around performance is based on approach configuration, rather than landing configuration. For Airbus fly-by-wire aircraft, the available approach configurations are CONF 2 and 3.

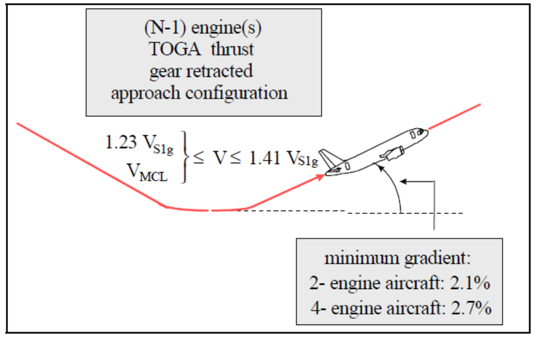
3.3.1.1. Aircraft Configuration

- One engine inoperative
- TOGA thrust
- Gear retracted
- Slats and flaps in approach configuration (CONF 2 or 3 in most cases)
- 1.23 $V_{S1g} \leq V \leq 1.41\ V_{S1g}$ and check that $V \geq$ VMCL

3.3.1.2. Requirements

The minimum gradients to be demonstrated:

		Approach Climb
Minimum climb gradient one engine out	Twin	2.1%
	Quad	2.7%



Matching chart - Cruise

TLARs and Mission

Matching chart

Landing
Equation

Take-off
Equation

Climb
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Powertrain architecture
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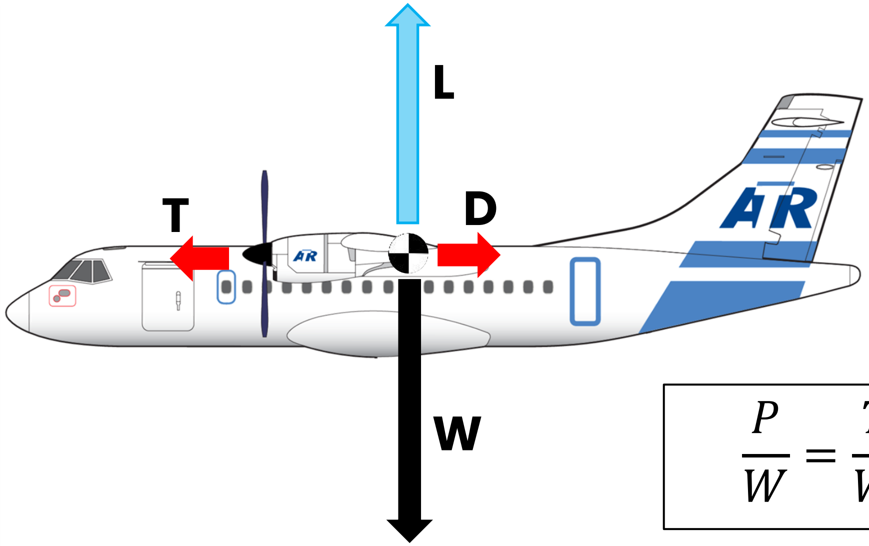


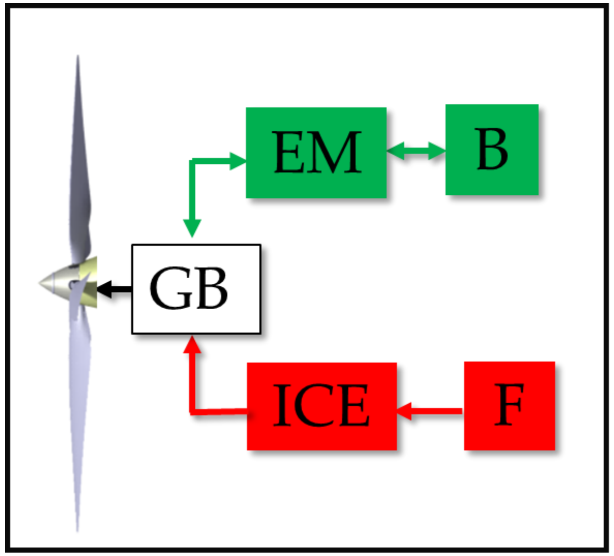
Thrust must equilibrate the aircraft drag (γ = 0°). The aircraft thrust, calculated at cruise altitude, has to be assessed at sea level

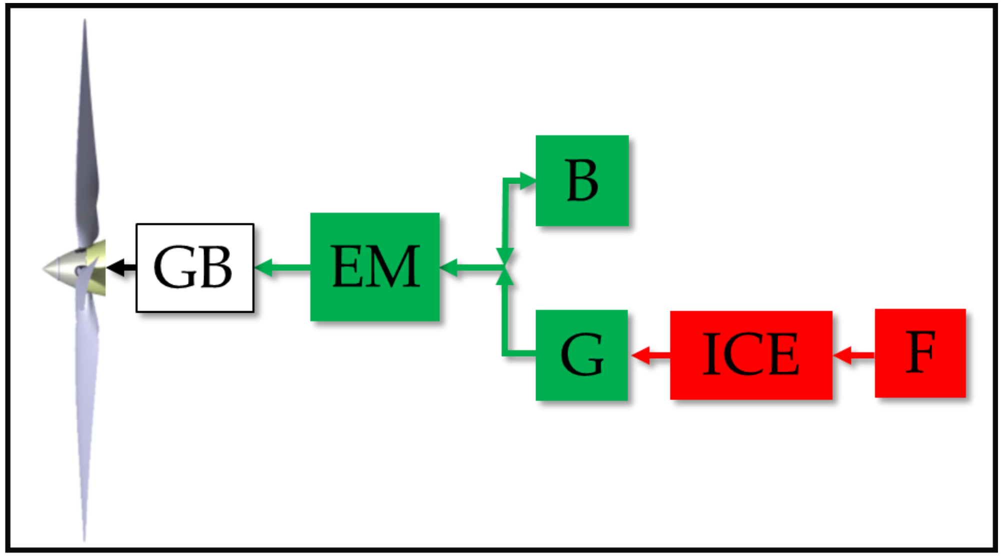
$$\boxed{\frac{P}{W} = \frac{T}{W}\frac{V}{\eta_p}} \qquad \eta_p = 0.85$$

$$\begin{cases} \frac{P}{W} = \frac{1}{\eta_p}\frac{\frac{1}{2}\rho V^3 C_D}{W/S} + \frac{1}{2}\frac{1}{\eta_p}\frac{\rho V^3 k}{W/S}\left(\frac{2W/S}{\rho V^2}\cos(\gamma)\right)^2 \\ \left(\frac{P}{W}\right) = \left(\frac{P}{W}\right)_{SL}\left(\frac{\rho}{\rho_{SL}}\right)^{0.75} \end{cases} \longrightarrow \boxed{\left(\frac{P}{W}\right)_{SL} = \frac{\left(\frac{P}{W}\right)}{\left(\frac{\rho}{\rho_{SL}}\right)^{0.75}}}$$

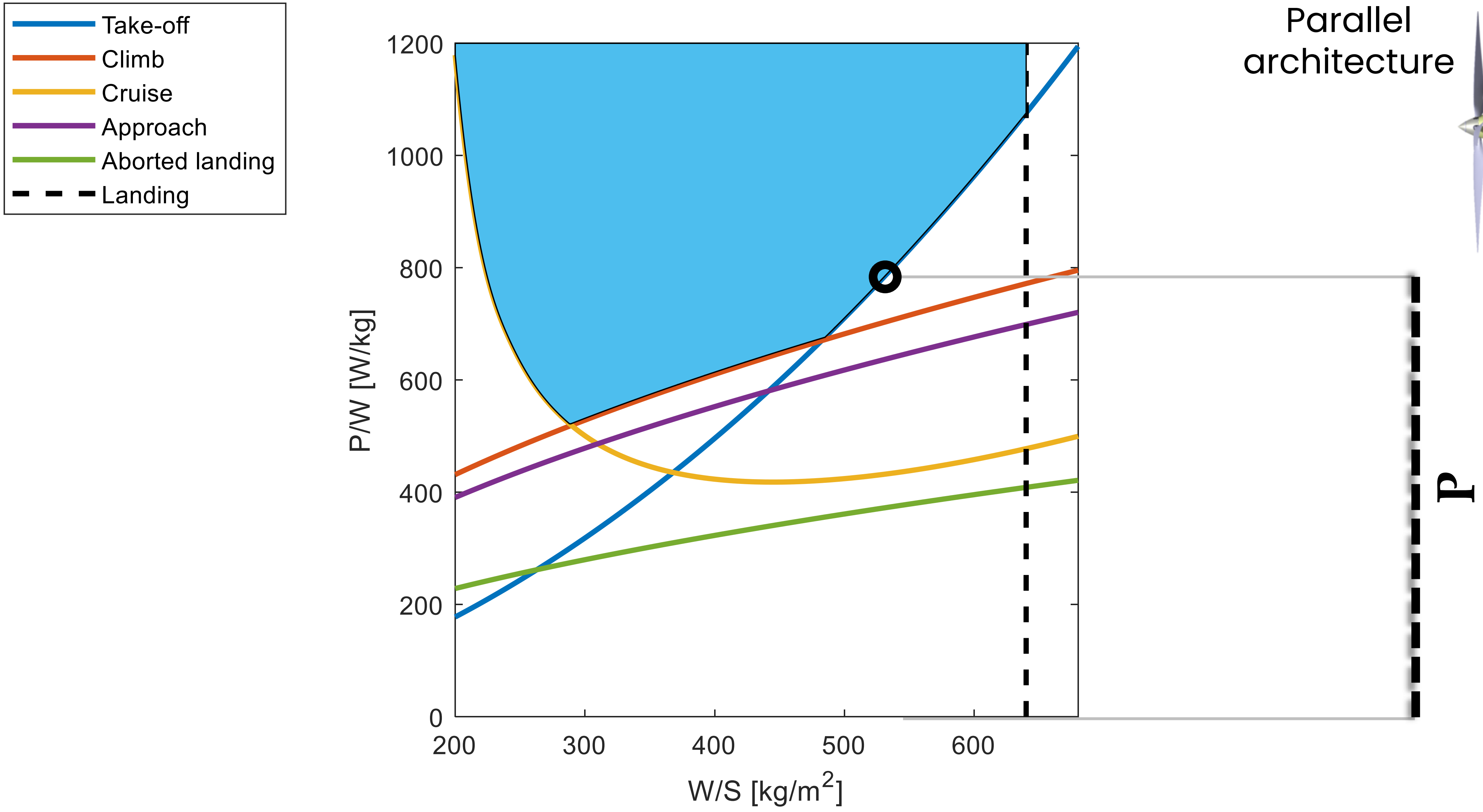
Matching chart

Parallel vs **Serial**

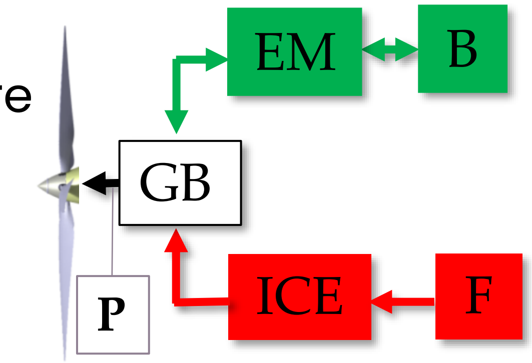




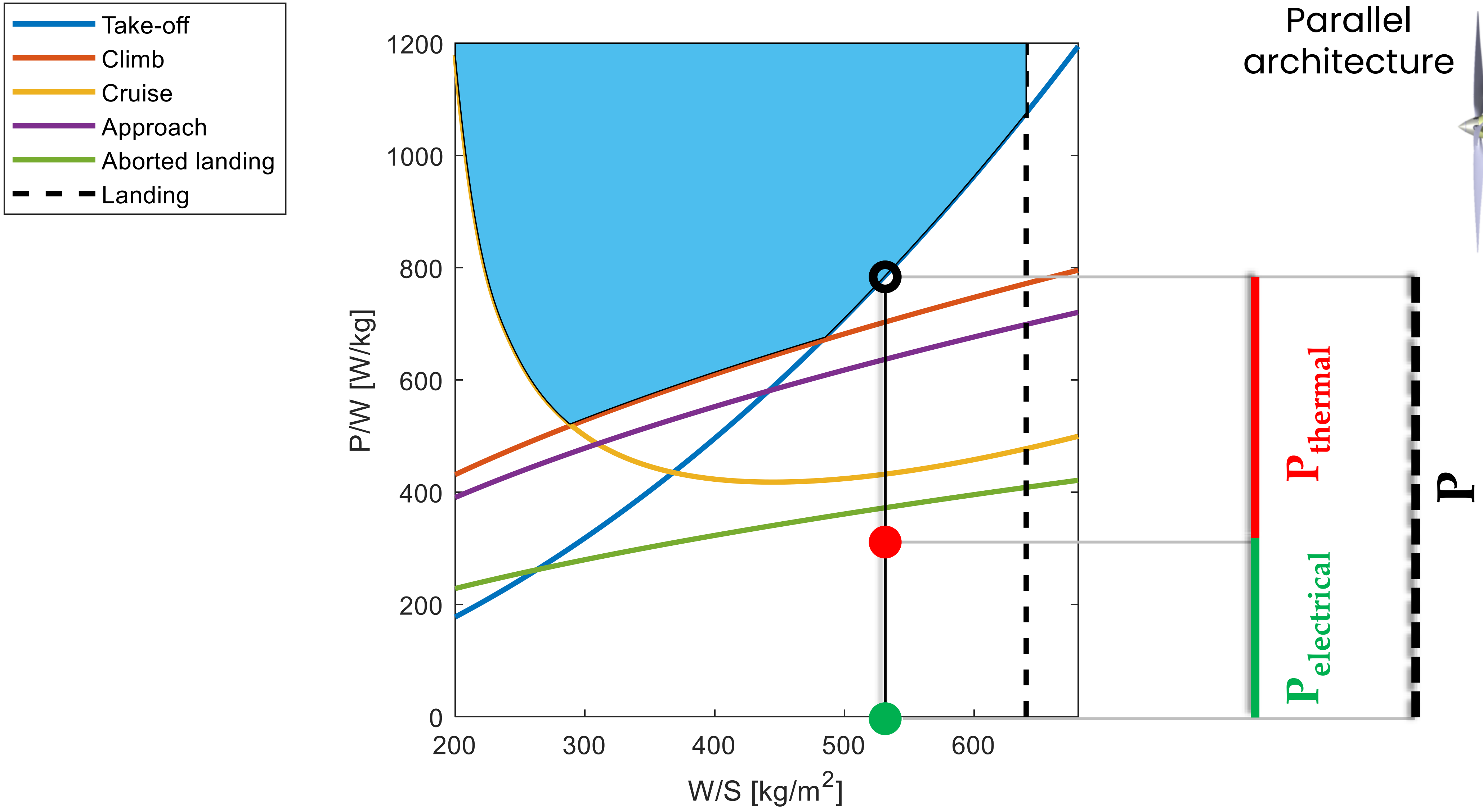
HEA - Powertrain sizing: Parallel

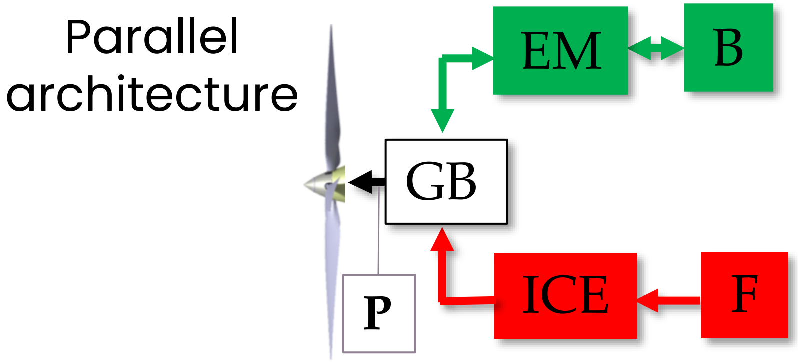


Parallel architecture

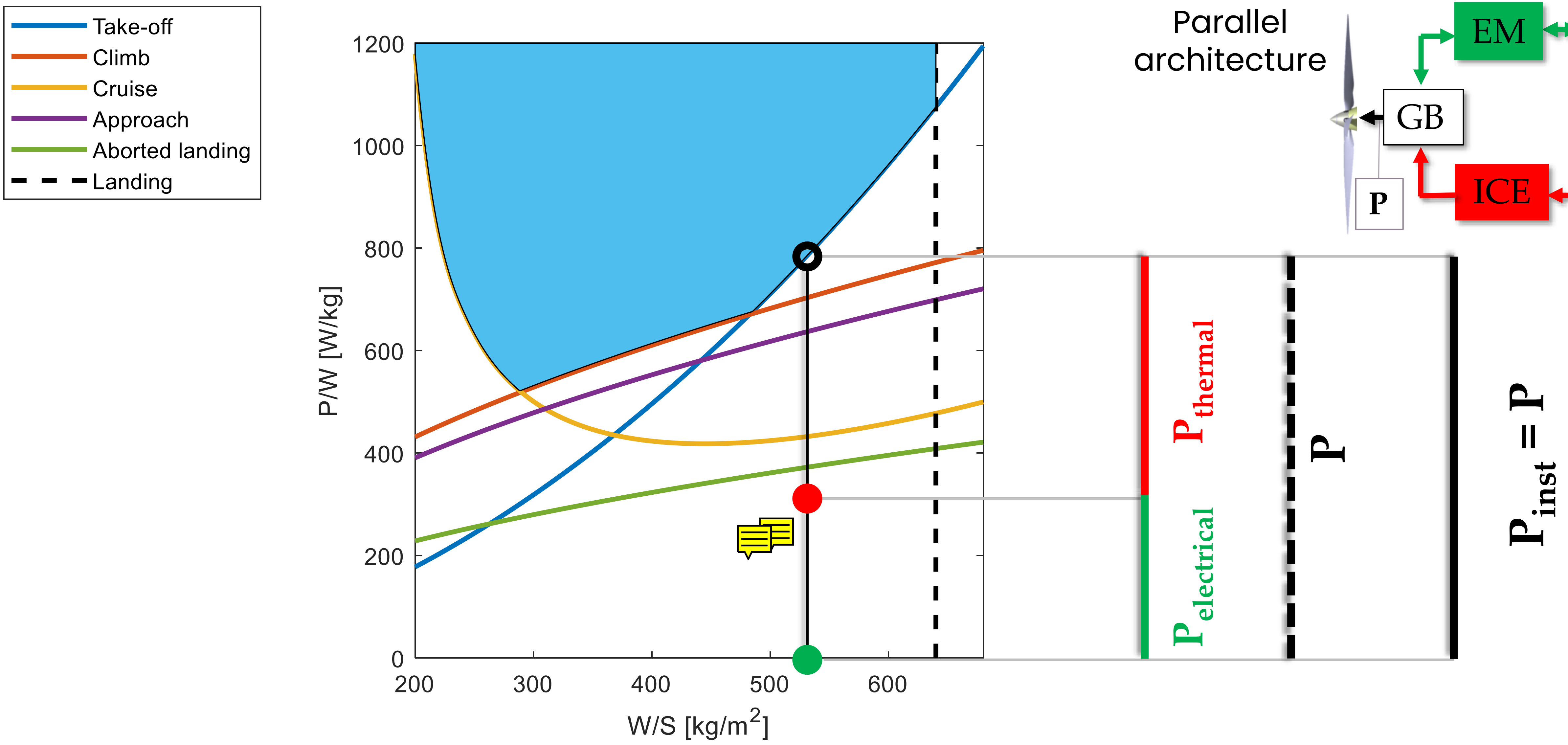


HEA - Powertrain sizing: Parallel

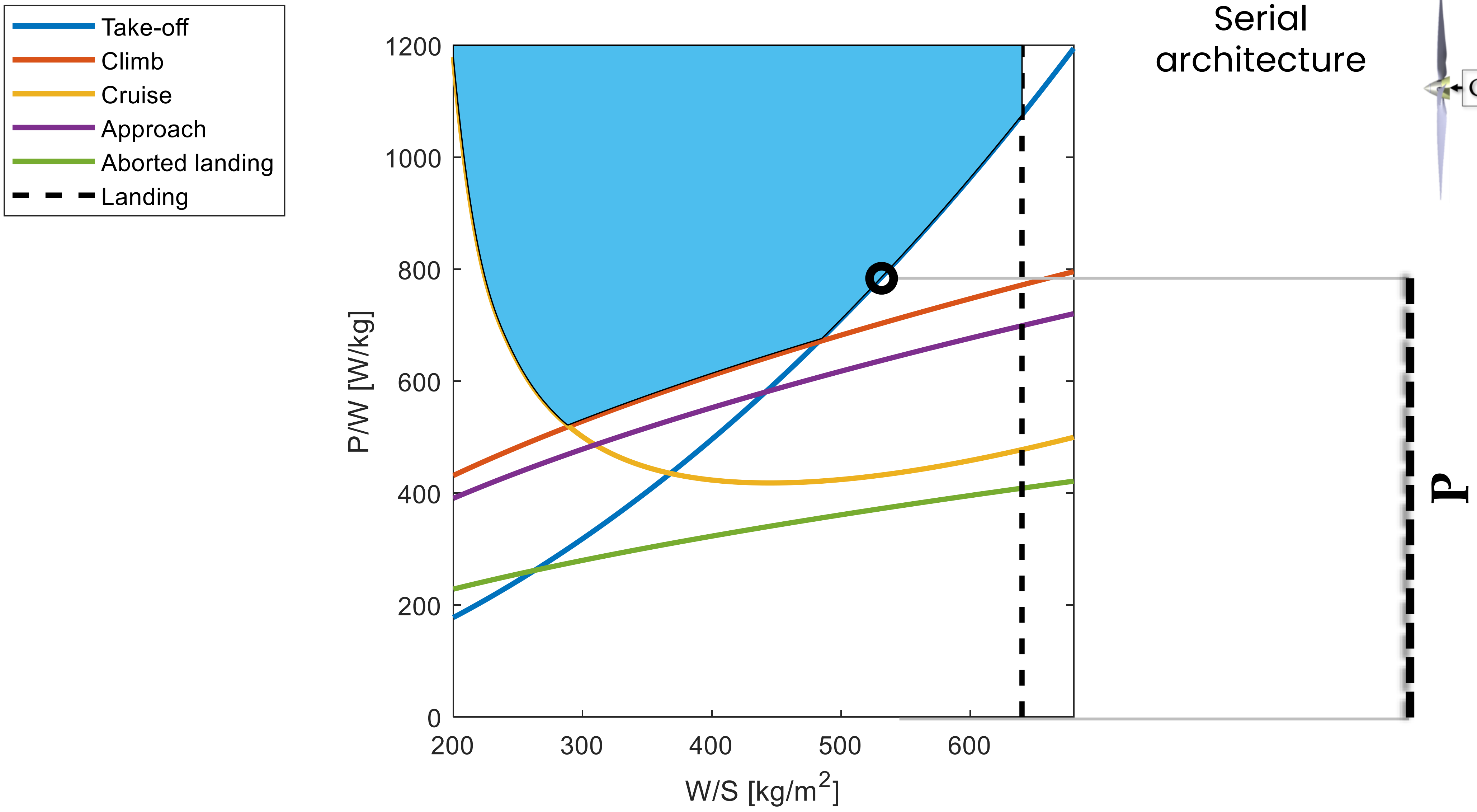




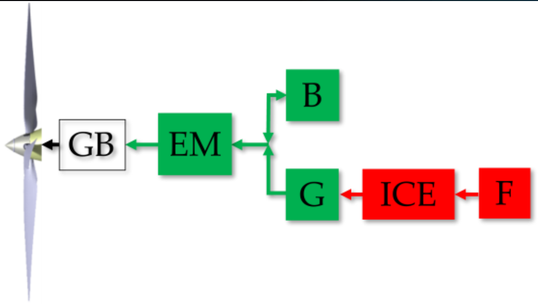
HEA - Powertrain sizing: Parallel



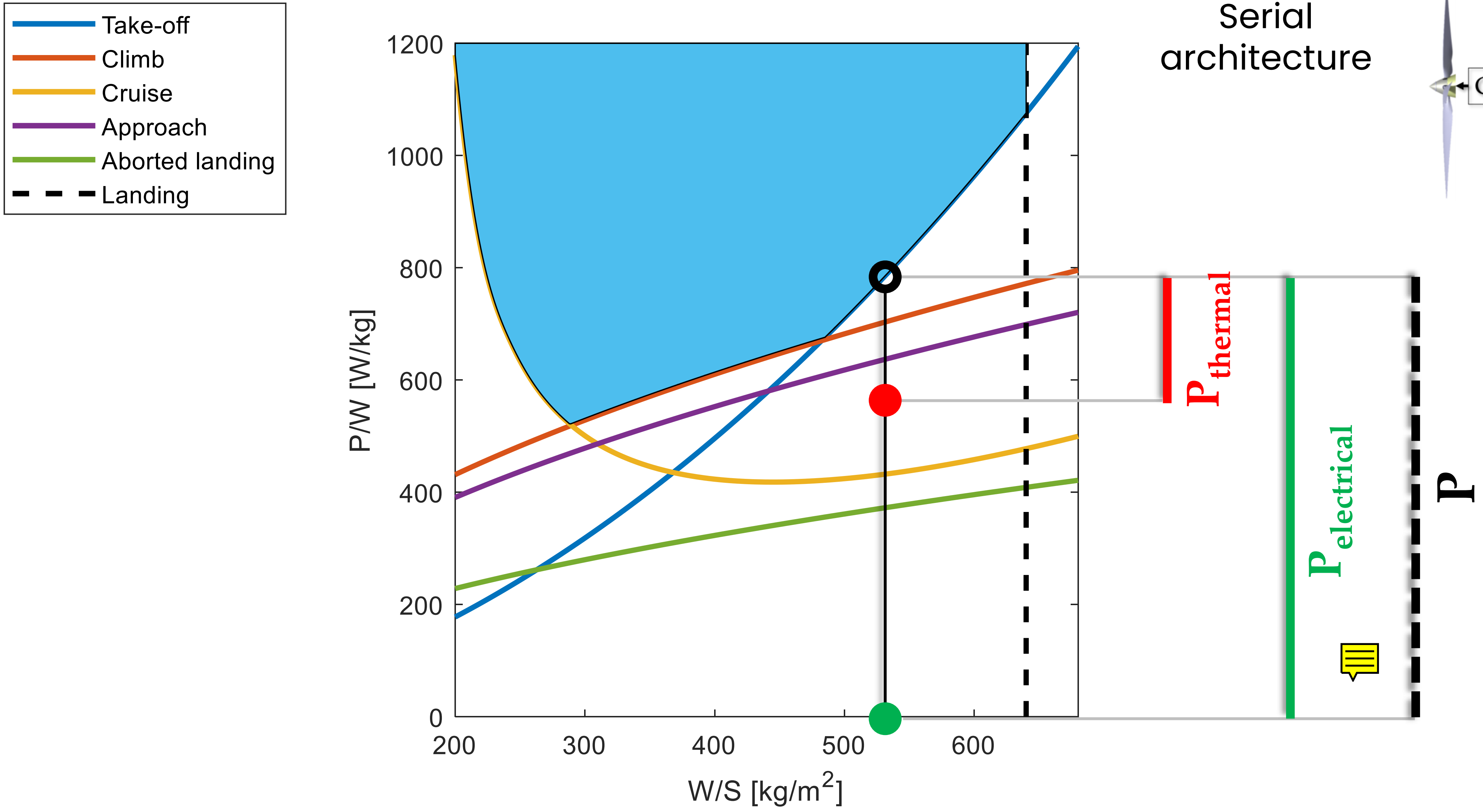
HEA - Powertrain sizing: Serial



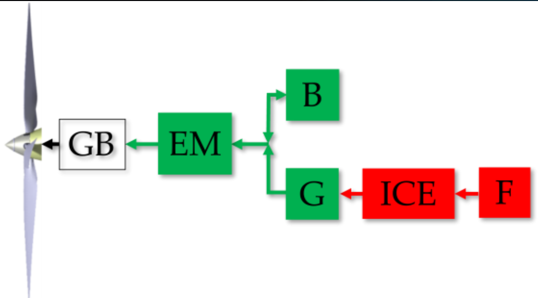
Serial architecture



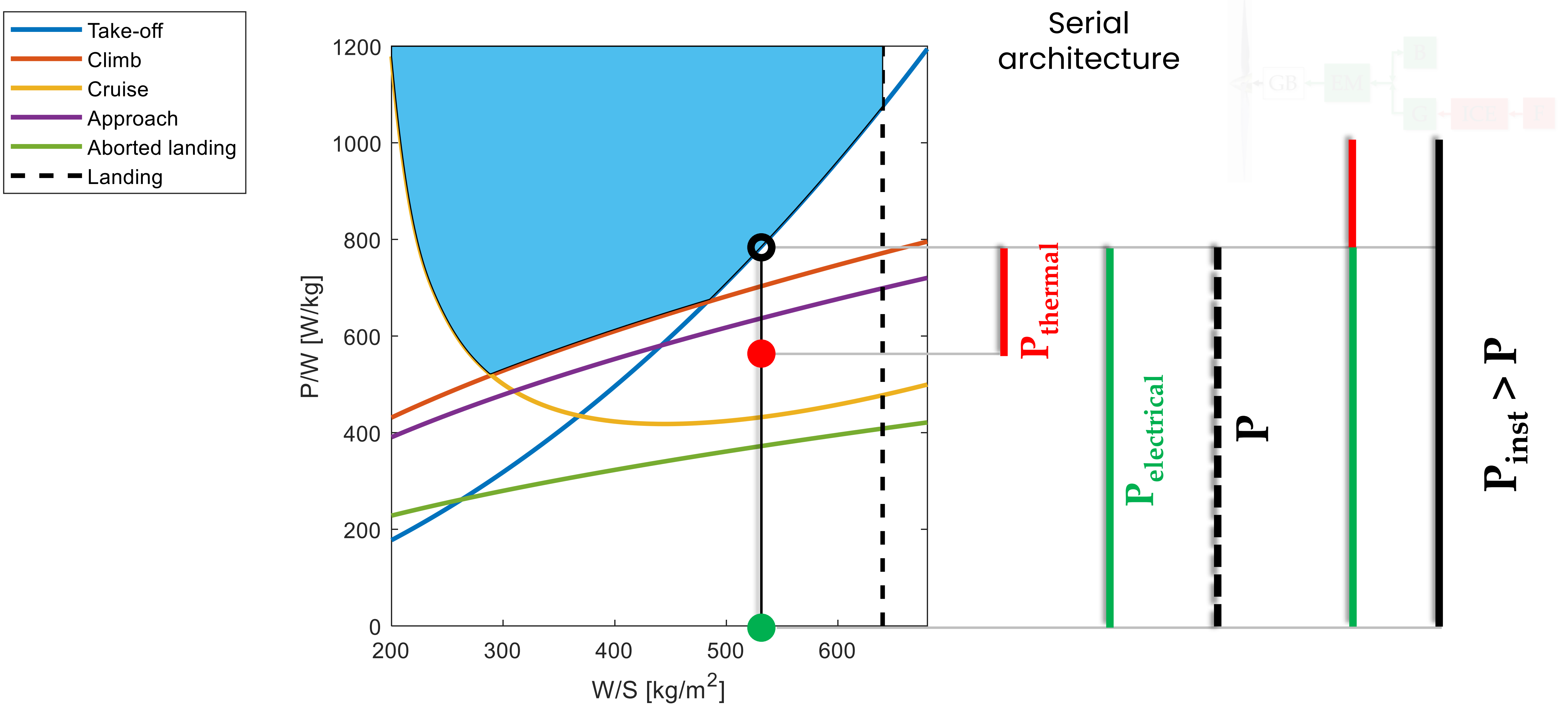
HEA - Powertrain sizing: Serial



Serial architecture



HEA - Powertrain sizing: Serial



Back-up slides