

**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

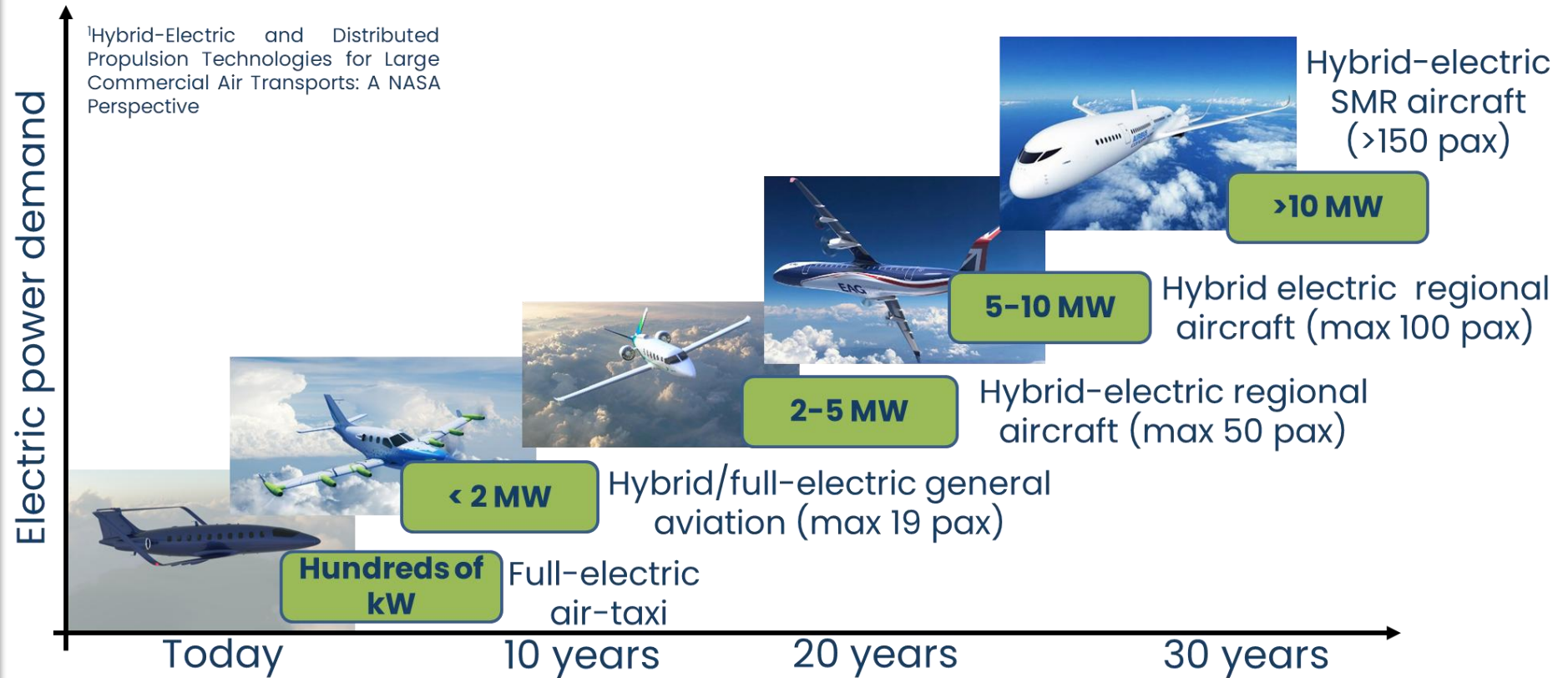
### Landing Equation

### Take-off Equation

### Climb 1<sup>st</sup>, 2<sup>nd</sup> and final segment Approach climb

### Cruise Equation

### Powertrain architecture Serial Parallel



# HEA - Top Level Aircraft Requirements



## TLARs and Mission

### Matching chart

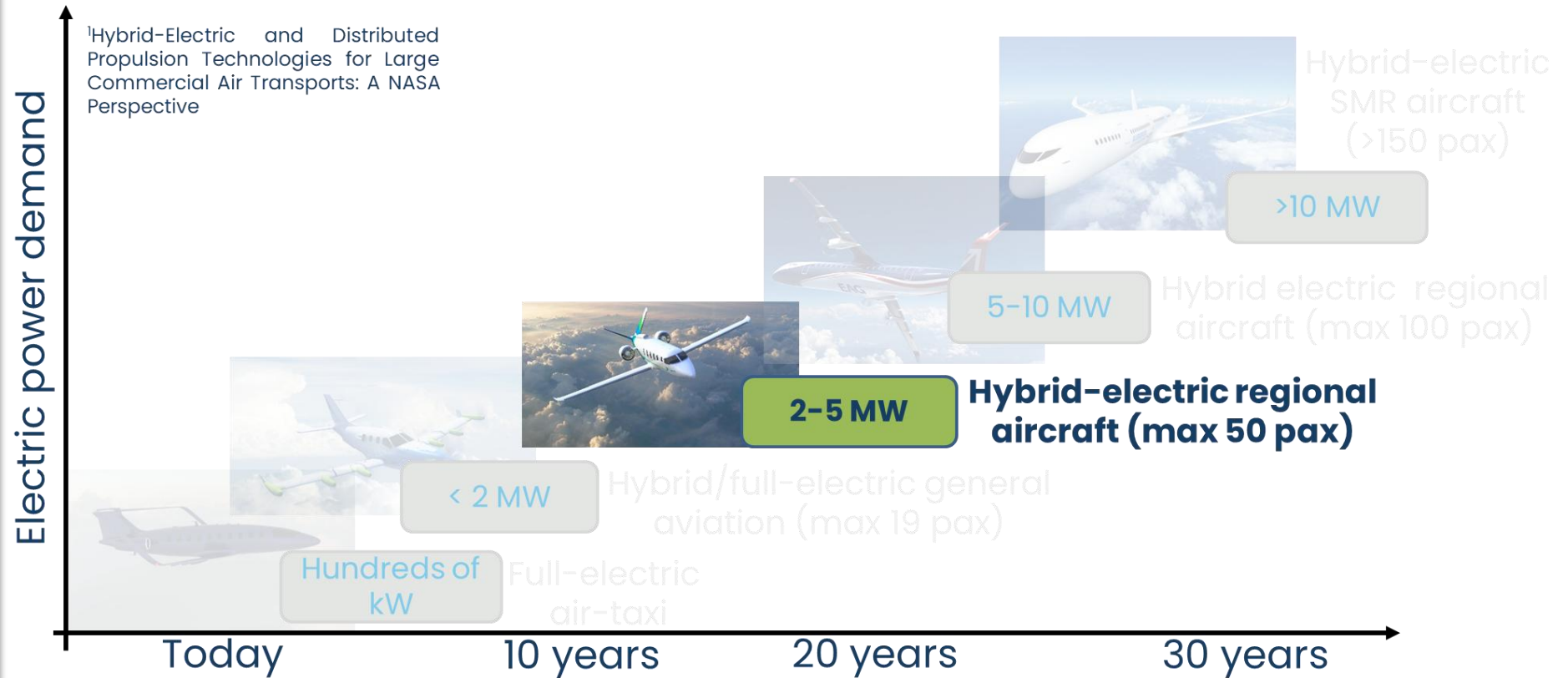
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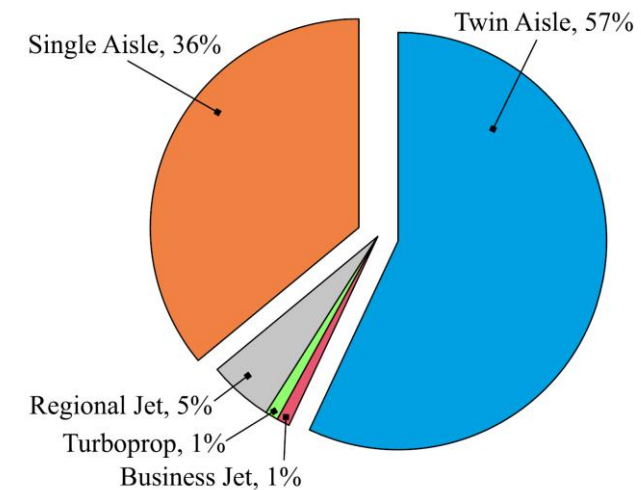
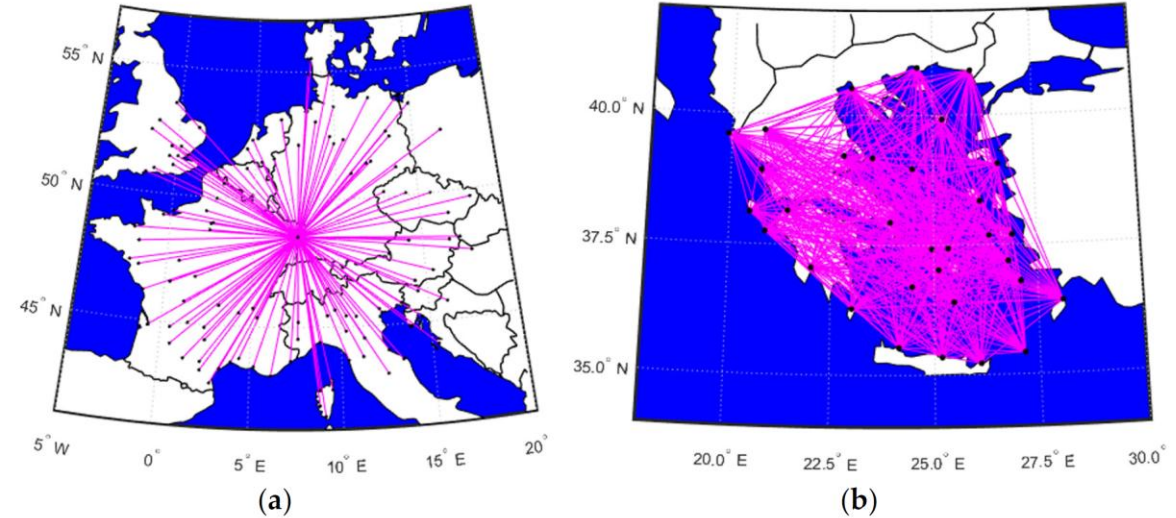
# HEA – Top Level Aircraft Requirements



## 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

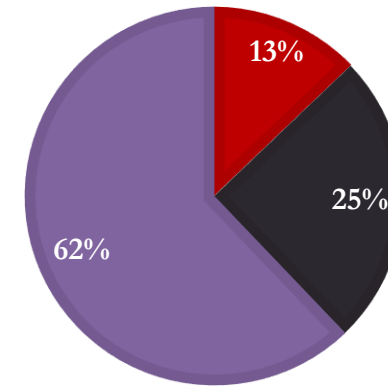


## Reference full-thermal regional aircraft

ATR 42-500



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

# HEA – Top Level Aircraft Requirements



## TLARs and Mission

### Matching chart

### Landing Equation

### Take-off Equation

### Climb 1<sup>st</sup>, 2<sup>nd</sup> and final segment Approach climb

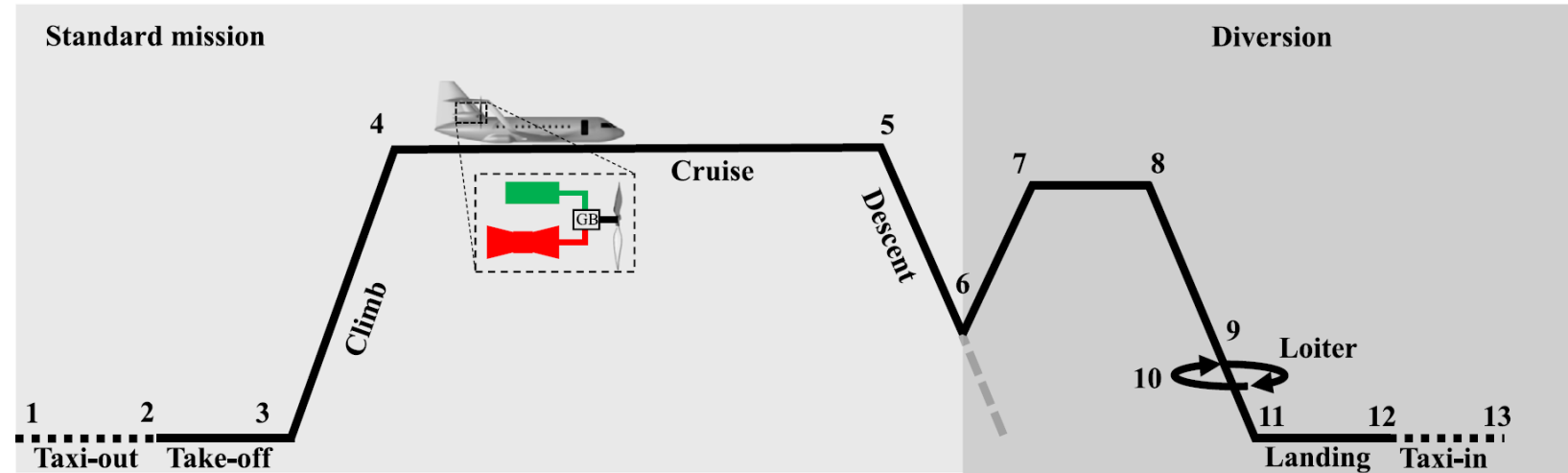
### Cruise Equation

### Powertrain architecture Serial Parallel

Some reference papers:

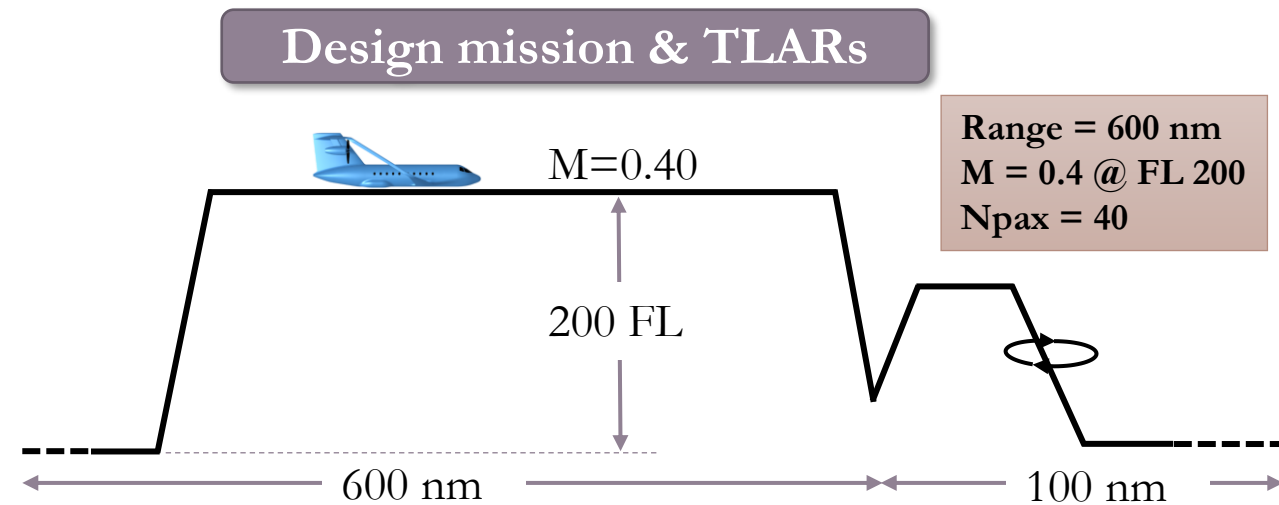
1. Abu Salem K. et al. «Review of hybrid-electric aircraft technologies and designs: Critical analysis and novel solutions». Progress in Aerospace Science, 2023.
2. Eisenhut D. et al. «Aircraft Requirements for Sustainable Regional Aviation». *Aerospace* 2021, 8, 61.
3. Brdnik A.P. et al. «Market and 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». 33<sup>o</sup> 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





# HEA - Mission definition



## Standard Mission

Taxiing: ?????

Take-off: ?????

Climb: ?????

Cruise: ?????

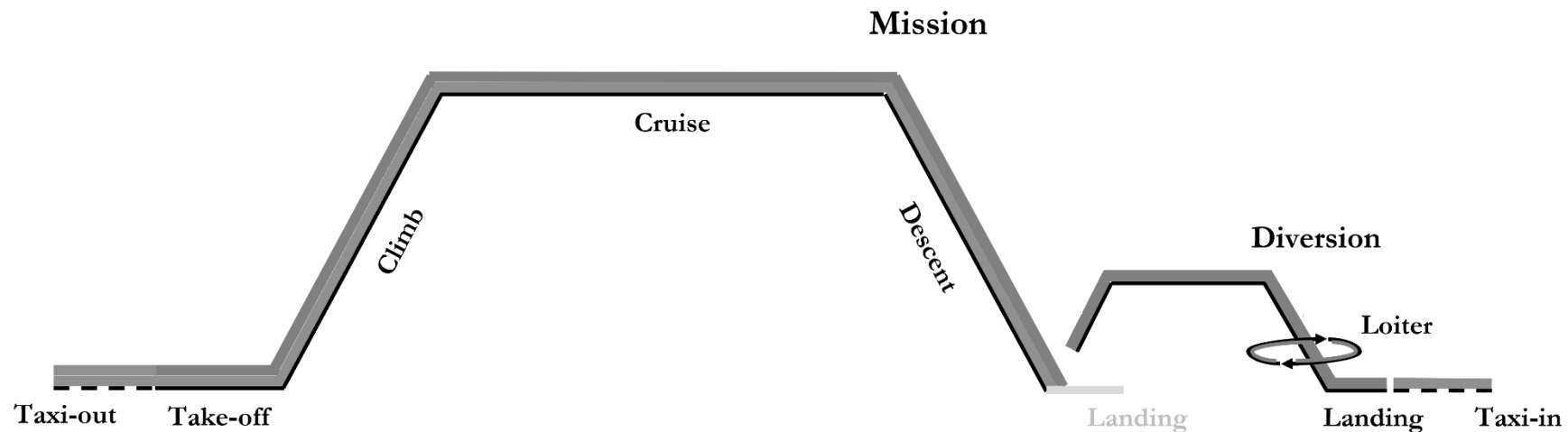
Descent: ?????

## Diversion

Climb: ?????

Cruise: ?????

Descent: ?????



# HEA – Mission definition



## Standard Mission

Taxiing: *Full electric*

Take-off: *Max available power*

Climb: *Thermal/Electric*

Cruise: *Thermal/Electric*

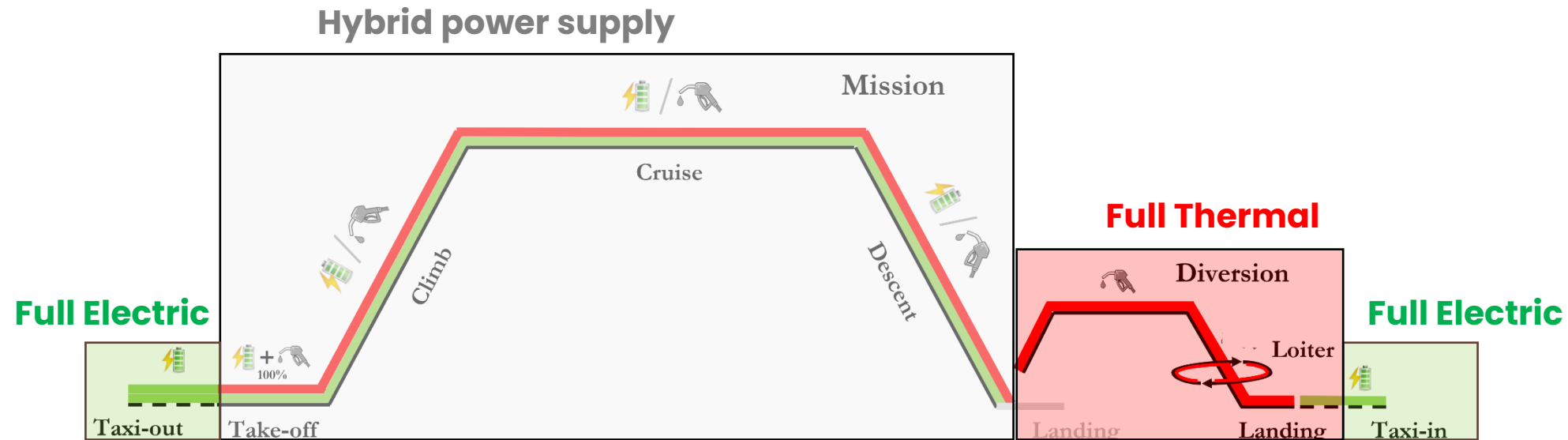
Descent: *Thermal/Electric*

## Diversion

Climb: *Thermal*

Cruise: *Thermal*

Descent: *Thermal*

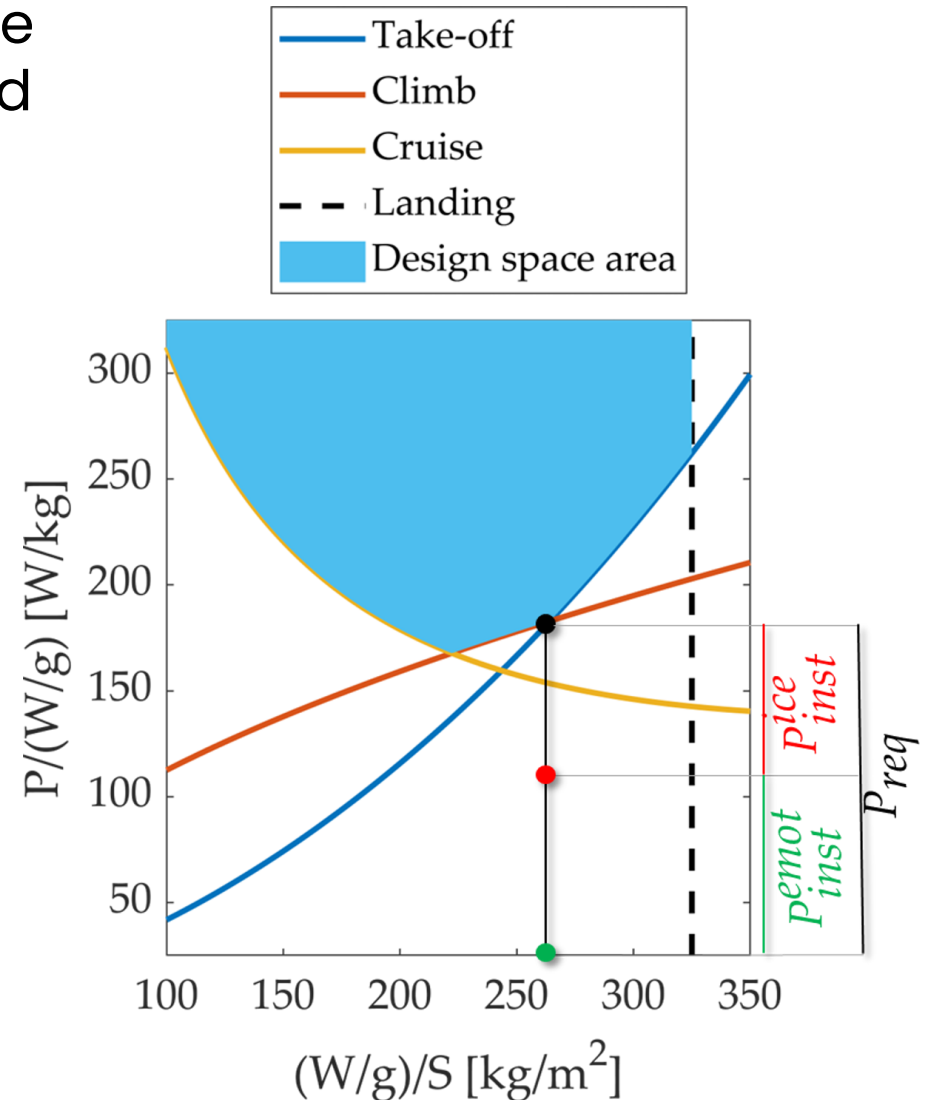
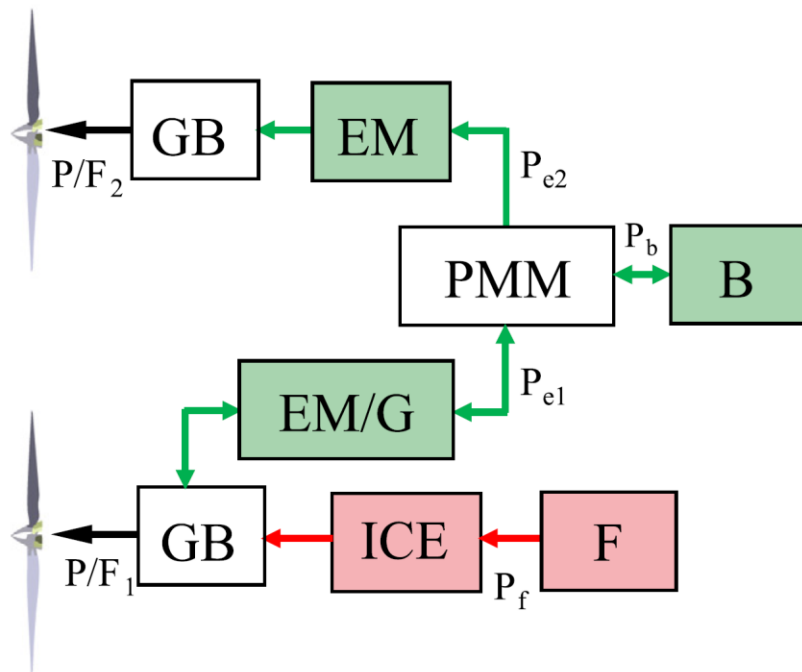


# HEA – Powertrain sizing

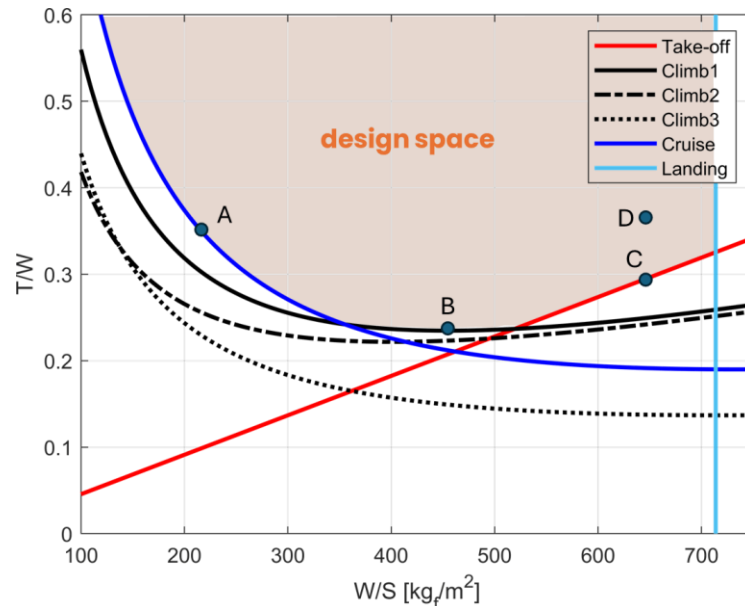
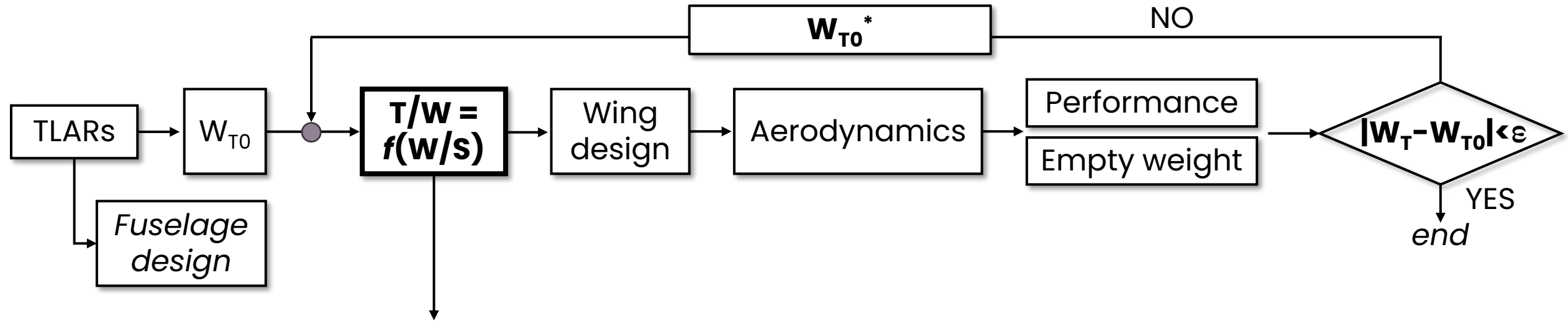


Degree of electric power hybridization defines the amount of electric and thermal power installed on board

$$H_p = \frac{p_{inst}^{emot}}{p_{inst}^{ice} + p_{inst}^{emot}}$$



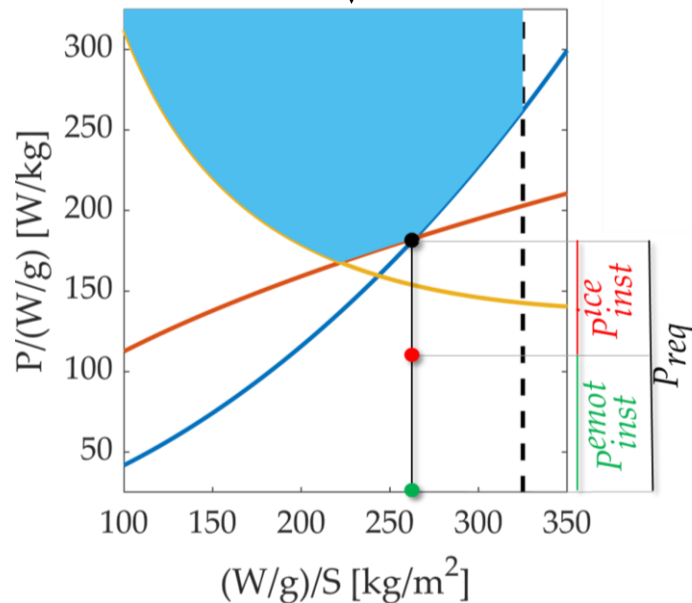
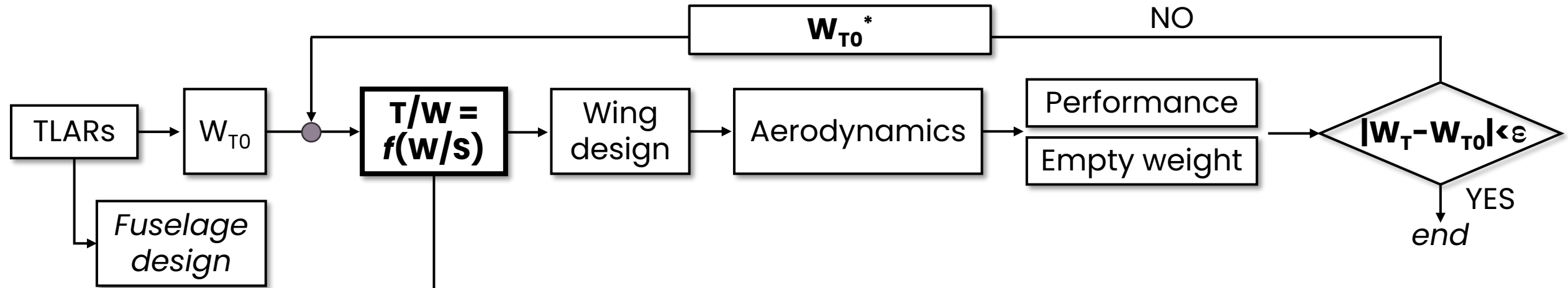
# The Aircraft Design Process



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



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!**



# Matching chart



TLARs and Mission

Matching chart

Landing  
Equation

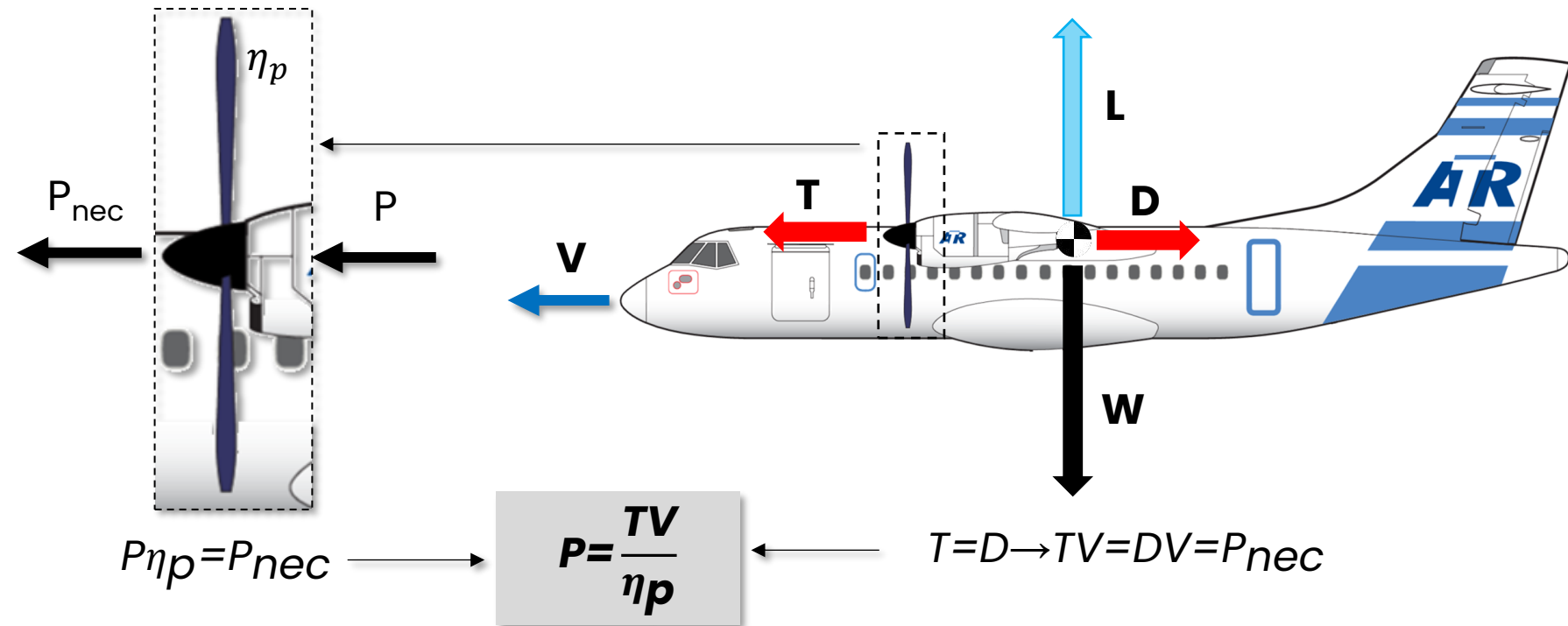
Take-off  
Equation

Climb  
1<sup>st</sup>, 2<sup>nd</sup> and final segment  
Approach/landing climb

Cruise  
Equation

Powertrain architecture  
Serial  
Parallel

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

$\eta_p$  = propeller efficiency

# Matching chart – Landing



TLARs and Mission

Matching chart

**Landing**  
Equation

**Take-off**  
Equation

**Climb**  
1<sup>st</sup>, 2<sup>nd</sup> and final segment  
Approach/landing climb

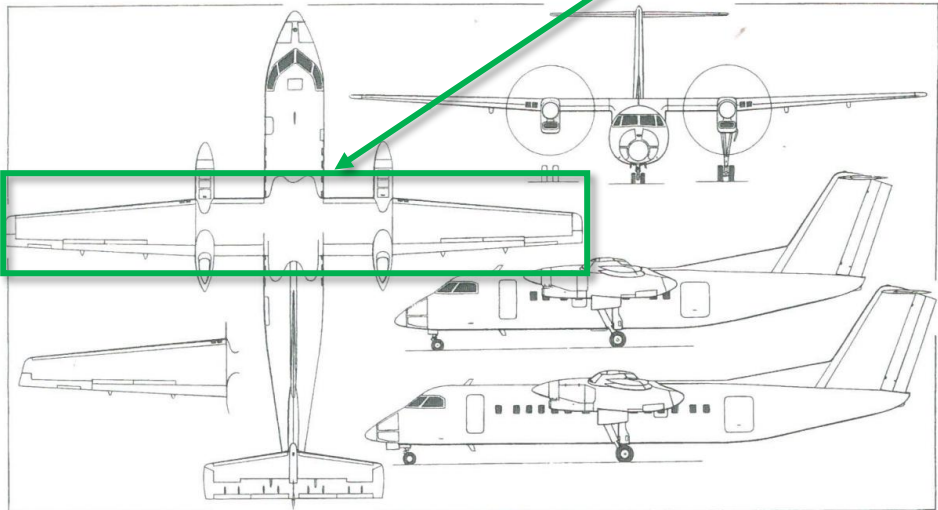
**Cruise**  
Equation

**Powertrain architecture**  
Serial  
Parallel

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

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)

		$C_{L,max}$	$\Delta C_{L,max}$
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
<b>Combinations:</b>			
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



TLARs and Mission

Matching chart

Landing  
Equation

Take-off  
Equation

Climb  
1<sup>st</sup>, 2<sup>nd</sup> and final segment  
Approach/landing climb

Cruise  
Equation

Powertrain architecture  
Serial  
Parallel

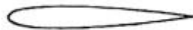
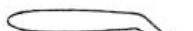










$$\frac{W}{S} \leq \frac{1}{2} \rho V_s^2 C_{Lmax}$$

Step 2: Assessment of  $\Delta C_{Lmax}$  due to flap/slat

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

Table 5.16 Characteristics of high-lift devices for several aircraft

No.	Aircraft	Engine	HLD	$C_t/C$	$b_t/b$	$\delta_{fmax}$	
						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

		$C_{Lmax}$	$\Delta C_{Lmax}$
Clean Airfoil		1,45	-
Plain Flap		2,25	0,80
Single-Slotted Flap		2,60	1,15
Double-Slotted Flap		2,80	1,35
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Fowler Flap and Slat		3,00	1,55

# Matching chart – Landing



TLARs and Mission

Matching chart

Landing  
Equation

Take-off  
Equation

Climb  
1<sup>st</sup>, 2<sup>nd</sup> and final segment  
Approach/landing climb

Cruise  
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Powertrain architecture  
Serial  
Parallel

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3D                      2D

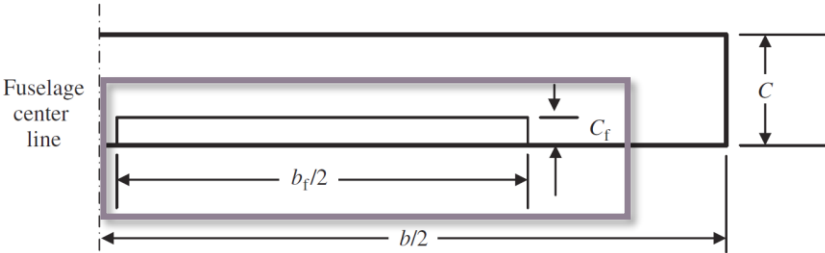
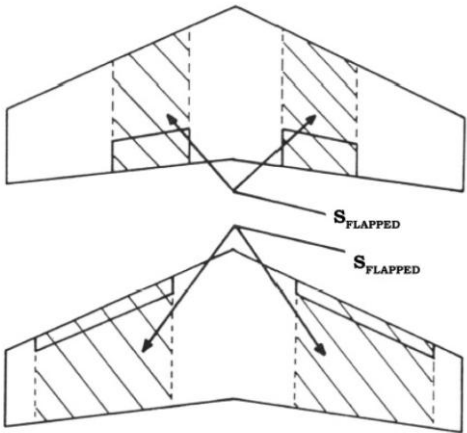


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7	Jetstream 41	Turboprop	Double-slotted	0.35	0.55	24	45



Superficie 'flappata'

# Matching chart – Landing



TLARs and Mission

Matching chart

**Landing**

Equation

**Take-off**

Equation

**Climb**

1<sup>st</sup>, 2<sup>nd</sup> and final segment  
Approach/landing climb

**Cruise**

Equation

**Powertrain architecture**

Serial  
Parallel

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

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

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



# Matching chart – Landing



TLARs and Mission

Matching chart

**Landing**  
Equation

**Take-off**  
Equation

**Climb**  
1<sup>st</sup>, 2<sup>nd</sup> and final segment  
Approach/landing climb

**Cruise**  
Equation

**Powertrain architecture**  
Serial  
Parallel

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

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

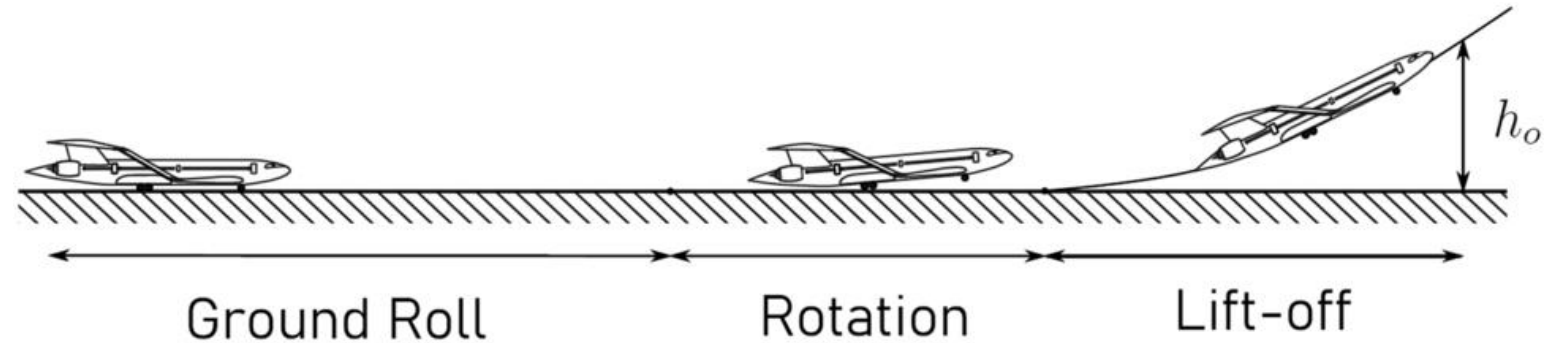
Landing  
Equation

Take-off  
Equation

Climb  
1<sup>st</sup>, 2<sup>nd</sup> and final segment  
Approach/landing climb

Cruise  
Equation

Powertrain architecture  
Serial  
Parallel



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

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

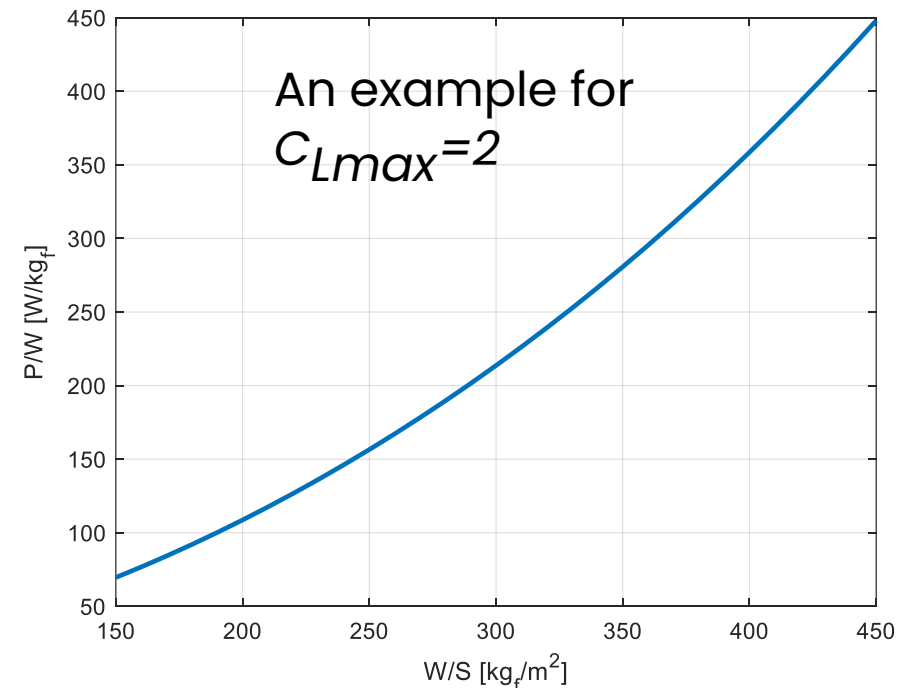
$$a_2 = b_{20} + b_{21} C_{Lmax} + b_{22} C_{Lmax}^2$$

$$b_{10} = 0.2792, b_{11} = -0.03285, b_{12} = -0.007541$$
$$b_{20} = 0.01076, b_{21} = -0.007067, b_{22} = 0.001276$$

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

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

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



# Matching chart – Climb segments



TLARs and Mission

Matching chart

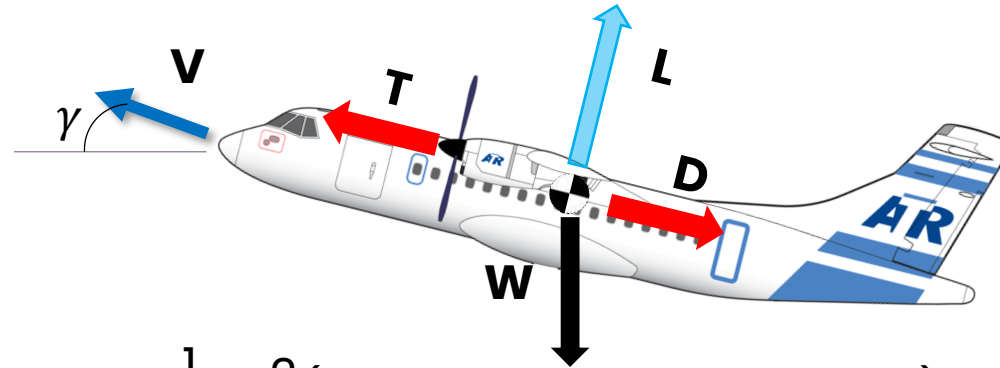
Landing  
Equation

Take-off  
Equation

**Climb**  
1<sup>st</sup>, 2<sup>nd</sup> and final segment  
Approach/landing climb

Cruise  
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**  
1<sup>st</sup>, 2<sup>nd</sup> and final segment  
Approach/landing climb

**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 <sup>st</sup> segment	2 <sup>nd</sup> segment	3 <sup>rd</sup> segment
$\gamma$ – two engines	0%	2.4%	1.2%
$\gamma$ – 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 Equation
- Take-off Equation
- Climb
  - 1<sup>st</sup>, 2<sup>nd</sup> and final segment
  - Approach/landing climb
- Cruise Equation
- Powertrain architecture
  - Serial
  - Parallel

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

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

	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
$\gamma$ – two engines	2.1%	3.2%
$\gamma$ – four engines	2.7%	3.2%



# Matching chart – Cruise



TLARs and Mission

Matching chart

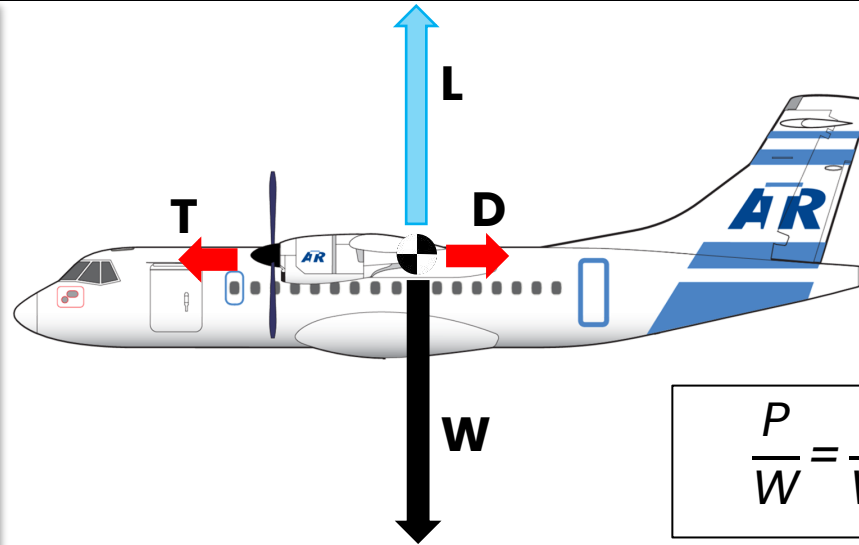
Landing  
Equation

Take-off  
Equation

Climb  
1<sup>st</sup>, 2<sup>nd</sup> and final segment  
Approach/landing climb

Cruise  
Equation

Powertrain architecture  
Serial  
Parallel

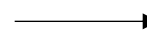


Thrust must equilibrate the aircraft drag ( $\gamma = 0^\circ$ ). The aircraft thrust, calculated at cruise altitude, has to be assessed at sea level

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



$$\left\{ \begin{array}{l} \frac{P_{CR}}{W} = \frac{1}{\eta_p} \frac{\rho V^2 C_{D0}}{W/S} + \frac{1}{\eta_p} \frac{k}{\frac{1}{2} \rho_{CR} V} \frac{W}{S} \\ \left( \frac{P_{CR}}{W} \right) = \left( \frac{P}{W} \right)_{SL} \left( \frac{\rho}{\rho_{SL}} \right)^{0.75} \end{array} \right.$$



$$\left( \frac{P}{W} \right)_{SL} = \frac{\frac{1}{\eta_p} \frac{\rho V^2 C_{D0}}{W/S} + \frac{1}{\eta_p} \frac{k}{\frac{1}{2} \rho_{CR} V} \frac{W}{S}}{\left( \frac{\rho}{\rho_{SL}} \right)^{0.75}}$$

# Matching chart



TLARs and Mission

Matching chart

Landing  
Equation

Take-off  
Equation

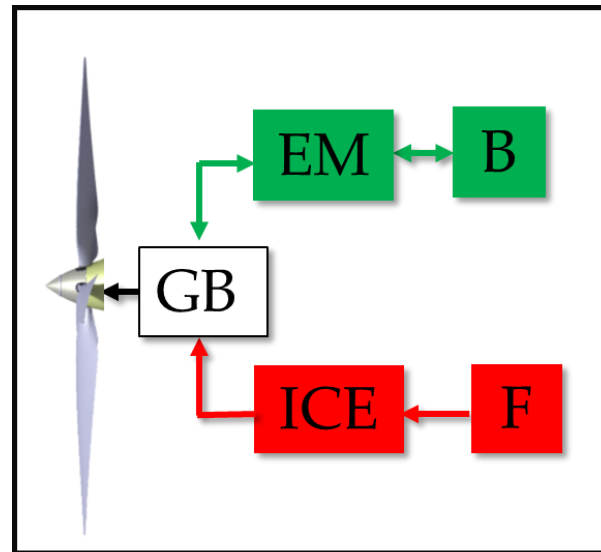
Climb  
1<sup>st</sup>, 2<sup>nd</sup> and final segment  
Approach/landing climb

Cruise  
Equation

**Powertrain architecture**

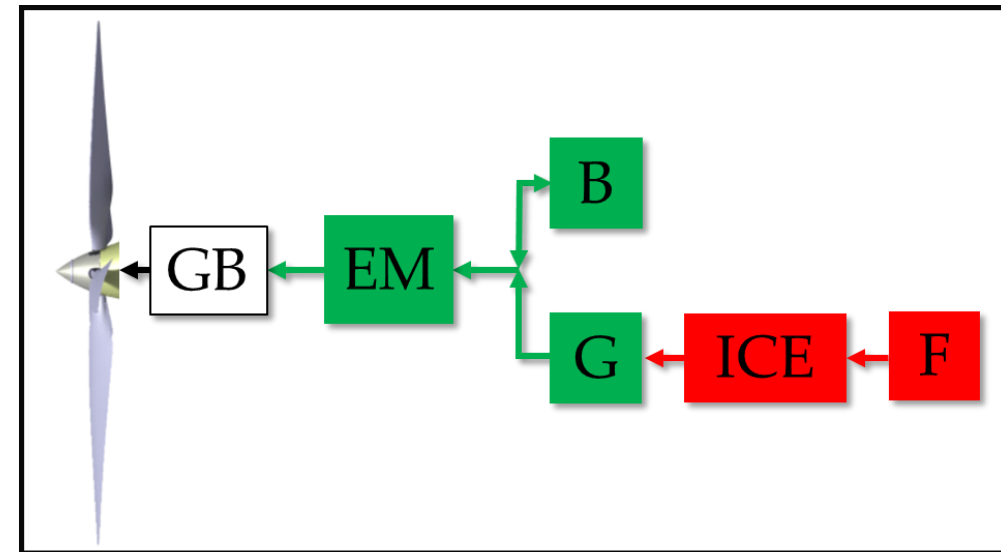
Serial  
Parallel

**Parallel**

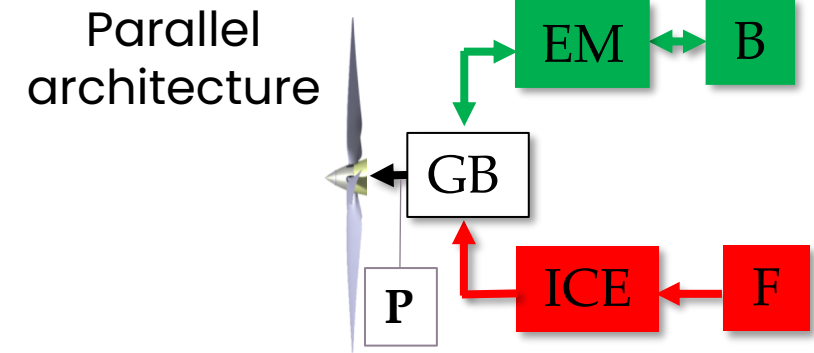
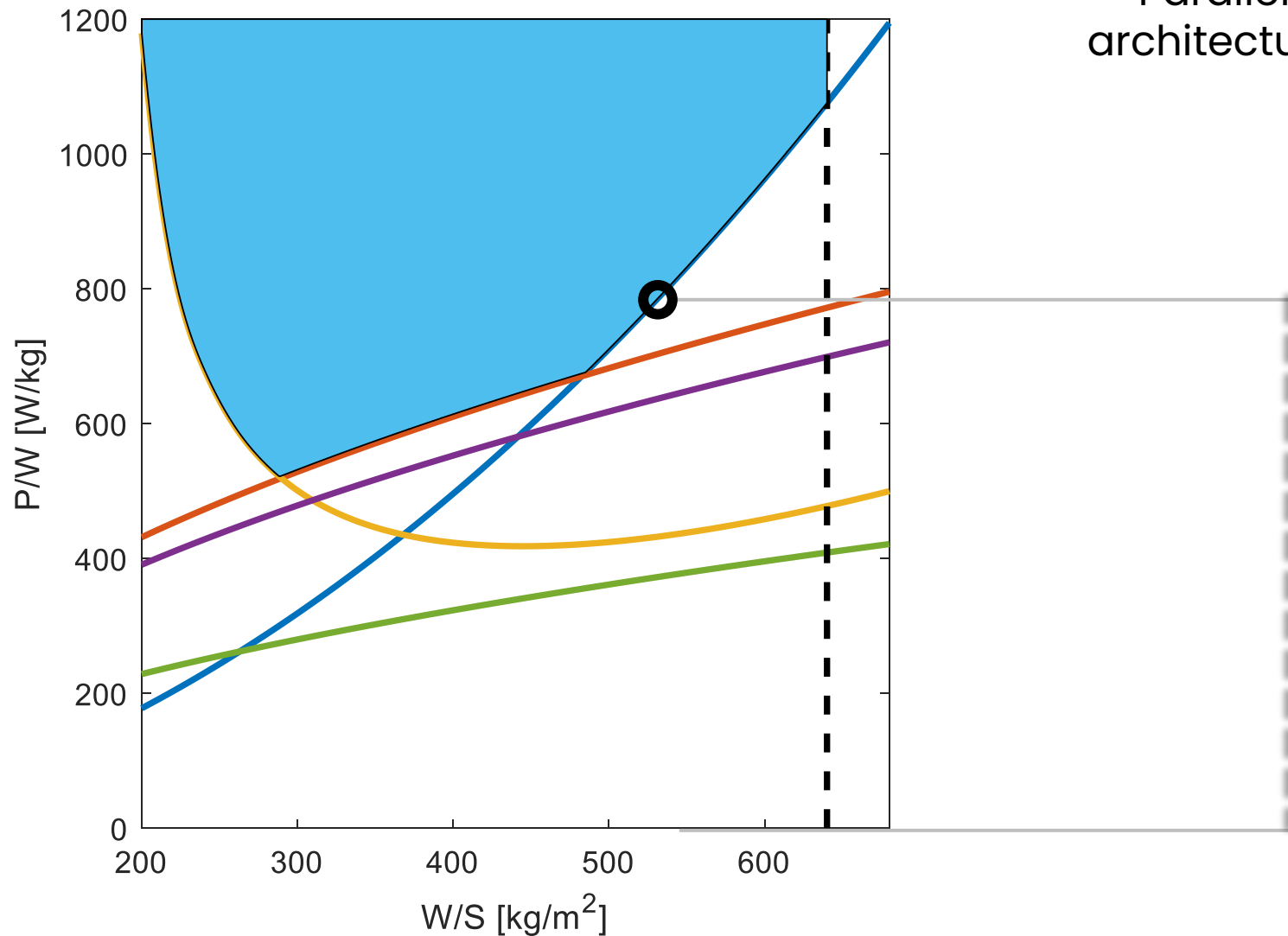
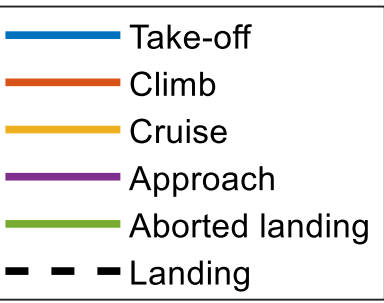


**vs**

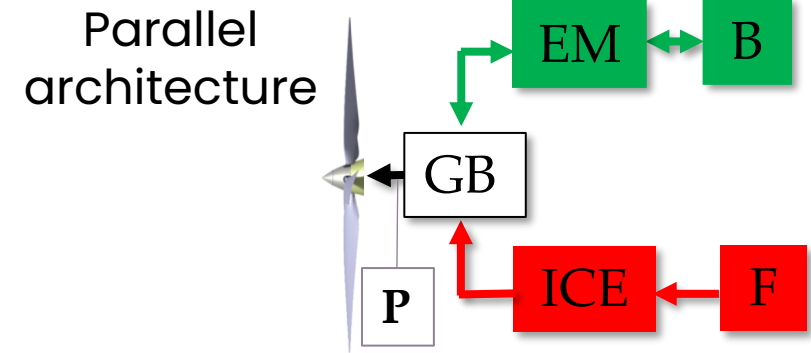
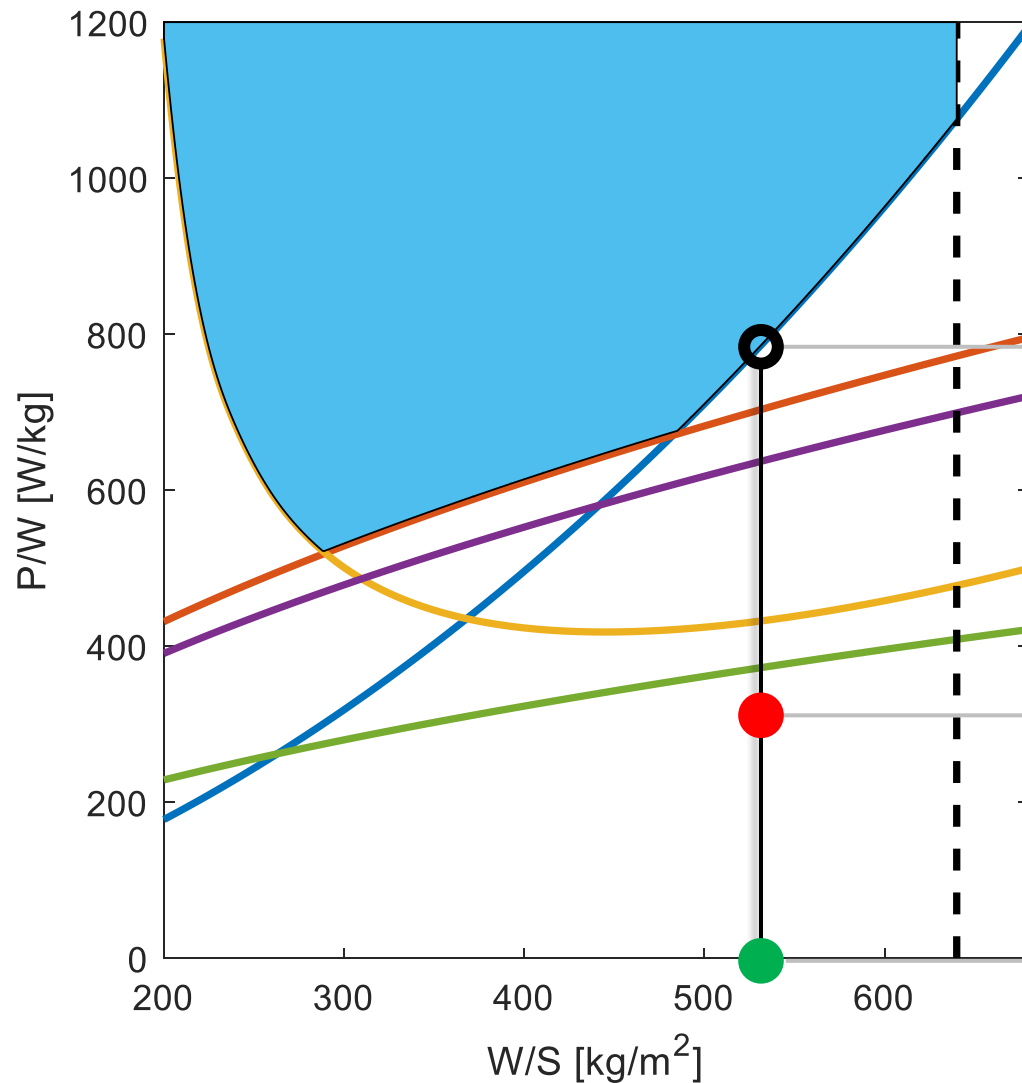
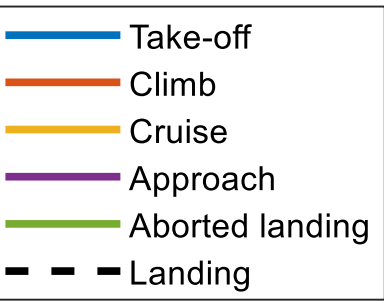
**Serial**



# HEA - Powertrain sizing: Parallel



# HEA - Powertrain sizing: Parallel

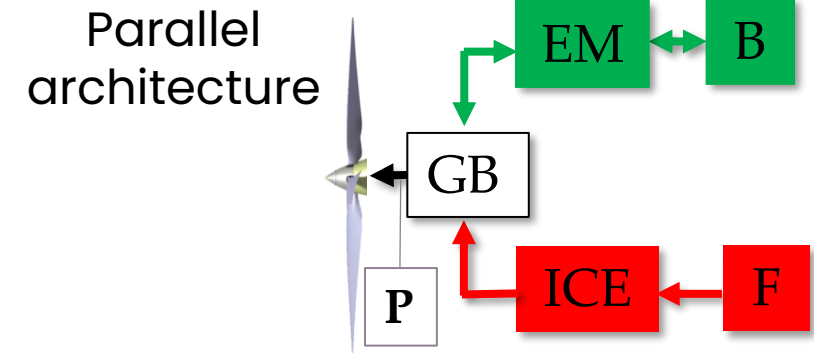
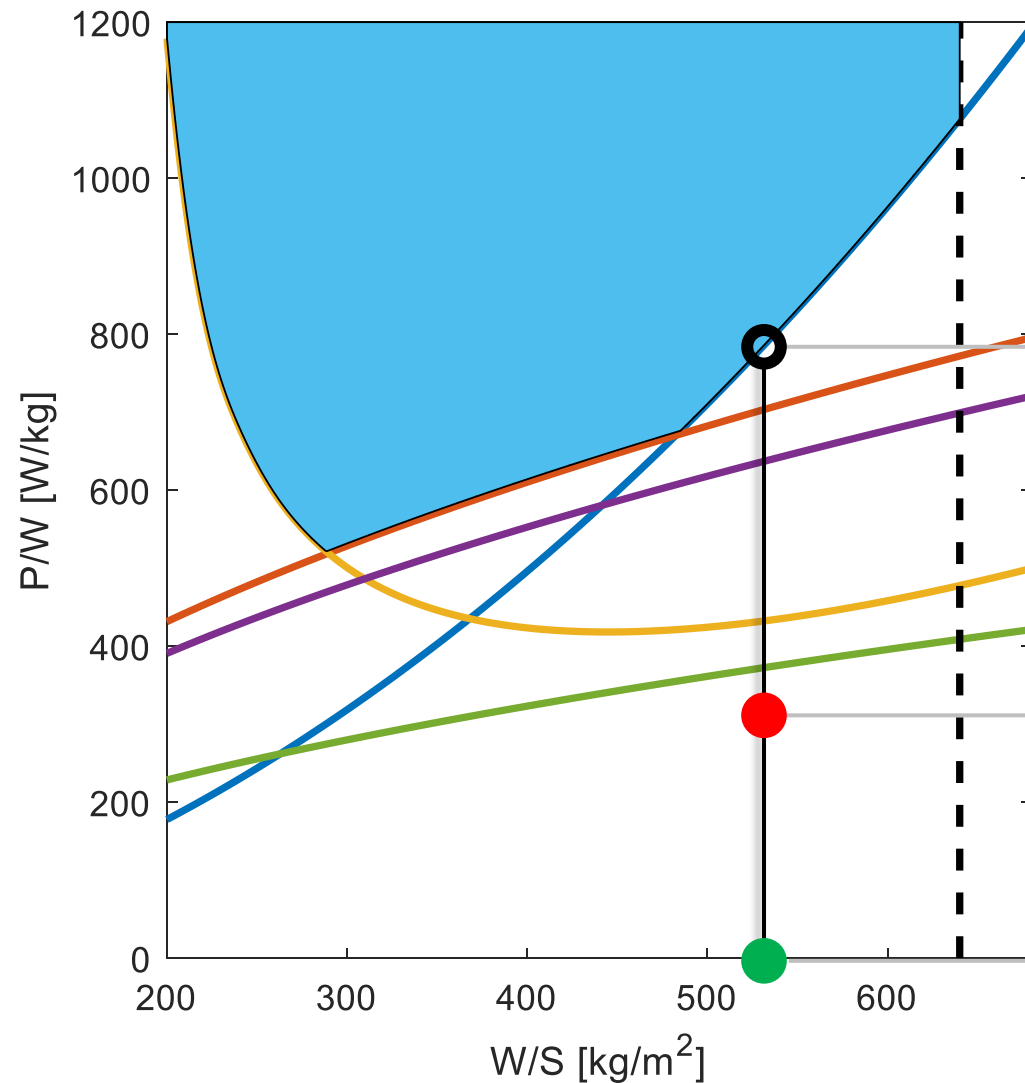
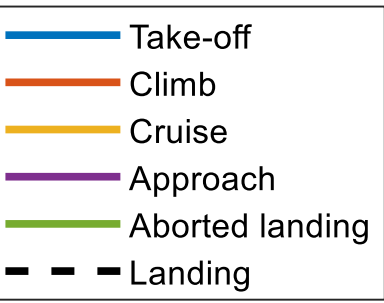


$P_{\text{thermal}}$

$P_{\text{electrical}}$

$P$

# HEA - Powertrain sizing: Parallel



$P_{\text{electrical}}$

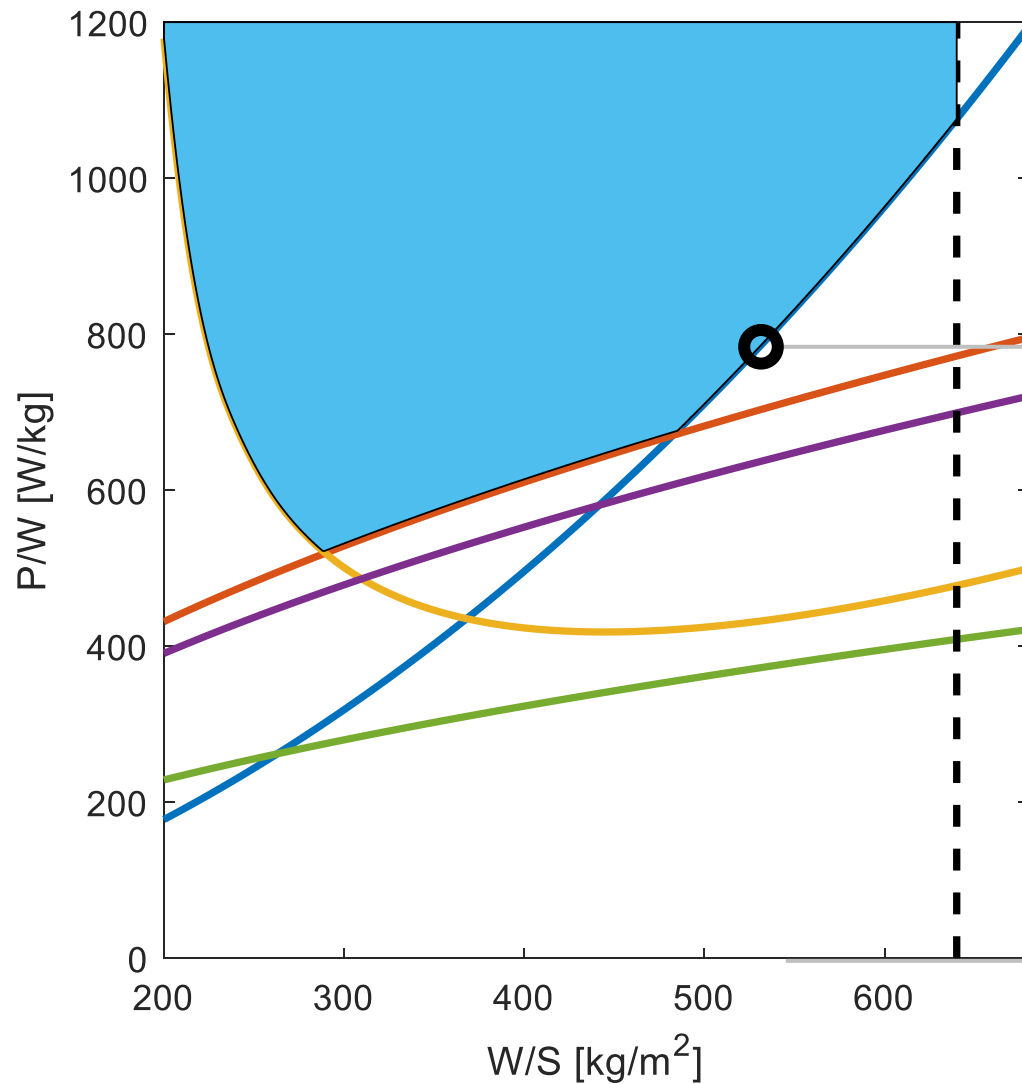
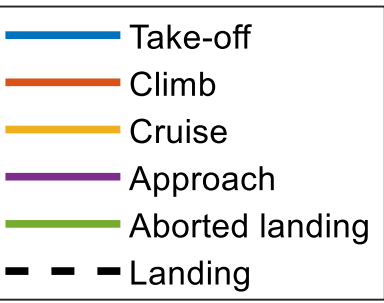
$P_{\text{thermal}}$

$P$

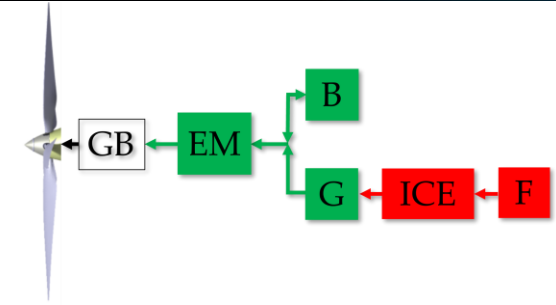
$P_{\text{inst}} = P$



# HEA - Powertrain sizing: Serial

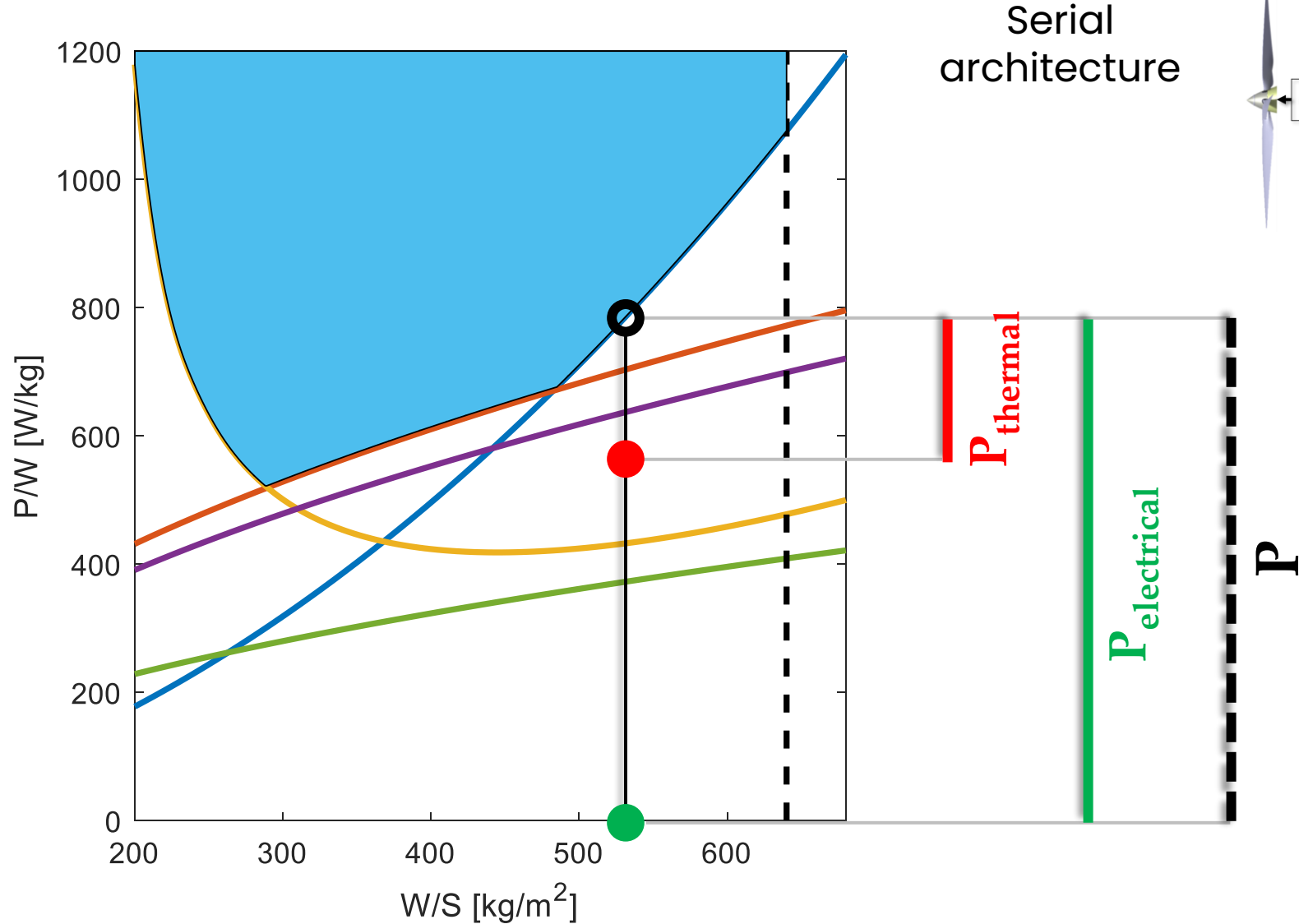
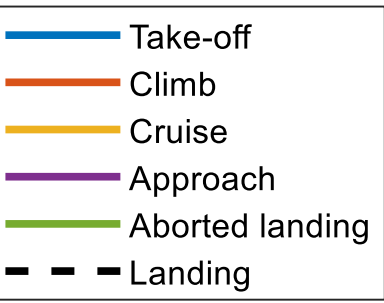


Serial architecture

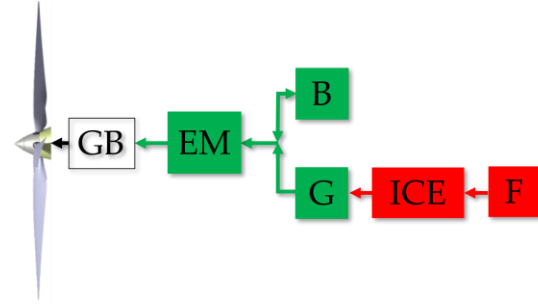


P

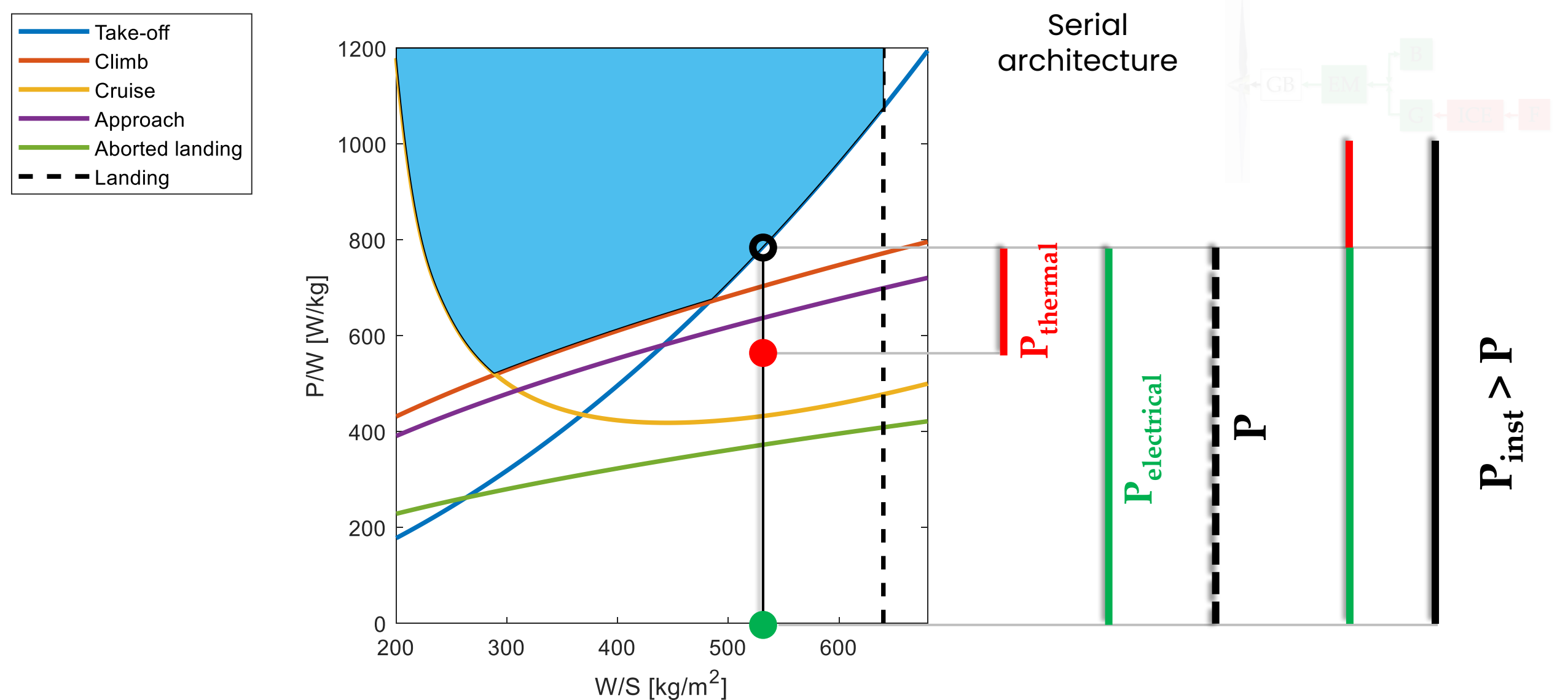
# HEA - Powertrain sizing: Serial



Serial architecture



# HEA - Powertrain sizing: Serial





**End**