



Politecnico
di Torino



Progettazione di veicoli
aerospaziali (AA-LZ)

E1. Conceptual Design of
subsonic commercial
aircraft

10. **Hybrid-electric aircraft**

Karim Abu Salem
karim.abusalem@polito.it

Giuseppe Palaia
giuseppe.palaia@polito.it



Hybrid-electric aircraft

Hybrid-electric aircraft

Battery

Definition and data

Electric motor

Definition and data

Power electronics

Definition and data

Powertrain architecture

Serial

Turbo-electric

Parallel

Serial/Parallel

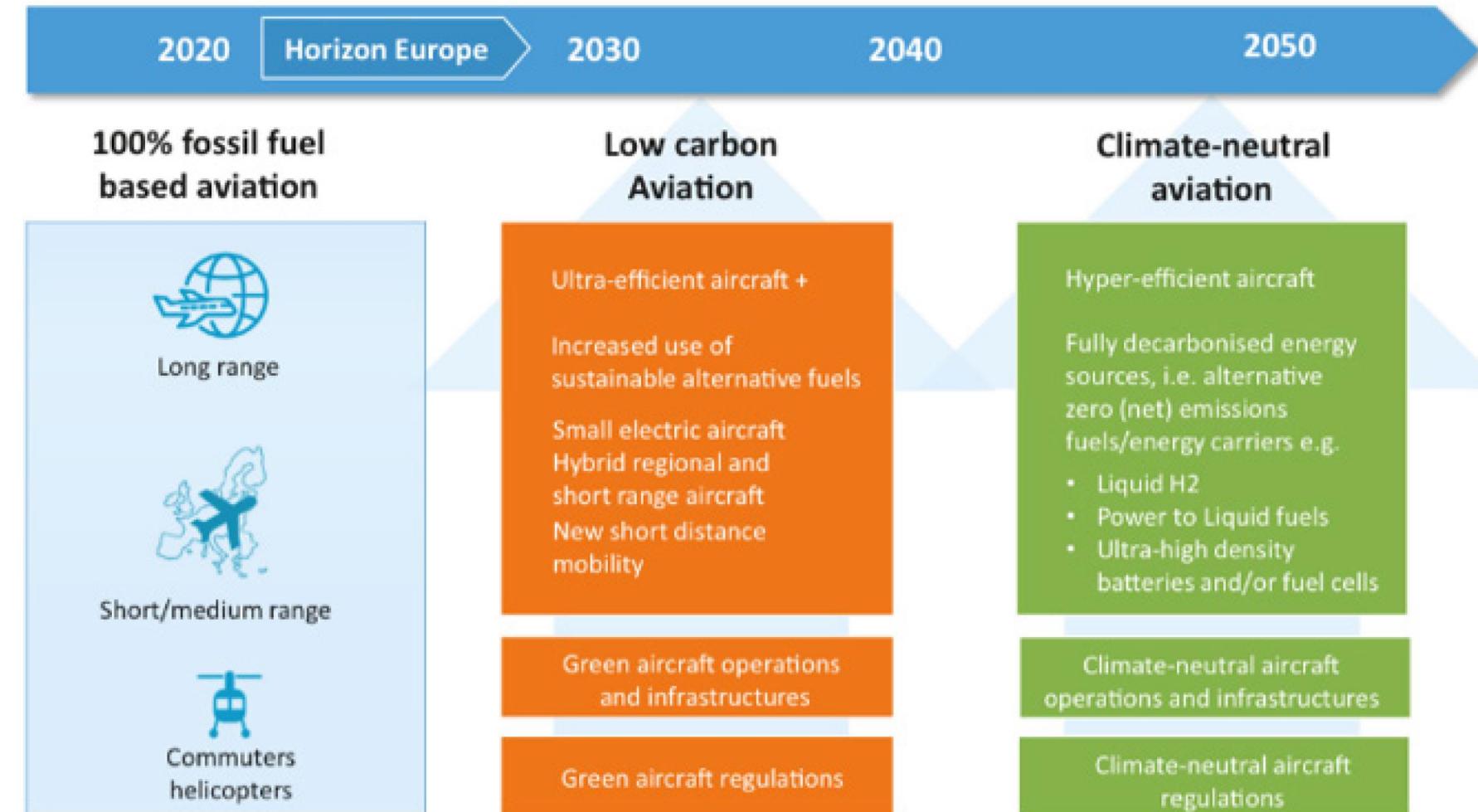
How to design HEA

Battery

Electric motor

Power management

"The next generation of disruptive aircraft offering 30 to 50% lower fuel burn and emissions compared to 2020 aircraft"





Hybrid-electric aircraft

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How to design HEA

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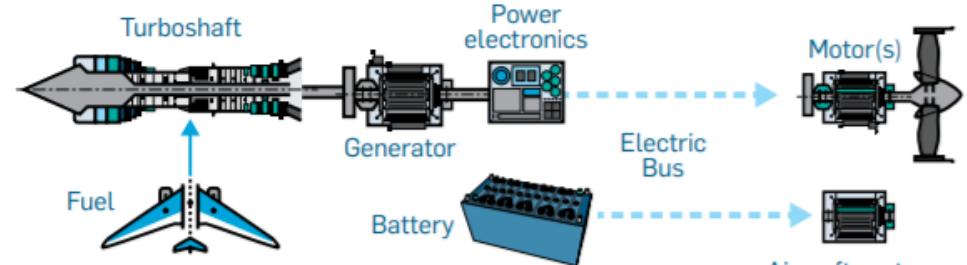
Power management

The **MEA** concept provides for the utilization of **electric power for all non-propulsive systems.**

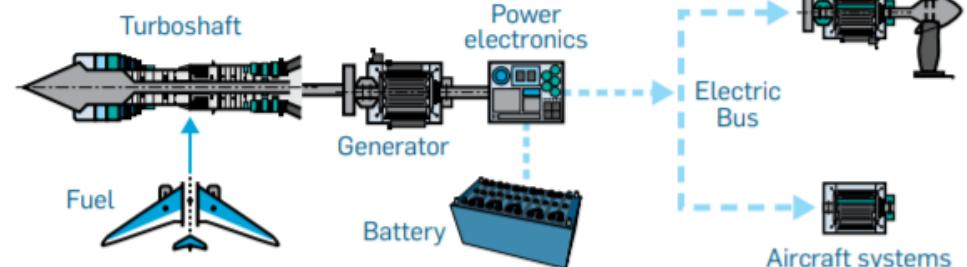
Traditionally these non-propulsive systems are driven by a combination of different secondary power sources such as hydraulic, pneumatic, mechanical and electrical.

The **Hybrid Electric** term refers to the use of electric components to generate power for the **propulsion system**

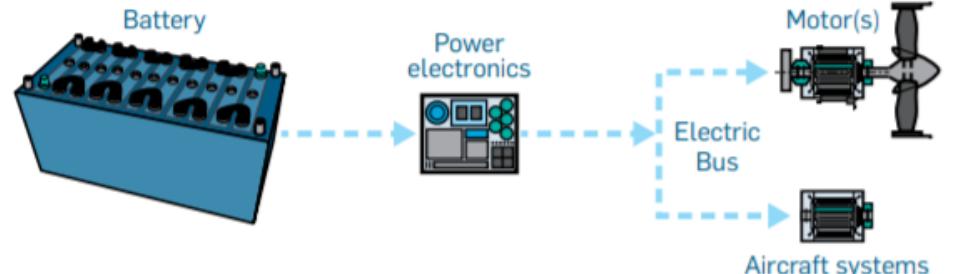
MORE ELECTRIC HYBRID



FULL HYBRID



ALL ELECTRIC





Hybrid-electric aircraft

Hybrid-electric aircraft

S: ha sempre una parte termica e una elettrica

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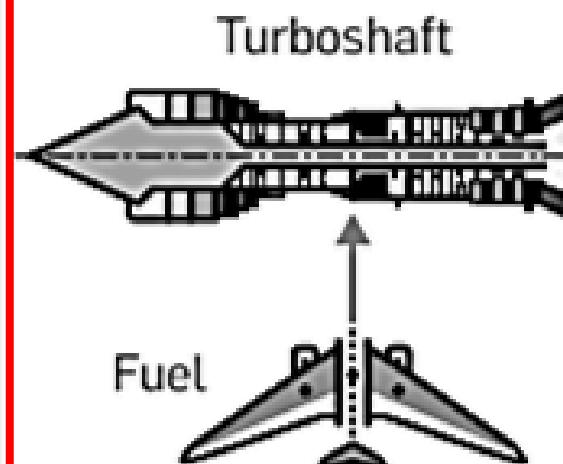
How to design HEA

Battery

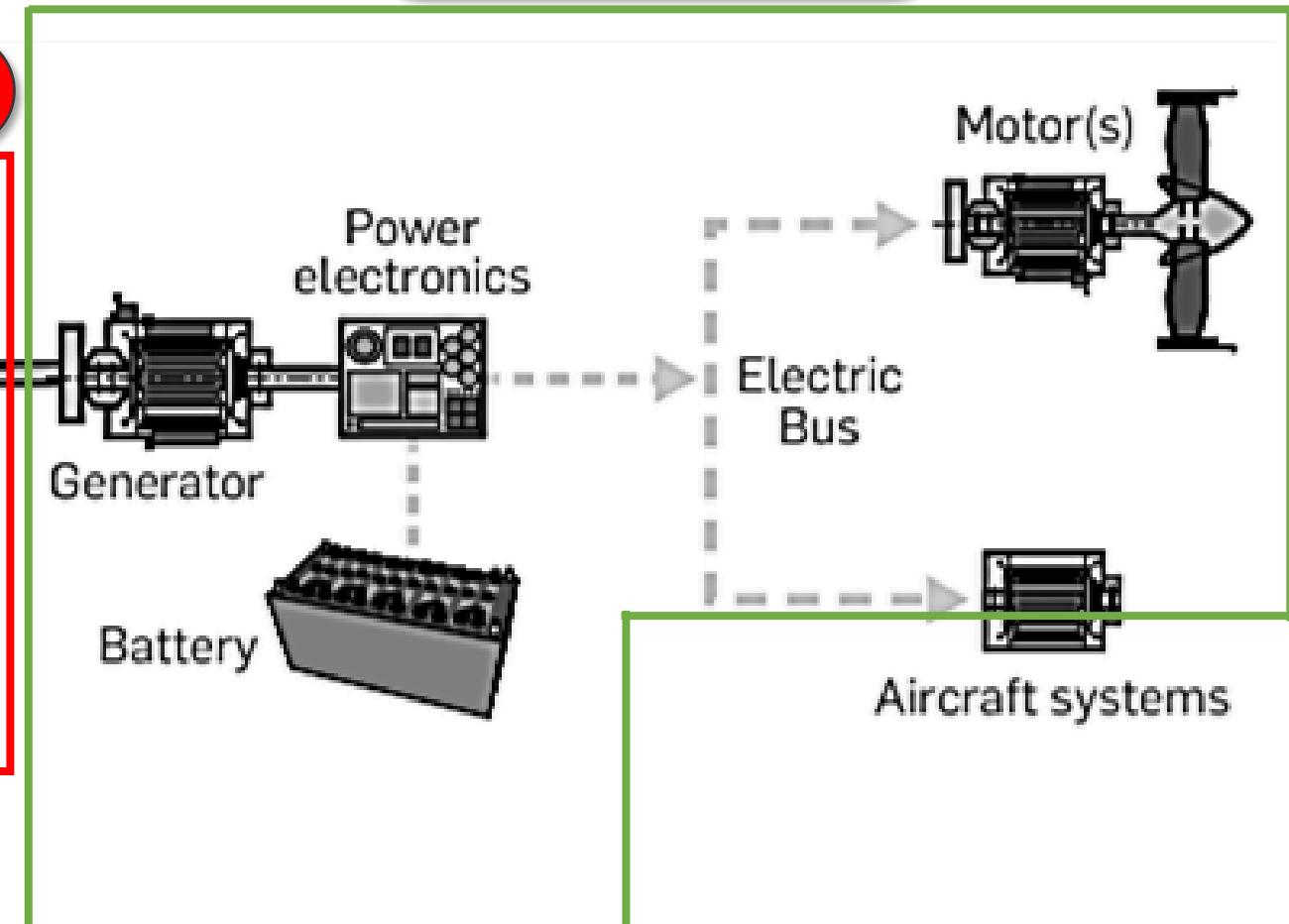
Electric motor

Power management

Thermal Chain



Electric Chain





Hybrid-electric aircraft

Hybrid-electric aircraft

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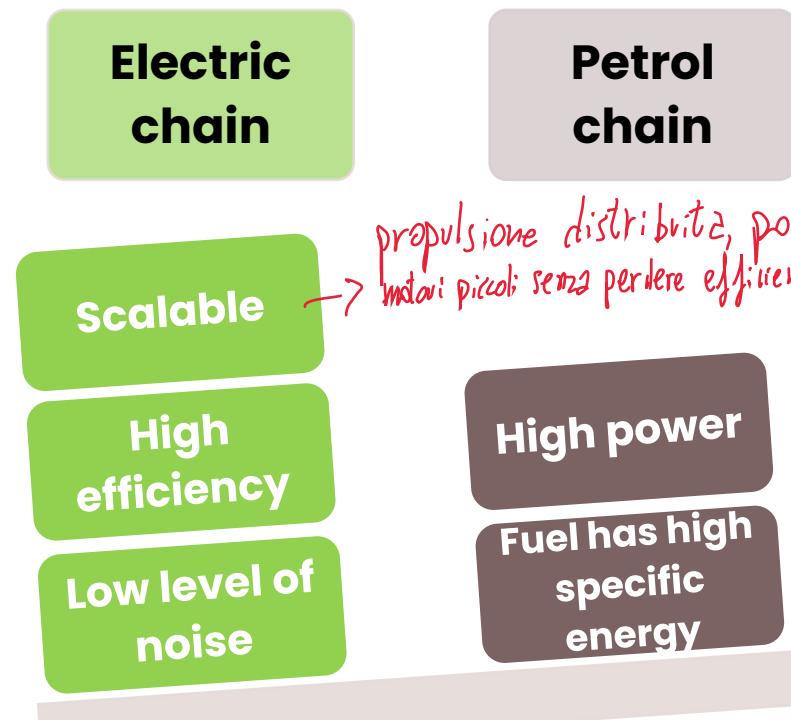
How to design HEA

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Power management

Electric chain vs thermal chain



Combustion engine

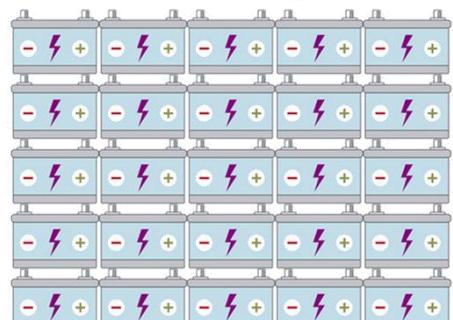


\approx

1 kg fuel

Currently

Electric engine



80 kg of batteries



Battery

Hybrid-electric aircraft

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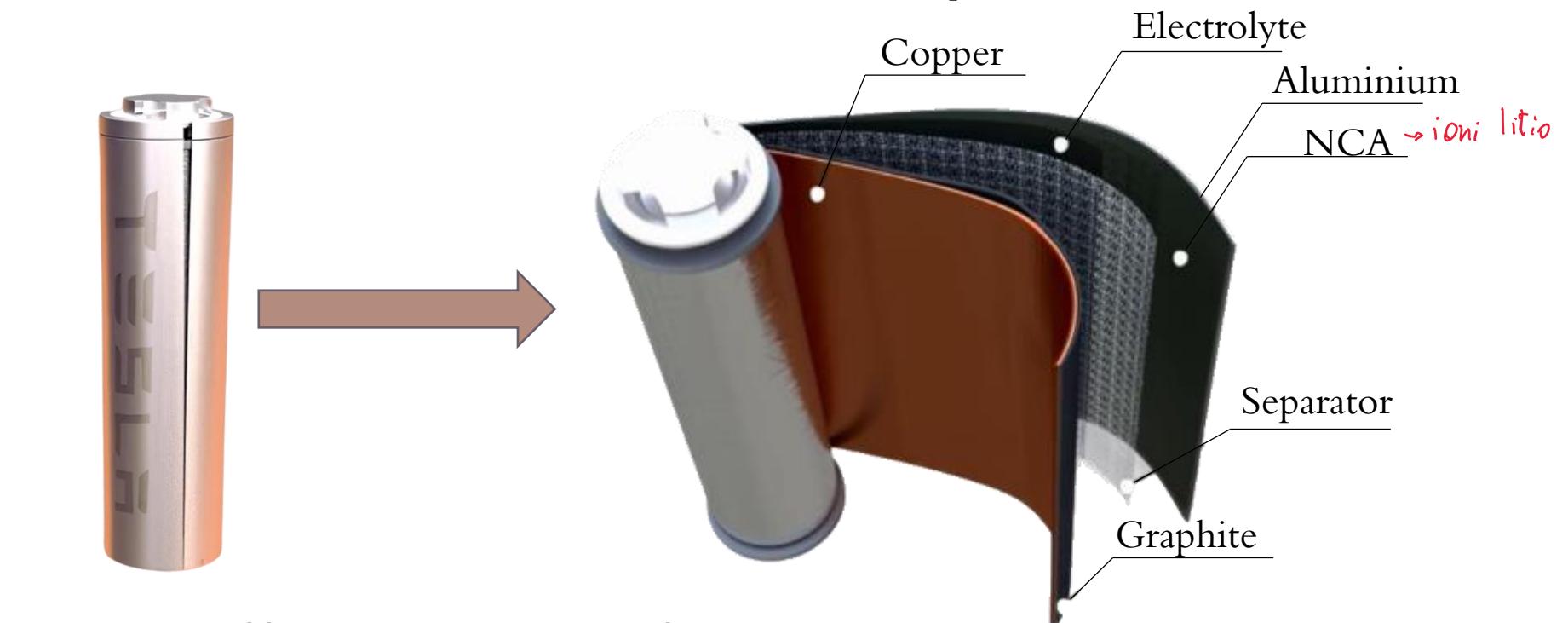
Battery

Electric motor

Power management

A battery is a practical electrical energy storage device consisting of one or more cells connected in series and/or parallel in order to provide desired output voltage, capacity, and power.

Lithium-ion battery



<https://www.youtube.com/watch?v=VxMM4g2Sk8U&t=339s>
<https://www.youtube.com/watch?v=9fCRWOa9gQk>



Battery

Hybrid-electric aircraft

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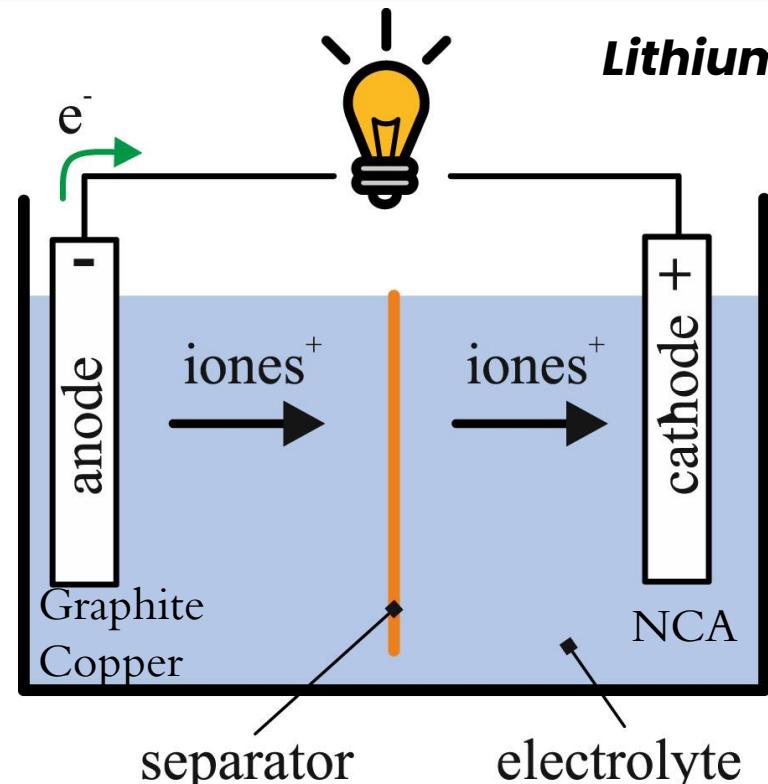
How to design HEA

Battery

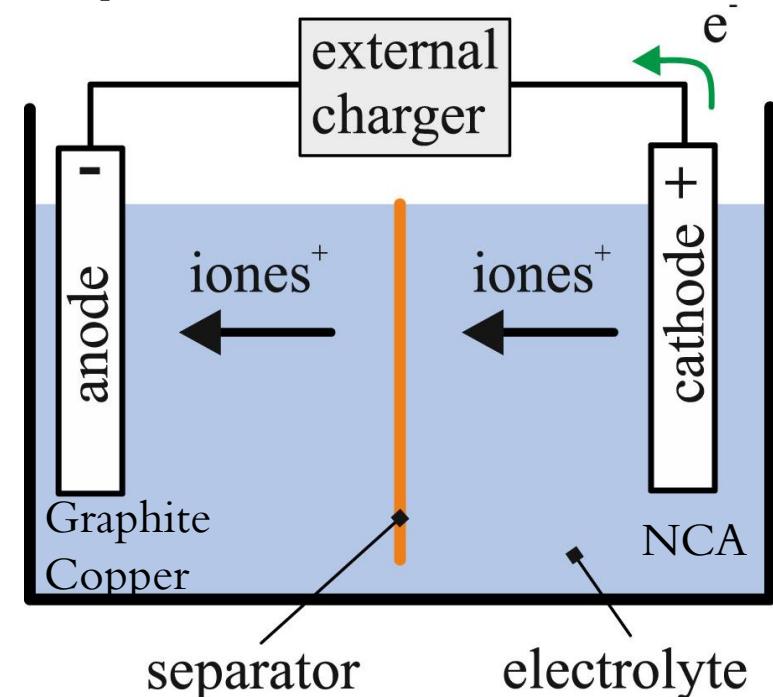
Electric motor

Power management

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(a) Discharging.



(b) Charging.



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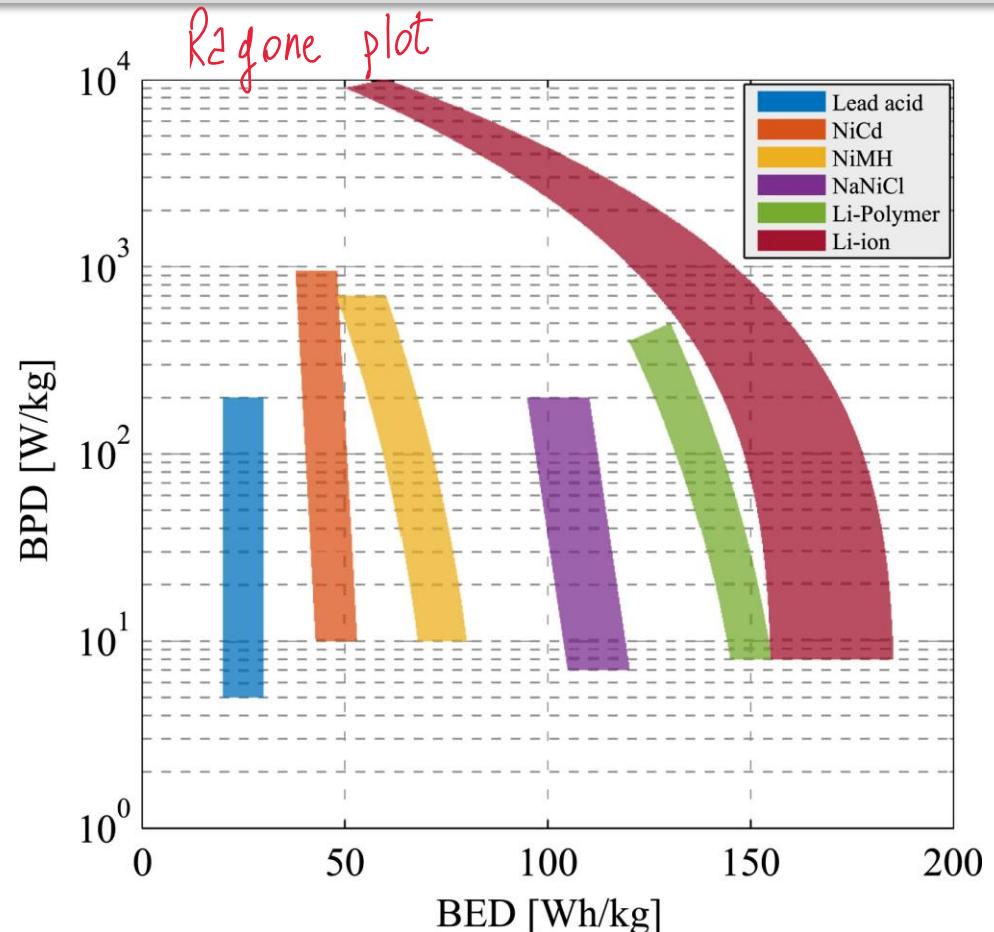
Electric motor

Power management

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Battery Power Density (BPD) is the ratio between the maximum power (measured in voltage) which can be supplied by the battery and the battery weight

Battery Energy Density (BED) is the ration between the energy (measured in kWh) stored in the battery and the battery weight





Battery

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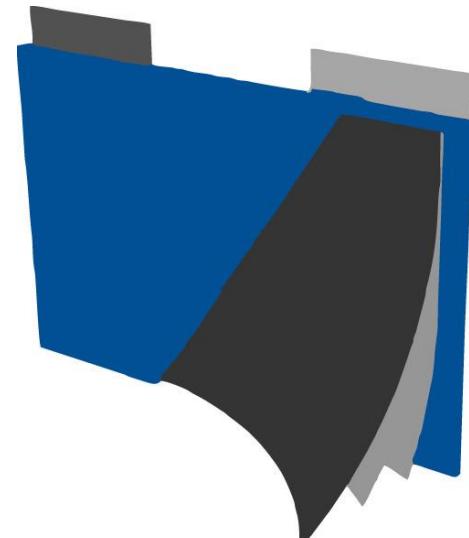
Battery

Electric motor

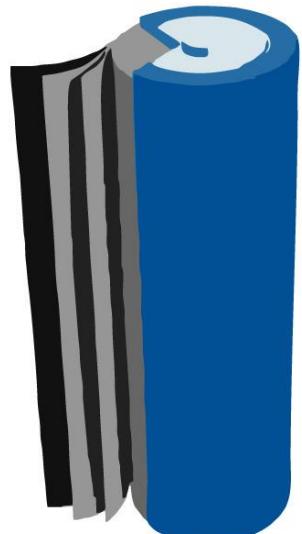
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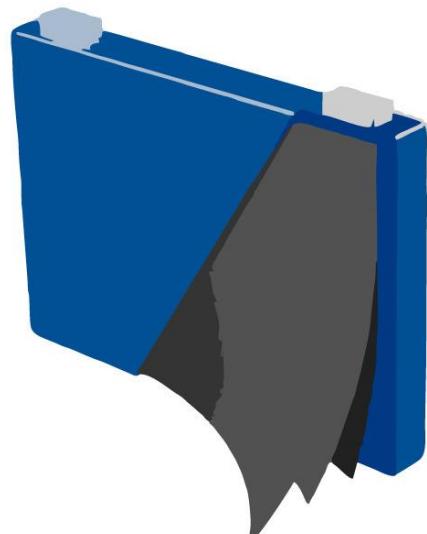
The shape of the single cell



(a) Pouch.



(b) Cylindrical.



(c) Prismatic.



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From the cell to the battery pack



Single module



Battery pack





Battery

Hybrid-electric aircraft

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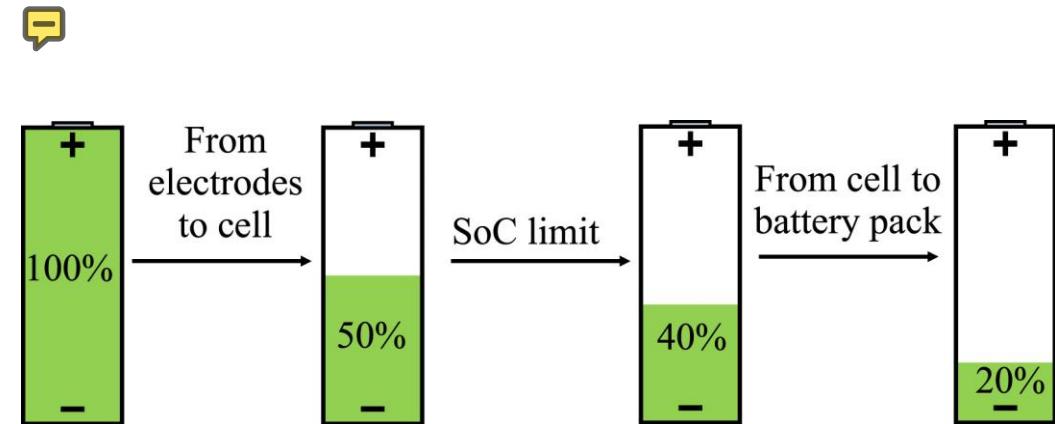
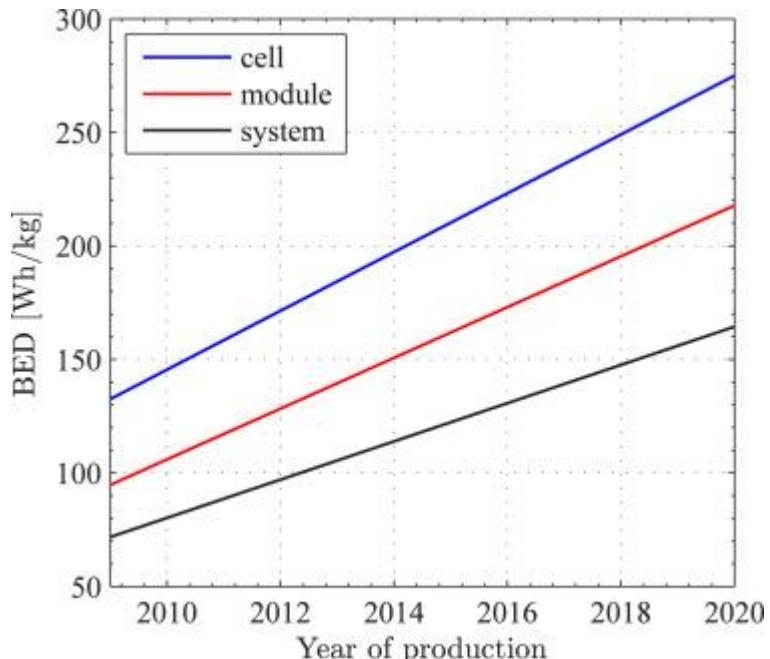
How to design HEA

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Electric motor

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Löbberding H., et al. From cell to battery system in BEVs: Analysis of system packing efficiency and cell types



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BED values (in Wh/kg) projection for Li-S and Li-O₂ battery.

Type	Forecast 2030		Forecast 2050	
	Cell	Battery pack	Cell	Battery pack
Li-S	500–650	385–500	800–950	652–775
Li-O ₂	600–750	426–533	1200–1400	942–1100



Abu Salem K., et al. Review of hybrid-electric aircraft technologies and designs: Critical analysis and novel solutions



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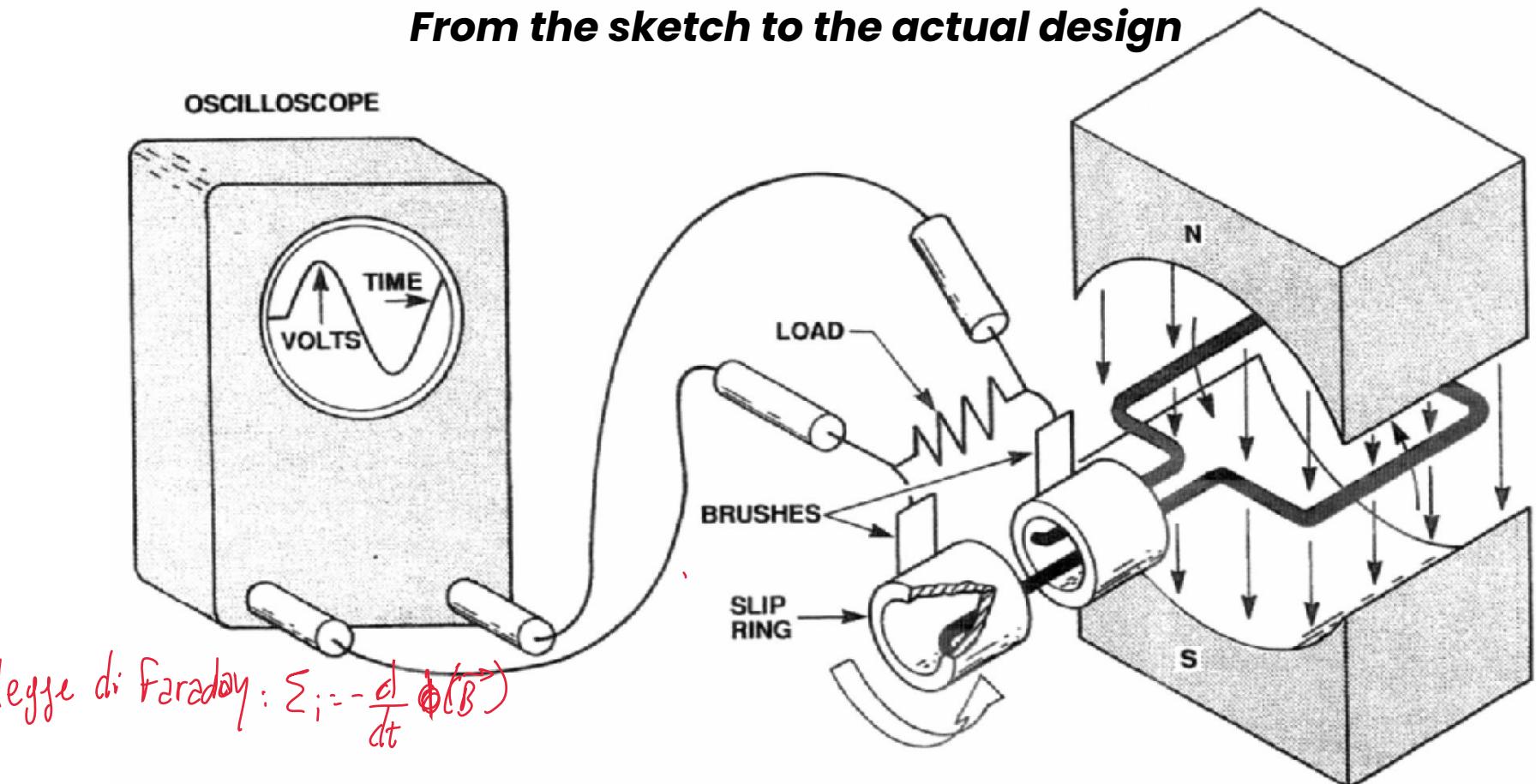
Battery

Electric motor

Power management

Electric machines are devices which convert electric power into mechanical power (electric motors) and vice versa (generators)

From the sketch to the actual design



$$\text{legge di Faraday: } \Sigma i = -\frac{d\Phi}{dt}$$



Electric motor

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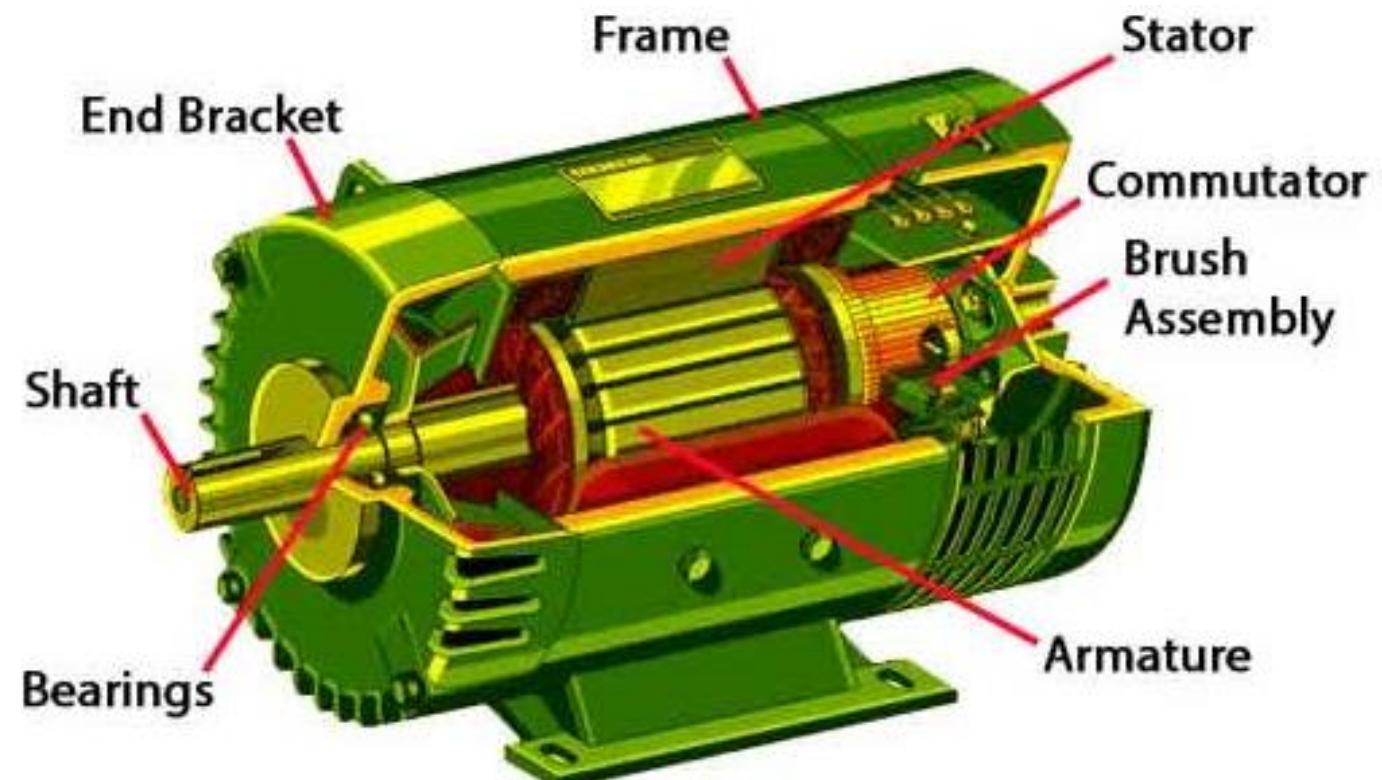
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Hybrid-electric aircraft

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Electric motor vs thermal engine

Higher Efficiency

Electric motors typically convert over 90% of electrical energy into mechanical energy, while thermal engines have efficiencies often below 40%

The efficiency of an electric motor (η) is calculated as the ratio of its mechanical power output (P_{out}) to its electrical power input (P_{in}):

$$\eta = \frac{P_{out}}{P_{in}} = \frac{T\Omega}{VI}$$

T = shaft torque, Ω = shaft angular speed
 V = Voltage, I = current



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Electric motor vs thermal engine

Higher Efficiency

Electric motors typically convert over 90% of electrical energy into mechanical energy, while thermal engines have efficiencies often below 40%

Reduced Emissions

Electric motors produce zero emissions, contributing to cleaner air

Lower Noise Levels

Electric motors operate much more quietly than thermal engines, reducing noise pollution

Scalability

Electric motor performance does not depend on motor size



Electric motor

Hybrid-electric aircraft

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Electric motor vs thermal engine

Simpler Maintenance

Electric motors have fewer components, which generally leads to lower maintenance needs and costs compared to the complex systems in thermal engines.

Regenerative Braking

Electric motors can recover energy during braking, converting it back into electrical energy to recharge batteries

Environmental Impact

Electric motors can be powered by renewable energy sources (like solar or wind), reducing reliance on fossil fuels



Electric motor

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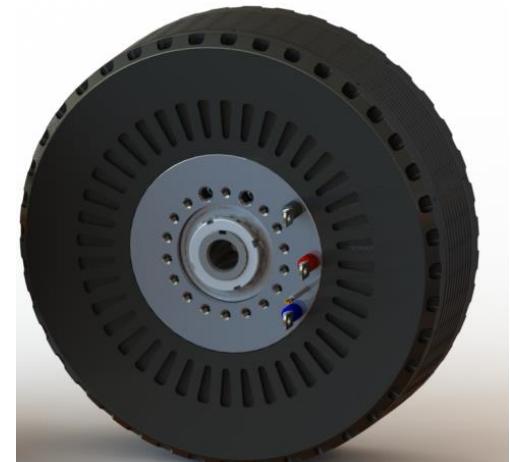
Electric motor

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A real electric motor for aviation: EMRAX 348

Mechanical		Electrical	
Type:	Axial flux motor / generator	Maximal battery voltage:	830 (HV) / 830 (MV) / 610 (LV)Vdc
Casing diameter:	348 mm	Peak power (at 3250 RPM):	340 kW
Axial length:	107 mm	Continuous power*:	up to 140 kW
Dry mass:	43,1 kg (AC) / 43,5 kg (CC) / 43,9 kg (LC)	Peak torque:	1100 Nm
		Continuous torque*:	up to 425 Nm
		Efficiency:	92-98%



<https://emrax.com/e-motors/emrax-348/>



Electric motor

Hybrid-electric aircraft

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Electric motor

Hybrid-electric aircraft

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How to design HEA

Battery

Electric motor

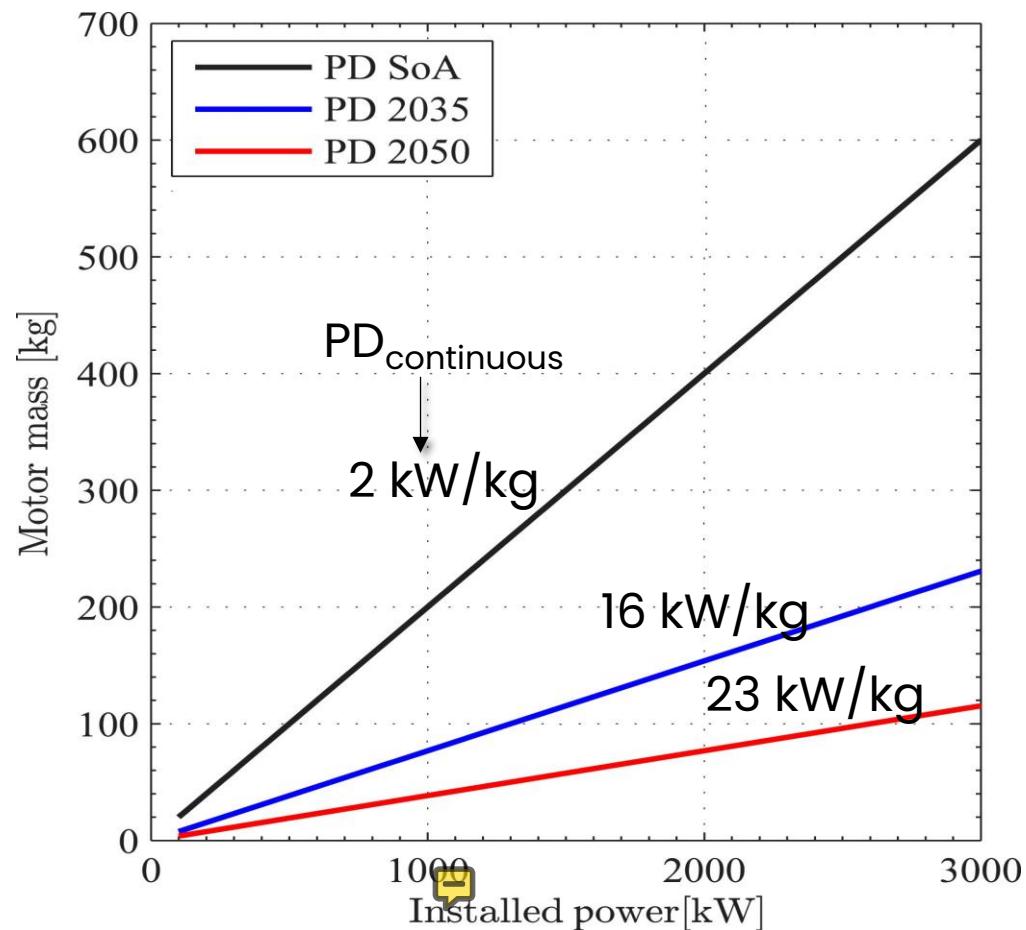
Power management

Electric machines are devices which convert electric power into mechanical power (electric motors) and vice versa (generators)

An important parameter is the **power density (PD)**

$PD_{continuous}$ is the ratio between the maximum continuous power and the electric motor weight

PD_{peak} is the ratio between the peak power and the electric motor weight





Electric motor

Hybrid-electric aircraft

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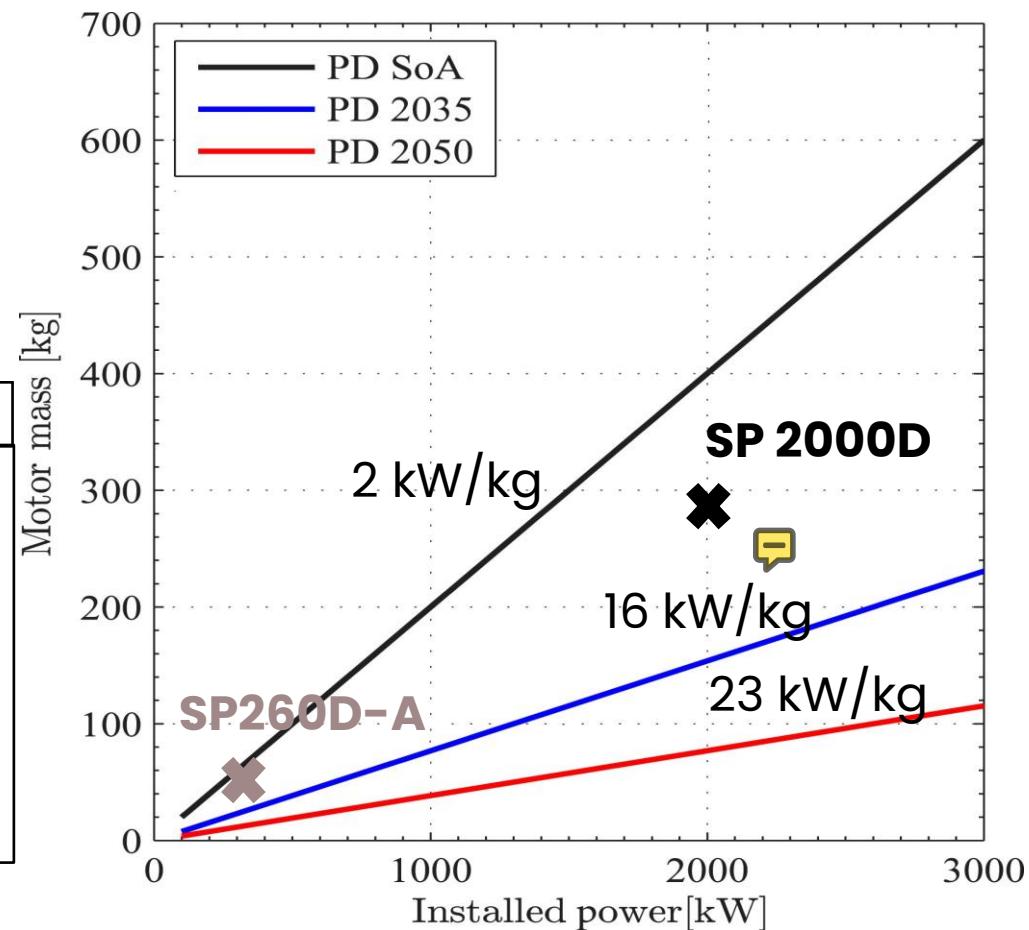
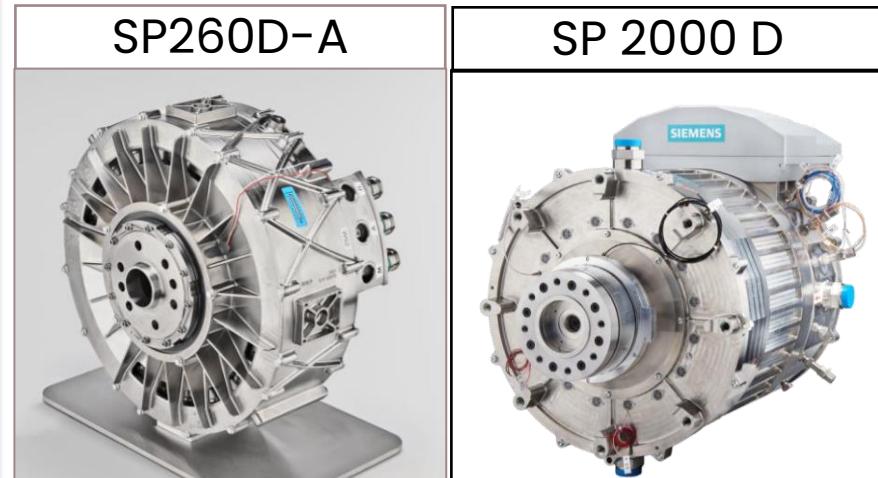
Battery

Electric motor

Power management

Electric machines are devices which convert electric power into mechanical power (electric motors) and vice versa (generators)

Current electric motor under development





Electric motor

Hybrid-electric aircraft

Electric machines are devices which convert electric power into mechanical power (electric motors) and vice versa (generators)

Battery

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Power management

the main goals in terms of PD have been defined by NASA:

- within 2035 a $PD=16\text{ kW/kg}$, and within 2050 a $PD = 23 \text{ KW/kg}$ is expected
- efficiency should be higher than 96%



Power electronics

Hybrid-electric aircraft

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Power electronics
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Serial/Parallel

How to design HEA
Battery
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Power management

The term power electronics refers to the electrical components which drive motors (e.g. inverters) and distribute power (e.g. circuit protection).

Necessary to manage high level of power

At high power levels, large amounts of waste heat are generated with even highly-efficient conventional electronics.

A half-megawatt motor operating produces as much waste heat as a barbecue grill

Superconducting motor/generators, power electronics, and conductors have been proposed as a way to raise efficiency

but introduce a different problem...

keeping high-temperature superconducting (HTS) materials sufficiently cold compared to the ambient temperature.



Power electronics

Hybrid-electric aircraft

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Power electronics

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How to design HEA

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Power management

The term power electronics refers to the electrical components which drive motors (e.g. inverters) and distribute power (e.g. circuit protection).

Prediction in terms of PD and efficiency have been defined by NASA:
within 2035 a $PD=19\text{kW/kg}$ and efficiency higher than 98% are expected,
while within 2050 a $PD=25\text{kW/kg}$ and efficiency higher than 99% are
expected



Powertrain architecture

Hybrid-electric aircraft

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Power electronics

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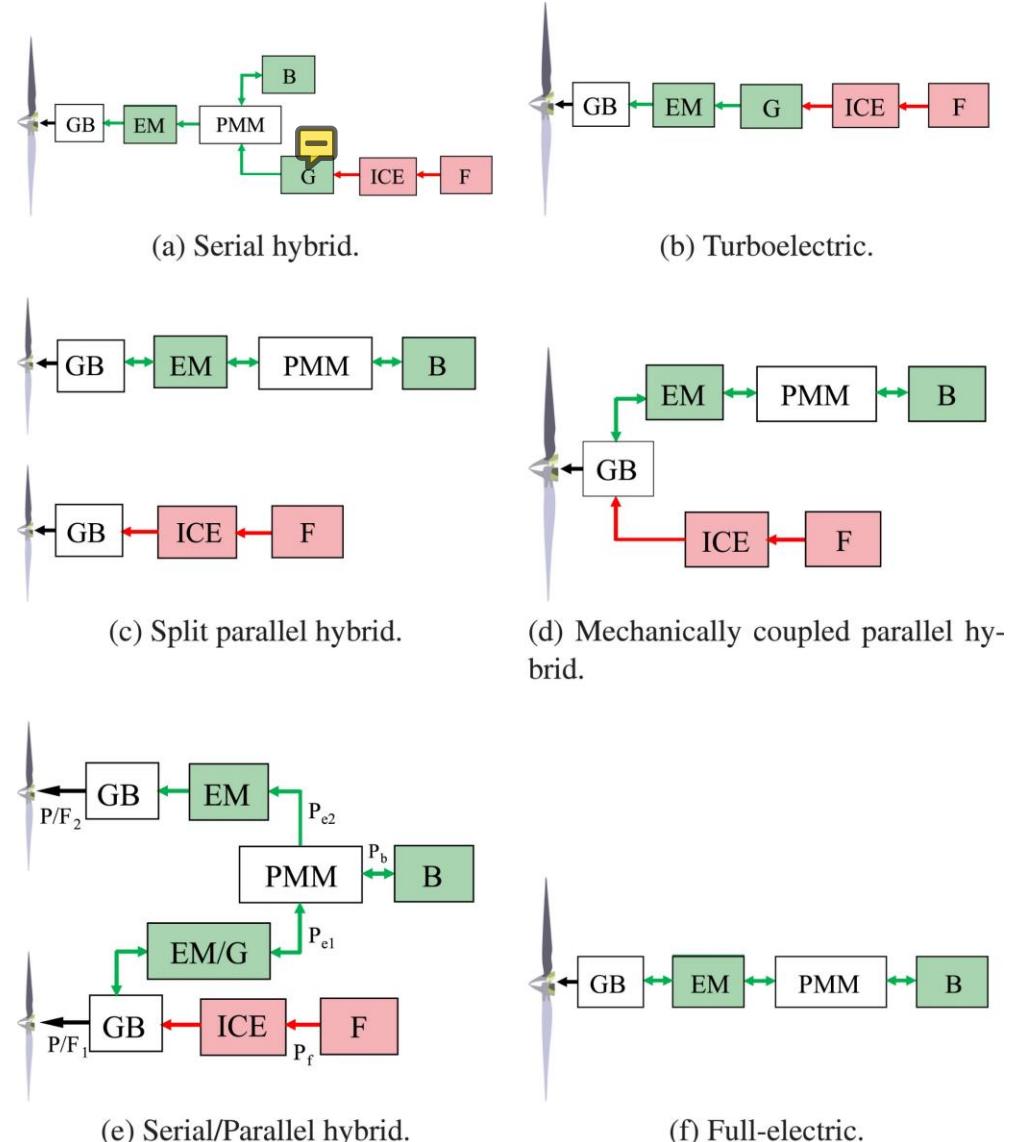
Serial/Parallel

How to design HEA

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Power management





Powertrain architecture

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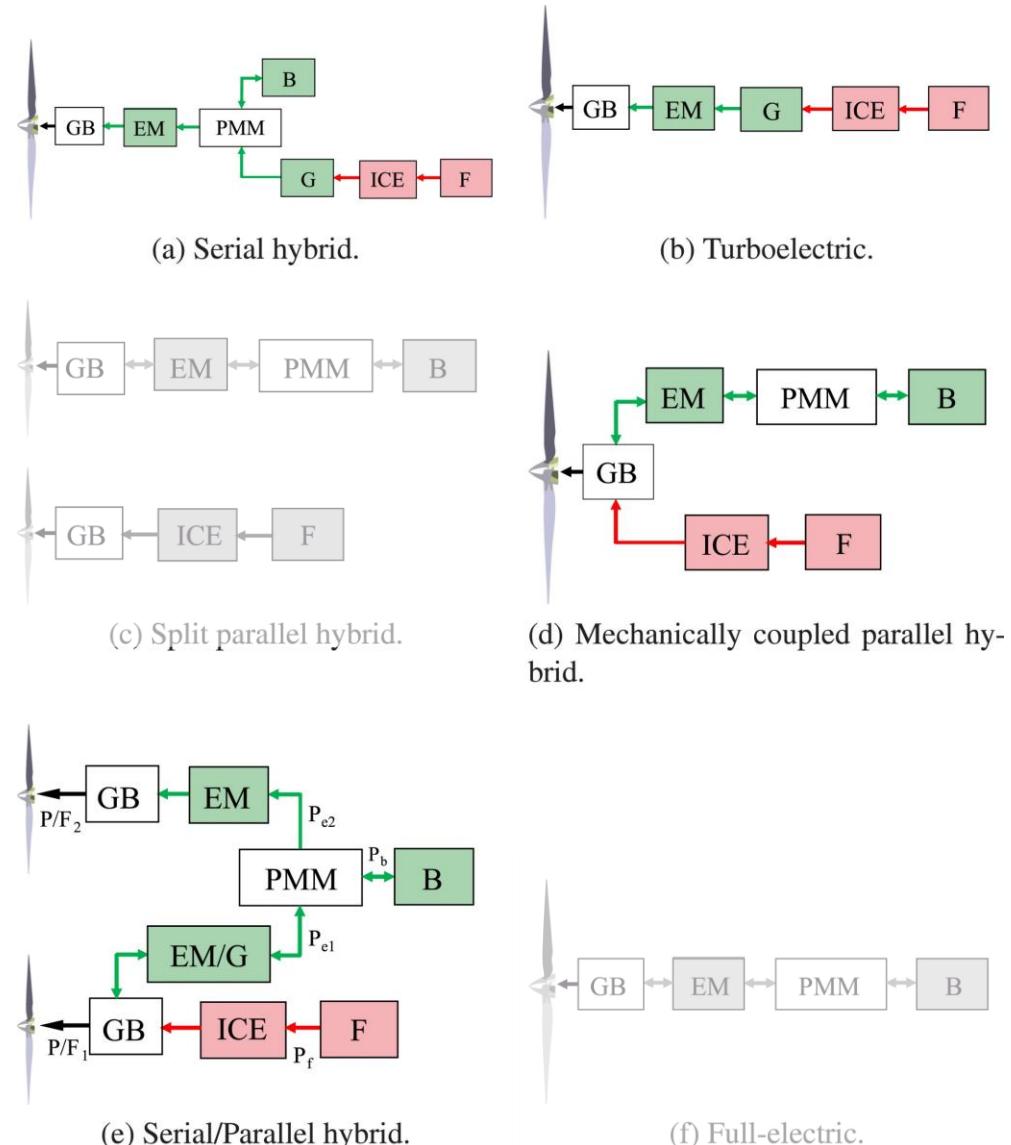
Serial/Parallel

How to design HEA

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Powertrain architecture

Hybrid-electric aircraft

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Definition and data

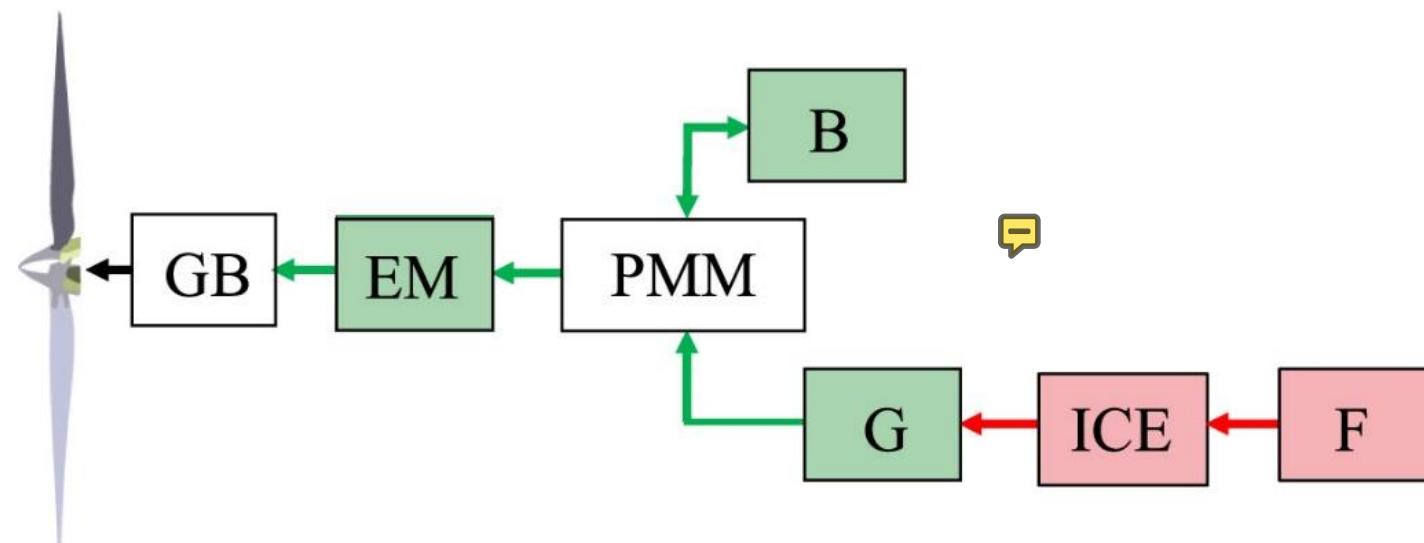
Power electronics
Definition and data

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Power management

The serial hybrid architecture has a **thermal chain** in **series** with the **electric** one. In particular, the thermal chain is composed of an internal combustion engine fed by the fuel, which generates mechanical power that is transformed into electric power by a generator. The electric chain is composed of the battery pack and one (or more) electric motors. A **power management module controls the power flow** coming from the generator and the battery pack so that, accordingly, **the battery pack can supply power or can be charged**.





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Hybrid-electric aircraft

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Power electronics

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How to design HEA

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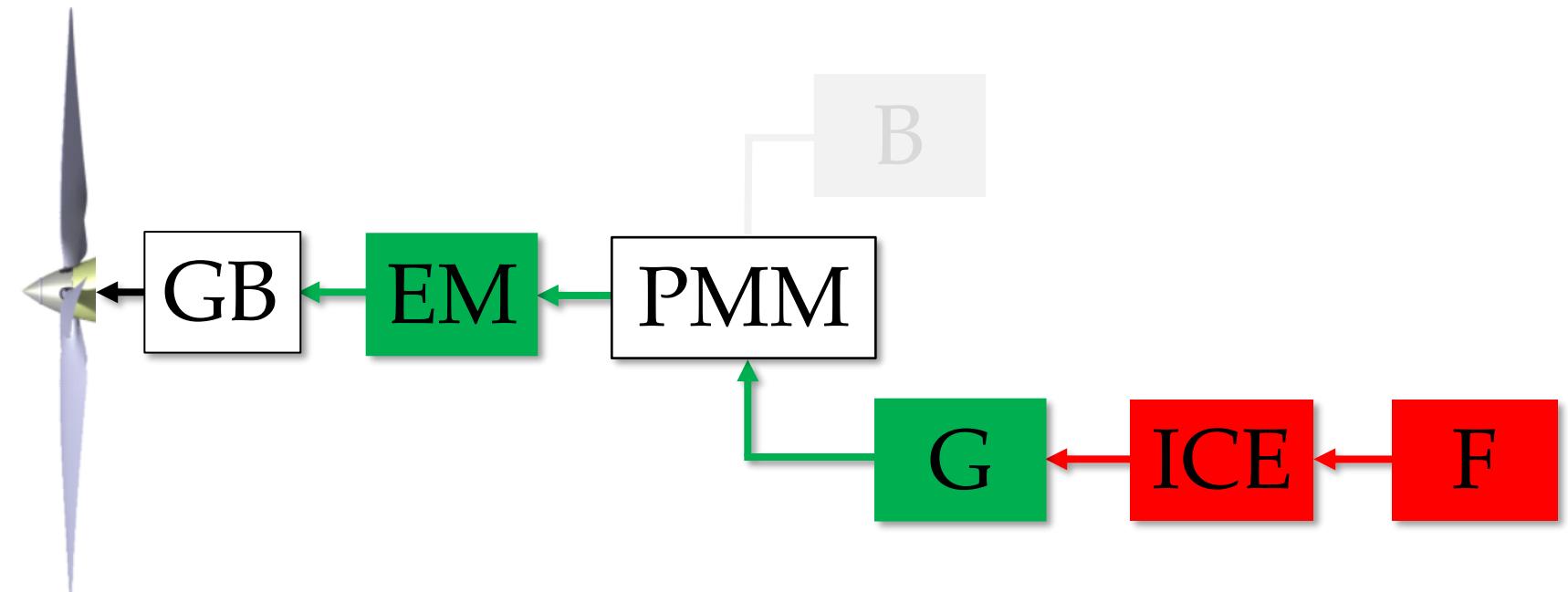
Electric motor

Power management

SERIAL



Power comes only from ICE



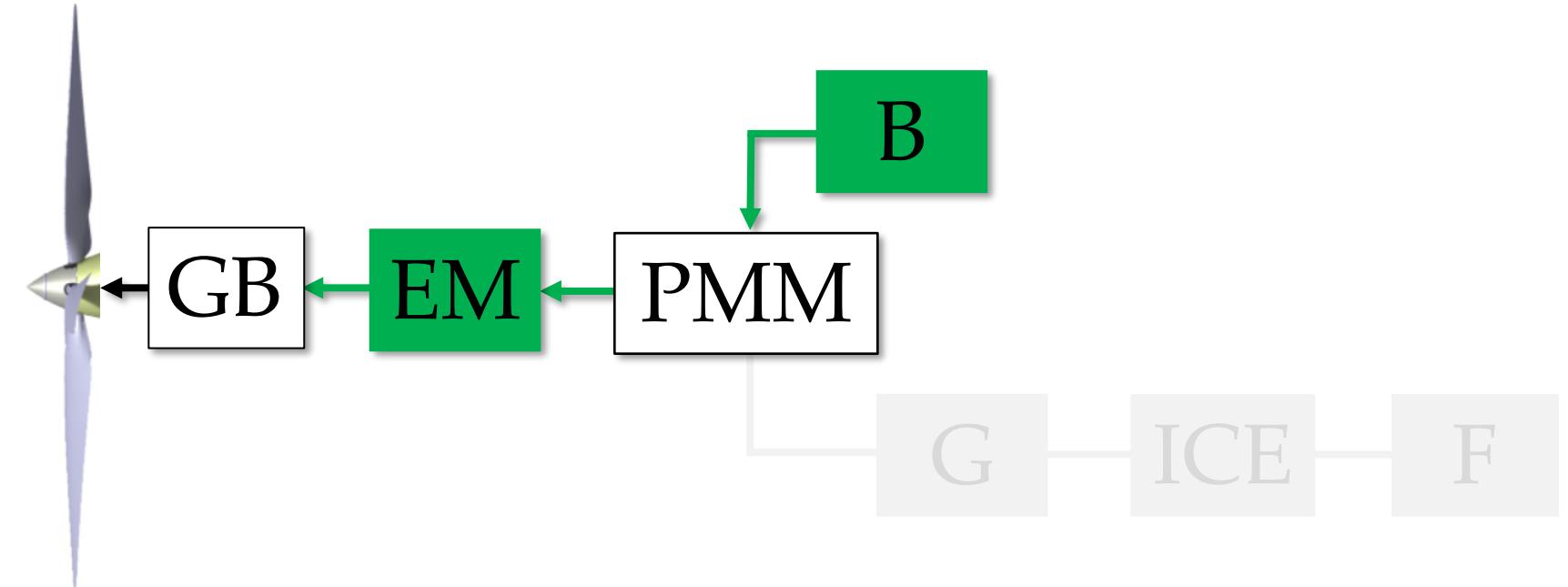


Powertrain architecture

Hybrid-electric aircraft

SERIAL

Power comes only from battery



Powertrain architecture

Serial

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Parallel

Serial/Parallel

How to design HEA

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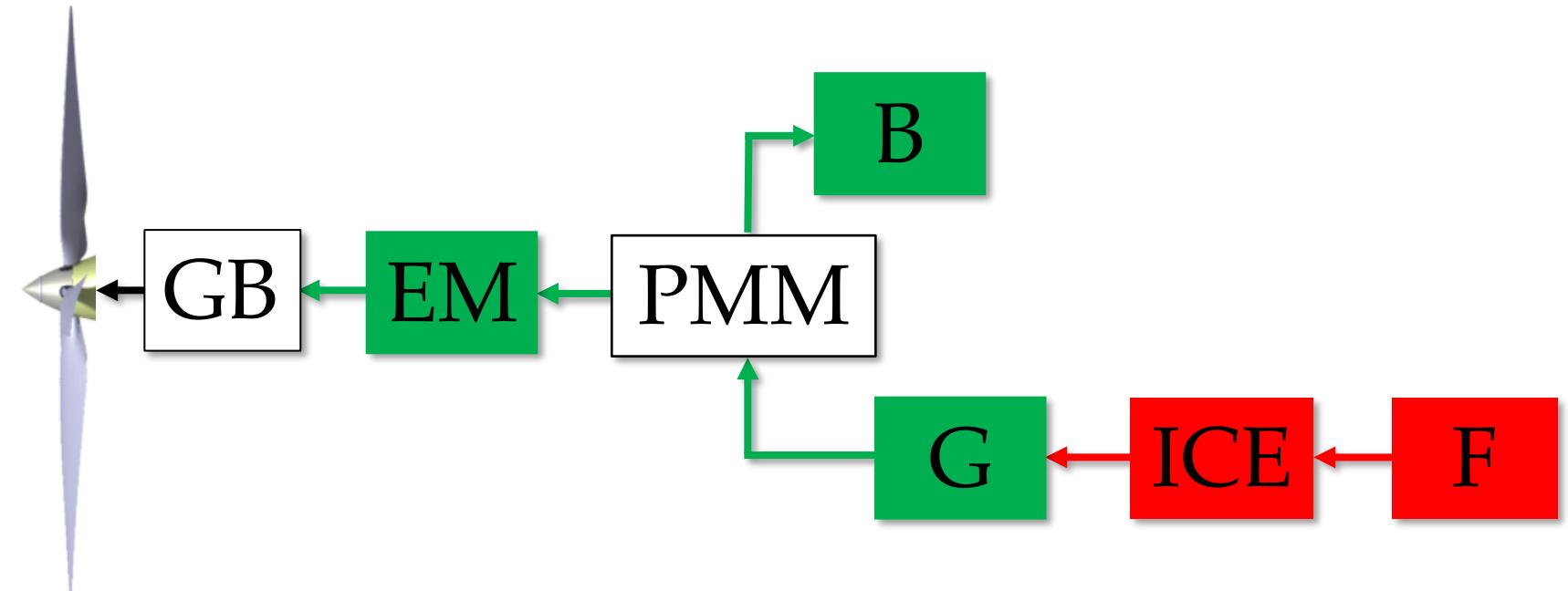


Powertrain architecture

Hybrid-electric aircraft

SERIAL

Battery is recharged



Powertrain architecture

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How to design HEA

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Powertrain architecture

Hybrid-electric aircraft

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Electric motor

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Power electronics

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How to design HEA

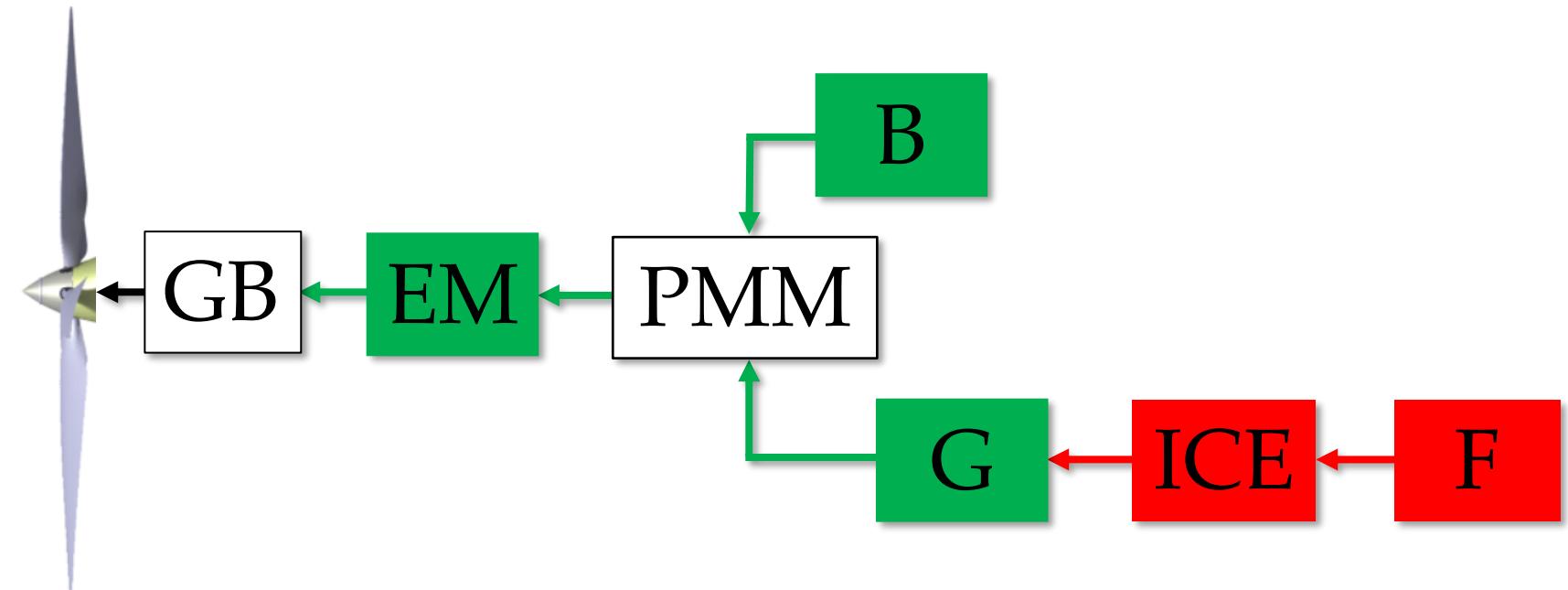
Battery

Electric motor

Power management

SERIAL

Power comes from both battery and ICE





Powertrain architecture

Hybrid-electric aircraft

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Definition and data

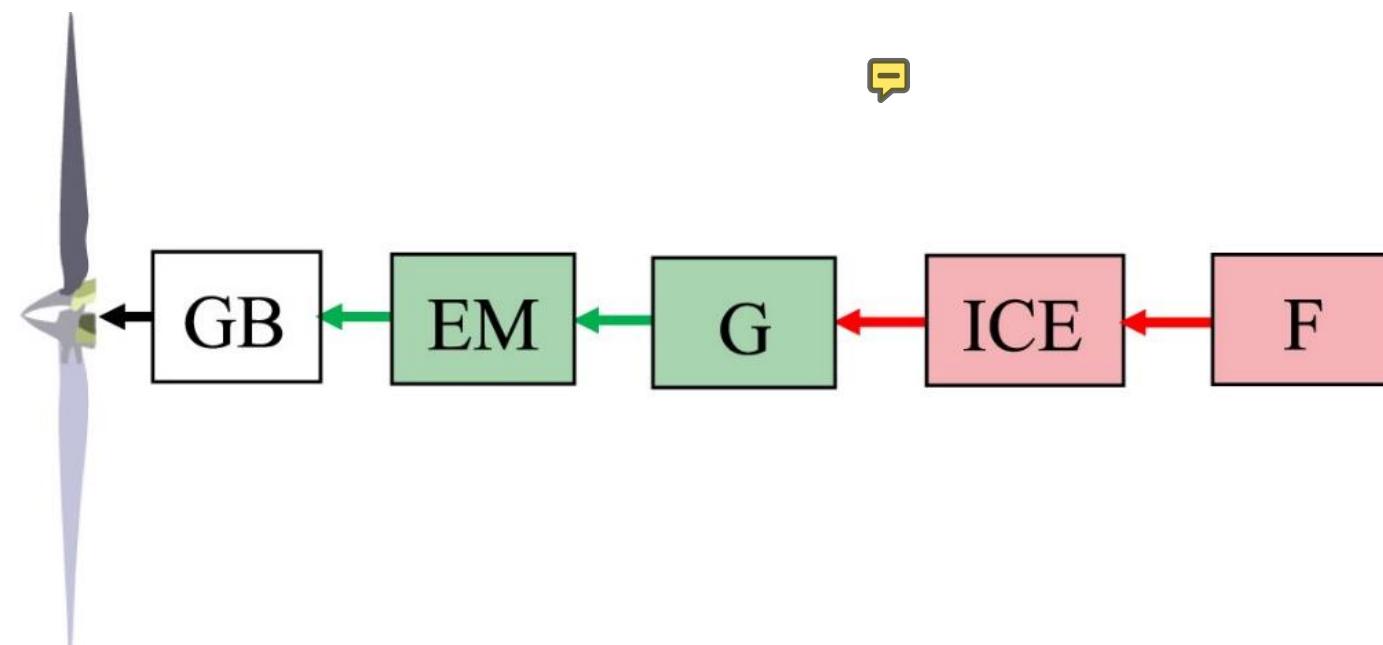
Power electronics
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How to design HEA
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Power management

The turboelectric architecture has a **thermal chain** in **series** with the **electric** one. The electric chain is composed of generators and electric motors, and the main difference with respect to the serial hybrid architecture relies in the fact that **the battery pack is missing** in the turboelectric powertrain, while all **the energy required for flying is provided by the fuel**





Powertrain architecture

Hybrid-electric aircraft

Battery
Definition and data

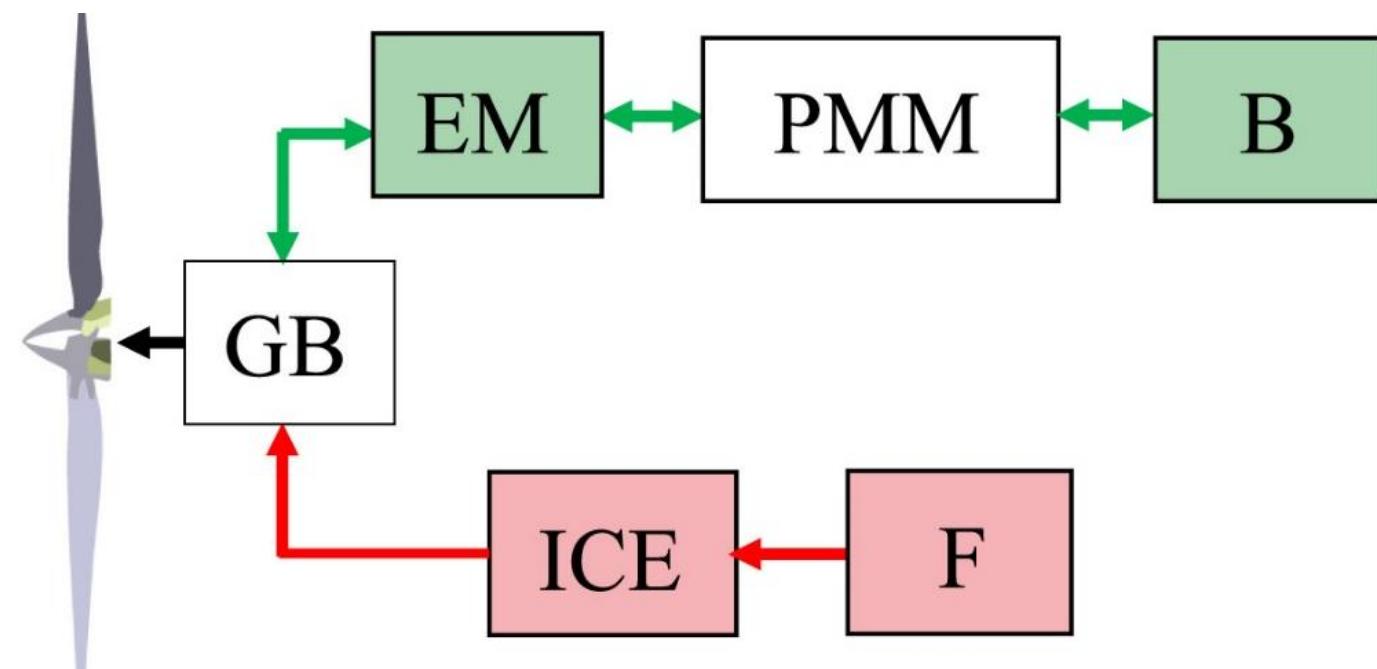
Electric motor
Definition and data

Power electronics
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How to design HEA
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Power management

The parallel hybrid has a **thermal chain** in **parallel** with the **electric** one. The thermal chain is composed of an internal combustion engine, fed by the fuel, which generates mechanical power; the electric chain is composed of one or more electric motors, powered by the battery pack. The electric motor can be mechanically coupled to the propeller/fan by means of a gearbox.





Powertrain architecture

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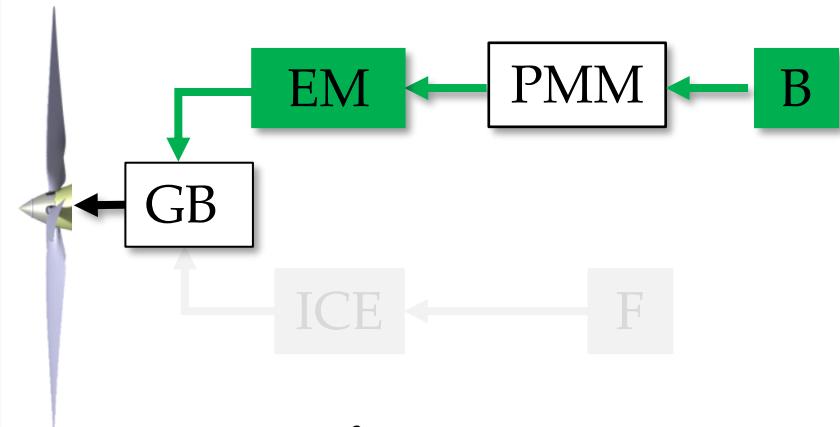
Battery

Electric motor

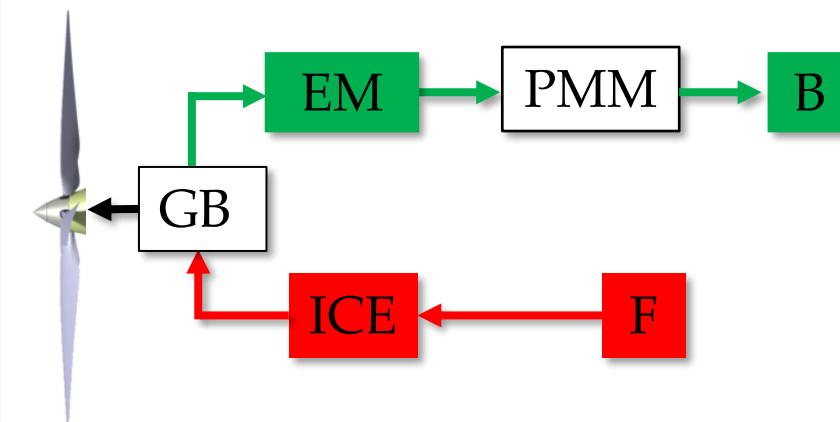
Power management

PARALLEL

Power comes only from battery



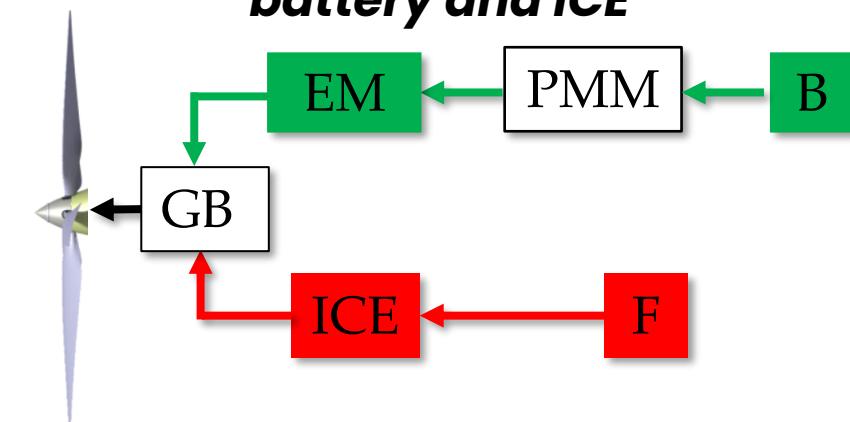
Battery is recharged



Power comes only from ICE



Power comes only from both battery and ICE





Powertrain architecture

Hybrid-electric aircraft

Battery
Definition and data

Electric motor
Definition and data

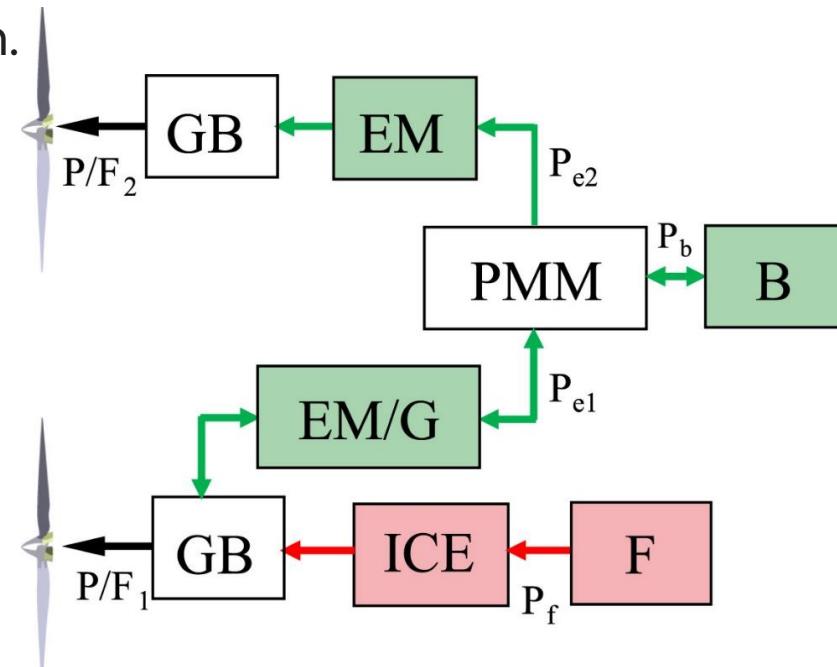
Power electronics
Definition and data

Powertrain architecture

Serial
Turbo-electric
Parallel
Serial/Parallel

How to design HEA
Battery
Electric motor
Power management

The serial-parallel hybrid architecture **merges** the **serial** and **parallel** features into a single configuration. A **power management module manages the power flow** between the battery pack and the electric machines. If the power comes from the battery pack, the electric machines act as electric motors; on the other way around, they act as generators, receiving the power from the thermal chain.





Powertrain architecture

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Parallel

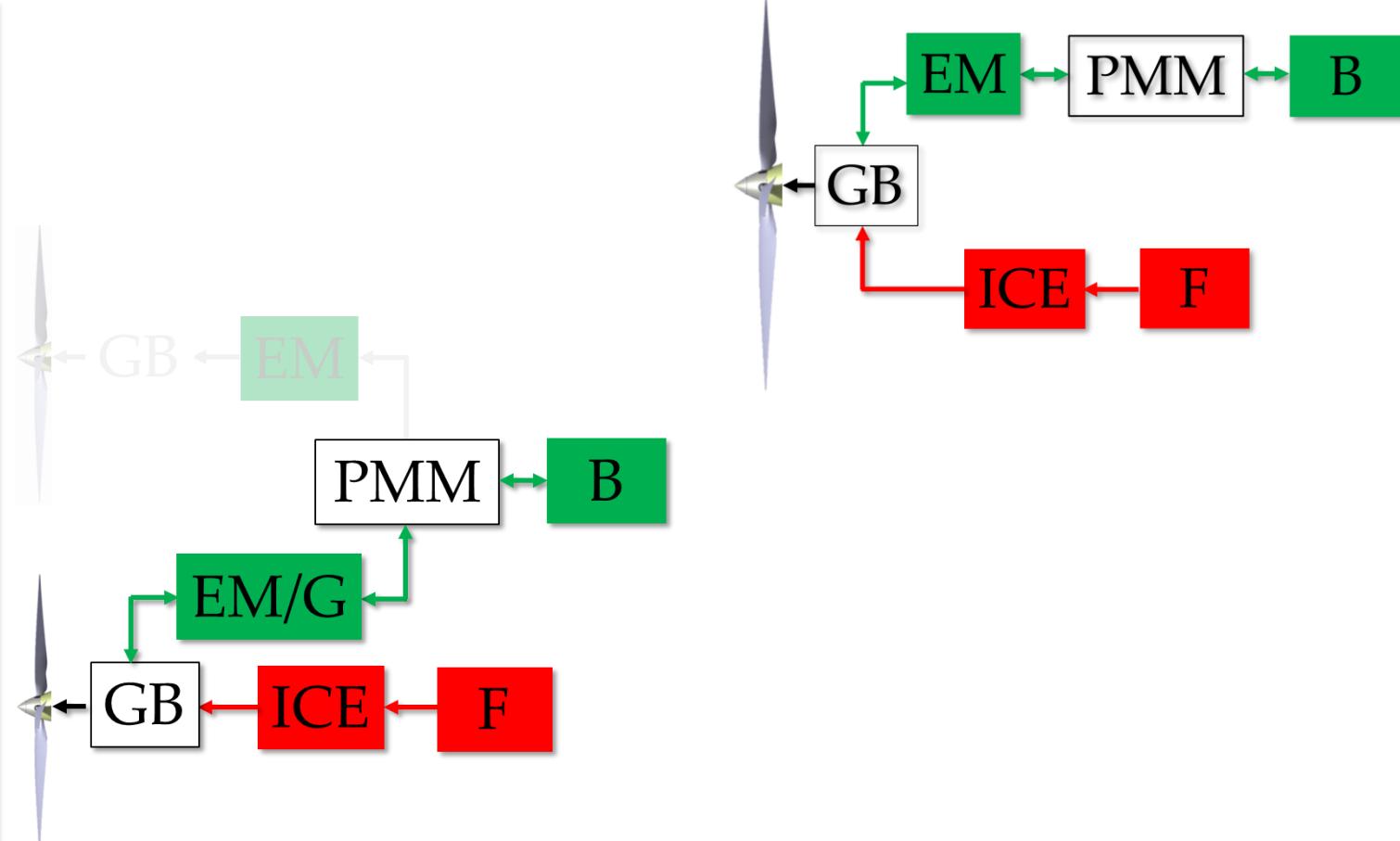
Serial/Parallel

How to design HEA

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Parallel powertrain



Powertrain architecture

Hybrid-electric aircraft

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Definition and data

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Parallel

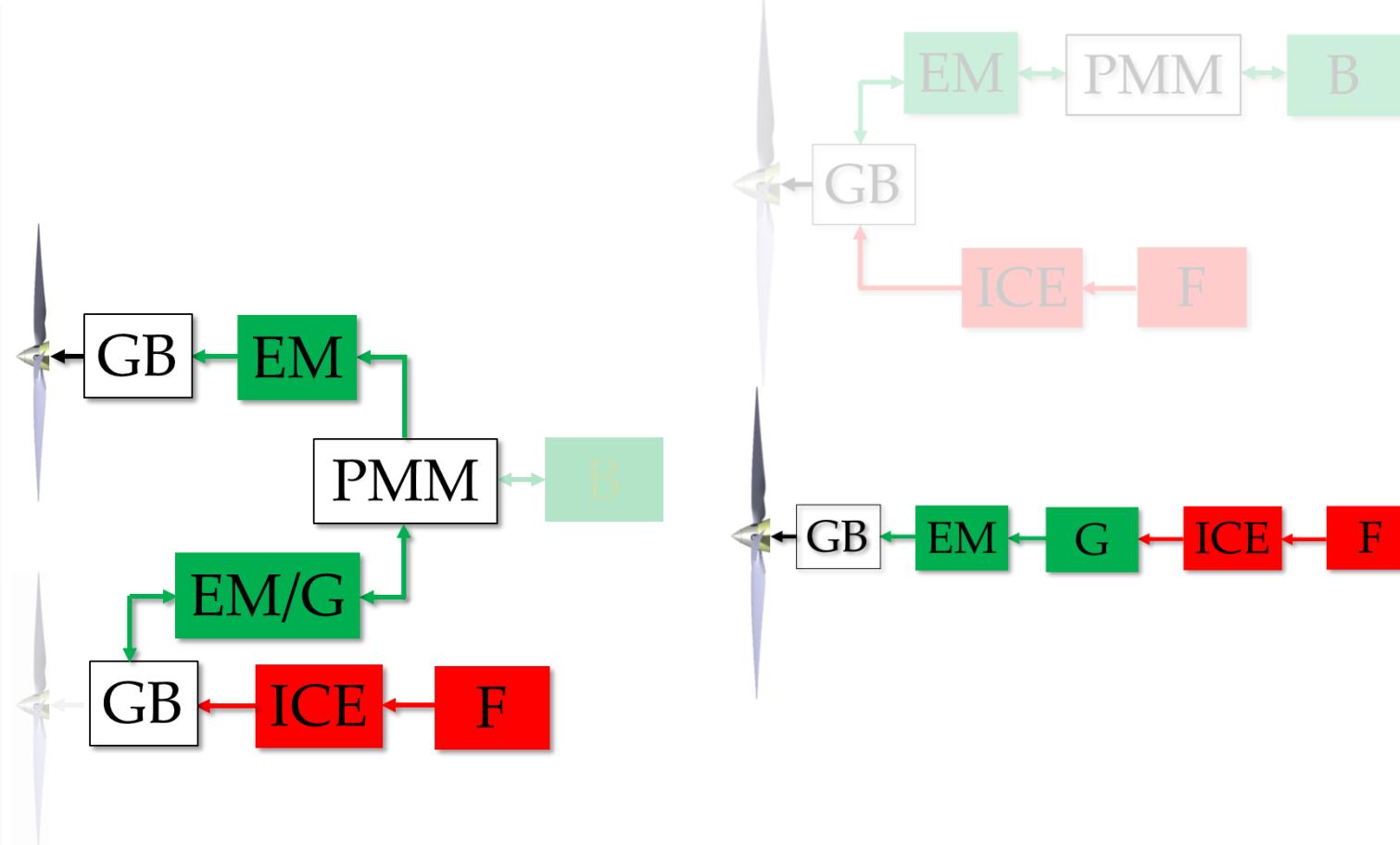
Serial/Parallel

How to design HEA

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Parallel powertrain

Turboelectric powertrain



Powertrain architecture

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Definition and data

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Turbo-electric

Parallel

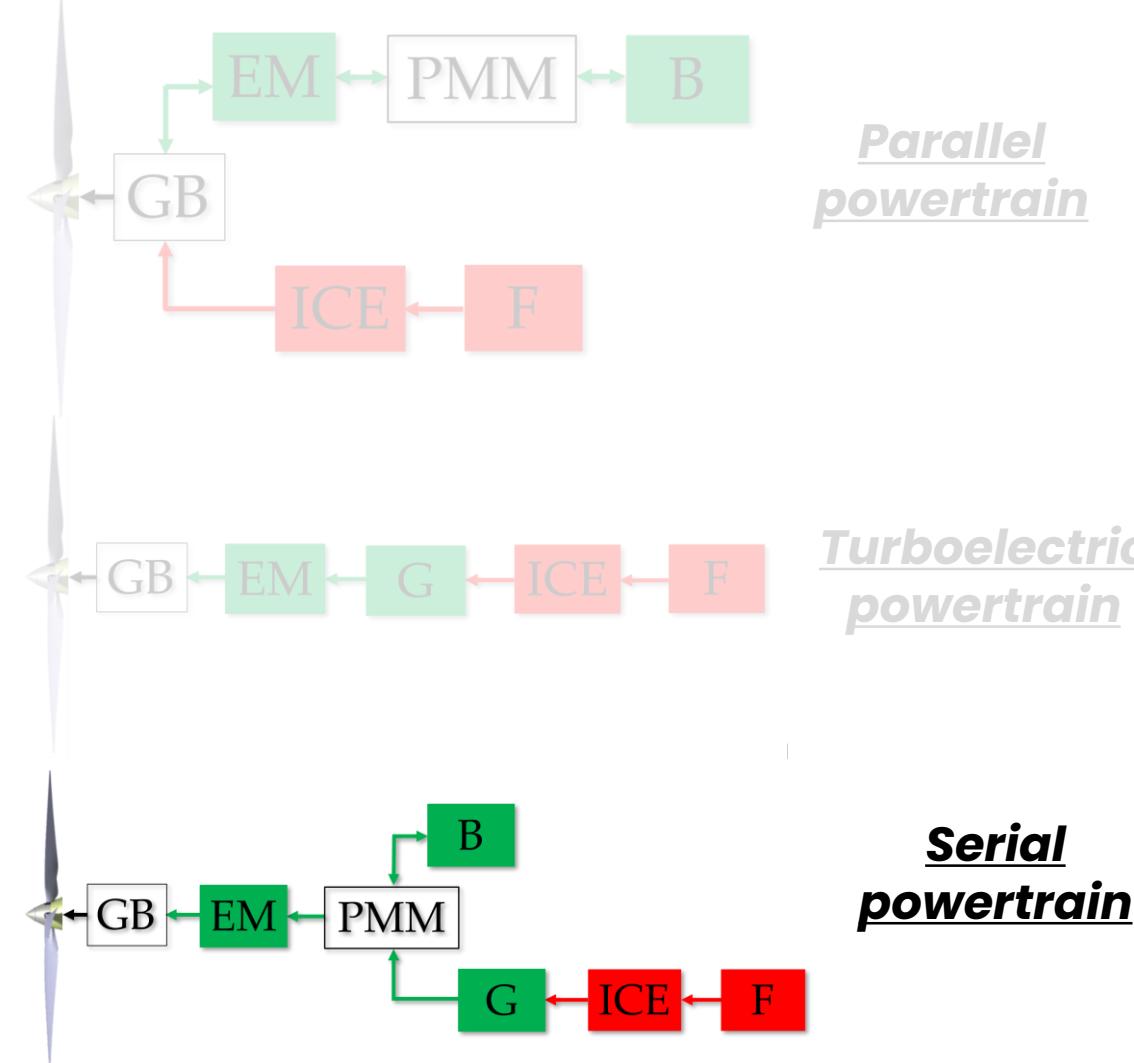
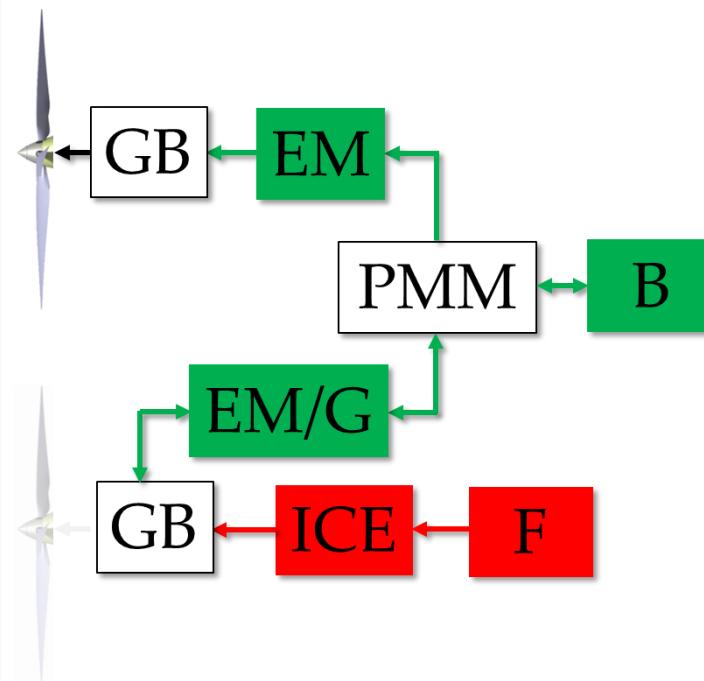
Serial/Parallel

How to design HEA

Battery

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Parallel powertrain

Turboelectric powertrain

Serial powertrain



Powertrain architecture

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Serial/Parallel

How to design HEA
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Power management

Specific design parameters can be defined to properly describe hybrid-electric powertrains, such as the degree of power hybridization degree H_P and the energy hybridization degree H_E .

H_P is defined as the ratio between the electric **installed power** P_e^i and the total installed power P_{tot}^i , that is, the sum of the electric installed power and the thermal installed power P_t^i .

$$H_P = \frac{P_e^i}{P_e^i + P_t^i}$$

if $H_P = 0$ no electric motor is onboard and all the power comes from the thermal engine

If $H_P = 1$ the installed power of the internal combustion engine is equal to zero, and the aircraft is full-electric

Si usa nel matching chart



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Specific design parameters can be defined to properly describe hybrid-electric powertrains, such as the degree of power hybridization degree H_P and the energy hybridization degree H_E .

H_E represents the ratio between the **energy** supplied by the battery pack (integral over time of power supplied by the battery P_b) and the total energy supplied by the battery pack and the fuel during the flight.

$$H_E = \frac{\int_0^t P_b dt}{\int_0^t (P_b + P_f) dt}$$

if $H_E = 0$ no power is supplied by the battery pack during the mission

If $H_E = 1$ the battery pack supplies the whole request of power to fly

Non vuol dire che a bordo non ha energia elettrica (o termica se =1), ma che in missione non ne uso



How to design HEA

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How to design HEA

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Power management

Electric chain vs thermal chain

Electric
chain

Scalable
High efficiency
Low level of noise

Petrol
chain

High power
Fuel has high specific energy

Forecast

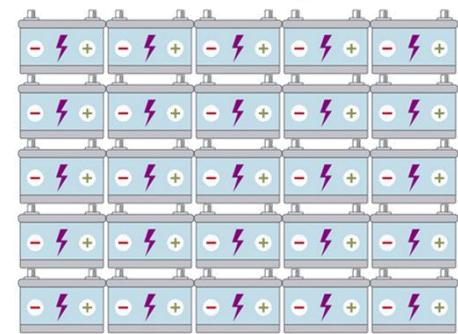
Combustion engine



≈

1 kg fuel

Electric engine



~~80 25 kg of batteries~~



How to design HEA

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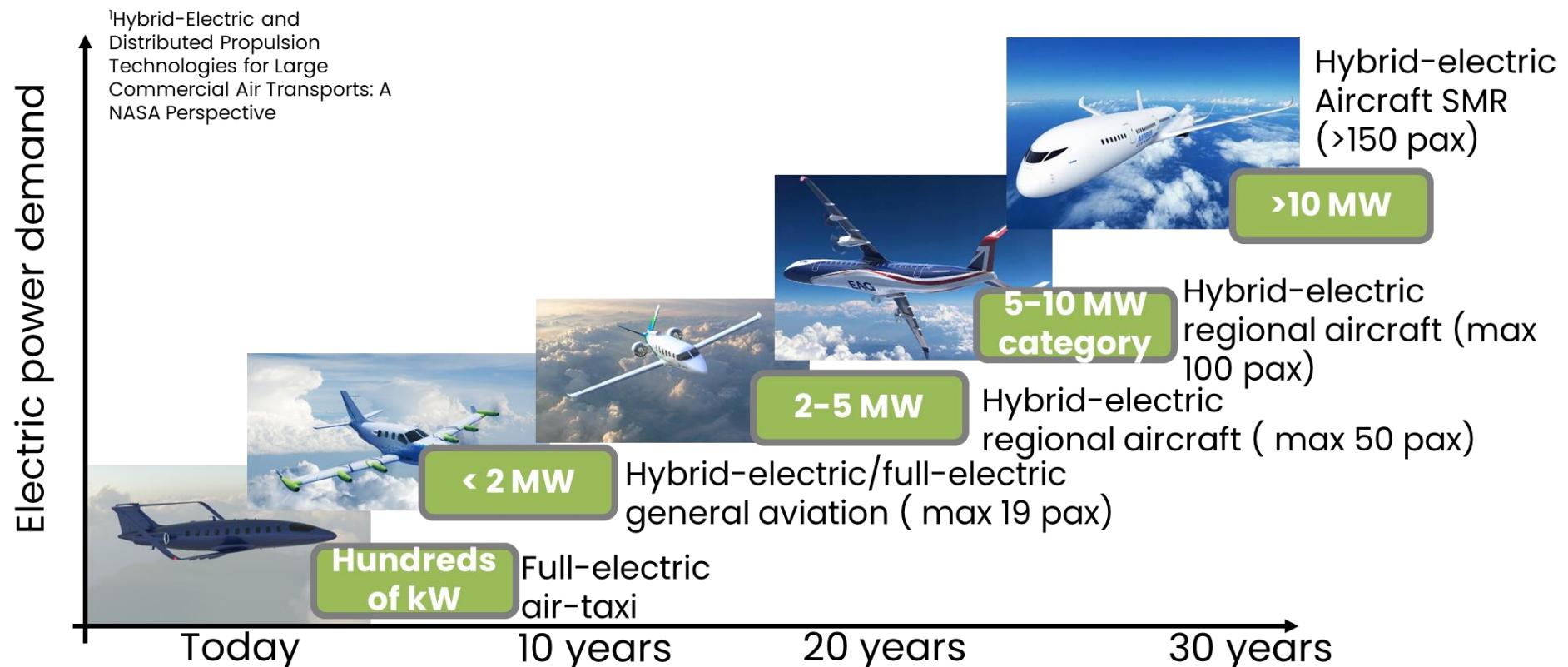
Serial/Parallel

How to design HEA

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How to design HEA

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How to design HEA

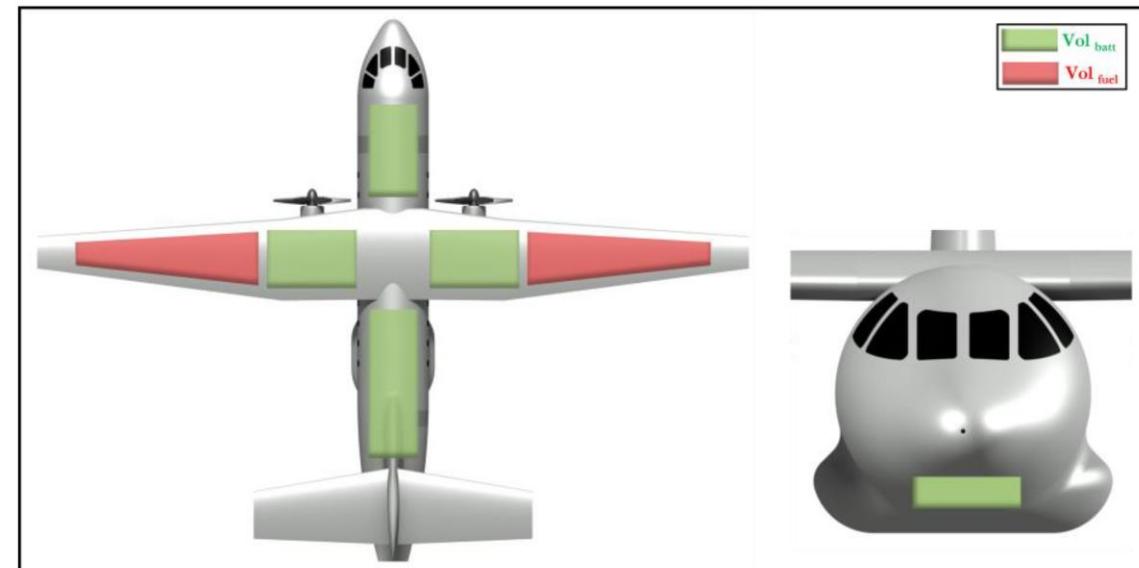
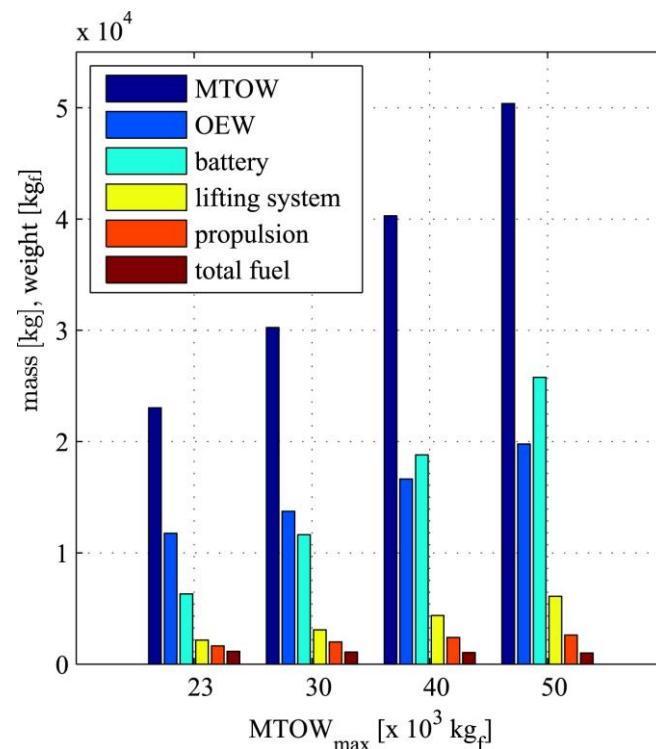
Battery

Electric motor

Power management

Battery mass represents a heavy component which can cause huge increase of the aircraft weight

Volume allocation for battery is fundamental





How to design HEA

Hybrid-electric aircraft

Battery

Definition and data

Electric motor

Definition and data

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Definition and data

Powertrain architecture

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Parallel

Serial/Parallel

How to design HEA

Battery

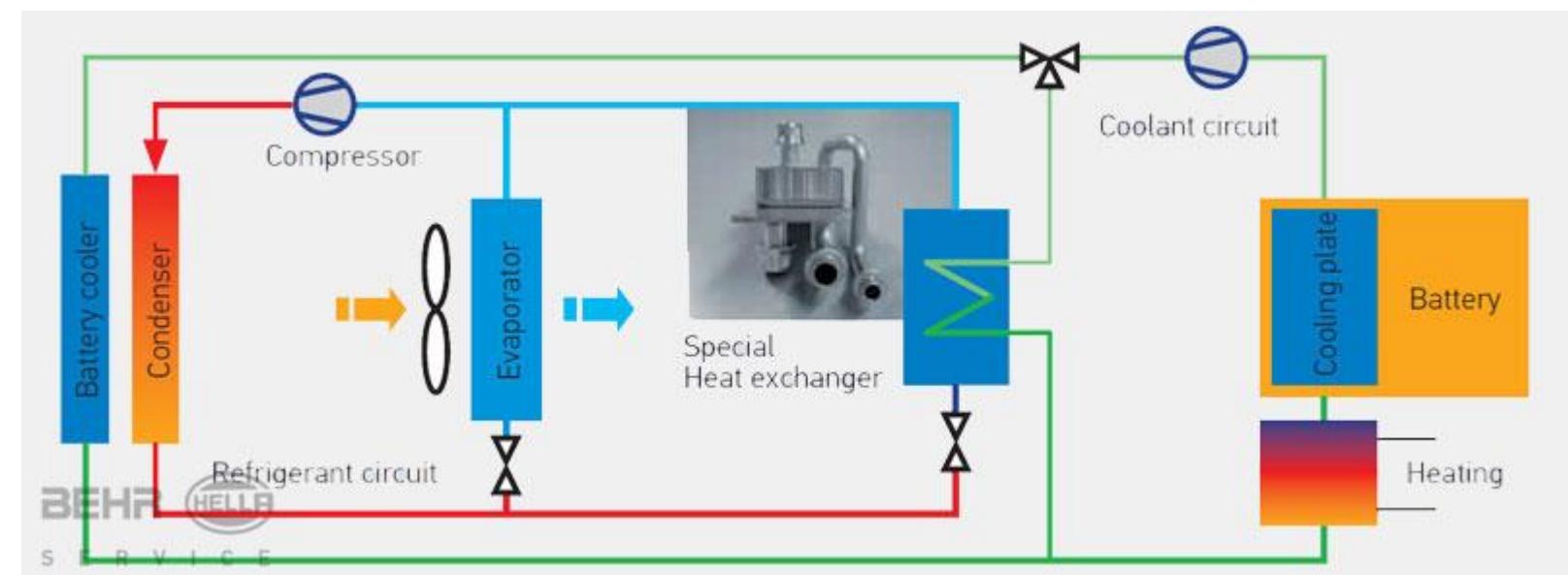
Electric motor

Power management

Battery mass represents a heavy component which can cause huge increase of the aircraft weight

Volume allocation for battery is fundamental

Thermal management must be taken into account





How to design HEA

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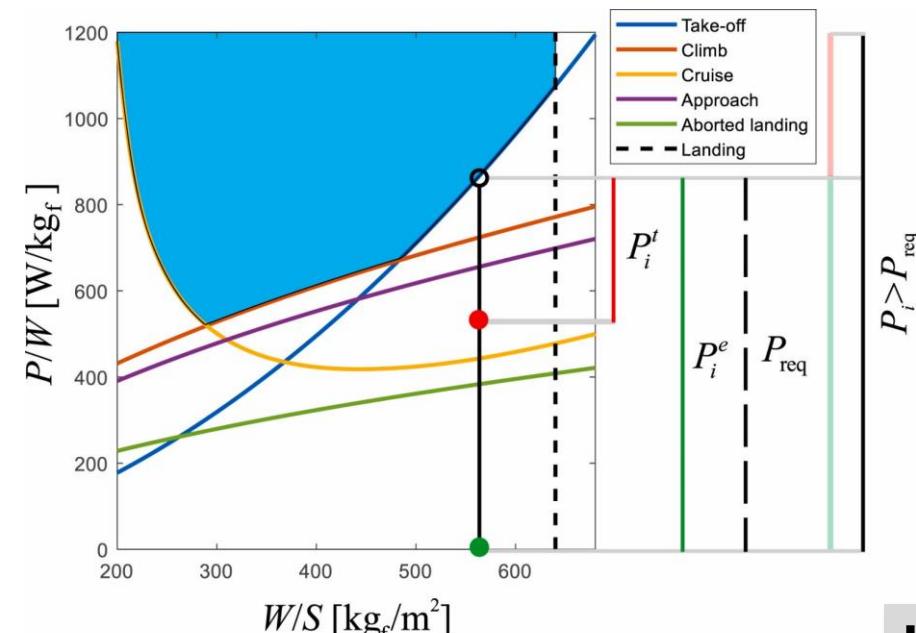
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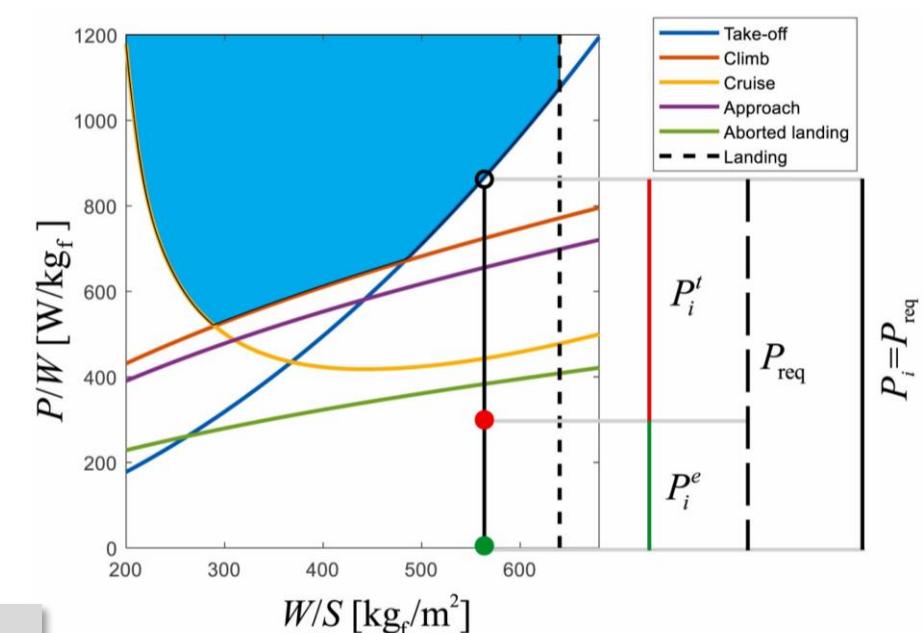
How to design HEA
Battery
Electric motor
Power management

The matching chart is a fundamental tool to assess installed power, also for the hybrid-electric aircraft

The choice of the powertrain architecture plays a crucial role



(a) Serial architecture.



(b) Parallel architecture.

H_P



How to design HEA

Hybrid-electric aircraft

Battery
Definition and data

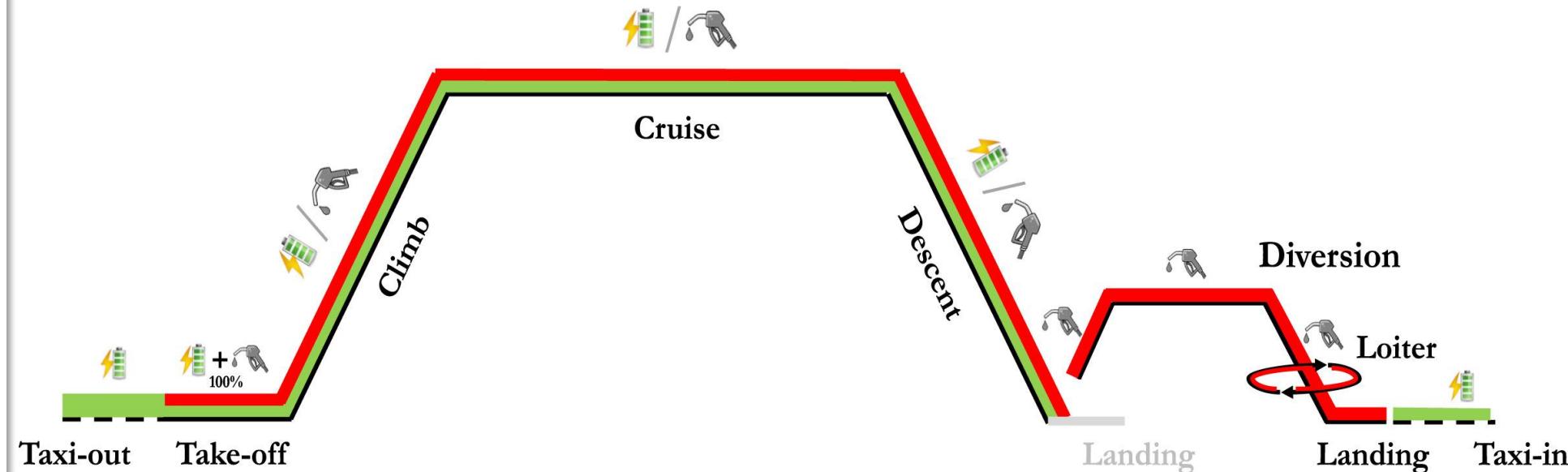
Electric motor
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How to design HEA
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The use of electric power installed on-bord plays a key role in the assessment of the hybrid-electric aircraft performance



H_E



Take home messages of this lesson

What is the definition of the term hybrid-electric

What are the main electric components of the hybrid-electric aircraft

What are the main powertrain architectures

What are the main pro and cons of hybrid-electric propulsion



Back-up slides