E2. Conceptual design of regional hybrid-electric aircraft

10. Introduction to Hybrid-Electric Aircraft

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Hybrid-electric aircraft

Hybrid-electric aircraft

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Electric motor
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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"

2020 | Horizon Europe | 2030 | 2040 | 2050

100% fossil fuel based aviation

Long range

Short/medium range

Commuters helicopters

Low carbon Aviation

Ultra-efficient aircraft +

Increased use of sustainable alternative fuels

Small electric aircraft
Hybrid regional and short range aircraft
New short distance mobility

Green aircraft operations and infrastructures

Green aircraft regulations

Climate-neutral aviation

Hyper-efficient aircraft

Fully decarbonised energy sources, i.e. alternative zero (net) emissions fuels/energy carriers e.g.

- Liquid H2
- Power to Liquid fuels
- Ultra-high density batteries and/or fuel cells

Climate-neutral aircraft operations and infrastructures

Climate-neutral aircraft regulations

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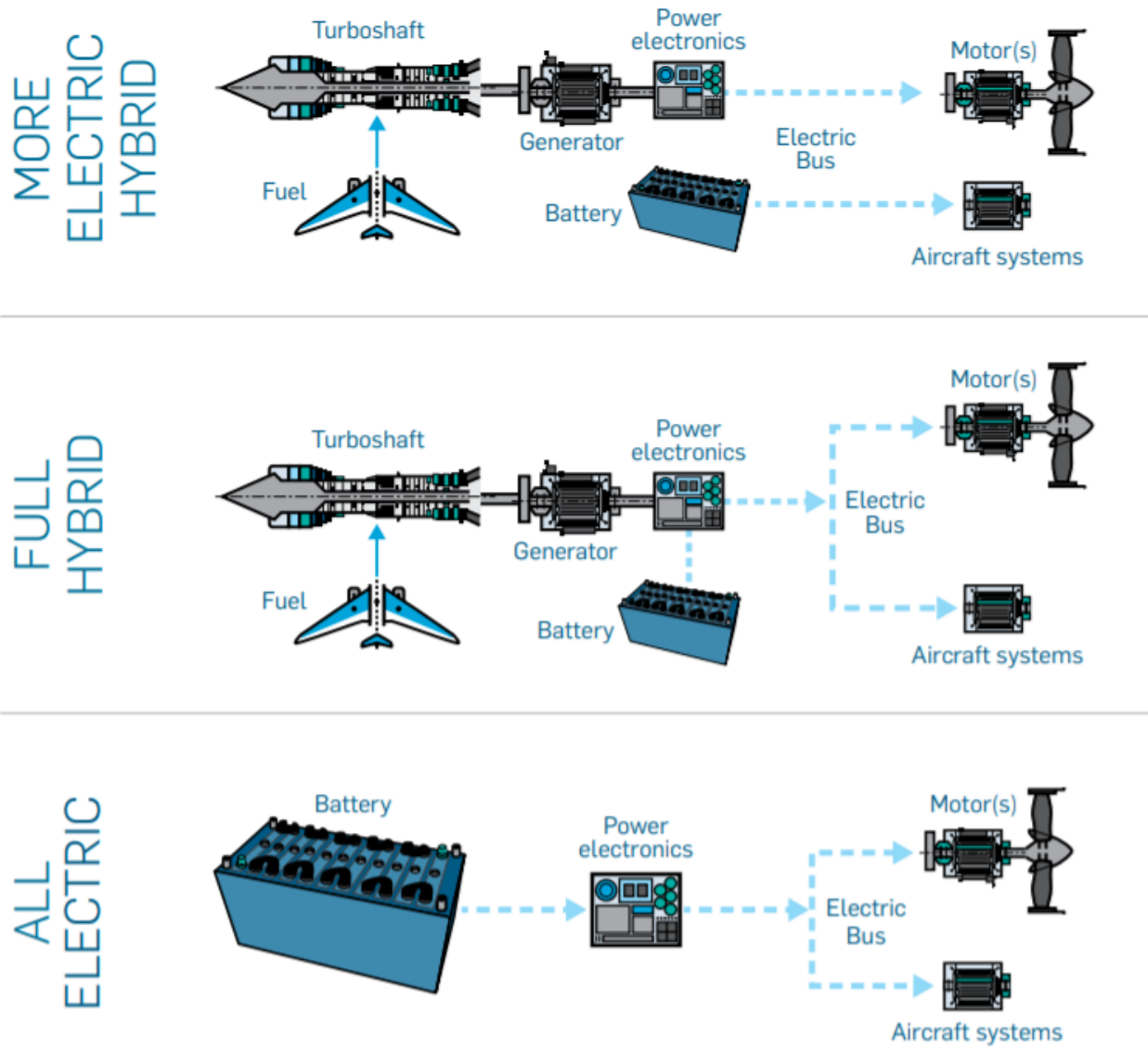
The MEA concept provides for the utilization of electric power for all non-propulsive systems.
Traditionally these non-propulsive systems are driven by a combination of different secondary power sources such as hydraulic, pneumatic, mechanical and electrical.

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



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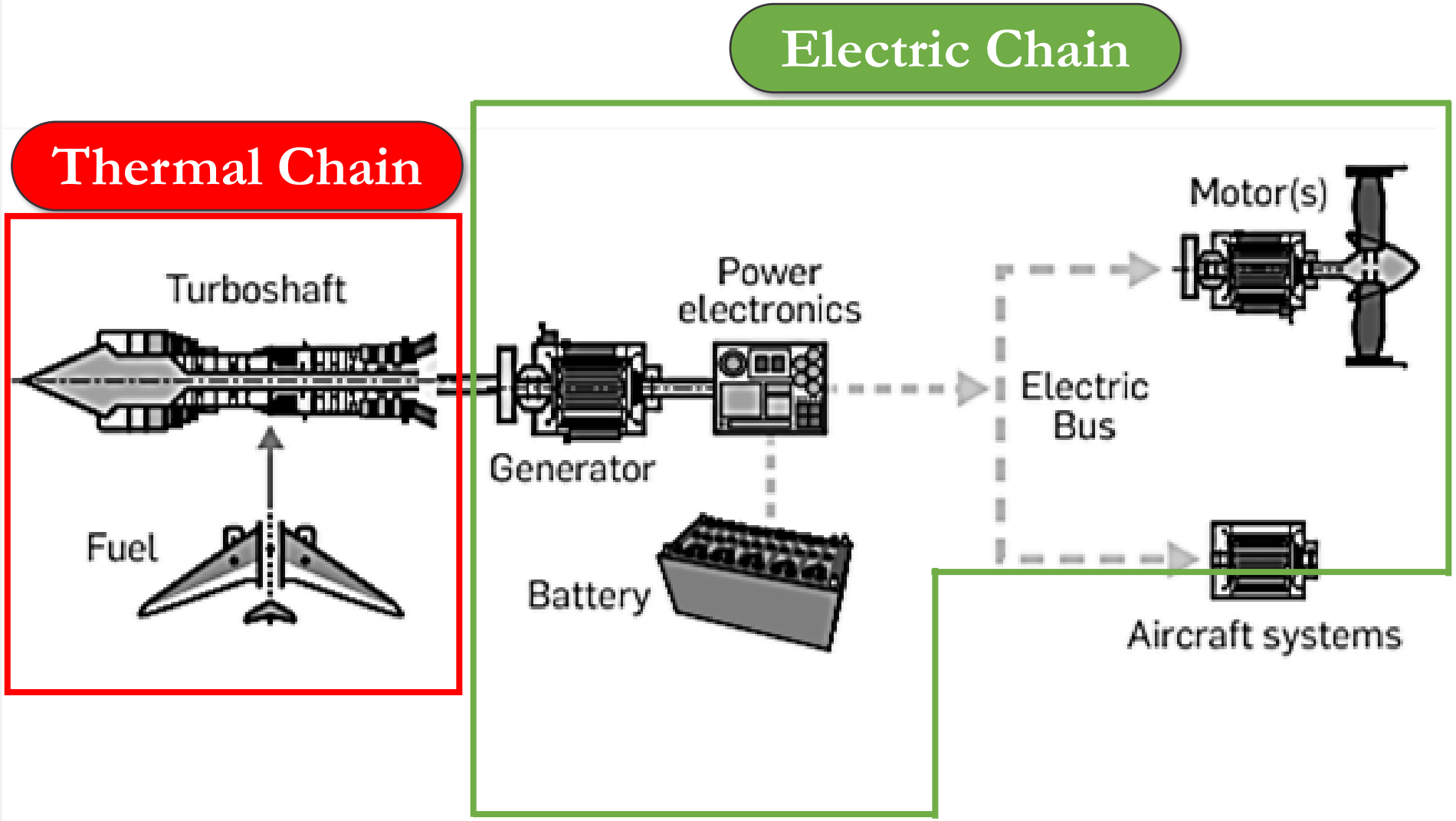
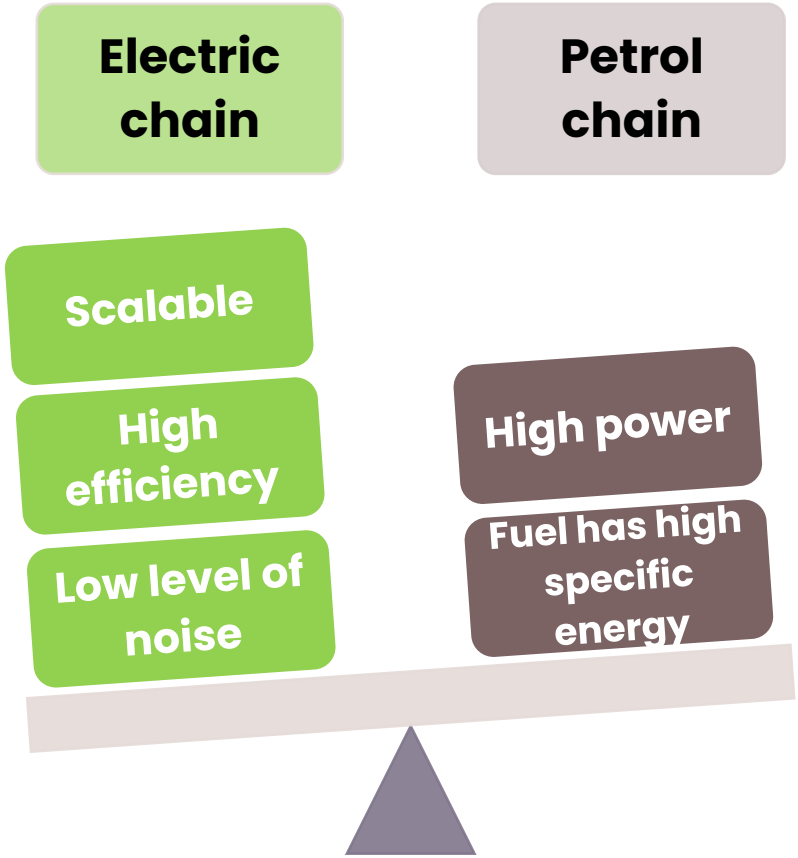
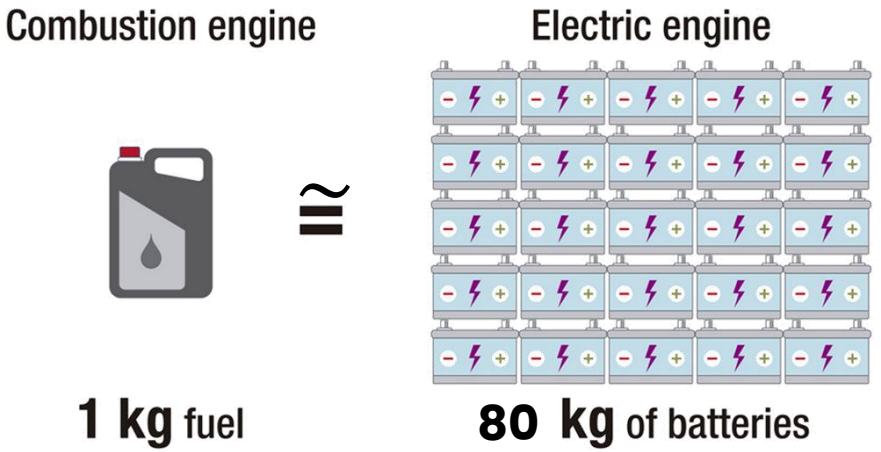


Hybrid-electric aircraft

Electric chain vs thermal chain



Currently



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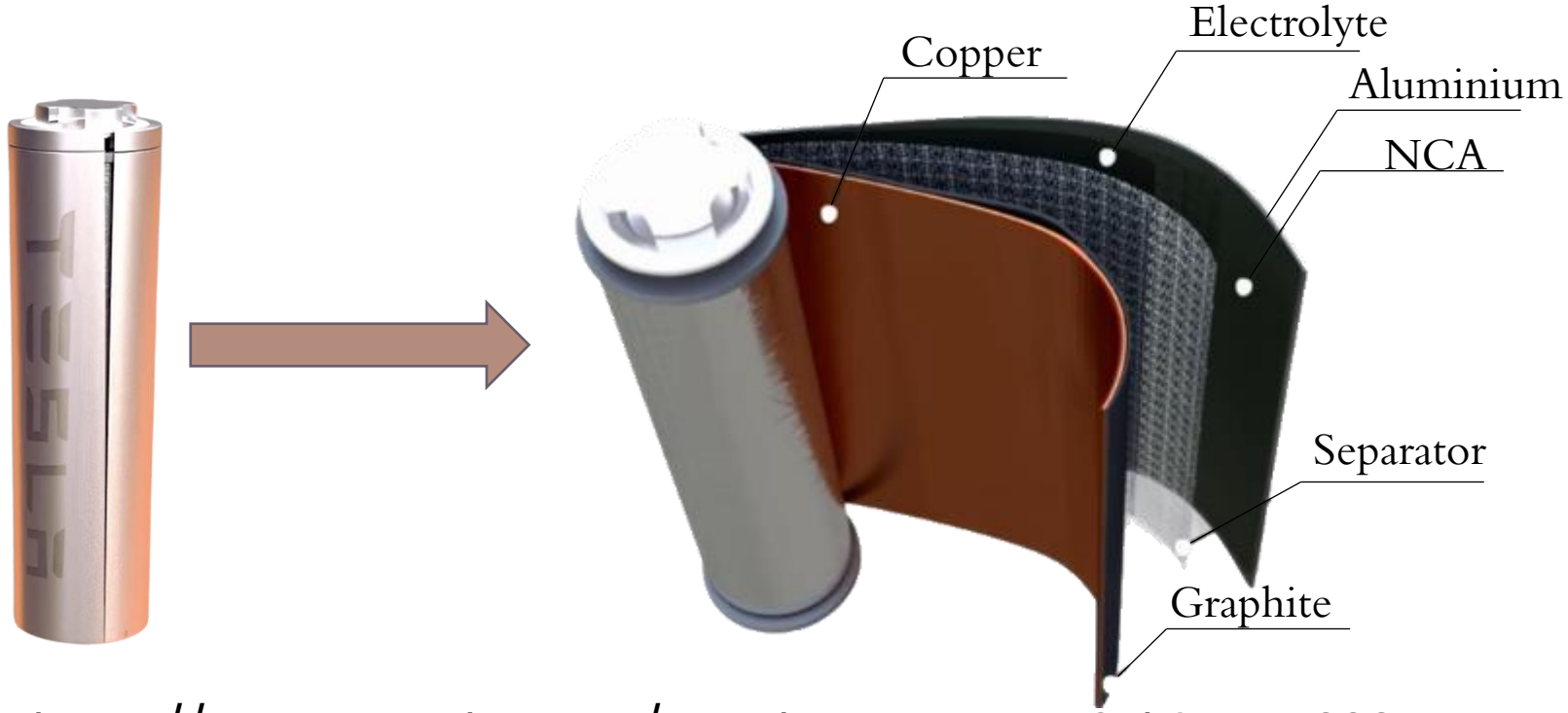
A battery is a practical electrical energy storage device consisting of one or more cells connected in series and/or parallel in order to provide desired output voltage, capacity, and power.

Lithium-ion battery



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

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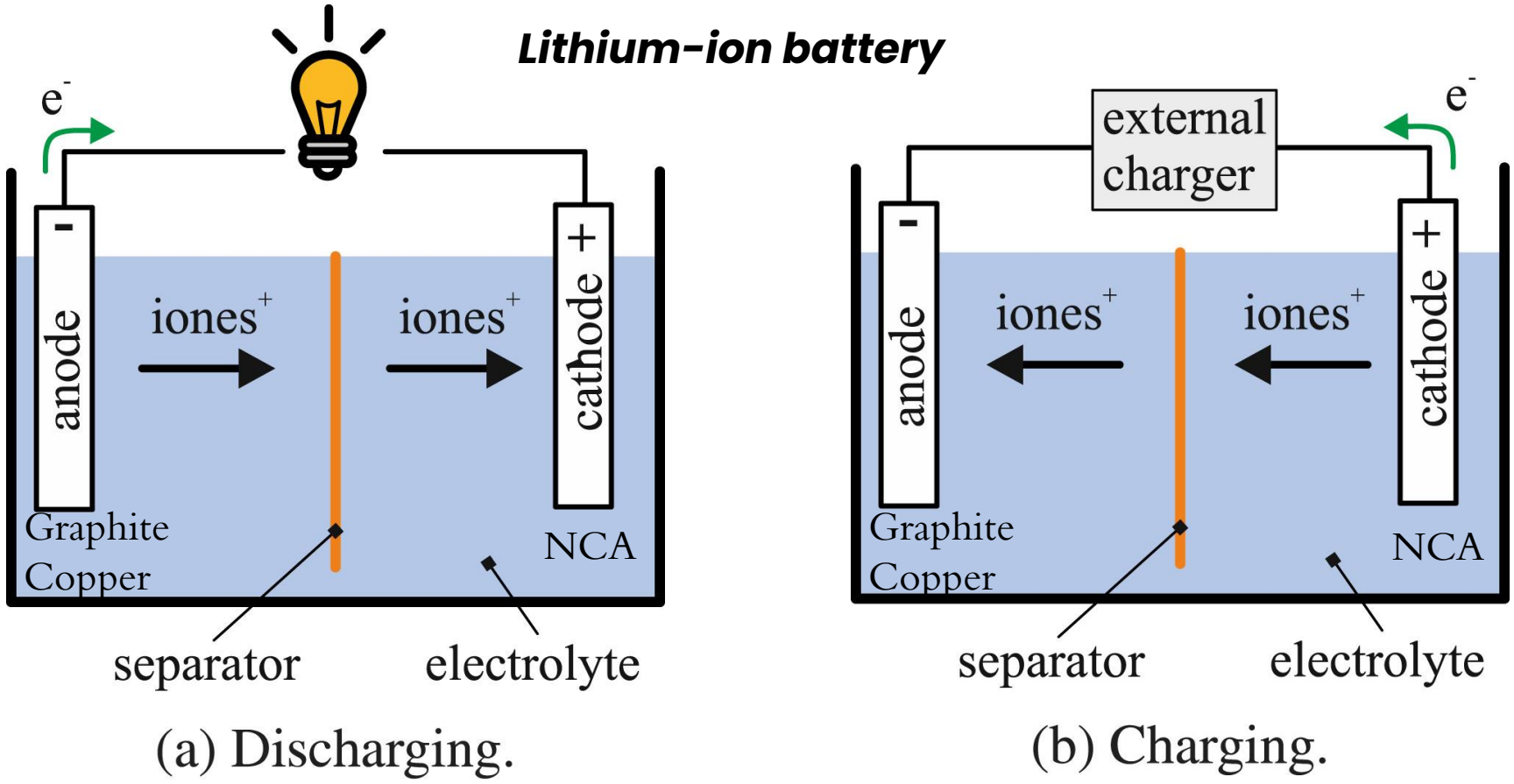
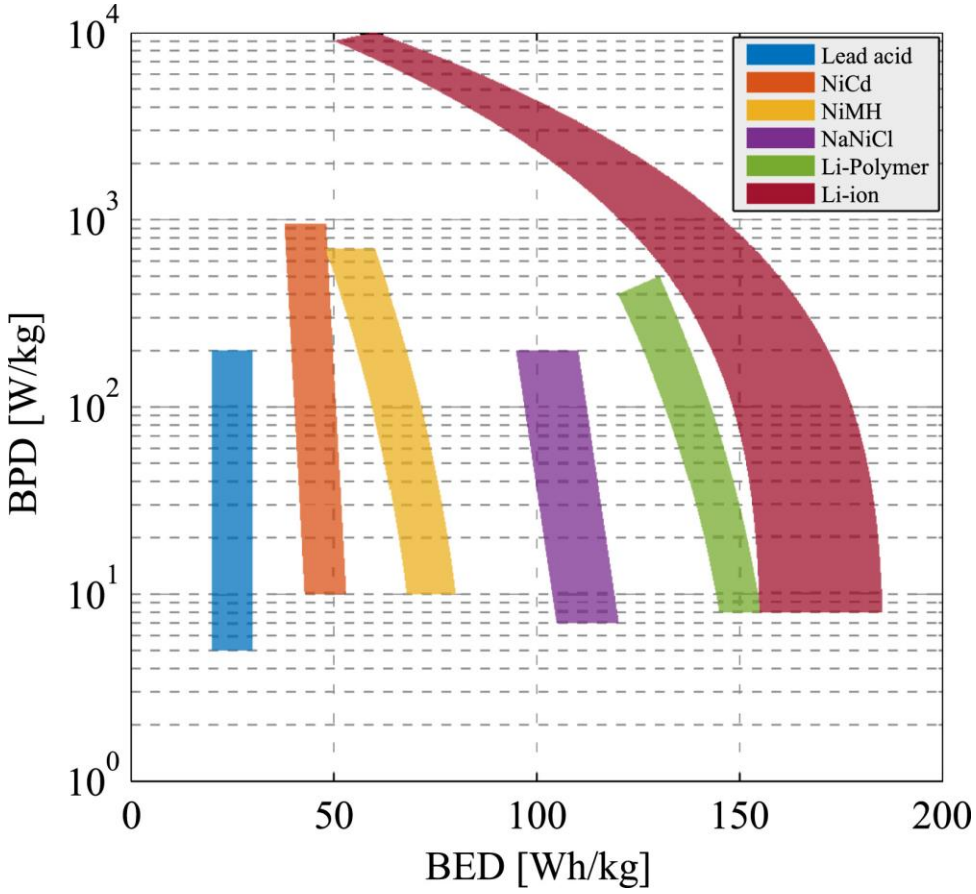


Battery

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.

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 ratio between the energy (measured in kWh) stored in the battery and the battery weight



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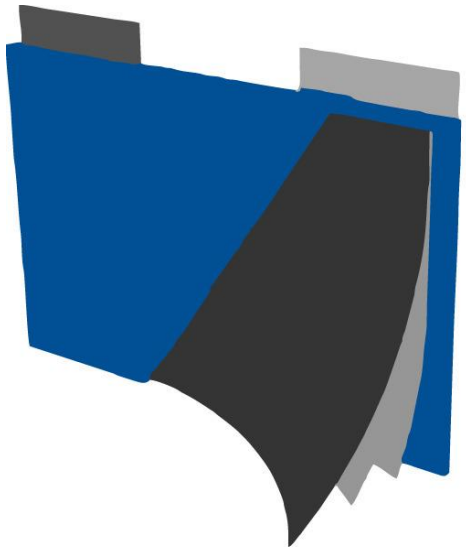
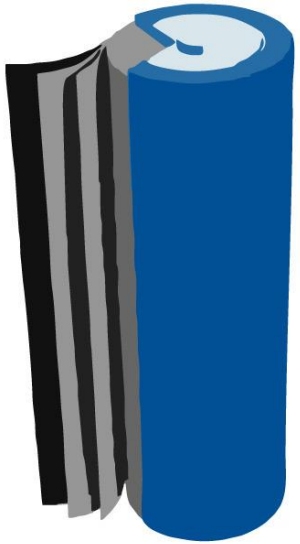
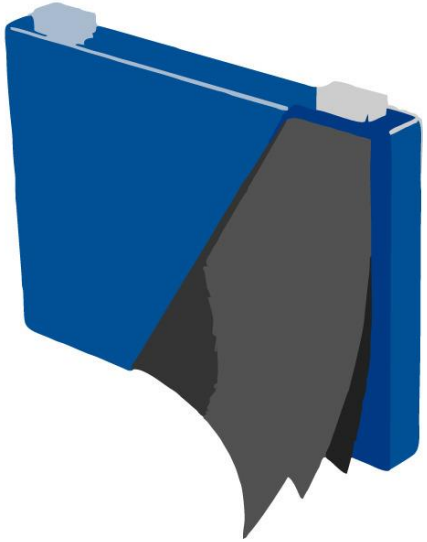
The shape of the single cell



(a) Pouch.



(b) Cylin-drical.



(c) Prismatic.

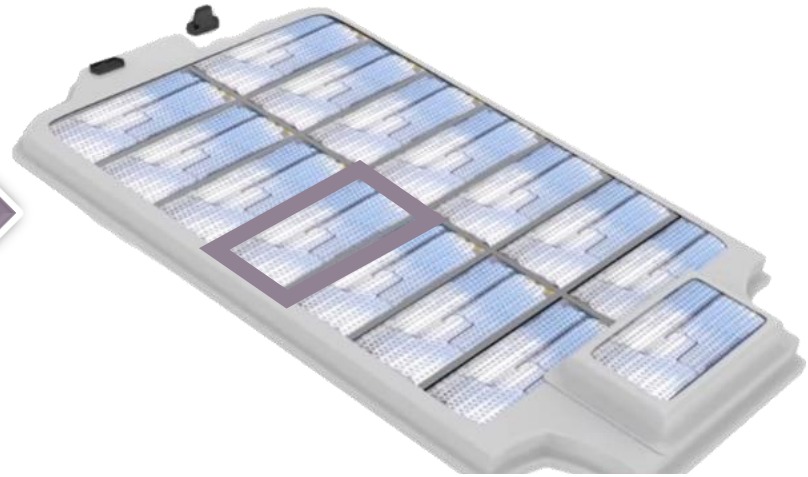
Battery

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.

From the cell to the battery pack

Single module

Battery pack



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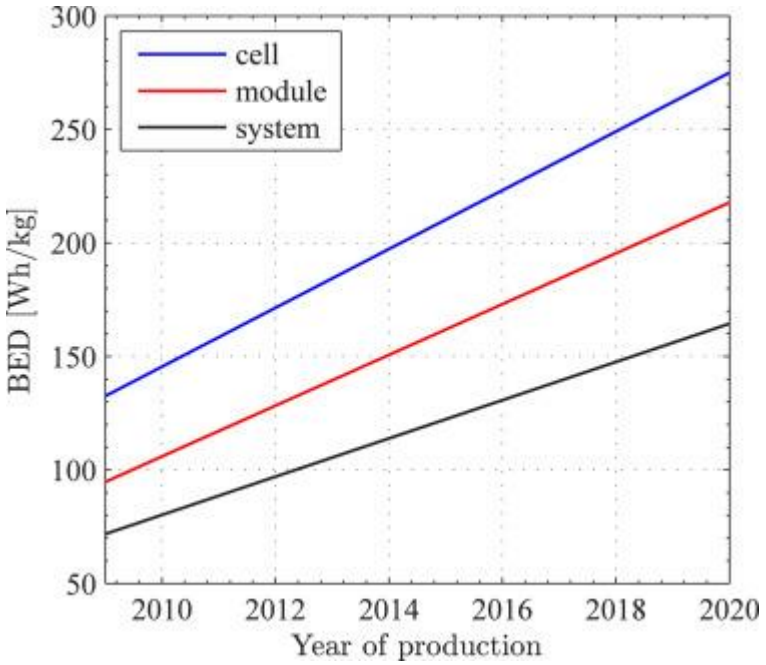

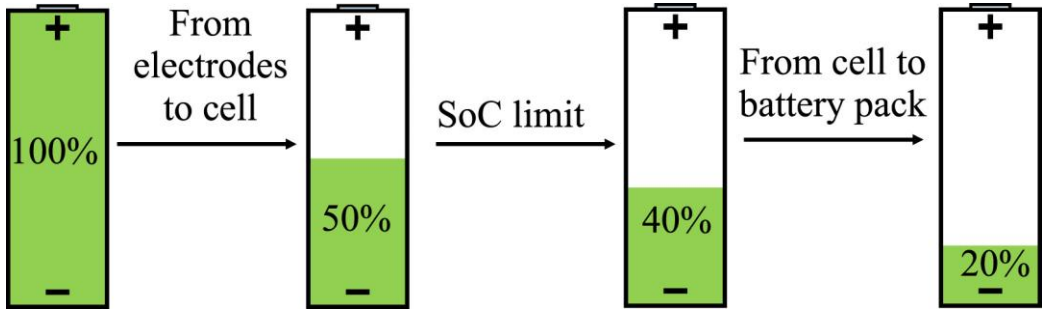

Löbberding H., et al. From cell to battery system in BEVs: Analysis of system packing efficiency and cell types

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BED values (in Wh/kg) projection for Li-S and Li-O_2 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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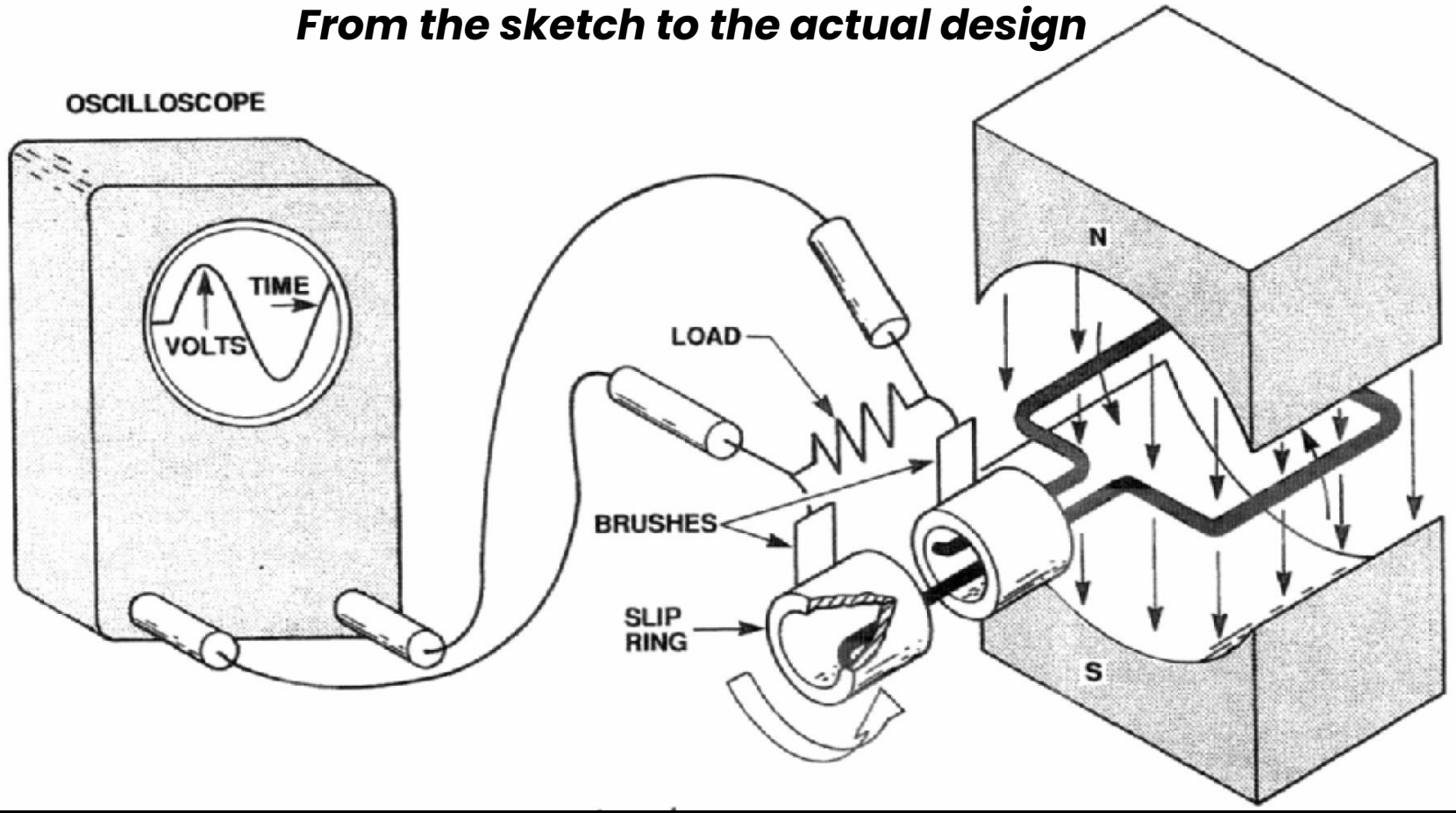
Electric machines are devices which convert electric power into mechanical power (electric motors) and vice versa (generators)

From the sketch to the actual design



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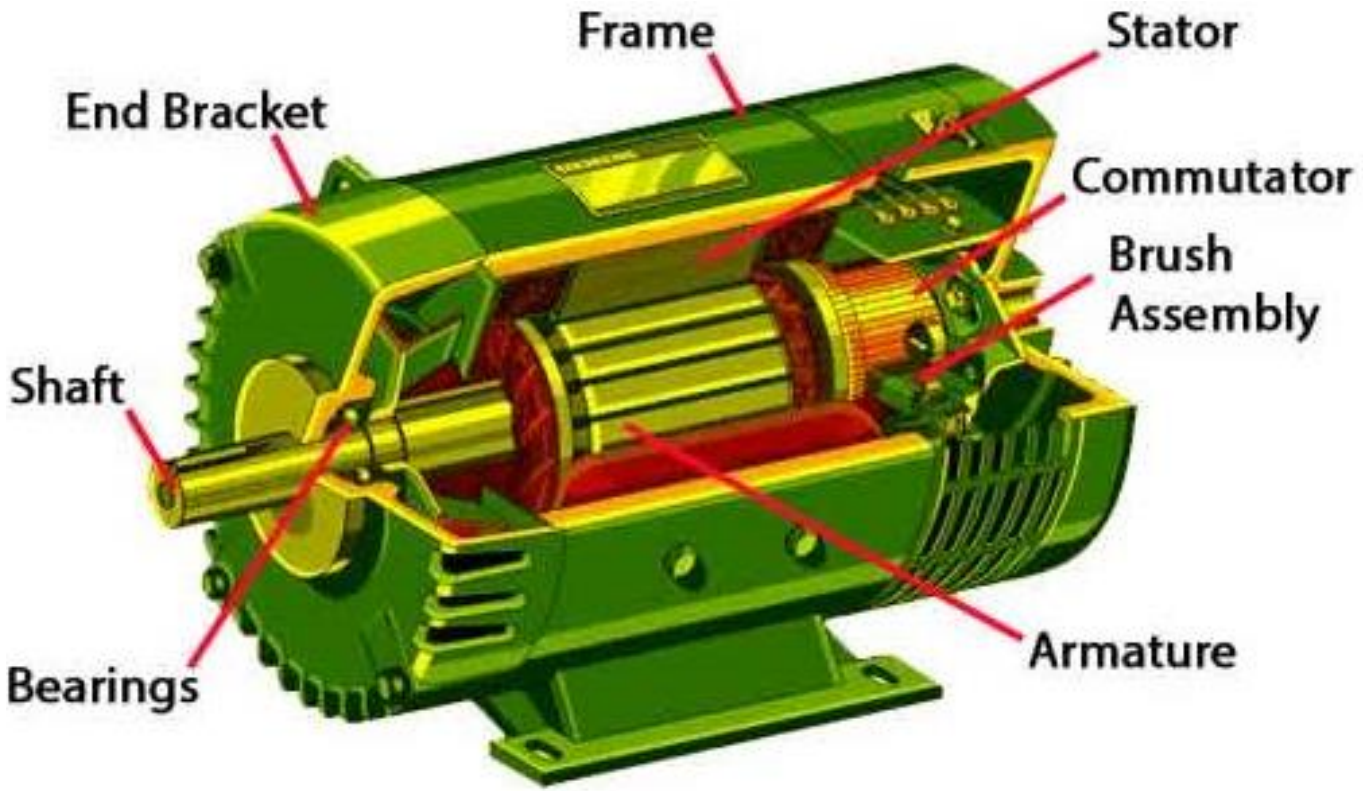

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Electric motor vs thermal engine

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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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

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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

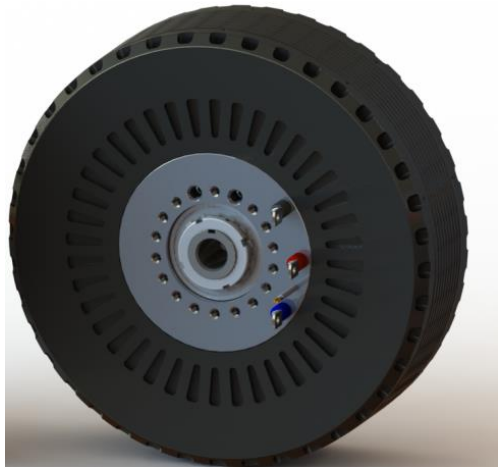
Electric motor

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

A real electric motor for aviation: EMRAX 348

Mechanical	
Type:	Axial flux motor / generator
Casing diameter:	348 mm
Axial length:	107 mm
Dry mass:	43,1 kg (AC) / 43,5 kg (CC) / 43,9 kg (LC)

Electrical	
Maximal battery voltage:	830 (HV) / 830 (MV) / 610 (LV)Vdc
Peak power (at 3250 RPM):	340 kW
Continuous power*:	up to 140 kW
Peak torque:	1100 Nm
Continuous torque*:	up to 425 Nm
Efficiency:	92-98%



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

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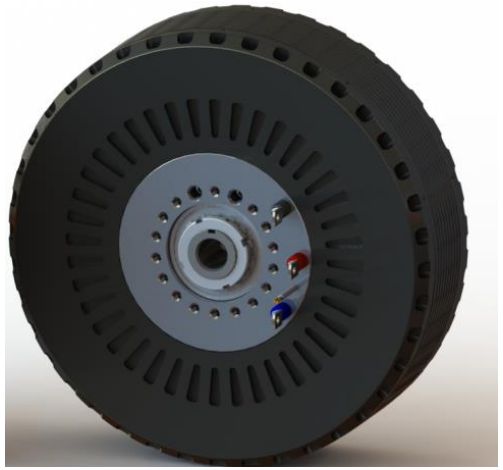

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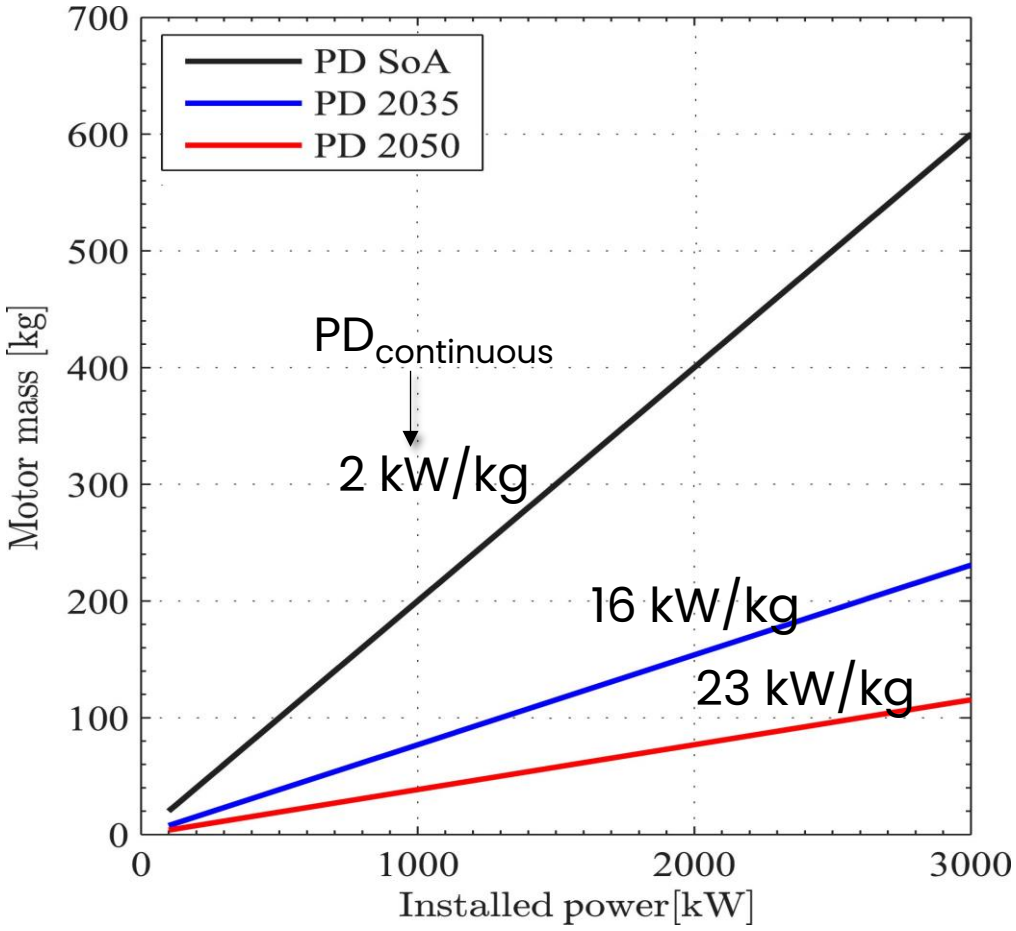
An important parameter is the power density (PD)

$PD_{continuous}$ 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



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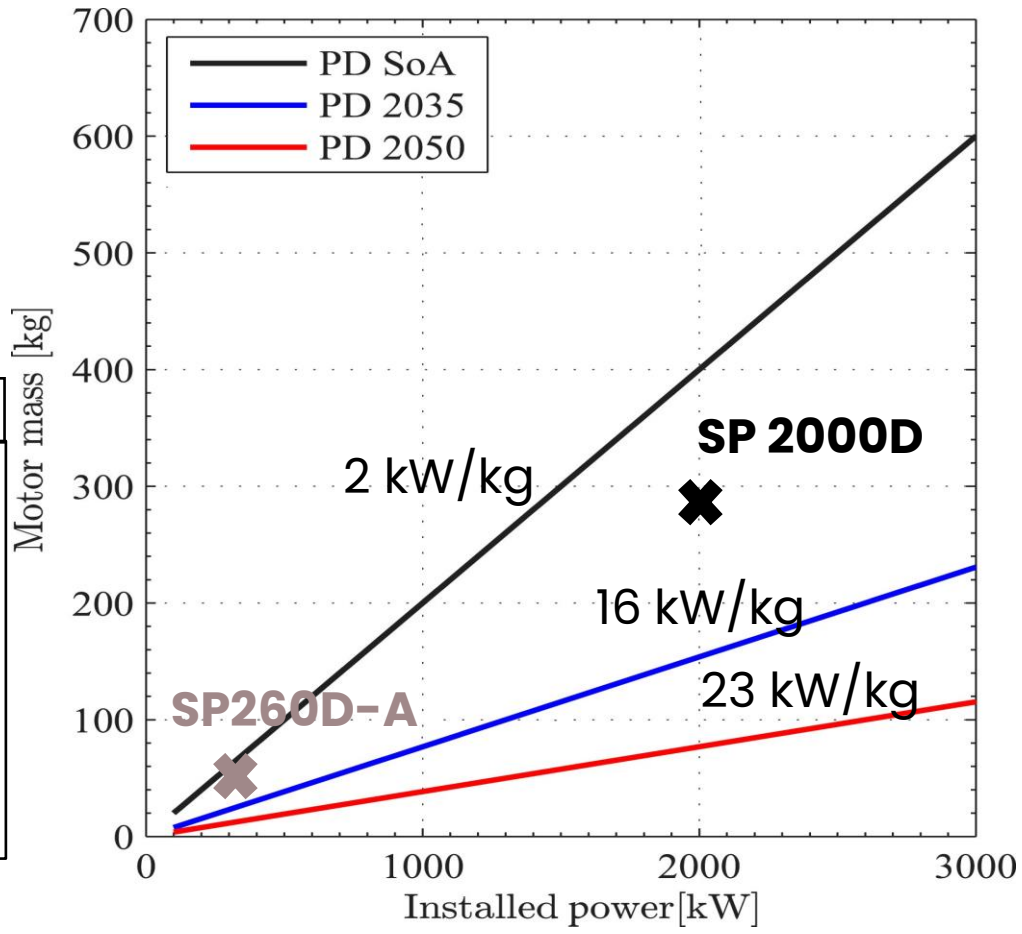
Current electric motor under development

SP260D-A

SP 2000 D



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

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

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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

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

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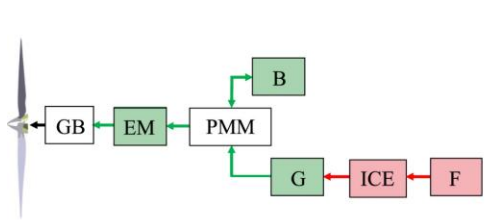
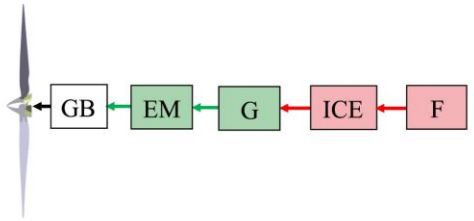
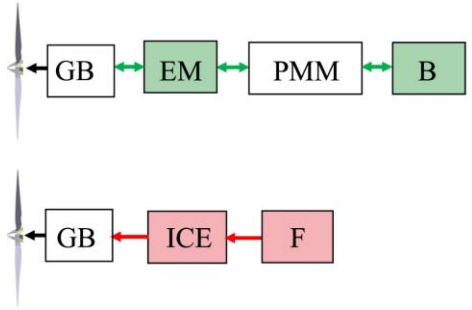


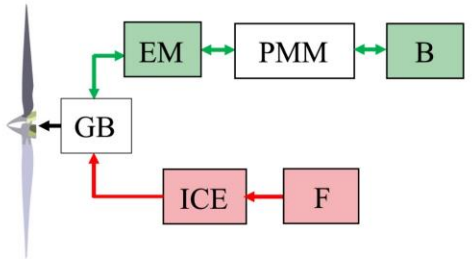
(a) Serial hybrid.



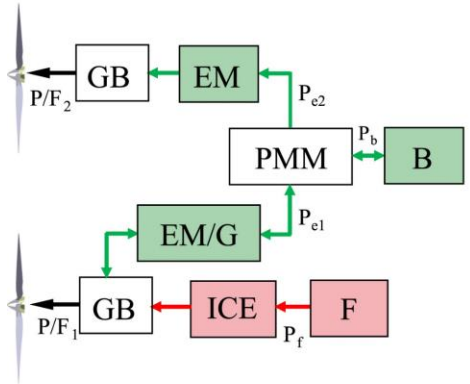
(b) Turboelectric.



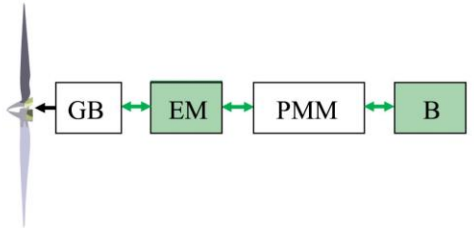
(c) Split parallel hybrid.



(d) Mechanically coupled parallel hybrid.



(e) Serial/Parallel hybrid.



(f) Full-electric.

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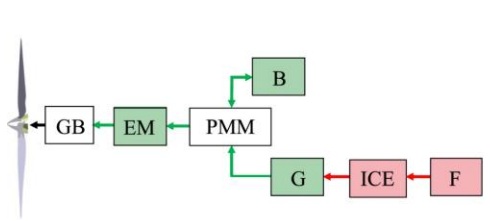

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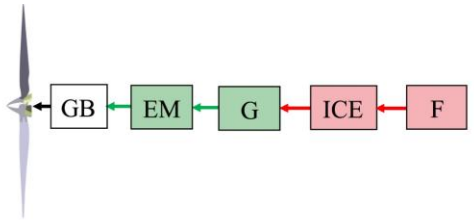
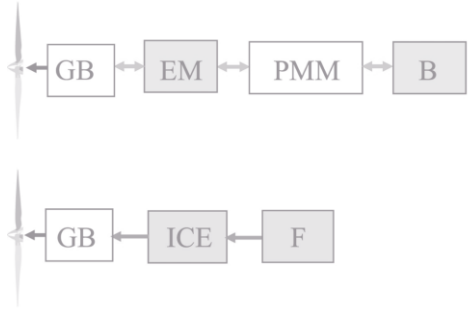


(b) Turboelectric.



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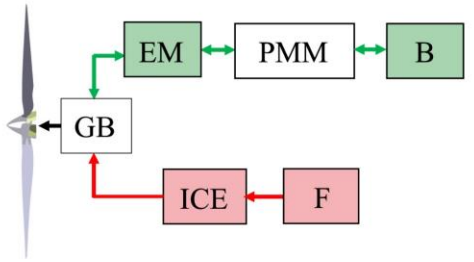

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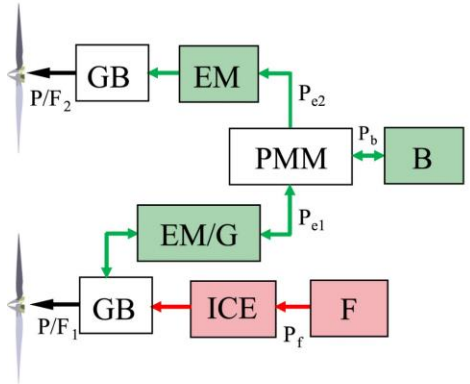
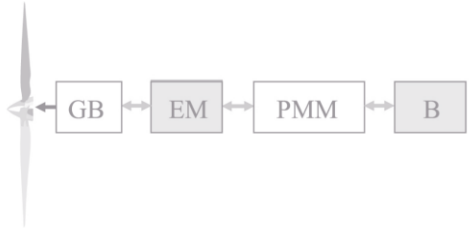


(e) Serial/Parallel hybrid.

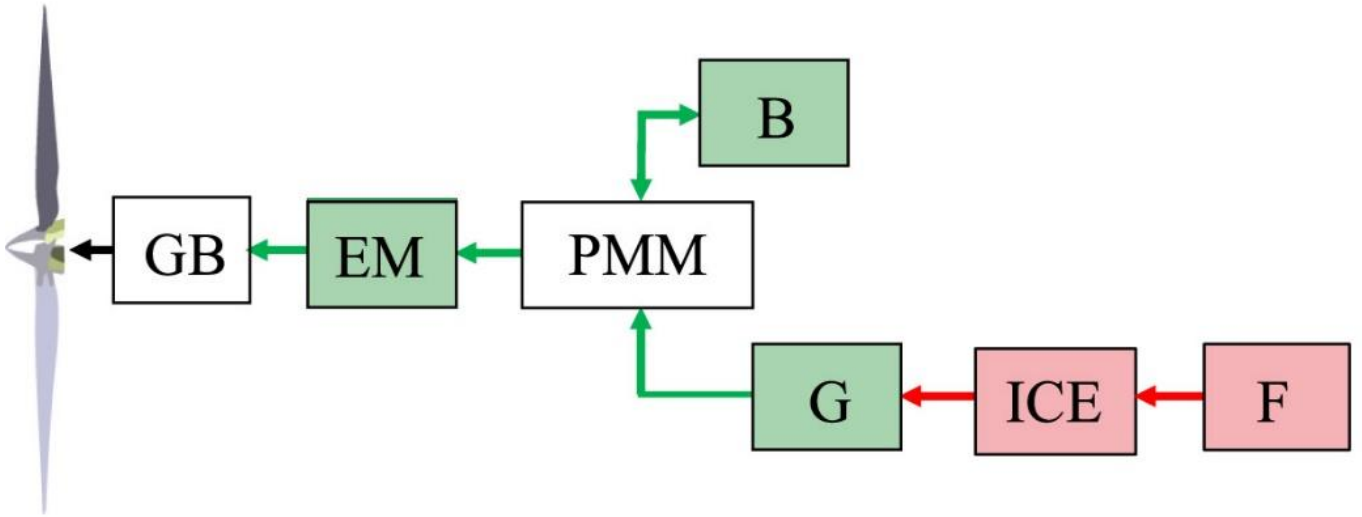


(f) Full-electric.

Powertrain architecture

SERIAL

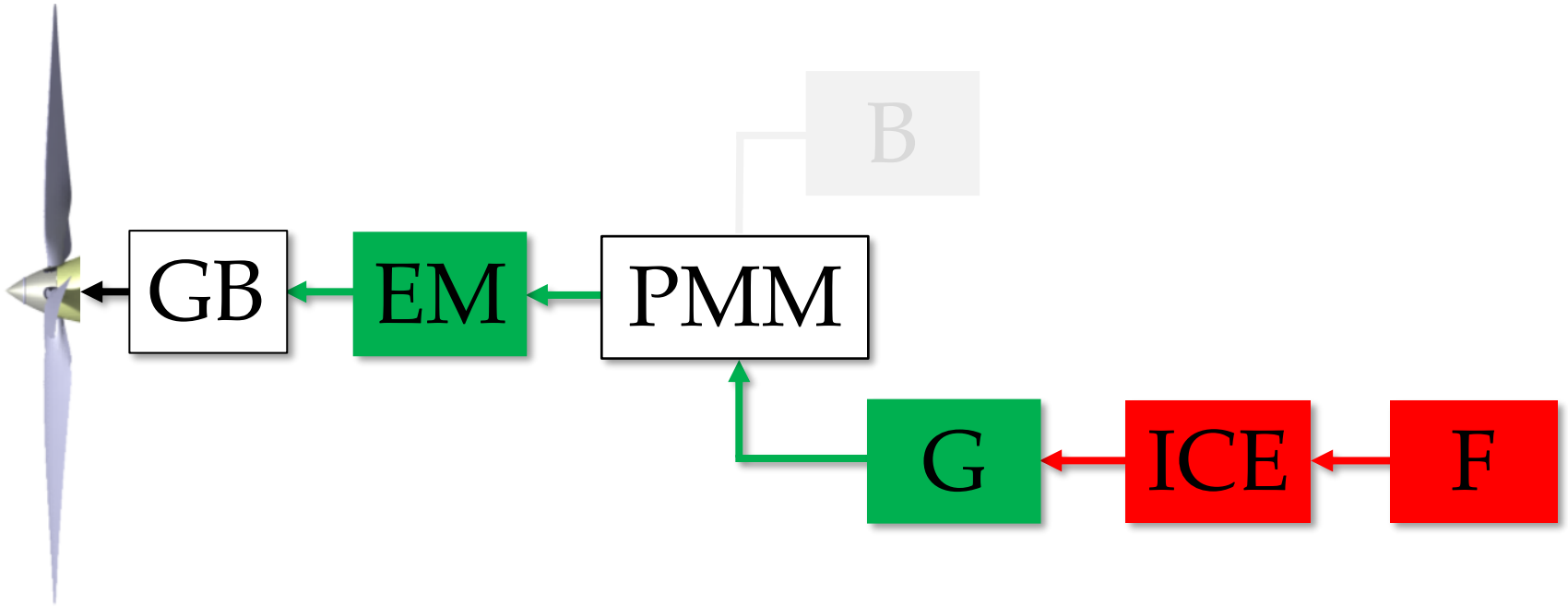
The **serial** hybrid architecture has a **thermal chain** in **series** with the **electric** one. In particular, the thermal chain is composed of an internal combustion engine fed by the fuel, which generates mechanical power that is transformed into electric power by a generator. The electric chain 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**.



Powertrain architecture

SERIAL

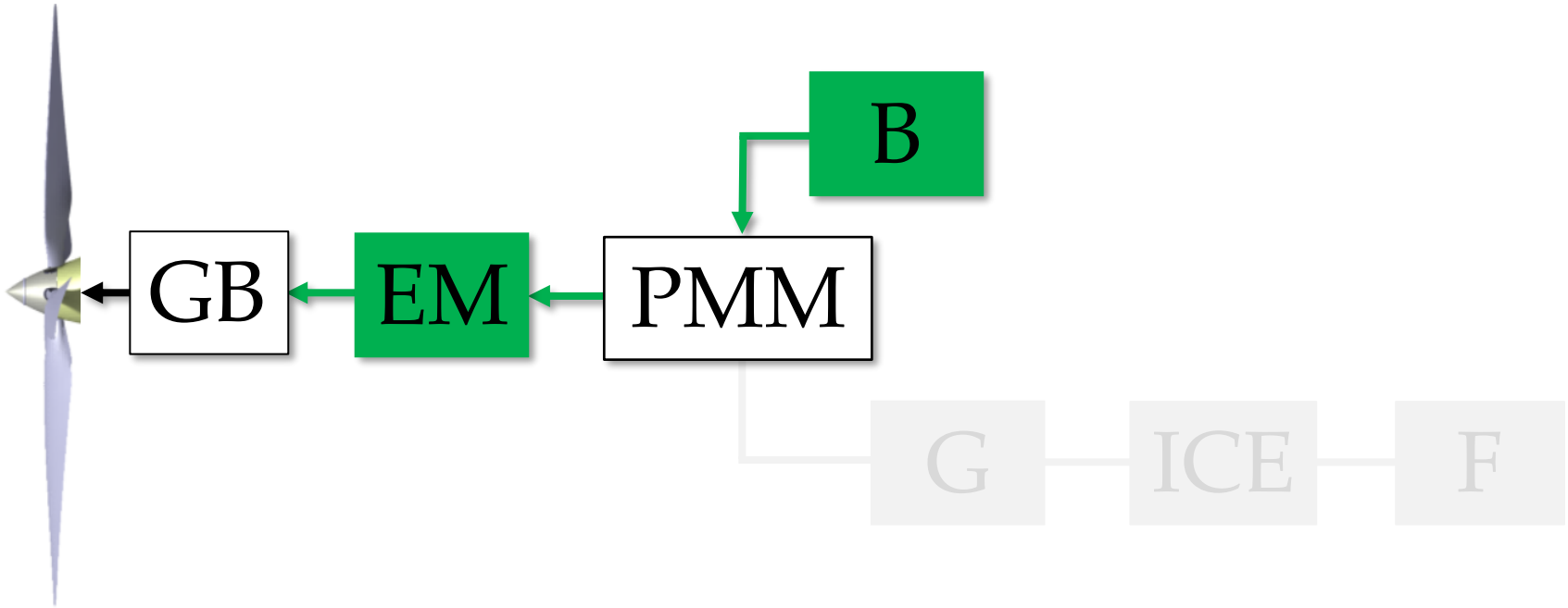
Power comes only from ICE



Powertrain architecture

SERIAL

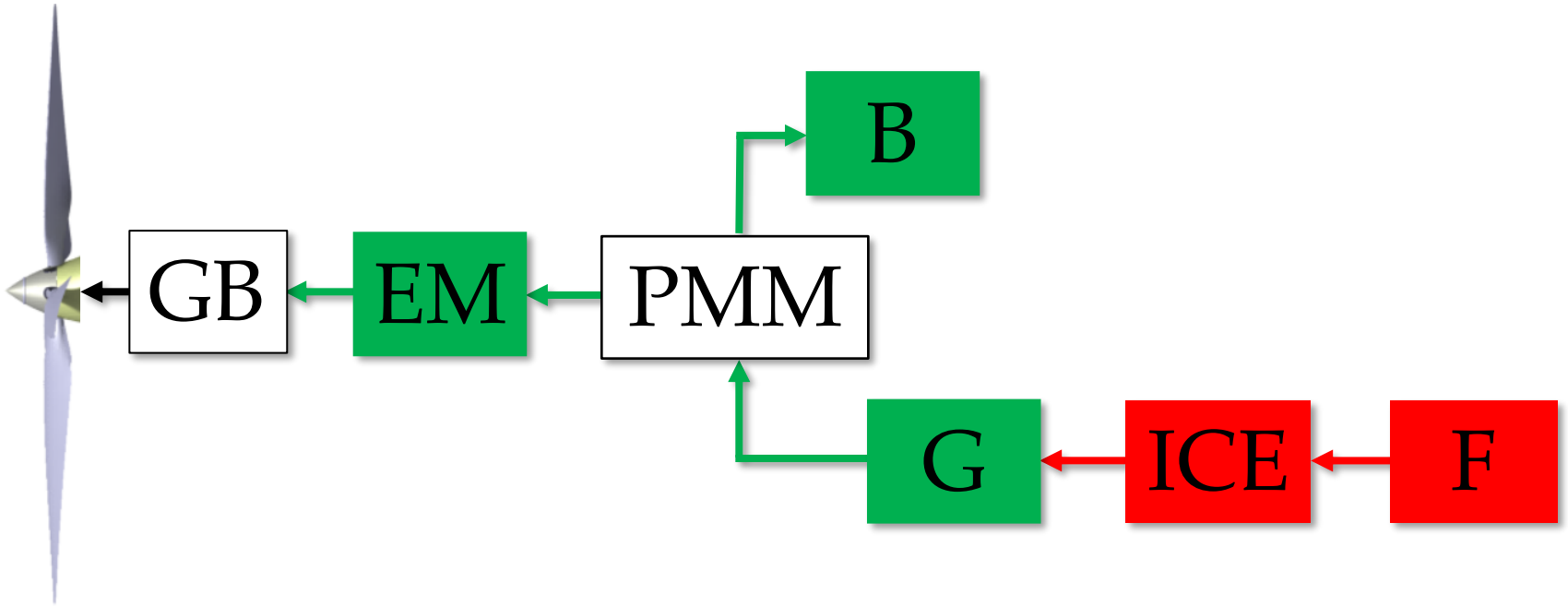
Power comes only from battery



Powertrain architecture

SERIAL

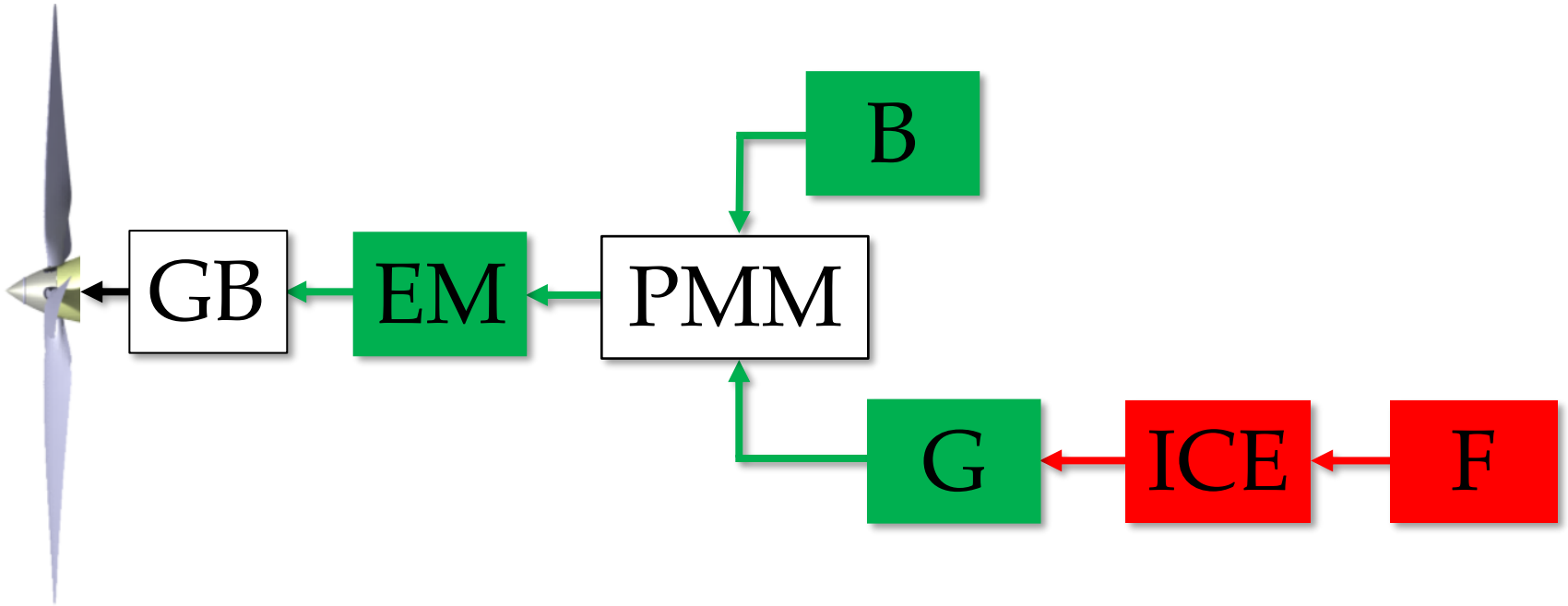
Battery is recharged



Powertrain architecture

SERIAL

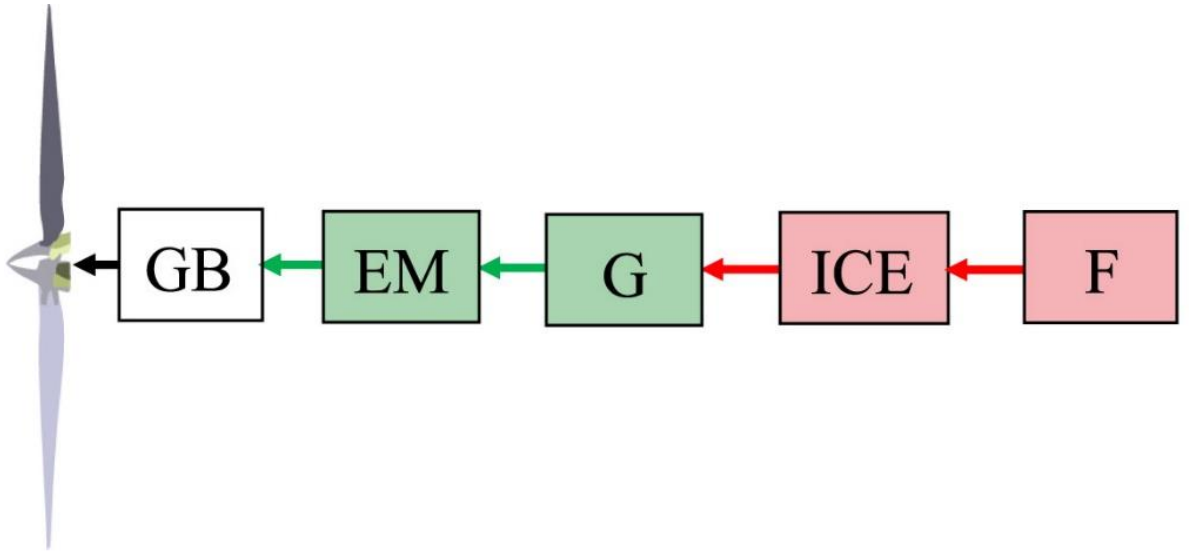
Power comes from both battery and ICE



Powertrain architecture

TURBOELECTRIC

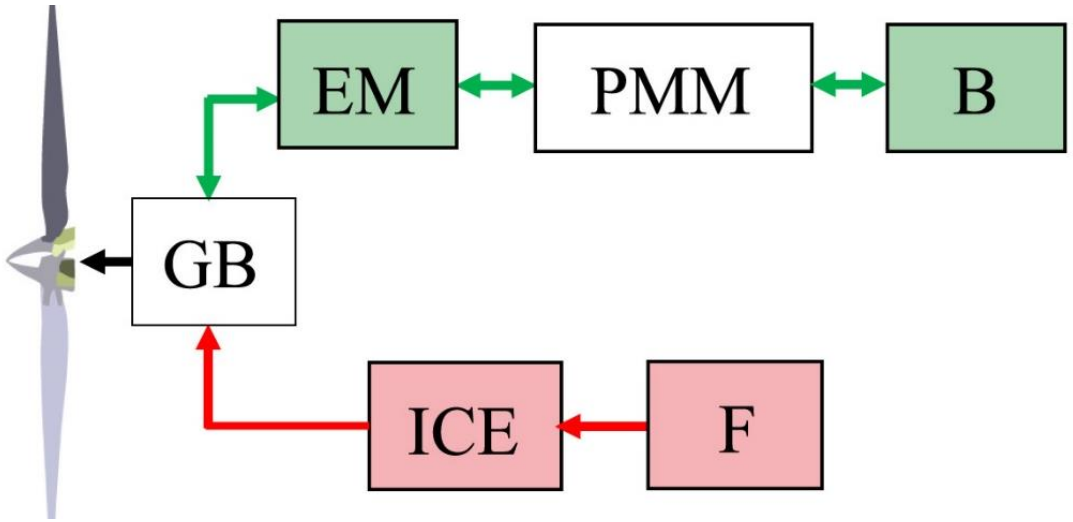
The **turboelectric** architecture has a **thermal chain** in **series** with the **electric** one. The electric chain is composed of generators and electric motors, and the main difference with respect to the serial hybrid architecture relies in the fact that **the battery pack is missing** in the turboelectric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



Powertrain architecture

PARALLEL

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

Hybrid-electric aircraft

Battery
Definition and data

Electric motor
Definition and data

Power electronics
Definition and data

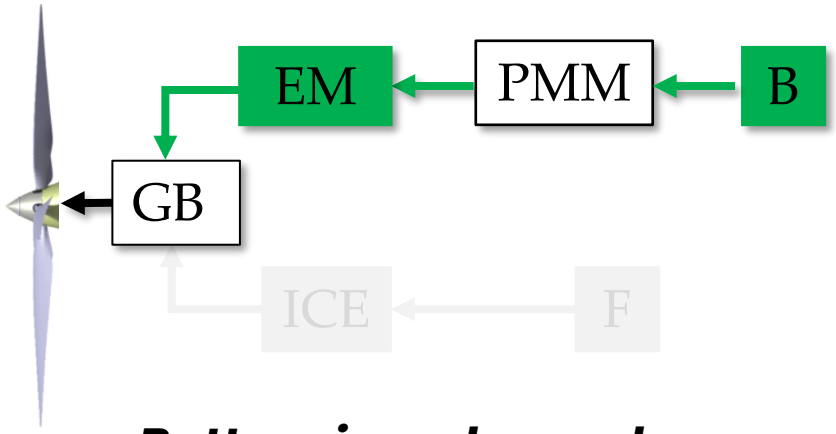
Powertrain architecture

Serial
Turbo-electric
Parallel
Serial/Parallel

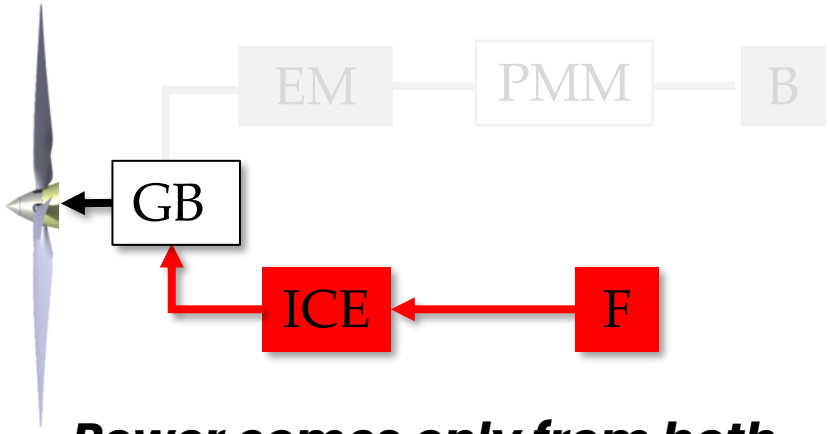
How to design HEA
Battery
Electric motor
Power management

PARALLEL

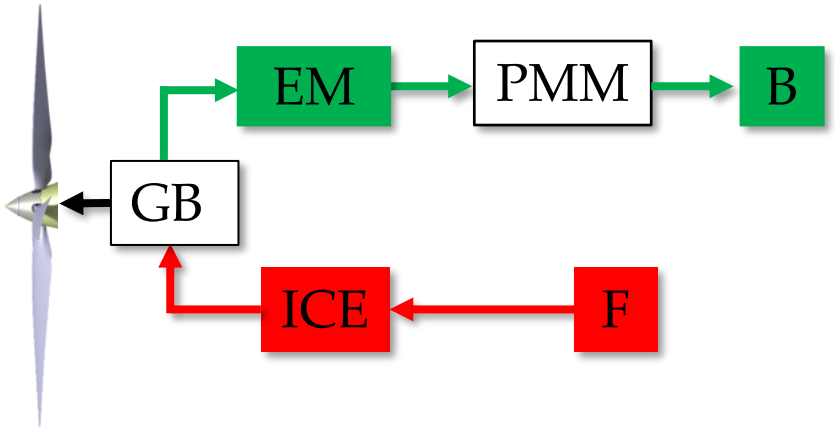
Power comes only from battery



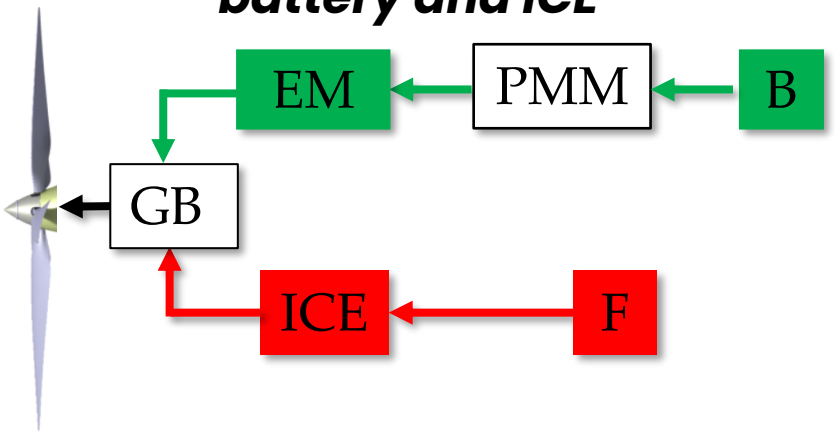
Power comes only from ICE



Battery is recharged



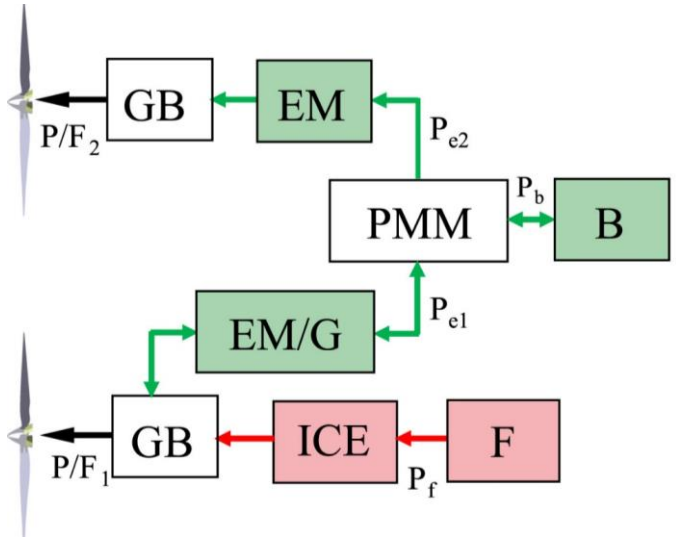
Power comes only from both battery and ICE



Powertrain architecture

SERIAL-PARALLEL

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

Hybrid-electric aircraft

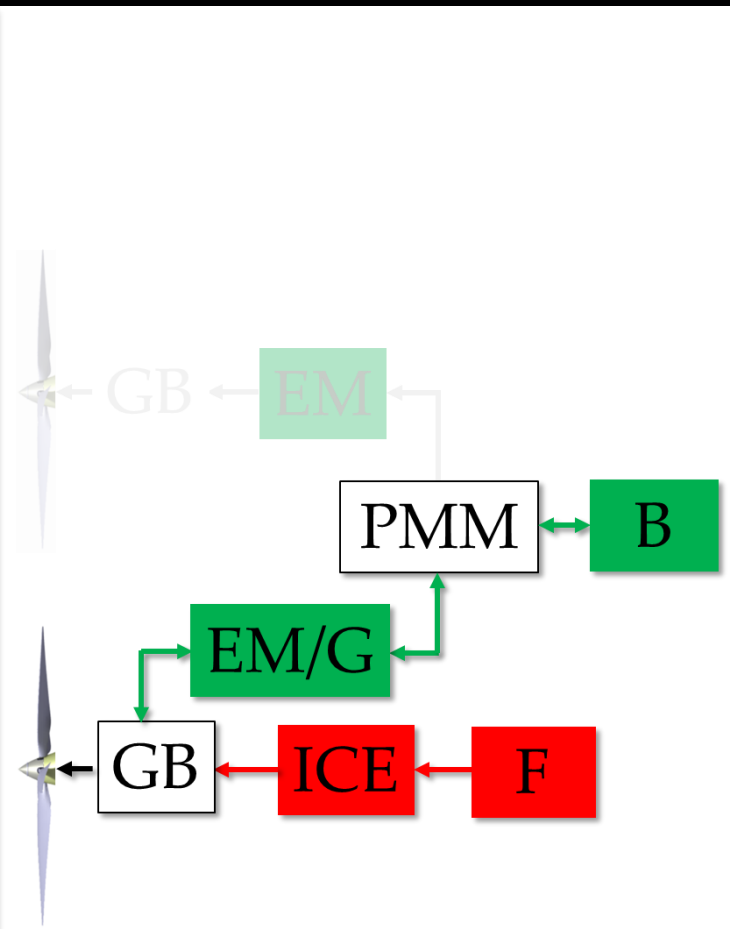
Battery
Definition and data

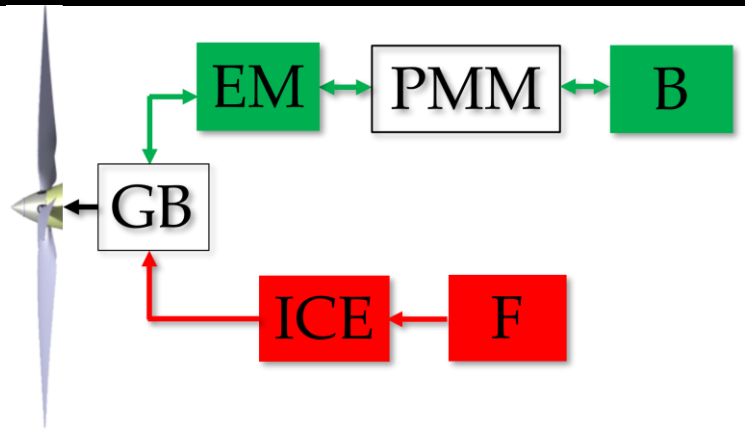
Electric motor
Definition and data

Power electronics
Definition and data

Powertrain architecture
Serial
Turbo-electric
Parallel
Serial/Parallel

How to design HEA
Battery
Electric motor
Power management





Parallel powertrain

Powertrain architecture

Hybrid-electric aircraft

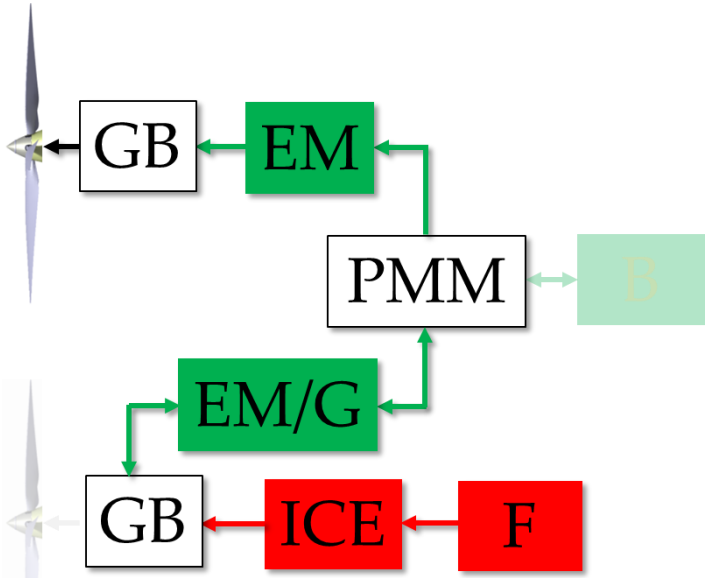
Battery
Definition and data

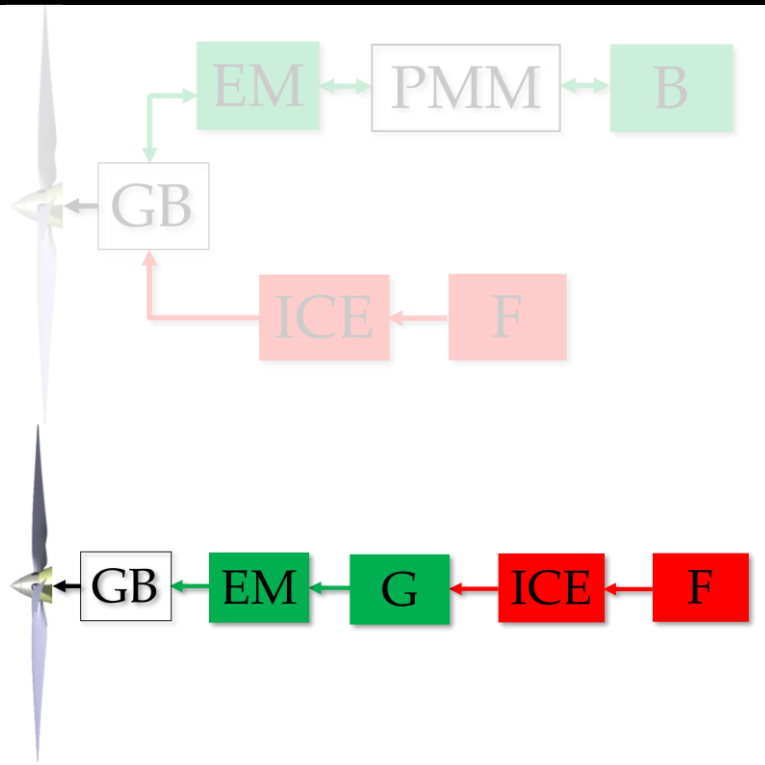
Electric motor
Definition and data

Power electronics
Definition and data

Powertrain architecture
Serial
Turbo-electric
Parallel
Serial/Parallel

How to design HEA
Battery
Electric motor
Power management





Parallel powertrain

Turboelectric powertrain

Powertrain architecture

Hybrid-electric aircraft

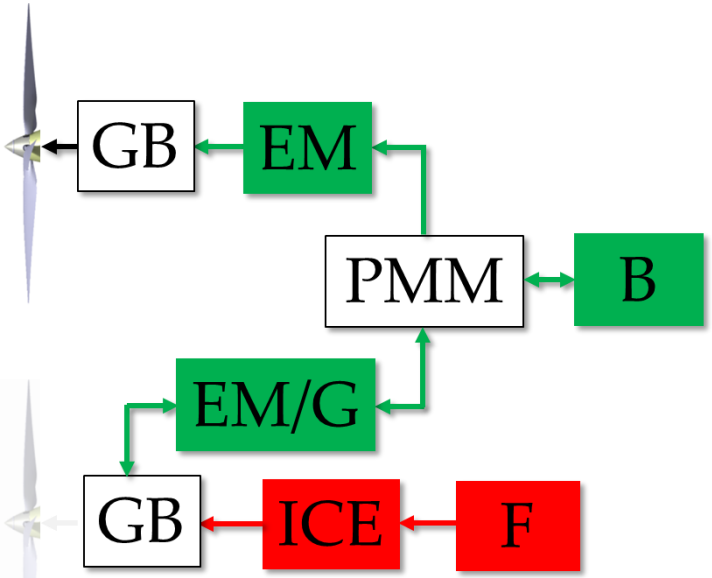
Battery
Definition and data

Electric motor
Definition and data

Power electronics
Definition and data

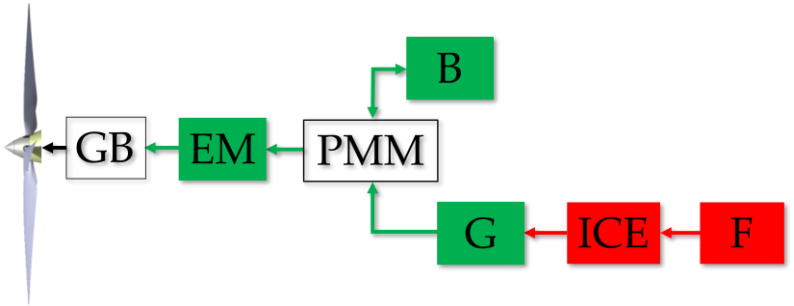
Powertrain architecture
Serial
Turbo-electric
Parallel
Serial/Parallel

How to design HEA
Battery
Electric motor
Power management



Parallel powertrain

Turboelectric powertrain



Serial powertrain

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

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Battery
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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.

$\boldsymbol{H_P}$ 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

Powertrain architecture

Hybrid-electric aircraft

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Power electronics
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Serial/Parallel

How to design HEA
Battery
Electric motor
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.

$\boldsymbol{H_E}$ 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.

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

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

How to design HEA

Hybrid-electric aircraft

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Power electronics
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Powertrain architecture
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How to design HEA
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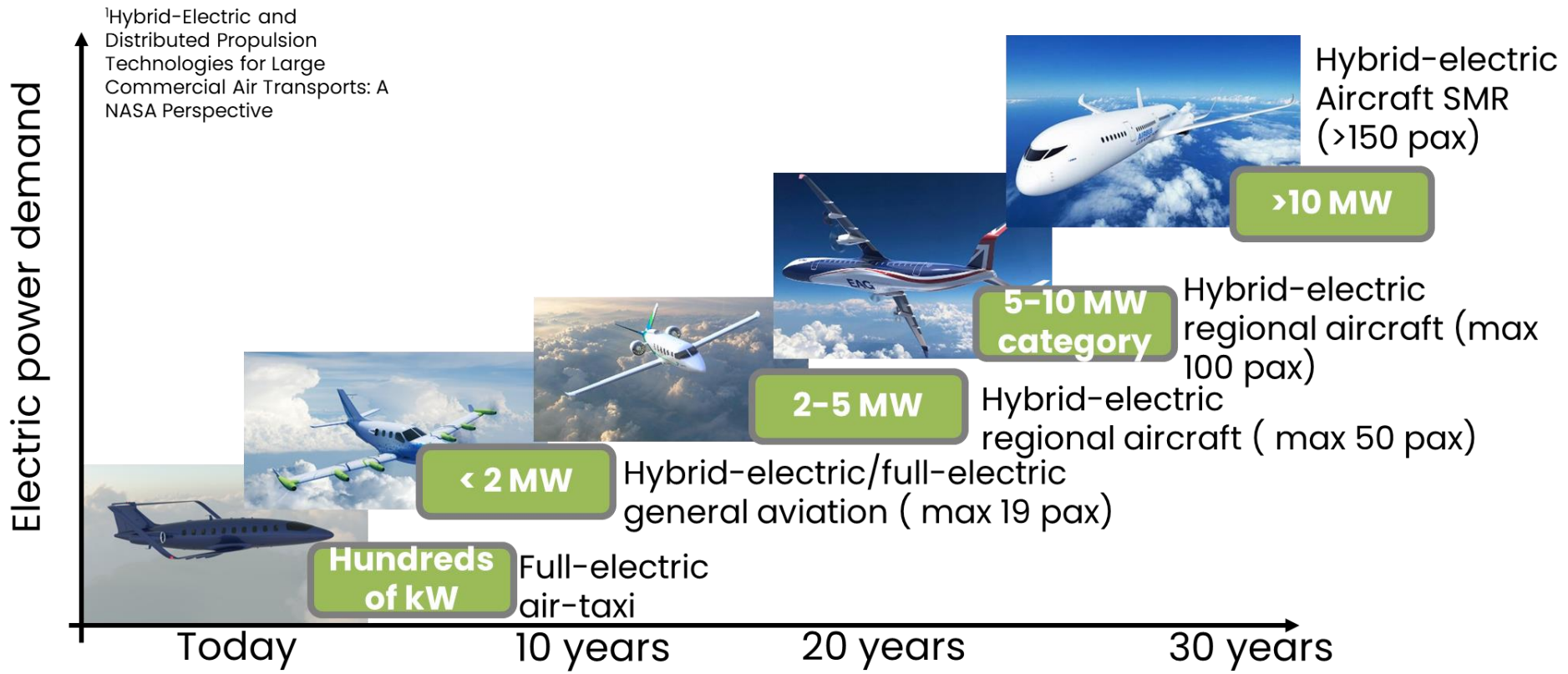

How to design HEA

Hybrid-electric aircraft

Battery
Definition and data

Electric motor
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Power electronics
Definition and data

Powertrain architecture
Serial
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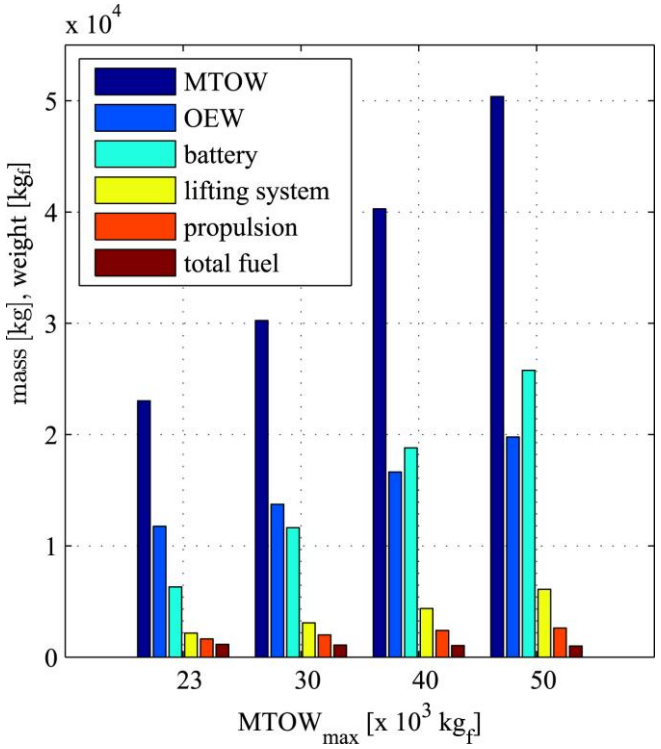
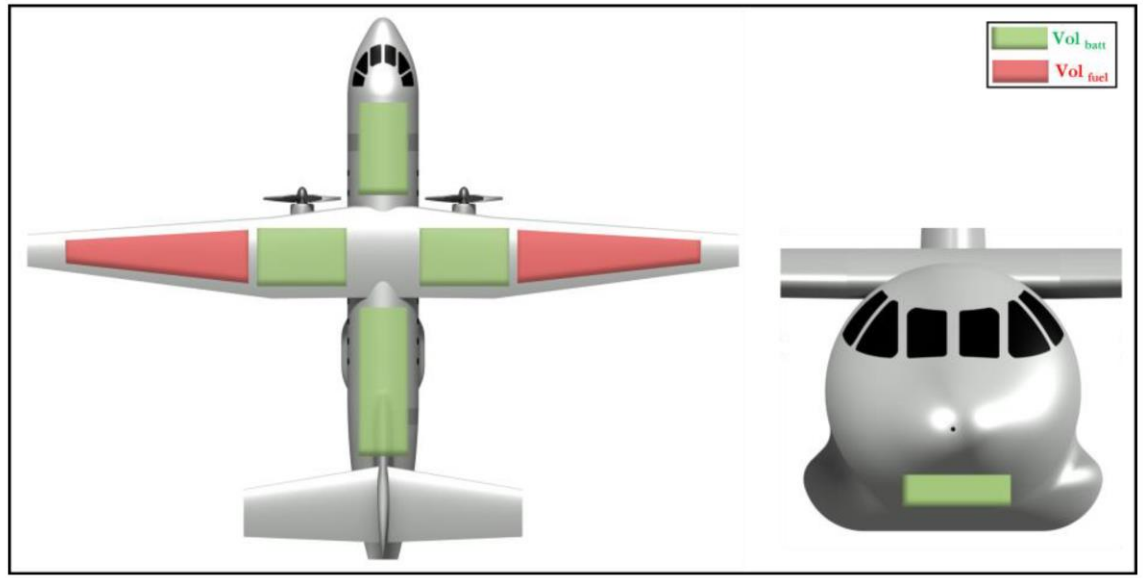
Parallel
Serial/Parallel

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.



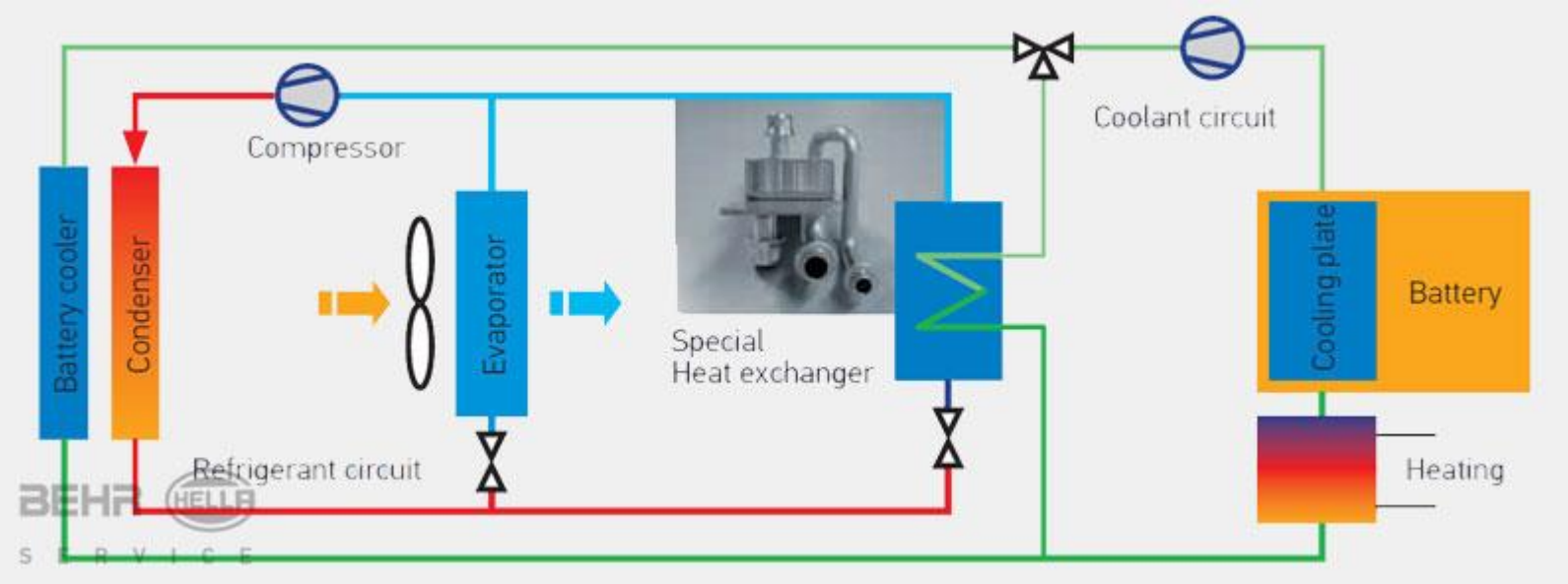


How to design HEA

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

Hybrid-electric aircraft

Battery
Definition and data

Electric motor
Definition and data

Power electronics
Definition and data

Powertrain architecture
Serial
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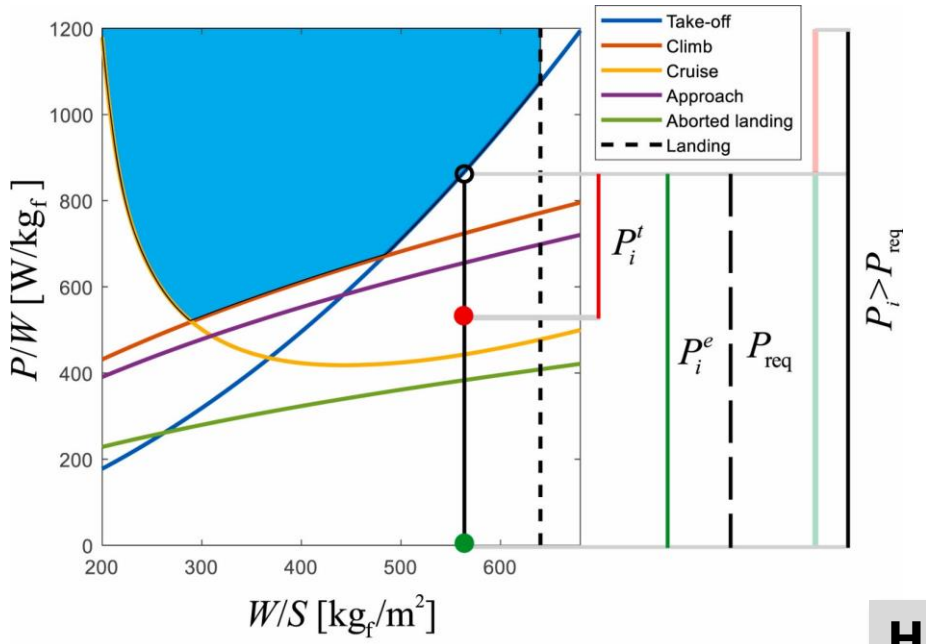
Serial/Parallel

How to design HEA

Battery
Electric motor
Power management

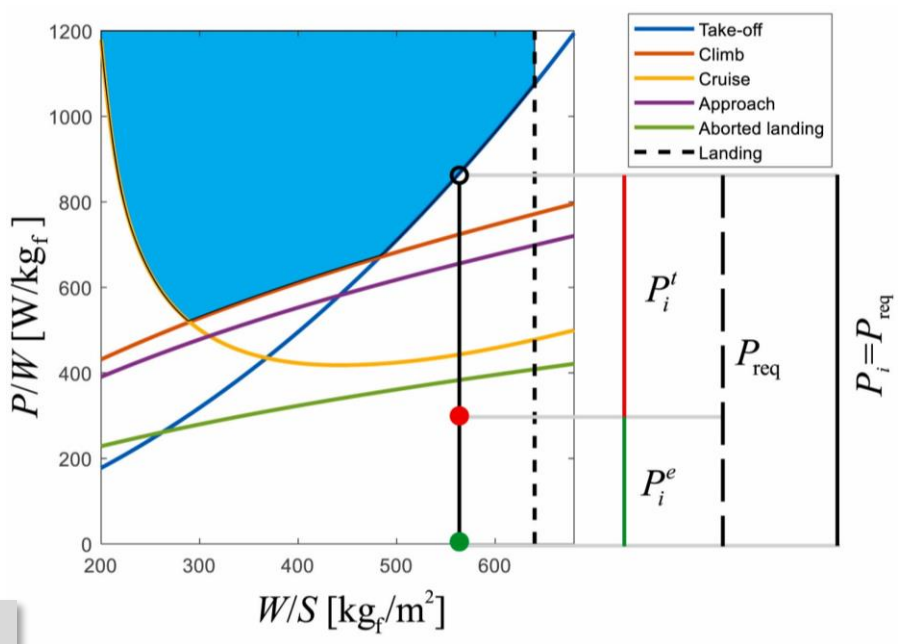
The matching chart is a fundamental tool to assess installed power, also for the hybrid-electric aircraft

The choice of the powertrain architecture plays a crucial role



(a) Serial architecture.

H_P



(b) Parallel architecture.

How to design HEA

Hybrid-electric aircraft

Battery
Definition and data

Electric motor
Definition and data

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Powertrain architecture
Serial
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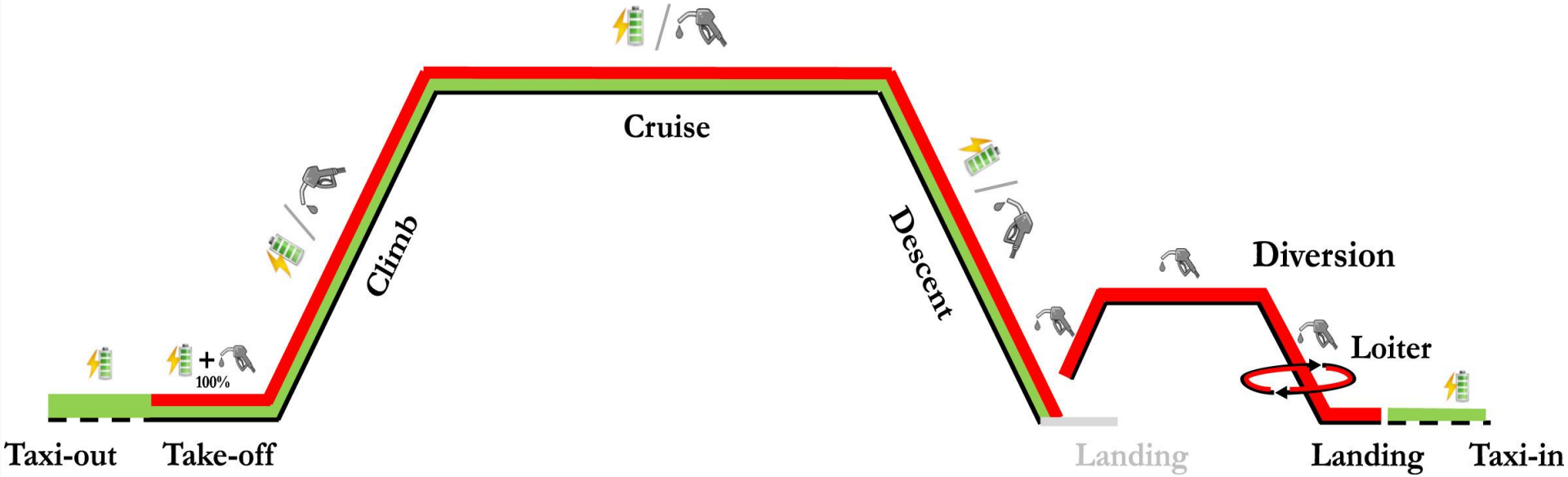
Serial/Parallel

How to design HEA

Battery
Electric motor
Power management

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

End