



# MEA 2021 MORE ELECTRIC AIRCRAFT

Bordeaux, France  
October, 20-21, 2021



## a typical MDO process for future Hybrid Electric aircrafts



*Laplace*

Xavier  
Roboam

on behalf of

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Y. Bertin, M. Fenot, E. Videcoq, A.  
Zeaiter (Phd Student)



P. Simon



This project has received funding from the [European Union's Horizon 2020 (cleansky 2 JTI) research and innovation programme, 2014-2024] under grant agreement No 715483

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- ✓ Engine benefits: design and operation may be revisited with power hybridization



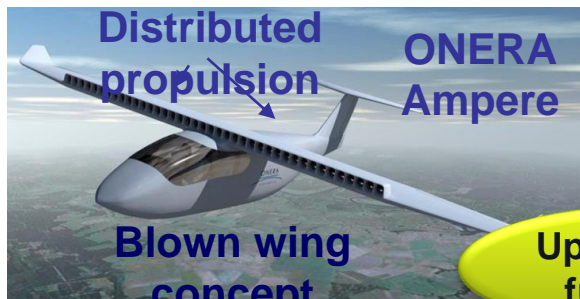
Gas turbine

- ✓ Energy benefits: turboshaft efficiency

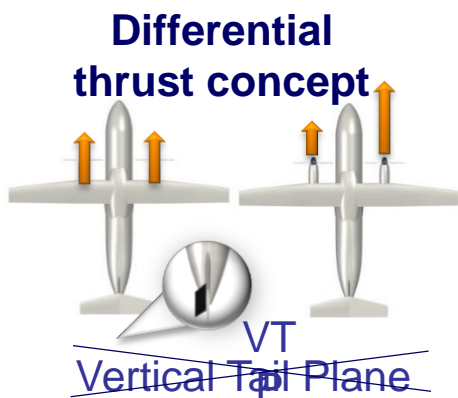
$\eta_{GT} \sim 10\%$  for thermal descent or taxi

$\eta_{GT} \sim 90\%$  for electric descent or taxi

- ✓ Aerodynamic benefits: several concepts



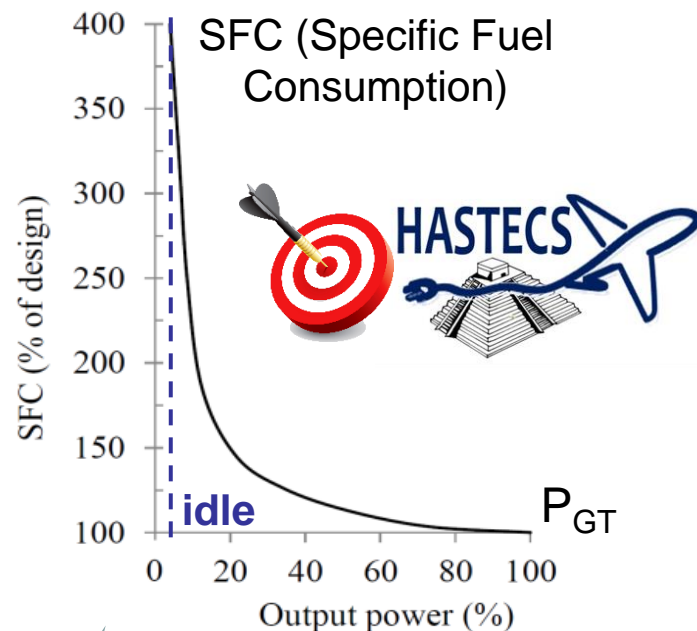
Up to  $-2.5\%^*$  fuel burn



$\sim -4.5\%^*$  Fuel burn



$< -13\%^* ??$  Fuel burn



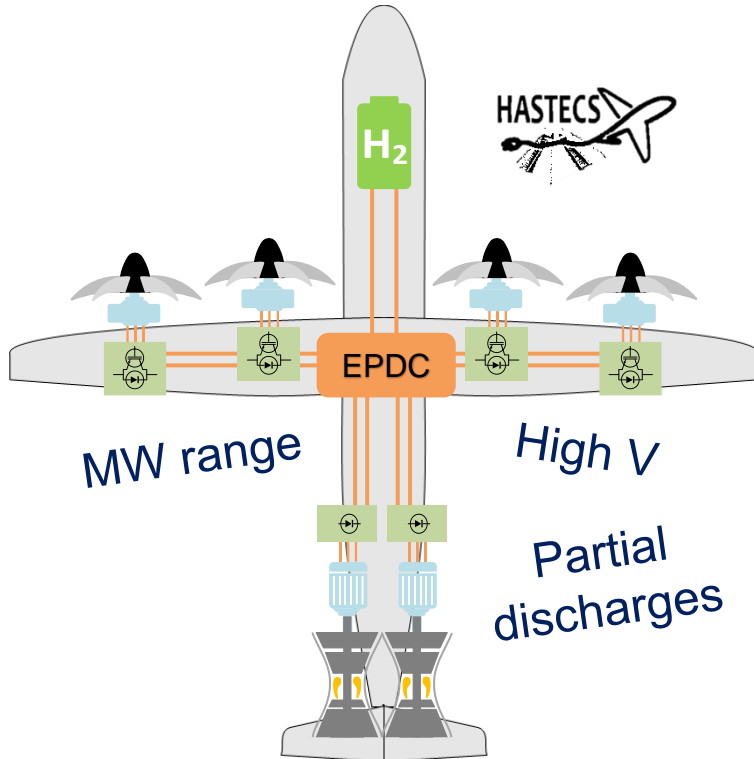


**H**ybrid **A**ircraft  
**A**cademic re**S**earch on **T**hermal  
 & **E**lectrical **C**omponents and **S**ystems



**AIRBUS**

## Series Hybrid electric Architecture



(regional, 70 pax)

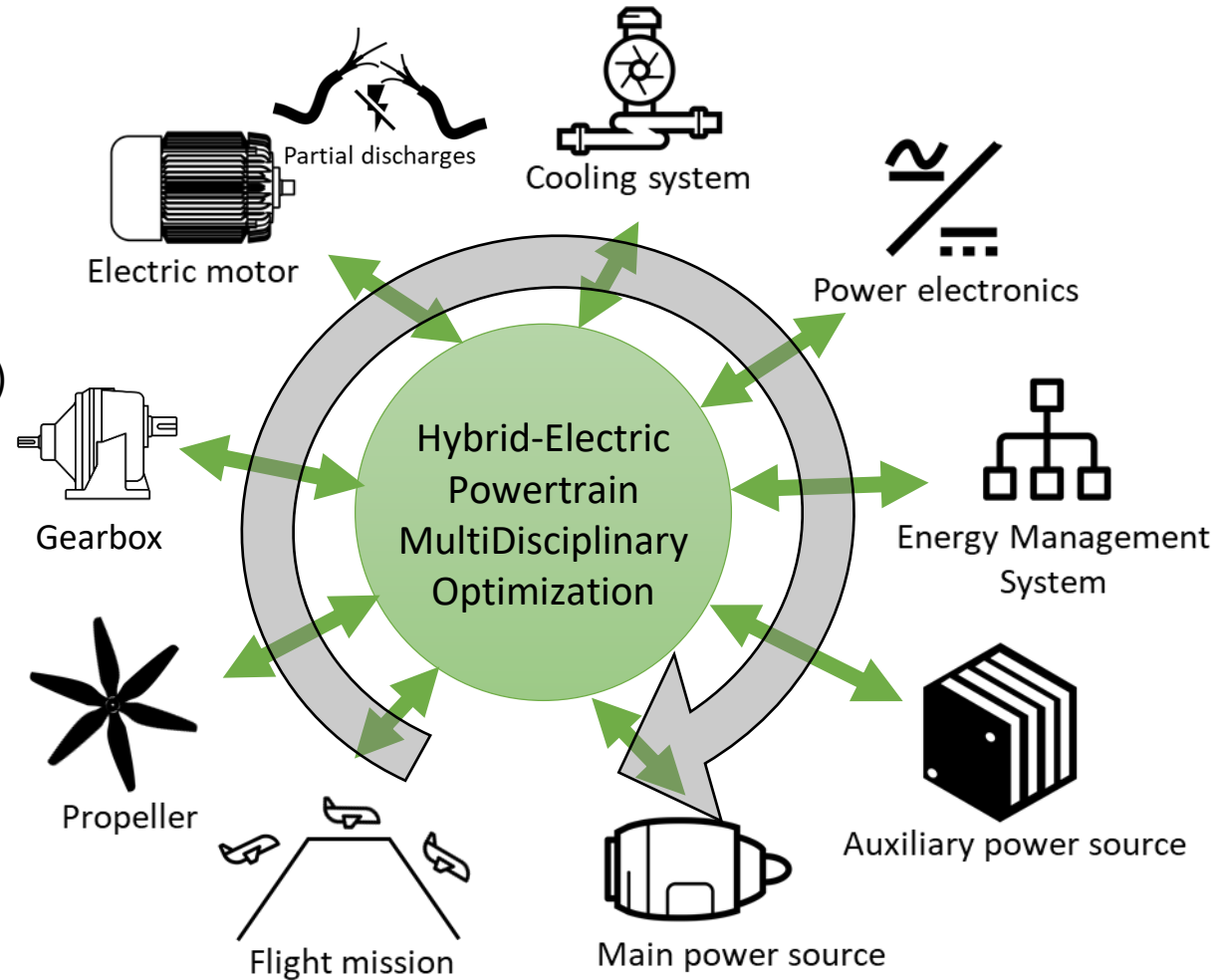
LEGEND	
PROPELLER + GEARBOX	
E-MOTOR + COOLING	
CABLE	
DC/AC CONVERTER + COOLING	
ELECTRICAL POWER DISTRIBUTION CENTER	
BATTERY/FUEL CELL	
AC/DC CONVERTER	
E-GENERATOR	
TURBOSHAFT	



# Multidisciplinary Design Optimization (MDO) of the hybrid-electric aircraft powertrain

A set of coupled sizing variables :

- Geometry (propeller, emotor)
- Mechanical (gearbox)
- Electromagnetic (emotor)
- Electrical (bus voltage)
- Source sizing (fuel cell, turboshaft)
- Energy management

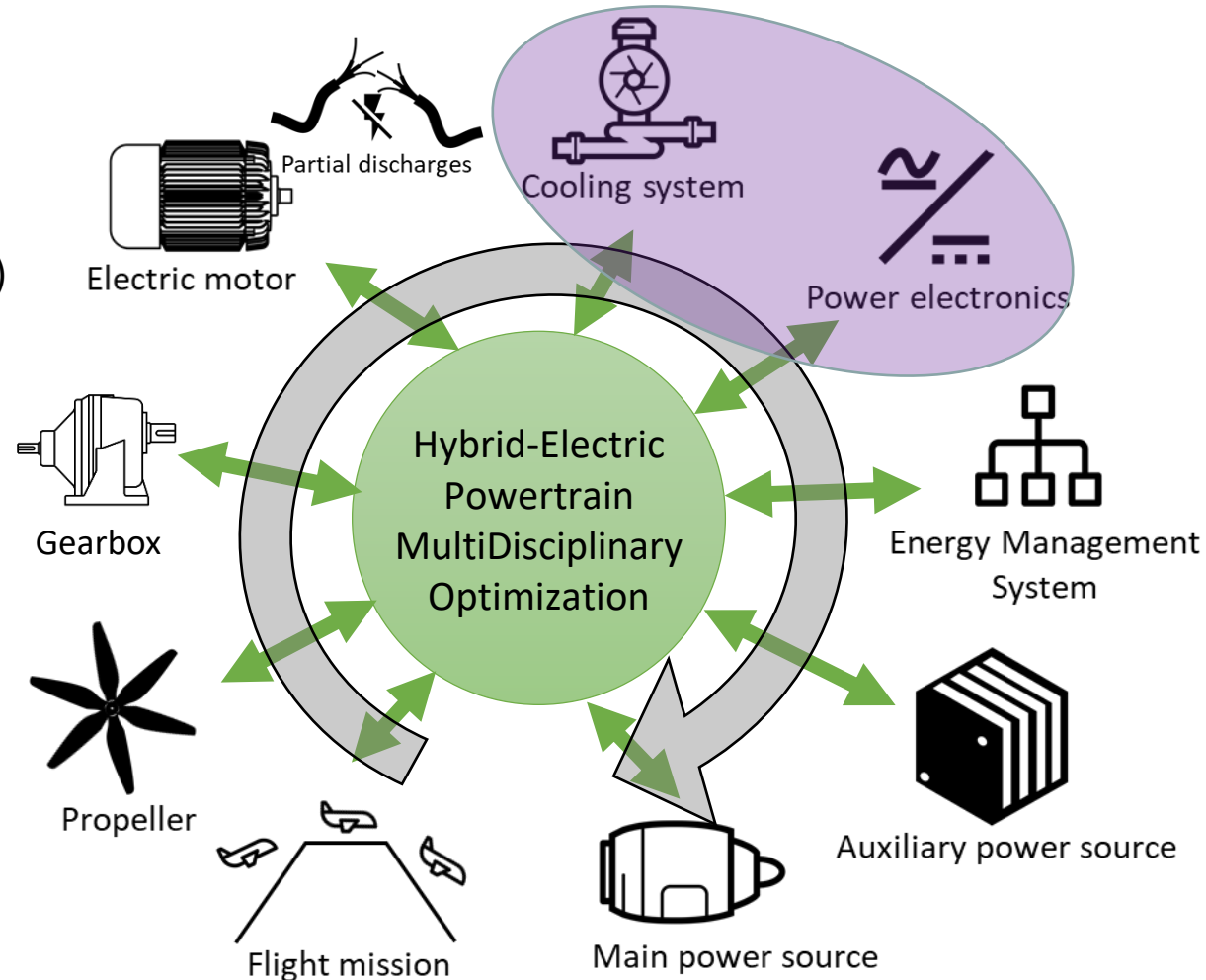


# Multidisciplinary Design Optimization (MDO) of the hybrid-electric aircraft powertrain

## ➤ Design of highly integrated power electronics with its cooling

A set of coupled sizing variables :

- Geometry (propeller, emotor)
- Mechanical (gearbox)
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# Multidisciplinary Design Optimization (MDO) of the hybrid-electric aircraft powertrain

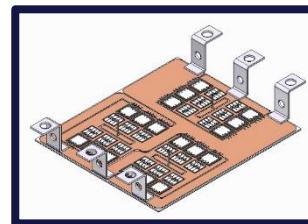
## ➤ Design of highly integrated power electronics with its cooling

Specific power increase  
(kW/kg)



Heat exchanger optimization (WP4)

Power Electronics losses reduction



Bus bar optimization



Improved components

Small rating components

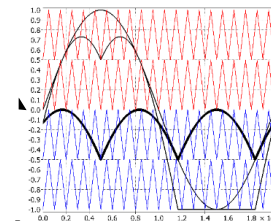
Control strategies

New generation IGBT

SiC components

Direct series association

Multilevel architecture

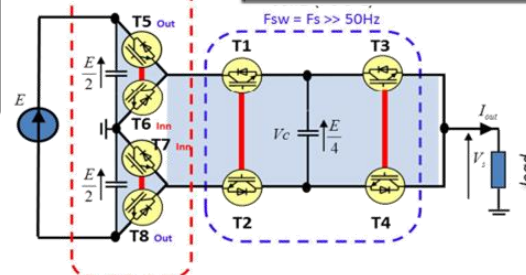


DPWMMIN  
5-level

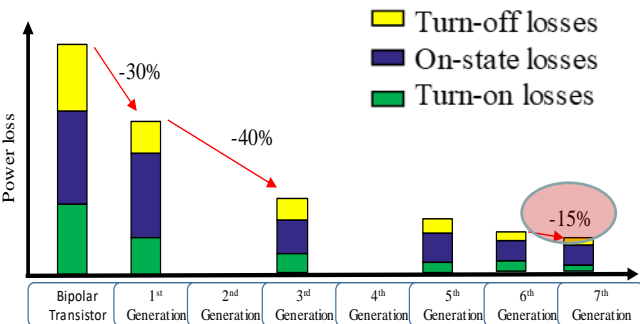
ANPC-5L  
Beyond 2kV bus

Cell2 (DC-2L)  
Fsw = 50Hz

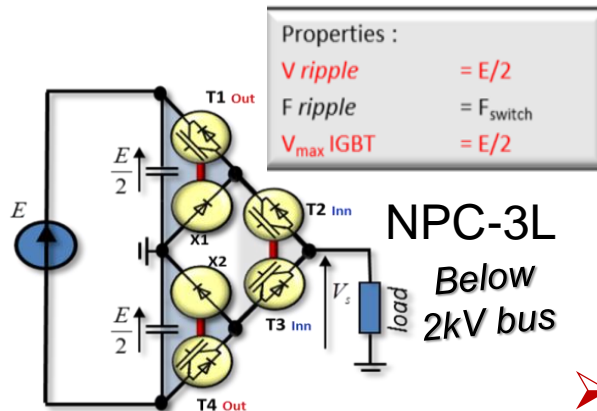
Properties :	
V ripple	= E/4
F ripple	= 4 * F <sub>switch</sub>
V <sub>max</sub> IGBT	= E/4



➤ MW range ;  $\eta \sim 99\%$



1200-1700V Si 7th generation @ low conduction losses



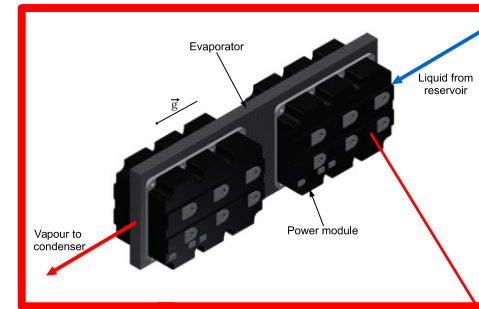
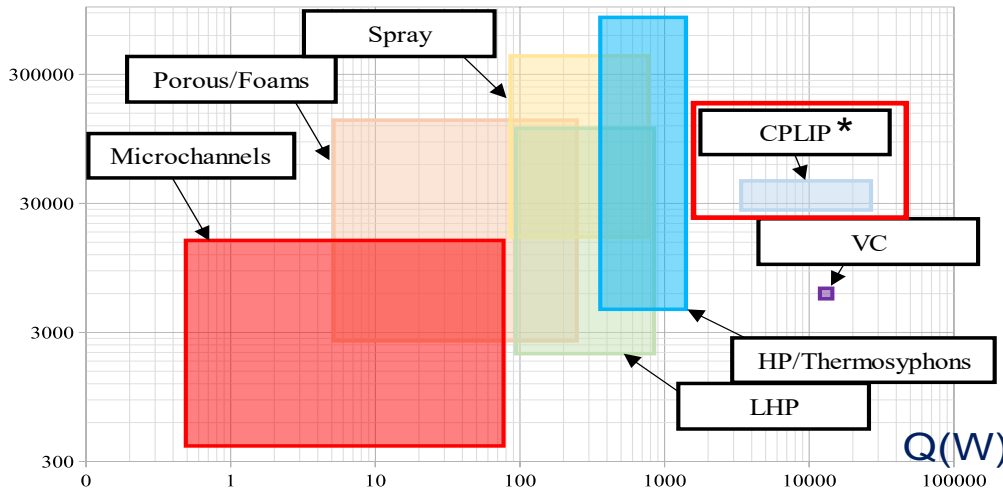
Properties :	
V ripple	= E/2
F ripple	= F <sub>switch</sub>
V <sub>max</sub> IGBT	= E/2

NPC-3L  
Below 2kV bus

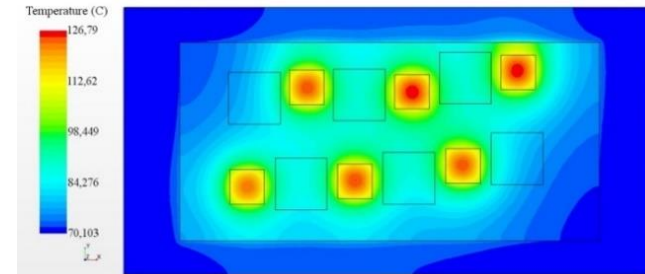
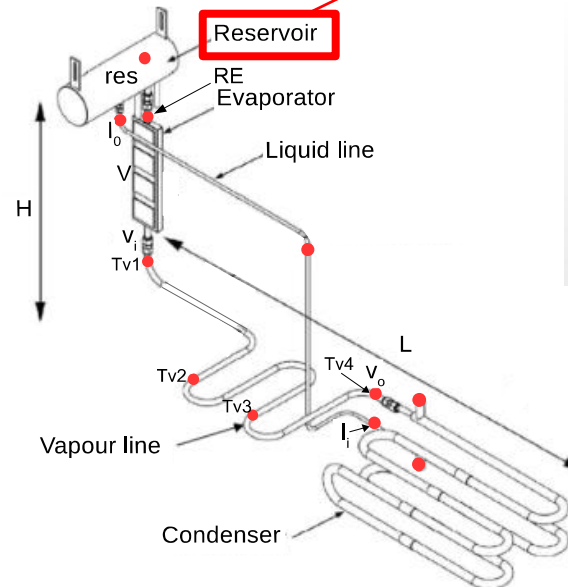
# Multidisciplinary Design Optimization (MDO) of the hybrid-electric aircraft powertrain

## ➤ Design of highly integrated power electronics with its cooling

Evaporator HTC ( $W/m^2 \cdot ^\circ K$ )



- Stability
- Reliability
- low mass
- Controlled temp



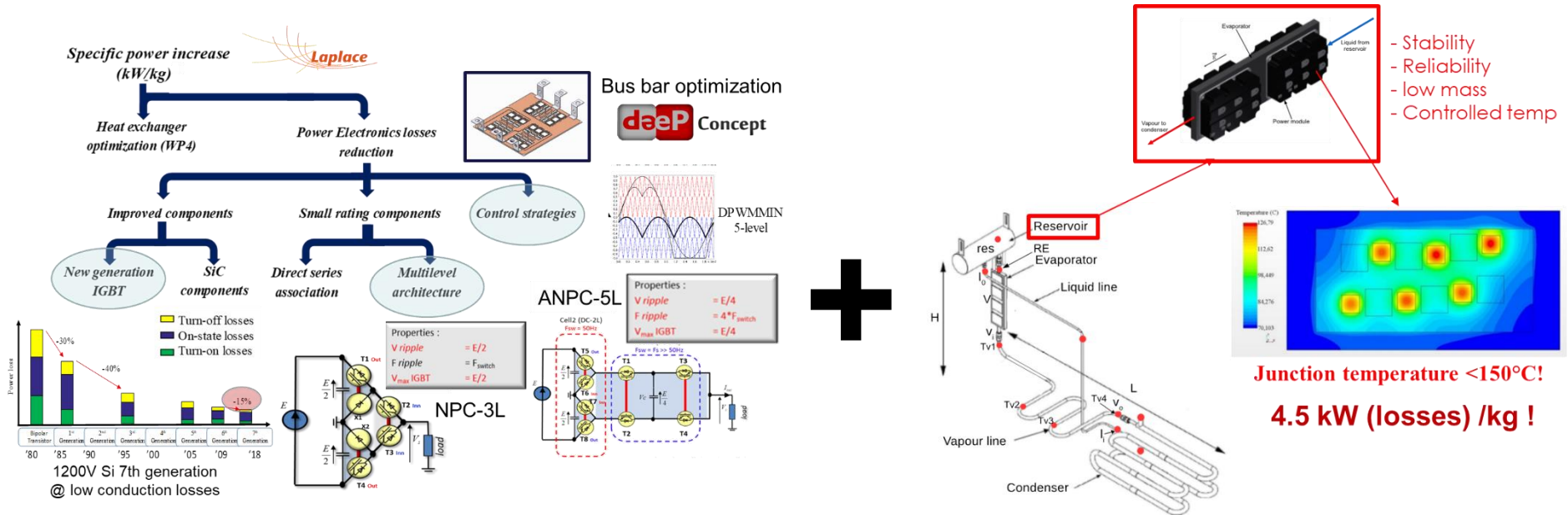
**Junction temperature  $< 150^\circ C$ !**  
**4.5 kW (of losses) /kg !**



\* CPLIP: Capillary Pumped Loop for Integrated power

# Multidisciplinary Design Optimization (MDO) of the hybrid-electric aircraft powertrain

## ➤ Design of highly integrated power electronics with its cooling



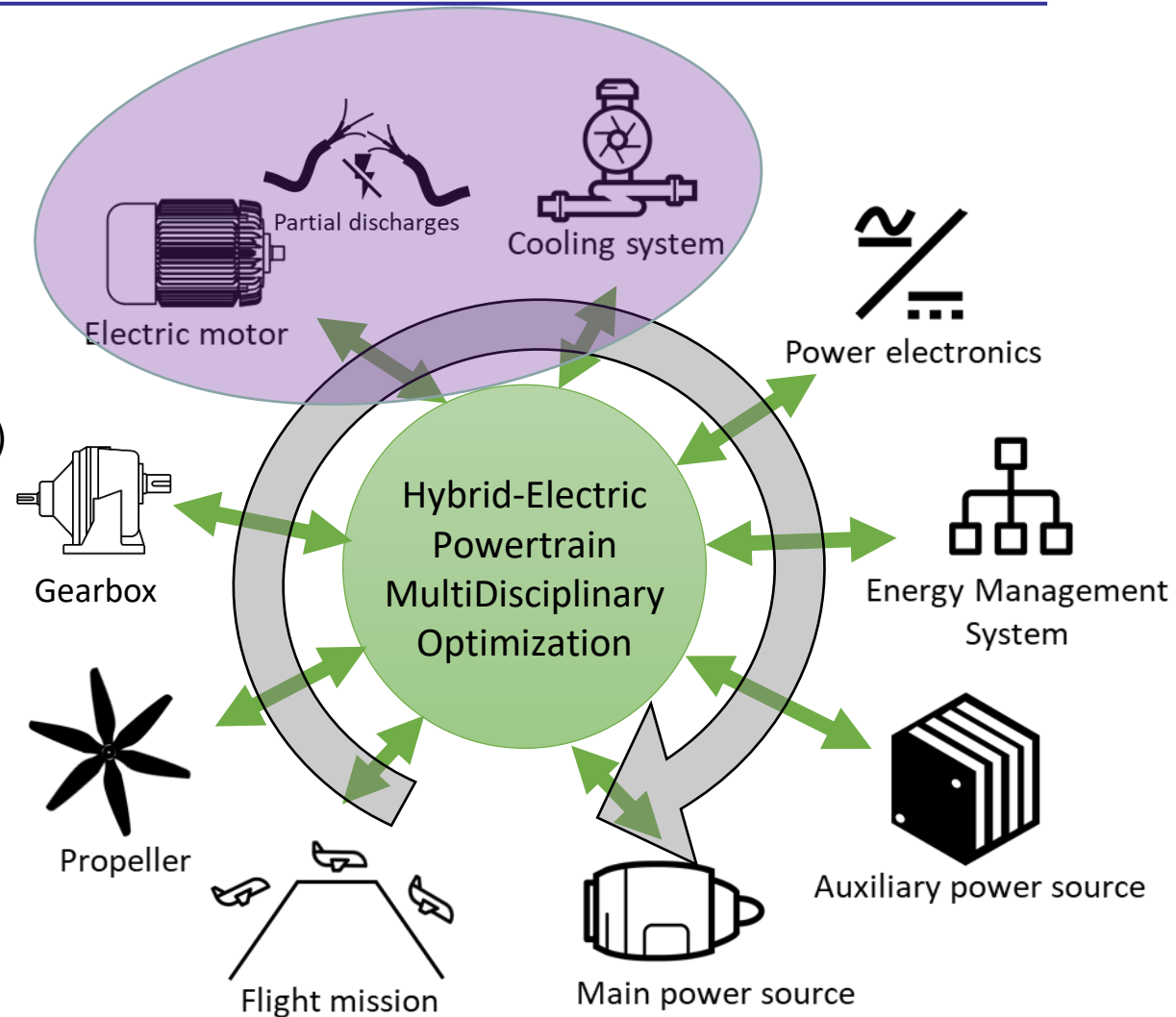
➤ MW range ;  $\eta \sim 99\%$  ;  $> 30\text{kW/kg}$



# Multidisciplinary Design Optimization (MDO) of the hybrid-electric aircraft powertrain

A set of coupled sizing variables :

- Geometry (propeller, **emotor**)
- Mechanical (gearbox)
- Electromagnetic (**emotor**)
- Electrical (bus voltage)
- Source sizing (fuel cell, turboshaft)
- Energy management



# Multidisciplinary Design Optimization (MDO) of the hybrid-electric aircraft powertrain

## ➤ Design of highly integrated eMotor with its cooling

Several drivers to increase both specific power and efficiency

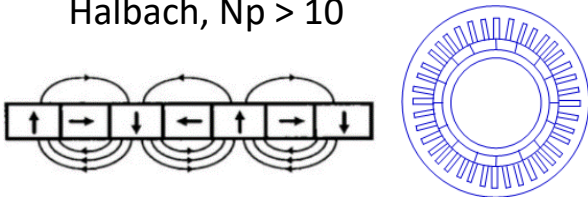
To decrease electric machine (PMSM) mass

- Increase peripheral speed up to 200m/s with sleeve having Strength tensile > 1600MPa

- Increase current densities:  $J_{rms} > 25A/mm^2$  et  $K_{rms} > 100$  kA/m for internal cooling inside slots

- Increase flux density in air gap: high temperature permanent magnets (SmCo or NdFeB):  $B_r(\text{SmCo}) = 1.16T$  for  $B_m=0.9T$

- Increase number of pole pairs: Halbach,  $N_p > 10$



And other drivers...

To decrease cooling system mass

Decrease losses  $\rightarrow \uparrow \eta$

- decrease Joule losses (DC and AC):

Twisted Litz wires

High filling coefficient

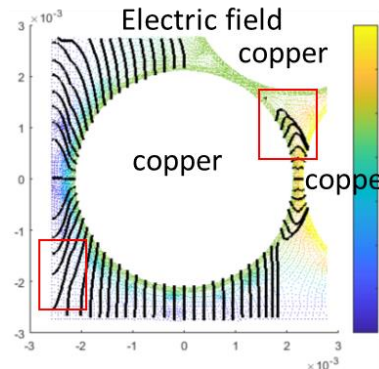
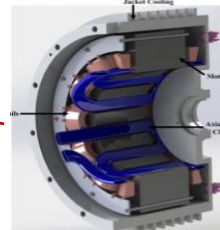
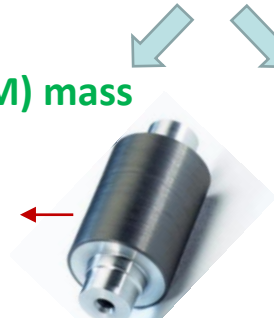
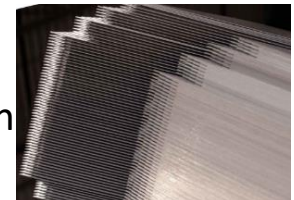
$$R_{AC}/R_{DC} \sim 1 \text{ for } 400\text{Hz @ } 5\text{kHz}$$



- Decrease iron losses:

- Use thin magnetic sheets (very thin sheets 100-200 $\mu\text{m}$  and future 50 $\mu\text{m}$ )

Design of winding with partial discharge tolerant insulation



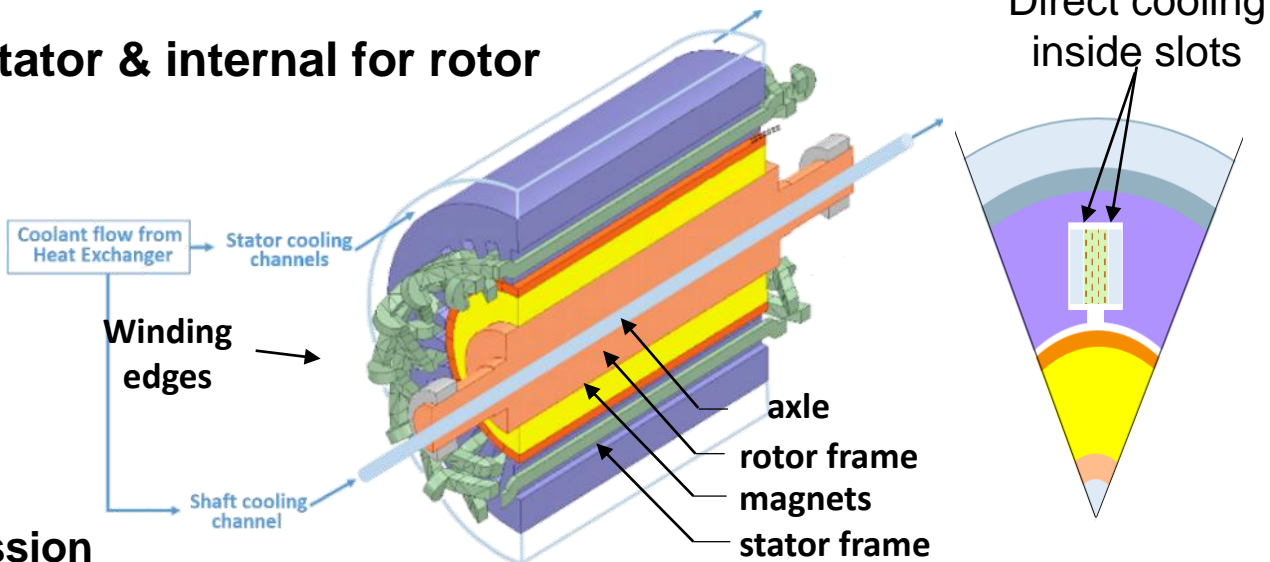
# Multidisciplinary Design Optimization (MDO) of the hybrid-electric aircraft powertrain

## ➤ Design of highly integrated eMotor with its cooling

External cooling for stator & internal for rotor

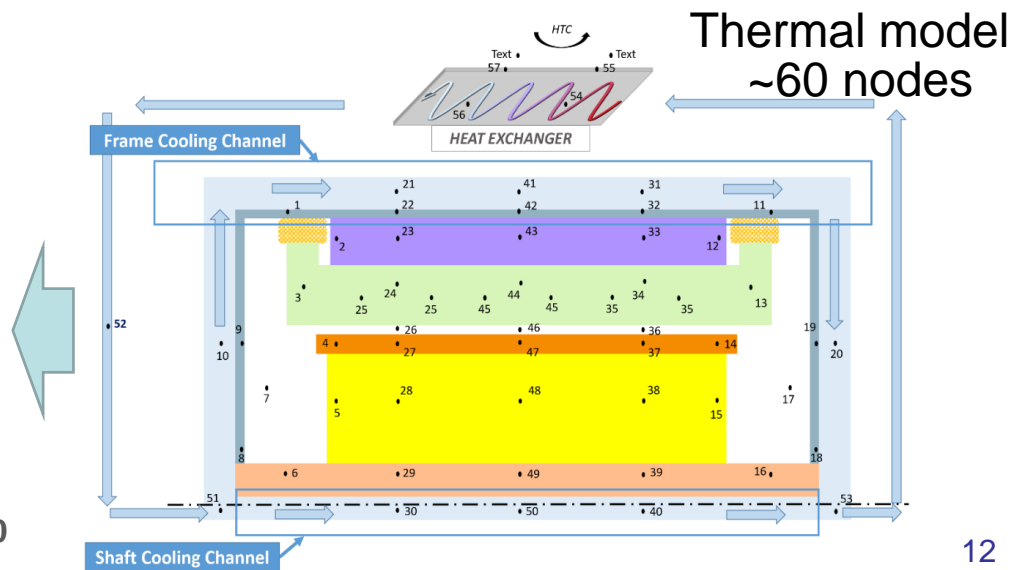
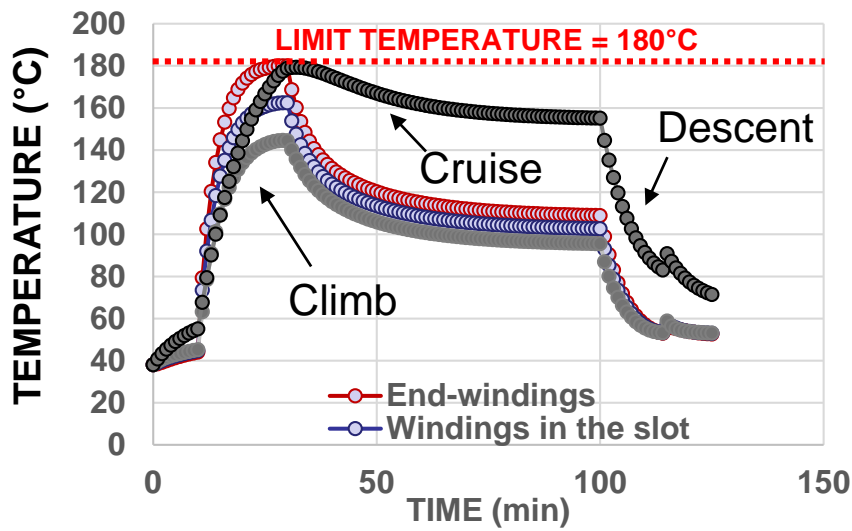
### Cooling system:

- ✓ Heat exchanger = nacelle
- ✓ Liquid cooling



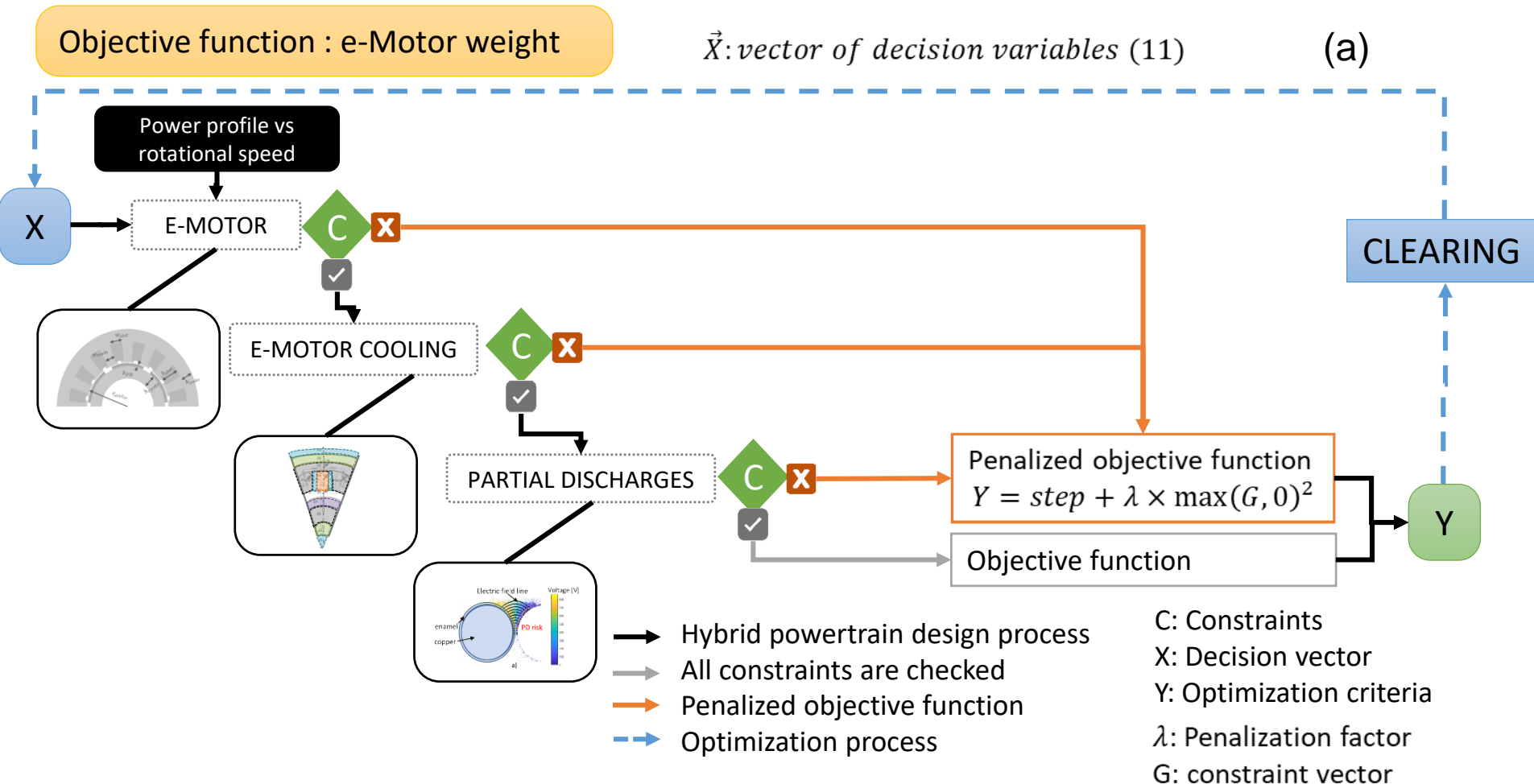
## ➤ Importance of thermal transient during flight mission

STATOR TEMPERATURE PROFILE (°C)



# Multidisciplinary Design Optimization (MDO) of the hybrid-electric aircraft powertrain

## ➤ Design of highly integrated eMotor with its cooling

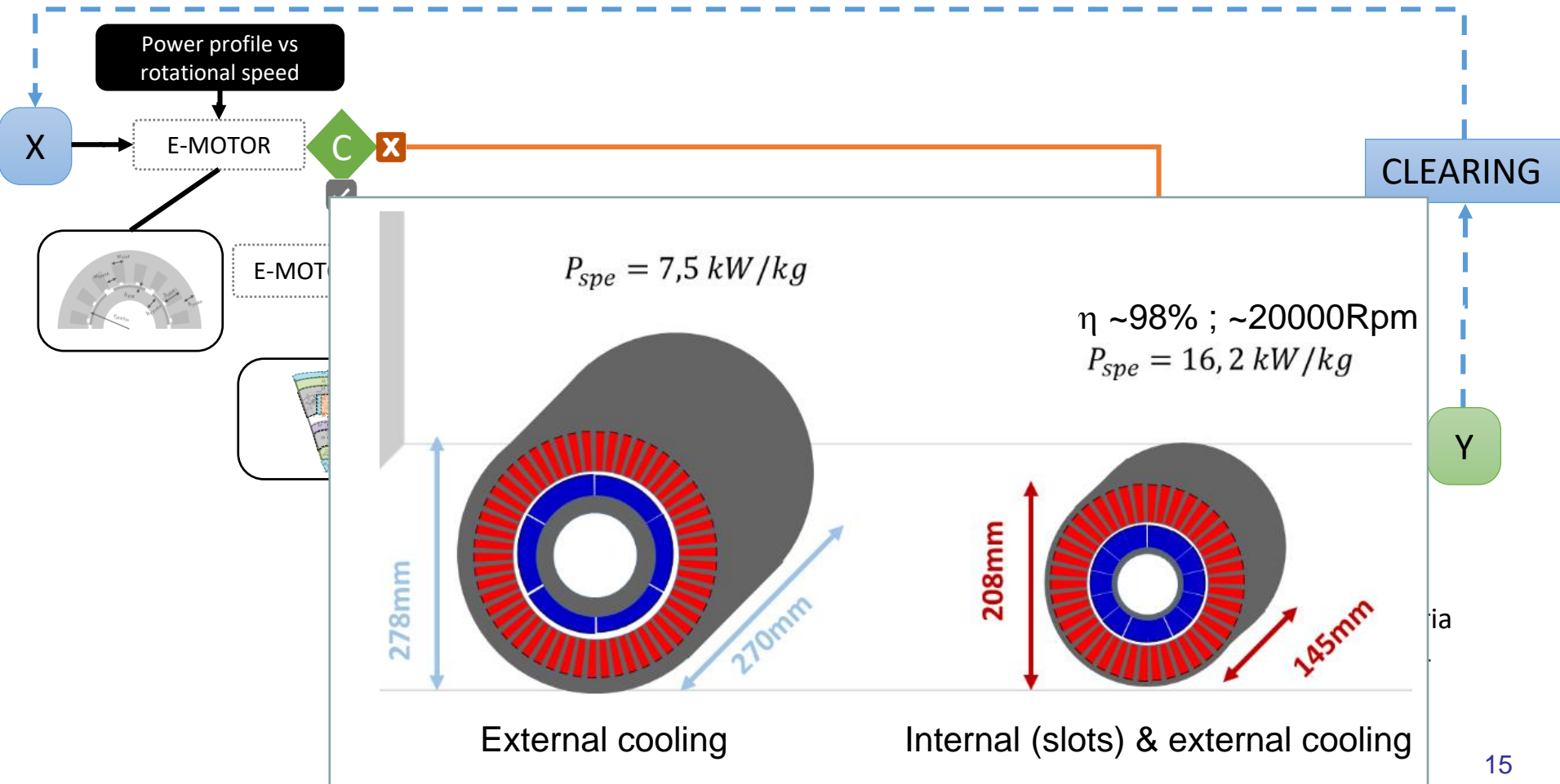


# Multidisciplinary Design Optimization (MDO) of the hybrid-electric aircraft powertrain

## ➤ Design of highly integrated eMotor with its cooling

Objective function : e-Motor weight

$\vec{X}$ : vector of decision variables (11)



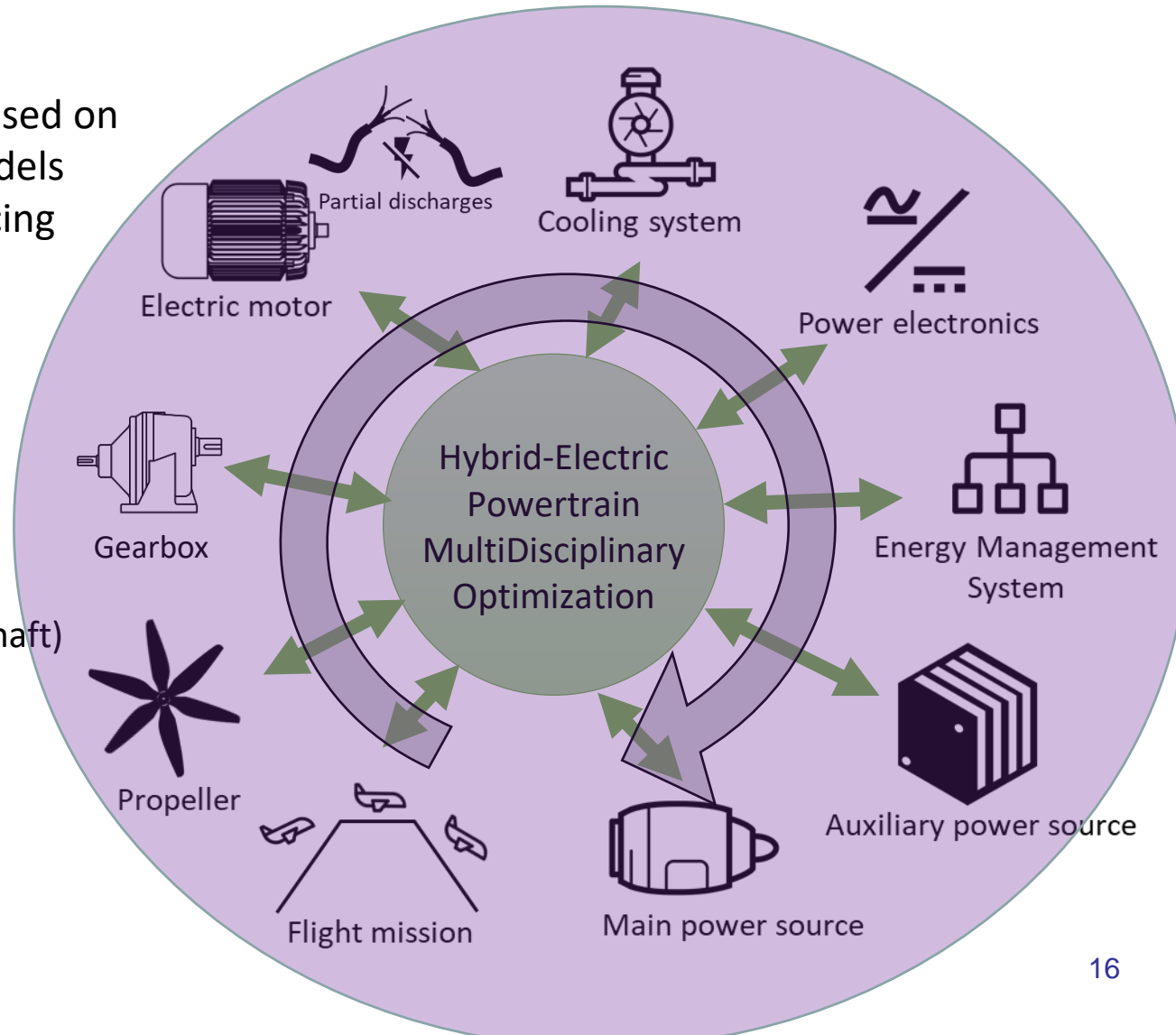
# Multidisciplinary Design Optimization (MDO) of the hybrid-electric aircraft powertrain

## ➤ MDO of the whole powertrain integrating snowball effects at aircraft level

Multidisciplinary model based on analytical or surrogate models (regression models) for facing complexity issue.

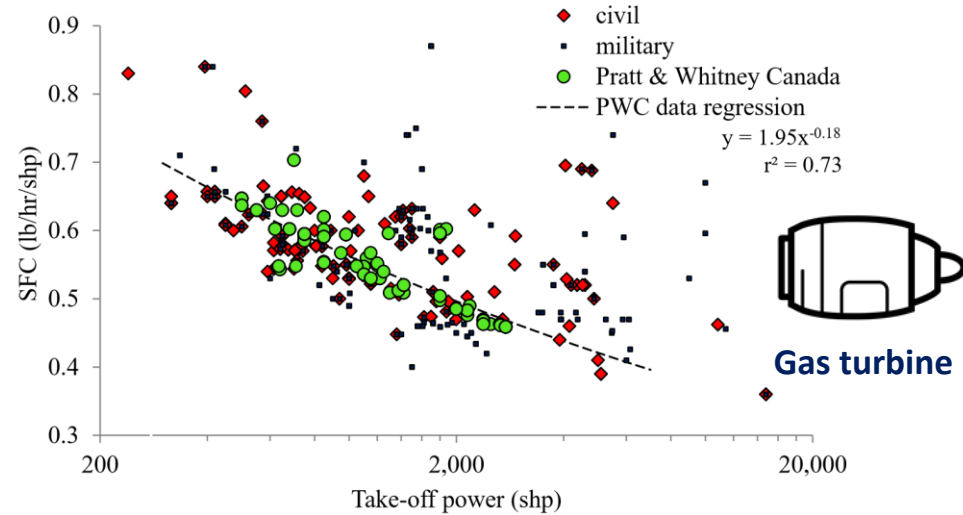
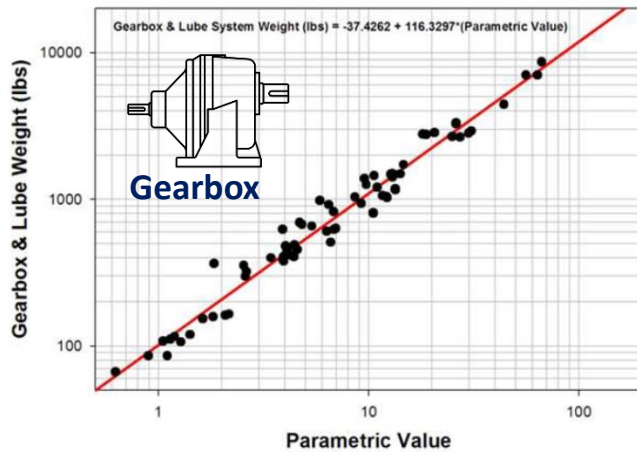
A set of sizing variables :

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- Source sizing (fuel cell, turboshaft)
- Energy management



## ➤ Gearbox, Gas turbine, Cables, Propeller

$$\text{Parametric Value} = (\text{hp}/\text{RPM}_{\text{out}})^{0.75} \cdot (\text{RPM}_{\text{in}}/\text{RPM}_{\text{out}})^{0.15}$$



### INPUT VARIABLES

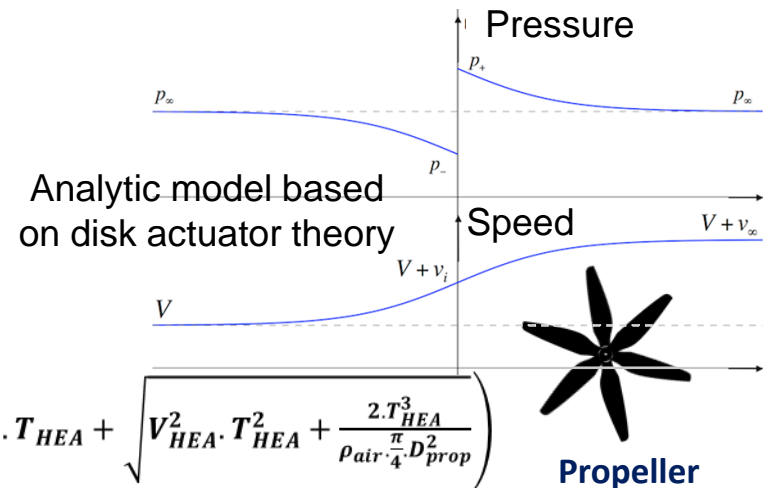
Cable electric power  
Power Factor  
Number of phases  
AC/DC voltage (depending on the cable)

### OUTPUT VARIABLES

Cable efficiency  
Cable warming  
Voltage drop  
Cable mass

### Cabling Data (Cu or Al)

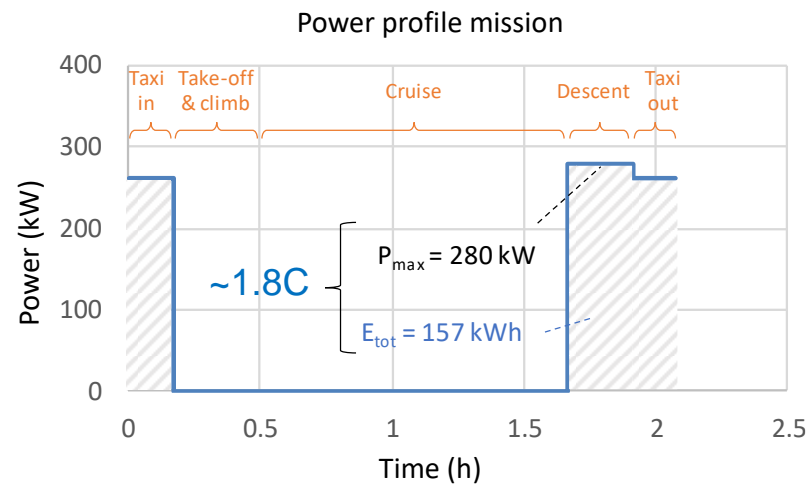
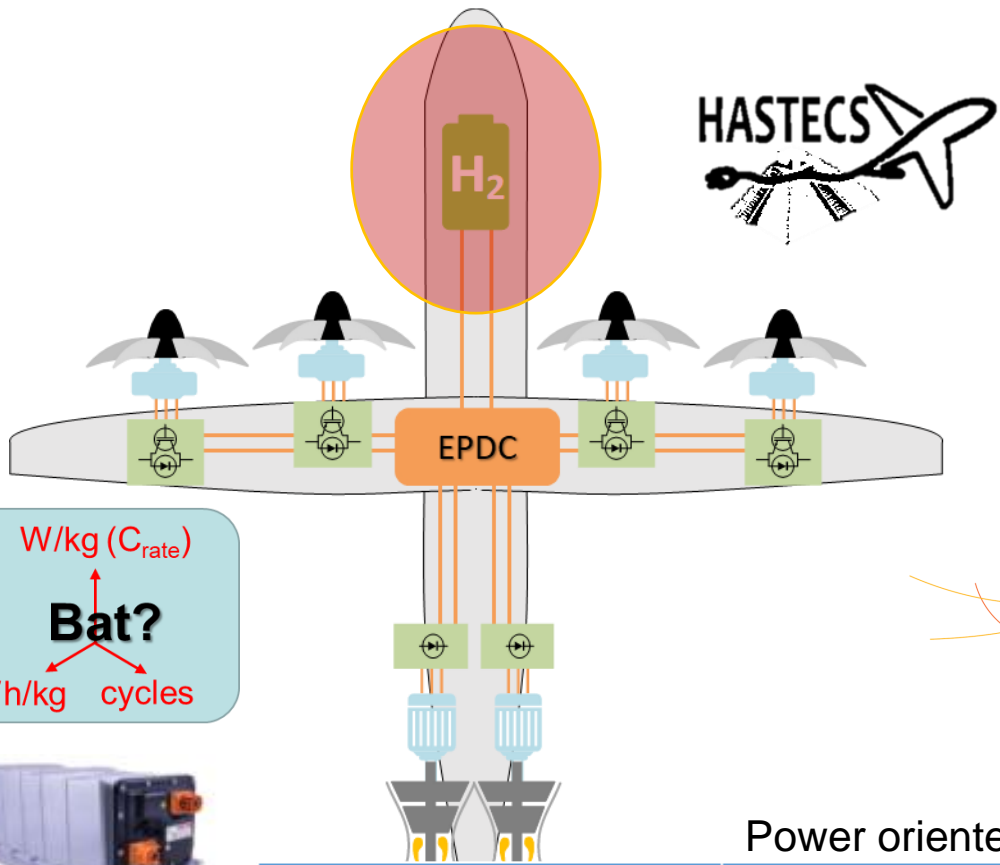
GAUGE	1	0	00	----
$K_c$ [-]	11e-4	8,4e-4	6,0e-4	----
$M_{lin}$ [g/m]	470	600	750	----
$R_{lin}$ [ $\Omega$ /m]	0,5e-3	0,4e-3	0,31e-3	----
$T_{cable_{max}}$ [ $^{\circ}$ C]	220	220	220	----



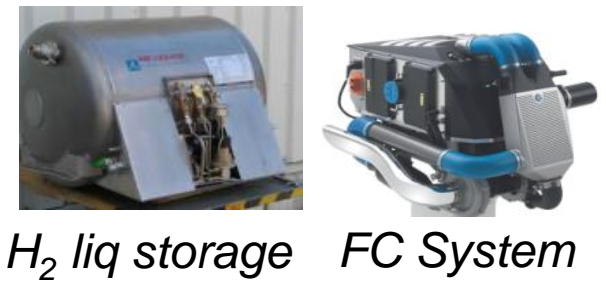
$$P_{shaft} = \frac{1}{2 \cdot k_{effd}} \cdot \left( V_{HEA} \cdot T_{HEA} + \sqrt{V_{HEA}^2 \cdot T_{HEA}^2 + \frac{2 \cdot T_{HEA}^3}{\rho_{air} \cdot \frac{\pi}{4} \cdot D_{prop}^2}} \right)$$

Propeller

## ➤ Road map on aux electrical sources: Batteries or Fuel Cells (FC) ?



**A promising device !**



W/kg ( $C_{rate}$ )

**Bat?**

Wh/kg    cycles



**Batteries**

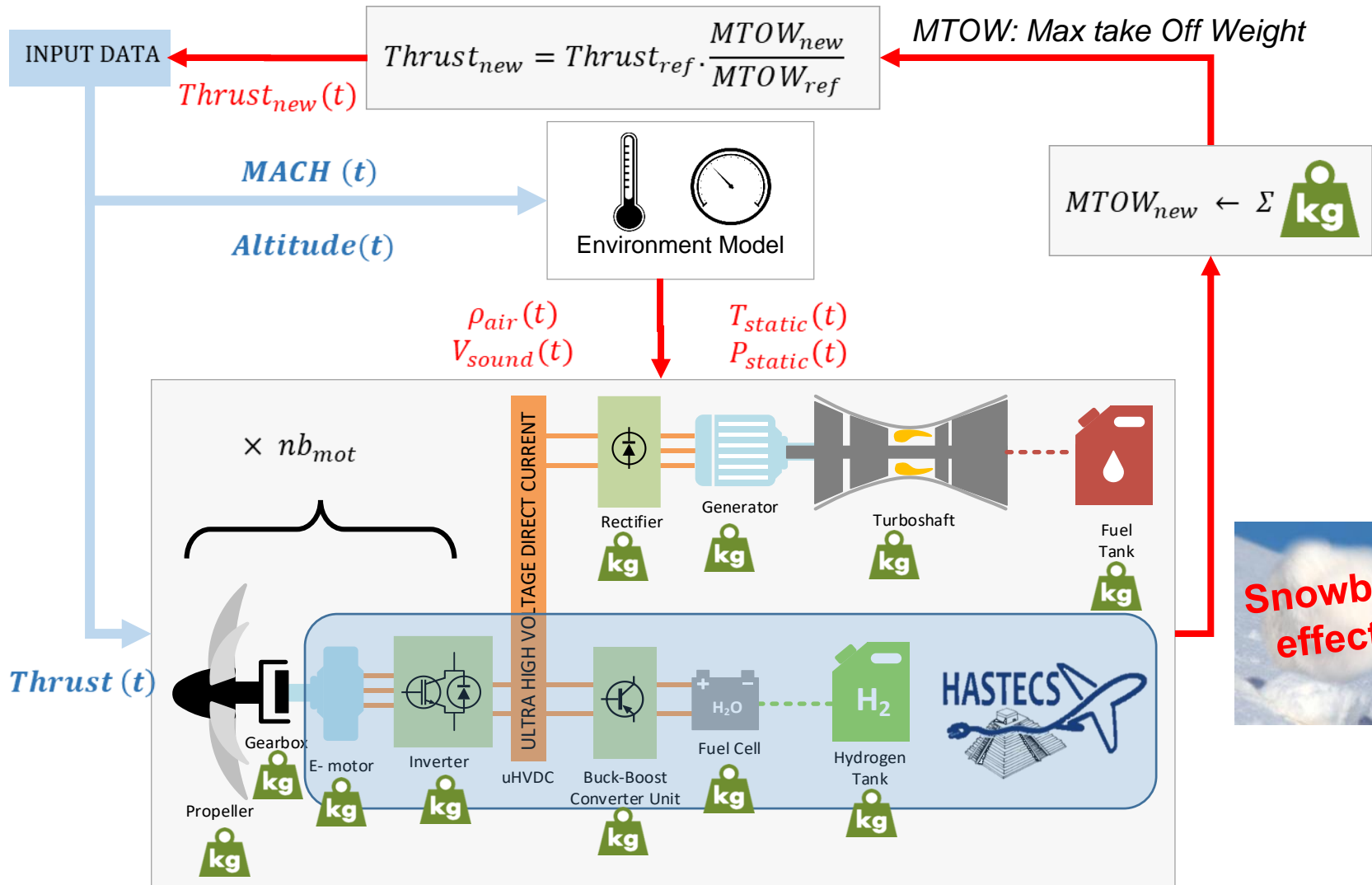
*Laplace*

		Power oriented	Energy oriented	
Specific energy $e_m$		LTO / TNO <sup>1,4</sup>	NMC Solid State <sup>3</sup>	FC System (LH <sub>2</sub> )
Perspectives (5 – 10 years)	Cell level	~ 180 – 200 Wh/kg	~ 650 Wh/kg	~ 1 kW/kg
	System level	~ 100 Wh/kg	~ 325 Wh/kg	~ 560 Wh/kg

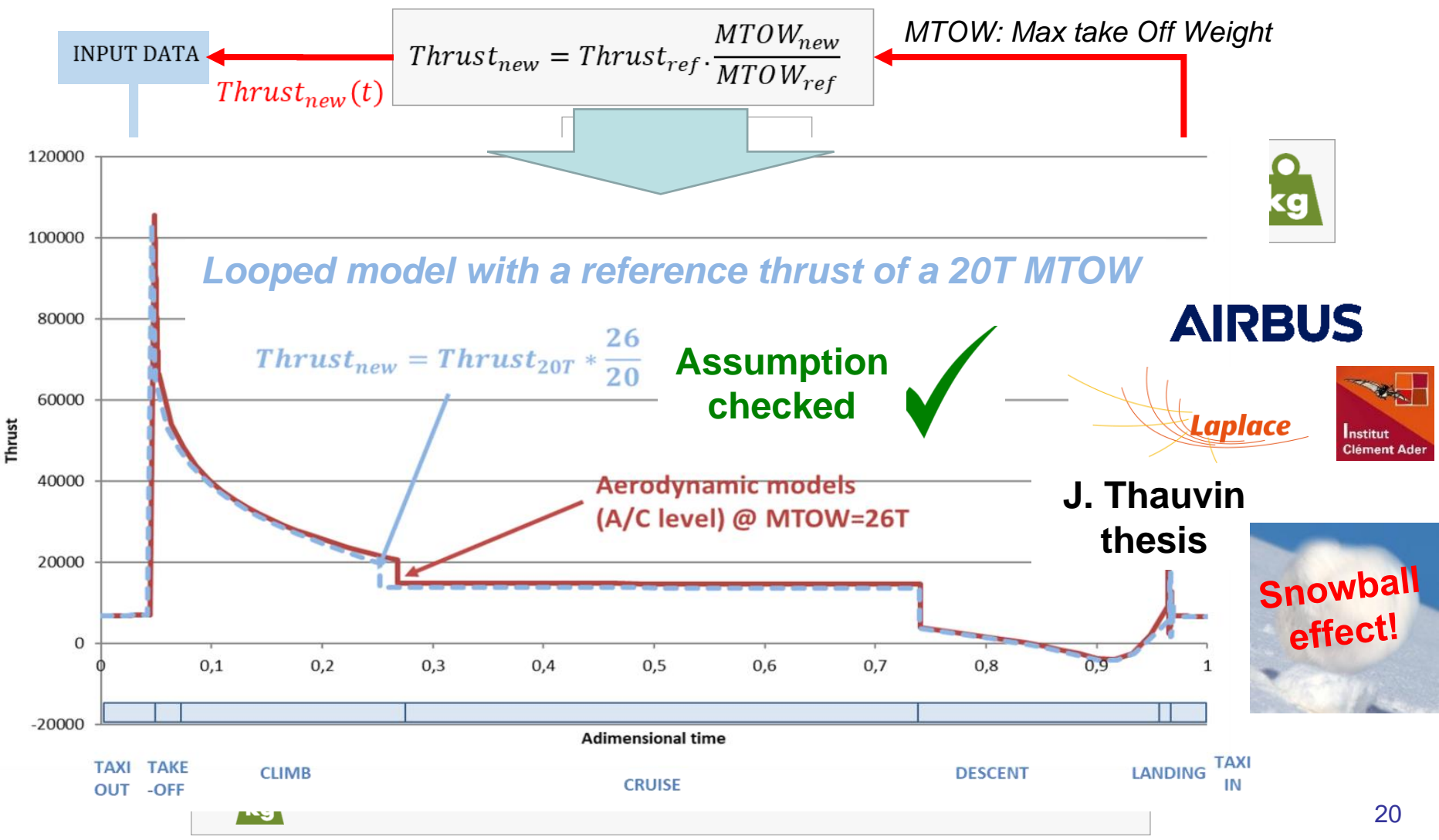
x 1.8



- **Snowball effect: higher device weights cause higher thrust needs with environment couplings => linearization thrust vs MTOW**



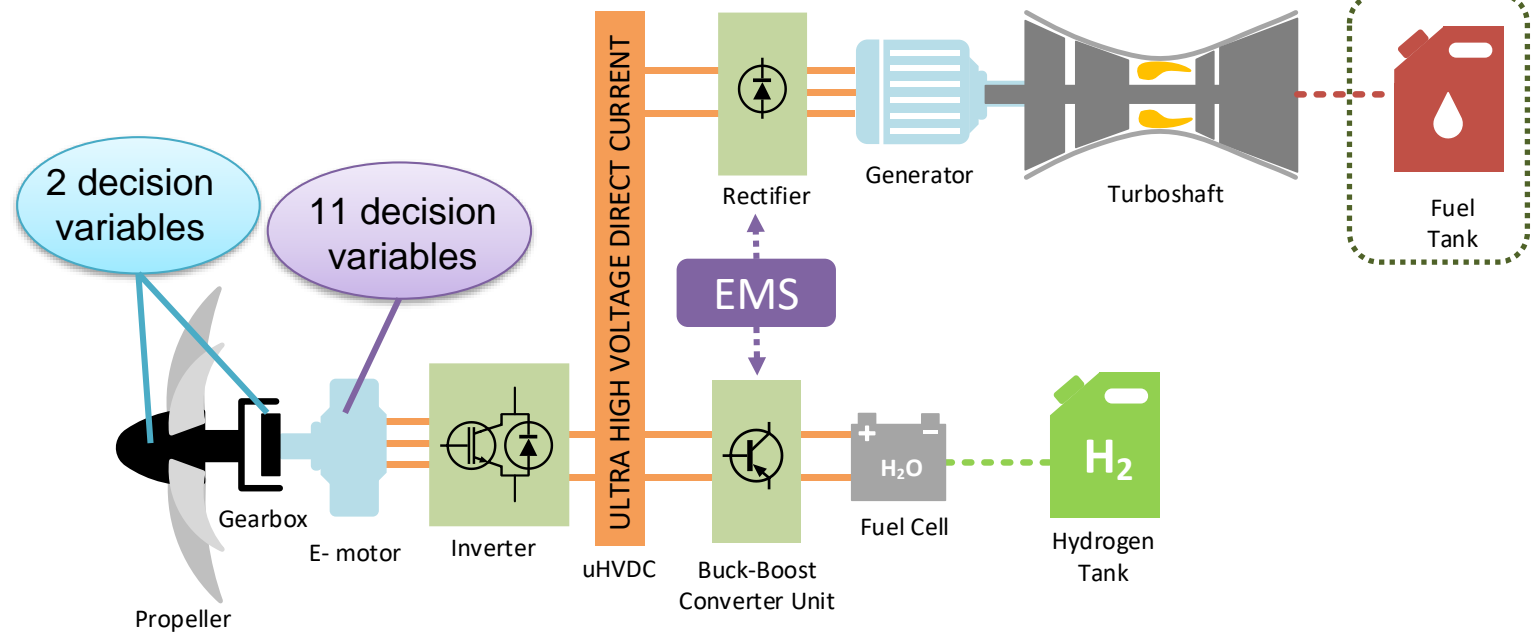
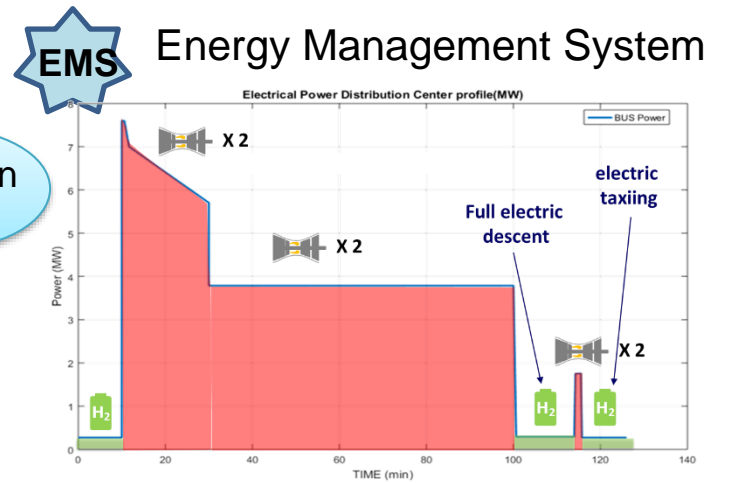
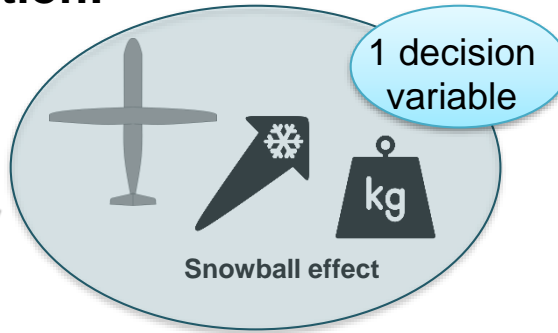
- **Snowball effect: higher device masses cause higher thrust needs with environment couplings**



- **Snowball effect: higher device masses cause higher thrust needs with environment couplings**

### 3 optimisation formulation:

- 1 e-Motor mass *local*
- 2 Powertrain mass *global*
- 3 Fuel Burn *global*



## ➤ Snowball effect: higher device masses cause higher thrust needs with environment couplings

### 3 optimisation formulation:

1. 14 decision variables for fuel burn optimization with “a light hybridization scenario” of EMS

Decision Variables	Name of variables	Lower bound	Upper bound
$R_{Thrust}$	Thrust ratio due to snowball effect	1	1.26
$D_{prop_{siz}}$ [m]	Propeller diameter	2	5
$R_{g_{box}}$ [-]	Gearbox ratio	1	20
$V_{uHVDC}$ [V]	Ultra-high direct current voltage	540	2040
$R_{alesage}$ [m]	Inner radius of the stator	0.05	0.25
$R_{drot_{lm}}$ [%]	Ratio between rotor diameter and active length	50	125
$R_{hs_{ral}}$ [%]	Ratio between stator slot and inner radius	10	150
$R_{g_{ral}}$ [%]	Ratio between the air gap thickness and the inner radius of the stator	1	10
$R_{pm_{ral}}$ [%]	Ratio between the magnet thickness and the inner radius of the stator	5	50
$B_{yoke_{max}}$ [T]	Maximum yoke flux density	1	1.53
$B_{teeth_{max}}$ [T]	Maximum teeth flux density	1	1.53
$N_{ce}$ [-]	Number of conductors per slot	1	4
$n_{ep}$ [-]	Number of slots per poles and per phases	1	3
$p$ [-]	Number of pole pairs	1	7



Optimizer used	CLEARING
Number of runs	~200
Duration	7 days

**Constraints**

- emotor constraints
- emotor cooling constraints
- partial discharges constraints

$$D_{prop_{siz}} \geq D_{prop_{check}}$$

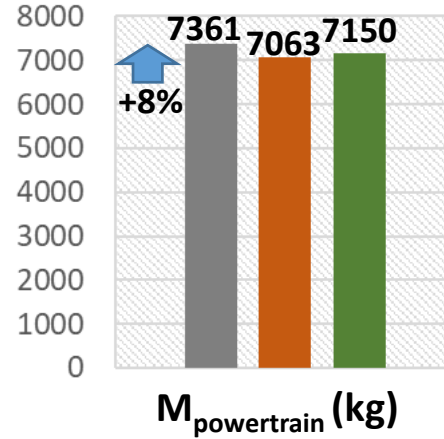
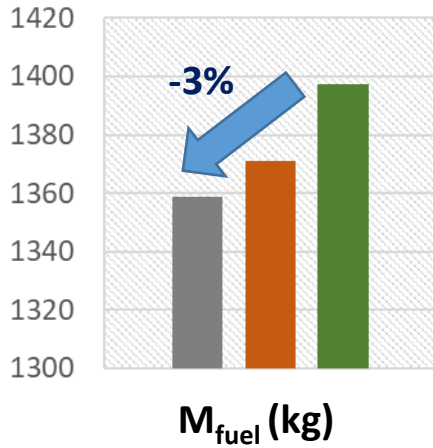
$$MTOW_{new} \leq MTOW_{ref} + 6T$$

$$R_{Thrust} \geq \frac{MTOW_{ref}}{MTOW_{new}} \text{ Snowball effect}$$

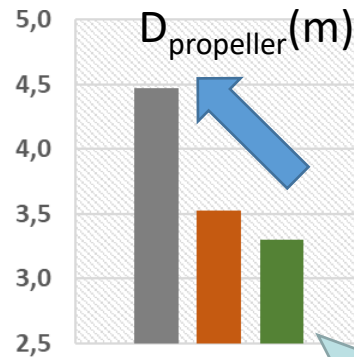

MDO CPU time  
(standard computer)  
~ 7 days with clearing



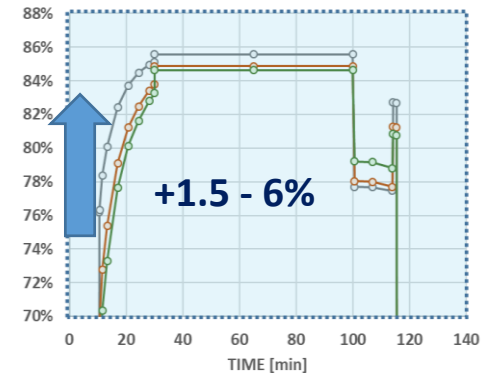
# Some results of the 3 MDO formulations



- ① Local optimization —
- ② Powertrain optimization —
- ③ Fuel burn optimization —

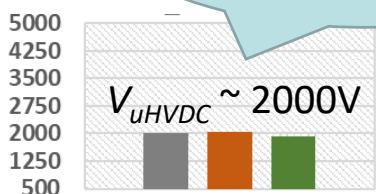


**Powertrain efficiency (%)**  
Propeller + gearbox + eMotor + inverter

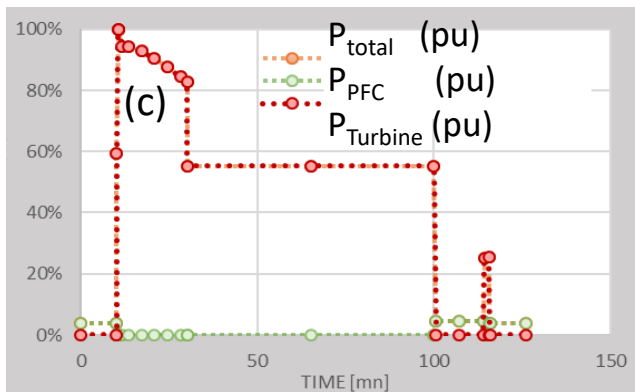
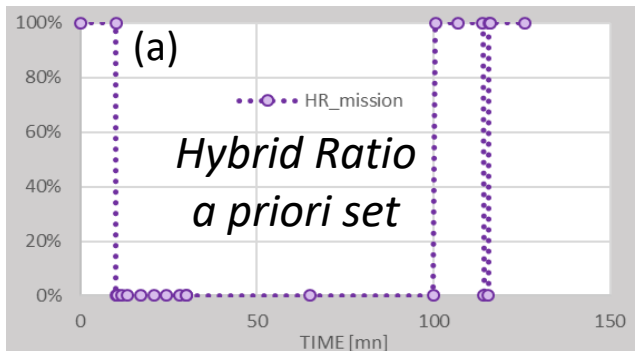
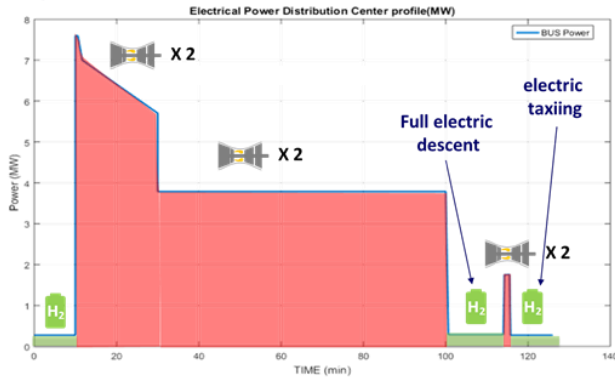


HVDC bus, another strong system coupling

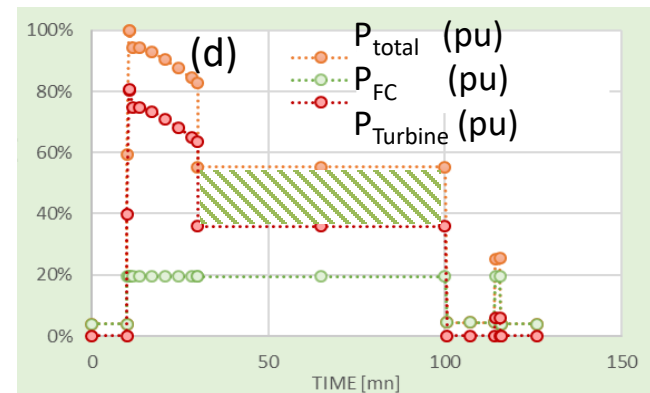
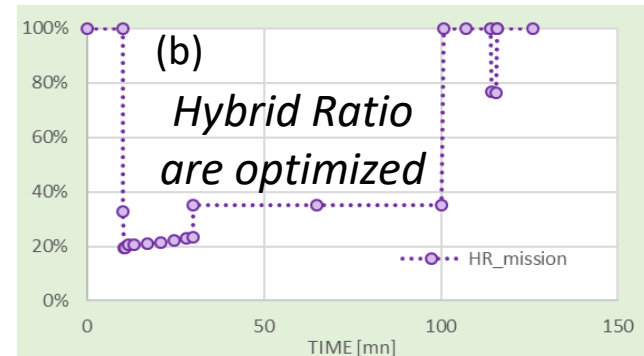
A typical and unexpected systemic coupling: propeller oversizing to increase powertrain efficiency



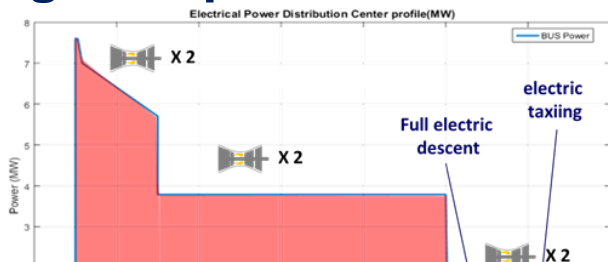
- EMS is a priori set during flight sequences



- EMS is optimized: hybrid ratio become additional decision variables

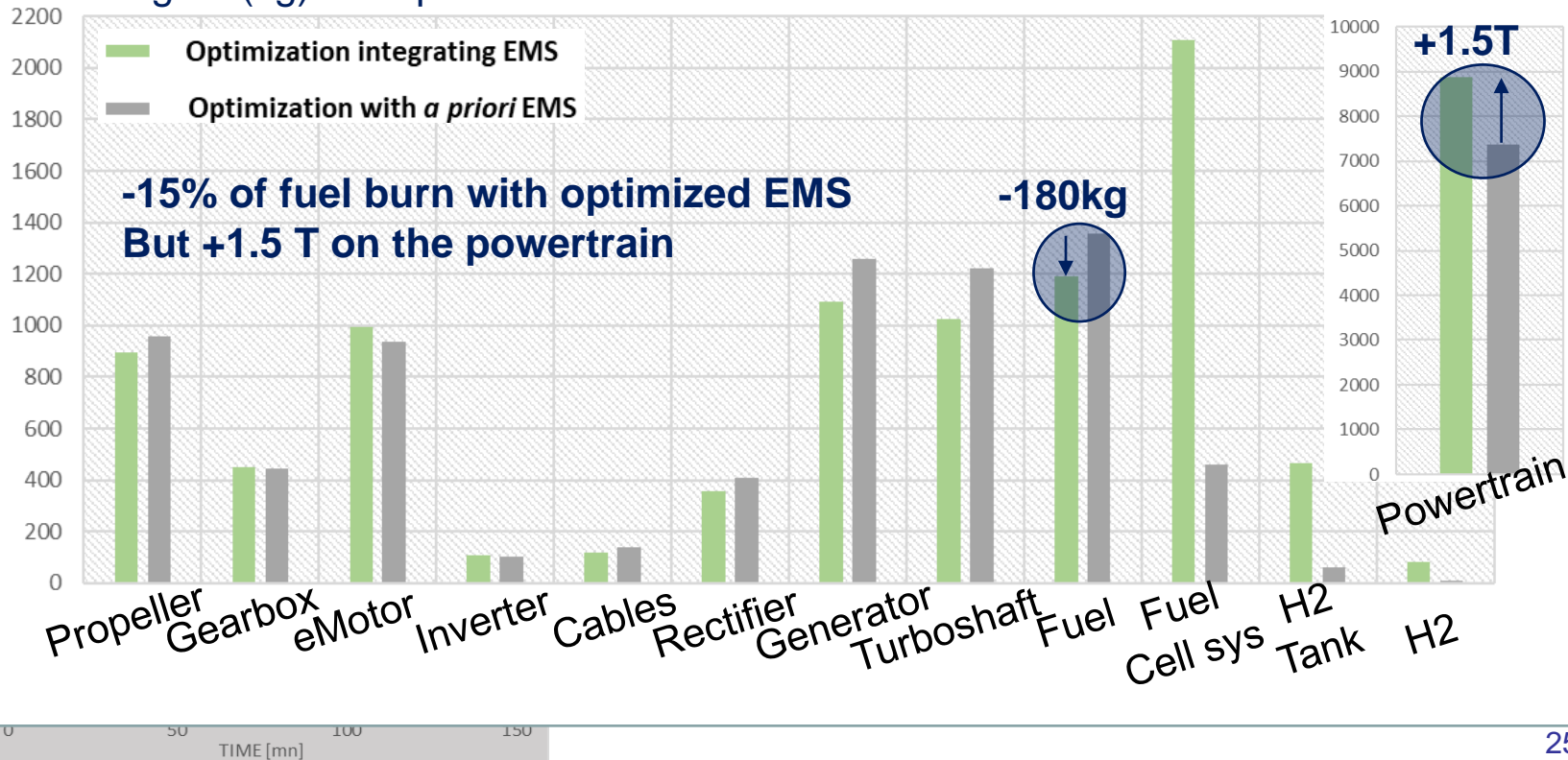


- EMS is a priori set during flight sequences

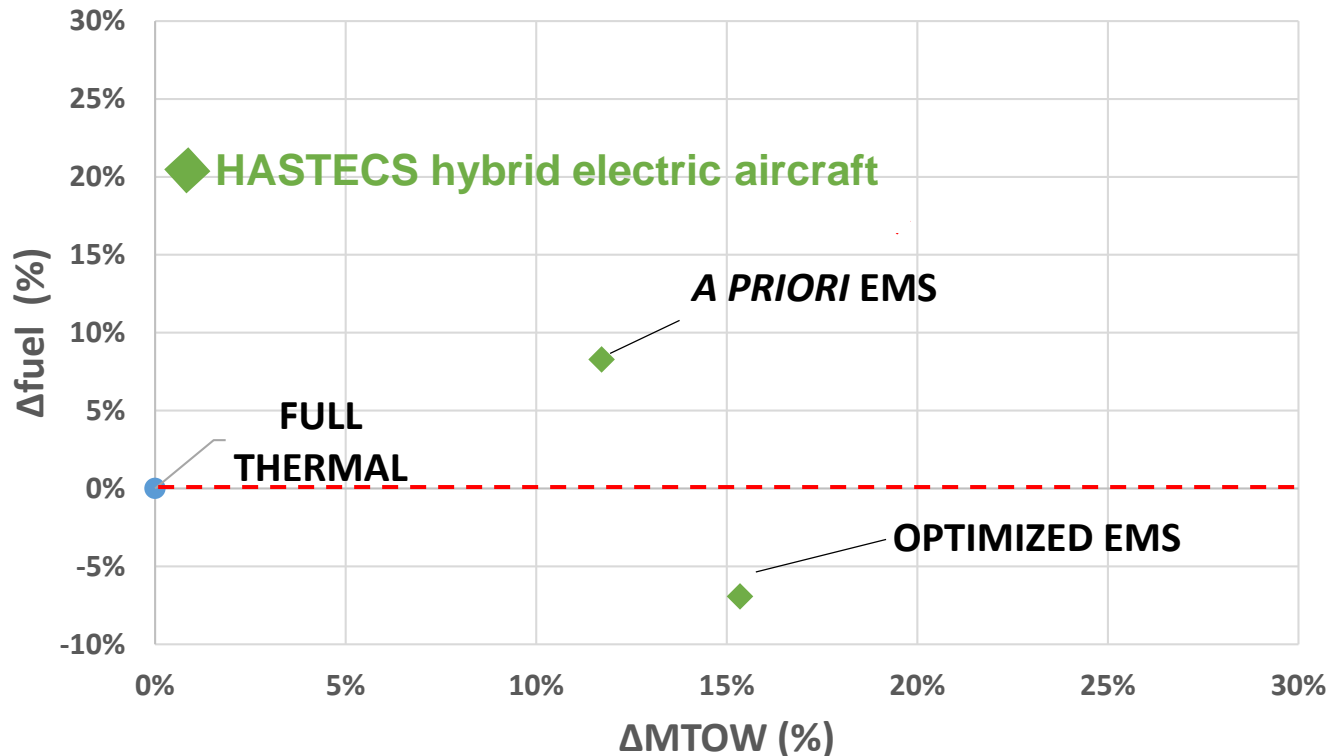


- EMS is optimized: hybrid ratio become additional decision variables

Weights (kg) for 4 power channels



- **Conclusion:** hybrid aircraft with heavier powertrain and potentially "greener" especially cumulating energy gains with aerodynamic benefits due to distributed electric propulsion



- **Prospect:** the actual breakthrough may be the ZeroE-H2 : with HASTECS models and using same MDO process, the MTOW of a ZeroE H2 should be +25% heavier than an optimized full thermal regional aircraft





# MEA 2021 MORE ELECTRIC AIRCRAFT

Bordeaux, France  
October, 20-21, 2021



## a typical MDO process for future Hybrid Electric aircrafts



**Final dissemination workshop**  
**Oct 27th**

**Free Registration (visioconf)**

[https://www.weezevent.com/hastecs-  
invitation-dissemination-workshop-poitiers-  
october-27th-  
2021?lg\\_billetterie=2&id\\_evenement=752315](https://www.weezevent.com/hastecs-invitation-dissemination-workshop-poitiers-october-27th-2021?lg_billetterie=2&id_evenement=752315)



Université  
de Toulouse

The  Book

**HASTECS: Hybrid Aircraft: reSearch on Thermal  
and Electric Components and Systems**

**Soon available in  
open access (HAL)**



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(cleansky 2 JTI) research and innovation programme, 2014-2024] under grant  
agreement No 715483

**Oct 20th 2021**