



JCGE
2019
Jeunes Chercheurs en Génie Électrique



Journées Annuelles du GDR SEE(S)

-
Conférence des Jeunes Chercheurs en Génie Electrique



14 Juin 2018

Road map scientifique

Xavier Roboam

Directeur de recherche CNRS

A NOTRE ALLIANCE MENAURE

SAS



**Non propulsive to
propulsive systems
of more electric
aircrafts**

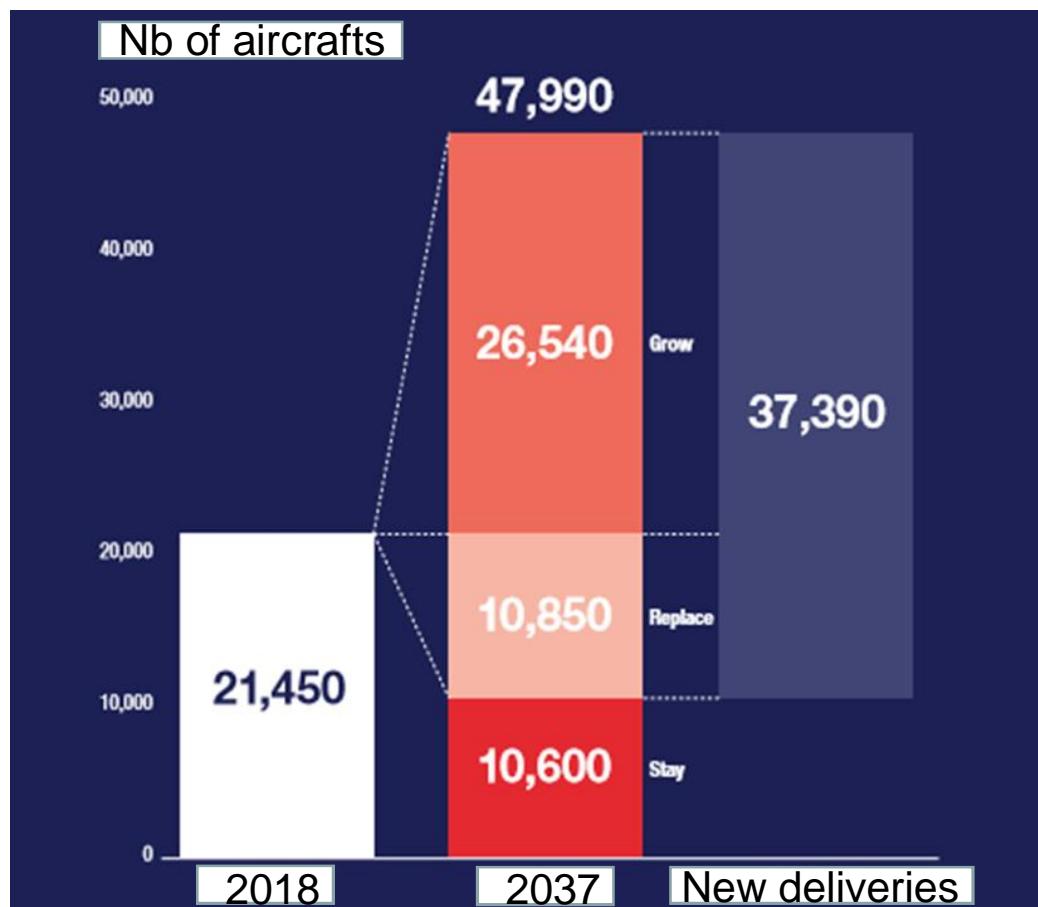
Context: towards greener aircrafts

860 million

Tonnes of CO₂ from airlines (2017)

~ 2% of human emissions

Rapport ATAG 2018 : « AVIATION BENEFITS BEYOND BORDERS »



Home > Entreprises & Finance > Services > Transport & Logistique

Aéronautique : 2 fois plus de passagers dans 20 ans, comment faire ? (Boeing, Airbus, Air France)

Par Fabrice Gliszczynski | 10/07/2014, 8:00 | 1204 mots



vols. 52 avions décollent aujourd’hui toutes les minutes et le nombre de passagers devrait croître de 5% par an. / Reuters (Crédits : DR)

Doublement du trafic aérien, doublement de la flotte d'avions d'ici 15 à 20 ans ! Un défi pour la filière aéronautique, les aéroports, la gestion du trafic mais aussi la formation des pilotes. État des lieux...

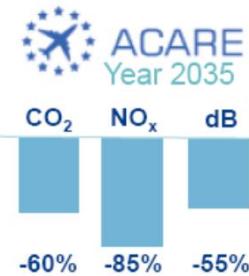
Air traffic growth is expected to double over the next 20 years + 3-4% per year

Context: towards greener aircrafts

GOALS*

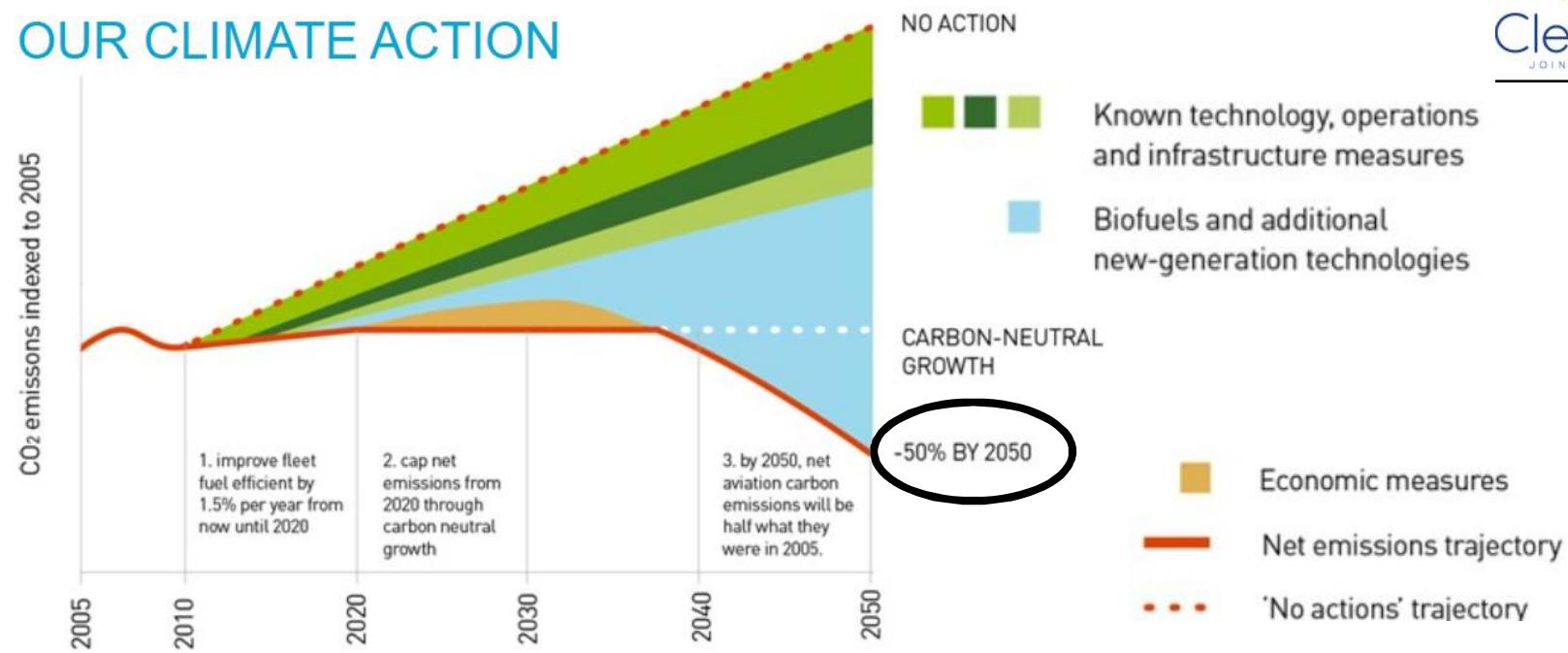
2050 technologies and procedure

- - 50-75% in CO₂
- - 70-90% in NO_x
- - 65% in perceived noise (flying Aircrafts)
- Emission-free when taxiing
- Designed and manufactured to be recyclable



* Relative to 2000 capabilities

OUR CLIMATE ACTION



Context: towards greener aircrafts



No “pollutant” aircraft
in Norwegian domestic
flights by 2025?

“Flygskam”: a shame
to take plane!

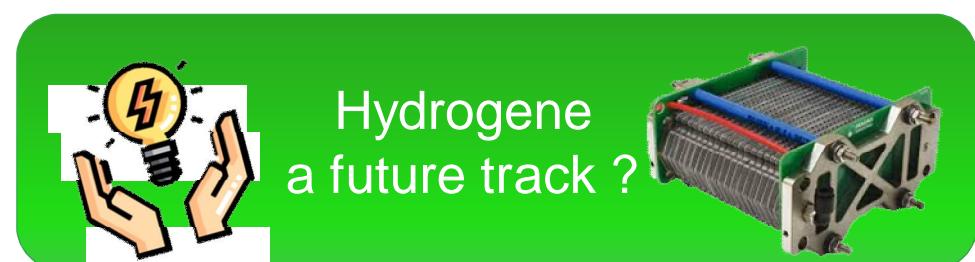


Greta
Thunberg

More efficient aircrafts
fuel burn below 3 liters / passenger for 100 km
even less than 2 liters for the A321neo

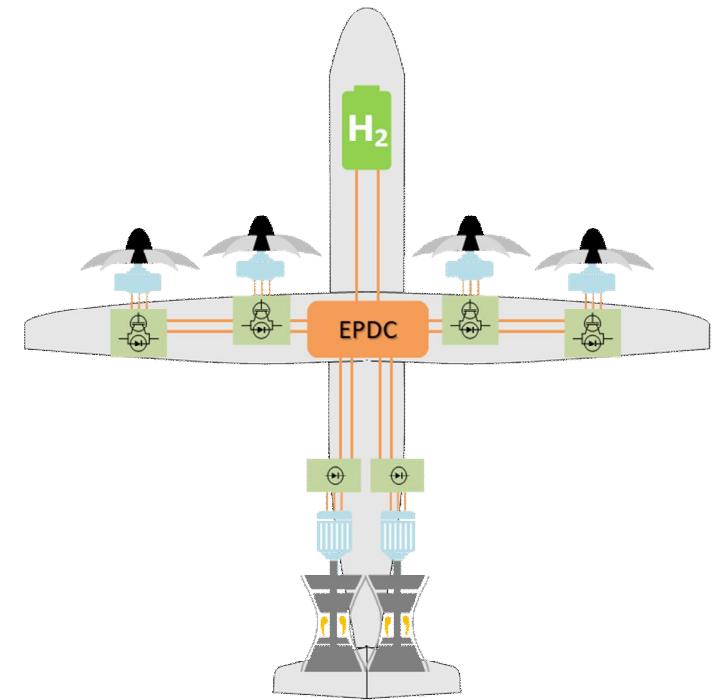
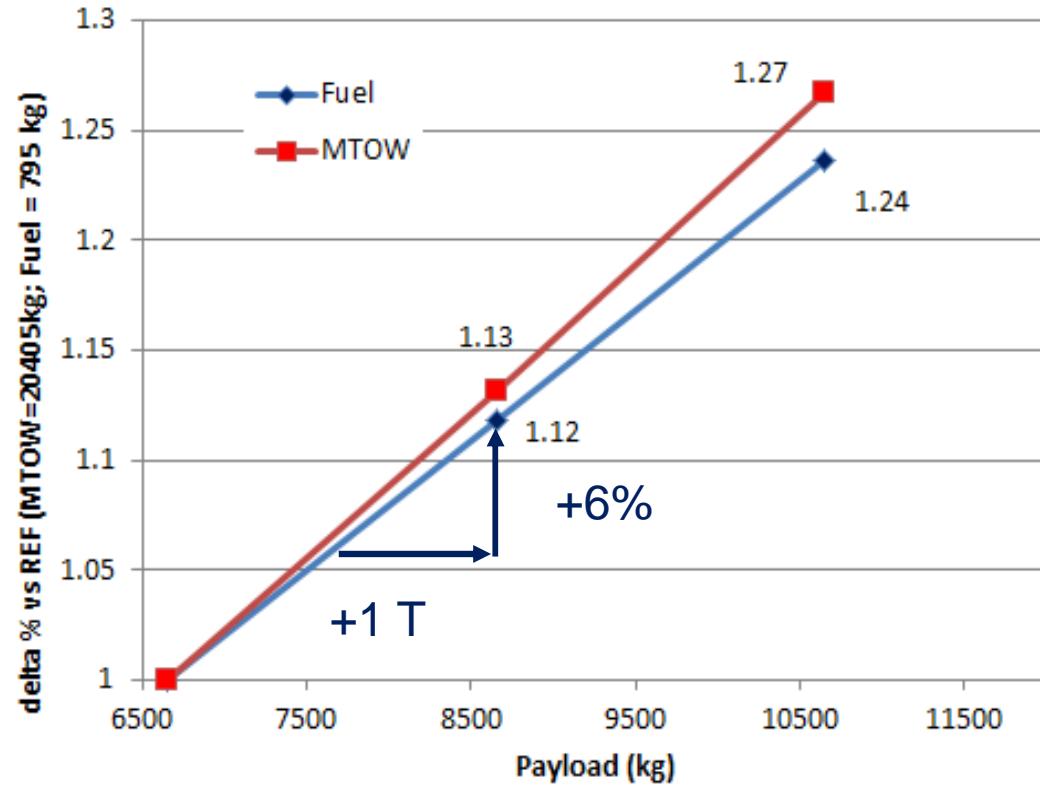


Use of biofuels
50 % less pollutant



and electrification of systems and drive powertrain...

Context: weight is the enemy!



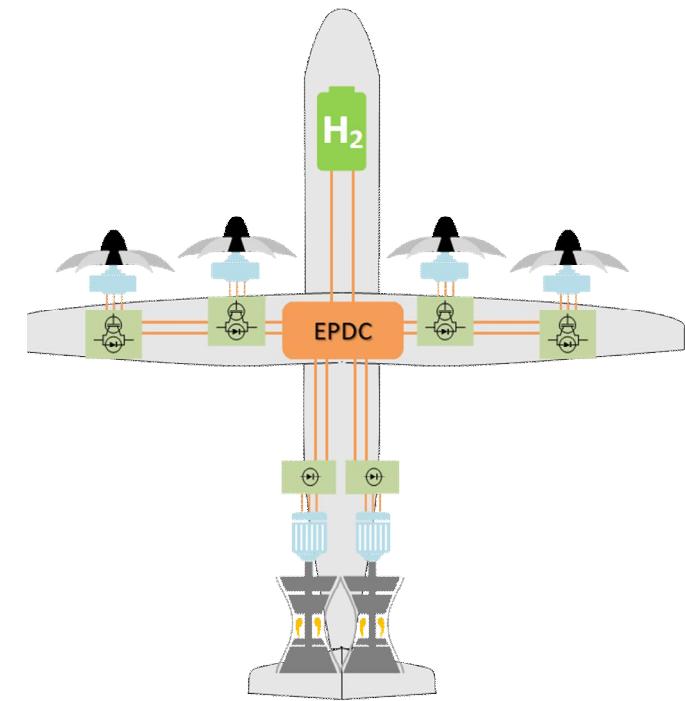
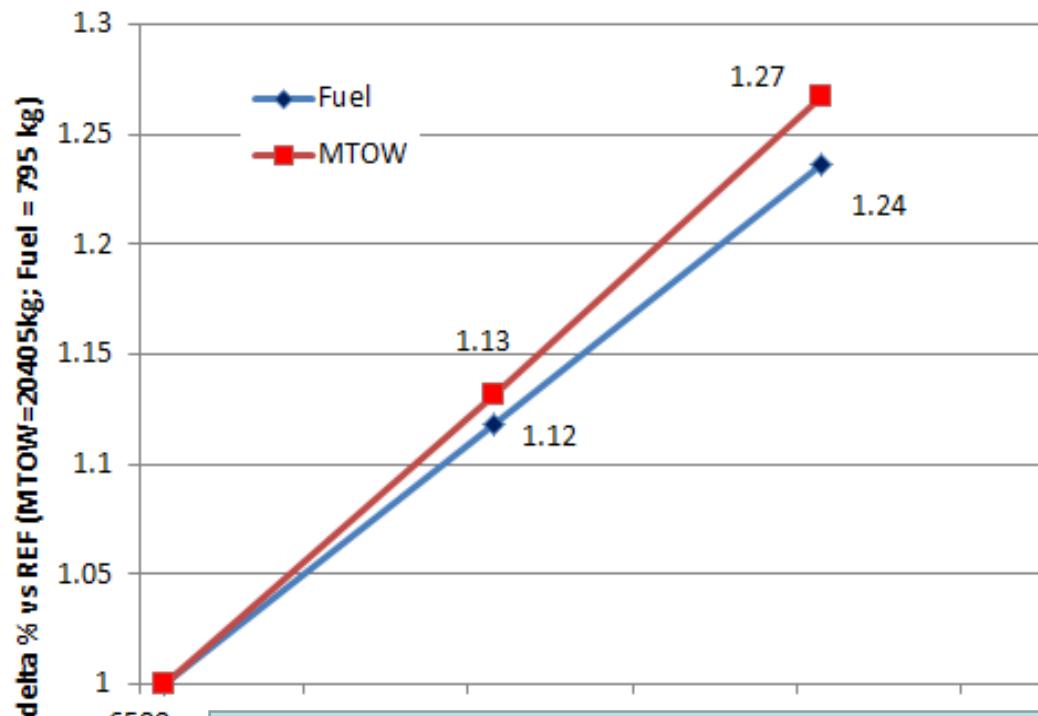
Gain fuel vs MTOW*
on regional Aircraft (400 nm)

For a design range of 400 nm

- Case 1: payload = 6650 kg, fuel burn = 795 kg
- Case 2: payload = Case 1 + 2000 kg => fuel burn = 889 kg (~ +12%)

➤ **Snowball effect: +6% of fuel / ton of additional payload**

Context: weight is the enemy!



fuel vs MTOW*
Final Aircraft (400 nm)

Additional weight also means additional costs

For a design

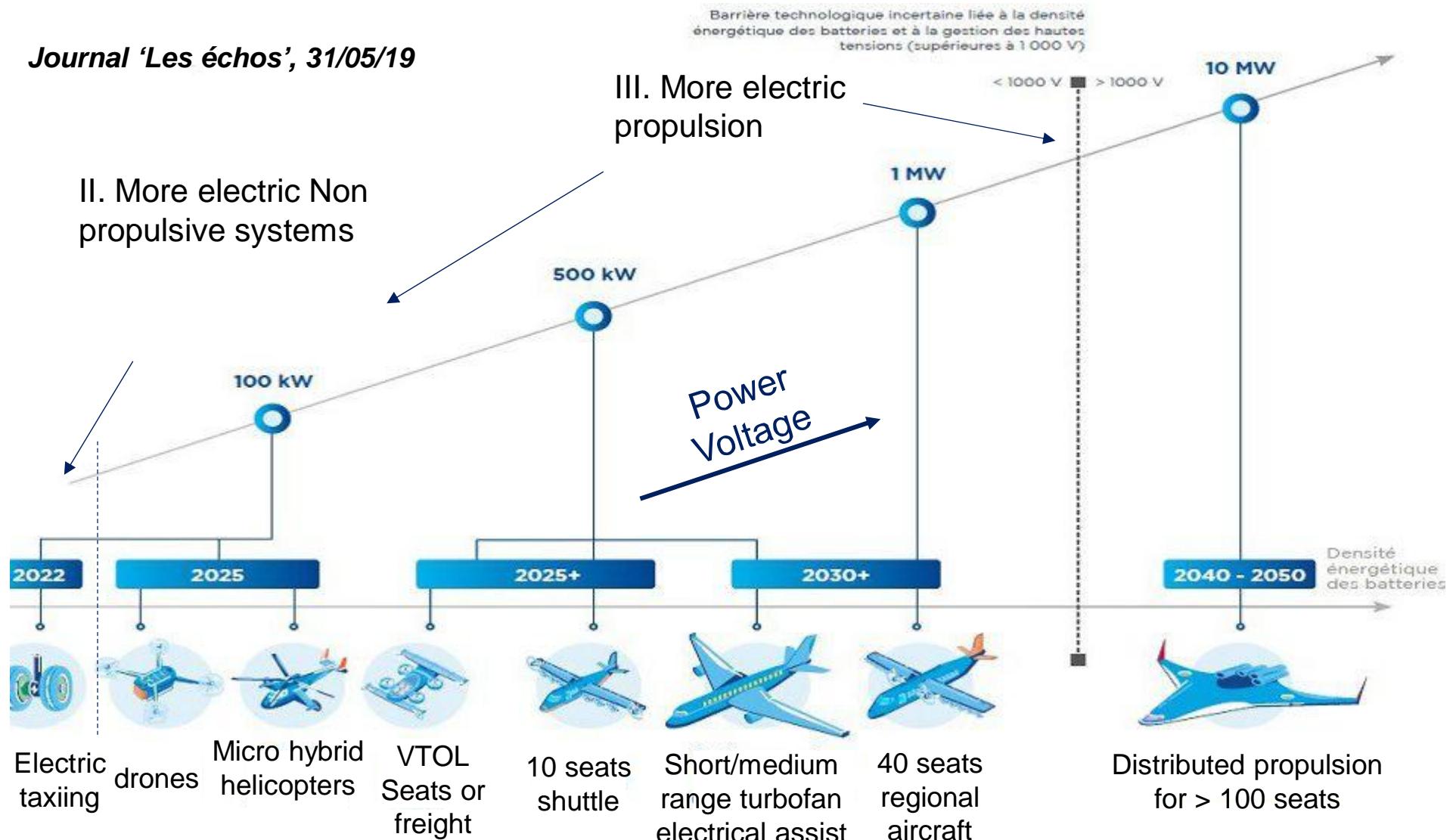
- Case 1: payload 1000 kg → fuel 1200 kg → cost 12% (12%)
- Case 2: payload 1200 kg → fuel 1440 kg → cost 14.4% (12%)

➤ **Snowball effect: +6% of fuel / ton of additional payload**

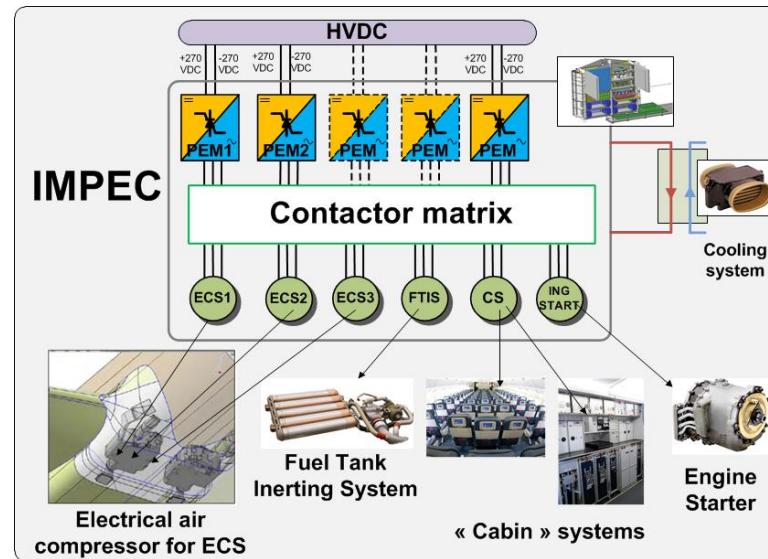
[Rob 12] X. Roboam, "More electricity in the air: Towards optimized electrical networks embedded in "more electrical aircraft", IEEE Industrial Electronics Magazine, Vol 6, 2012

Road maps for more electric aircrafts

Journal 'Les échos', 31/05/19



II. More electric non propulsive systems



0 – 100kW
230VAC or 540VDC

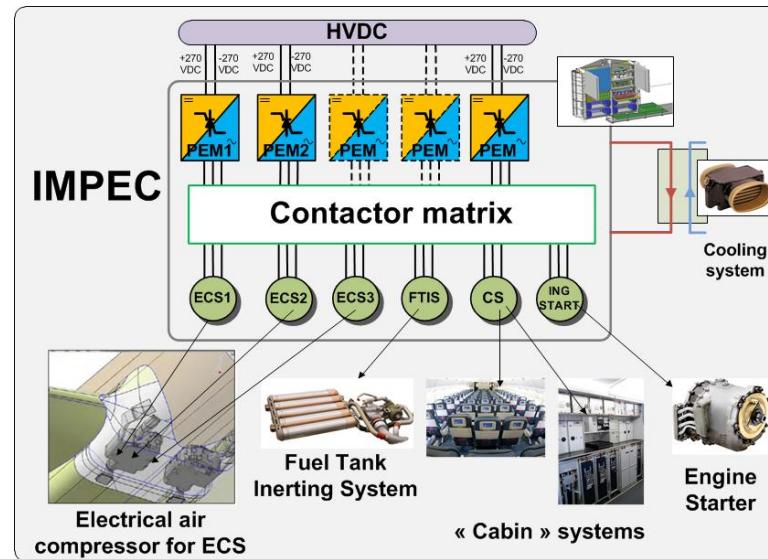
III. More electric propulsive systems



100kW – X MW
Some 100V - kVs

Road map Scientifique, X. Roboam

II. More electric non propulsive systems



0 – 100kW
230VAC or 540VDC

III. More electric propulsive systems

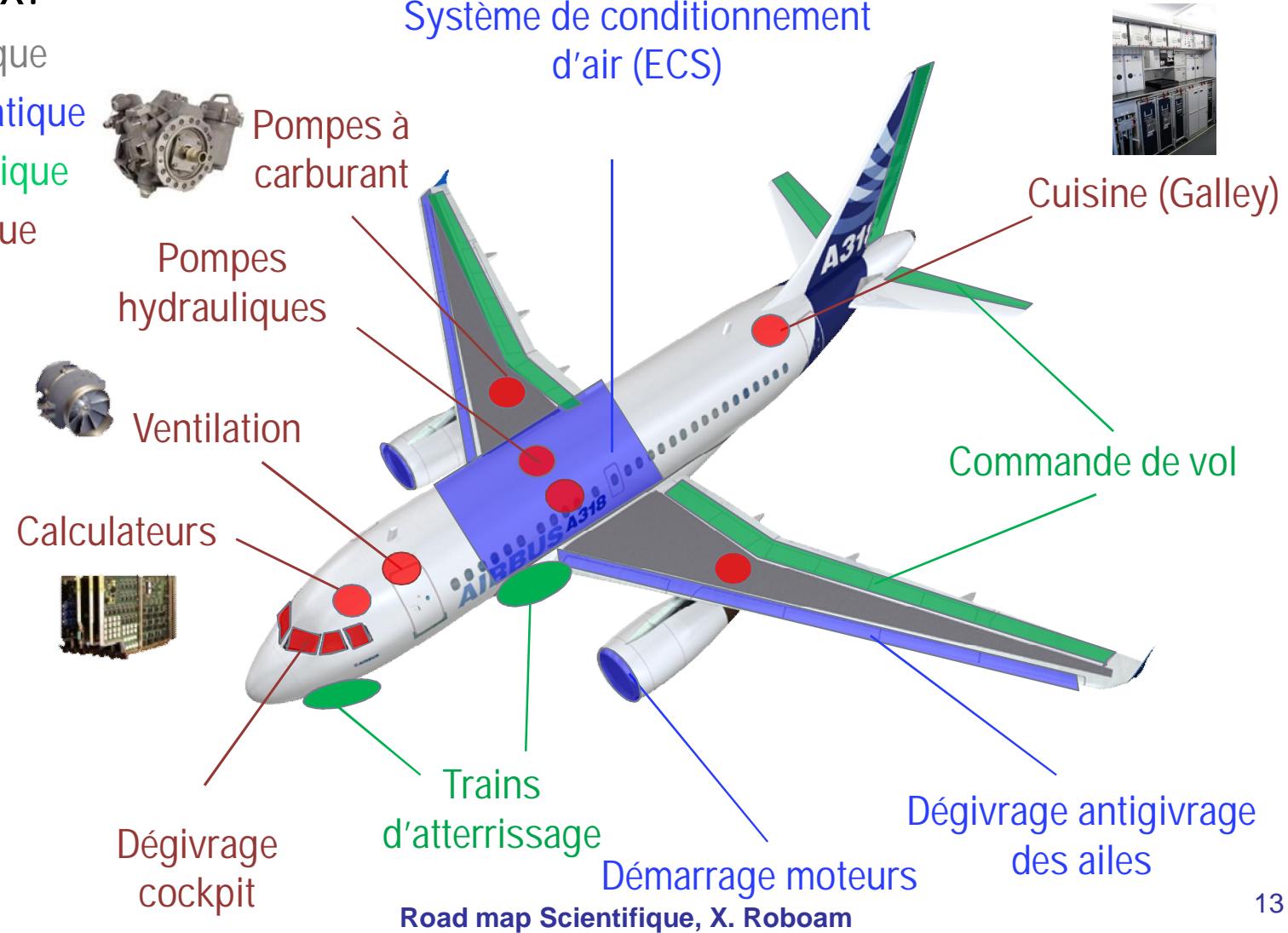


100kW – X MW
Some 100V - kVs

II. More electric non propulsive systems

- Avion conventionnel type A320/A330 : 4 vecteurs énergétiques, 3 réseaux:

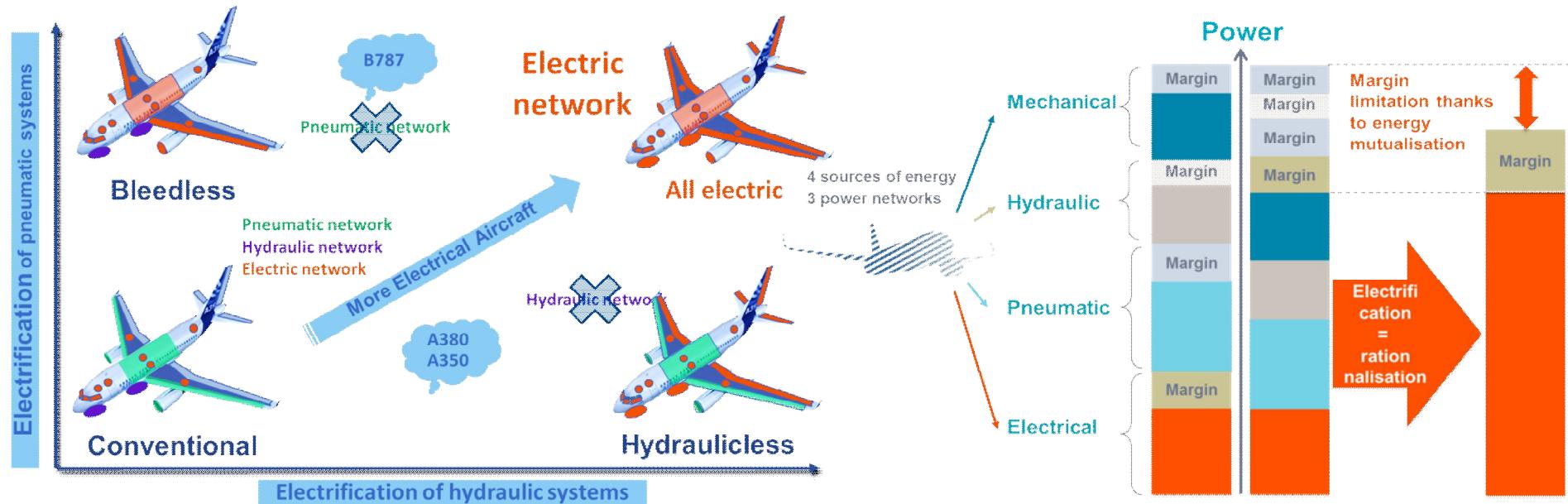
- Mécanique
- Pneumatique
- Hydraulique
- Electrique



II. More electric non propulsive systems

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Energy Rationalization : The More Electrical Aircraft



Power network rationalization

Legacy aircraft power networks have few power exchanges whereas MEA will ease power rationalization with margin reduction

Easier Maintenance: health monitoring

OVERALL AIRCRAFT OPTIMIZATION

II. More electric non propulsive systems

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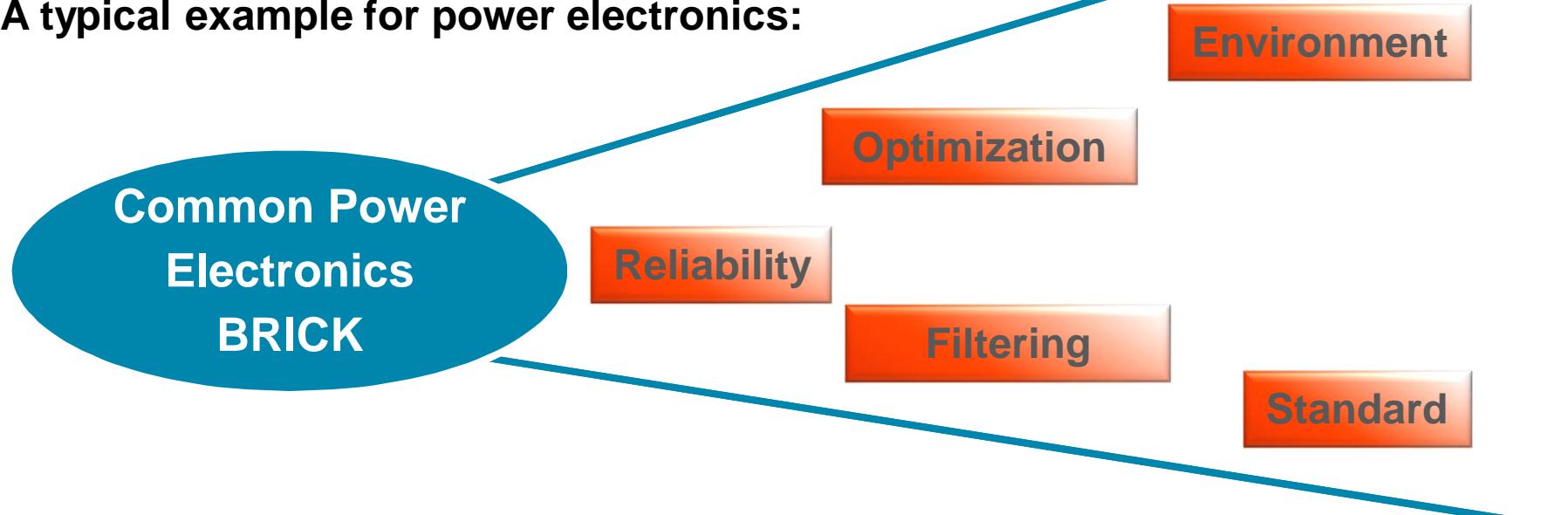
Going towards industrialization

Standardized Component :

- Cost / Weight / Performance at the target level
- Enabler to reduce development time and development cost



A typical example for power electronics:



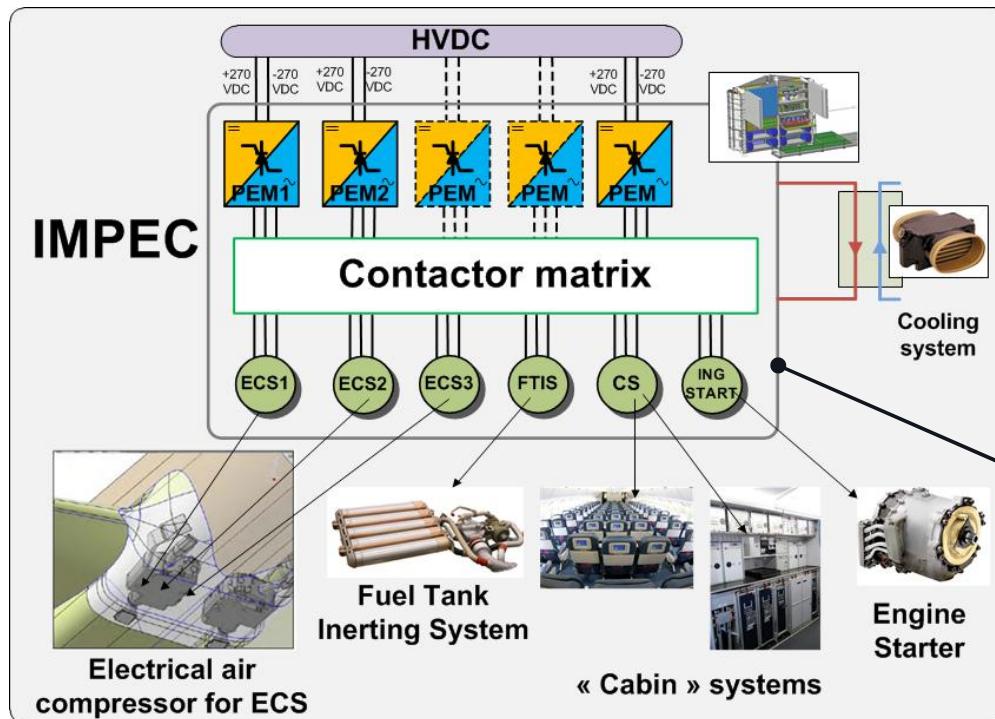
Same Component for multiple Aircraft applications

II. More electric non propulsive systems

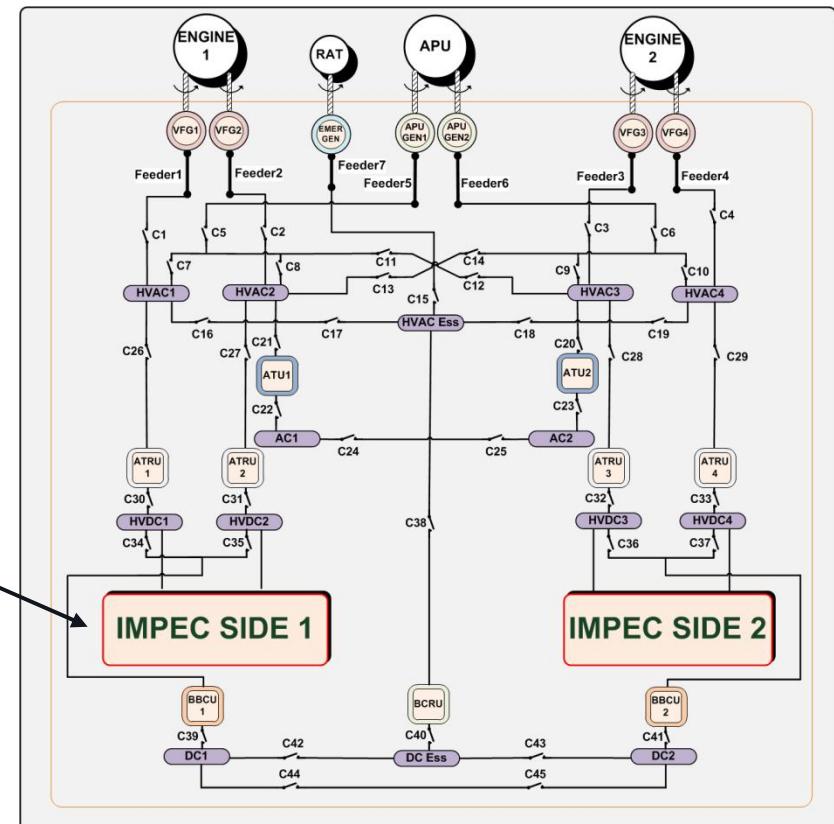
“Integrated Modular Power Electronics Cabinet” (IMPEC): new electrical power distribution with standardized components

2 main devices:

- A set of standard power electronics modules (PEM)
- A contactor matrix



Implementation of IMPEC within a complete MEA network

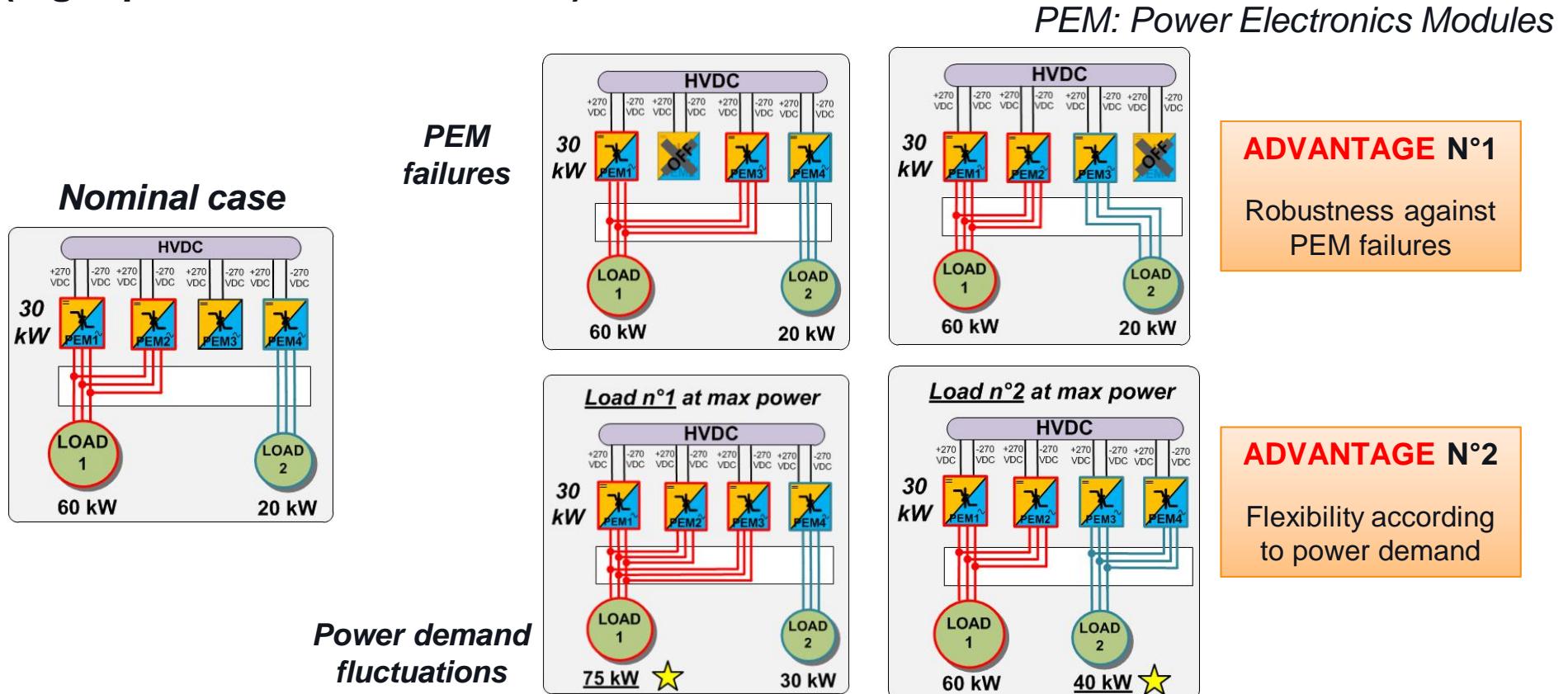


Thesis of X. Giraud, Methodologies for the optimal design of the Integrated Modular Power Electronics Cabinet (IMPEC), Toulouse, 2013

Road map Scientifique, X. Roboam

II. More electric non propulsive systems

Reconfiguration possibilities depending on operation cases
(flight phases, PEM states, etc)



Thesis of X. Giraud, *Methodologies for the optimal design of the Integrated Modular Power Electronics Cabinet »* (IMPEC), Toulouse, 2013

II. More electric non propulsive systems

Optimal design problem

Design objective

Minimization of the power center weight : « $\min(W_T)$ »

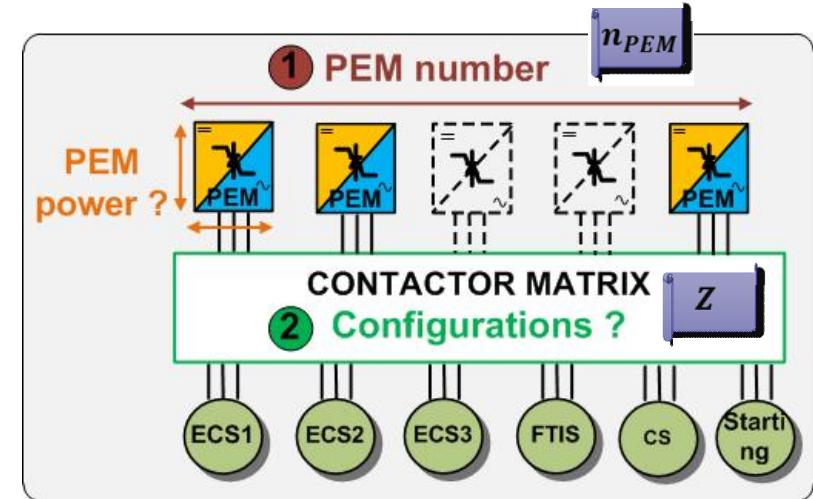
2 design variables

- 1) Number of PEM (and its power)
- 2) Contactor matrix reconfiguration

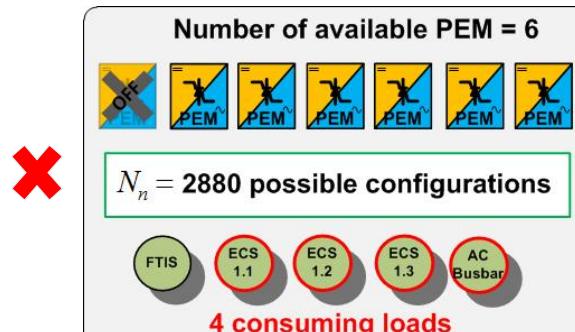
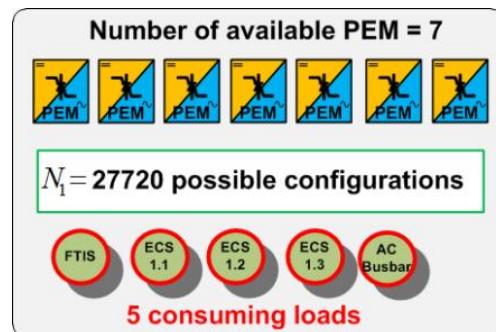
$$z_{l,m}^c = \begin{cases} 1, & \text{load } « l » \text{ connected to PEM } « m » \text{ during the case } « c » \\ 0, & \text{sinon} \end{cases}$$

W_T
 n_{PEM}
 Z

PEM: Power Electronics Modules



A first glance shows a combinatorial explosion !!!



$\times \quad \times \quad \dots \quad \rightarrow$

Z

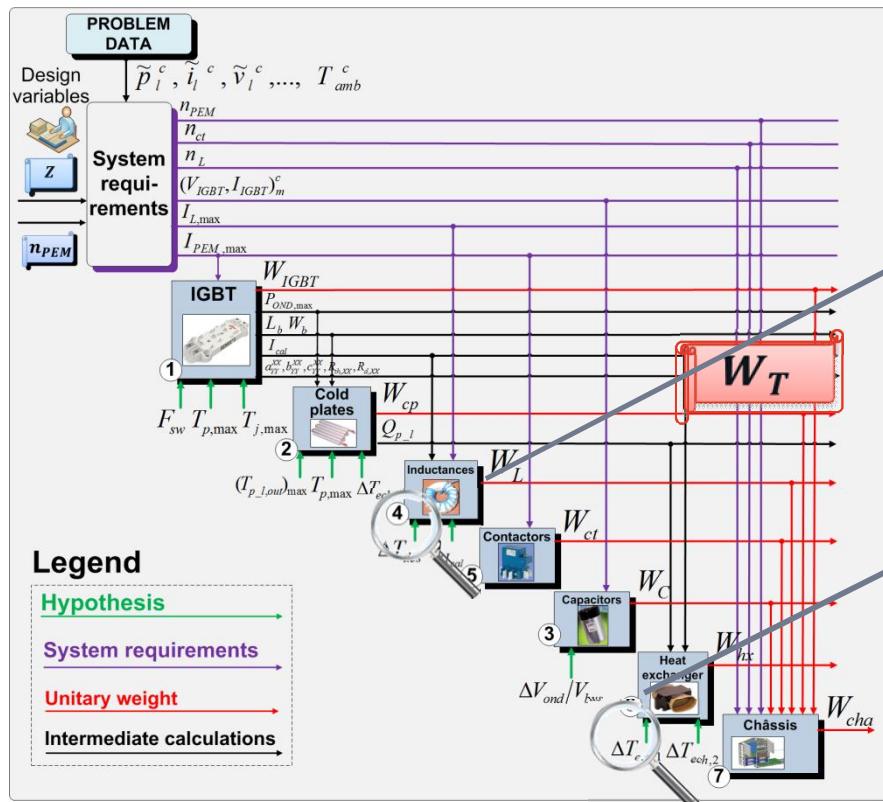
Number of reconfiguration solutions $\prod_{k=1}^K N^k$

Number of loading cases $C \approx [1000;3000]$

II. More electric non propulsive systems

Optimal Procedure features

- Formalisation through a **N-square diagram (N2D)**
- INTER BLOCKS** : sequential calculations by introducing **design hypothesis**



- INTRA BLOCK**. Simple and rapid relationships:

- Use of datasheet
- Analytical equations
- Scaling laws
- Response surfaces

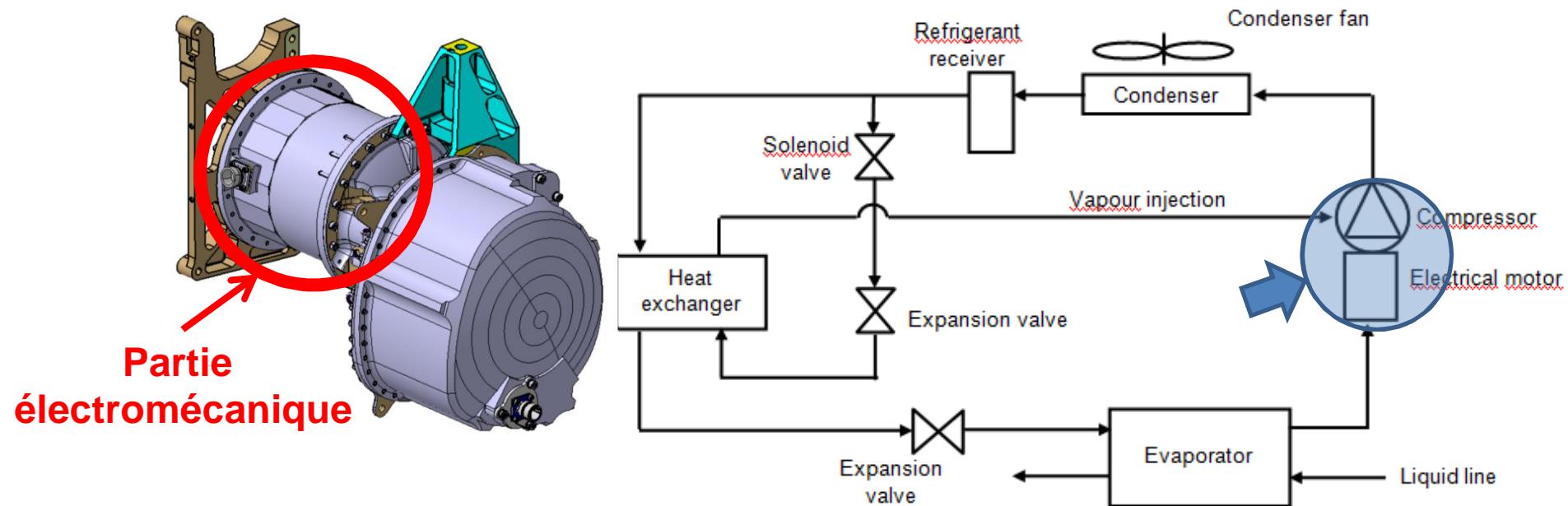
Rapid model derivation through a sequential N2D procedure

Heuristic search

- 1) Greedy algorithm: PEM power search with min nb of contactors in 2 steps:
- 2) Local heuristic search to reach min weight with min nb of inductances

II. More electric non propulsive systems

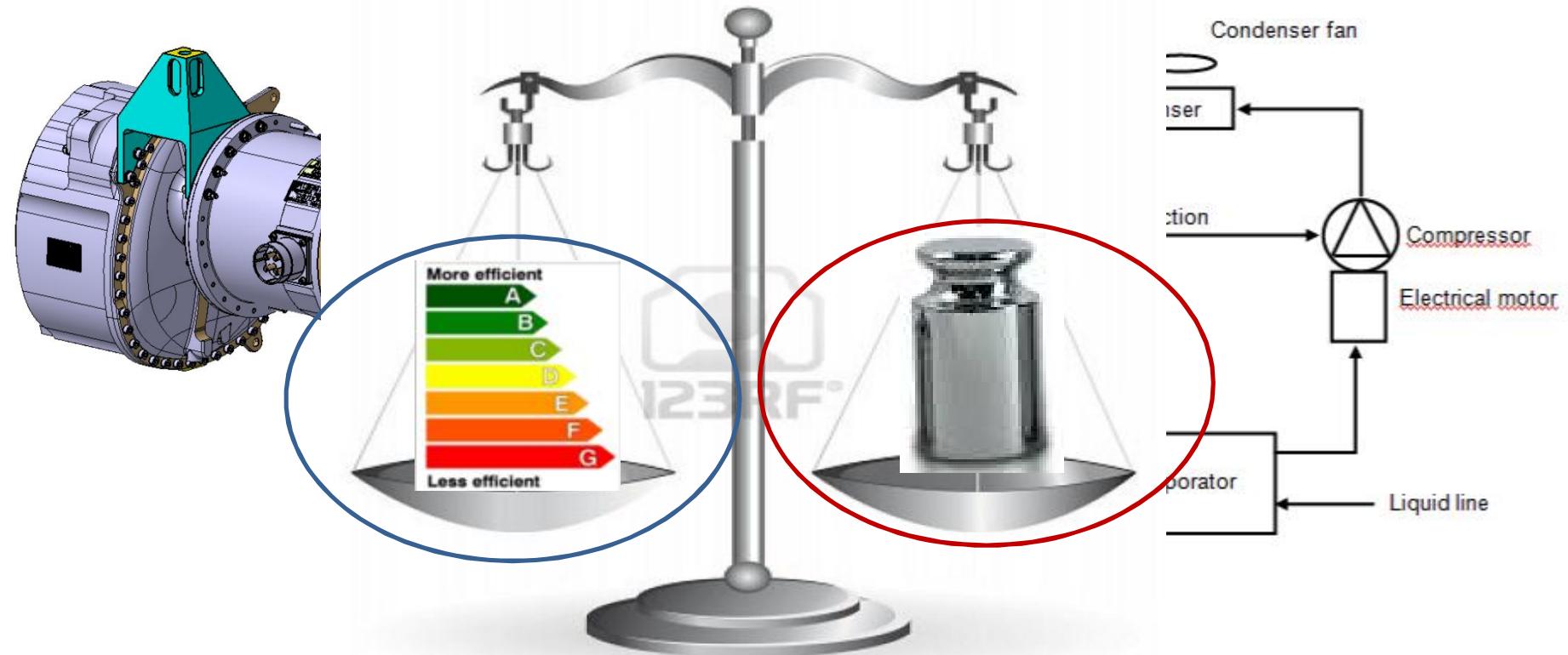
Typical issue: global optimization of electromechanical part of a VCS (Vapour Cycle System) for supplemental cooling of A380



Le système VCS (Vapour Cycle system) assure le refroidissement des électroniques. La fonction du moto-compresseur est :

- d'assurer l'écoulement du réfrigérant à travers le système hermétique ;
- de faire monter la pression entre l'évaporateur et le condenseur.

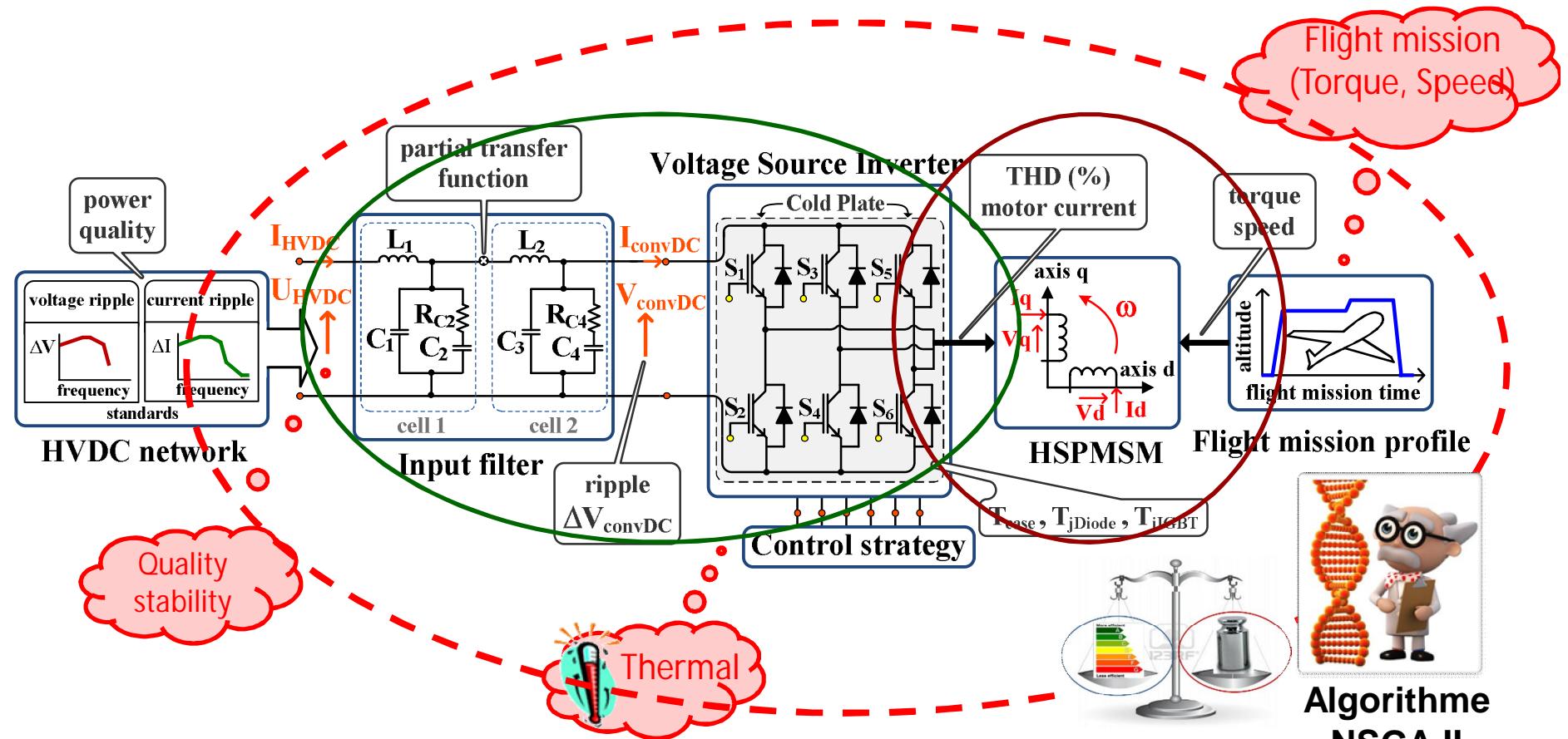
II. More electric non propulsive systems



Optimiser le compromis masse - pertes système en intégrant les couplages du raccordement au réseau HVDC (norme) à la mission de vol (plan couple – vitesse)

II. More electric non propulsive systems

Méthodologie: 3 approches d'optimisation



- Optimisation séquentielle : deux boucles (**Actionneur** puis **Filtre-Onduleur**)
- Optimisation **Globale** : mono boucle
- Optimisation Multi-niveaux

II. More electric non propulsive systems

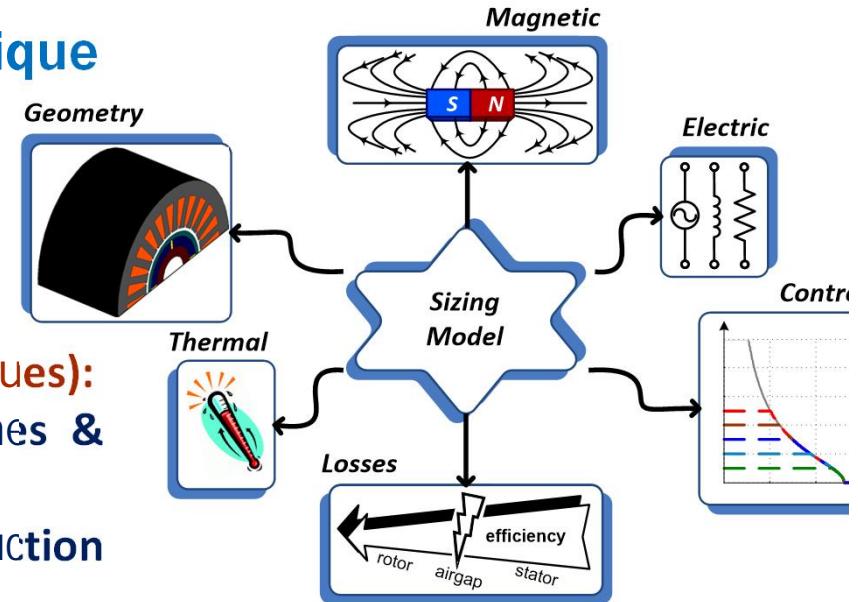
1^{ere} boucle : l'actionneur électromécanique

- Modèle analytique multiphysique

- 12 variables d'optimisation (2 discrètes, 10 continues):
 - géometrie (rayon alésage, entrefer, encoches & poles, aimants)
 - électromagnétique (densité courant, induction culasse)
 - mécanique (couple, vitesse de base)

- 18 contraintes:
 - géométriques
 - satisfaction mission
 - thermique (culasse, bobinage, aimants),
 - THDi
 -

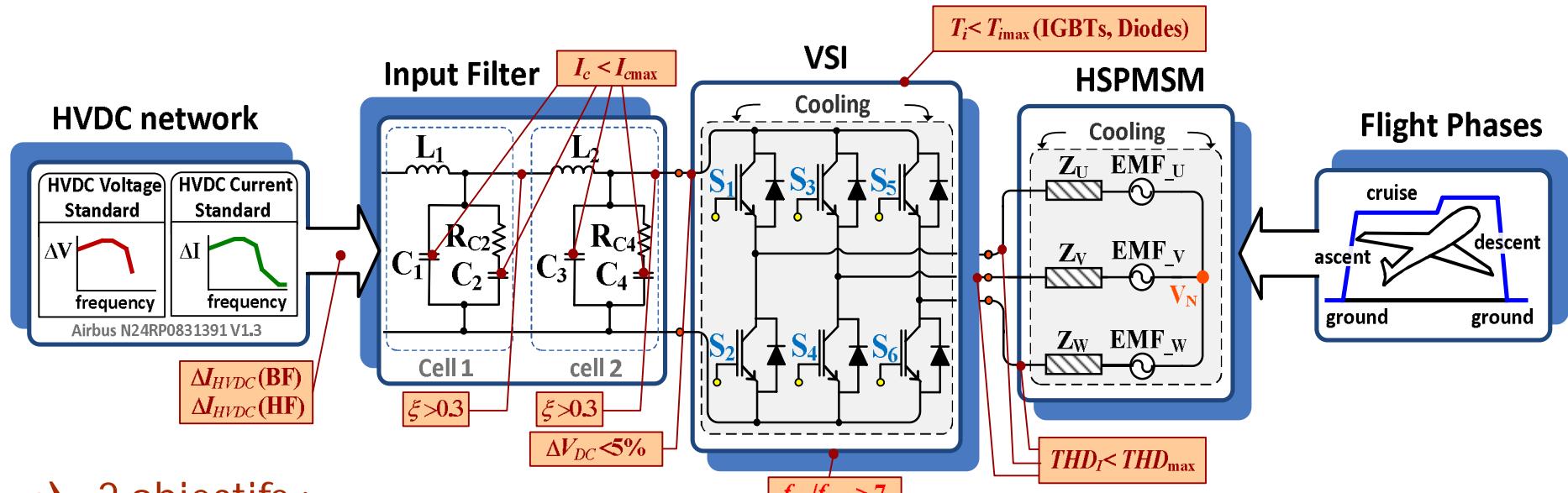
- 2 objectifs : masses et pertes moyennes



II. More electric non propulsive systems

2^{eme} boucle : onduleur & filtre d'entrée

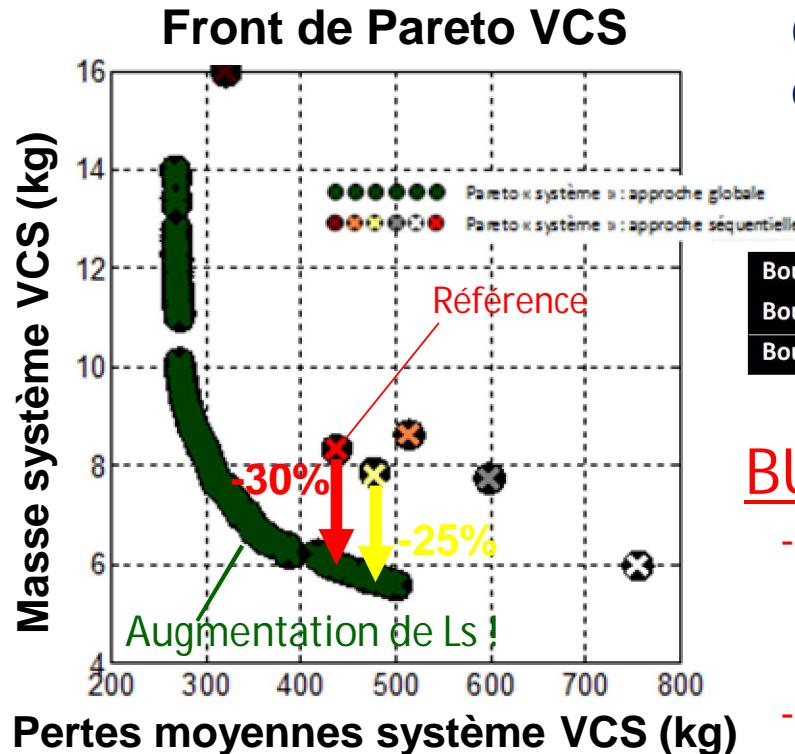
- 6 variables d'optimisation (continues):
 - 4 paramètres filtre d'entrée (R , L , C)
 - 2 paramètres onduleur : Calibre IGBT et fréquence de commutation
- 11 contraintes de qualité (standards, F_{sw}/F_{act} , THD_I , ΔV_{ond}), stabilité et thermique



- 2 objectifs :
 - minimisation masse (L,C filtre, pack IGBT, plaque froide)
 - minimisation pertes : onduleur (switching, conduction), filtre (R, L, C)

II. More electric non propulsive systems

Comparatif approche séquentielle vs mono boucle



Global approach clearly outperform sequential optimization (involving system couplings : R_s , L_{syn} , Φ , p)

	Temps CPU [min]	Taille du modèle	Taux réalisable [%]	Convergence
Boucle « Actionneur »	15	✓	30	✓✓✓
Boucle « onduleur + filtre »	30	✓✓	21	✓✓
Boucle Globale	120-180	✓✓✓	10	✓

BUT Global Optimization

- reaches "convergence limit": initialized with solutions issued from sequential approach
- Confidentiality issues: cannot be used in industrial project with several partners (or "competitors")



To search an intermediate approach with:

- Easier convergence
- Acceptable computational (CPU) time
- Respecting confidentiality issues (separated device models)

II. More electric non propulsive systems

Approche d'optimisation multiniveaux



N (here 2) subsystems
=> N+1 optimization loops

$$[R_s, L_{syn}, \phi, p] \rightarrow X_{Global} = [R_s, L_{syn}, p, \phi]$$

Decision variables are the coupling variables between Subproblems

[R_s, L_{syn}, p, ϕ] $\rightarrow I_{actuator}, V_{actuator}$
input variables of filter-inverter Problem

No direct interaction between subsystems



System problem

$$\begin{aligned} \text{Min } M_{sys} &= M_{HSPMSM} + M_{Fil-Inverter} \\ \delta P_{sys} &= \delta P_{HSPMSM} + \delta P_{Fil-Inverter} \end{aligned}$$

Constraints

$$G_{sys} = [G_{HSPMSM}, G_{Fil-VSI}]$$

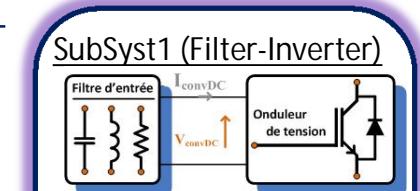


- Constraints
- - Objectives
- Local Variables
- System variables

$$\begin{aligned} M_{Fil-VSI} &\\ \delta P_{Fil-VSI} &\\ G_{Fil-VSI} & \end{aligned}$$

$$\begin{aligned} M_{HSPMSM} &\\ \delta P_{HSPMSM} &\\ G_{HSPMSM} & \end{aligned}$$

$$\begin{aligned} R_s, L_{syn} &\\ p, \phi & \end{aligned}$$

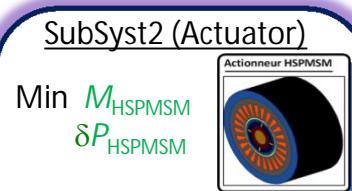


$$\begin{aligned} \text{Min } M_{Fil-Inverter} &\\ \delta P_{Fil-Inverter} & \end{aligned}$$

$$X_{Fil-VSI} = [L_1, C_1, C_2, R_{C2}, F_{sw}, I_{op}]$$

Constraints:

$$G_{Fil-VSI} = [g_1, g_2, \dots, g_{11}]$$



$$\begin{aligned} \text{Min } M_{HSPMSM} &\\ \delta P_{HSPMSM} & \end{aligned}$$

$$X_{HSPMSM} = [J_s, N_{epp}, g_y, b_y, R_{dr}, R_{lr}, K_p, K_r, N_{bp}, T_{pb}]$$

Constraints:

$$G_{Act} = [g_1, g_2, \dots, g_{18}]$$

$$\begin{aligned} g_{19}(R_s - R_s)^2 &< \varepsilon_1 \\ g_{20}(L_{syn} - L_{syn})^2 &< \varepsilon_2 \\ g_{21}(\phi_s - \phi_s)^2 &< \varepsilon_3 \end{aligned}$$

Additional (coordination) constraints

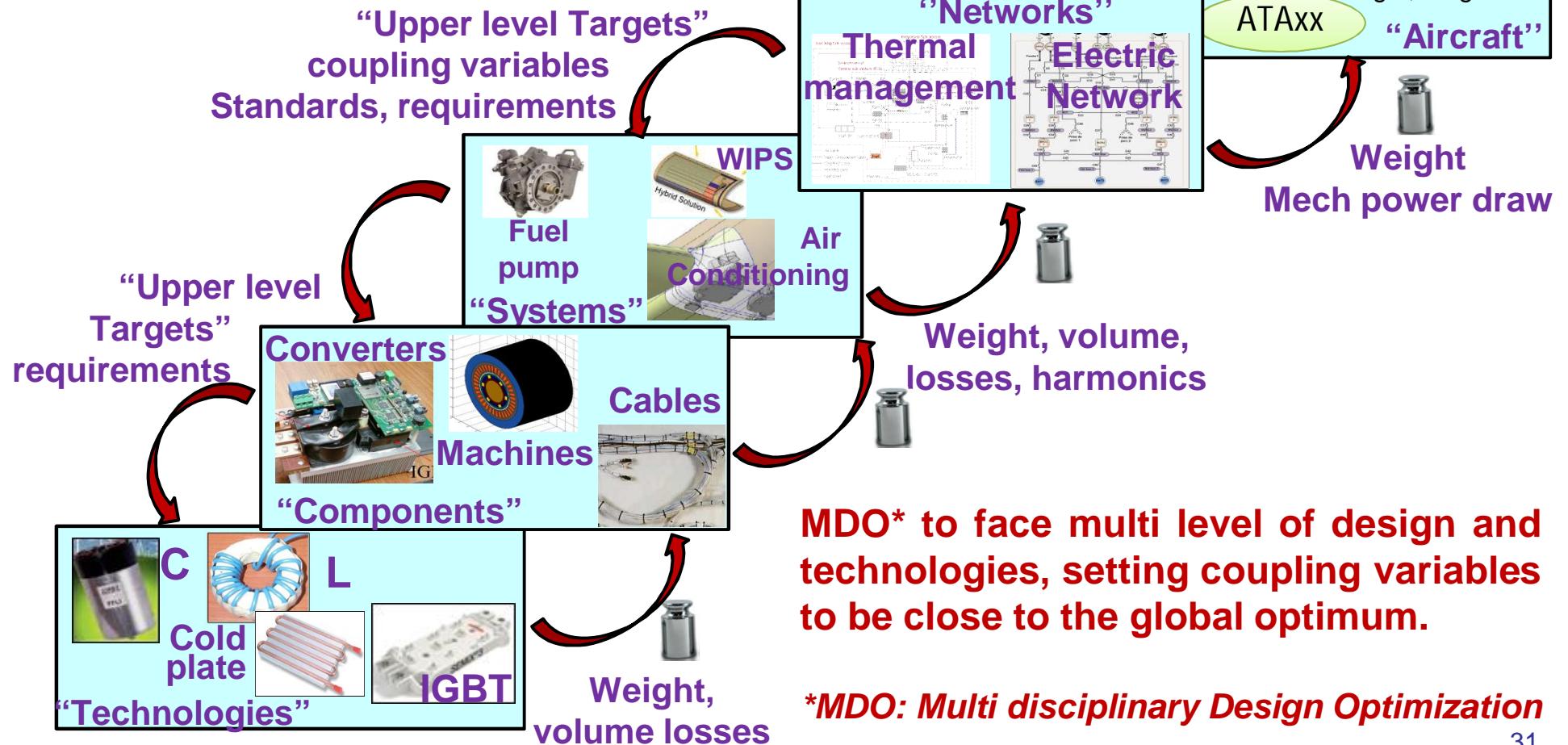
[R_s, L_{syn}, ϕ] are not decision variables but targets in the actuator Problem

Optimize each component (SubSystem) in a local loop while global objectives are explored at the system level !

II. More electric non propulsive systems

Integrated design by optimization of electrical systems: a complex issue !

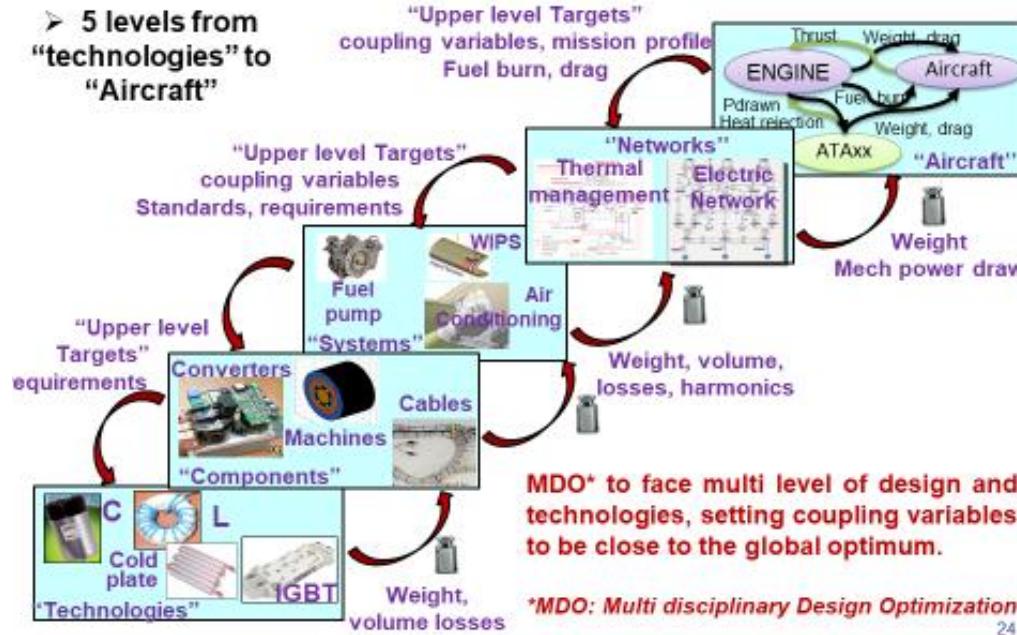
- 5 levels from “technologies” to “Aircraft”



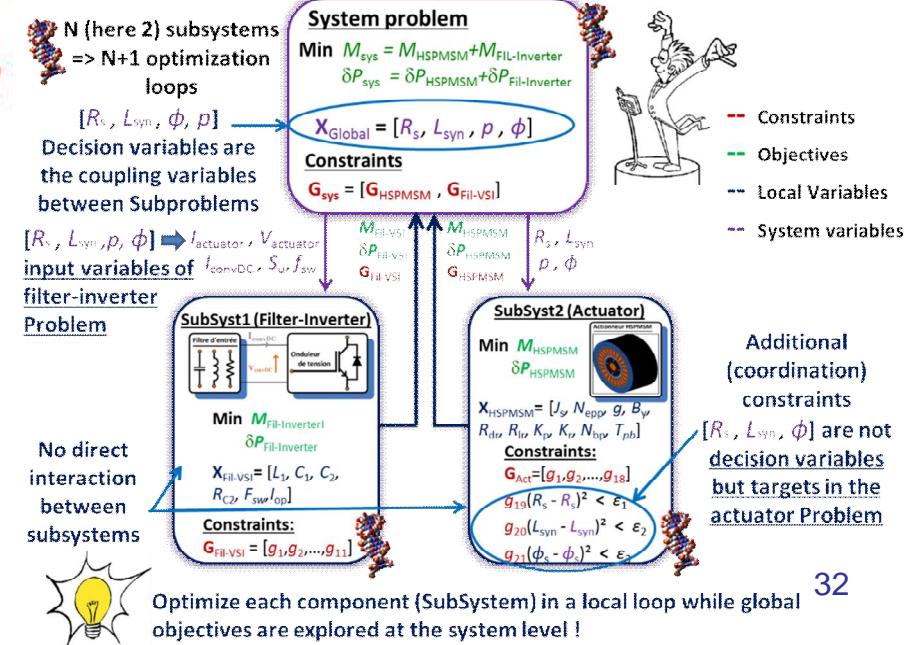
II. More electric non propulsive systems

Integrated design by optimization of electrical systems: a complex issue !

- 5 levels from "technologies" to "Aircraft"

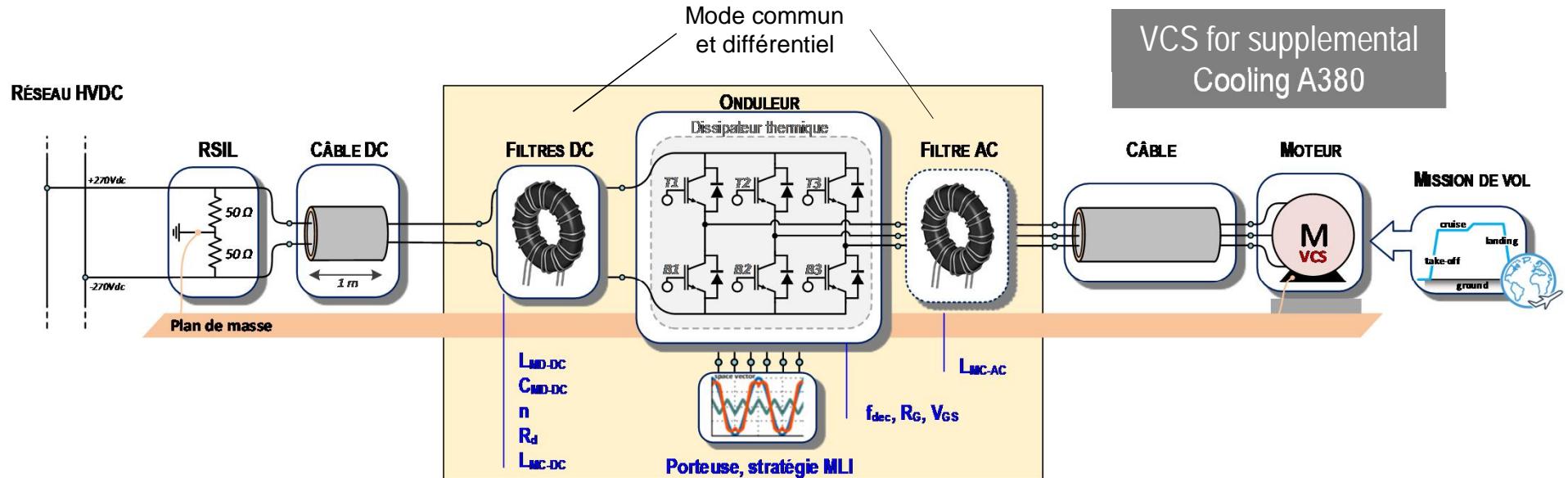


Remaining scientific
(methodological)
challenges on that topic



II. More electric non propulsive systems

- Conception par optimisation de la chaîne électromécanique sous contraintes CEM



Défi majeur: Augmenter la densité de puissance des systèmes électriques

En électronique de puissance,

Utilisation de semi-conducteurs grand gaps



Assurer la non régression de nouvelles technologies vis-à-vis de problèmes CEM

Emissions conduites de mode commun

≈ 4 kW/kg



20 kW/kg

Thèse V. Dos santos, Modélisation des émissions conduites de mode commun d'une chaîne électromécanique. Optimisation paramétrique de l'ensemble convertisseur filtres sous contraintes CEM, Mars 2019

II. More electric non propulsive systems

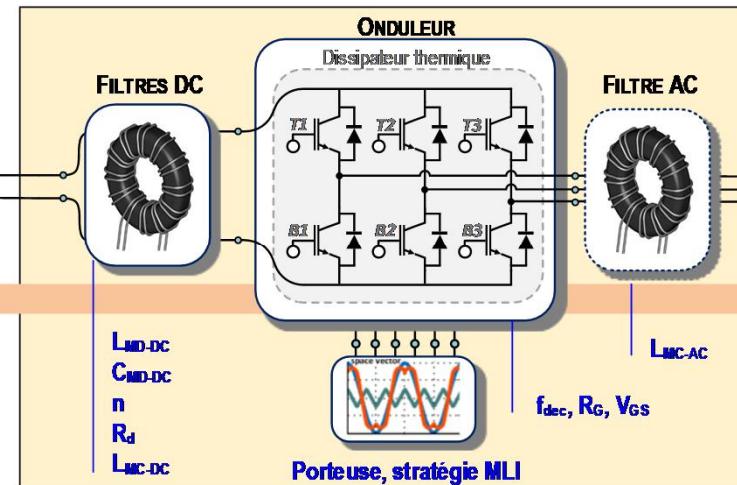
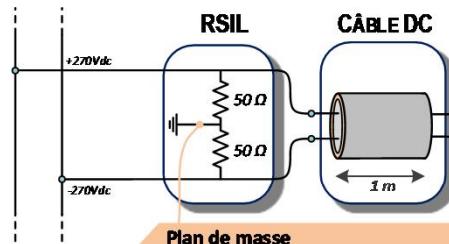
Plateforme expérimentale



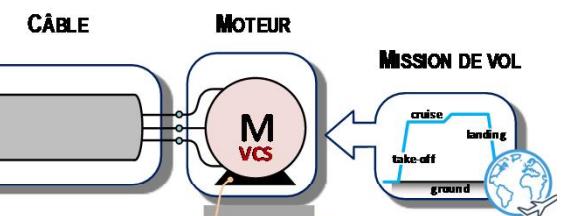
II. More electric non propulsive systems

- Conception par optimisation de la chaîne électromécanique sous contraintes CEM

RÉSEAU HVDC



Supplemental Cooling A380



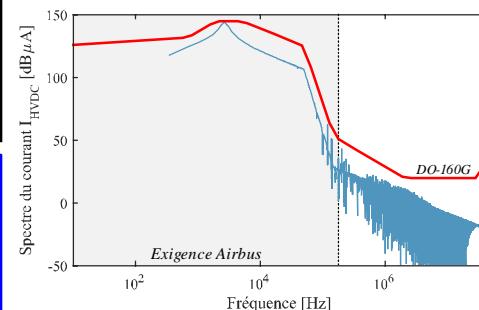
Optimisation « onduleur + filtres »

- Deux objectifs:

- Minimisation masse (filtres, dissipateur)
- Minimisation des pertes (filtres, onduleur)

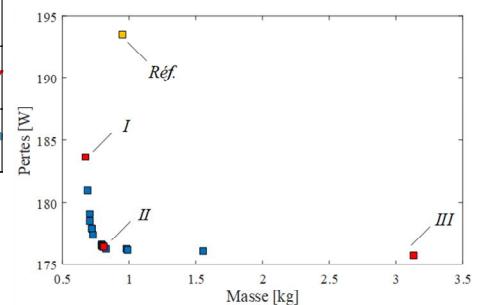
- 9 variables d'optimisation continues + 2 discrètes

- 5 paramètres (R , L , C) du filtre DC - $C_{MC-DC} = 47 \text{ nF}$
- 1 paramètre (L) du filtre AC
- f_{dec} , R_G , V_{GS} , porteuse, MLI



Contrainte CEM

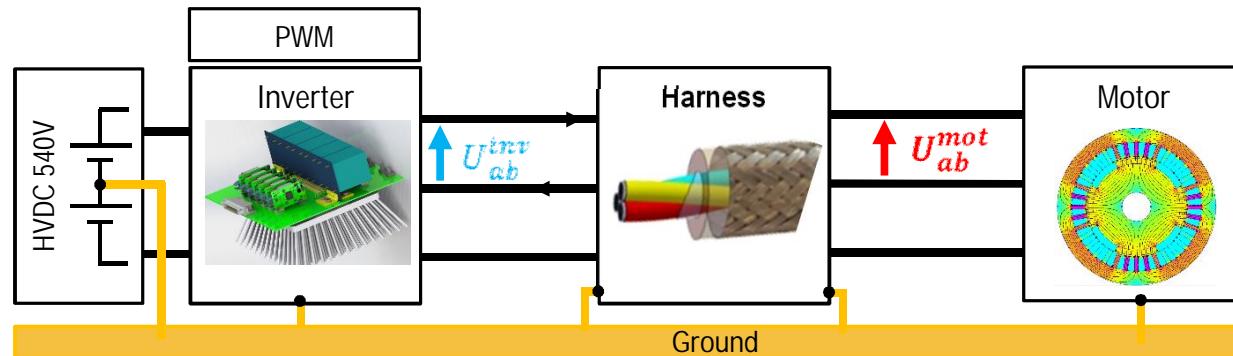
Front de pareto



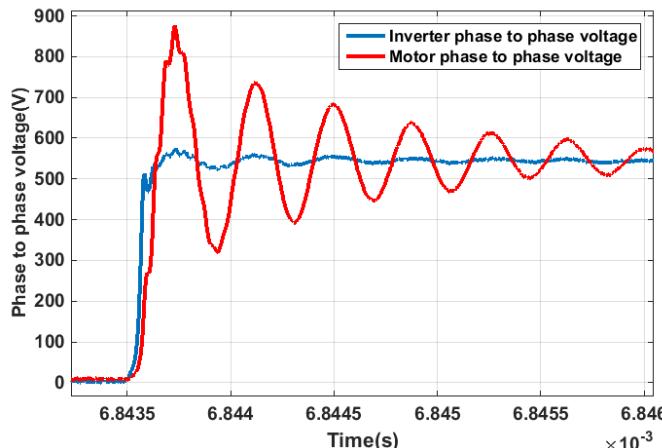
Thèse V. Dos santos, Modélisation des émissions conduites de mode commun d'une chaîne électromécanique. Optimisation paramétrique de l'ensemble convertisseur filtres sous contraintes CEM, Mars 2019

II. More electric non propulsive systems

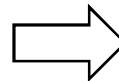
- Conception de la chaîne électromécanique sous contraintes de décharges partielles
- **Phase to phase** overvoltage in electromechanical chain : inverter + harness + motor



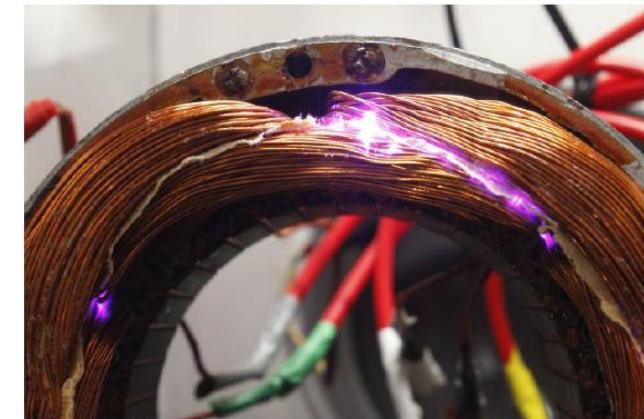
- Example of measured overvoltage on AC motor + 2m harness fed by IGBT inverter (IRT platform)
Overvoltage at motor terminals



propagation and reflection phenomena along harness cause overvoltage across motor phases



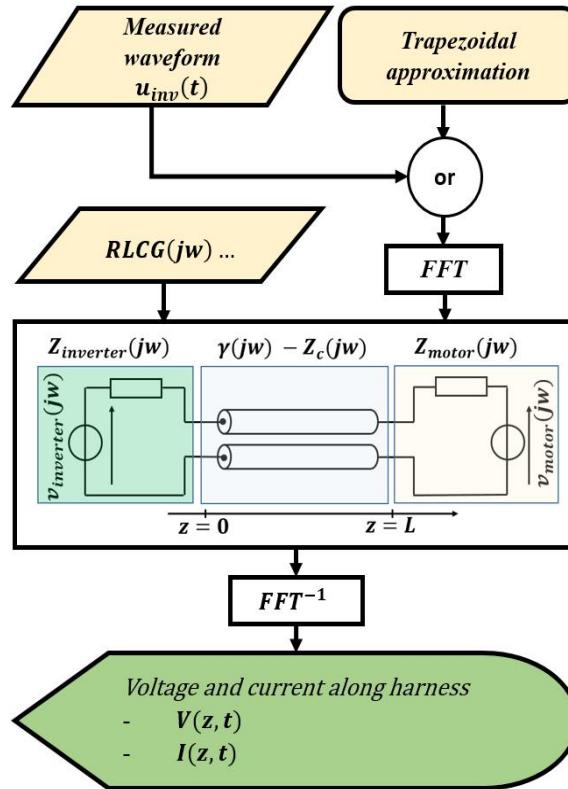
Partials discharges risks



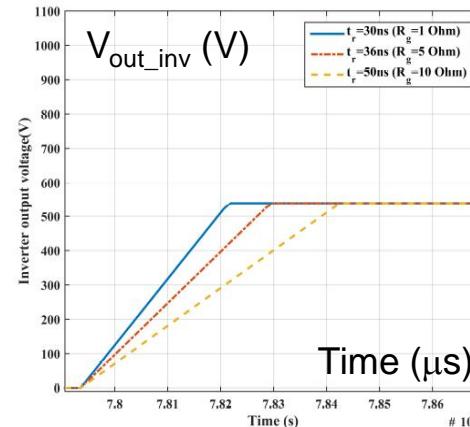
Thèse de Bouazza Taghia: "Modélisation et optimisation paramétrique d'une chaîne électro mécanique pour la prévention du risque de décharges partielles dans un actionneur aéronautique"

II. More electric non propulsive systems

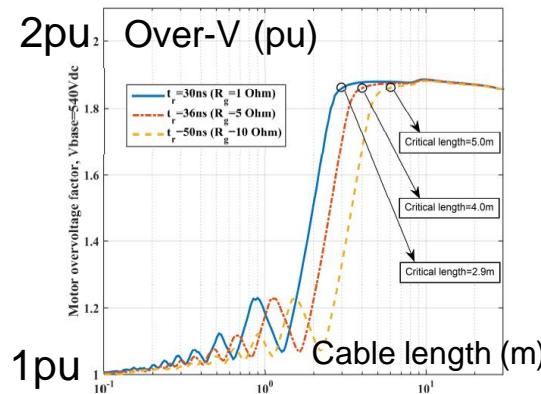
Overvoltage vs. inverter dv/dt and harness length



General synoptic of proposed overvoltage calculation algorithm



CREE CAS100H12AM1 SiC inverter voltage (trapezoidal approximation)

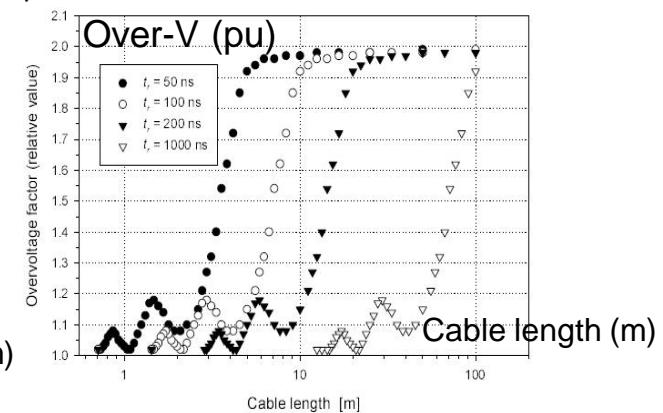


Overvoltage ratio in function of harness length : AWG18-EN2267-010A

Conventional method: without motor impedance (harness terminations as opened circuit):

- Z_{motor} assumed = 5000Ω
- $Z_{inverter}$ assumed = 0Ω

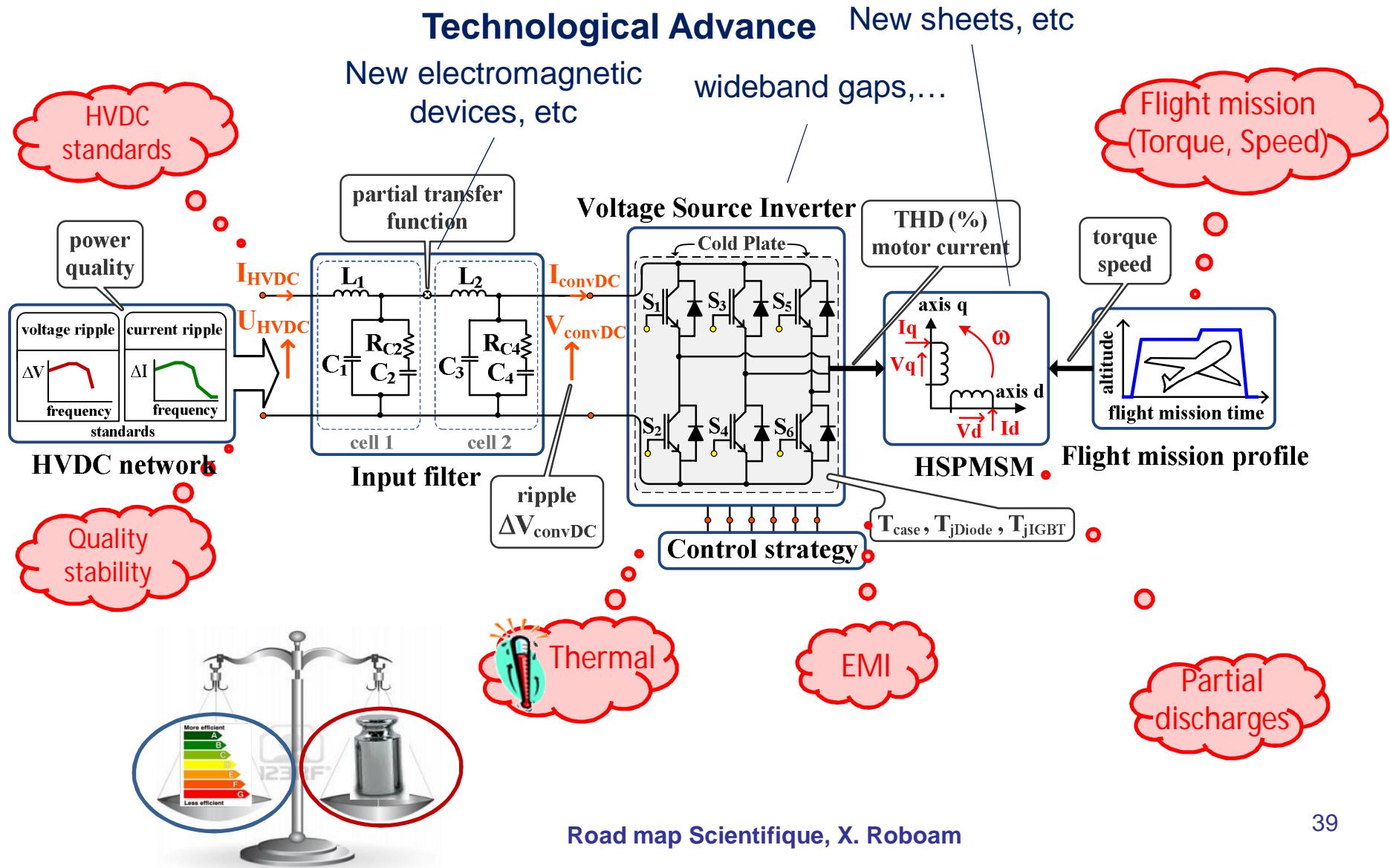
Conventional vision leads to consider that high dV/dt (SiC) provokes over voltages (1.8 – 2 pu) even at low cable lengths



Overvoltage ratio in function of harness length , EIC Standard (60034-18-41)

II. More electric non propulsive systems

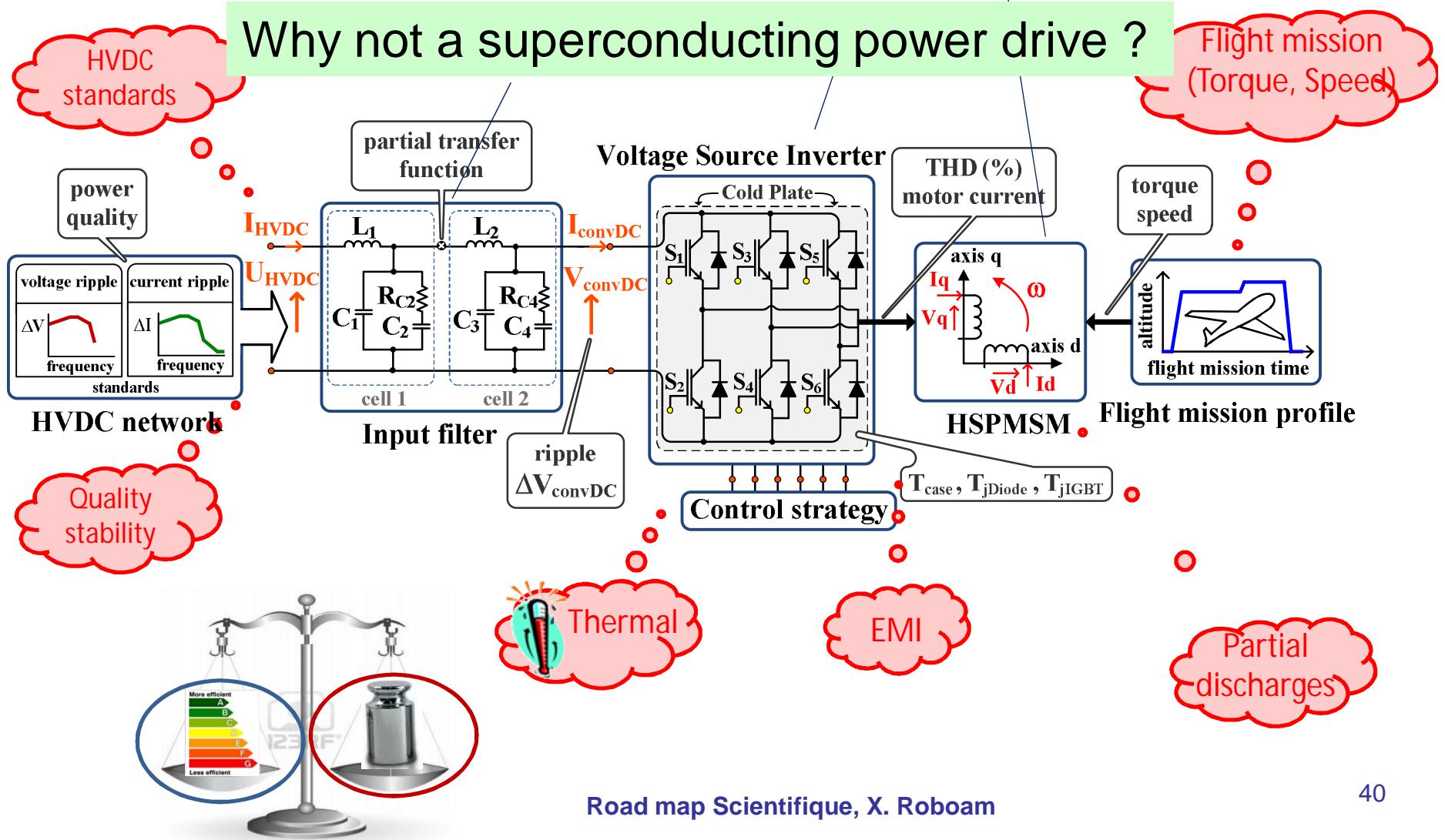
Multiple challenges, multiple constraints to face



II. More electric non propulsive systems

Multiple challenges, multiple constraints to face ... and beyond that ?

Technological Advance New sheets, etc.



II. More electric non propulsive systems

Why not a superconducting power drive ?



MOTEUR SUPRACONDUCTEUR POUR L'AÉRONAUTIQUE GREEN-SAFRAN

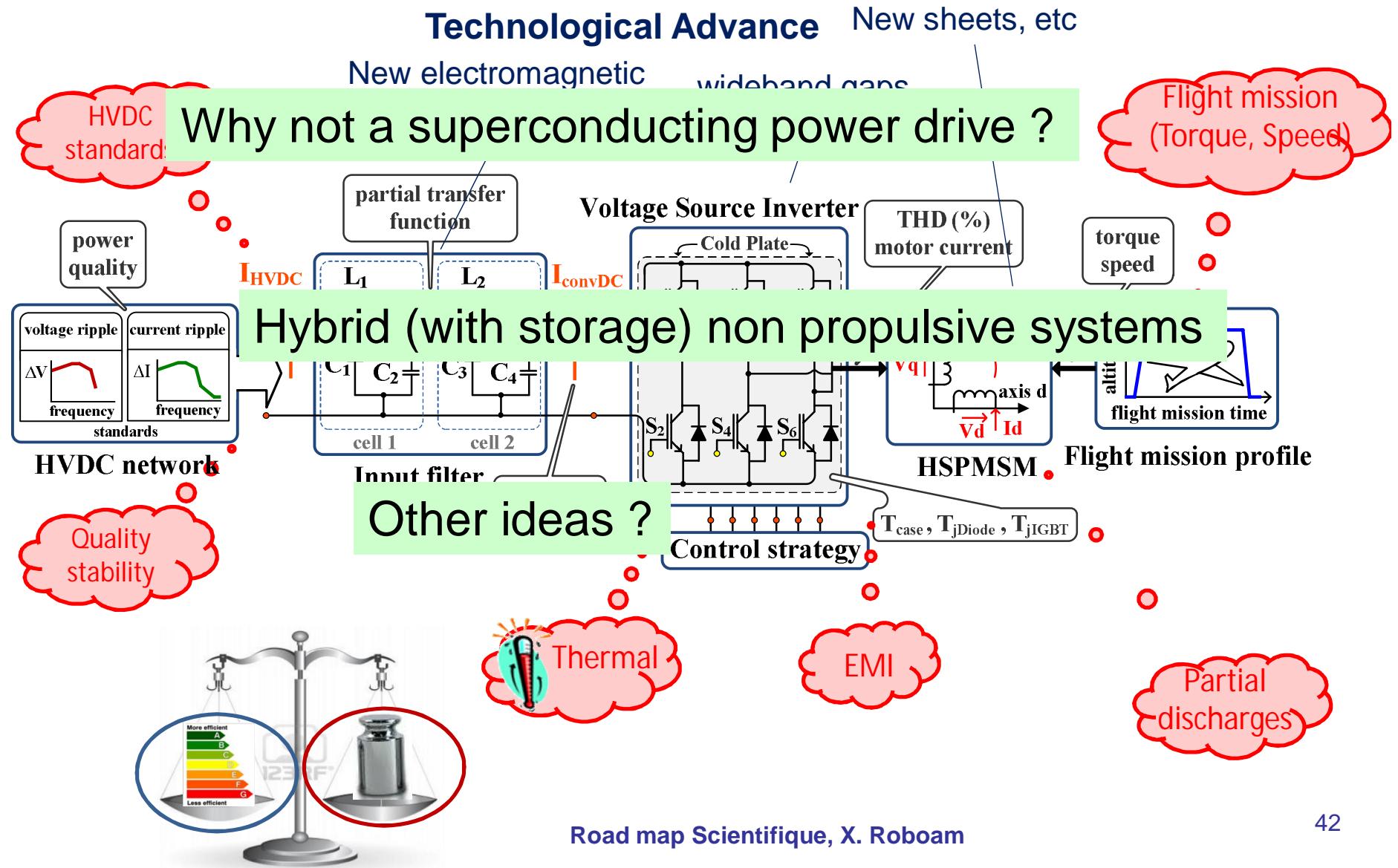


- Inducteur supraconducteur induit cuivre

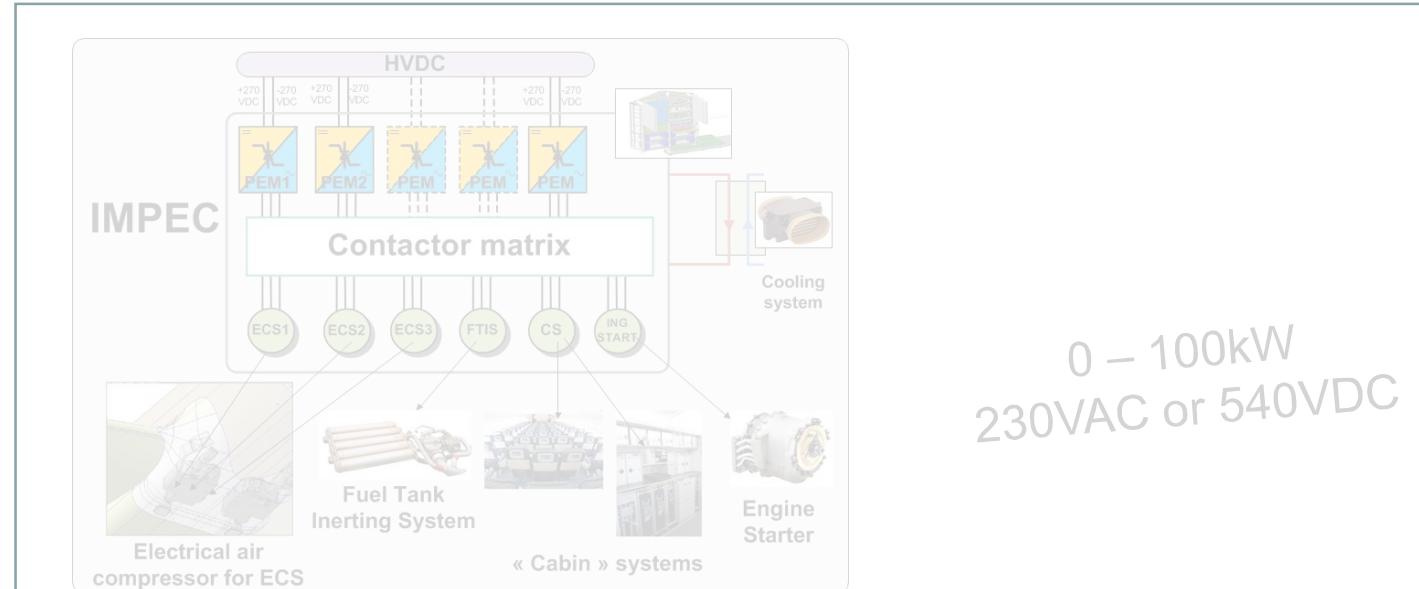
Puissance nominale	50 kW
Vitesse de rotation	5.000 tr/min
Couple nominal	95 N.m
Densité de courant cuivre	10 A/mm ²
Température d'utilisation	30 K
Rendement minimum	> 95%
Couple massique	> 5kW/kg

II. More electric non propulsive systems

Multiple challenges, multiple constraints to face ... and beyond that ?



II. More electric non propulsive systems



III. More electric propulsive systems



100kW – X MW
Some 100V - kVs

Road map Scientifique, X. Roboam

III. More electric propulsive systems



Join Over 200 International Experts Discussing
Electric & Hybrid Propulsion Technology For The
Next Generation of Aircraft



A strongly emergent topic



Prof Dr. Josef Kallo, Coordinator Energy System Integration, German Aerospace Center

THE NEW ERA OF ELECTRIC AVIATION IN FIXED-WING, EVOTL & UAM

**DEVELOPMENTS IN ENERGY STORAGE FOR MEA AND AEA:
HEALTH MONITORING AND HYDROGEN FUEL CELLS**

**FROM MORE-ELECTRIC TO ALL-ELECTRIC: HYBRID & ELECTRIC
PROPULSION AND DRIVE TRAIN**

EVENING WORKSHOP

**TECHNOLOGY NEED FOR ELECTRICAL COMPONENTS WITH GROWTH OF AIRCRAFT MARKET FROM
URBAN AIR MOBILITY TO LARGE AIRCRAFT WITH MEGAWATT SCALE PROPULSION SYSTEM**

The electrical and hybrid aircraft : objectives, orientations and stakes
Urban air mobility : scientific and technical challenges
The real roadmap to the future of electric air mobility
Perspectives and activities on hybrid/electric propulsion
Challenges and solutions for certified electric aircraftin commercial applications
Electric propulsion units : design aspects & performance levels

Road map Scientifique, X. Roboam

III. More electric propulsive systems

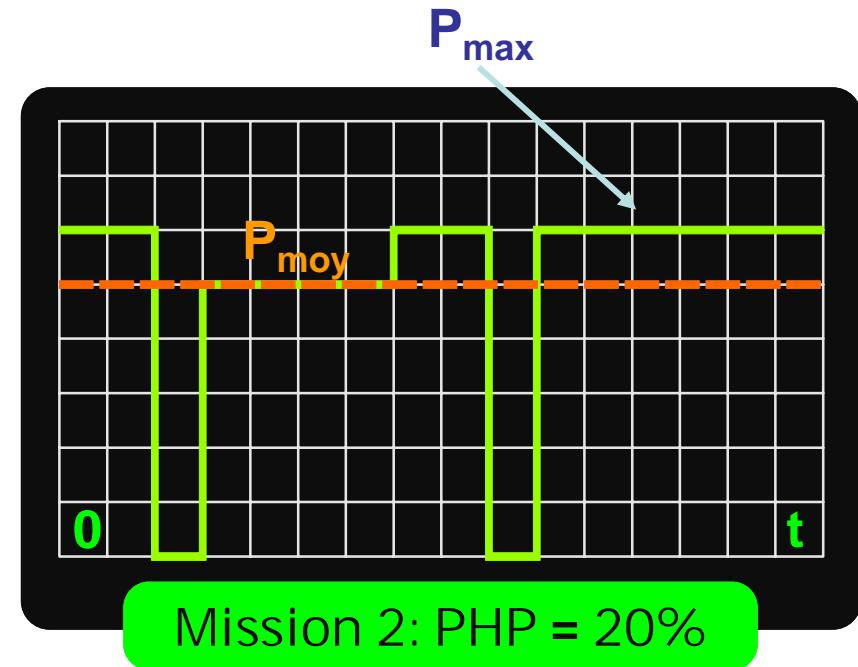
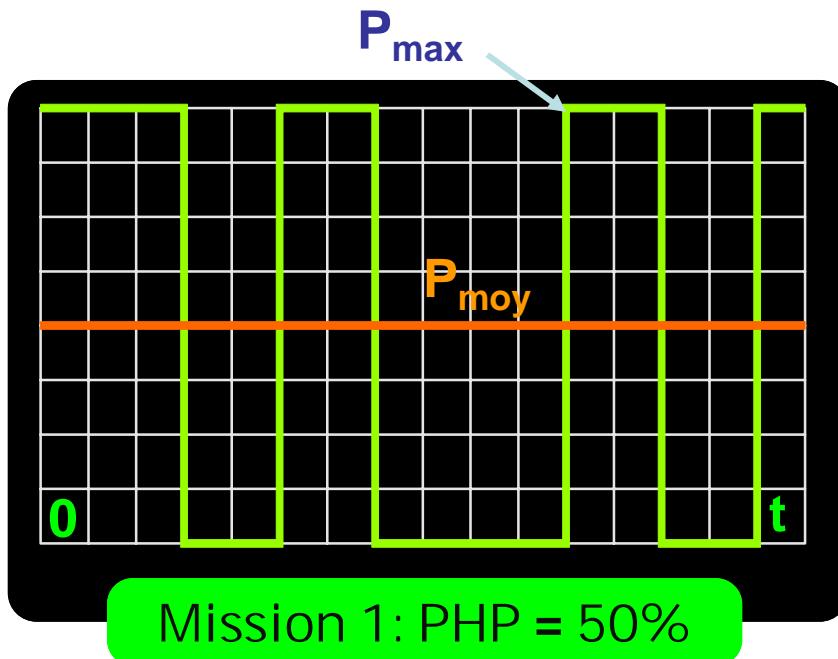
The hybrid electric aircraft among all hybrid electric vehicles

➤ Indicateurs d'hybridabilité énergétique

[Thèse Akli, Toulouse 2008]

- ❖ PHP (Potentiel d'Hybridation en Puissance) :
évalue le degré potentiel de réduction de la taille de la source d'énergie primaire

$$PHP = 1 - \frac{moy(P_{sp})}{\max(P_{sp})}$$



PHP = 0 => (moy = max) pas de downsizing
 PHP = 1 moyenne nulle



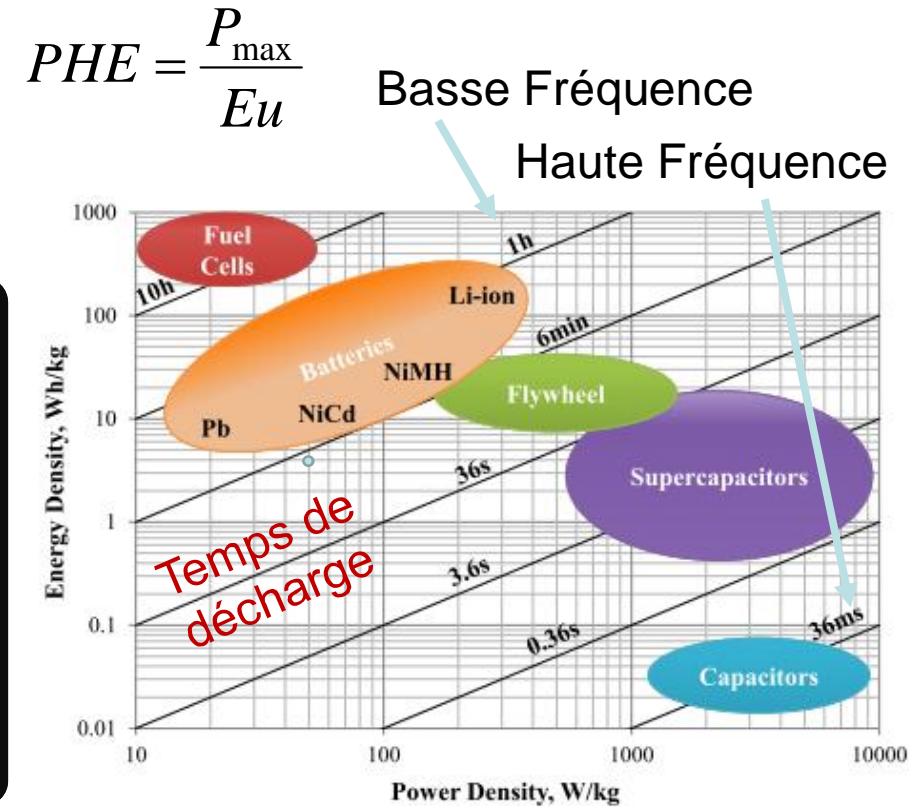
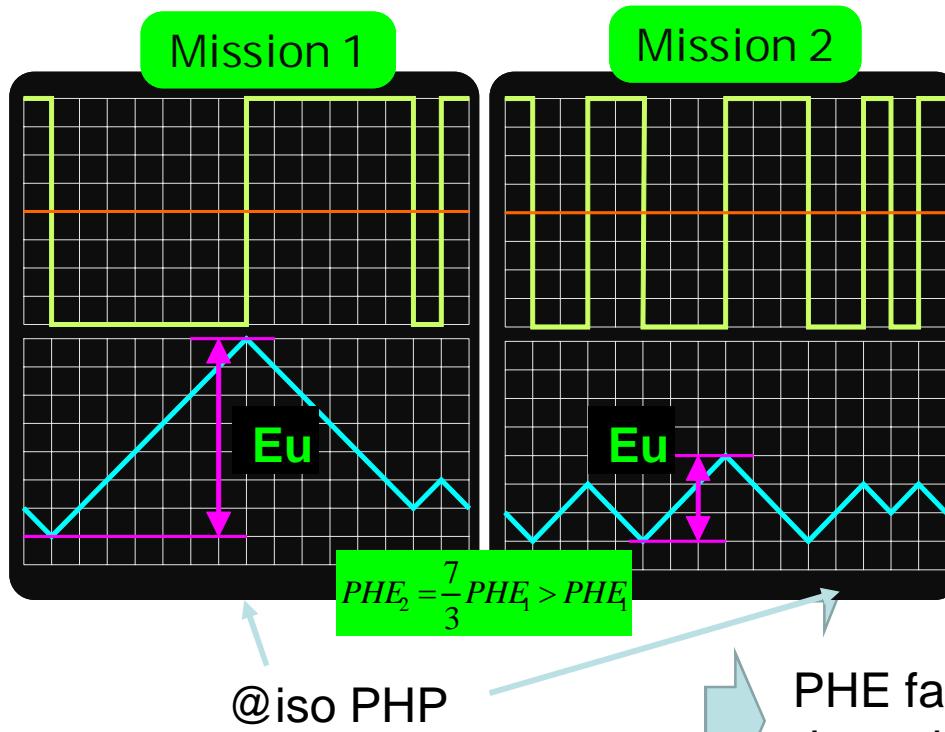
PHP faible, downsizing
puissance difficile

III. More electric propulsive systems

The hybrid electric aircraft among all hybrid electric vehicles

➤ Indicateurs d'hybridabilité énergétique

- ◆ PHE (Potentiel d'Hybridation en Energie) : évalue la fréquence et la régularité des intermittences de la mission



PHE faible (basse fréquence d'intermittence),
downsizing énergie 'difficile' (couteux en stockeur)

III. More electric propulsive systems

The hybrid electric aircraft among all hybrid electric vehicles

$$PHP = 1 - \frac{moy(P_{sp})}{max (P_{sp})}$$

PHP faible,
downsizing
puissance 'difficile'

PHE faible
downsizing
énergie 'couteux'

$$PHE = \frac{P_{max}}{E_u(\text{stockage})}$$

	Car			Train			Ship		Aircraft
	Urban	Rural road	Motorway	Local service	Switching	Urban transp.	Container	Passenger ferry	Regional (200 nm)
PHP (%)	94%	85%	74%	65%	83%	91%	43%	63%	32%
PHE (mHz)	66 mHz	30mHz	12 mHz	3 mHz	29 mHz	20 mHz	n/a	n/a	0.22 mHz

Plus favorable
pour hélicoptères

- ✓ Hybridabilité de la propulsion d'aéronefs difficile énergétiquement
 - Peu d'intermittence, pas de récupération au freinage
 - Peu de régimes transitoires : mission énergétique quasi statique
 - Downsizing Turbine à gaz : « grosses turbines » plus efficaces
- ✓ Power management « simple » (vision « par séquences »)

III. More electric propulsive systems

Why an hybrid electric aircraft ?

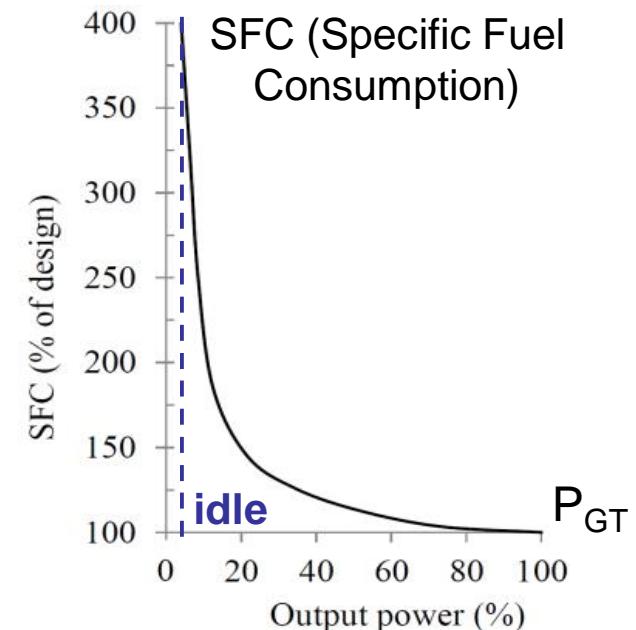
- ✓ Aerodynamic benefits: several concepts



- ✓ Energy benefits: turboshaft efficiency

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

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

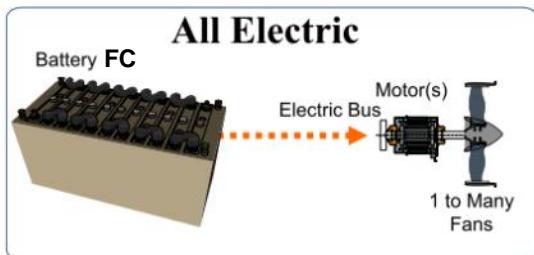


J. Thauvin, Exploring the design space for a hybrid-electric regional aircraft with multi-disciplinary design optimisation methods
PHD Thesis of Univ Toulouse & Airbus Oct 2018

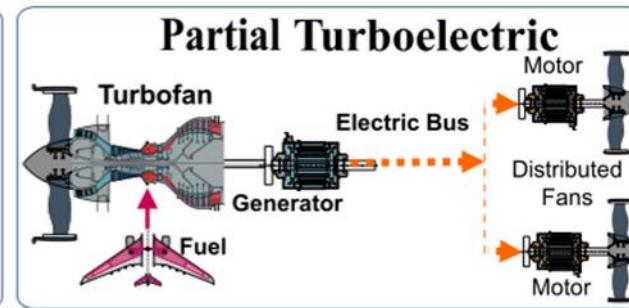
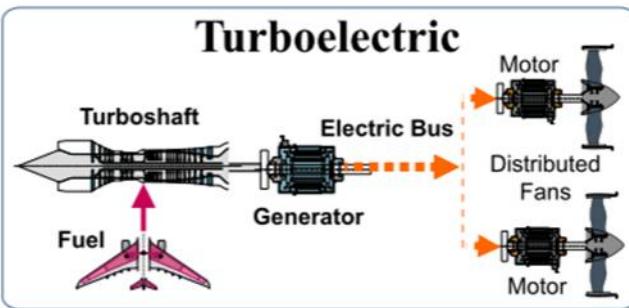
III. More electric propulsive systems

Several Hybrid Architectures

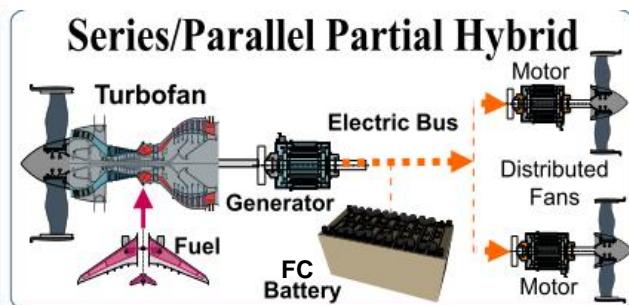
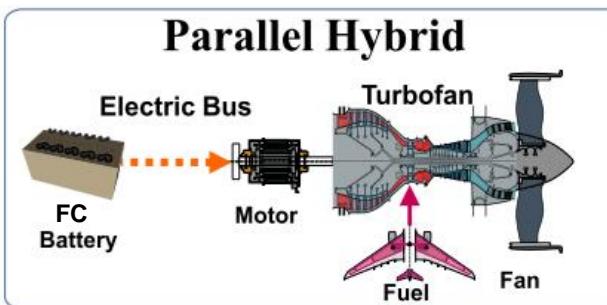
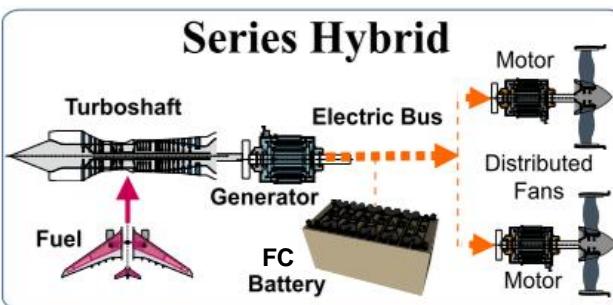
- 3 main categories:



all electric



turboelectric



hybrid electric

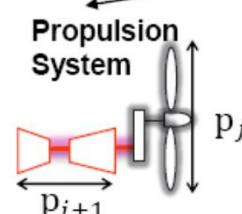
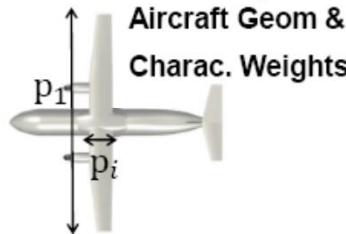
III. More electric propulsive systems

Complex architectures leading to “ultra complex MDO”*

Methods and Tools - XMDO - Linking mission description and aircraft design

- p : vector of design variables

$$\vec{p} = [\underbrace{p_1, \dots, p_i}, \underbrace{p_{i+1}, \dots, p_j}, \underbrace{p_{j+1}, \dots, p_k}, \underbrace{p_{k+1}, \dots, p_l}]$$



Energy Management Strategy

- Hybrid ratio, priority rules,...

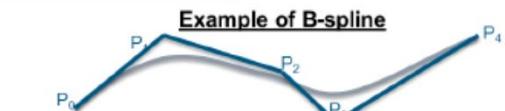
Control laws

- Propeller rpm,...
- Flap deflection angle,...

Mission Profile

- Altitudes
- Speeds (V_x, V_z)
- Distances

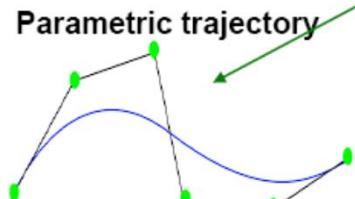
Temporal parametric B-splines



- Linked through flight equations:

$$\begin{cases} m(t, p) \frac{dV(t, p)}{dt} = Thrust(t, V, h, T0, p) \cdot \cos(\alpha + \varepsilon) - Drag(t, \alpha, V, h, T0, p) - m(t, p) \cdot g \cdot \sin(y(t, p)) \\ m(t, p) V(t, p) \frac{dy(t, p)}{dt} = Thrust(t, V, h, T0, p) \cdot \sin(\alpha + \varepsilon) + Lift(t, \alpha, V, h, T0, p) - m(t, p) \cdot g \cdot \cos(y(t, p)) \end{cases}$$

- ...solved as follows:



J. Thauvin, Exploring the design space for a hybrid-electric regional aircraft with Multi-Disciplinary Design Optimisation methods, PHD Thesis of Univ Toulouse & Airbus Oct 2018

*MDO: Multi disciplinary Design Optimization

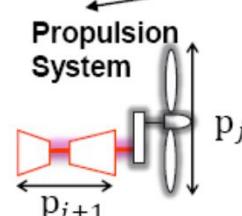
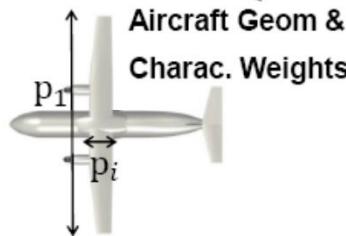
III. More electric propulsive systems

Complex architectures leading to “ultra complex MDO”*

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Energy Management Strategy

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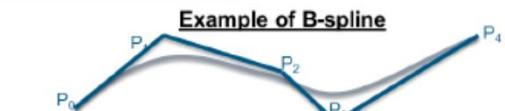
Control laws

- Propeller rpm,...
- Flap deflection angle,...

Mission Profile

- Altitudes
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- Distances

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Selected optimisation algorithms

- Non-convexity/multimodality of the design space identified with gradient-based algorithms



Typ 30-50 decision variables

Combination of gradient-free algorithms:

CMA-ES + Subplex

global stochastic *local deterministic*

Optimisation criteria

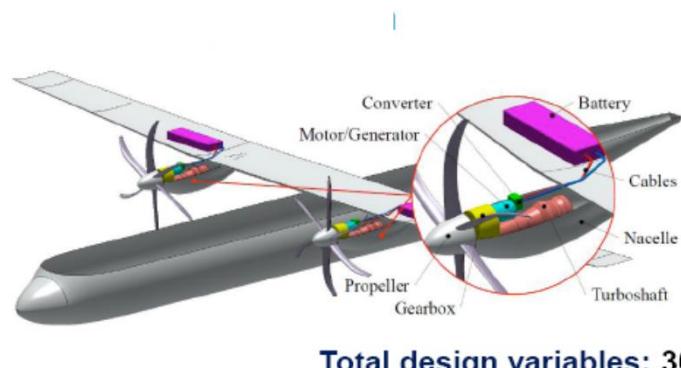
Minimise fuel burn of design mission

*MDO: Multi disciplinary Design Optimization

III. More electric propulsive systems

Complex architectures leading to “ultra complex MDO”*

Parallel Hybrid (PH) Architecture: optimization results:

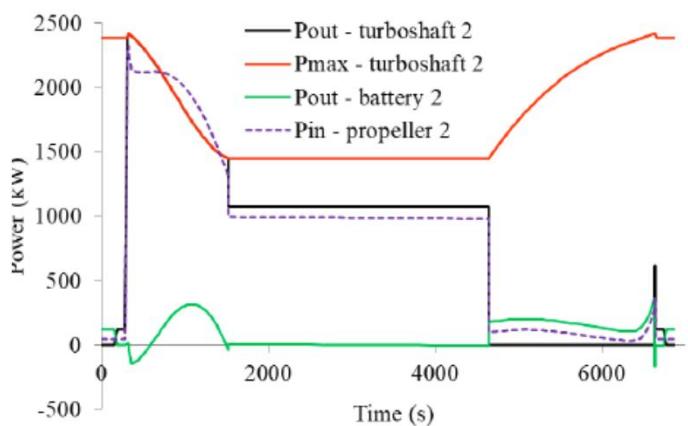


Energy management settings

- For each segment, optimiser sets turboshaft rating = P_{out} / P_{max}
- Battery power found by mission evaluation solver

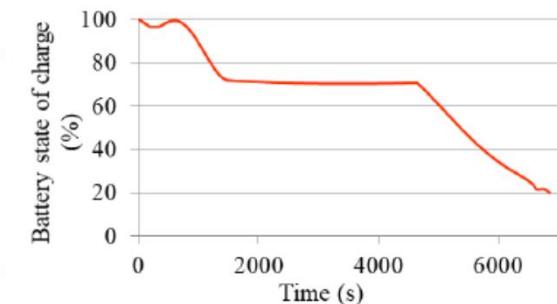
Results for 2025 techno

	REF	PH	$\Delta\%$	
Max Take-Off Weight [kg]	20,000	22,900	14%	Batt: 1,500 kg
Fuel burn on 400 nm [kg]	808	735	-9%	



Energy use:

- ✖ Energy recovering in descent
- ✓ Start & Stop in taxi
- ✓ Start & Stop in descent
- ✓ Engine downsizing (15% e-boost)
- ✓ Low max. electrical power (~260 kW/battery)
- ❗ Batteries are fully discharged



J. Thauvin, Exploring the design space for a hybrid-electric regional aircraft with multi-disciplinary design optimisation methods

PHD Thesis of Univ Toulouse & Airbus Oct 2018

*MDO: Multi Disciplinary Optimization

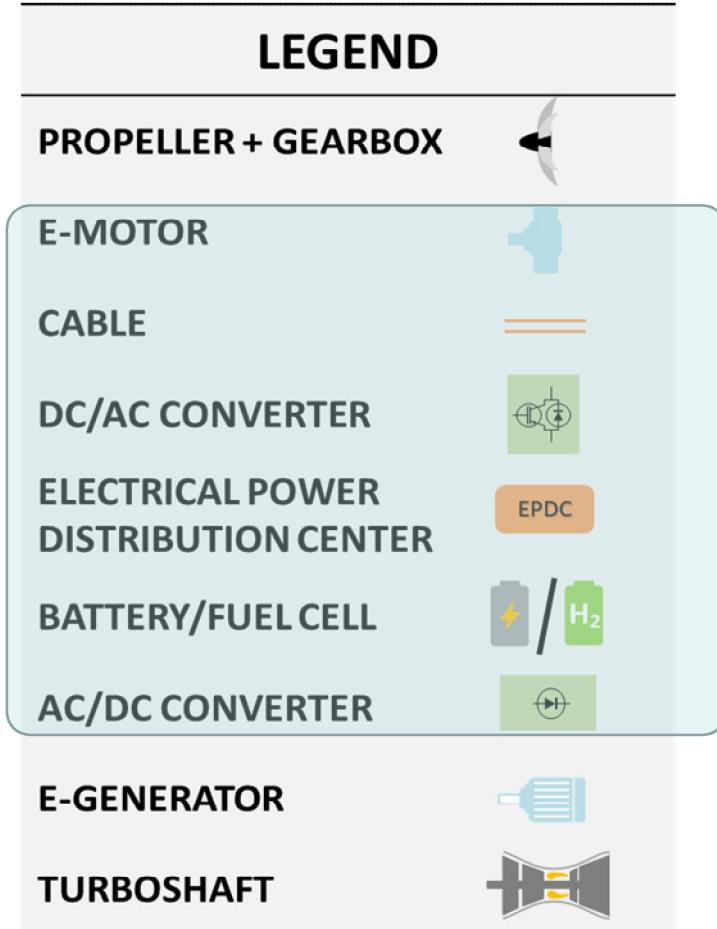
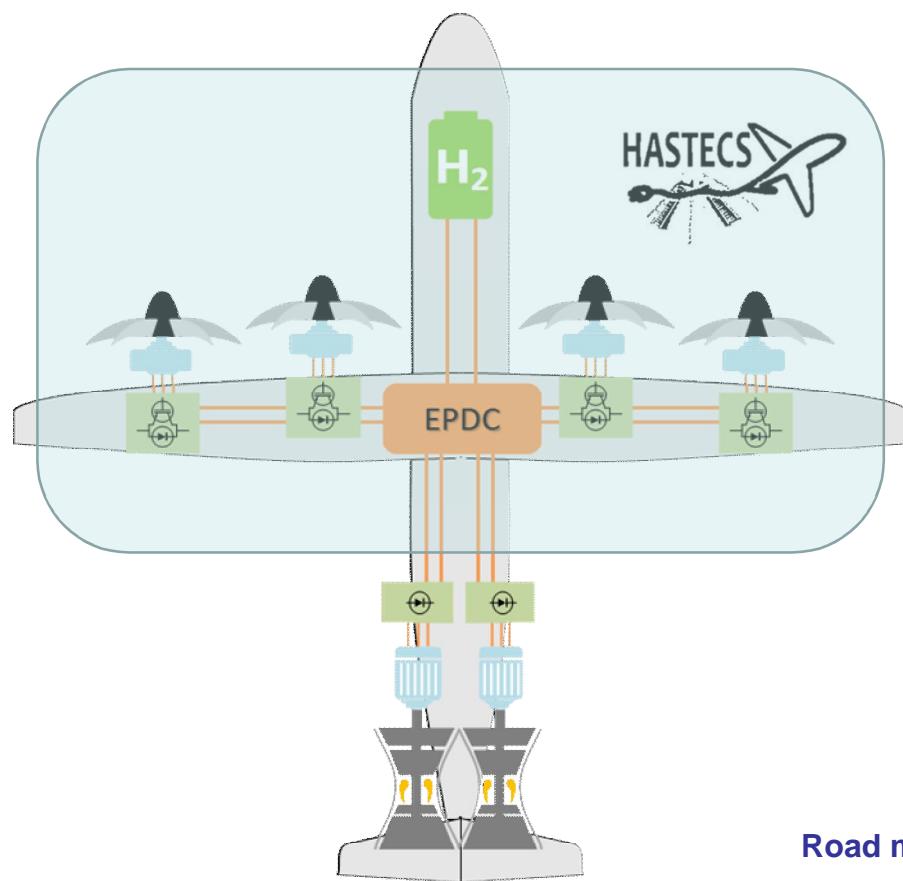
III. More electric propulsive systems



Hybrid aircraft
Academic reSearCh on Thermal
 & Electrical CComponents and Systems

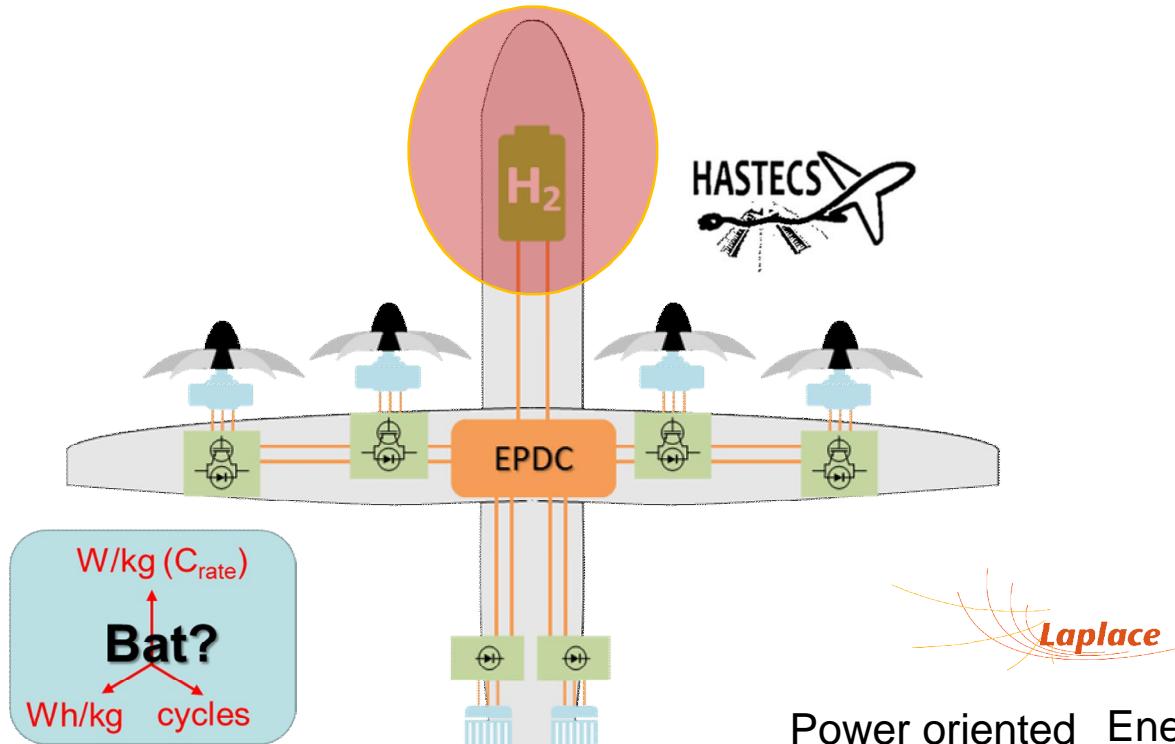


SERIAL HYBRID ELECTRIC ARCHITECTURE



III. More electric propulsive systems

About auxiliary sources: Batteries or Fuel Cells (FC) ?



A promising device !



H₂ liq storage FC System



Batteries

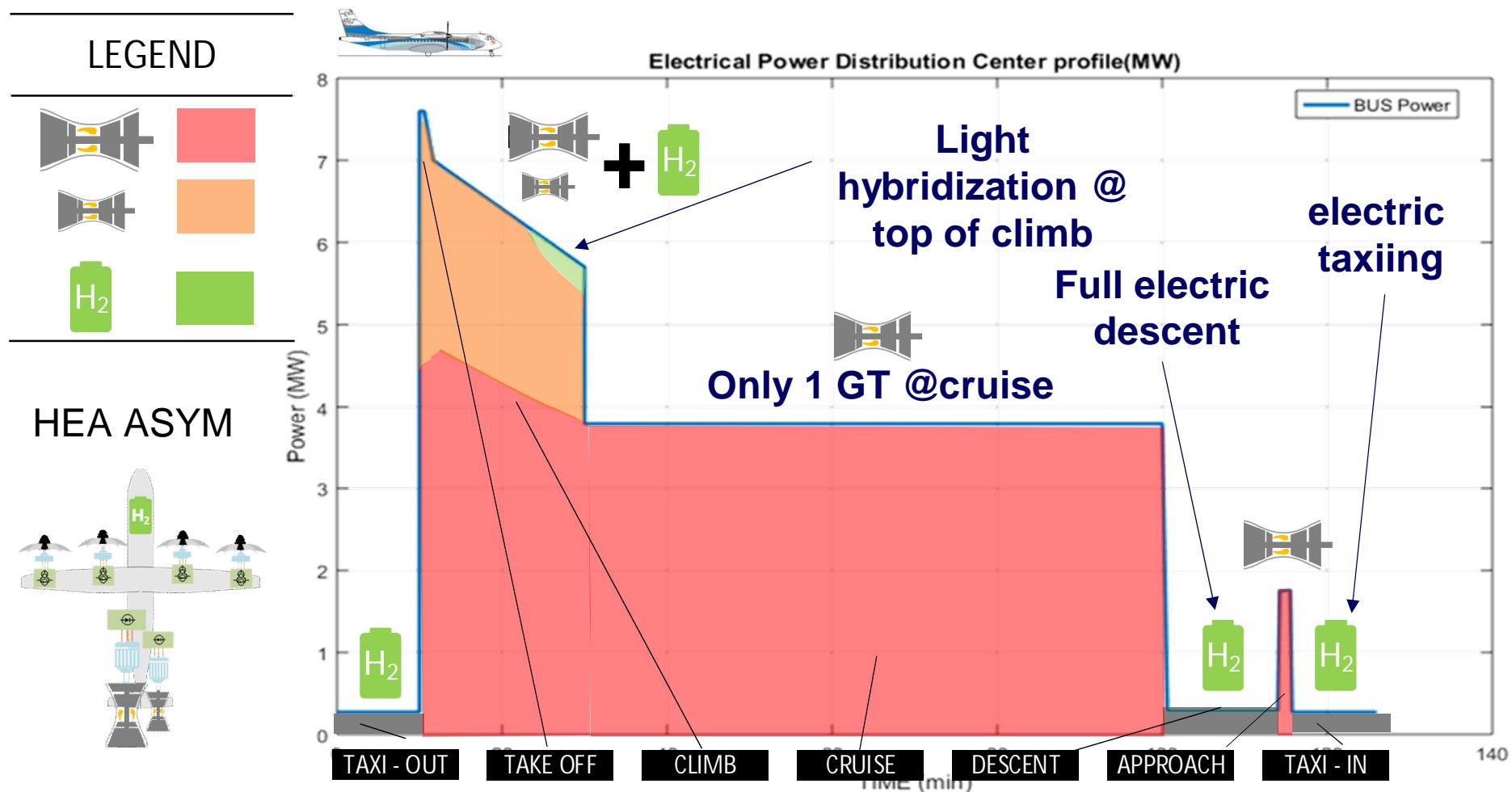
Power oriented Energy oriented

Specific energy e_m		LTO / TNO ^{1, 4}	NMC Solid State ³	FC System (LH ₂)
Today	Cell level	~ 90 – 140 Wh/kg	~ 450 Wh/kg	~ 570 W/kg
	System level	~ 70 Wh/kg	~ 225 Wh/kg	~ 320 Wh/kg
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

III. More electric propulsive systems

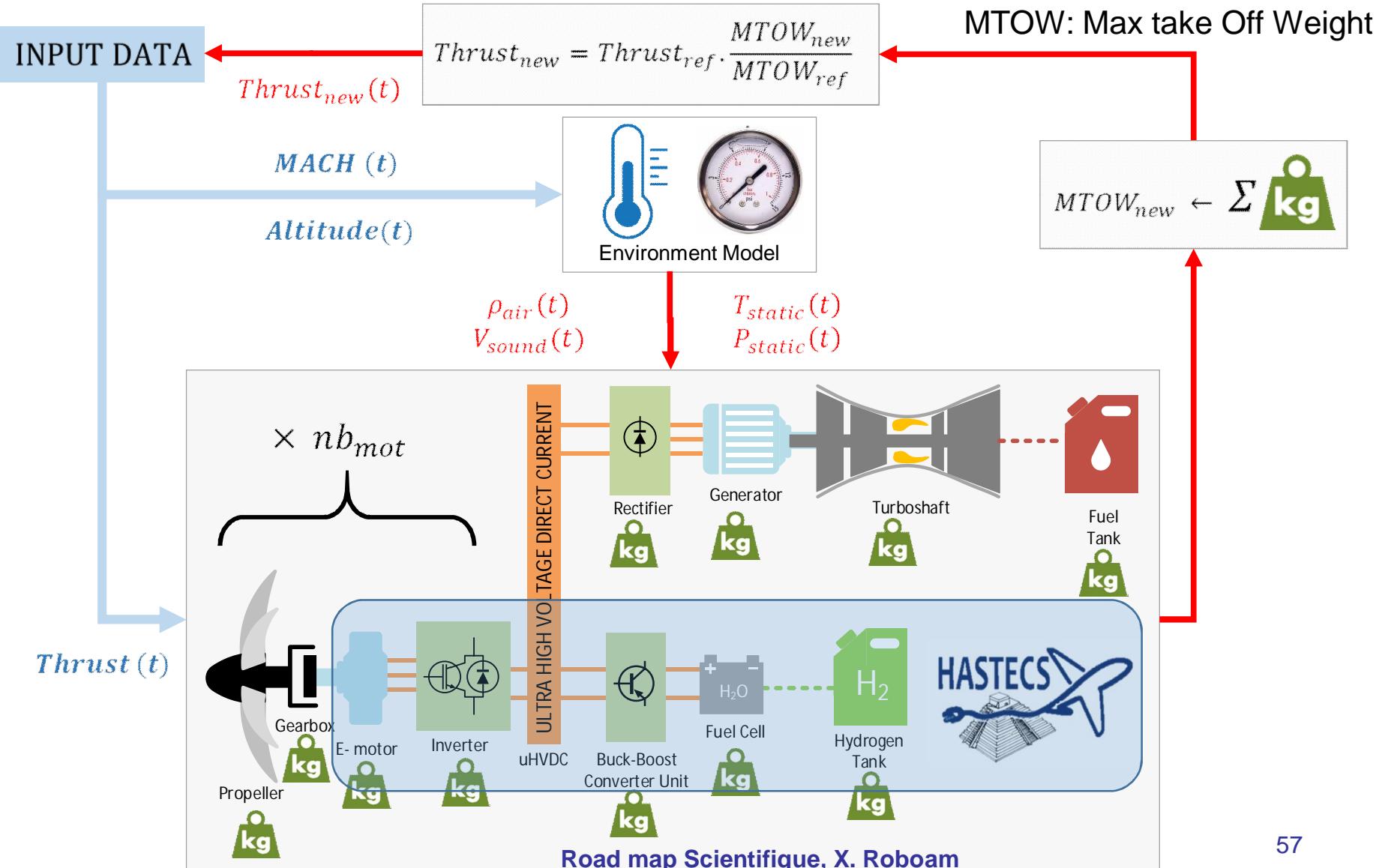
Energy management of hybrid AC

- Example of Asymmetrical Architecture (HEA ASYM)



III. More electric propulsive systems

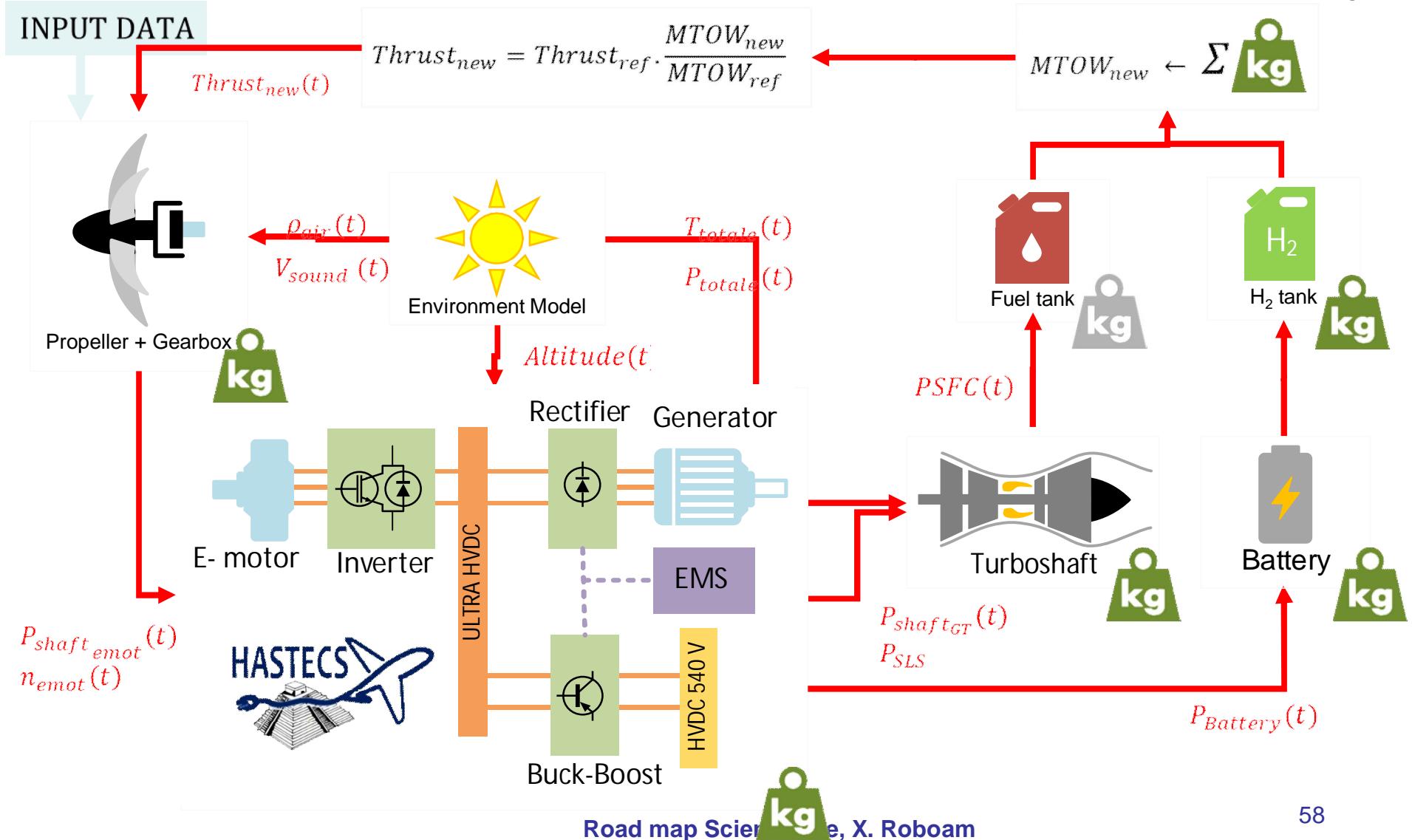
Integrated design process for optimization



III. More electric propulsive systems

Integrated design process for optimization

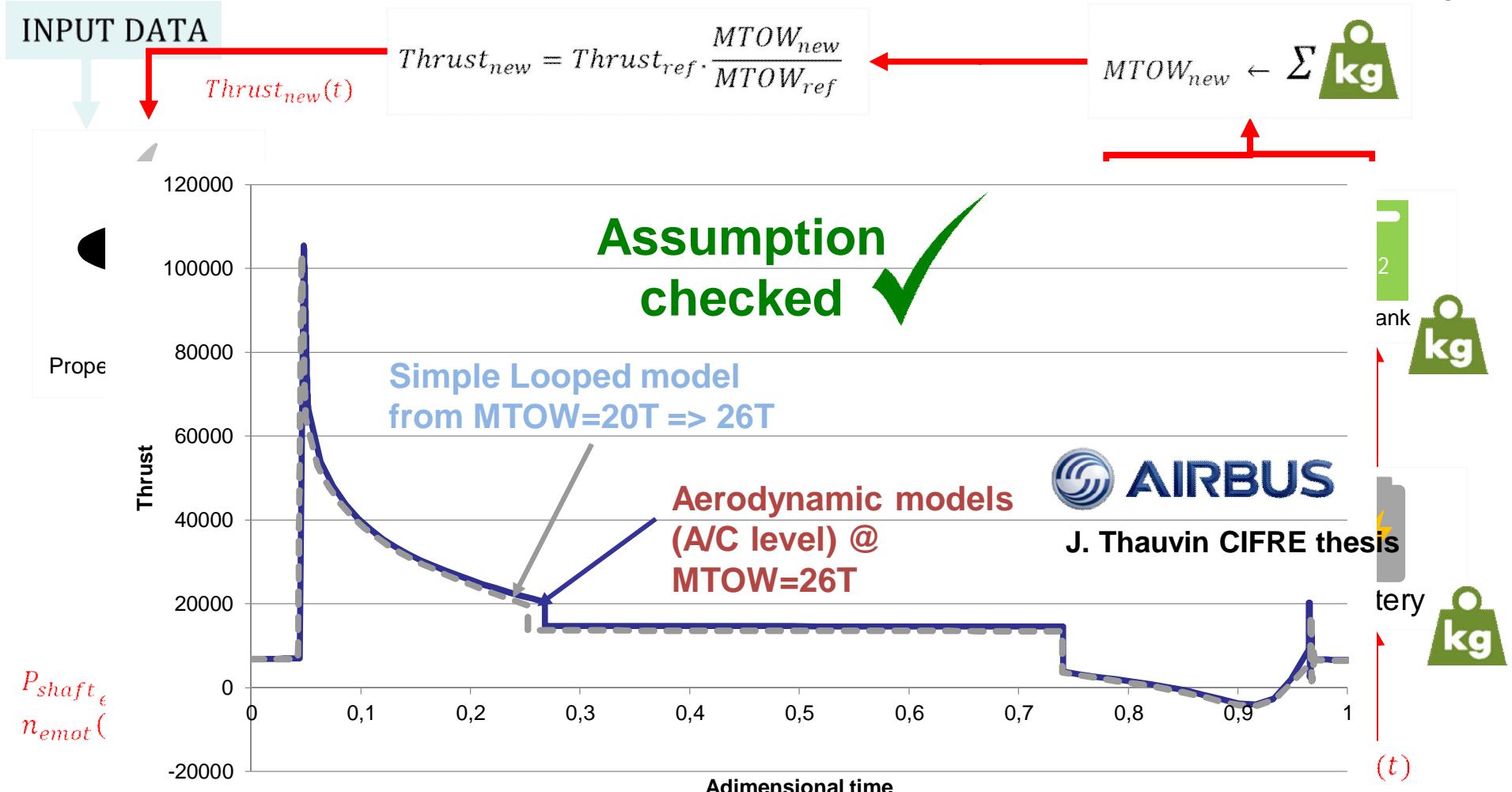
MTOW: Max take Off Weight



III. More electric propulsive systems

Integrated design process for optimization

MTOW: Max take Off Weight



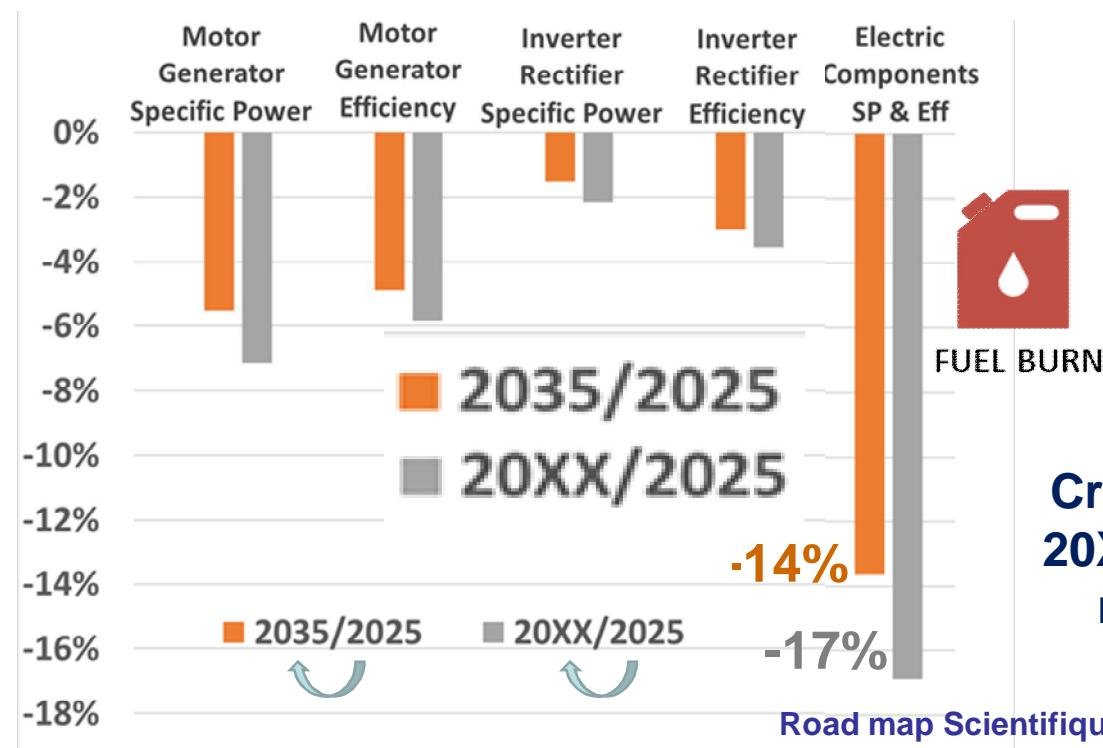
III. More electric propulsive systems

Technologies are sensitive!

	2025 target	2035 target	20xx target
Emotor/ Egenerator			
Specific Power	5 kW/kg	10 kW/kg	15 kW/kg
Efficiency	96%	98.5%	99%
Power Electronics			
Specific power	15 kW/kg	25 kW/kg	35 kW/kg
Efficiency	98%	99.5%	99.8%



Technological targets



How to
reduce kg
and fuel?

Crossing from 2025 to 2035 then
20XX targets, fuel burn would be
reduced by 14% then 17%!!!

III. More electric propulsive systems

To optimize electric motors

Several drivers to increase specific power and efficiency

Decrease weight of electric motor (PMSM)

- Increase peripheral speed:

Sleeve: Carbon Fiber Reinforced Plastic



- Increase surface current densities:

According to the cooling method: external cooling $\rightarrow K_{rms}=79\text{ kA/m}$, $J_{rms}=8\text{ A/mm}^2$

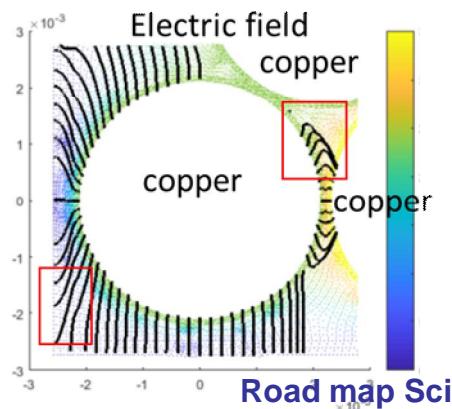


- Increase airgap flux density:

Low sensitivity to the demagnetization
 $Br(\text{SmCo})=1.16\text{ T}$ for $B_m=0.9\text{ T}$



And other drivers...

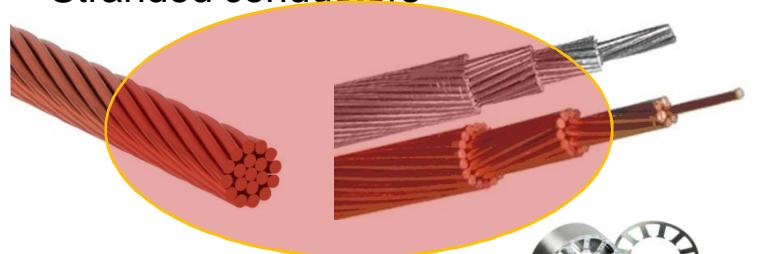


Decrease weight of cooling system

Decrease losses

- **Decrease joule loss (DC and AC):**

Stranded conductors



- **Decrease iron loss:**

Low thickness of Vacoflux 4000: 0.35mm



Design winding and insulation to face partial discharges

uHVDC
 $V_{bus} \sim 1-3\text{ kV}$

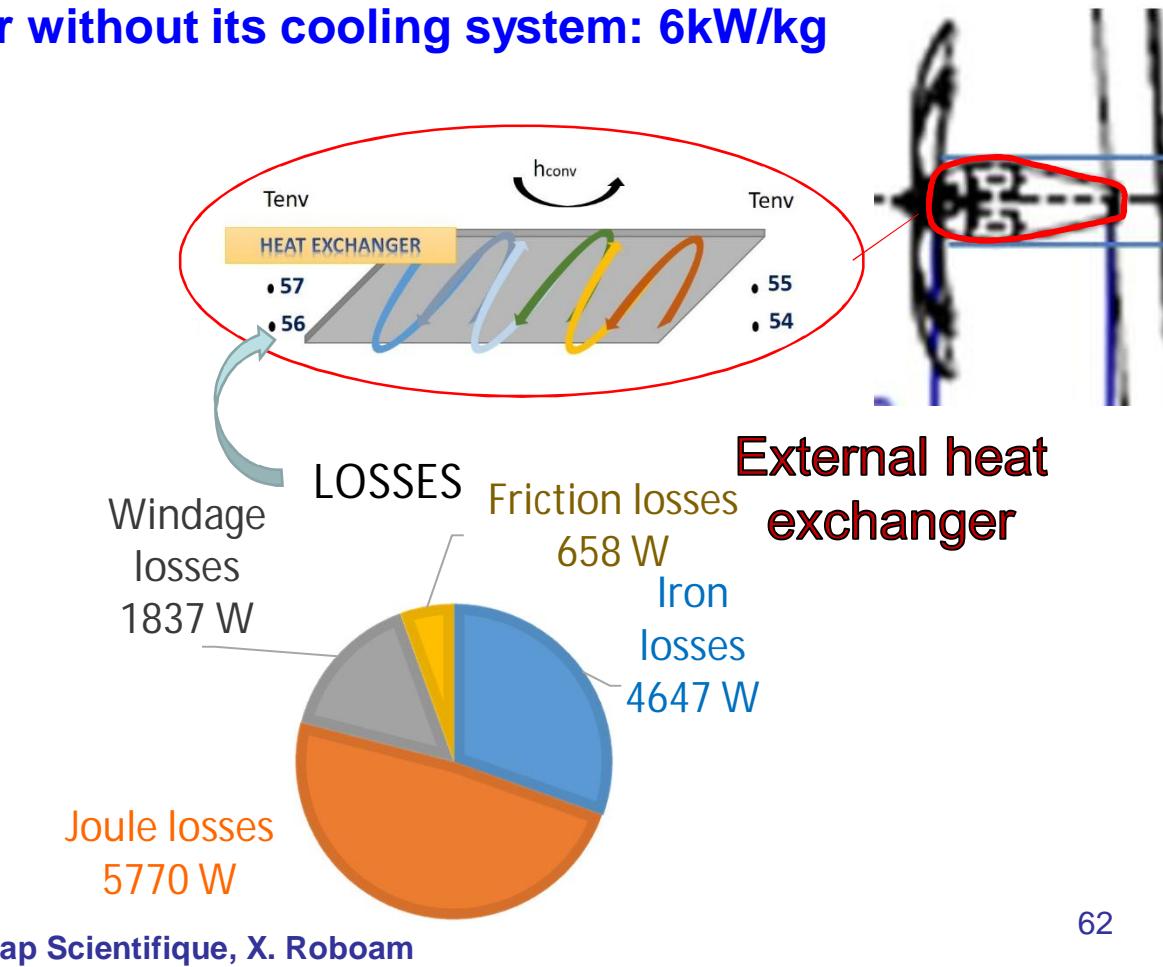
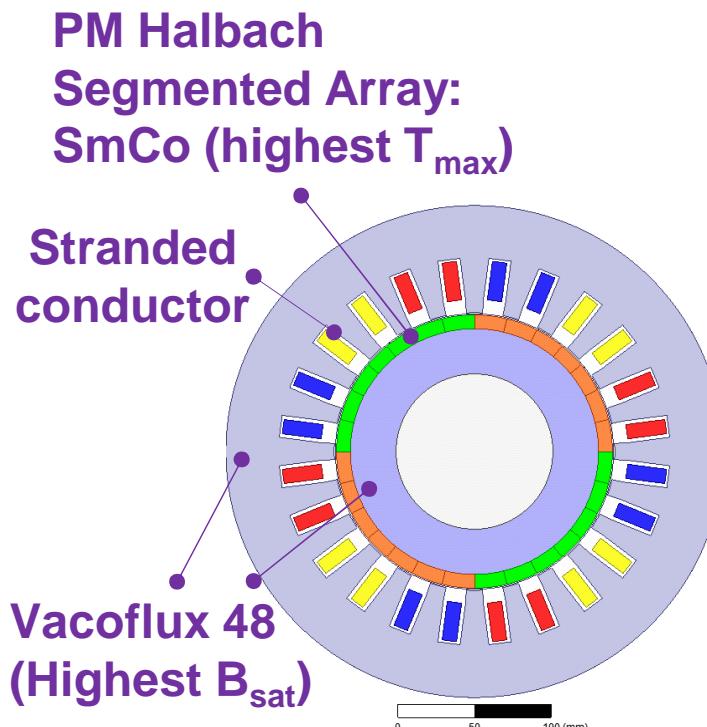
III. More electric propulsive systems

To optimize electric motors and its cooling

Dedicated sizing tools to optimize electric motor design with high specific power and efficiency

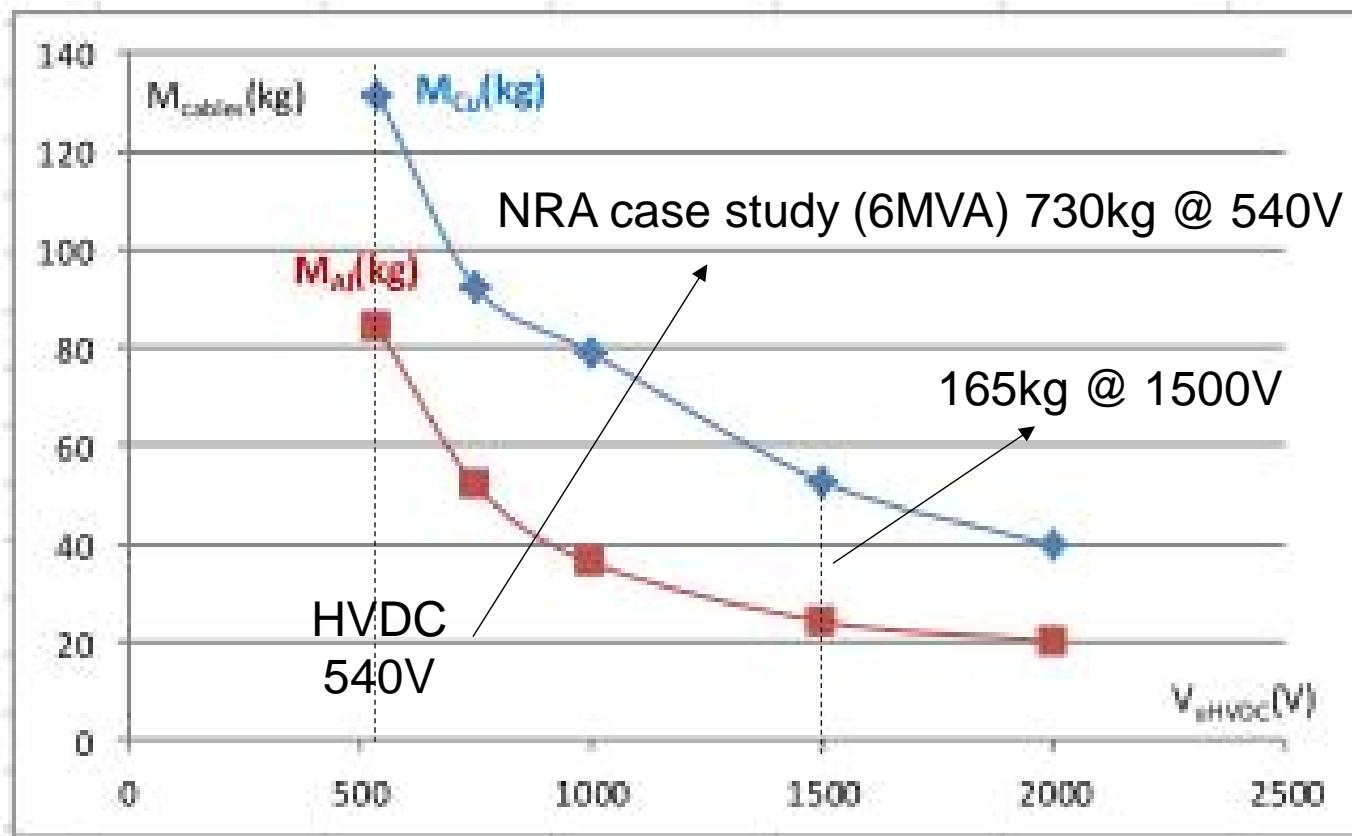
➤ Results: electric motor with its cooling system:

- Specific power of eMotor without its cooling system: 6kW/kg
- Efficiency: >98%



III. More electric propulsive systems

uHVDC cables (without consideration of partial discharges)

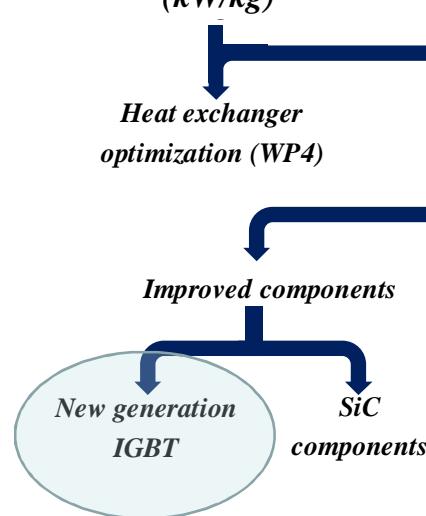


- Hyperbolic shape : $M_{cables} \propto 1/V_{bus}$ (without Partial Discharges)
- Huge cabling weight in HVDC (540V) for series architecture.

III. More electric propulsive systems

To optimize power electronics

Specific power increase
(kW/kg)

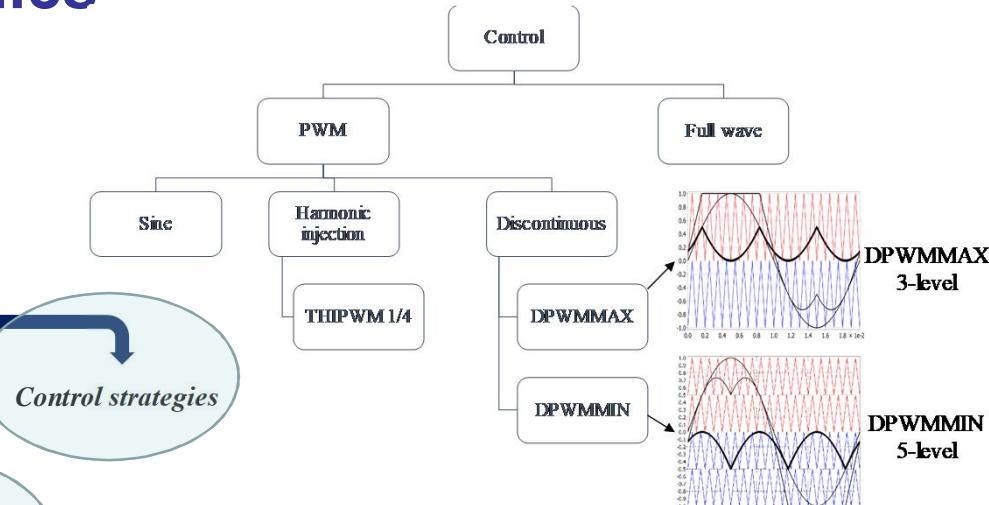


Power Electronics losses reduction

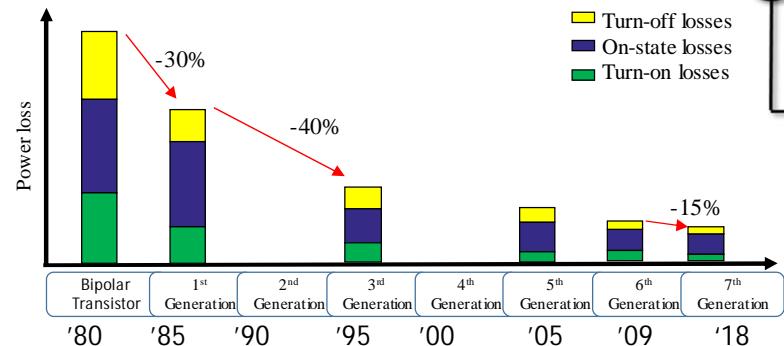
Small rating components

Direct series association

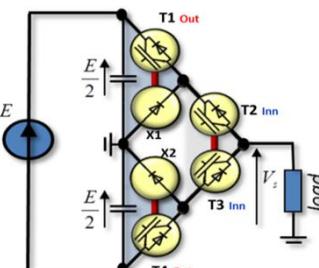
Multilevel architecture



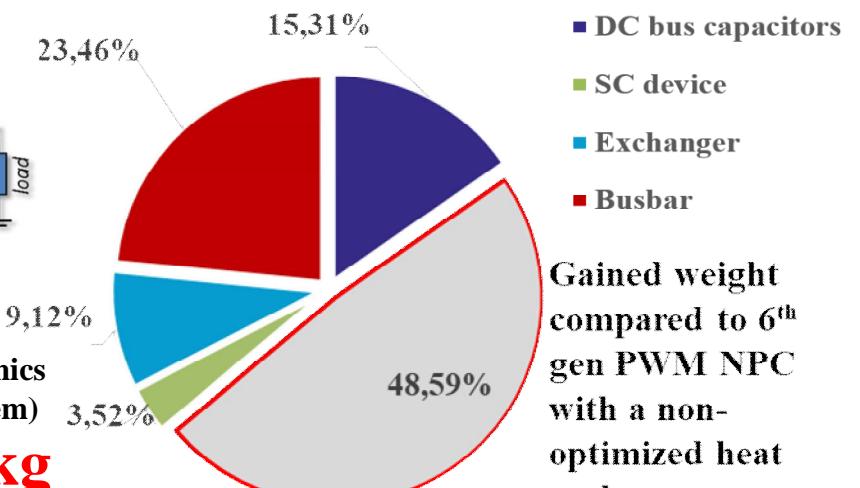
3-level DPWMMAX NPC weight distribution (7th Gen. 1700V IGBT and optimized heat exchanger)



- Turn-off losses
- On-state losses
- Turn-on losses



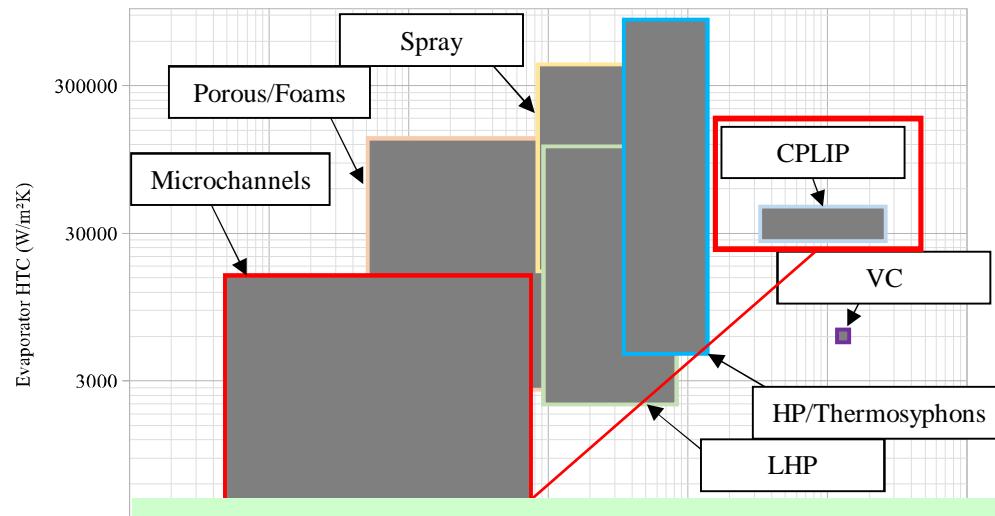
(Power electronics + cooling system)
19 kW/kg



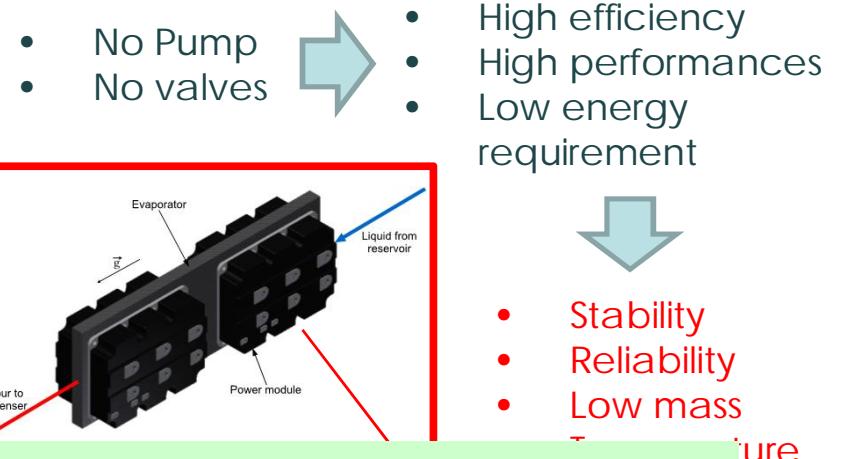
III. More electric propulsive systems

To optimize power electronics and its cooling

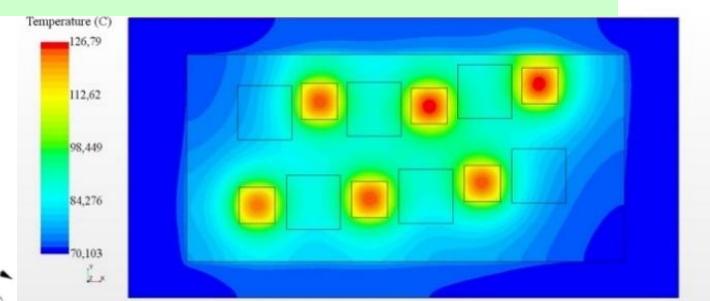
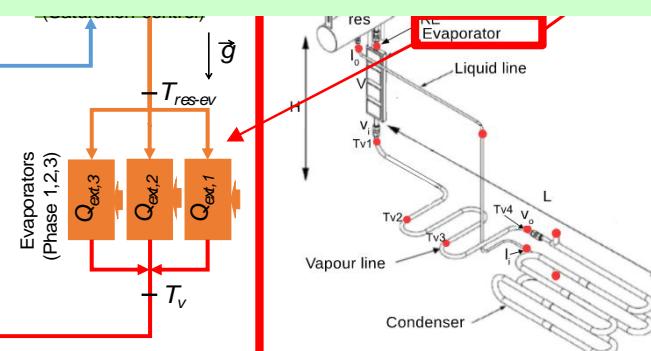
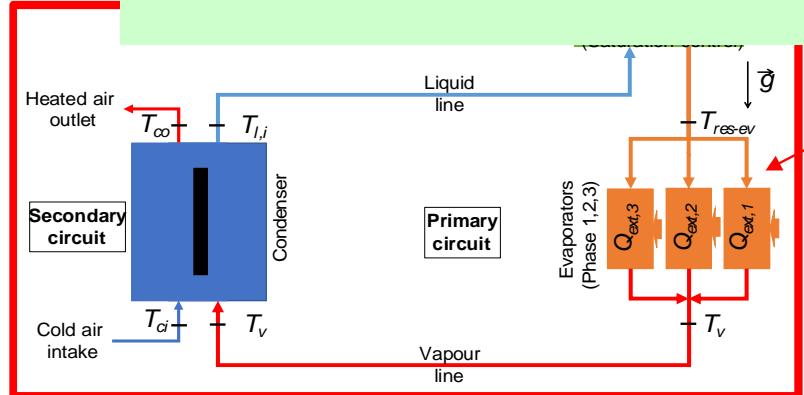
- High performance cooling technologies
- To maximise the Heat Transfer coefficient (HTC)



- CPLIP: Capillary Pumped Loop for Integrated Power



Beyond 20kW/kg by optimizing bus bar 3D packaging and cooling condenser



Junction temperature <150°C!

III. More electric propulsive systems

About full electric aircraft: some figures



Décollage d'un A320

=

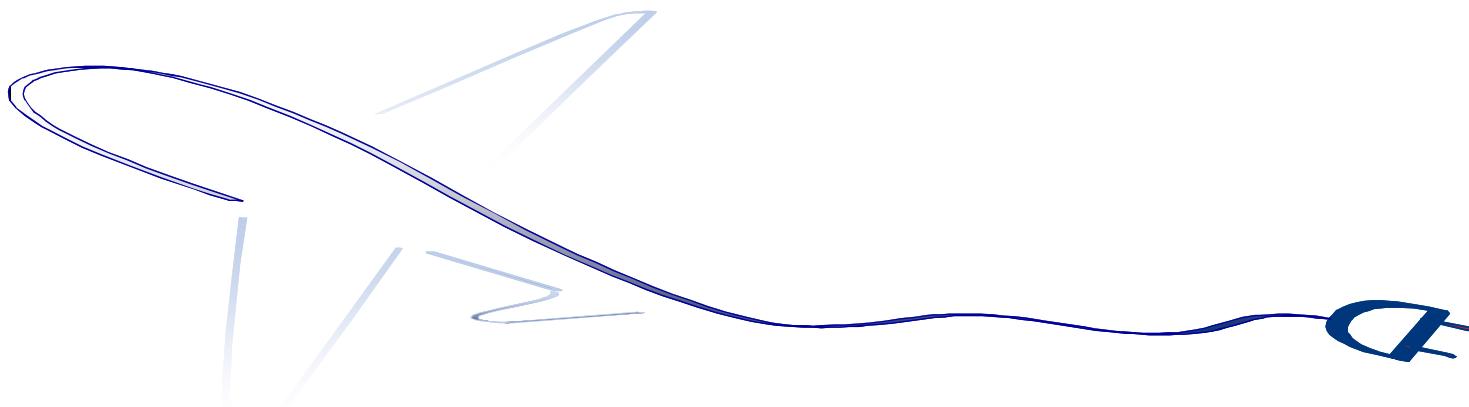
Puissance de 200 Renault ZOE

III. More electric propulsive systems

About full electric aircraft: some figures

With high energy density batteries 400 Wh/kg

Regional aircraft = 370 km (Paris – Lyon) [J. Thauvin, 2018]



Probably only for small
size aircrafts



Drone
logistique
"cargo"

III. More electric propulsive systems

About full electric aircraft: why not with H2?

Rough assessment of a Full Hydrogen Aircraft with liquid H2 storage

- MTOW (Fuel Cells) = 28.5 Tons : + 3 T vs Hybrid Electric Aircraft **+ ~10-15%**
including snowball effects on weights

Components	Weights (kg)
Propeller	4 x 134 kg
Gearbox	4 x 100 kg
Electric motors	4 x 176 kg
Cables	93 kg
Inverters	4 x 71 kg
Fuel cell + Aux + H2	1 x 6388 kg



Assessments:
 Liquid H2 storage @20°K
 with 20% of H2 weight in tank
 $\eta_{FC} = 60\%$
 FC stack : 4kW/kg
 Auxiliaries : 2.7 kW/kg
 Vbus @ 2 kV

III. More electric propulsive systems

About full electric aircraft: why not with H₂ and supra ?

Rough assessment of a Full Hydrogen Aircraft with liquid H₂ storage

➤ MTOW (Fuel Cells) = 28.5 Tons (+ 3 T vs Hybrid Electric Aircraft) + 10-12%

Components	Weights (kg)
Propeller	4 x 134 kg
Gearbox	4 x 100 kg
Electric motors	4 x 176 kg
Cables	93 kg
Inverters	4 x 71 kg
Fuel cell + Aux + H ₂	1 x 6388 kg

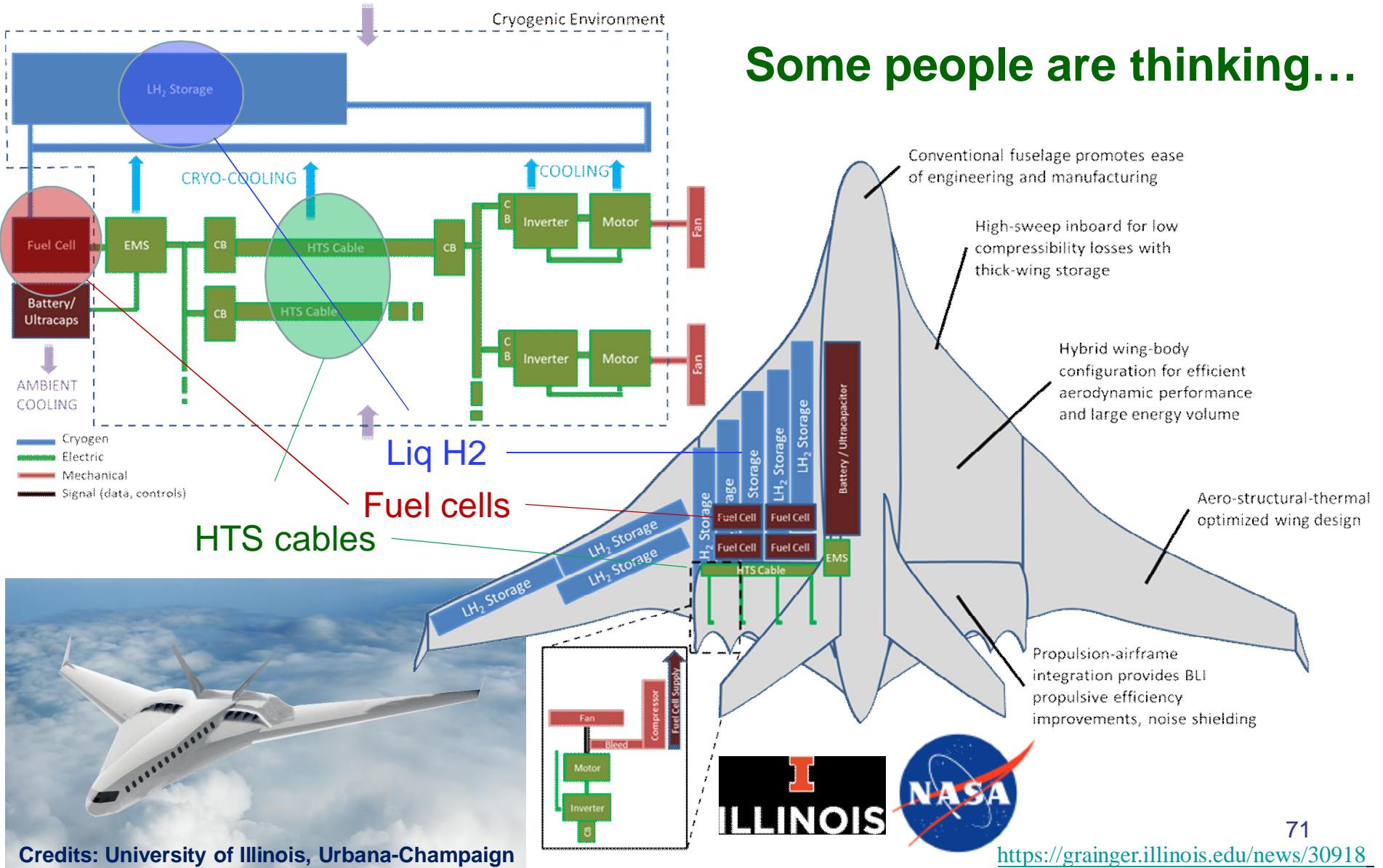


Assessments:
 Liquid H₂ storage @20°K
 with 20% of H₂ weight in tank
 $\eta_{FC} = 60\%$
 FC stack : 4kW/kg
 Auxiliaries : 2.7 kW/kg
 Vbus @ 2 kV

When thinking a cryogenic H₂ @20°K
 why not thinking mutualizing H₂ with
 superconductivity ???

III. More electric propulsive systems

About full electric aircraft: why not with H₂ and supra ?

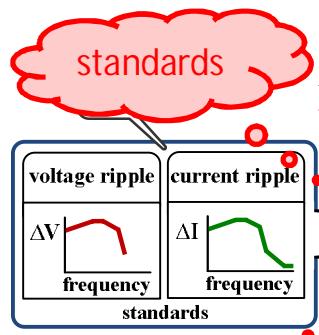


Pour finir road map scientifique ?

Multiple challenges, multiple constraints to face ... and beyond that ?

Hybridization and alternative sources

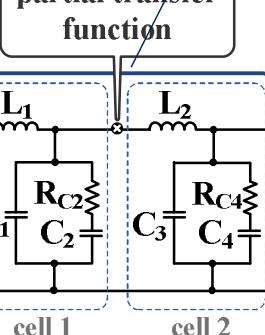
Batteries, fuel cells, H₂



HVDC network

Technological Advance

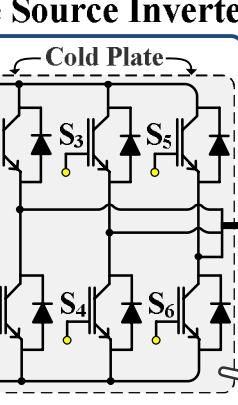
New electromagnetic devices, etc



Input filter

Voltage Source Inverter

wideband gaps,...



HSPMSM

New material

Superconductivity?

Flight mission

Flight mission profile

Partial discharges

EMI

MDO

Surrogate models

Sensitivity analysis



And also methodologies to face complexity and optimization



Solar Impulse

4 moteurs électriques

Batteries et piles à combustibles

200 m² de panneaux solaire PV

63 m d'envergure (comme l'A340)

Vers l'avion solaire : rêves ou réalisés ?

Pour finir vraiment



Solar Impulse

4 moteurs électriques

Batteries et piles à combustibles
200 m² de panneaux solaire PV

63 m d'envergure (comme l'A340)



Décollage d'un A320

=

10 stades de rugby !

Des questions ?

Vers l'avion solaire : rêves ou réalisés ?