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"HASTECS": a typical MDO process for future greener Hybrid Electric Aircrafts

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Abstract

In the framework of hybrid and full electric design of future greener aircrafts, this paper focuses on the multidisciplinary design optimization (MDO) of the powertrain system for a series hybrid electric architecture. This powertrain associates gas turbines and electric (typically fuel cells) sources, a "ultra HVDC" (beyond the kV) electric distribution with its power electronics (multilevel inverters) supplying a surface-mounted PMSM in order to maximize the specific power of each device. This actuation system drives propellers sized for a typical regional aircraft. This study has been achieved in the EU Cleansky II program, in the "HASTECS" project (Hybrid Aircraft: reSearch on Thermal and Electric Components and Systems). After an introduction of the MDO context, the main technological choices are described. It involves multi-physical aspects (electric, magnetic, mechanical, thermal, partial discharges and insulation, energy management and flight mission) and takes several heterogeneous design constraints into account. The MDO process aims at reducing the fuel burn with regard to a wide set of constraints. The results show the crucial sensitivity of the electro-thermal coupling, especially the importance of thermal transient modes during flight sequences. High performance thermal cooling devices are then required with 2 phase high performance cooling devices for power inverters and with an "internal cooling" inside stator slots of the PMSM. The MDO leads to high power density devices, beyond 30 kW/kg for power inverters and 10 kW/kg for electric motors including cooling and satisfying all design constraints (insulation, thermal, magnet demagnetization, etc) over the flight mission.

Introduction

In 2019, transportation was the fastest growing sector, contributing to environmental degradation. Finding sustainable and less polluting solutions is a key element in solving this problem, particularly for the aviation sector, which accounts for around 2-3% of global CO₂ emissions [lat_13]. With the advent of Covid-19 having blocked the air traffic, this latter may tend to a fairly permanent slow down, but this pandemic reinforces the need to move towards a "cleaner sky" and respect for the environment. The ACARE (Advisory Council on Aviation Research and Innovation in Europe) sets environmental objectives for 2050 technologies with a 75% reduction in CO₂ emissions per passenger kilometer and a 90% reduction in NO_x emissions. The perceived noise emission of flying aircrafts should be reduced by 65%. These figures are relative to the capabilities of a typical new aircraft in 2000. In this context, electric and hybrid electric propulsion [Ber_18], [Sar_15] offers opportunities to integrate new technological bricks providing additional degrees of freedom to improve overall aircraft performance, limit the use of non-renewable fossil resources and reduce the aircraft

environmental footprint. On the other hand, compared to a conventional aircraft, electrification leads to a significant increase of the aircraft mass with today's technologies which makes power integration a critical issue [Tha_18]. Consequently, new technologies for improving efficiencies and specific power of aircraft components are needed. Moreover, this requires the optimization of the aircraft both at component level and at system level. To overcome those challenges, Multidisciplinary Design Optimization (MDO) approaches investigating the optimization of aircraft architectures with new technologies of components are of great interest. Such approaches have been specifically developed for optimizing complex systems taking account of multiple disciplinary fields and multiple levels of design from the elementary components to the whole aircraft system [Gaz_17], [Hoe_18], [Iwa_16], [Mar_13], [Pet_21].

This paper explores the propulsion chain of a hybrid regional aircraft starting with technological designs at device level (power electronics, cooling, electric motor, etc). Then, extracting surrogate models from local designs, the issue is to progress towards the integrated optimal design by formulating a MDO process of the

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whole powertrain, putting in the optimization loop the the main technological couplings, the EMS (Energy Management Strategy), the snowball effects due to weight variations and the aircraft environment, especially with the flight mission.

“HASTECS”: a technological design vision of powertrain devices with high integration targets

In the framework of Cleansky II, targeting greener aircrafts, the HASTECS project (Hybrid Aircraft: reSearch on Thermal and Electric Components and Systems) was aiming at designing the powertrain devices of a series hybrid electric regional aircraft (70 pax, range: 600nm with a global propulsion power beyond 5MW). The vision of that project was both methodological (modelling/simulation, MDO, etc) and technological, especially coupling electrical and thermal assessments which completed the technological device design with an integrated optimal design of the whole powertrain: 6 work package involving 6 PHD thesis and 2 post-doctoral studies have lead to the results summarized in the paper which were related to:

- Highly integrated power electronics [Err_19] and its high performance cooling [Acc_20], [Aye_21]
- Highly integrated eMotor [Tou_20] and its high performance cooling [Zea_20];
- Facing environment constraints due to high power/voltage: partial discharges [Col_20]
- Prospects towards high energy density batteries and fuel cells [Tog_19]
- Integrated Optimal Design of the powertrain [Pet_21]

Coordinated by Toulouse INP, the structure and the research involvement in the HASTECS project is illustrated in Fig.1.

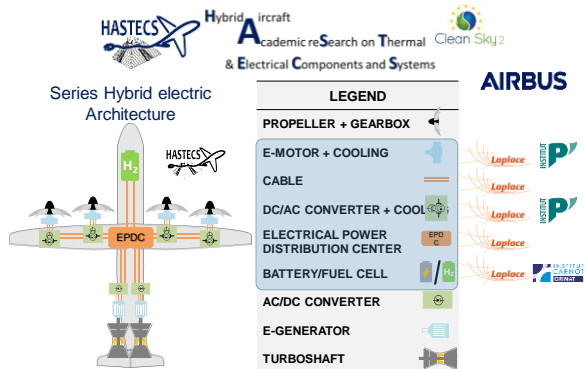


Fig. 1: The HASTECS framework

Local optimization of power electronics

Several technological and structural choices have been made [Err_19] to increase the specific power or power electronics (see Fig 2.a) keeping the efficiency at the highest standards. Based on the HASTECS requirements, the 7th generation of Si IGBTs have been preferred to new wide gap devices thanks to their low conduction losses leading to power inverter efficiencies in the order of 99%. Multilevel inverter structures have been selected with 3 level NPC

structure for HVDC bus below 2kV and 5 level ANPC structure beyond 2kV. Inside the MDO process presented in the next section, 1200V and 1700V IGBTs have been rated depending on the bus voltage situation. Specific PWM strategy with loss minimization and bus bar optimization (taking account of partial discharge constraints) have completed the electrical design of this MW range converter.

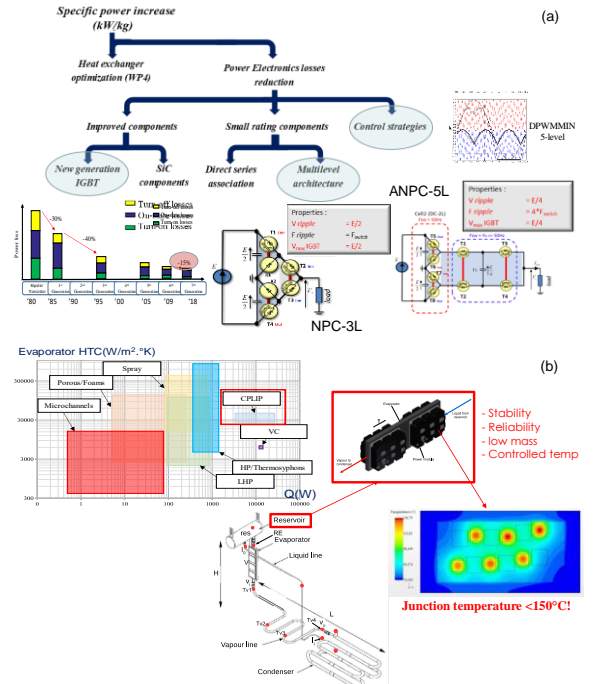


Fig.2: Design of highly integrated power electronics (a) with cooling (b)

The local optimization of this power converter has converged towards a 2kV DC bus; the next section will highlight that this DC bus standard also deals with the system (powertrain) optimum, taking account (among other system couplings) of electric machine association fulfilling partial discharge constraints and cabling sizing.

But the integration of such a power converter with low volume/weight also brings critical thermal problems. The study conducted by [Acc_20] proposes a very high performance two-phase cooling (see Fig. 2.b): the capillary pumped cooling system (CPLIP) optimization allows the power module to evacuate 4.5 kW/kg of thermal losses considering the whole thermal sub system! Coupling the power electronic design with this high performance cooling device, the MW range power converter offers specific powers beyond 30kW/kg !

Local optimization of the actuator with partial discharges tolerance

In the same way, the actuation sub system has been optimally designed [Tou_20] following several drivers to increase both specific power and efficiency (see Fig 3.a). Main drivers are related to high speed actuator with limited but increased peripheral speeds, temperature tolerant high flux densities permanent

magnets (SmCo). Specific stator windings with twisted Litz wires have been designed to limit AC Joule losses at high frequencies. Ultra-thin magnetic sheets are also used to lower the iron losses. Furthermore, a deep study on partial discharge tolerance in the insulation system of the eMotor stator has been achieved in [Col_20].

Numerous design constraints drive the actuation system optimization but the most sensitive is certainly the motor temperature limits. As for power electronics, high performance water cooling system has been studied in [Zea_20] with a glycol water jacket for the external cooling of the stator and a rotor shaft cooling. But in order to overshoot the specific power target (10kW/kg) set for the final HASTECS eMotor design, an additional cooling channel directly inside stator slots has been required to face Joule Losses (see Fig 3.b).

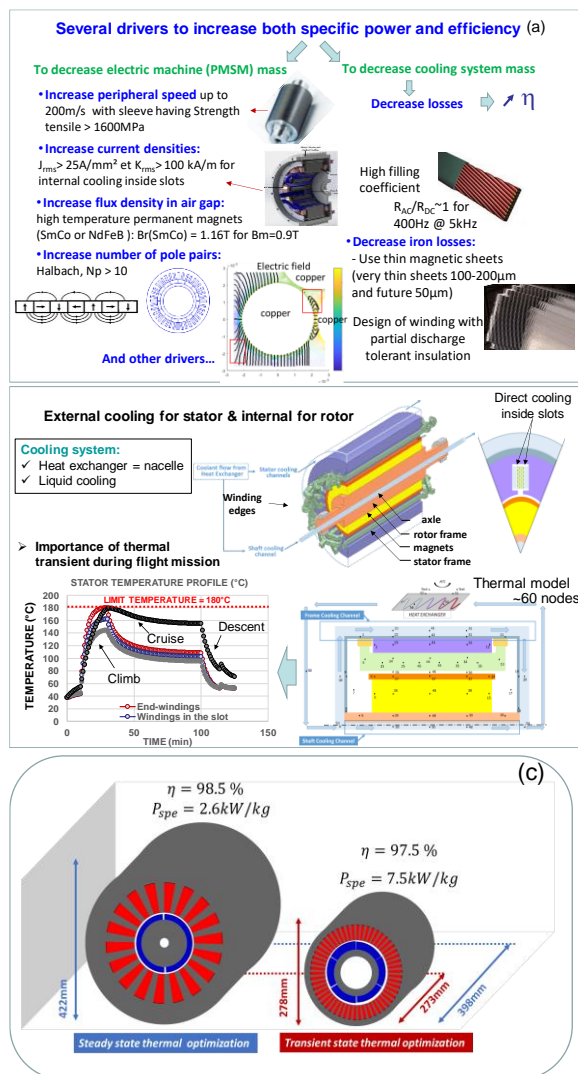


Fig.3: Design of highly integrated electric motors (a) with cooling (b); influence of thermal transients (c)

Coupling the electromechanical design with that cooling device, it has been analysed that transient states due to thermal inertia in the actuator were predominant and should be exploited during the flight mission: as illustrated on Fig 3.b, thermal limits are

reached at top of climb especially inside the stator end windings. Thus exploiting thermal inertia with transient state thermal model (see Fig 3.c right), the actuator compacity is far beyond the results obtained with optimization based on quasi static thermal model (see Fig 3.c left).

A local optimization (see Fig .4.a) only minimizing the eMotor mass is presented below: in that process, a large set of multiphysical constraints are integrated by coupling thermal limits with partial discharge tolerance and with other geometrical and electromagnetic constraints. Note also that this optimization and all the ones that follow are achieved over the flight mission, fulfilling constraints for all flight sequences. In particular, the thermal limits are derived in all over the flight mission.

As illustrated in Fig. 4.b, the insertion of water cooling directly inside stator slots has strongly increased the specific power of this high speed SMPMSM actuator beyond 15kW/kg with high efficiencies (>98%).

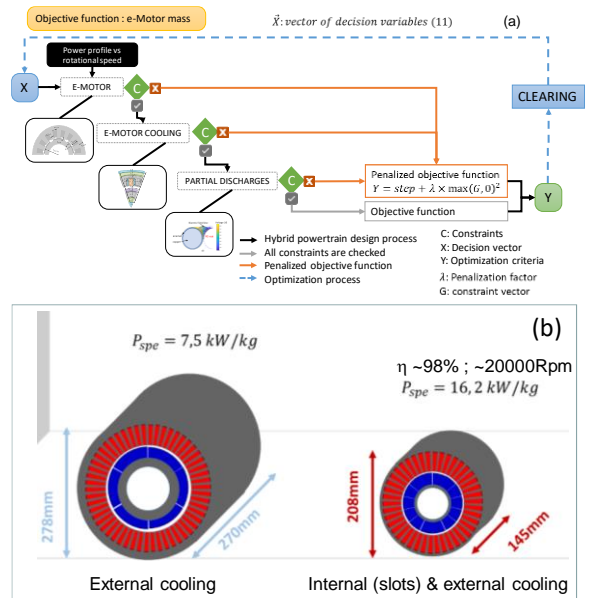


Fig.4: actuator local optimization: (a) the process ; (b) results without and with internal cooling inside slots

MDO of the Hybrid Electric powertrain

On the MDO process formulation

Beyond the study of each powertrain device separately, a Multidisciplinary Design by Optimization (MDO) has been conducted in [Pet 21]. The MDO process involves a large set of surrogated models (see Fig.5), some of them being directly obtained from HASTECS work packages. Complementary models for gas turbine, propeller, cables and gearbox have been derived from the state of the art and with the help of Airbus studies [Tha_18].

Prospective state of the art and modelling of high energy density batteries vs fuel cells

To complete the design and modelling task in HASTECS and to progress towards the system integration of the whole powertrain, a state of the art and modelling study on auxiliary electric sources

embedding future high density batteries and fuel cells has been done by [Tog 18].

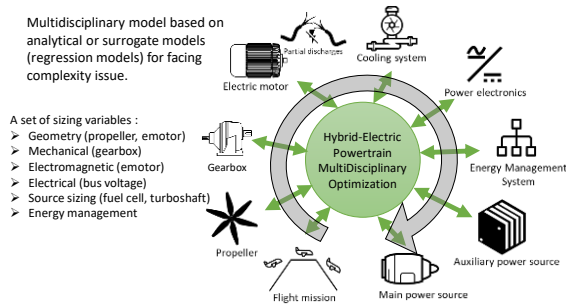


Fig.5: Multidisciplinary Design Optimization (MDO) process of the Hybrid Electric powertrain

This prospective study has clearly shown that energy density of fuel cells is significantly higher than best Lithium Ion batteries such as NMC solid state technologies (see Fig6.b). It is important to notice that this comment is only related to the mission typically involved in regional flights: this trade-off was based on particular power-energy requirement (see Fig6.a): $P_{max} = 280kW$; $E_{tot} = 160kWh$ for auxiliary electric sources controlled with a simple EMS which “a priori” sets the hybrid ratio (HR: electric vs full (electric + thermal) power ratio) at:

- * HR=1 for full electric operation during taxi and descent ;
- * HR = 0 for full thermal operation during climb and cruise sequences.

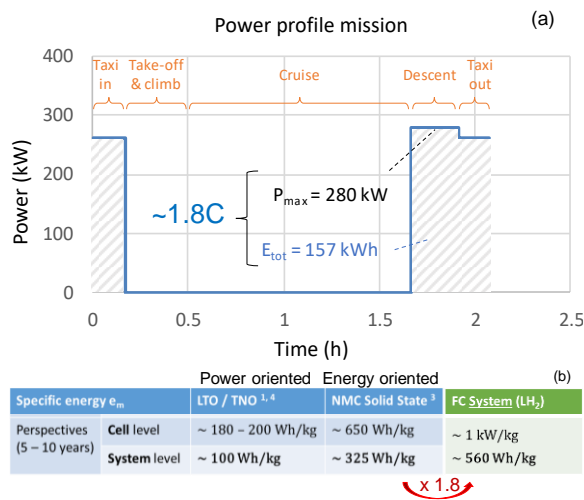


Fig.6: batteries vs fuel cells tradeoff for a regional flight

For the fuel cell system, the Wh/kg ratio is derived considering both the fuel cell stack with its balance of plant and the gas storage device. For this latter, a cryogenic (20°K) liquid storage has been selected for hydrogen assessing 20% of H₂ in tank weight. A specific power of 1.5kW/kg has been assessed for the fuel cell stack and its balance of plant (including the thermal management device).

Global optimization of the whole powertrain

The MDO of the whole hybrid electric powertrain was

the last target of the HASTECS project. Once all the powertrain devices are modelled, an implicit loop estimates the required thrust to take off the aircraft. Indeed, as illustrated in Fig. 7, weight variations during MDO convergence in sized devices induce a snowball effect as the aircraft Maximum Take-Off Weight (MTOW) is derived from unit weights involving itself subsequent thrust needs. This sizing loop may be complex involving couplings with both structure and aerodynamic (drag penalties). In our case, the problem has been simplified by linearizing the equation between variations of the global mass (MTOW) and the required thrusts:

$$Thrust_{new} = Thrust_{ref} \times (MTOW_{new}) / (MTOW_{ref})$$

This approach has been validated (for a limited mass range), by comparison between this linear model and complete aerodynamic models detailed in [Thau_18].

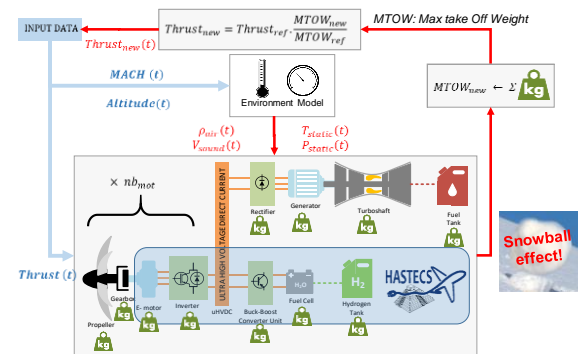


Fig.7: system integration with environment couplings and snowball effect

Three different MDO formulations (see Fig. 8.a) have been compared in the results below:

- 1) A “local optimization” only minimizing the eMotor weight; in that cases, other powertrain devices are considered with fixed rating and the snowball effect is involved;
- 2) A first global optimization minimizing the whole powertrain mass;
- 3) A second global optimization minimizing the fuel burn of the overall hybrid electric aircraft.

When a simple EMS is coupled in the optimization process with “a priori” set hybrid ratio (HR) as defined in Fig 6.a, the third (fuel burn minimization) global MDO involves 14 decision variables with a large (15) and heterogeneous set of design constraints coupling electrical, electromechanical, thermal constraints and involving the partial discharge tolerance (filling factor verification for stator windings). A supplementary constraint has been added at aircraft level to integrated the snowball effect.

The clearing procedure [Pet_21] was used for optimizing the propulsion system of the hybrid aircraft. Clearing is a niching elitist genetic algorithm which usually outperforms standard genetic algorithms on difficult problems with multiple non-linear constraints and multimodal features. The CPU time required for

solving each optimization case on a standard computer was about 7 days.

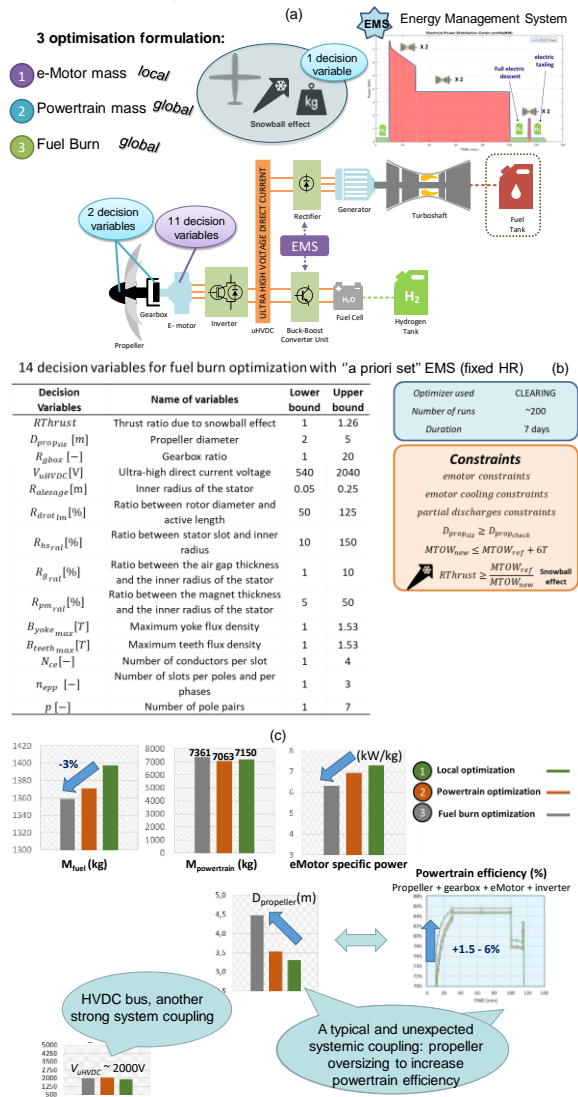


Fig.8: integrated optimal design of the whole powertrain system

The optimal aircraft solution in terms of kerosene consumption has been logically found with the "fuel burn optimization" which consumption is 3% lower than the one offered by the "local optimization" (see Fig.8.c left). But it should be noted that the formulation for "fuel burn optimization" involves a powertrain mass slightly increased (7361kg are obtained with reference to the 7063kg obtained with the powertrain mass minimization). In fact, as illustrated on the Fig. 8.c, the propeller diameter is enlarged in order to maximize the propeller (consequently the powertrain) efficiency: indeed, the powertrain efficiency is increased by 1.5% to 6% depending on the flight sequences regarding the "fuel burn optimization" with respect to the "local optimization". The efficiency improvement of the propeller (downstream in the powertrain) reduces the maximum values of the design powers for the other upstream components, consequently reducing the kerosene consumption. This systemic effect is clearly a typical result which highlights the interest of such a

MDO process involving main system couplings. On the opposite, it is not surprising to notice that the formulation with a "local optimization" induces the highest specific power for the electric motor. Let us note that all results presented in that sub section have been obtained without the direct stator cooling inside slots. As illustrated in Fig 4.b, adding an internal cooling allows quasi doubling motor specific powers. Finally, this MDO process couples a set of domains (power electronics, machine and cooling, partial discharges) leading to an optimal bus voltage range around 2 kV which constitutes the best trade-off in this case study.

Conclusions

In this paper, the main results of the HASTECS Cleansky II project have been presented, synthesizing a set of technological designs at device (power electronics, eMotor, auxiliary electric sources) level. The study has also assessed environment constraints related to the flight mission involving partial discharge constraints impacting especially at high altitudes and with high voltage operation.

Finally, a global tradeoff has been completed in Fig. 9 comparing different solutions and assessments ("Targets") in the fuel burn vs MTOW plan: it displays the relative variations with reference to a full thermal aircraft optimized with the same models but without electric hybridization. Two different levels of assessments ("2025" vs "2035" targets) are compared: the main difference between those two targets is related to the performance of cooling devices for power electronics and electric motors for which a direct cooling inside stator slots is added. In that Figure, the "simple EMS" previously presented (see Fig. 6.a) with "a priori set" hybrid ratio is compared to a "Optimized EMS" MDO for which EMS is inside the optimization loop (i.e. the hybrid ratio become decision variables).

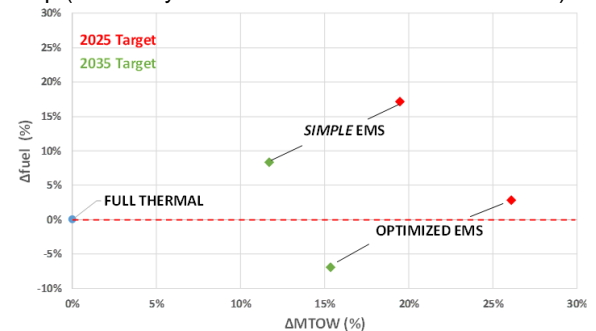


Fig. 9: tradeoff assessing hybrid-electric aircraft with respect to a conventional aircraft as a reference point

This display clearly shows a major issue: "despite the technological progress, electric hybrid solutions are heavier than thermal solutions". Regarding the EMS influence, the "optimized EMS" which significantly increases the fuel cell nominal power leads to a significant decrease of the fuel burn but this is not without consequences on the MTOW

which has been increased by 4%-7% with respect to the previous ("simple EMS") case.

Finally, with reference to a full thermal optimized aircraft, an "optimized EMS" allows operating a hybrid aircraft that may consume the same amount of kerosene for the 2025 target. By improving the technology (i.e increasing specific powers), the HASTECS 2035 hybrid-electric aircraft would consume 6% less fuel than its full-thermal equivalent. Let us finally note that only the consequences of energy efficiency and powertrain weight have been assessed in that study as a unique influence on the fuel burn. Going towards distributed electric propulsion architectures may offer additional gains in terms of aerodynamics with several innovative concepts such as blown wing, boundary layer ingestion or wing tip propellers.

These prospective results highlight the main issue of the hybrid-electric aircrafts: the powertrain mass is significantly increased with reference to a full-thermal optimized aircraft. The future full electric zero-emission aircraft may constitute "the actual technological breakthrough" which has to be more deeply studied as recently proposed by Airbus. But huge technological and safety (certification) challenges are in front of engineers being a major track towards greener aircrafts!

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