D6.1

GAP ANALYSIS AND PRELIMINARY ROADMAP ON HEP DEVELOPMENT

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EXECUTIVE SUMMARY

After three years of IMOTHEP, this report provides a first synthesis of the results of the project. This includes a first technology gap analysis for the development of a hybrid electric aircraft as well as some research streams already identified for the maturation of the required technologies.

Four hybrid aircraft configurations have been investigated within IMOTHEP together with the components of their hybrid electric power train. These components were specifically designed as part of the project based on specifications stemming from aircraft configuration studies. This allowed an integrated assessment of the potential benefit of hybridization with consistent technologies assumptions. The characteristics and performances of these configurations are summarised in the report. A literature review was also performed to enrich the assessment of the interest of hybridization with additional external studies.

The general conclusion, at this stage, is that current results do not allow to conclude on an actual potential benefit of hybridization for large aircraft of the short-medium range category, for which at the same time developing hybrid propulsion would represent a huge technological step for the development of electric systems. For regional aircraft, a promising configuration could be identified, which uses a gas turbine as a range extender of a fully electric aircraft, while some benefits can be obtained with parallel hybrid systems but for short range and with batteries' performances at the upper end of the projection for 2030-2035.

Regarding technologies, batteries are the primary enabler for regional configurations. Improvement of chemistry will mostly come from other sectors but dedicated research is required to ensure that future products answer the specific requirements of aviation. Other electric components are less impacting and performances reached by design performed with IMOTHEP already provide a good basis. However, these components represent developments completely out of current electric systems specifications and will therefore require dedicated development efforts.

At a more systemic level, cooling and high voltage electric distribution emerge as a major challenge, particularly for the most demanding SMR application case.

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TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

Glossary

Acronym	Signification
AC	Alternating Current
BLI	Boundary Layer Ingestion
BWB	Blended Wing Body
CINEA	European Climate, Infrastructure and Environment Executive Agency
CS	Clean Sky
DC	Direct Current
DEP	Distributed Electric Propulsion
DoE	Design of Experiment
ECS	Environmental Control System
EIS	Entry Into Service date
EPU	Electric Propulsion Unit (electric motor + its power electronic)
GT	Gas turbine
HEP	Hybrid Electric Propulsion
HV	High Voltage

L0	Preliminary (conceptual) design loop
L1	Integrated design loop
L2	Refined designed loop
L/D	Lift-to-drag ratio
MEA	More electric aircraft
MTOM	Maximum Take-Off Mass
NOx	Nitrogen Oxides
OEI	One Engine Inoperative
OEW	Operating Empty Weight
PO	Project Officer
PSFC	Power Specific Fuel Consumption
REG-CON	Conservative regional aircraft configuration
REG-RAD	Radical regional aircraft configuration
SMR	Short-Medium Range
SMR-BAS	Baseline SMR (2035 conventional technologies)
SMR-CON	Conservative SMR aircraft configuration
SMR-RAD	Radical SMR aircraft configuration
TLAR	Top Level Aircraft Requirement
TMS	Thermal Management System
WP	Work Package
WTP	Wing Tip Propeller

1. INTRODUCTION

To pursue the goal of drastically reducing the greenhouse gas emissions of commercial aviation, the top-level objective of IMOTHEP is to assess the potential offered by hybrid electric propulsion (HEP) for reducing aircraft fuel consumption beyond the performance of conventional propulsion technologies projected to 2035. IMOTHEP follows a holistic approach considering technologies for hybrid electric power trains together with aircraft and propulsion architectures, as well as the needs for tools, infrastructures, demonstrations and even regulatory adaptations for the development of HEP. The ultimate goal is to identify the key enablers of HEP and to build a European aviation sector-wide roadmap for the maturation of the technology.

The core of IMOTHEP is an integrated end-to-end investigation of hybrid-electric power trains for commercial aircraft, performed in close connection with the design and performance analysis of a selection of candidate aircraft concepts and propulsion architectures. Aircraft configurations were selected on the basis of their potential for fuel burn reduction and their representativeness of a variety of credible concepts, with a focus on regional and short-to-medium range missions. From a first conceptual aircraft design (based on initial experts' assumptions for HEP components), target specifications have been defined for the architecture and components of the hybrid propulsion chain, triggering the investigation of technological solutions with a twenty year timeframe perspective. The performance resulting from these analyses of the electric components and power chain are synthesized through subsequent aircraft design loops to assess the potential fuel burn reduction of the selected aircraft configurations, compared to conventional technologies extrapolated to 2035. This will allow identifying key technological enablers for HEP, as well as major technology gaps on which research should be focused for the emergence of the technology for civil air transport.

After three years of the project, results from the complete assessment are not available yet and it is still too early for building a complete picture. However, carrying out a first gap analysis and issuing a preliminary roadmap seem useful to synthesize current results and measure the progress of the project. This can also be useful for providing inputs and guidelines for the orientations of further research on HEP.

Accordingly, this report presents a preliminary analysis of technology gaps for HEP and proposes an initial vision for the development roadmap. At this stage of the project, the report builds on the analysis of the performance gaps between the first results of components studies and the technology assumptions used for the first design loops, as well as on the trends observed from the first two design loops of the configurations. It also considers the major technology streams that are today identified to achieve the projected performances.

2. TECHNICAL SCOPE

Addressing the challenge of climate change requires studying solutions for commercial aircraft that forms the bulk of aviation's emissions. Accordingly, IMOTHEP focuses on short and medium range (SMR) aircraft, which represent a significant part of current fleet and aircraft emissions[1]. It investigates also HEP for regional aircraft that generate a smaller share of aviation emissions but may be a more accessible candidate for HEP implementation, and therefore an important first step in the HEP roadmap.

Table 1 summarises the main top-level aircraft requirements (TLAR) considered for both missions.

Table 1: IMOTHEP TLAR for regional and SMR aircraft

Top Level Aircraft Requirements	Regional	SMR
EIS	2040+	2040 +
Standard Capacity (Standard Design LOPA)	40 seats @ 32" seat pitch	150 PAX
Design Range (in standard layout)	600 nm	2750 nm
Typical Mission (in standard layout)	≥200 NM- 250 NM	800 nm
Design Mach number	0.4 [0.40 - 0.48]	0.78 [0,78 - 0.82]
All Engines Operative Ceiling @ ISA	20000 ft	≥ 38500 ft
Take Off Field Length @ SL, ISA, MTOW, dry concrete runways	≤ 1100 m	≤ 2200 m
Landing Field Length @ SL, ISA, MLW, dry concrete runways	≤ 1100 m	≤ 1800 m

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[1] From Schäfer 2019, 900 nm missions represent 80% of flight and 36% of fuel used – 1500 nm missions represent more than 90% of flights and 48% of fuel.

In addition to these TLARs, the design target for the studied configurations is to achieve a minimum level of emissions reductions[2] compared to the conventional technologies currently in service on the 2014-generation aircraft:

- 45% for the regional aircraft,
- 40% for the SMR.

These represent 10% more emissions reductions than the target pursued in Clean Sky 2 including the effect of conventional technologies projected to 2035.

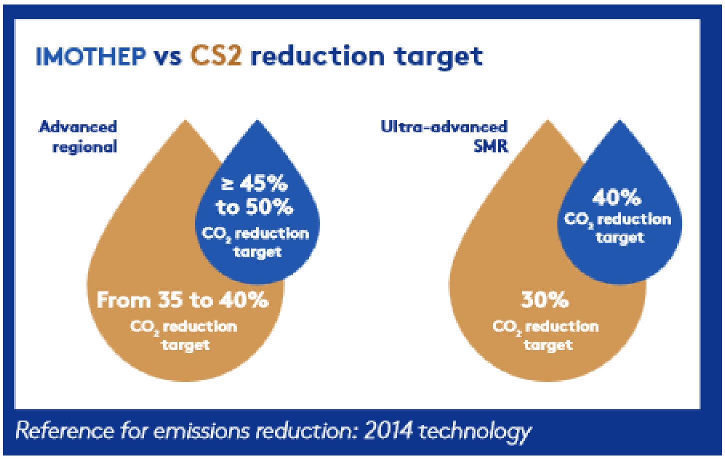

Figure 1: IMOTHEP vs. CS2 reduction target

For each of the considered missions (regional and SMR), IMOTHEP is investigating two different aircraft configurations: a "conservative" one, with "moderate" evolutions of aircraft architecture, and a radical one, with more disruptive evolutions (Table 2). The goal is in particular to identify the synergies between HEP power train definition and aero-propulsive integration, and the level of disruption in overall aircraft design from which introducing HEP brings a significant benefit.

The conservative regional is close to an ATR42 configuration. It embarks a parallel hybrid propulsion system with battery electricity storage and electric assistance to the thermal turboshaft (combining cycle-integrated assistance to the compressor and mechanically-integrated assistance to the shaft).

The radical regional uses distributed electric propulsion with propellers distributed at the leading edge of a high-aspect ratio wing. Wingtip propellers are also considered as an option for this configuration. The initial propulsion system was a series hybrid system (turboelectric).

The conservative SMR exhibits a conventional tube-and-wing configuration but with distributed propulsion using electric fans located at the trailing edge of the lower surface of the wing. It uses a turboelectric power train.

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[2] So far, mainly fuel-burn related CO2 emissions are considered, on the overall flight path. Later in the project, this might be specialized per flight phase, or extended to other type of emissions (eg. NOx) if the level of analysis permits.

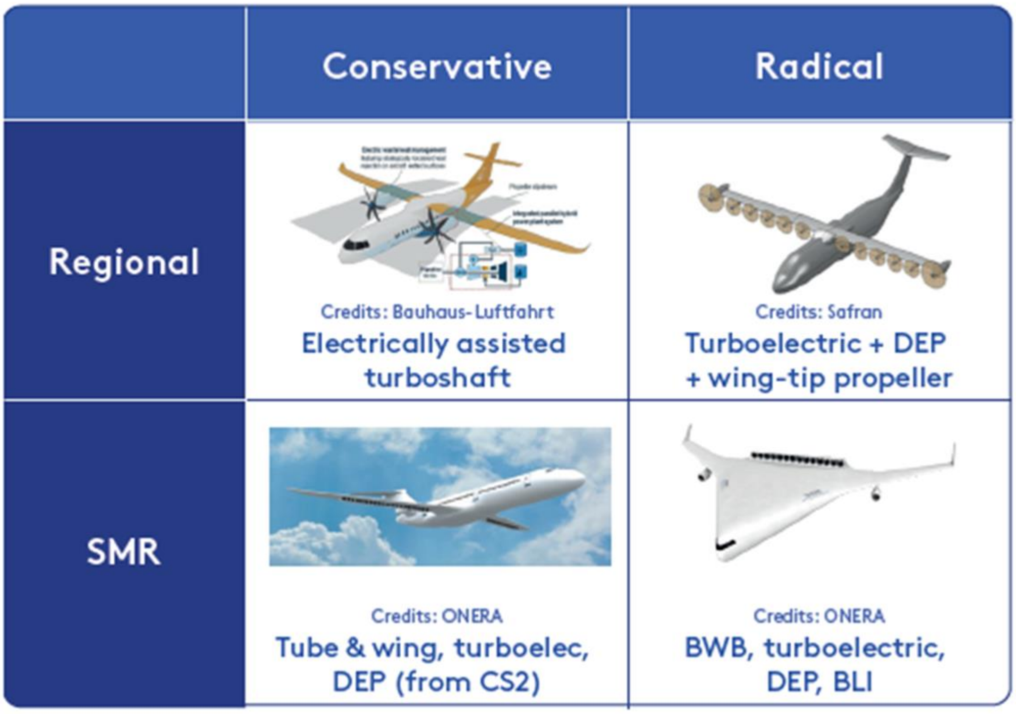
Last, the radical SMR is also turboelectric but explores the potential of a blended-wing-body configuration with boundary-layer ingestion (BLI).

Three successive design loops are to be performed during the project (Figure 2):

- A conceptual design loop, L0, mostly based on technology assumption projected to 2035, which provides specifications for the study of the various components and sub-systems of the aircraft, as well as for the aeropropulsive integration studies;
- A multidisciplinary design loop, L1, integrating refined designs and the outcomes of the components, sub-systems and aeropropulsive integration studies;
- A last refined design loop, L2, integrating higher fidelity models and the outcomes of refined components ‘studies.

This report is issued at the end of the second design loop, L1, and therefore already integrates components’ performance that are no longer assumptions but results from designs based on basic technology assumptions for 2035.

Table 2: IMOTHEP initial candidate aircraft configurations



	Conservative	Radical
Regional	Credits: Bauhaus-Luftfahrt Electrically assisted turboshaft	Credits: Safran Turboelectric + DEP + wing-tip propeller
SMR	Credits: ONERA Tube & wing, turboelec, DEP (from CS2)	Credits: ONERA BWB, turboelectric, DEP, BLI

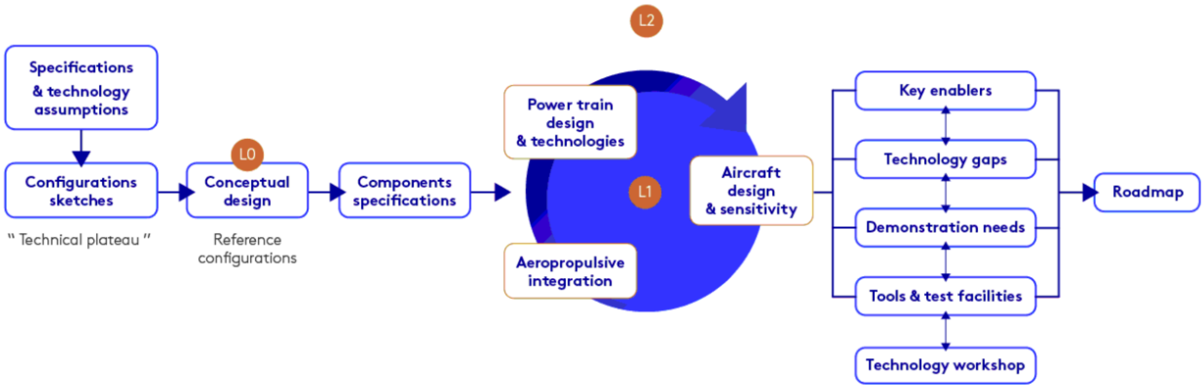


Figure 2: IMOTHEP methodological approach

Also interesting for the elaboration of the HEP roadmap are the configurations studied in CENTRELINE and NOVAIR EU projects for an entry into service (EIS) in 2035:

- a long range aircraft (340 PAX over 6500 nm at Mach 0.82) using a BLI tail fan driven by a turboelectric architecture for CENTRELINE;
- A parallel hybrid propulsion system for a SMR aircraft in NOVAIR (150 PAX over 800 nm at Mach 0.78).

Published results of these studies are included in the analysis.

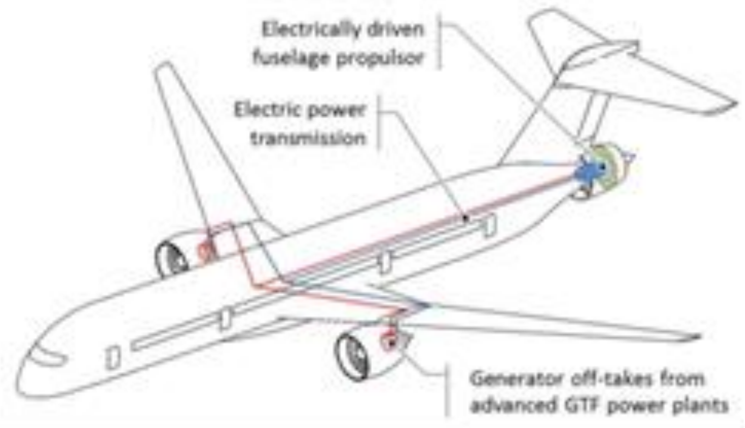


Figure 3: CENTRELINE architecture.

3. KEY ENABLERS AND TECHNOLOGY GAPS

In IMOTHEP, key enablers for the achievement of the targeted emissions reductions shall be identified from the performance analysis of the studied configurations that assemble the different components' technology. Sensitivity analyses provide the technology gaps between the components' performance, stemming from technological studies in WP2 to WP5, and the required level of performance to reach the emissions reductions target.

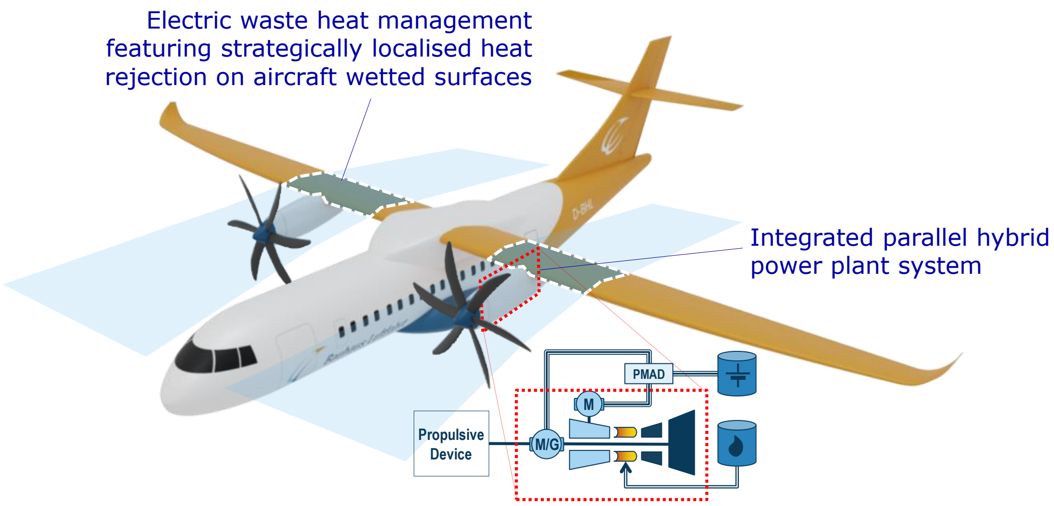
Nevertheless, this approach cannot be fully developed at the current intermediate stage of the project, for which it is still too early to draw final conclusions about the key enablers. Sensitivity analyses have been performed at individual technology level, but the most relevant ways to combine these improvements towards the target are still unclear. In order to establish a first gap analysis and a preliminary roadmap, this report mainly builds on the analysis of the performance gaps between the first results of components studies and the technology assumptions used for the first design loops, as well as on the trends observed from the first two design loops of the configurations. Some preliminary sensitivity results are also included. In addition, technology gaps do not lay at components' level only. Some are more relevant from system or sub-systems. This is the case of thermal and power management for example. These will be also analyzed in this report. Finally, the report considers the major technology streams that IMOTHEP partners identified to achieve the projected performances and close the gaps.

3.1. PRELIMINARY OBSERVATIONS FROM CONFIGURATIONS STUDIES

3.1.1. IMOTHEP CONFIGURATION STUDIES

A detailed presentation of the four configurations studies is available in [4] and [5]. The followings only provide a brief synthesis and high level conclusions.

The Regional-Conservative (REG-CON) is the only parallel hybrid architecture studied in IMOTHEP. Based on an ATR configuration type (Figure 4), it uses an electric assistance to the turboshaft, which combines direct mechanical assistance to the power shaft and electric assistance to the compressor. The thermal management system of the hybrid electric power train makes use of the wing wetted surfaces in the propeller's stream as heat exchanger. For the preliminary design loop, the level of assistance was kept constant at 5% (ratio of supplied electric power to total supplied power including fuel) all along the flight, with a constant split between the shaft and compressor. This led to a total installed electric power per turboshaft of about 550 kW fed by a DC voltage of 540 V. The total mass of batteries for power supply was about 3600 kg of batteries (with specific energy on pack level of 310 Wh/kg). Performances evaluation showed that such simplistic hybridization strategy (mostly consisting of a pure substitution of kerosene energy by electricity stored in batteries) might lead to limited block fuel reductions over short range only. The battery energy density was the main driver of the fuel burn, while the global efficiency of the electric power train had a limited influence. For example, the sensitivity analysis performed showed that without any change in the energy management strategy, the battery's energy density on pack level should be at least 500-600 Wh/kg whereas a nominal hypothesis of 310 Wh/kg was considered in the initial assumptions for 2035.


Electric waste heat management featuring strategically localised heat rejection on aircraft wetted surfaces

Integrated parallel hybrid power plant system

Figure 4: Regional conservative (REG-CON) configuration

The concept was further refined in the next design loop (Loop 1). Based on a review of last developments in batteries, a more ambitious specific energy of 408 Wh/kg (1C, pack level) was selected[3]. Batteries are postionned in the extended belly fairing of the aircraft. Together with the propulsion system, they were sized for the typical mission. Taxi-out and taxi-in phase are performed in fully electric mode, and batteries are charged during the descent phase to provide the required energy for taxi-in (which proved to have little impact on battery mass). Batteries also fully power the non-propulsive electric systems of the aircraft for the typical mission (an all-electric architecture is assumed). Results from the components studies in the technology work packages of IMOTHEP were included in the design. Various hybridization strategies were investigated by varying the hybridization degree along the different flight segments[4]. Results showed that bringing electric assistance only during the high power phases (take-off, climb, go-around) was not beneficial and that hybridization shall be used during cruise, which contributes most to the total block fuel even for a regional short mission. On the contrary, using electric assistance for reserves proved not to be beneficial. In addition, adding all electric assistance to the power shaft proved to be the most efficient strategy. The best configuration was obtained with a hybridization degree (H_p) of 15%[5] (which corresponds to a ratio of electrical power assistance to engine shaft

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[3] This corresponds to the combination of an optimistic cell energy density of 550 Wh/kg (upper limit assessed from last batteries' development) and a cell to pack ratio of 0.742.

[4] The hybridization degree is the ratio between the supplied electric power and the total supplied power (electricity plus power contained in the fuel). H_p is kept constant along each segment.

[5] Fuel burn reduction increases with hybridization degrees, but for $H_p > 15\%$, no configuration could be defined within all imposed constraints

power of 30%) during take-off, climb and cruise. A 9.6% block fuel reduction was obtained for the typical mission compared to the baseline aircraft (ATR 42-derived reference aircraft adapted to IMOTHEP TLARs and updated with technology projection to 2035). By contrast, ramp fuel (sum of block fuel and reserve fuel) increased by 2.5%, and for the design mission, both block fuel and ramp fuel increased by 6.1 and 8.8%, respectively. For this configuration, the battery mass (2670 kg) represented 12.5 % of the MTOM, and up to 1 MW of electric assistance was provided to each turboshaft. Some results of the sensitivity analysis to electric systems are provided in Table 3. Sensitivity analysis showed that a 20% increase of battery's cells specific energy (to 655 Wh/kg) brings a 1.5% fuel burn decrease compared to the initial configuration. Efficiency and specific power of electric systems proved to have limited influence. It was also found that supplying energy to the non-propulsive systems with an all-electric aircraft was representing a significant part, about 40%, of the battery use and mass. This suggests exploring other options for non-propulsive systems.

Table 3: Sensitivities to electric systems for the REG-CON

Parameter	Nominal value	% variation	Design ramp fuel
Battery specific energy	408 Wh/kg	± 20%	-1.5 / +2.4%
Battery discharge efficiency	95%	± 2%	± 0.2%
EM specific power	17.1 kW/kg	+ 20%	- 0.32 %
PE specifc power	8 kW/kg	+ 20%	- 0.39%
Power off-take	167 kW	+ 6%	+ 0.5 %

The Regional-Radical (REG-RAD) configuration resulting from the preliminary design loop (L0) is illustrated in Figure 5.

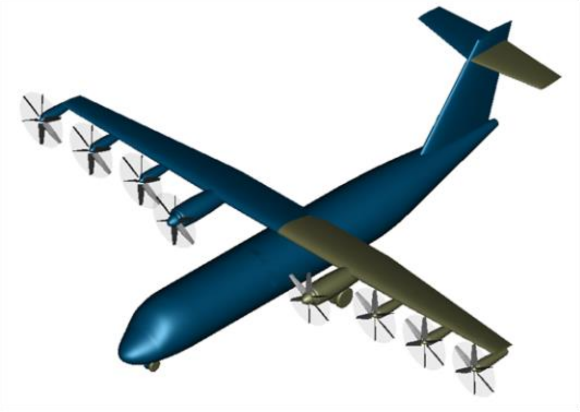
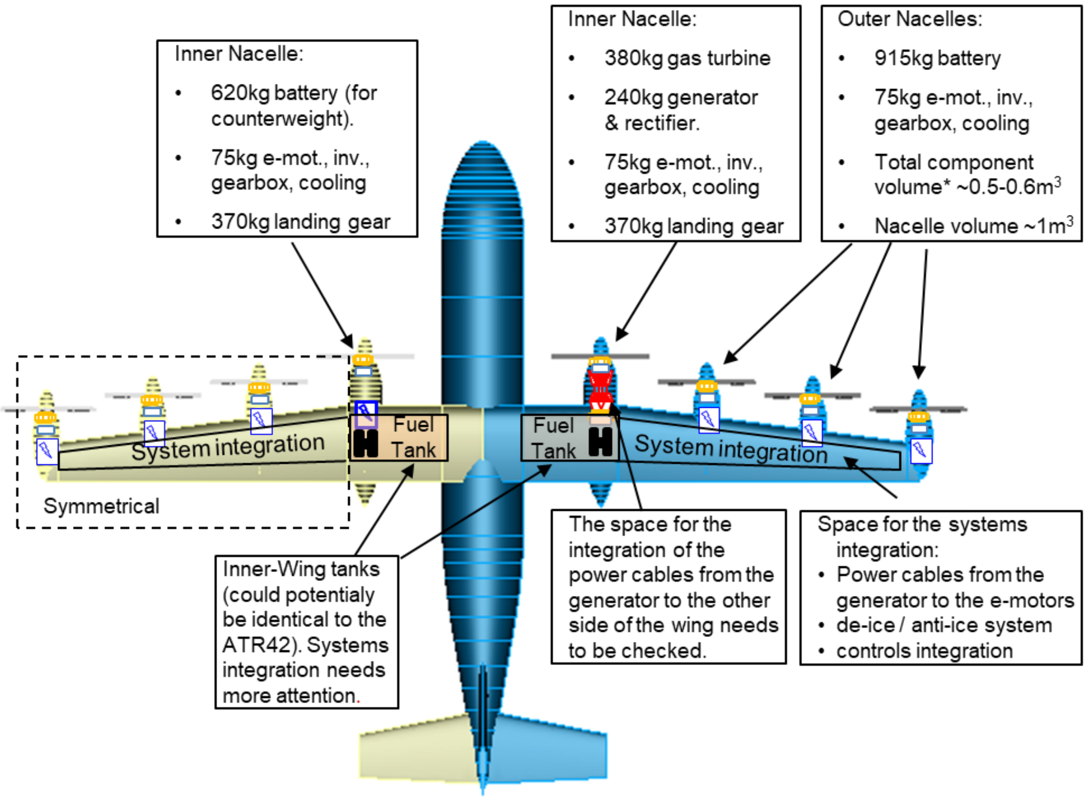


Figure 5: REG-RAD initial configuration with distributed electric propulsion

It used a turboelectric architecture to drive six propellers distributed on the leading edge of the wing in addition to the propellers installed on the two turboshafts that drive the electric generators. Electric power was about 300 kW per engine and an 800 V DC voltage is used. The configuration allowed an increase of the total propeller area (compared to the reference twin-turboshaft configuration), as well as an increase of the wing lift at take-off. In this first design loop for which only low-fidelity tools were used, not all the potential advantages brought by the configuration were included (e.g. wing mass effects, potential advantage for high lift device) so that the performance comparison with the reference configuration was incomplete. However, the analysis evidenced that the increase of propulsive efficiency resulting from the larger propellers' disk area did not compensate alone the mass penalty introduced by hybridisation. Important mass reduction of the energy generation and distribution system was of primary importance for this configuration. Based on these results and additional ones from other DLR's studies, the IMOTHEP team did not consider this turbo-electric configuration to be promising. For the second design loop, it was replaced by a fully electric configuration with a thermal range extender.


Inner Nacelle:
- 620kg battery (for counterweight).
- 75kg e-mot., inv., gearbox, cooling
- 370kg landing gear

Inner Nacelle:
- 380kg gas turbine
- 240kg generator & rectifier.
- 75kg e-mot., inv., gearbox, cooling
- 370kg landing gear

Outer Nacelles:
- 915kg battery
- 75kg e-mot., inv., gearbox, cooling
- Total component volume* ~0.5-0.6m^3
- Nacelle volume ~1m^3

Inner-Wing tanks (could potentialy be identical to the ATR42). Systems integration needs more attention.

The space for the integration of the power cables from the generator to the other side of the wing needs to be checked.

Space for the systems integration:
- Power cables from the generator to the e-motors
- de-ice / anti-ice system
- controls integration

Figure 6: New REG-RAD configuration for second design loop (L1)

The new configuration (Figure 6) still uses distributed electric propulsion and wing-tip propeller. All propellers are driven by electric motors (~300 kW each), a battery pack being installed in each nacelle except one that hosts a turbogenerator, which serves as range extender. Batteries are sized for the typical range of 200 nm and design payload of 4240 kg, while the design range of 600 nm with a 4876 kg payload is performed using the range extender. In the first case, the aircraft embarks 6115 kg of batteries (with an energy density of 475 Wh/kg at cell level, 360 at pack level). In the extended range mode, the mass of batteries is decreased to 5505 kg and the aircraft can achieve 180 nm in electric mode. Due to the batteries, the REG-RAD has a 50% higher MTOM than the conventional baseline turboprop. The electric components' characteristics from IMOTHEP technology work packages were included in this second design loop, as well as the increase of the lift coefficient allowed by blowing the wing. Whereas no fuel burn reduction was obtained with the initial configuration, a 60% block energy reduction was obtained over the 200 nm performed in full electric mode. This mostly results from the high efficiency of the electric chain (>95% propulsion chain efficiency and 90% charge-discharge efficiency of the battery), whereas the gas turbine efficiency, with around 40% power efficiency, is significantly lower. In the range extender mode, the REG-RAD is 20% more efficient than the baseline aircraft over the 600 nm mission. These translates in a 100% fuel burn reduction over the 200 nm mission, and a 36 to 40% fuel burn reduction over the 600 nm mission. The main reason for the improved efficiency, is that a big portion of the mission is flown electrically, and that a high aeropropulsive efficiency is reached during cruise, due to better PSFC (bigger turboshaft) and better L/D (bigger wing area), which compensates for the 50% MTOM increase. Some sensitivity results are provided in Table 4. For batteries, the nominal specific energy (1C) was varied from 404 Wh/kg to 556 Wh/kg (extreme assumptions from the battery performance review performed within IMOTHEP, see 4.1.1). This mostly impacted the MTOM of the aircraft (-16.5% to + 21.3%) with a limited influence on the block energy (-2.1% to +3.1%), which is mostly due to the constraints imposed on wing sizing in the design process. Sensitivity studies also demonstrated a strong impact of energy off-takes for de-icing and ECS: an offtake reduction of 80kW is equivalent to around 8% zero-lift drag reduction. Performances are also sensitive to the propulsive efficiency of the electric power train[6] but not to the specific power of the EPU[7]. As a conclusion, this parallel/series hybrid configuration exceeds the performance targets set for IMOTHEP but constitutes a quite different hybridization scheme than initially envisaged and a kind of singular point compared to the other configurations for which both electric and thermal modes work together.

Table 4: Sensitivities to electric systems for the REG-RAD

Parameter	Nominal value	Variation	Block energy
Battery specific energy	475 Wh/kg	404 – 556 Wh/kg	-2.1 / +3.1%
Propulsive efficiency	95%	± 5%	~ ± 5 %
EPU specific power	7.4 kW/kg	+ 20%	< 0.1 %
Power off-take	160 kW	- 50 %	~ -5 %

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[6] Including propeller, gearbox, inverter or e-motor efficiency

[7] Electric Propulsion Unit: electric motor + inverter

The SMR-Conservative (SMR-CON) configuration builds on the previous DRAGON configuration designed by ONERA within Clean Sky 2 [3] and resized for IMOTHEP's TLARs. It accommodates 24 electrically driven fans at the trailing edge of the lower surface of the wing, with an installed electric power of 820 KW per engine (Figure 7). Two turbogenerators located at the rear of the fuselage produce a maximum electric power of 21 MW, delivered to the EPUs by a DC power transmission with a voltage of 3000 V (each turbine engine drives two generators with a unit power of 5.3 MW). For this configuration and the initial technology assumptions, Loop 0 results (conceptual design) showed that distributed propulsion was bringing an increase of propulsion efficiency that over-compensated the mass penalty of hybridisation and the energy transmission losses. The fuel burn for the design mission was reduced by 6.5%, while the MTOW of the aircraft was 5% higher compared to the conventional configuration projected to 2035 (baseline configuration). Sensitivity analyses evidenced that the most influencing design parameter for the fuel burn was the fan overall pressure ratio, which should be lowered as much as possible without compromising the aerodynamic design. From a technology point of view, the efficiency of electric machines proved to be the most influencing parameters (specific power had less influence) and emerged as the first target for technology investigations. During Loop 1 (multidisciplinary design), the outcomes of the components' studies were taken into account: integrated design of the EPU (with air or liquid cooled options), design of the cables with their insulation, turboshaft and generator models, update of power electronics efficiency and energy density, and a preliminary estimate of the thermal management system. Compared to the initial design assumptions (based on projection from literature and experts' view to 2035), these resulted in a lower specific power (kW/kg) and a slightly higher efficiency for both the EPU and the generator, and a higher PSFC for the turboshaft (+23%) (Table 5). The fan pressure ratio of the e-propellers was also decreased from 1.25 to 1.15 to limit the impact of the lower performance of the turbomachinery. These led to a decrease of the performances of the configuration and to a higher fuel burn compared to the baseline configuration (+1.3% for the typical mission, +7.9% for the design mission). The interim conclusion for the SMR-CON concept is that HEP does not seem to bring any advantage compared to conventional propulsion with the current conservative technology assumptions used for the components' design. First sensitivity studies were also performed to identify the key enablers for this configuration. The parameters explored through a Design of Experiment (DoE) encompassing 200 points, included the specific power (kW/kg), power density (kW/L) and efficiency of the electric machines (EPU and generator), the turboshaft PSFC and the DC bus voltage. The dominating parameter was the PSFC of the turboshaft. As all the energy is produced on board, this PSFC determines the amount of energy that is available at the input of the electric power chain. To identify the most important parameters of the electric chain, the PSFC was fixed for further sensitivity analysis. This showed that the EPU's power density (kW/l) is the highest source of variability, second comes the voltage and third the power generation efficiency. Outcomes are that it is critical to improve the EPU's power density to values higher than 10kW/L against 3.8 to 6 for current design, and voltage to values higher than 2kV, in order to reduce the variability in the aircraft performances and ensure a good performance level. The strong influence of power density of the EPU is in some way specific to the highly distributed propulsion used on the configuration. It is due to the integration constraints associated with the distribution of the propulsion on 24 fans with small diameters. A low density leads to a long EPU with a drag penalty.

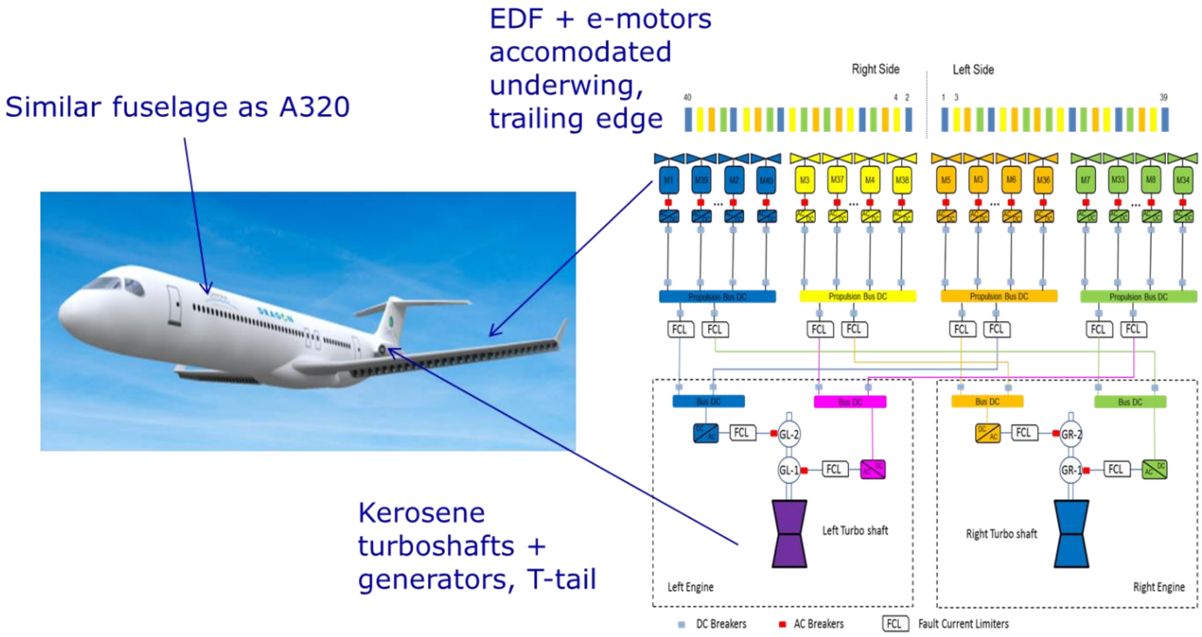

Figure 7: SMR-CON's turboelectric DRAGON configuration

Table 5: Evolution of some components performances between L0 and L1 (SMR-CON)

Components	Initial assumption (L0)	Achieved performance (L1)
EPU specific power (kW/kg)	13.2	4.6 – 9.2 (air / liquid cooling)
EPU efficiency	0.96	0.975 – 0.967 (air / liquid cool.)
PSFC turboshaft kg/kWh	0.133	0.164
Generator specific power (kW/kg)	13.5	9.65
Generator efficiency	0.95	0.99

The initial design of the SMR-Radical (SMR-RAD) in Loop 0 is illustrated in Figure 8. As the SMR-CON, it used a turboelectric architecture driving a total of 18 electrically-driven fans distributed on the upper side of the BWB fuselage. This distributed propulsion was also ingesting the boundary layer developing on the fuselage, which improves the aeropropulsive efficiency. Unit electrical power per fan was about 1100 kW and the total electric power delivered by the turbogenerators was 22.5 MW. A DC voltage of 3000 V was also used for the SMR-RAD. To separate the respective benefits from hybridisation and from the BWB shape, the comparison of performance was made between BWB configurations using conventional turbofan (so-called 0HEP concept) and DEP. As for the SMR-CON, DEP was bringing an increase in propulsive efficiency thanks to a large fan area and reduced fan pressure ratio. A fuel reduction of 13% was observed compared to the turbofan version without including BLI effect. Again, the fuel burn proved to be sensitive to the fan area. Sensitivity analyses also evidenced an influence of the PSFC of the turbogenerators on the fuel burn, which was larger than the influence of the assumptions on the electric systems. In subsequent Loop 1, the more refined “SMILE” airframe shape, stemming from an ONERA study [6], was introduced (Figure 9). The number, location and size of the ducted fans was reoptimised for the new shape with the goal of maximizing propulsive efficiency by maximizing total fan area (size and number of the propulsors have limitations related to installation space and mass and drag of the fan casings, ducts and pylons). Compared to the initial version, the number of electric fans decreased to eight. The performances of the different components of the propulsion chain (turboshaft and electric power chain) were refined based on the inputs from the components design studies performed in the technology work packages of IMOTHEP. These resulted in particular in a lower specific power for both the electric motors and the generators, and in a lower efficiency of the ducted fans. In this process, the analysis evidenced a strong benefit of moving towards a more electric aircraft (MEA), and to remove the air bleed on the turboshaft (bleeding was generating a 10% increase of fuel consumption). Finally, including all the refinements, the hybrid electric BWB did not demonstrate any fuel burn reduction compared to the BWB using turbofan (the 2035 EIS SMR-0HEP), which achieved a 24% fuel reduction compared the reference aircraft (2014 technologies) and 6% compared to the baseline aircraft (conventional aircraft with 2035 technologies – SMR-BAS). One should note that, for this second design loop, the design and performances of the electric components of the power train were based on conservative technology assumptions for 2035. At this stage, the effect of BLI was investigated with low-fidelity methods only. Furthermore, the complete thermal management system was not yet introduced. Cooling system masses were estimated using a general specific power assumption from L0. The interim conclusion for the SMR-RAD concept is that HEP does not seem to bring any advantage compared to conventional propulsion if conservative technology assumptions are made. More aggressive technology developments are required for the design of the power train. Furthermore, more detailed analysis (e.g. with high-fidelity methods) of the aero-propulsive integration, and in particular the BLI potential, is needed.

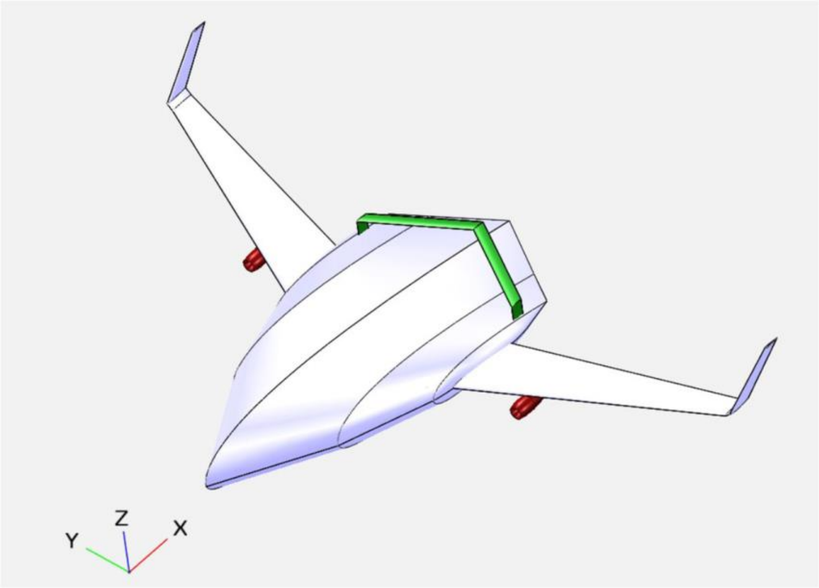

Figure 8: SMR-RAD - preliminary BWB configuration from the first design loop (L0); figure adopted from Sgueglia, 2020? [ref tebd]

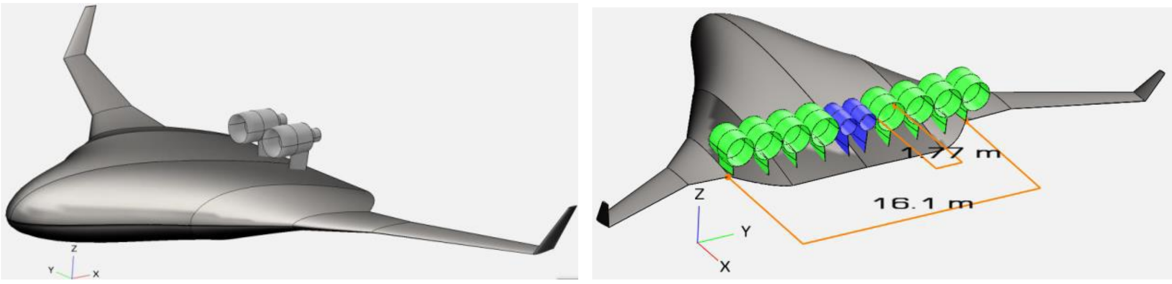

Figure 9: BWB SMILE shape from ONERA

(left "no HEP" aircraft, right HEP configuration turbogenerators in blue and electric fan in green)

Interim conclusions from IMOTHEP configuration studies

The initial results of Loop 0 were suggesting a larger potential for fuel burn reduction for the SMR configurations than for the regional ones, this result being obtained with a consistent set of technology assumptions for all configurations. This could be attributed to a larger potential for an increase of propulsive efficiency in case of configurations using turbofan instead of propellers. However, the introduction of the outcomes of the components studies in Loop 1 did not confirm this initial conclusion and did no longer evidence any benefit from hybridization for the SMR configuration. Yet, these results were obtained with conservative technology assumptions for the design of the electric components. Loop 1 results show the need for technology assumptions that are on the aggressive side, both for the electric components and the ducted fans (in terms of mass, drag and efficiency). In addition, some subsystems are still to be better taken into account in the configuration design. This is in particular the case for the TMS. From a general point of view, superconductive technologies, which are investigated in WP5 of IMOTHEP, could emerge as a key enabler by allowing significant mass reduction of electric systems.

An important caveat attached to the current conclusions regarding the SMR configurations lies however in the comparison of the performance of the turboshafts of the hybrid configurations with those of the turbofan of the baseline aircraft. A detailed sizing and design of the turboshafts was performed in IMOTHEP, whereas only projections for the global performances of turbofans to 2035 were used. This induces a bias in the performance comparison, which shall be further investigated considering the major influence of the PSFC for the hybrid configurations (an efficient chemical to mechanical energy conversion is required to ensure viability of the turboelectric concepts)..

Regarding the regional aircraft, the turboelectric option is no longer considered as a promising option and was dropped from the IMOTHEP roadmap. Remaining options are the parallel hybrid systems and the fully battery powered electric aircraft with thermal range extender, two systems that highly rely on batteries' performances and energy substitution rather than block energy decrease (although in case of fully electric flight with batteries, the global efficiency of the power train is improved).

3.1.2. ADDITIONAL STUDIES OF INTEREST

Of a particular interest to complement the configuration studies performed within IMOTHEP is the **CENTRELINE EU project** that ended in November 2020 [1]. The general idea of the CENTRELINE concept is to implement boundary layer ingestion (BLI) on the fuselage of a conventional tube-and wing-configuration, which represents about 50% of the viscous drag of the aircraft. The purpose of BLI is to reduce the engine's jet excess momentum required to generate the thrust and therefore the associated kinetic energy loss, as well as to reduce the loss of kinetic energy in the wake of the vehicle ("wake filling"). Turboelectric hybridization facilitates the installation of an aft-fuselage BLI fan by allowing the use of an electrically-driven fan that is powered by energy offtakes through electric generators on the two aircraft's main engines located under the wing. The project performed a detailed analysis of the configuration and of its main technical aspects: aerodynamic design of the BLI propulsion system, structural integration, design of the turboelectric power chain and vehicle overall design, including safety considerations and failure cases analysis. The estimated TRL reached at the end of the project is 3.

The study was performed for long range aircraft, 6500 nm, with 340 PAX at M 0.82. The final configuration uses a 10 MW electric engine to drive the BLI fan[8] and one 3.67 MW generator installed on each main turbofan engines. Compared to the configurations studied in IMOTHEP, the level of power is in a similar range for the electric generators, but is five to ten times higher for the electric motors. A DC power transmission is used with a DC link voltage of 2640 V, which is a compromise between minimising the cables' mass and the insulation effort that affects cooling performance of the motor and power electronics (the total mass of DC cables is 690 kg). Permanent magnet radial flux electric machines are used for

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[8] The shaft power of the fan is actually limited to 7 MW.

both the electric motor and the generators. An electric efficiency of 96.5% was assumed for electric machines, and values close to 98.5/99% for power electronics. These values are consistent with those adopted in IMOTHEP for the first design loop. From the information of [1], a power density of 11 KW/kg can be computed for the BLI fan's engine, which is again consistent with the assumptions made in IMOTHEP.

Performances were evaluated compared to a conventional reference configuration based on 2035 technology progress. The additional propulsion system results in a 3.8% increase of the operating empty weight (OEW) compared to the reference aircraft, the propulsion system being 14% heavier (16.3% of the OEW instead of 14.8% for the reference). The turboelectric chain and the BLI fan represent 17.6% of the propulsion system's mass. The total transmission efficiency of the turboelectric power train is 91.9% during cruise. The overall turbo-electric power train specific power is 2.1 kW/kg (for a power extraction on the main engines corresponding to a fan shaft power of 5 MW).

The final fuel burn reduction of the CENTRELINE configuration is 3.2% compared to the 2035 reference. The stepwise performance analysis performed within the project allows to identify the parameters driving the final efficiency of the configuration (Figure 10). The introduction of the idealized BLI fan without taking into account the sizing and mass effects yields a fuel burn reduction of 9.9%, which increases to 10.7% when taking into account the cascading effects on aircraft sizing. Electric power transmission losses and the weight of the electric power chain are the two major factors impinging the potential fuel burn reduction, resulting in a 5% decrease of the BLI fan's benefit. The need to maximise the efficiency of the electric power chain is consistent with the result obtained on the DRAGON configuration. The losses introduced when taking into account aircraft 3D aerodynamics constitute the next major parameter influencing the performance of the configuration (1.5% benefit reduction).

Globally, the configuration performs comparatively better than those studied in IMOTHEP but falls short of the emission reductions targets of both CENTRELINE and IMOTHEP, which are above 10% compared to the performance of reference conventional aircraft in 2035. The target is obtained only in the idealized case for which the HEP system's penalties are not factored in. The project made a simplified estimation of the potential for improvement using high temperature superconductivity (HTS) assuming that a cryogenic heat sink was available on-board and without taking into account all the consequences of the implementation of such a system. For such HTS system, a total electric power train efficiency of 96% and a total specific power of 5 kW/kg were assumed. The fuel burn reduction could be improved from 3.2% to 5.2%. A similar estimation using a mechanical drive train for the BLI fan (global efficiency 98% and specific power 10 kW/kg) yielded a fuel reduction of 6.2%.

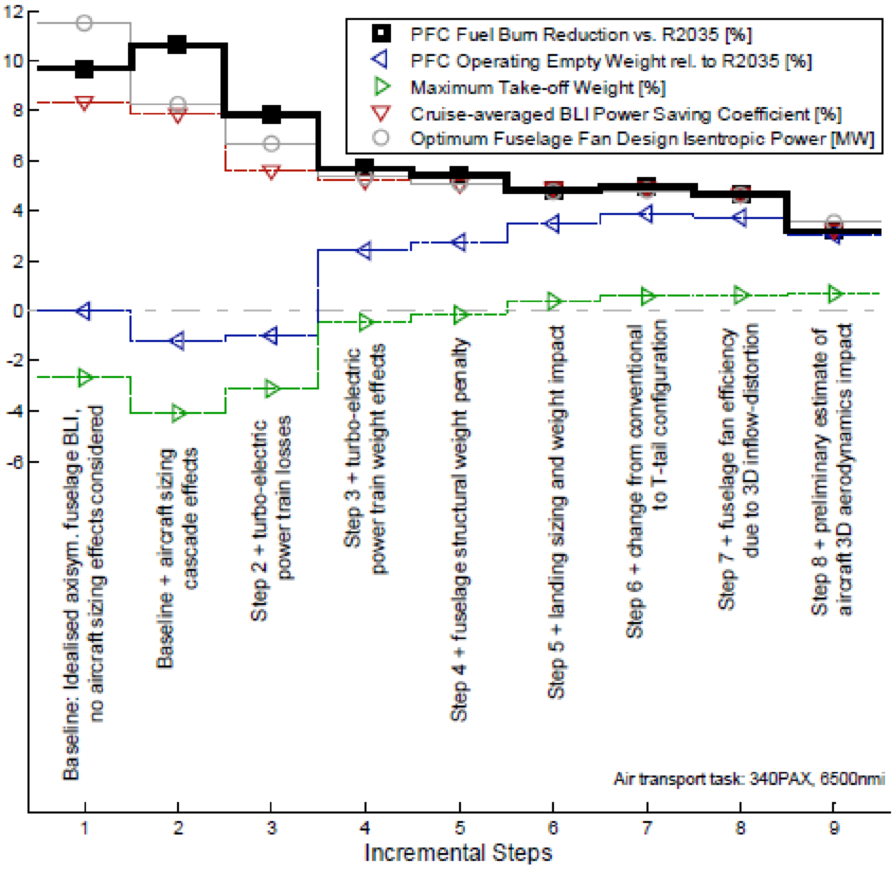

Figure 10: Influence of the different design parameters on the fuel burn reduction of CENTRELINE concept [1]

Also of interest to complement the configuration analysis performed within IMOTHEP is the investigation of **parallel hybrid propulsion for the SMR aircraft by NLR and TU Delft in the context of the NOVAIR project** (Clean Sky 2) [2]. Parallel hybrid propulsion is used to downscale the main turbofan engines of an A320 class aircraft projected to 2035 technology level. In this case, electric power is added to the turbofans only during take-off and climb. Selected missions specifications are very much in line with those adopted in IMOTHEP: a typical range and design range of 800 nm[9] with a cruise Mach number of 0.78 and 150 PAX. Technology assumptions for batteries are at the upper end of the technology projections for IMOTHEP with density specific energy of 500 Wh/kg (extreme disruptive assumption adopted in IMOTHEP). On the contrary, assumptions for electric machines and power electronics tend to be in the lower end of IMOTHEP ones, with a specific power of 7.5 kW/kg and efficiency of 0.95 against 11+ kW/kg and 0.96 respectively for IMOTHEP. The reference “A320-2035” configuration for the performance comparison exhibits a quite ambitious fuel burn reduction of 30% compared to the current A320neo. As far as parallel hybrid is concerned, fuel burn but also energy consumption are parameters of interest. The NOVAIR study also

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[9] A lower MTOW of 73.5t was applied in this study

looked at the impact on NOx. The reductions in fuel and energy consumption are achieved by downscaling the engine - which results in a lower engine mass and a better performance during cruise - and compensating the thrust reduction during take-off phase by providing additional power to the low pressure turbine shaft using electric motors. The fuel consumption can be further reduced by providing electric power for a longer period during the climb phase however this increases the total energy consumption. Beyond a certain level of assistance during climb, the increase of mass of the batteries counteract this fuel burn reduction. Therefore, the optimal settings for the electric power supply during take-off and climb varies depending on whether the fuel or the energy consumption is optimised. A fuel burn reduction of 7% could be obtained (with an associated 3% reduction of the energy consumption) for a 13.3% downscaling of the turbofans with a power split (ratio of electric power to thermal power) of 17% during take-off and 15% during climb. Energy consumption can be reduced by 5%, with a fuel burn reduction of 6.5% for a 14.6% downscaling with a power split of 15% during take-off and no electric assistance during climb. From the sensitivity analysis, the reduction of the energy consumption turned out to be not that sensitive to an increase of electric machines' power density nor of batteries' specific energy beyond 500 Wh/kg because it depends primarily on the engine downscaling that is limited by the increase of temperature at the high pressure turbine inlet. Fuel burn reduction is more sensitive to batteries' specific energy as it is also impacted by the mass of batteries. Engine downscaling may also increase NOx emissions due to the increase of temperature and could lead to a different optimisation point. A regret is that the study does not provide a sensitivity for lower energy density of the batteries, as the selected value is already at the upper end of the expectation for 2035[10]. With the selected optimistic value, the parallel hybrid concept appears to compete with the more disruptive configurations using turboelectric distributed propulsion studied within IMOTHEP.

3.1.3. COMPLEMENTARY VIEW FROM LITERATURE SURVEY

A literature review was performed in 2019 during the preparation of the IMOTHEP project. At that time, it evidenced strong uncertainties on the configurations that best benefit from hybridization, as well as on the fuel burn reductions that the technology could potentially provide. Studies also exhibited large level of discrepancies on the technology assumptions and on the level of modelling used for the performance assessment. The potential for fuel burn reduction was generally lower than 15%.

At mid-term of IMOTHEP, it was interesting to update this literature review with more recent publications in order to compare the trends observed in IMOTHEP with other studies.

Regarding on-going projects on HEP, some announcements on the North-American side are worth mentioning:

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[10] Side evaluations were nevertheless performed with 200 Wh/kg, which resulted in the infeasibility of HEP on the A320.

- In July 2021, Pratt & Whitney Canada announced a 163 M CAD public funding to support their demonstration of a parallel hybrid propulsion system on a De Havilland Dash 8-100 in cooperation with Collins Aerospace, with a 30% fuel burn reduction target;
- In October 2021, NASA and GE announced their partnership for a demonstrator programme including ground-testing and flight-testing an integrated 1 MW power train on a Saab 340 B and a GE CT7-9B turboshaft, a secondary objective of the project being to provide data and guidance for certification and regulation;
- During the 2022 Farnborough Air Show, GE claimed they had been the first in the world to test, in conditions representative of high altitude, an electric system of the Megawatt and multi-kV class for hybrid propulsion.

At this stage however, no conference paper was found related to these projects.

Table 6 and Table 7 list the recent publications collected and analysed in the current survey. Studies for regional aircraft are mostly at conceptual level with low-fidelity methods. For SMR, NASA recently published the SUSAN concept. On the contrary, no new publication was found regarding the ECO-150 concepts that was one of the major published concepts at the time of IMOTHEP preparation.

Table 6: Recent publications on regional hybrid aircraft

Year	Authors	Organisation	Subject / abstract	Level of investigation
2018	M.C. Camaretti et al.	Univ. Naples	Exploration of the hybridisation of an ATR 42-300 without any resizing of the aircraft.	Conceptual Low-fi
2021	T. V. Marien et al.	NASA	**Results for an Electrified Aircraft Propulsion Design Exploration** Design exploration study to determine the impact of HEP technologies on a set of regional transport aircraft concepts (18, 48, and 70 passenger turboprops, as well as 50 and 78 passenger turbofan aircraft configurations).	Conceptual, parametric
2021	F. Orefice	Unic Naples	**Hybridization and Mission Analysis of a Regional Turboprop** Application HEP to an aircraft similar to ATR42 with technologies close to SoA (250 Wh/kg pack level for batteries) and no major change to the production chain	Conceptual Low-Fi
2021	D. Quillet et al.	Univ. Sherbrooke / P&W	**Parallel Hybrid-Electric Powertrain Sizing on Regional Turboprop Aircraft with Consideration for Certification Performance Requirements** Evaluation of the impact of OEI overshoot power requirement on parallel hybrid-electric powertrain considering two design approaches: design will downsized GT and OEI climb constraint / original GT and ignore OEI climb constraints (DASH-8-300)	Concptual Low fidelity
2022	N. Moebs et al.	Univ. Stuttgart	**Adaptive Initial Sizing Method and Safety Assessment for Hybrid-Electric Regional Aircraft** Futprint 50 project. Conceptual study (initial sizing) considering various hybrid-electric powertrain architectures	Conceptual Low fi
2022	F. Orefice et al.	Univ. Naples	**Powertrain Model Improvement for Hybrid-Electric Regional Aircraft** Application of mathematical modelling tool and bateery sizing methodology to a 40 PAX regioanl with serial/parallel hybrid propulsion.	Conceptual
2022	G. Cinar & al.	Georgia Tech	**System Analysis and Design Space Exploration of Regional Aircraft with Electrified Powertrains** This paper explores the design spaces of a thin-haul and a regional aircraft with parallel hybrid electric propulsion architectures and an entry into service date of 2030.	Conceptual Low-Fi

Table 7: Recent publications on SMR hybrid aircraft

Year	Authors	Organisation	Title / abstract	Level of investigation
2020	Ch. Lents et al.	UTRC	Parallel Hybrid Propulsion & Secondary Power System Architecture Exploration and Evaluation	
2022	R. H. Jansen et al.	NASA	**Subsonic Single Aft Engine (SUSAN) Transport Aircraft Concept and Trade Space Exploration** Design and investigation of hybrid electric aircraft with DEP and a single aft engine, for 180 PAX and 750 nm economic mission	Conceptual + HiFi CFD & refined analyses

3.1.3.1 Regional aircraft

In the publications reviewed, a first approach to hybrid regional aircraft consists in retrofitting existing models such as the ATR 42 or the Dash 8 by introducing a parallel hybrid power train. In this case, HEP is the only technology improvement implemented. Parallel hybrid power trains, thanks to energy storage in batteries and electric assistance to thermal engines, provide the opportunity to substitute some decarbonized electricity to fossil fuel in the energy used by the aircraft, as well as some possibilities to look for a better optimisation of the global propulsion system. In particular, it is often associated with a downsizing of the gas turbine that can be sized for cruise conditions. Generally, batteries bring an electric assistance to the turboshaft during take-off and climb, and very often in cruise also.

Camaretti & al. (Univ. of Naples) explored the benefit for different downsizing of the gas turbine and level of electric assistance during flight, the increasing mass of batteries reducing the payload of the aircraft. State of the art batteries were considered. Absolute fuel burn reduction, between -2.81% to -12.4%, could be obtained at the expense of 6 to 20 PAX compared to the initial capacity of the ATR 42-300. However, translated in fuel burn reduction per PAX for the same range, an absolute 2.81% decrease in fuel burn results in a 11% consumption increase per PAX. Quillet & al. (Univ. of Sherbrooke) investigated the influence of taking into account the "One Engine Inoperative" (OEI) climb requirement on the benefit of downsizing the gas turbines on a retrofitted Dash 8-300 (aircraft's geometry, structure and engine nacelles unchanged). They found that introducing this constraint annihilates the benefit of downsizing the turboshafts. They performed their study for a 270 nm mission and various payloads (36 to 54 PAX) defining the possible mass of batteries transported. The energy density of the batteries was 240 Wh/kg at pack level. Fuel burn reduction varied from 2.5% for 54 PAX to 8% for 36 PAX compared to the reference version carrying the same payload. At 45 PAX, the hybridization ratio was 10.45% with a 216 kW electric motor and 1783 kg of batteries. However, if for a similar payload of 36 PAX, the fuel burn decreases by 8% compared to the reference, the fuel burn per PAX increases compared to the reference carrying 54 PAX (36.9 kg/PAX vs 28.5 kg/PAX). Therefore, hybridization does not seem to bring any advantage here.

A next step consists in resizing the aircraft for HEP at constant technology level. Marien & al. (NASA) used a 500 Wh/kg energy density for the batteries (pack level) and performed a parametric variation of the electric motor's power and batteries' size, resizing the aircraft to maintain a constant payload. Electric assistance was used for both climb and cruise. Fuel burn reduction between 9.1% and 13.6% was obtained respectively for a 48 PAX / 459 nm and a 70 PAX / 488 nm aircraft. However, a strong constraint of the study was the requirement that the aircraft was capable to perform the design mission without the EAP system operational (fuel-only mode). An interesting result was that block fuel and block energy depended mostly on the total amount of supplied electric energy with limited influence of the level of assistance during climb. Cinar & al. (Georgia Tech) investigated a similar approach on a ATR 42-600 for a 800 nm mission and an energy density of 500 Wh/kg at cell level (about 400 Wh/kg at pack level if we assume a 20% packing loss). The authors considered as high the risk that infrastructure were not available everywhere for such an aircraft and, therefore, imposed recharging the battery during cruise and/or descent segments. In-flight charging proved to be inefficient and to reduce block fuel savings provided by hybridization. Finally, fuel burn was only reduced by -1.29%. Introducing electric taxiing led to a fuel burn reduction of 7.8% (this enabled a higher degree of electrification both in the design and operation of the aircraft). Due to the constraints introduced in these two studies, it is difficult to draw clear conclusion on the benefit of HEP.

The other studies considered stronger evolutions of aircraft architectures. Orefice & al. 2021 (Univ. of Naples) considered an aircraft close to an ATR 42 aircraft with technologies closed to the state of the art, and adopted an architecture close to the PEGASUS of NASA, with wing-tip propeller (WTP) and a BLI propeller at the tail. The MTOW was kept unchanged compared to ATR 42 at 24 t to prevent major change in the structure. The hybrid propulsion system was a parallel / series one. Batteries' energy density is 250 Wh/kg at pack level. They are sized for a 200 nm mission. A 22% block fuel reduction was obtained for a 76% assistance in take-off and climb. It increases to 27% with a 9% assistance in cruise. These gains look quite high compared to the previous studies, considering the modest energy density used for the batteries. Same authors (2022) further studied serial / parallel hybrid configuration using DEP (8 engines) plus two gas turbines at the wing tip for 600 nm design range and 40 PAX at M 0.42 (TLAR very close to IMOTHEP). Assumption on battery energy density was 500 Wh/kg. A block fuel reduction of 51.4% was obtained on the typical mission of 200 nm with hybridization during climb and cruise (21.6% on the design mission). For a 350 Wh/kg battery, block fuel reduction is still 28%. These figures again look quite high. There are also in contradiction with IMOTHEP team conclusion that the turboelectric configuration was not interesting.

Moeabs & al. (univ. of Stuttgart), as part of Futprint50, the sister study of IMOTHEP, explored various configurations for 50 PAX aircraft with a design range of 432 nm. These include: simple electrically assisted turboshaft (GT boosted), GT boosted + WTP, GT boosted + tail BLI, parallel/series hybrid with DEP and WTP, as well as hydrogen configurations that are out of the scope of IMOTHEP. Here the EIS is 2035-2040, similar to IMOTHEP target. Regarding technology assumptions, two scenarios were considered, a conservative and an optimistic one (corresponding assumption in Table 8). The conclusion was that HEP provided an advantage only for optimistic scenario with WTP and BLI, and that hybrid-electric powertrains do not offer great amounts of fuel energy savings, if any (although there was room for further optimisation as this was only a configuration screening). Maximum fuel burn reduction is 7% for the optimistic assumption on the BLI architecture. However, the 10% increase of L/D thanks to BLI on a regional aircraft seems actually optimistic.

Table 8: Technology assumptions in Moebs & al.

Scenario	Conservative	Optimistic
Batteries	300 Wh/kg	400 Wh/kg
L/D	14.5	15.5
WTP – L/D (cruise/climb)	+3% / +5%	+5% / + 10%
BLI	+3%	+ 10%

The various results are summarised in Table 9 and compared with IMOTHEP "Loop 0" results for the conservative regional (REG-CON).

Table 9: Comparison of results between IMOTHEP REG-CON and literature results

Study	REG-CON "0"	Camaretti	Marien	Quillet	Cinar	Orefice	Orefice	Futprint 50
Configuration type	ATR42	ATR42	ATR42	ATR42	ATR42	Pegasus	DEP	ATR42
PAX / range (nm)	40 / 600	48 / 296	48 / 459	50 / 270	50 / 800	48 / 200	40 / 600	50 / 432
EIS techno	2035	2020	2020	2020	2030	2020		2035
Batt. Energy density	310	SOA	500	240	~400	250	500	300 / 400
Hybridization	Constant	Climb & cruise	Climb & cruise	Climb & cruise	Climb & cruise	Climb & cruise	Climb & cruise	
Battery mass	3600	650 to 5700		1783*		3000	4300	6837 - 2818
MTOW	22400	16900		19500		24000		25800 - 18020
Fuel burn	Increase	Increase (/PAX)	-9,10%	-2,50%	- 1.3 / -7,81** %	-27%	-21.6% (-51%)	Increase / -7%
Remark			Mission possible on fuel only		Charge in flight ** + e-taxi			Conservative / optimistic case

*45 PAX

From this survey, the following conclusions can be drawn.

- The range of technology assumptions for batteries has significantly decreased compared to the initial literature review for the IMOTHEP preparation and is now between 250 and 500 Wh/kg at pack level, which is closer to the range considered in IMOTHEP.
- There are still strong divergences between the studies regarding the potential benefit of HEP. However, the two studies of Orefice & al. look surprisingly optimistic and would need deeper insight to understand where the benefit comes from.
- It is difficult from this survey to infer an actual clear benefit of HEP to reduce sensibly aircraft emissions. At least, it seems that energy density at the upper bound of the assumptions range are required, as well as a reduced range compared to current regional aircraft.

These observations do not change fundamentally the conclusions of IMOTHEP Loop 1 or call in question the orientations for next steps regarding regional configurations.

3.1.3.2 SMR aircraft

Although NASA classifies the SUbsonic Single Aft eNgine concept (SUSAN, Jansen & al., 2022) as a regional aircraft[11], we include it in the SMR category as its TLARs are close to those of IMOTHEP for SMR: 180 PAX, Mach 0.785, with a design range of 2500 nm and an economic mission of 750 nm. The configuration of the aircraft could have been inspired from the ONERA's DRAGON concept (Figure 11): it features 16 distributed electric fans at the trailing edge under the wing. However, the concept introduces an original peculiarity: it uses only one single turbofan, located at the tail of the aircraft and ingesting the fuselage boundary layer, to produce thrust directly and drive four generators producing 20MW of electrical power for the 16 distributed electric fans. A relatively small rechargeable battery is used in combination with the turboelectric system to optimize the performance and sizing of the turbofan. In addition, a large single use battery is used only in

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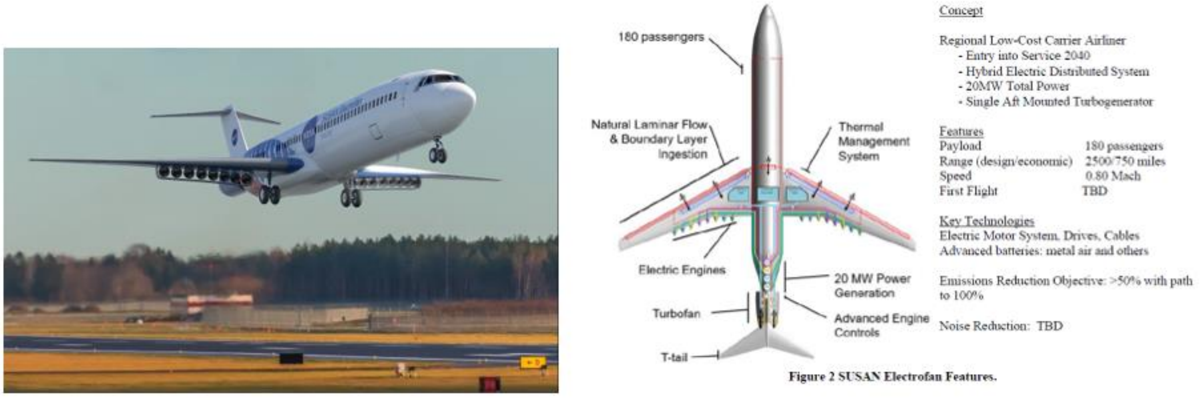
[11] The number of PAX and the range of the aircraft were determined based on the study of three US domestic carriers and two European regional carriers

engine out scenarios to power the propulsion system and allow the aircraft to safely conduct an emergency landing (this battery allows about 30 minutes of flight).



Concept

Regional Low-Cost Carrier Airliner
- Entry into Service 2040
- Hybrid Electric Distributed System
- 20MW Total Power
- Single Aft Mounted Turbogenerator

Features

Payload	180 passengers
Range (design/economic)	2500/750 miles
Speed	0.80 Mach
First Flight	TBD

Key Technologies
Electric Motor System, Drives, Cables
Advanced batteries: metal air and others

Emissions Reduction Objective: >50% with path to 100%

Noise Reduction: TBD

Figure 2 SUSAN Electrofan Features.

Figure 11: NASA SUSAN hybrid electric concept (Jansen & al., 2022)

HEP is used on SUSAN for multiple purposes:

- enabling single turbofan operation on a large transport category aircraft;
- increasing aerodynamic and propulsive efficiency through placement of electric engines;
- optimized turbofan sizing and efficiency through control and electric boosting; and
- reducing control surface sizing through thrust augmentation.

The investigation of the concept is still underway with high fidelity CFD integration studies and detailed analysis of subsystems such as the thermal management system, electric fans or ducted turbofan with BLI. Certification aspects are also addressed. For the time being, NASA published only initial performance estimates, including only first order effects and a subset of the envisaged technologies. Compared to a 2005 baseline aircraft, the block fuel for the 750 nm is reduced by nearly 27%, with a 29% decrease of the TSFC of the propulsion system in cruise. If we refer to IMOTHEP analysis, the baseline aircraft for 2035 achieves a fuel burn reduction of about 19% for the economic mission compared to the 2014 reference aircraft. This would infer that the initial estimate of the benefit of SUSAN compared to a 2035 conventional aircraft is less than 7%. However, technology assumptions used for the electric systems are not disclosed in the publication.

Lents & al. (UTRC) performed a large scale screening of parallel hybrid turbofan propulsion (PHTP) for single aisle aircraft. The analysis focused on a tube-and-wing aircraft configuration and on a two spool geared turbofan gas turbine, with an electric machine attached to each spool that can inject power into the shaft or extract power from the shaft. Multiple options have been explored for the hybridization strategy and the powering of secondary subsystems (landing-gear, de-icing, ECS, etc.). In particular, three levels of propulsion hybridization were considered: light hybridization with electric power only for taxi, partial hybridization with electric power to the engine for transient needs, and full hybridization that adds a substantial amount of battery energy to inject power into the engine during take-off and climb. Unfortunately, the paper does not detail the TLARs for the mission, nor the technology assumptions that are used. The evaluation is at conceptual level with an integrated tool allowing to study millions of combinations of aircraft subsystems in a few hours. The full hybridization provides the largest fuel burn reduction, yet with a limited advantage compared to partial hybridization, but the lowest energy reduction. The full PHTP does not have a large enough fuel burn reduction to offset the electric energy needed for climb assist. There is a fuel burn reduction associated with injecting electric power into the engine during climb, but this reduction is limited due to the fuel burn associated with carrying the weight of the larger required battery. Finally, all configurations are close to each other, with a benefit about 5% compared to the baseline. Another conclusion from the study was that full electrification of the subsystems with these electrified propulsion systems does not necessarily provide the optimal solution.

Table 10: Fuel burn and energy reduction for best configurations (Lents & al.)

% reduction / baseline	Fuel burn	Total energy
Best light PHTP	4.7	4.1
Best partial PHTP	5.0	4.4
Best Full PHTP	5.2	2.8

For these two studies, the potential benefit of HEP does not seem to exceed 5 to 7%, for low fidelity evaluations, which seems consistent with the findings of IMOTHEP SMR studies. But the technology assumptions for the various systems are unknown.

3.1.4. PRELIMINARY CONCLUSIONS FOR RESEARCH ORIENTATION

From the previous overview of hybrid electric concepts, including IMOTHEP, CENTRELINE and NOVAIR, some classes of electric systems can be identified with regard to the required technological development and maturation. In particular, power range of interest can be identified for the different subsystems depending on HEP architecture, as synthesised in Table 11.

Table 11: Characteristics of electrical subsystems for the different configurations

Configuration	Architecture	Total elec. power (kW)	Motor unit power (kW)	Generator unit power (kW)	DC Voltage
REG-CON	parallel	2000	1000	n.a.	540
REG-RAD turboelectric	turboelectric	1800	300	900	800
REG-RAD plug-in	Plug-in (elec / turboelec)	2245	300	2245	800
SMR-CON	turboelectric	22000	820	11000	3000
SMR-RAD	turboelectric	22000	2400	10900	3000
NOVAIR	parallel	7600	3800	n.a.	
CENTRELINE	Partial turboelectric	10000	10000	3700	2640

Table 11 evidences a relatively large spreading of the electric systems' characteristics even within the same class of aircraft. For regional, e-motor power and DC voltage remain respectively bellow 1 MW and 800 V, while all SMR use a ~3000 V distribution network. Generators' required power is more dependent on the architecture, full turboelectric system for SMR introducing the highest generator power (11 MW). Similarly, the range of power for SMR e-motors is large, from less than 1 MW to 10 MW for the extreme case of CENTRELINE. Regarding the two IMOTHEP SMRs, solution with two 5.5 MW generators is also considered with a view to redundancy (although the single generator is dual channel to ensure some redundancy), integration aspect needing more insight.

In first order, Table 11 suggests the development of the following classes of system for the regional and SMR respectively.

Table 12: Preliminary classes of systems for HEP development

	Regional class	SMR class
Distribution	< 1 kV	~3 kV
Electric motor	0.3 to 1 MW	~1 to 10 MW
Generator	~1 MW / 3 MW*	~5 MW / 10 MW

* Two classes depending on the type of architecture (turboelectric or plug-in)

Table 12 clearly evidences the technological step between the regional and SMR mission. In particular, going beyond 1 kV for the electric distribution is very ambitious compared to existing electric system on-board aircraft and raise significant issues with regard to insulation, partial discharge, ageing or arcing problems. Also for electric motor development, there are up to two steps in reaching 1 and 5 MW of required power. Regarding generators, the specific REG-RAD configuration also introduces strong technologic requirements that come close to the lowest SMR ones. From these two different levels of ambition between the regional and the SMR, it can also be inferred that the time horizon for the SMR is certainly longer.

A conclusion from configuration studies is that reaching performances for electric systems on the lower end of technology projections for 2035 is not sufficient. Therefore, research shall be oriented towards the more ambitious and aggressive technology developments and innovative solutions.

Another conclusion from this overview is that refining, and maybe broadening, concept analysis is still required to assess whether hybridization is likely or not to bring any benefit for emissions reduction of commercial aircraft and, if yes, for which technology assumptions. The work continues in IMOTHEP and should yield conclusions within the two next years. However, this exploration of concepts remains an important axis of the HEP development roadmap.

3.2. TECHNOLOGY GAPS – ELECTRIC COMPONENTS LEVEL

As mentioned earlier in this report, a first gap analysis can be performed at the level of the individual performance of the components of the power train.

Whatever the configuration selected from the four configurations studied in the IMOTHEP project, the synoptic of the electrical power chain to ensure propulsion will be the same as presented in the figure below and could be applied for engine hybridization or full electrical solution.

Each component of this power chain has a specific role to play and, for each of them, different solutions can be imagined depending on the A/C configuration:

Power source: equipment that produces electrical energy on board.

Different options include:

1) Electrical generator driven by a motor group/turbine (HEP for IMOTHEP);
2) Battery: element which provides electricity in electrochemical energy storage;

3) Fuel Cell: element which generates electricity by consuming H_2 and O_2 – needs associated systems called build of plant to ensure proper supply of the Fuel Cell, a source of heat generation.

Convertor: equipment composed of several Power Electronics Components (MOSFET, IGBT, …), which adapts the input voltage toward the specified output voltage. Several architectures are possible depending on the voltage characteristics, the level of power and the reversibility or not.

Electrical Distribution Center: Equipment that generally manages the electric network through contactors – to connect or disconnect the different bus bar or loads thanks to dedicated logics (software), embedded directly in the Electrical Distribution Center or in a dedicated Controller Unit on Board.

Motor control Unit (or MCU): equipment that drives the eMotor through the adaptation of the input voltage to specific output voltage – using Pulse Width Modulation Approach (PWM), composed of Power Electronics Components (MOSFET/ IGBT …) – several architectures are possible depending of the voltage characteristics and the level of power.

eMOTOR : Electric Motor generating torque from Electrical power. Different motor families exist (Radial Flux, Axial Flux …). Optimization of this rotating machine needs in particular to master magnetic circuit performance and also the cooling systems.

For these different subsystems and components of the electric power chain, Table 13 provides three levels of performances:

- Those corresponding to the “state of the art” components (SoA);
- The performances obtained for the first design of components performed within IMOTHEP based on technology assumptions for 2035;
- The projected performances stemming from the existing body of literature, considering a conservative evolutionary scenario and a more disruptive scenario.

The first scenario considers that the current technologies will follow a “natural” evolution to reach new values in 2035 – values that have been taken as inputs for the study of the different configurations done during the first conceptual design loop, Loop 0 ("assumptions Loop 0"). The second scenario imagines that a disruptive approach could be introduced, leading to more attractive values in 2035 – pending that research on the identified topics have been performed in the meantime. For both scenarios, the table identifies candidate technologies and the associated required research.

Table 13: Technology gap analysis – Conservative technology development

				Expected Evolution of current Technology		
Subsystem / equipment	**Parameter**	**SoA 2020**	**IMOTHEP L1**	**2035 value**	**Candidate technology**	**Challenges**
Electric motors (direct drive)	Power density (kW/kg)	6	Liquid cooling 6.0 (<3kRPM, 0.5-1MW) 14.8 (6kRPM, 2MW)	11 (> 2 MW) **17 (< 2 MW)**	Radial Permanent Magnet Synchronous Motor (PMSM)	- Efficient cooling (oil flooded) - High frequency / speed machine - Improved toplogies (additive manufacturing)
	Efficiency (%)	95	Liquid cooling 96 (<3kRPM, 0.5-1MW) 98 (6kRPM, 2MW)	96		- Control of losses in materials - Enhance materials and associated manufacturing process in order to get all benefits of new materials
	Power range (aeronautic machines)	250-500 kW	500 kW 1 MW	> 1 MW		
Electric generators	Power density (kW/kg)	5-10 (100-250 kW) 10-15 (1 MW)	~12 kW/kg (1 MW) ~10 kW/kg (11 MW)	20 (0.1 - 3 MW)	Radial Permanent Magnet Synchronous Motor (PMSM)	Liquid cooling, Low Loss Steel, high-speed systems Advanced high energy density permanent magnet High Breakdown-Strength Insulating Materials, Nanocomposite-Based Magnetic Materials
	Efficiency (%)	95	98% (1 MW) 99% (11 MW)	98		
	Rotational speed (x1000 rpm)	5-20 (100-250 kW) 5-15 (1 MW)	24,5 (1 MW) 9.5 (11 MW)	5-30 (100-250 kW) 5-20 (1 - 3 MW)MW)		
	Power range (aeronautic machines)	~250 kW	1 - 11 MW			

				Expected Evolution of current Technology		
Subsystem / equipment	**Parameter**	**SoA 2020**	**IMOTHEP L1**	**2035 value**	**Candidate technology**	**Challenges**
Power convertors	Power density (kW/kg)	8	DC/AC & AC/DC Liquid cooling 20.8 (0.5-1MW) 27.9 (2MW)	20	Major candidate technologies: SiC and GaN with voltage levels that are already available, but with higher current ratings and improved switching loss behaviour	- High current GaN modules - Higher current SiC modules than already available - SiC packaging for higher junction temperature SiC components
	Efficiency (%)	96	DC/AC & AC/DC Liquid cooling 99.2 (0.5-1MW) 98.6 (2MW)	99		Ultra Fast short circuit protection for GaN devices for increased reliability
Electrical network	DC Voltage	115/230Vac 270/540Vdc	<1000Vdc (0.5-1MW) 3000Vdc (2MW)	800 - 1000	*(linked to distribution technologies)*	High voltage issues: - partial discharge - space charge - human protection - product integrity (linked to colateral dammage)
Distribution	Protection device	115/230Vac 270/540Vdc	<1000Vdc (0.5-1MW) 3000Vdc (2MW)	1000	Hybrid technology (Electromechanical and semiconductor devices)	- Reliability of contactor - Fail safe solution
	Standard parts (connectors / cables, busbar)	115/230Vac 270/540Vdc	<1000Vdc (0.5-1MW) 3000Vdc (2MW)	1000	Hifh voltage and/or high curent technologies	- Insulation material - Connexion principle

				Expected Evolution of current Technology		
Subsystem / equipment	**Parameter**	**SoA 2020**	**IMOTHEP L1**	**2035 value**	**Candidate technology**	**Challenges**
Batteries	Energy density (Wh/kg) Cell / Pack	250 / 200	L0 assumption: 300 to 400 L1 revision: - cell: 404 to 560 - pack: 360 to 408	450-500 (cell), 400-450 (pack)	Advanced Li-metal or anode-free cell with Ni-rich cathode and all-solid-state electrolyte (or high Li concentration inorganic liquid electrolyte)	**General research needs on batteries:** - Li metal anodes: fabrication and handling, protection, controlled anode/solid electrolyte interface, high Li plating rates without formation of dendrites (for high C-rates); - Novel solid electrolyte materials: stability, ion-conductivity, mechanical properties, transfer kinetcis and interfacial resistance; - Electrode/electrolyte interface: Understand better phenomena at interface, improve manufacturing processes to achiev low interfacial resitance; - New cell design & manufacturing processes **Research needs for aeronautic batteries:** - Design of battery cells meeting aeronautic requirements (high energy density, high discharge rates, high cycle life) optimizing potentially conflicting targets; - Development of light-weight, safe, reliable battery modules and systems including sensing and management
	Power density (kW/kg)	~0.9 kW/kg (4C)		3.5-4 kW/kg (cell, 8C) 3-3.5 kW/kg (pack)		
	Volumic energy density (Wh/l)	230 (pack)		800		
	Battery efficiency (%)	0.93		0.95		
	Depth of discharge	0.7		0.85-0.9		

Table 14: Technology gap analysis – Aggressive technology development

				Agressive/disruptive development of technologies		
Subsystem / equipment	**Parameter**	**SoA 2020**	**IMOTHEP L1**	**2035 value**	**Candidate technology**	**Challenges**
Electric motors (direct drive)	Power density (kW/kg)	6	Liquid cooling 6.0 (<3kRPM, 0.5-1MW) 14.8 (6kRPM, 2MW)	17	Disruptive motor configuration : axial, radial, 3D, exotic… Superconducting technology	- Improved magnetic materials - Improved magnetic flux sources - Improved cooling - Increases operating speed (possible use of gearbox) - Improved winding technologies and manufacturing processes
	Efficiency (%)	95	Liquid cooling 96 (<3kRPM, 0.5-1MW) 98 (6kRPM, 2MW)	98	Disruptive motor configuration : axial, radial, 3D, exotic… New material (magnetic & electrical) Superconducting technology	- Mastering and minimisation of losses: high performance materials, specific design/toplogy, high fidelity modeling - Enhance materials and manufacturing process
	Power range (aeronautic machines)	250-500 kW	500 kW 1 MW	MW class	Conventional >500 kW Superconducting >1 MW	
Electric generators	Power density (kW/kg)	5-10 (100-250 kW) 10-15 (1 MW)	~12 kW/kg (1 MW) ~10 kW/kg (11 MW)	25	Magnetically geared machines with low losses ferromagnetic pole pieces Homopolar excitation superconducting machine (fixed superconducting coils) Superconducting bulks	High performance/low losses magnetic materials Improve shielding properties and mechanical strength of superconducting bulks
	Efficiency (%)	95	98% (1 MW) 99% (11 MW)	98		
	Rotational speed (x1000 rpm)	5-20 (100-250 kW) 5-15 (1 MW)	24,5 (1 MW) 9.5 (11 MW)	30		
	Power range (aeronautic machines)	~250 kW	1 - 11 MW	multi-MW		

				Agressive/disruptive development of technologies		
Subsystem / equipment	**Parameter**	**SoA 2020**	**IMOTHEP L1**	**2035 value**	**Candidate technology**	**Challenges**
Power convertors	Power density (kW/kg)	8	DC/AC & AC/DC Liquid cooling 20.8 (0.5-1MW) 27.9 (2MW)	30	- High voltage and high current GaN/SiC with switching frequencies in the MHz region for GaN and in the 300kHz-500kHz region for SiC. - Improved passives as magnetic cores and capacitor materials and types for higher power density.	- Research on GaN/SiC technology - Research on ultra low loss passives with small volumes and high max. saturation - Reliable High voltage high current GaN devices and packages. - Reliable High voltage high current SiC devices and packages
	Efficiency (%)	96	DC/AC & AC/DC Liquid cooling 99.2 (0.5-1MW) 98.6 (2MW)	99		
Electrical network	DC Voltage	115/230Vac 270/540Vdc	<1000Vdc (0.5-1MW) 3000Vdc (2MW)	3000	*(linked to distribution technologies)*	High voltage issues: - partial discharge - space charge - human protection - product integrity (linked to colateral dammage)
Distribution	Protection device	115/230Vac 270/540Vdc	<1000Vdc (0.5-1MW) 3000Vdc (2MW)	3000	Full semiconductor devices	- Power density - Integration
	Standard parts (connectors / cables, busbar)	115/230Vac 270/540Vdc	<1000Vdc (0.5-1MW) 3000Vdc (2MW)	3000	Carbon nanotube technology Superconducting technology	- Integration / Installation - Robustness / Lifetime

				Agressive/disruptive development of technologies		
Subsystem / equipment	**Parameter**	**SoA 2020**	**IMOTHEP L1**	**2035 value**	**Candidate technology**	**Challenges**
Batteries	Energy density (Wh/kg) Cell / Pack	250 / 200	L0 assumption: 300 to 400 L1 revision: - cell: 404 to 560 - pack: 360 to 408	600 (Li-rich SSB cell) 700-1000 (Li-S SSB cell) 540-900 (pack)	Li-rich / anode free SSB; Li-S SSB	**Research needs for Li-S electrochemistry:** - proof of concept of Li-S approach(es) with long cycle life - demonstration at relevant scale (20+ Ah) **For aero batteries (integration):** - same needs as for conservative 2035 outlook
	Power density (kW/kg)	~0.9 kW/kg (4C)		4-6 kW/kg (7-10C for Li-rich SSB) 7-12 kW/kg (10-12C for Li-S SSB)		
	Volumic energy density (Wh/l)	230 (pack)		1800 (Li-rich cell) 1000-1500 (Li-S cell) 800-1000 (pack)		
	Battery efficiency (%)	0.93		0.98		
	Depth of discharge	0.7		1		

3.3. TECHNOLOGY GAPS – SYSTEMIC LEVEL

This second part analyses more systemic gaps, in particular issues related to the electric architecture such as safety / operability, thermal management or power management.

Safety and operability analysis were focused on distributed electric propulsion that was adopted on three of the four IMOTHEP concepts. Failure case analysis was performed using state-of-the art figures for the SMR-CON that uses 24 electric engines. In terms of available thrust and power during the different phases of the flight, the analysis evidenced no safety issue. However, the failure of one EPU appeared not to be a rare event, with one failure to be expected for 100 hours of flight, which could have some impact on the aircraft operational availability. One engine inoperative does not raise safety issue a priori (the resulting loss of thrust is about 4%) but, depending on certification rules, the aircraft could not be allowed to start a new mission without repairing, which could affect operational availability. This point needs to be further investigated in close connection with certification. If flying is not allowed with one EPU inoperative, research would be needed in order to determine whether oversizing of the respective components can mitigate this problem and how much oversizing is really needed. Research is also needed on the the impact of radiation and temperature on durability of power electronics.

In the investigation of the two SMR configurations, cooling and thermal management emerged as acritical issues for both the design of the aircraft and its propulsion system. An architecture could be defined to ensure the global cooling of the propulsion system, but at this stage the impacts on drag and mass remain unclear. Due to the lower quality of heat to be dissipated, the use of ram-air (directly or indirectly through stages of the propulsion process) becomes a significant factor for overall aircraft design. It proves to be very difficult to assess the correct cost that is induced by the need for cooling air in terms of additional drag but mostly in terms of additional weight. Developing a parametric model requires performing many designs. In addition, the current system is too demanding for the gas turbine (the size of the gas turbine would need to be increased, which would induce an increase of the SFC). For these configurations with high level of installed power (about 2 x 10 MW of electric generation), the most critical issue is the cooling of the generator. Compared to a gas-turbine, the heat quality for dissipation of an electric generator is low. There is a trade-off between the generator weight and its efficiency. Current findings indicate that a heavier, more efficient generator is the better choice for the overall system, but this trade-off has only been explored by scaling laws just by comparing different generator designs. For the current design, a heat exchanger has been located in front of the gas turbine in the nacelle, which results in a higher SFC due to pressure losses and higher temperature at the inlet. Alternative solutions need to be explored: use of a secondary air flow (turbofan configuration, with the drawback of nearly double frontal area), use of bleed air in an external heat exchanger or a dedicated electric engine powering a cooling fan. This issue of generator cooling might also be difficult for the REG-RAD configuration. As a conclusion, sizing of the cooling system and ram-air system needs to be better understood and improved assessment tools are required. Additional solutions such as phase change or superconductivity may be required for cooling large equipment of three MW or more.

Feasibility of a high voltage electric cabling remains a critical issue. Even if nowadays designs and installation guidelines exist for 540V DC and 230V AC voltages, extrapolations for voltage up to and beyond kilovolt are not trivial and implicit. Some works are ongoing to limit or even eliminate the presence of partial discharge in cables, connectors and harnesses (insulation material, geometries, manufacturing process…). About the installation item, solutions were defined to prevent issues by experimental approaches (use of spacing, specific material, segregation…). But for higher voltage level, these investigations have to be reinforced by modelling approaches in order to have a more extendable and wider view. A critical question is whether insulation solutions exist that ensure a sufficient lifetime with no alteration for voltage beyond 1 kV, as replacing cables at regular intervals would represent a critical maintenance issue. An alternative question could be whether some alteration could be allowed and the certification rules be adapted accordingly. For the regional aircraft, the lower voltage facilitates the work on partial discharges and arcing. However, investigation on the SMR showed that voltage in the range of 1 kV would not be feasible due to a huge penalty in terms of number of cables, mass and so on. The same observation is applicable to the protection devices regarding the voltage level and the intrinsic characteristics of a DC distribution. The breaking capacity of such devices to comply with these requirements in aviation conditions are not yet achieved. The maturity of the technologies have to be addressed regarding the increase in power (i.e. in electric current, especially if batteries are in the electrical network) with a step by step approaches. The arcing issues can be put in parallel of this topic with moreover the impacts on the installation rules and considering the investigation to carry out on the detection and clarification of this event.

The previous chapter already addressed batteries with a view to their energy performances. Additional aspects need to be underlined here considering the critical role batteries play for regional configuration. Beyond energy density, developments are critical regarding safety (avoidance of thermal runaway at high temperatures), fast charging cycles and lifetime. Current concepts assume exchangeable pack, which is a constraint for integration. Requirements in the automotive industry, which drive technology development, do not imply the same constraints as aviation for charging cycle. Specific research is required to enable battery cycling life and charge/discharge rates compatible with aircraft usage, incl. on-ground procedure and infrastructure. There is also a need for adequate battery check, maintenance and/or refurbishment procedures synchronised with the aircraft maintenance schedule while mitigating obsolesce. Last, certification of batteries is an important topic.

4. TOWARD A ROADMAP: DIRECTIONS FOR RESEARCH

At this interim stage of the project, rather than already proposing an actual roadmap for HEP development, the following chapters elaborate on the gap analysis to detail the main axes of research that should be pursued for the emergence of hybrid propulsion. The goal is to highlight the technology streams that seem the most promising to increase the performances for the electric systems towards the targets required for HEP. The presentation is structured by categories of electric and other systems.

Even if some technologies stemming from other sectors, such as the automotive industry, can be reused as a starting basis for aviation, no extensive synergies can clearly be expected with other sectors due to aviation peculiarities, in particular the altitude of operation and the mass constraints. The range of considered power and voltage is also outside of the automotive application. Specific technology stream should therefore be developed for aviation and its specific requirements.

In addition to the development and maturation of the electric components of the hybrid power train, the development roadmap toward a hybrid aircraft needs to address the other critical aspects of hybrid propulsion. A first identified one is the thermal management of the whole electric architecture. Designing a light yet highly efficient cooling system is key for the feasibility and performances of the hybrid aircraft, with a major challenge associated to the low-grade internal heat release (i.e. up to few 100°C, instead of >1000°C) from which it is difficult to evacuate substantial amounts of energy. A complementary approach to cooling technologies could investigate the possibility of more advanced electric components capable of withstanding higher temperature, up to 200 or 400°C for example. As already mentioned, pursuing aircraft configuration studies is instrumental in order to identify the right architecture and the required technology developments. But configuration studies are also necessary because of the strong interaction of the component and their integration onboard the aircraft. Cooling and thermal management, or the optimal compromise between efficiency and mass are typical examples of issues that can only be addressed in close connection with the vehicle definition and the integration of the systems. The need for superconductivity or for additional research on aeropropulsive integration or noise impacts are other examples.

A last package that will be investigated in the next periods of IMOTHEP is related to the required tools and infrastructures needed for the development of hybrid aircraft, as well as the need for adaptation of the certification process and of the means for the compliance demonstration. This will constitute an important part of the roadmap, which is not yet developed at this stage of the project.

4.1. ENERGY GENERATION

4.1.1. BATTERIES

Currently, batteries for mobile applications are mainly developed for automotive, as the market segment is much larger than aviation, and electrification of aircraft propulsion is still in its infancy. Thus, currently available battery cells may fit for small or niche applications, such as the lower segment of CS-23 general aviation or urban air mobility, and even there the developments for cells and packs are still far from being completed. Two elements need to be further developed and demonstrated: (a) Battery cell technologies that are fit for the specific use cases and (b) their integration into the aircraft.

For (a), battery cell technologies need to be developed that are at the same time safe, have ultra-high energy density and sufficient power capability, can operate under the harsh aeronautic environmental and operating conditions with suitable cycle life and costs. Suitable candidates are Li-metal or Li-rich anode-free solid-state batteries with an energy density between 450 Wh/kg (expected to be market-ready before 2030) and 600 Wh/kg (in 2030), and Li-S solid-state batteries with an energy density of 700+ Wh/kg (beyond 2030). A caveat regarding these high performances battery solutions is that they are currently emerging outside of Europe. A significant European effort is thus required to close the gap. In addition, many performance indicators, such as continuous fast charge/discharge capabilities and cycle life are still not well assessed. Most likely, application specific electrochemical formulation and cell designs will be needed.

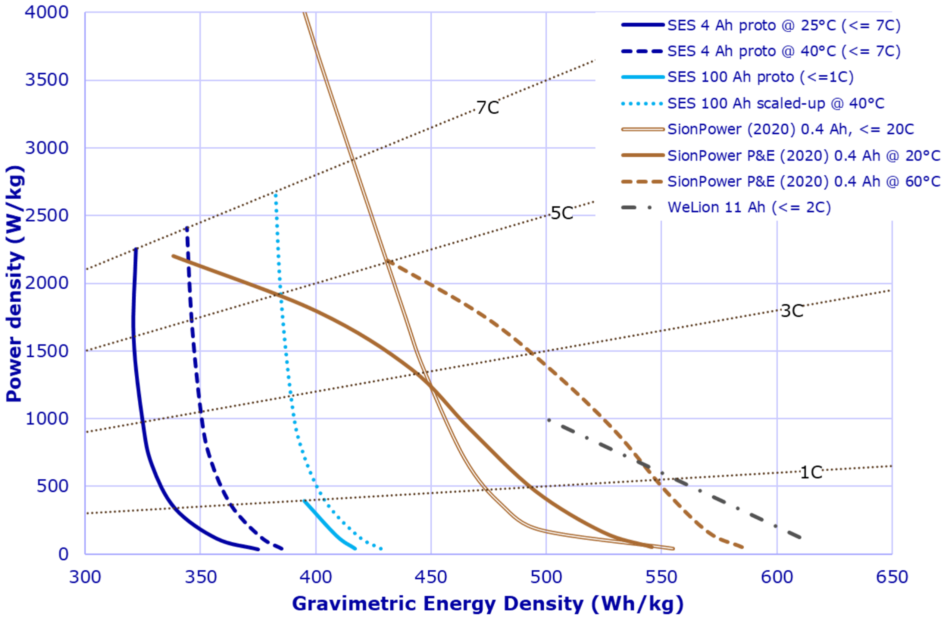


Figure 12: Current industrial prototypes and products (source H. Kuenhelt, IMOTHEP)

Concerning (b), aircraft integration, the CS-25 HER aircraft battery with a MWh energy content needs to be safe by design and ultralightweight (below 10% cell-to-pack weight penalty), include sensing and electrical, thermal and safety management. Such battery needs to be developed and tested together with the selected electrochemistry and cells.

Certification procedures of such batteries will need to account for the continuous progress in battery electrochemistry to prevent costly recertification of upgraded battery systems.

4.1.2. TURBOGENERATORS

The current technological landscape, associated with bold commitments and goals is going to require a different approach from both propulsion system and aircraft manufacturers. Together with advancements in generators design, HEP is driving developments in gas turbine design as well.

Electrical generators are the heart of the hybrid propulsion aircraft since they constitute the sole link between the mechanical power input (turbine) and the electric propulsion system (electric motors). The viability of the HEP requires then very high-power density generators (> 15 kW/kg) with high efficiency (> 0.98). Hence, high speed operation is necessary which necessitates efficient cooling management together with the use of materials having high electromagnetic, thermal and mechanical performances.

An important work regarding multiphysics design (electromagnetic, thermal and mechanical) has been accomplished in the frame of WP4 of the IMOTHEP project. On the other hand, gas turbines are still the core of the power generation in aviation, and they have also to accommodate advances in electrical motors, generators, batteries while - at the same time - being lightweight, efficient and sustainable. The process of designing a Hybrid Electric Propulsion system for future aircrafts will pose additional challenges and will bring further complexities compared to a more traditional "Jet-A Gas Turbine only" propulsion system. Design of such a propulsion system and its integration with the airplane is going to require more interaction with the airplane manufacturer on several topics. To list a few, strong synergies will be required for the optimal choice of energy storage locations and chemistry, distribution, and conversion systems, and thermal management system.

Nonetheless, it is still required for partly-hybrid systems that the gas turbine delivers the required power by consuming as little as possible of fuel (lower SFC target than CEO and NEO and advancements in overall propulsive efficiency).

A good level of interaction between turbine and generator designers permitted many data exchanges as to improve the overall design of the "turbo-generator" integration.

4.2. ELECTRIC MOTORS

The electrical machines are an important and influential equipment in this new context of more electric propulsion. The development of new hybrid and electric propulsion architectures, like assisted turbomachine or distributed electric propulsion, for different aircraft configurations leads to new needs, power levels and performances for electrical machines. Electrical architectures involving power beyond 300 kW and the voltage exceeding 1 kV induce new constraints that are unusual in the aeronautical field.

Electrical machines are facing new targets in terms of specific power (> 10 kW/kg) while keeping a high efficiency (> 0.96) and high reliability level, despite the specific environment of integration into the aircraft.

To address these challenges, different axes can be investigated. The specific power can be improved by the definition of new cooling management, from the heat sources (decrease of the losses, reduction of thermal resistance), through the winding design (high temperature material) to the cooling technology (enhanced liquid cooling close to hot spot or mixed technologies). Note that this aspect has to be validated also at the system and aircraft level for the overall thermal management system.

In another way, the efficiency can be improved by the use of high performance materials (for the magnetic and conductor parts) and sometimes in conjunction with manufacturing process (for instance additive manufacturing).

A natural question is always running on what is the good compromise between high specific power and high efficiency. Again, the assessment has to be performed according to the aircraft systems view.

Finally, the reliability, or the fault tolerant capabilities, can be enhanced by the study of innovative topologies (axial, toroidal winding) while keeping performances, and the use of innovative material to support this new constraint (thermal and electrical insulation).

Among the topics covered in the IMOTHEP project, thermal aspects are evaluated with a close interaction to the TMS work package.

4.3. POWER ELECTRONICS

Power electronics converters play a crucial role in the realization of future electric aircraft architectures. Due to the envisioned DC grid backbone as means of power transfer, AC/DC rectification will take place on the interface of generation to DC grid, DC/DC conversion as interface to (battery) electric energy storage and finally DC/AC conversion at the interface towards electric (engine drives). Hence, parameters such as power weight (kW/kg) or power density (kW/l) need to be optimized as good as possible. This also implies efficiency targets as the cooling system is a major contributor to the above-mentioned variables.

The integration of new power semiconductor materials (SiC, GaN) will enable higher switching frequencies leading e.g. to smaller filter components. With respect to anticipated higher DC voltages as high as 3 kV, it seems that Silicon Carbide will play a more significant role than GaN devices for 2 and 3 level topologies based on higher breakdown voltages. For modular multilevel topologies, Gallium Nitride can also proof beneficial. In all variants, a power weight higher than 20 kW/kg with efficiency higher than 99% is foreseen as target for 2030+. The question if the cooling system will be liquid or air based can only be seen in context of the overall system design, e.g. if a cooling circuit is already available for other aircraft components.

The overall system size will be defined by the individual component parameters but also by their integration and the connection strategy. Further the cooling strategy plays a vital role in system optimization as well as assembly because heat sinks (liquid or forced air) will ultimately contribute to system size and weight. Advances in laminated bus-bars to deal with power cooling may enable planar multilayer power distribution while fulfilling low volume and weight requirements, avoiding the need for space of wires due to bending radius. Artificial intelligence methodologies are also promising for the design of the cooling of electronic components. Also, for improved integration, the form factors of the components become important for them to fit to each other in a constrained volume. Table 15 gives some targets that look feasible for 2035 according to existing roadmaps (e.g. Automotive council UK, Electric Components and Systems SRIA).

Table 15: Power density advances towards 2035

Parameter	Inverters/Active Rectifiers	DCDC converters
Volumetric Power Density (kW/l)	+80%	+100%
Gravimetric Power Density (kW/kg)	+100%	+200%
	15	20 (non iso) 15 (isolated)

Considering the huge number of power electronics devices integrated in those converters, robustness of such systems needs to be assessed and accurate measures such as redundancy need to be defined and implemented. In this context, it is also worth to highlight that SiC and GaN are considered more robust with respect to cosmic radiation failures than conventional Silicon technologies and further will lead to increased reliability. Of course, current assessments need to be repeated with future device generations as also semiconductor manufacturers might reduce margins with newly gained knowledge on device functionality and intrinsic mechanisms.

Since the power electronics converters are not available on product level, they need to be developed and made available. Besides the development process, the boundary conditions need to be addressed to provide suitable products. This involves detailed specifications with a freeze of base requirements, as well as provision of a standardization and qualification environment for MVDC and LVDC components for aerospace use.

4.4. ELECTRIC NETWORK AND DISTRIBUTION

If a shift to Higher Voltages - already initiated by the more-electric aircraft trend - appears as a solution to allow the development of future aircrafts, special design efforts are needed to make the utilization of "HV" as safe as for current electric systems on conventional aircraft. If the voltage magnitude envisioned may be considered as easy to master for industrial applications at sea level, it is no more the case for aviation applications. Hence, a major concern when increasing the voltage is the appearance and the development of physical phenomena (Partial Discharges, Space charges) leading to a gradual degradation of traditional insulation materials which ultimately may influence safety. Finally, pressure (i.e. altitude) and temperature changes are aggravating factors for these phenomena. Last but not least, electrical arcs consequences will not be the same for the power magnitude envisioned.

"High Voltage" energy transportation and distribution are therefore key issues for future aircraft developments. New cables, harnesses, connectors, switches, circuit breakers and other equipment have to be specifically developed while keeping in mind weight considerations (which is never the case for industrial applications).

Regarding cables, very first calculations confirmed by simulations tend to show that a large number of cables of gauge "0000" (to allow current transport while limiting heat generation) will have to be employed. The weight of such "0000" cable is already of the order of 1200g /m. An increase in the thickness of the insulation to avoid the development of the previous phenomena generates an increase in weight of at least of 230g / m for a cable, leading to a 1,5kg/m/cable hypothesis for the power range investigated here. It must also be noted that specific connectors will have to be developed while taking their weight into account. Finally, the necessary harness installation equipment (estimated at this stage between 30% and 50% of the total weight) will have to be added to the previous values.

Regarding distribution components, most of them have to be developed for the voltage (and power) range under study but the targeted value for the electrical centre specific power is estimated to be 20 kW/kg.

4.5. THERMAL MANAGEMENT

The introduction of a multitude of electrical components in drive trains also introduces an equal amount of heat sources. These heat sources are not clustered at a few specific locations as in legacy aircraft, but are distributed within the airframe. The thermal management of the vast number of heat sources is a challenge and requires careful consideration of all of them. One of the complicating factors is not just the rejection of heat generated by internal resistance of the electrical components, but moreover the additional constraints on the operative temperature range for the various components. This implies that, under all kinds of operational circumstances, it is of utmost importance to control the component temperatures and to assure a minimum chance of exceeding the operative range of temperatures in order to avoid damage or failure of components. For the larger heat sources, a local dedicated cooling solution is mandatory. For the smaller heat sources, either a local less impacting solution (e.g. surface heat exchangers) or a generic cooling approach such as using cold air from the ECS-system might suffice.

Research on the thermal management system (TMS) is directed towards the two points mentioned above: assessment of necessary heat rejection and how to accomplish this, and control of the component temperatures

As an example, generator cooling for the SMR-CON is a highly demanding task. In take-off conditions at full thrust, the four generators produce 5.5 MW of power each. Of this power, about 3 percent is being converted into heat, assuming an optimistic efficiency of the electrical machines, 2 percent is lost in the power electronics, and 1 percent is lost in the mechanical drive lines. Following an industrial estimate, the generator weight is 278 kg and has a diameter of 0.577 m and length of 0.301 m. The venom is in the cooling of these generators. Based on the heat losses, two heat exchangers - one of them using fuel as coolant - are needed to cool the oil that takes the heat out of the generator and associated power electronics (fuel cooling is only assumed to be active in certain high-powered stages of the flight profile). The weight of the heat exchangers is estimated at 75 kg for the fuel-oil heat exchanger and 93 kg for the air-oil heat exchanger. In addition, there is a normal fuel-oil heat exchanger of 30 kg to cool the engine oil. The associated volumes of the heat exchangers create a huge challenge for the integration in the airframe. It remains to be seen if this cooling approach is indeed sufficient, or if more advanced approaches will become necessary.

Furthermore, the integration effort on TMS in IMOTHEP is focused on achieving a principal thermal management analysis capability that can be used in the very early stages of development to get an impression of weight and volume of the required TMS. Knowledge of weight and volume of the TMS feeds directly into the design approach to achieve the required top level aircraft requirements. This implies that, based on only a limited set of approximate data, a reasonable estimate of heat rejection and component interference needs to be developed in order to support the sizing of the TMS and the ECS. The approach is based on assumed efficiencies of drive train components, and on the combination of a bay model (a coarse compartment model of the aircraft), connected with the interacting (sub-) systems of the drive train. Realistic closure of the model using limited data and a lot of assumptions is ongoing, where partners from technology work packages (WP3, WP4 and WP5) will provide a sanity check of the final data and coefficient values used.

5. CONCLUSIONS AND PROSPECTS

With a view to the elaboration of a roadmap for the maturation and development of hybrid electric propulsion for commercial aircraft, a number of outcomes of the combined studies performed in IMOTHEP on electric power trains and aircraft configurations are noteworthy.

A major element of a roadmap is the final target pursued, part of which the targeted final application is key. From the investigations performed to date within IMOTHEP, as well as from the studied literature sources, it remains difficult to define with certitude the application cases of hybrid electric propulsion.

For the SMR aircraft, some consolidation is still needed by the end of the IMOTHEP project (in particular regarding the performances of the gas turbine to ensure that the comparison with the baseline aircraft is fair). Nevertheless, current results do not allow to conclude on an actual potential benefit of hybridization for this category of aircraft, which at the same time would represent a huge technological step for the development of electric systems. This is all the more true that, at an early stage of investigation, the potential benefit needs to be significant enough to justify the investment in technology and ensure that, at the end of a development phase, an actual fuel burn reduction is obtained compared to a conventional incremental approach. This naturally shifts the SMR target to longer term horizons in the roadmap, as the potential result of gradual technology improvements achieved on lower power demanding machines.

For regional aircraft, the fully electric aircraft with a thermal range extender seems to offer promising perspectives. The concept will be further refined by the end of IMOTHEP to confirm its viability and potential. Beside this specific architecture, turboelectric power train is not seen as a solution, while the conclusions for parallel hybrid are lukewarm. From our analyses, at least, significant battery performances seem required for a benefit mainly achievable on short range missions, which would not exceed 10%. It is noticeable however that an industrial interest is still manifest for this kind of solution (cf. Clean Aviation). In any case, both solutions, parallel hybrid and electric with range extender, strongly rely on battery performances that constitute a critical brick of the technology roadmap. In that field, aviation will not be leading for the development of high energetic chemistries but will need to develop the required research streams to ensure that the developed products satisfy its particular requirements in terms of operating conditions, safety and certification.

For the parallel hybrid architecture, the performances of electric systems have a lower influence on the feasibility of the regional hybrid aircraft. The electric aircraft with thermal range extender is directly sensitive to the efficiency of the electric power train, but much less to the specific power of electric machines and power electronics. The performances achieved by the electric motors designed within IMOTHEP with rather conservative assumptions provide a satisfying initial basis. These performances are already beyond current state of the art and close to the technology projections to 2035. They need to be confirmed through a maturation plan, including the development of a demonstrator. For this configuration, the generator is a more challenging component. Its efficiency has a direct impact on the range extender mode of the aircraft (close to 1 to 1 in variation percentage) but the preliminary design performed within IMOTHEP already reach 0.975 (specific power has a lower influence). In fact, the major challenge is the required level of power, 3 MW, which is much beyond the current state of the art, represented by the generators implemented on the Boeing B787 (250 kW each). Successive incremental power increases in generator prototypes might be required for its maturation.

A later SMR development will require further increase of power for almost all components, with associated thermal issue, although, depending on the selected configuration, distributed propulsion is an efficient way to limit power at the EPU level. This could be seen as an incremental development beyond the regional aircraft. Nevertheless, a major additional challenge will be to deal with the involved voltage for power distribution, for which no synergy can be found with the regional aircraft. In addition, flight altitude is also higher, inducing even higher difficulties. However, as underlined earlier, going to hybrid SMR also require further configuration studies to first identify a promising architecture.

These conclusions are grounded on the results of IMOTHEP so-called “Loop 1” design process. A last design iteration is starting and will enable, on the one hand, to refine the key issues and critical enablers for the REG-RAD configuration, and on the other hand to consolidate the confidence in the conclusions regarding SMR by refining the aggressive SMR-RAD design (and potentially identify disruptive levels of performance to achieve the emission reduction target). While this next iteration is not expected to revert the preliminary conclusions exposed in this report, it might bring some further insight especially in the gap analysis used as entry for the roadmap.

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