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IMOTHEP European project

An investigation of the potential of hybrid electric propulsion for reducing emissions of commercial aircraft

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ABSTRACT

The primary goal of the IMOTHEP European project was to achieve a key step in assessing the potential of hybrid thermal-electric propulsion for reducing commercial aircraft fuel consumption beyond the performance of conventional propulsion technologies projected to 2035. For that, technical objectives included identifying the propulsion architectures and associated aircraft configurations for which HEP brings a benefit, but also investigating the most promising technologies for the components of a hybrid propulsion chain. Beyond, the final objective was to propose a research and technology roadmap for the maturation of hybridization for commercial aircraft.

IMOTHEP investigated four aircraft configurations, their power train architecture and the associated components for the regional and SMR missions. Results did not confirm hybridization as a solution for reducing CO₂ emissions of SMR aircraft in the short to medium term. An aircraft concept and hybrid architecture that benefits from hybridization is still to be identified for this class of aircraft, while the technical challenges, especially associated to the required high voltage for power distribution, push the emergence of an operational aircraft to a longer term horizon, beyond 2035-2040. For regional aircraft, IMOTHEP identified a promising configuration exceeding initial project's targets. The fully electric aircraft with a thermal range extender ("plug-in" hybrid) offers an unrivalled energy efficiency over the 200 nm typical mission of regional aircraft and still achieves a fuel burn reduction with the extender mode over the 600 nm design mission. Beside this original architecture, for regional aircraft, turboelectric power train does not look interesting, while the conclusions for parallel hybrid are lukewarm: at least, significant battery performances are required and the maximum foreseen benefit, a fuel burn reduction about 10%, is mainly achievable on short-range missions.

The paper exposes the main results of the studies performed on electric power trains and aircraft configurations. It concludes on the main orientations for further maturing hybrid electric propulsion.

Keywords: hybrid electric propulsion

NOMENCLATURE

BLI	Boundary Layer Ingestion
BWB	Blended Wing Body
DEP	Distributed Electric Propulsion
EPU	Electric Propulsion Unit (electric motor + its power electronic)
EWIS	Electrical Wiring and Interconnection system
HEP	Hybrid Electric Propulsion
LH ₂	Liquid hydrogen
MTOW	Maximum Take-off Weight
REG-C	Conservative concept of hybrid regional aircraft
REG-R	Radical concept of hybrid regional aircraft
SMR	Short-Medium Range
SMR-C	Conservative concept of hybrid SMR
SMR-R	Radical concept of hybrid SMR
TLAR	Top Level Aircraft Requirements
TRL	Technology Readiness Level

1.0 INTRODUCTION

Hybrid electric propulsion (HEP) has emerged during the 2010's as a disruptive way to reduce aircraft fuel burn and CO₂ emissions, including for commercial aviation. If full electrification of commercial aircraft appeared hardly possible beyond short-range regional aircraft, the combination of electric and thermal energy sources and motors in the propulsion chain was opening an enlarged design space for the aircraft, creating opportunities for optimising propulsion integration and for synergies between propulsion and airframe. A broad scope of propulsion architectures and aircraft configurations can be envisaged and many concepts have been proposed to date, including electricity storage in batteries to provide assistance to thermal machines ("parallel hybrid" architecture), direct production of the electricity on board ("turboelectric") or the combination of both. This implies introducing in aviation brand new electric technologies compared to current aircraft, which represent a disruptive step in terms of power compared to current aviation electric systems and the development of a series of specific components such as batteries, motors, power electronics or cabling. These components' characteristics and the associated challenges depend on the targeted aircraft, of the selected architecture and of the level of hybridization¹. A key question is also to identify among the broad variety of concepts the most promising ones and their actual potential for reducing fuel burn and CO₂ emissions.

The IMOTHEP European project was initiated in 2020 to answer this question and to explore the required electric technologies. Main technical objectives included identifying the propulsion architectures and associated aircraft configurations for which HEP brings a benefit compared to the evolutionary developments of conventional technologies by 2035, and investigating the most promising technologies for the components of a hybrid propulsion chain. For that, the project deployed a holistic approach and a tightly coupled multidisciplinary investigation of hybrid propulsion architectures, their integration on the aircraft and the design of the components of the electric power train. Based on the performance assessment of candidate configurations and on sensitivity analyses, key enablers and technology gaps were identified to build a final roadmap for the maturation of electric technologies and hybrid propulsion architectures.

The project ended in June 2024 and this paper provides a general overview of the work performed and a synthesis of the main results. Finally, it presents the general conclusions that were derived regarding the potential and perspectives of HEP, as well as some orientations for future development.

¹ Ratio between supplied electric power and thermal power.

2.0 THE IMOTHEP PROJECT

The review of the existing body of literature prior to the elaboration of the IMOTHEP project [1] highlighted the diversity of possible solutions and the number of degrees of freedom that hybrid electric propulsion offers. It also evidenced a significant variability in the estimates of the potential benefit of HEP for reducing fuel burn and aircraft emissions. Results depended on assumptions that were heterogeneous between studies and often optimistic for battery capabilities. In addition, there were discrepancies in the level of modelling, a difficulty being to perform the analysis with the relevant level of fidelity as hybridization may generally bring a benefit through the search for synergies at aircraft level and through a careful optimisation of the propulsion integration. Such optimisation, together with the accurate estimation of the performances, require a tightly coupled investigation of hybrid power trains with aircraft and propulsion architectures, supported by high fidelity tools and consolidated technological assumptions.

Facing this quite heterogeneous and uncertain landscape for HEP, a primary goal of the IMOTHEP project was to perform an assessment with homogeneous and well mastered specifications, assumptions and design methodologies, based on consolidated characteristics of electric systems. The core of IMOTHEP was an integrated end-to-end investigation of the power train of hybrid-electric commercial aircraft, performed in close connection with aircraft configuration and propulsion integration.

IMOTHEP relied on the design of four aircraft configurations representative of various hybrid propulsion architectures. From the preliminary design of these configurations, target specifications (e.g., engine power or total installed power) were defined for the architecture and components of the hybrid electric propulsion chain, which were investigated in the technology work packages of the project with a twenty-year timeframe perspective. In return, these technological studies provided performances estimates, based on actual preliminary design, for the components of the power train, which fed the performance assessment of the aircraft. Two subsequent design loops were performed within the project, with an increasing level of fidelity, to assess the achievable performances and refine the components' requirements. Through vehicles' performances and sensitivity studies, the analysis allowed to identify key technological enablers, as well as technology gaps for HEP, and provided an estimate of the potential benefit for fuel burn reduction compared to reference configurations based on conventional technologies extrapolated to 2035. This gap analysis, together with an investigation of the tools and facilities required for the maturation of HEP, supported the elaboration of a development roadmap that constituted the ultimate outcome of IMOTHEP (Figure 1).

While some developments of HEP could lead to demonstration for small aircraft in a relatively short term, addressing the challenge of climate change requires exploring technologies for commercial aircraft. Therefore, the focus of IMOTHEP was on SMR and regional missions, which represent the bulk of current flights and a significant share of aviation's emissions². Table 1 lists the corresponding specifications that were established with Airbus and Leonardo at the beginning of the project. They represented a compromise between market's needs and orientations, and initial guess regarding hybrid aircraft feasibility.

The project explored two configurations for each mission, a "conservative" one, with "moderate" evolutions of aircraft architecture compared to nowadays aircraft, and a radical one, with more disruptive evolutions (Table 2). In particular, this allowed identifying the synergies between HEP power train definition and aero-propulsive integration, as well as the level of disruption in overall aircraft design from which introducing HEP may bring a significant benefit.

² From Schäfer [2], 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.

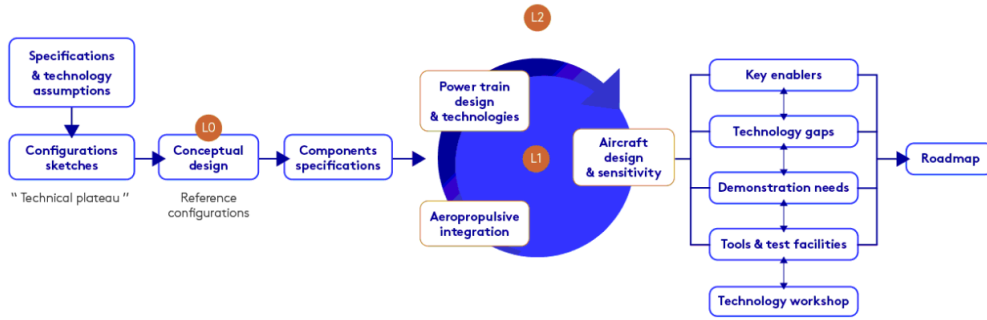


Figure 1: IMOTHEP's methodological approach

Table 1: specifications for the targeted regional and SMR missions

Mission	PAX	Speed	Range
Regional	40	Mach 0,4	600 nm (typ. 200 nm)
SMR	150	Mach 0,78	\geq 1200 nm (typ. 800 nm)

Table 2: Initial aircraft configurations for IMOTHEP concepts studies

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

For regional, the conservative configuration (REG-C) explored the lowest level of hybridization: a conventional twin-turboshaft aircraft (ATR42 like) using electric assistance from batteries to thermal engines (combining cycle-integrated assistance to the compressor and mechanically integrated assistance to the shaft). The choice built on earlier studies concluding that such parallel hybrid architecture was best suited for short range. The radical regional (REG-R) investigated distributed electric propulsion with propellers distributed at the leading edge of a high-aspect ratio wing, and the possible use of wingtip propellers to reduce induced drag. The initial propulsion system was a series hybrid system (turboelectric). It was later abandoned due to insufficient perspective of fuel burn reduction, and replaced by a fully electric propulsion system for short range mission (up to 200 nm) and the use of a turbogenerator as a range extender for the design range of 600 nm. This later configuration is referred to as "plug-in hybrid".

For SMR, within the timeframe to 2035, most of the previous studies preserved the conventional “tube & wing” approach, but proved difficulties in demonstrating strong benefit of hybridization (the maximum fuel saving from the existing body of literature was generally below 15%, often with optimistic assumptions). Therefore, IMOTHEP decided to investigate the potential benefit of a more disruptive approach, trying to make use of all potential aerodynamic benefits and synergies of an advanced revolutionary design, in order somehow to evaluate the far end benefit of hybridization. The envisaged radical configuration (SMR-R) was a blended winged-body (BWB) with massively distributed turboelectric propulsion, designed to make a maximum use of airframe boundary layer ingestion. The conservative configuration (SMR-C) was an evolution of the DRAGON configuration proposed by ONERA within CleanSky2 [3]. It exhibited 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 also used a turboelectric power train.

For electric systems, the primary focus of IMOTHEP was on conventional conductivity. Superconductivity was also investigated at both system level and component level, as it could be a game changer, especially for applications with the highest power. Except for superconductive power train, aircraft were designed for drop-in fuels³. Technology investigations covered the whole power train from energy generation to thrust generation, including the general electric architecture of the system. They proposed preliminary designs for electrical components based on the specifications stemming from the aircraft design and on primary technology assumptions for 2035⁴. The project also dedicated efforts to the aerodynamic integration of the propulsion system. This was instrumental for a careful optimization of the propulsion integration to the airframe but also for a correct evaluation of the performances. This was particularly true for strongly integrated configuration using DEP and BLI, for which a simple assessment of the propulsive balance from the sum of separated estimates of drag and thrust is no longer possible.

Figure 2 provides a global view of the technical scope covered in IMOTHEP.

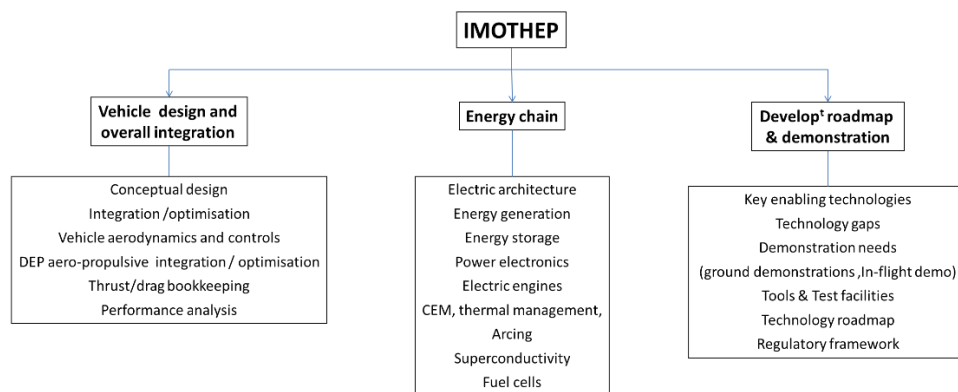


Figure 2: Technical scope of IMOTHEP

3.0 MAIN ACHIEVEMENT AND RESULTS

3.1 Electric power train for hybrid electric propulsion

The specifications of the electrical systems studied in IMOTHEP directly come from the configuration studies. They are summarised in Table 3. It 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

³ Drop-in fuels have properties similar to current jet fuels and can be mixed with them without any adaptation of aircraft or infrastructure. These can be fossil Jet-A1, or synthetic fuels fuel made from renewable or non-renewable carbon sources.

⁴ Technology at TRL 6 in 2030 to 2035 for an entry into service EIS by 2035 to 2040.

V, while all SMR use a ~ 3000 V distribution network. Generators' required power is more dependent on the architecture (in particular the plug-in hybrid REG-R requires a high power generator), full turboelectric system for SMR introducing the highest generator power (11 MW, possibly obtained with two 5.5 MW generators). Similarly, the range of power for SMR e-motors is large, from less than 1 MW to about 3 MW. Compared to generators, the use of distributed electric propulsion allows machines with lower power.

All the components of the propulsive chain were designed and sized for these specifications in accordance with the electric architectures defined for each power train. In a first step, design of electrical systems used conservative technology assumptions for 2035 (meaning state of the art technology upgraded with improvements expected to reach TRL 6 by 2030).

Table 3: Specifications for electrical systems from IMOTHEP configuration studies

Configuration	Architecture	Total elec. power (kW)	Motor unit power (kW)	Generator unit power (MW)	DC Voltage
REG-C	parallel	2000	1000	n.a.	540
REG-R turboelectric	turboelectric	1800	300	0.9	800
REG-R plug-in	Plug-in (elec / turboelec)	2245	300	2.245	800
SMR-C	turboelectric	22000	820	5.5 / 11	3000
SMR-R	turboelectric	22000	2400	5.5 / 11	3000

Both parallel hybrid and plug-in hybrid configurations use batteries as a primary source of electric power. Research works on all-solid-state batteries (ASS-B), as well as batteries with highly concentrated liquid electrolyte (HCE) were performed within IMOTHEP, with experimental and numerical studies [4]. For configuration studies however, the project performed a large screening of up-to-date batteries, as well as most recent announcements, in order to determine a range of plausible values for the 2035 horizon (Figure 3). The rapid evolution of the technologies makes uncertain these projections for 2035. In particular, manufacturers may announce high performances for advanced prototypes tested at laboratory scale, but those may not be representative of the conditions of use and of the requirements for an aircraft. The selected values, leading to a specific energy at pack level between 360 and 408 Wh/kg, are within these projections, yet in the upper end of the projected range.

SMR configurations, as well the regional plug-in makes use of a turbogenerator for energy generation. For each configuration, the project studied a complete gas turbine architecture, including flow path performances, integration aspects with the electrical machines, cooling aspects and preliminary estimation of geometries and weights. Similarly, preliminary sizing of the electrical generator was carried out, including trade-offs on geometries, materials, electro-magnetic technologies, weight, loading, integration/coupling etc. Surface mounted permanent magnet machines were selected with oil cooling.

Similarly, the project investigated electric motors designs. Proposed configurations were permanent magnet synchronous machine with inner rotor. Liquid cooled and air-cooled were both investigated for a range of temperature in the engine, from the usual one (180°C) to a challenging one (300°C). The analysis also considered direct drive and integrated drive option with a gearbox.

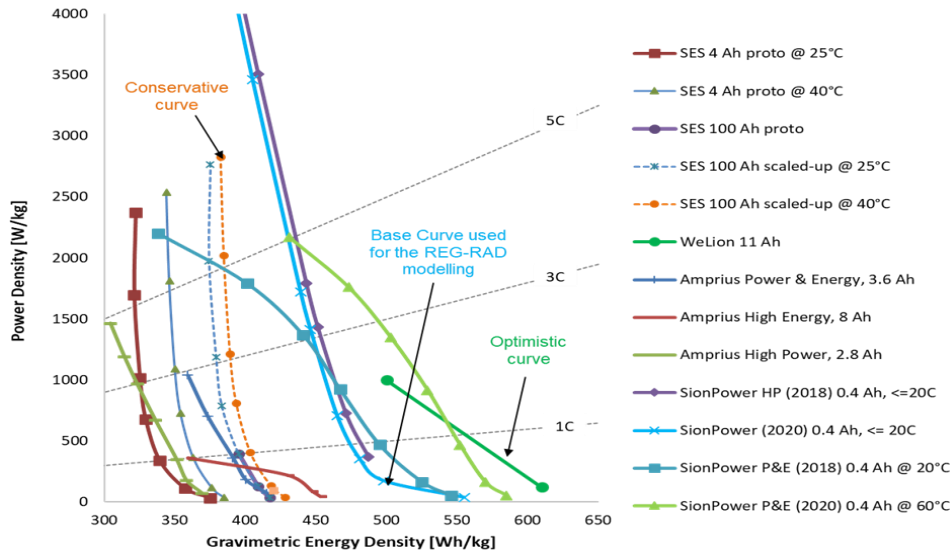


Figure 3: synthesis of recent developments in batteries performances (source AIT)

A general observation is that IMOTHEP studies could identify design for electrical machines that over-perform current state of the art, using technology assumptions qualified as conservative or medium aggressive, meaning corresponding to the state of the art improved with the first technologies mature by 2030. For electric motors, performances close to the projections from the existing body of literature or experts' judgement could even be reached (Table 4). The highest performances can only be reached with liquid cooling. Rotational speed is an important parameter, higher speed helping reaching high specific energy. The results also show the benefit that could be obtained from electrical machines able to work at higher temperature than current ones. For electric generators (Table 8), efficiencies close to the projection could be reached. However, if specific power is close to state of the art values but for more powerful machines than existing ones, projection for 2035 were not reached. For such machines, there is a trade-off between efficiency and specific power. Considering thermal issues, efficiency is a key target for the design. In effect, cooling of electrical machines and of their power electronics appeared to be a significant challenge, calling for the best possible efficiency, or alternatively for machine able to operate at higher temperature, for example 300°C. Disruptive technologies were also explored, including advanced topology, new magnet technologies or high temperature insulation. Performance assessment showed that they could increase specific power by 95% at EPU level.

Similarly, designs were proposed for the power electronics of all the configurations. Wide-band-gap power semiconductors beyond 3 kV are not available on the market but will be in the near future to enable three level topologies or submodules (2x 1.5 kV) even for SMR configurations, though the overall power can only be achieved with a combination of submodules. Specific power in the range of 15 to 25 kW/kg (+/- 30%) could be reached with liquid cooling, without accounting for the required additional systems (pipe, pump, heat exchanger) nor the EMI protection. Efficiency reached 98.8%. These values exceed state of the art figures collected at the beginning of IMOTHEP (8 kW/kg and 96% efficiency) and are close to initial projections to 2035 (20 kW/kg, 99%).

Table 4: KPI of IMOTHEP design for electric motors and generators

Aircraft	Motor specification	T _{max}	Specific power kW/kg	Efficiency %	SoA	Projection 2035 (littérature)
REG-CON	600 kW 20-35 kRPM		19.1	97.8	6 kW/kg 95% ≤ 500 kW	[11 – 17] kW/kg 98 % MW class
REG-RAD (integral drive)	300 kW 1500 RPM		13.1	95.5		
SMR-CON	0.82 MW 5700 rpm	180°C 300°C	12.9 16.6	98.00 97.74		
SMR-RAD	2300 kW 3100 rpm		6.5	98.12		

Generator specification	Cooling	Spec. power kW/kg	Efficiency %	SoA	Projection 2035
2 – 6 MW 8000-15000 rpm	Liquid cooled	9 / 11	98.5	8 kW/kg 96 % ≤ 1 MW	[12 – 16] kW/kg >98,5 % MW class

To assemble the hybrid power train, safe an operable electrical architectures could be designed for all the studied configurations. Solutions for power management scheme were also identified, covering the various flight situations. A fault tree analysis (FTA) was performed on the architectures to capture the reliability of the power supply path for propulsion functionality, based on combination of individual failure rate of electrical components. A noticeable results from the studies of distributed propulsion is that the multiplication of EPU's may lead to a relatively high probability of having one EPU failed if state of the art failure rate of electric components are considered⁵. Thanks to the high level of redundancy, this does not affect safety but may induce operational issues with frequent inoperative aircraft if all EPU's are required to be in working conditions for allowing the flight. A conclusion is that an improved reliability should be pursued for the components of the power train.

Finally, electric wiring and interconnection system (EWIS) appeared as a major technical challenge for most of the configurations. Preliminary sizing of cables was achieved using the usual rules and constraints prioritization (temperature, volume, weight and losses) and the impact of the distribution voltage was analysed for the considered electric architectures. For the regional aircraft, a maximum distribution voltage of 800 V was used but uncertainties remains on the feasibility of the cabling from an integration point of view due to the size of the harness, which induces rigidity and bending constraints for installation. In addition, the preliminary analysis of EMI for a reference installation of the cables within the wing, taking into account thermal and spacing constraints, concluded that conducted emissions exceeded the susceptibility level of DO160, calling for additional shielding or filtering. For the SMR, the analysis showed that cabling was hardly feasible for a distribution voltage bellow 2 kV. Such distribution voltage is far beyond current state of the art and raises multiple critical issues: partial discharges, insulation and insulation lifetime, arcing phenomena, installation rules and protection devices.

Last, thermal management also emerged as a key consideration for the design of hybrid aircraft. Until a very late stage in the project, the feasibility of the thermal management for the SMR configurations remained questionable. The two main critical points were the cooling of the electric generator near the gas turbine and the cooling of the electric motors in the electric propulsion units (EPU's). The issue could only be solved during the last iterations of the project thanks to the increased efficiency of electric machines, which reduced the rejected heat loads. Given the penalty of the cooling concepts regarding additional weight and drag, it is clear that efficiency takes priority over power density

⁵ Data from NASA were used.

when designing electric components. Generally speaking, it proves to be difficult to assess the correct cost that is induced by the need for cooling air in terms of additional drag and weight. Detailed evaluations are required.

To conclude this overview of IMOTHEP studies on electric systems and components for HEP, two classes of electric systems emerge at first order, based on IMOTHEP experts' point of view and additional exchanges with other European stakeholders. They are synthesized in Table 5. Scope 1 is characterised by a distribution voltage below 1 kV and electric machines with power below 1 MW. It is believed that corresponding technologies could reach TRL6 by 2030. Scope 2 represents a much higher step for electric technologies requiring multi-kV distribution voltage and multi-MW electric machines. It is not expected that TRL6 could be reached for these technologies before 2035/2040, especially regarding high voltage distribution and related issues.

Table 5: Preliminary classes of systems for HEP development⁶

	Scope 1	Scope 2
Distribution	< 1 kV	~3 kV
Electric motor	0.3 to 1 MW	1 to 10 MW
Generator	~1 MW	5 to 10 MW

Technologies required for the regional concepts studied in IMOTHEP generally belongs to scope 1, with the noticeable exception of the electric generator of the hybrid plug-in REG-R, which is closer to scope 2 with a 3 MW power. Therefore, they could be available for a parallel hybrid configuration such as the REG-C for an EIS in 2035, and probably a bit later for the hybrid plug-in. On the contrary, the maturation of the technologies required for a SMR aircraft naturally pushes the time horizon for such aircraft beyond 2040.

3.2 Performances of investigated hybrid aircraft

As described on Figure 1, after the preliminary design of aircraft configuration from which components' specification were derived, two successive design loops were performed to refine the configuration and integrate the results from the components and aeropropulsive integration studies. The last design loops was only performed for the two radical configurations.

In assessing the benefit of hybridization for reducing fuel burn, IMOTHEP devoted a particular attention to setting references allowing to clearly identify the contribution of hybridization from the contribution of other design feature such as, for example, the adoption of a blended wing body configuration [5]. A reference aircraft ("REF") was defined by adapting an existing aircraft (the ATR 42-600 for the regional and the A320neo for the SMR) to the TLARs of IMOTHEP and a 2014 technology level, representing a state-of-the art aircraft. The baseline aircraft ("BAS") is then the extrapolation of reference aircraft's conventional architectures to technology available in 2035/2040. This baseline is the reference for assessing the benefit of introducing HEP compared to conventional architecture. The comparison is primarily based on the fuel burn that directly relates to CO₂ emissions at tail pipe for hydrocarbon fuels. For architectures using batteries charged at ground, emissions also depend on how the electricity is produced, and therefore on the future evolution of the energy mix worldwide. This, as well as life cycle analysis aspects, were beyond the scope of IMOTHEP. The tentative targets for IMOTHEP was to achieve at least 10% more fuel burn reduction than conventional technologies projected to 2035. Last, for the blended wing body, a "OHEP" reference configuration was also defined, which does not use hybrid propulsion but

⁶ This table also takes into account values from the hybrid tail configuration studied in the Centreline European project

conventional turbofans, in order to isolate the specific contribution of the unconventional aerodynamic shape.

3.2.1 Regional aircraft

The Regional-Conservative (REG-C) explored the parallel hybrid architecture. 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. An extensive presentation of the configuration is available in [6].

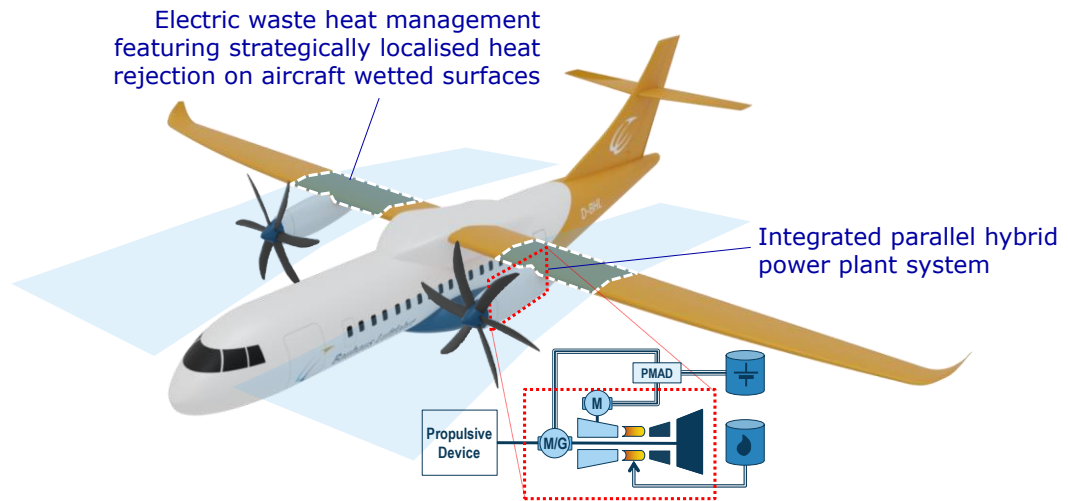


Figure 4: regional conservative (REG-C) configuration (credit Bauhaus Luftfahrt)

Batteries are positioned in the extended belly fairing of the aircraft. A specific energy of 408 Wh/kg was assumed at pack level (1C). 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). Various hybridization strategies were investigated by varying the hybridization degree along the different flight segments⁷. Adding all electric assistance to the power shaft proved to be the most efficient strategy. The best configuration was obtained with an hybridization degree (H_p) of 15%⁸ during take-off, climb and cruise⁹. A 9.6% block fuel reduction was obtained for the typical mission compared to the baseline non-hybrid aircraft. 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. Batteries' specific energy was the main design parameter. Efficiency and specific power of electric systems proved to have limited influence. Supplying energy to the non-propulsive systems with an all-electric aircraft represented a significant part, about 40%, of the battery use and mass. This suggests exploring other options for non-propulsive systems.

⁷ 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.

⁸ Fuel burn reduction increases with hybridization degrees, but for $H_p > 15\%$, no configuration could be defined within all imposed constraints

⁹ This corresponds to a ratio of electrical power assistance to engine shaft power of 30%.

Initially, the Regional-Radical (REG-R) configuration was using a purely turboelectric architecture with distributed electric propulsion. This configuration was abandoned at the end of the initial conceptual design loop due to its poor performances. It was replaced for next design loops by a fully electric configuration with a thermal range extender, also referred to as "plug-in" hybrid.

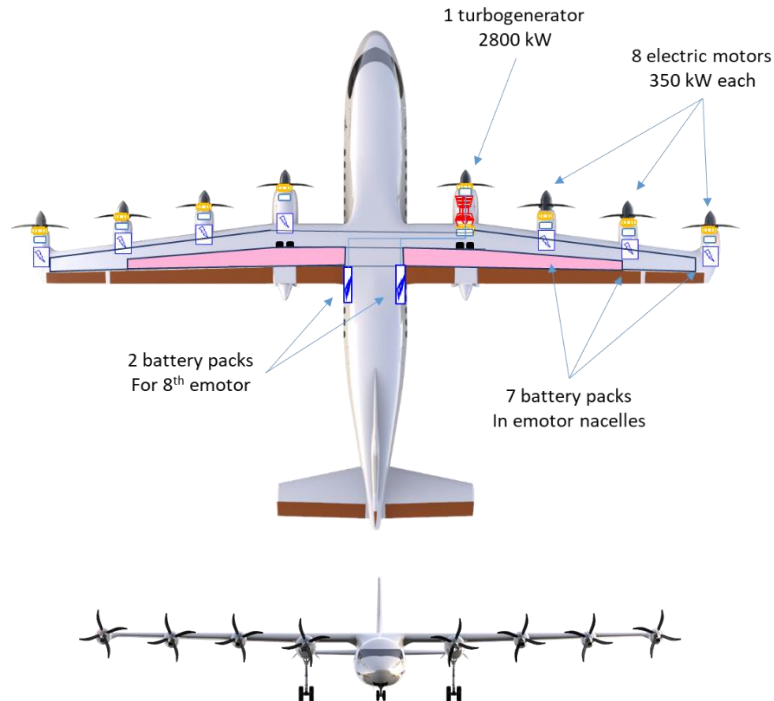


Figure 5: regional radical (REG-R) configuration (credit DLR)

The configuration (Figure 5) still uses distributed electric propulsion and wing-tip propeller. All propellers are driven by electric motors (~ 350 kW each). A battery pack is installed in each nacelle, except in the eighth one that hosts a 2.8 MW turbogenerator, which serves as range extender. Batteries were 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 5370 kg of batteries (with an energy density of 405 Wh/kg at pack level). In the extended range mode, the mass of batteries is decreased by 650 kg and the aircraft achieve only a part of the mission in electric mode. A noticeable feature of the configuration is that it uses a unique turbogenerator, which allows to improve the turbine efficiency compared to two smaller machines. The drawback is the lack of redundancy in case of engine failure, which induces some constraints for the performance of the design range: the initial part of the flight must be performed in extender mode in order to preserve the batteries for diversion in case of engine failure. This also implies that diversion landing fields are available within the electric range of the aircraft. Regarding safety, each propeller is powered by a dedicated battery to avoid cross-feeding and common failure mode (the motor located in the turbogenerator's nacelle is fed by the two batteries located in the fuselage). In a similar manner, the turbogenerator drives eight rectifiers with eight separated pole pairs.

Due to the batteries, the REG-R configuration is 47% heavier than the conventional baseline aircraft, with a MTOM of 22700 kg. On the typical mission performed in full electric mode and therefore with a 100% fuel burn reduction, the aircraft is 55% more energy efficient than the baseline. The significant decrease of the block energy results from the high efficiency of the electric chain ($>95\%$ propulsion chain efficiency & 90% charge-discharge efficiency of the battery), whereas the gas turbine efficiency, about 40%, is significantly lower. In terms of distance achieved per unit of energy used, the REG-R in electric mode is 82% more efficient than the baseline. In the range extender mode, the REG-R is 21% less efficient than the baseline but still achieve a 4% reduction

in block energy over the 600 nm mission. This translates in a 20% fuel burn reduction over the 600 nm mission thanks to the substitution of kerosene by energy stored in the batteries. Sensitivity analyses demonstrated that battery specific energy impacted the MTOM of the aircraft but had limited influence on the block energy in full electric mode: a variation of $\pm 15\%$ resulted in a variation of block energy between -2.1% and $+3.1\%$. This 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 were also sensitive to the propulsive efficiency of the electric power train but not to the specific power of the EPU.

3.2.2 Short-medium range aircraft

The SMR-Conservative (SMR-C) configuration builds on the previous DRAGON configuration designed by ONERA within Clean Sky 2 [7] 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 6). Two turbogenerators located at the rear of the fuselage produce a maximum electric power of 21 MW, delivered to the EPU's 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). A detailed description of the configuration is provided in [8].

The initial conceptual design, based on technology assumptions from literature and experts' judgement, exhibited a fuel burn reduction of 6.5 % compared to the conventional configuration projected to 2035 (baseline aircraft). Distributed propulsion was bringing an increase of propulsion efficiency that over-compensated the mass penalty (5 %) of hybridisation and the energy transmission losses. This gain was not confirmed in the next design loop, when refining the design and introducing the outcomes of the components' studies performed within IMOTHEP, using at this stage conservative technology assumptions for the design of the electrical systems. For the final configuration, the fuel burn was increased compared to the baseline configuration (+1.3% for the typical mission, +7.9% for the design mission).

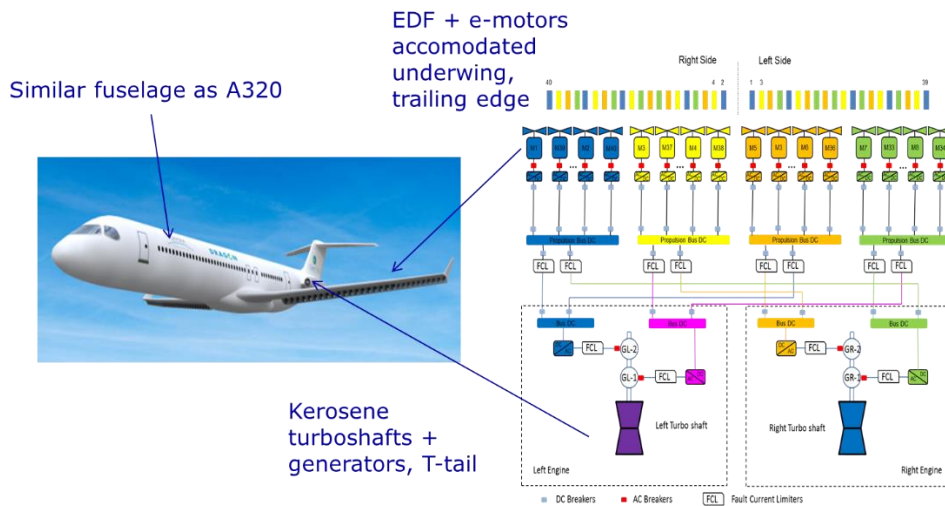


Figure 6: SMR-C turboelectric DRAGON configuration (credit ONERA)

Sensitivity studies were 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. It was shown that no combination of improvements of the various electrical subsystems could lead to a 10% fuel burn reduction compared to the baseline aircraft, if the improvement of the PSFC was not at least 7% compared to the design

performed within IMOTHEP with 2035 technology assumptions. Sensitivity studies did not reveal strong expectations from improving electric systems' performances. The EPU's power density (kW/l) was the highest source of variability, second came the voltage and third the power generation efficiency. Outcomes were that it was critical to maximise the EPU's power density, and increase voltage to values higher than 2kV. The strong influence of power density of the EPU is 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.

As the SMR-CON, the SMR-Radical (SMR-RAD) uses a turboelectric architecture with electrically-driven fans, in this case distributed on the upper side of a BWB fuselage. This distributed propulsion is ingesting the boundary layer developing on the fuselage to improve the aeropropulsive efficiency. The initial version (preliminary design) featured 18 electrical fans, with a unit electrical power per fan of 1100 kW and a total electric power delivered by the turbogenerators of 22.5 MW. A DC voltage of 3000 V was also used. To separate the respective benefits from hybridisation and from the BWB shape, the performances were compared between the BWB configurations using conventional turbofan (so-called OHEP concept) and DEP. As for the SMR-C, 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.

In the next design loop, the more refined "SMILE" airframe shape, stemming from an ONERA study [9], was introduced (Figure 7). 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 (based on conservative technology assumptions for 2035). 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 no longer demonstrate any fuel burn reduction compared to the BWB using turbofan (the 2035 EIS SMR-OHEP), which achieved a 26% fuel reduction compared the reference aircraft (2014 technologies) and 6% compared to the baseline aircraft (conventional aircraft with 2035 technologies) . A complete description of the work is available in [10].

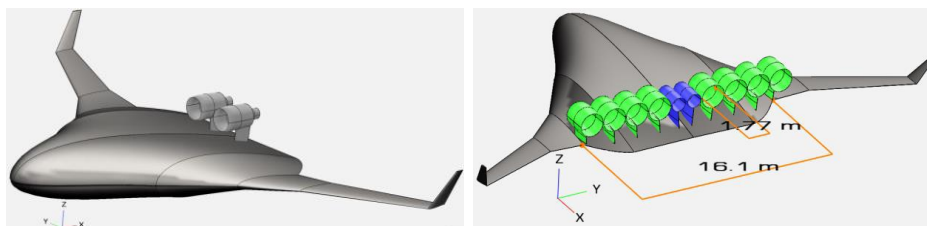


Figure 7: BWB SMILE shape from ONERA (Left: "no HEP" aircraft -Right HEP configuration turbogenerators- in blue and electric fan in green, Design loop L1)

The configuration was further refined in the final design loop. This included a number of model improvements (turboshaft model, ducted fan and BLI model¹⁰, thermal management, aerodynamics) as well as improved performances of electric machines obtained from designs based on aggressive technology assumptions (and therefore low TRL technologies). To increase fan diameter, the turbogenerators were moved below the

¹⁰ From low fidelity analysis, a 2% drag reduction in cruise was estimated

wing (Figure 8). These refinements led to a slight decrease of the performances of the configuration and a higher fuel burn than the "O-HEP" configuration (+2.7%). This was due to a larger mass (~5%) and a drag increase (~5%) that were not compensated by the improved TSFC (~6%). Even with aggressive assumptions on the electric power train, the REG-R is still not more efficient than the BWB propelled by conventional turbofans. At this stage, it proved difficult to identify clear direction to improve the performances.

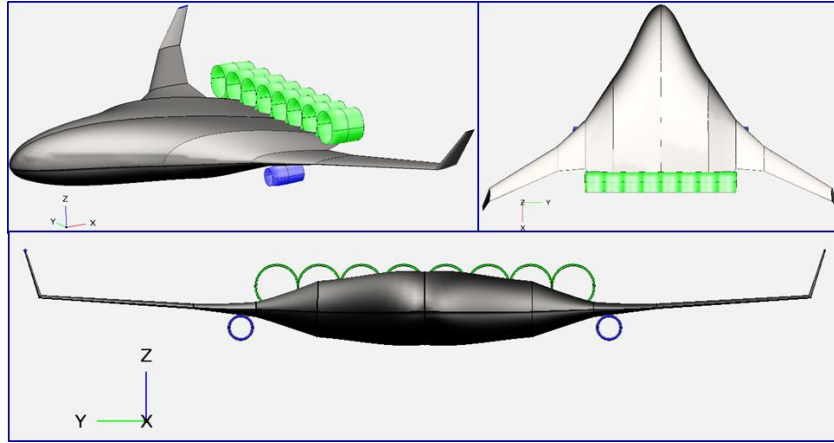


Figure 8: Final SMR radical design (design loop L2, credit NLR)

A conceptual analysis of the potential benefit of using a superconductive power train was finally done on the SMR-R. Superconductivity is a possible solution to alleviate the mass, high voltage and thermal management issues raised by the high level of power encountered on the SMR. It also promises extremely high efficiency. The choice was made of low temperature superconductivity using liquid hydrogen as a fuel for the aircraft and cooling agent for the superconductive chain. Power electronics was excluded from the superconductive chain as it was considered too low TRL and too demanding in terms of coolant mass flow. Evaluations of the hydrogen mass flow rate required for electric systems cooling also showed that it was not possible to cool cables, electric cores, generators and electric motor without exceeding the fuel burn of the gas turbines. Superconductivity was therefore limited to cables, cores and electric generators. A gravimetric index of 0.35 was used to account for the LH₂ tank. Mass estimates were introduced for the required heat exchangers, pumps and for the cables. The resulting power train, including the LH₂ tank, is about 30% heavier than the non-superconducting one (due to the strong impact of the LH₂ tank). The aircraft is nearly 10% heavier. Finally, the energy consumption was only slightly lower than the initial SMR-R and still higher than for the "O-HEP". A quick analysis showed that implementing the required LH₂ tank in the BWB shape requires more volume than available. Either the airframe should be enlarged or the design range decreased. As a conclusion, superconductivity did not appear as improving the energy performance of the SMR-R. However, it could be objected that the relevant reference for assessing the benefit of this superconductive hybrid aircraft is a hydrogen burn aircraft for which hydrogen would also come with a penalty on energy efficiency due to low density cryogenic storage. Yet, the design of such a reference aircraft was beyond the scope of IMOTHEP.

4.0 GENERAL CONCLUSIONS REGARDING HEP

IMOTHEP assessed the performance of four aircraft configurations with a close coupling with the investigation and design of their hybrid power train. Configurations involved various types of hybrid architectures that were selected based on the results of previous studies and for complementarity with other European projects (e.g. the Centreline project that investigated a hybrid BLI tail fan configuration [11]). Additional insight was also given during the project to recently published studies in order to complement and evaluate the consistency of the project's finding with other sources [1].

The results obtained at both configuration and electrical components levels lead to a number of conclusions regarding the potential and perspectives of HEP.

4.1 Application to short-medium range aircraft

The applicability of hybridisation to short-medium range aircraft is of particular relevance with a view to climate change and the reduction of CO₂ emissions of commercial aviation, as this segment represents a significant part of air traffic emissions. However, from IMOTHEP studies, hybridisation cannot yet be envisaged for SMR.

First, implementation of a hybrid power train would represent a huge technological step, far beyond the current state of the art. This is true for electrical machines, and more particularly electric generators with a range of power between 5 and 10 MW, which call for incremental developments benefiting from prior lower power applications. But, the major hurdle is certainly the multi-kV distribution power that is required for such aircraft and comes with multiple challenges for EWIS including partial discharges, arcing, protection and breaking capacity for DC currents or cable insulation. No design or installations rules can be extrapolated from current practices for such voltage. The maturation of the required technologies pushes the development of a hybrid SMR to longer term horizon, beyond 2040.

Next, no promising HEP architecture could be identified for the SMR with the TLARs investigated within IMOTHEP. Parallel hybrid is not likely to work for such configuration¹¹ while turboelectric does not seem to bring sufficient improvement of propulsive efficiency to compensate the mass penalty. Additional insight in studies published during the course of IMOTHEP [1] did not reveal configurations for which the benefit of hybridization exceeds a 7% fuel burn reduction. In addition, most of the studies were at conceptual level, with a level of fidelity comparable to IMOTHEP preliminary design. The obtained fuel burn reductions are close to the value assessed for the initial SMR-C, a value that was not confirmed by a more refined analysis. Results from sensitivity analyses do not suggest that improvement of the performances of electric components beyond those reached by the design performed within IMOTHEP are likely to significantly change the conclusions, while there are significant feasibility challenges, especially from the point of view of high voltage and high power electric distribution.

Superconductivity was expected to be a potential game changer but the preliminary analysis performed within IMOTHEP could not confirm this. Additional comparison with a conventional aircraft fuelled with hydrogen would be necessary to yield a complete conclusion. Nonetheless, superconductivity would certainly ease the introduction of hybridization on large power aircraft, especially from the point of view of distribution voltage, if a promising configuration was identified.

4.2 Application to regional aircraft

A first conclusion of IMOTHEP (consolidated by additional studies, in particular from DLR) is that the turboelectric architecture does not seem promising. The improvement of propulsive efficiency brought by distributed electric propulsion is not sufficient to compensate the mass increase due to the hybrid electric power-train.

Parallel hybridisation seems best suited for short range, typically 200 nm, and is expected to bring a maximum fuel burn reduction about 10%, for assumptions on batteries' specific energy in the high end of current expectations for the next decade. Beyond this range, fuel burn reduction decreases quickly, even leading to a fuel burn increase. Therefore, interest depends on market projections in the range of 200 nm (370 km). Eurocontrol indicates that flights below 500 km represent about 29% of departure flights from EU27 plus the UK (and 6% of CO₂ emissions) [12]. According to Futprint50 EU project [13], 80% of regional flights are shorter than 400 km. The minimum fuel burn reduction expected at the level of conceptual studies might also be a decision factor for the launch of a disruptive product. It seems that 10% is a minimum for an aircraft manufacturer.

¹¹ Parallel hybrid was not investigated for SMR in IMOTHEP based on anterior results. Results obtained for regional tend to confirm that parallel hybrid can only work for aircraft with limited range.

Electric technologies for such architecture could reach TRL 6 by 2030. Major uncertainty might be the projection of specific energy at this time horizon for aviation batteries, battery specific energy being the main enabler for parallel hybrid.

The plug-in hybrid is the most promising configuration identified within IMOTHEP, exceeding the target set for the project (-10% fuel compared to CleanSky 2 targets). It achieves zero direct emissions up to 200 nm, with a block energy reduction of 55% over this range, and a 20% fuel burn reduction over 600 nm using the range extender. The concept would still deserve further investigations regarding the constraints associated with the range extender mode, the battery charging during the typical duration of a rotation (about 20 mn for a regional) as well as the EWIS integration. But the concept exhibits an unrivalled efficiency. It shares a number of technologies with the parallel hybrid, though with higher distribution power, for which TRL 6 could be reached by 2030. The 3 MW electric generator raises a higher challenge by this time horizon. Importantly, the concept is not too sensitive to batteries' specific energy. The development of certifiable batteries matching the concept requirements is a major enabler of the configuration.

Regarding CO₂ emissions, it shall be kept in mind that, with parallel hybrid, fuel burn reduction does not directly translate in emissions reduction as there is substitution of kerosene by electricity produced on ground. Therefore, benefit for CO₂ depends on the local grid energy mix or the local production of electricity (this aspect was out of the scope of IMOTHEP and highly depends on local conditions). This is even truer for the fully electric aircraft, the emissions of which are directly those for the production of the electricity. For the parallel hybrid aircraft, considering the expected fuel burn reduction in the range of 10%, the possible emissions associated with the production of electrical systems (in particular batteries) and the disparity of electricity sources amongst the addressed markets, it might also be relevant to perform a full life cycle analysis, taking into account battery life duration, in order to establish the actual benefit of deploying the solution.

5.0 CONCLUSION AND PROSPECTS

The primary goal of the IMOTHEP project was to achieve a key step in assessing the potential of hybrid thermal-electric propulsion for reducing aircraft fuel consumption beyond the performance of conventional propulsion technologies projected to 2035. For that, technical objectives included identifying the propulsion architectures and associated aircraft configurations for which HEP brings a benefit, but also investigating the most promising technologies for the components of a hybrid propulsion chain. Accordingly, in IMOTHEP, aircraft design and performance evaluations were closely linked to the study and design of the various components of the power train. This allowed mastering the technology assumptions underpinning aircraft performance evaluation and going beyond pure conceptual design only based on projections of global components' performances. This also provided a higher degree of realism in the assessment of the feasibility and time to market of the possible hybrid configurations.

At the end of the project, consolidation and further detailed studies would certainly still be necessary. There are also intrinsic uncertainties in exploring revolutionary technologies and original or disruptive solutions could have been missed. However, the work performed gives a much improved view on the potential and challenges of hybridization, as well as on the aircraft missions that could benefit from it.

In particular, IMOTHEP showed that hybridization is not a candidate for SMR aircraft in the short/medium term, at least for the TLARs defined within IMOTHEP. Further exploratory research would be required to enlarge configuration screening for different TLARs and operational scenarios in order to identify a potential relevant use case. In addition, considering the huge technology gap represented by high power aircraft, required technologies are likely to emerge through incremental progress based on lower power systems and therefore in a longer term.

For the time being, a research and technology roadmap for HEP should rather be focused on the regional aircraft for which at least one promising architecture could be identified. The so-called "hybrid plug-in", a full electric aircraft on short ranges, with a turboelectric range extender for long ranges, exhibits an unrivalled efficiency. The conclusions for parallel hybrid, a more conservative approach, are more lukewarm. Significant battery performances are required and the maximum foreseen benefit, a fuel burn reduction about 10%, is mainly achievable on short-range missions (typically 200 nm). However, from a technology development perspectives, it shares many technologies with the hybrid plug-in. Therefore, both technology can be integrated in a common roadmap.

The corresponding roadmap is primarily focused on technologies referred to as "scope 1" in Table 5: distribution voltage below 1 kV and power of electric machines below 1 MW. Yet, higher power should be targeted for electric generator for the plug-in hybrid configuration. Since the start of the IMOTHEP project, strong interest has also developed for hybrid electric propulsion using a fuel cell as the main source of electric power. Therefore, fuel cell-based systems could also be an important technology stream of the roadmap for HEP, but this pathway was marginally studied in IMOTHEP, the primary focus of which was thermal hybrid.

A corner stone of the roadmap is obviously the development and maturation of batteries that are the primary enabler of the candidate hybrid configurations. In that domain, specific energy is a major target for the development. It results from cell specific energy and pack-to-cell ratio. Regarding the first parameter, aviation will most probably not be leading, battery chemistry development happening mostly outside of aviation industry. However, IMOTHEP partners' view is that aviation should certainly establish collaboration with research organisations and battery manufacturers to progress on battery chemistries and designs that are suited for the specific aviation needs such as safety, operation conditions, fast charging capability or requirements for certification. With regard to safety, strong expectations are put on all-solid-state batteries (ASS-B) that should bring significant progress with regard to thermal runaway and to the associated constraints on packaging to ensure non-propagation to neighbouring cells and fire safety. Packaging and integration is a major axis on which aviation shall focus its efforts, targeting a high pack-to-cell ratio, high voltage, including sensing and electrical, thermal and safety management and withstanding operation conditions. This effort on packaging would benefit from a collaborative approach within the aviation sector to establish standards for aviation batteries (format & specifications) in order to reduce the dependency of battery integration to the technological evolution of cells. It goes together with important activities on certification with the need to perform demonstration to support certification development as the current lack of experience with batteries leads to strong requirements for their certification. This work should also account for the continuous progress in battery electrochemistry to prevent obsolescence or costly recertification of upgraded battery systems. From this point of view, it is also key to have a collaborative approach together with certification bodies to establish an adjustable process for the certification in the range of power and energy involved on aviation project.

Naturally, the other bricks of the propulsion also need to be developed and certified. In that domain, the technologies and designs explored within IMOTHEP provide a good starting basis already offering a sufficient performance level for the feasibility of the selected regional concepts. These technology streams need to be matured to TRL 6 through further research and development activities. In that domain, power distribution deserves a special mention as cabling remains a difficulty for a configuration such as the plug-in hybrid due to integration issue.

As a final step, IMOTHEP built a comprehensive roadmap for the maturation of the technologies required for the selected regional configurations [14]. This roadmap, established with the broad scope of European research, academic and industrial partners involved in IMOTHEP, is to serve as a guideline for the proposal and development of future projects towards the maturation of hybrid electric aircraft. It is available on the project website (<https://www.imothep-project.eu>).

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Additional documentation on IMOTHEP work and on the proposed roadmap for HEP development is available on the project website <https://www.imothepproject.eu> and on Zenodo within the IMOTHEP community.