IMOTHEP European project: an investigation of hybrid electric propulsion for commercial aircraft

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This paper presents an overview and the preliminary results of the IMOTHEP European project that explores the potential of hybrid electric propulsion for reducing CO_2 emissions of commercial aviation. IMOTHEP assesses the benefit of hybridization on four different configurations of hybrid aircraft covering regional and SMR missions and representing different levels of disruption in aircraft design. This assessment is performed in close connection with the investigation of the electric components and the architecture of the hybrid power train. Configurations studies provide the specifications for the component design and performance estimations, which in return are synthesized through the performance assessment of the aircraft. The ultimate goal is to identify technology gaps and key enablers for hybridization, in order to elaborate a development roadmap for promising applications.

I. Nomenclature

AC	*Alternative Current*
BLI	*Boundary Layer Ingestion*
DC	*Direct Current*
DEP	*Distributed Electric Propulsion*
EIS	*Entry Into Service*
EPU	*Electric Propulsion Unit (electric motor + power electronic)*
EWIS	*Electric Wiring Interconnection System*

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GHG	*Greenhouse Gas*
HEP	*Hybrid Electric Propulsion*
MTOW	*Maximum Take-off Mass*
PSFC	*Power Specific Fuel Consumption*
SMR	*Short Medium Range aircraft*
TLAR	*Top Level Aircraft Requirement*

II. Introduction

Facing the challenge to drastically reduce and even cancel its greenhouse gas emissions, aviation is exploring a large panel of technologies, amongst which introducing some electrification in the main propulsion is seen as a disruptive way to reduce fuel consumption. If full electrification of commercial aircraft appears hardly possible beyond short-range regional aircraft with limited payload, hybridization with thermal engines opens a large design space and offers a broad scope of possible configurations to look for lower emissions. Many architectures have been proposed to date. Parallel hybrid power chains, 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 better optimise the global propulsion system. On the contrary, series hybrid, or turboelectric, produces all the electricity on board from thermal machines but offers some perspective for optimising the efficiency of the whole propulsion system, in particular through distributed propulsion. Combination of parallel and series are also explored. Obviously, this implies introducing in aviation electric technologies that represent a disruptive step compared to the level of power of the current electric systems on board aircraft. These technologies raise challenges in terms of energy and power density of electric systems, power bus voltage, protection against partial discharges and electromagnetic interference or thermal management. The technology gap is strongly dependant on the category of aircraft considered, as well as on the type of implementation of hybridization that is envisaged. Beside, a question is, among the broad variety of concepts, to identify which ones are the more promising and what their actual benefit could be for reducing fuel burn and GHG emissions. A review of the existing body of literature evidences uncertainties on the answer, which for a large part arise from large discrepancies in the level of modelling of the different studies and in the assumptions made, in particular for the electrical systems or for the mission specifications. In addition, the benefit of hybridization generally results from a synergistic optimisation of the aircraft configuration. This, together with an accurate estimation of the performances, require a tightly coupled investigation of hybrid power trains with aircraft and propulsion architectures, as well as performing high fidelity analyses with consolidated technological assumptions based on detailed components study.

To go beyond these uncertainties, the IMOTHEP project was initiated in 2020 with the primary goal of achieving a key step in the assessment of the potential of hybridization for reducing commercial aviation fuel burn and associated CO_2 emissions. Main technical objectives include 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 deploys 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.

In a longer-term perspective, IMOTHEP is also considering the next steps for the development and maturation of HEP. It analyses certification issues and needs for regulatory evolutions for the emergence of hybrid propulsion, as well as the tools and facilities required for the maturation of the technology. The ultimate goal is to identify the gaps and key enablers for HEP and assemble a European sector wide roadmap for the maturation of electric technologies and hybrid power architectures.

The project is still under progress and has not reached its conclusions, but it has already produced significant achievements and could already perform a complete integrated assessment of a number of hybrid aircraft configurations. This paper first provides a general overview of the project, detailing the followed approach and the work performed. It then highlights the results obtained to date and the preliminary conclusions on HEP potential, on technology gaps and on the orientations for a development roadmap.

III. Project background: a state of the art of HEP

During the 2010s, the rapid evolution of the performances of electrical components promoted electrification as a potential promising option for aviation. However, if full electrification seemed possible for light aircraft, performances anticipated for batteries let little hope for a fully electric commercial aircraft in a predictable future. In such context, interest developed for partial electrification through hybridisation, mixing electric and thermal engines with on board electricity production or storage. The underpinning idea is to offer additional degrees of freedom for optimising the aircraft performance and reduce the fossil block fuel consumption, possibly through the substitution of stored electricity to kerosene. This resulted in a profusion of initiatives, such as Zunum or Faradair, proposing 19 PAX aircraft based on available technology and reducing environmental impacts. However, when considering commercial aviation segments, which represents the bulk of aircraft emissions, the required payload capability, cruise speed and range make the design challenge much more complex. In addition, a variety of hybridization concepts can be imagined as illustrated on Figure 1.

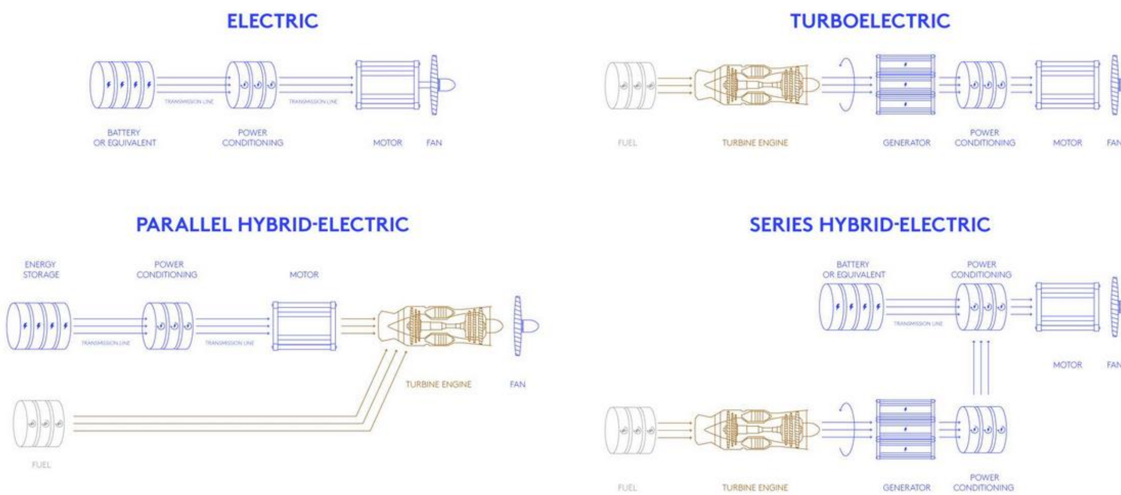

Figure 1: Different types of electrification of aircraft propulsion

A typical implementation of parallel hybrid electric is to integrate an electric motor in the turbine engine of a conventional aircraft and to provide electric boosts from batteries during parts of the flight. This allows optimizing the gas turbine performances throughout the mission profile, and in particular sizing the turbomachines for cruise conditions instead of take-off or top-of-climb. Renewable electricity produced at ground may also substitute to fossil kerosene and result in emissions reductions, even in case increased aircraft mass induces higher global energy consumption. Studies by NASA & Boeing [1], Rolls-Royce [2], TU Delft [3] or UTRC [4], on a 150 PAX aircraft sized for a 3500 nm mission, estimated a possible block fuel reduction between 5% and 13.9% (even 21.7% with part of the cruise in pure electric mode) on an operational range of 900 nm. Optimistic values were nevertheless used for battery specific energy with values beyond 600 to 750 Wh/kg. According to NASA, the same technology applied to a regional aircraft (45 PAX, 600 nm) showed energy consumption benefits only considering specific energy above 750 Wh/kg [5]. An evolution of this parallel hybrid architecture featuring electrical assistance on the low-pressure spool system was studied by BHL, resulting in a 3.5% fuel reduction for a 500 nm mission, but again with a high specific energy of 1000 Wh/kg [6]. A conclusion of the study was that benefits of parallel hybrid are larger for lower power classes of aircraft and very short range.

With turboelectric architecture, electricity is produced on board by a turbo-generator and distributed to electric engines. Here, the benefit can only come from an innovative integration of the propulsion system aiming at developing synergetic effects with the airframe. This is a key asset of HEP to provide additional freedom in terms of thrusters positioning. NASA Pegasus regional concept [7] used assisted wing-tip propellers, an electric tail propeller ingesting the boundary layer of the fuselage for cruise, plus electric inboard propellers for take-off and climb. A similar approach was applied by DLR [8] leading to a series/parallel partial hybrid power train using wing tip propellers to reduce drag and enhance yaw control to downsize the vertical tail. A 6% reduction of fuel burn was obtained.

The use of turboelectric power train to drive a tail fan for boundary layer ingestion (BLI) on the fuselage was also explored for long-range aircraft in the EU project DisPURSAL [9]. It predicted a 7.3% fuel burn reduction for a wide-body over a 4800 nm mission [10]. For the NASA STARC-ABL concept [11], preliminary studies predicted a fuel burn reduction up to 12%, but higher fidelity studies resulted in reductions of fuel burn of 2.7% and 3.4% with regard to a 2035 reference aircraft for 900 nm and 3500 nm missions.

For the turboelectric architecture, a natural extension is to distribute many propellers along the wingspan. An illustration of distributed electric propulsion (DEP) is the well-known NASA's X-57 (fully electric) demonstrator, which uses distributed propellers to increase wing lift at low speed and wing tip propellers for main propulsion. SAFRAN and ONERA obtained a 4% fuel burn reduction with a comparable layout on a turboelectric commuter [12]. For SMR type missions, with 150 PAX and a cruise speed around 0.78, both Empirical Systems Aerospace with the ECO150 aircraft and ONERA with the DRAGON concept distributed the propulsion across the wing using a large number of ducted fans. In the case of the ECO150 [13], analyses showed a decrease of 11.5% in fuel burn for a sizing mission of 3500 nm with respect to a 2035 conventional airliner. For DRAGON [14], the gain was about 5% considering a sizing mission of 1200 nm and significant progress at electrical components level for an EIS in 2035. In the frame of Clean Sky 2, TU Delft investigated two distributed propulsion options based on serial hybrid electric architectures (battery assistance except for cruise). In both cases, aerodynamic benefits did not balance the increased mass of the propulsion system. A conclusion was that hybrid aircraft should use little or no batteries [15]. The investigation of a similar architecture for a regional aircraft also demonstrated that a careful optimisation of the aerodynamic integration of DEP was required to obtain benefits.

Coupling BLI effects with distributed propulsion was investigated by NASA with the N3-X concept [16] , a hybrid wing body aircraft (7500nm, M 0.84) equipped with a turboelectric distributed propulsion system. Using superconducting components cooled by liquid hydrogen, this system brought a 20% fuel burn reduction compared with the same BWB propelled by turbofans.

This rapid and non-exhaustive overview of concepts studied during the 2010's highlights the diversity of possible solutions and the number of degrees of freedom that hybrid electric propulsion offers. It also evidences a significant variability in the estimates of the potential benefit of HEP for reducing fuel burn and aircraft emissions, which ranges from a few percent to 20% in the best case. Results also depend on assumptions that are heterogeneous between studies and often optimistic for battery capabilities. Last, there are discrepancies in the level of modelling, a difficulty being to perform the analysis with the relevant level of fidelity. The obtained improvements of fuel burn, generally below 15%, demonstrates the need to perform a careful synergetic optimisation of the configuration. This, together with an accurate estimation of the performances, requires a tightly coupled investigation of hybrid power trains with aircraft and propulsion architectures. High fidelity tools and consolidated technological assumptions, based on detailed components study, shall support the investigation.

Additional studies were published after the initiation of IMOTHEP. Recent publications related to regional aircraft illustrate different approaches from the retrofitting of existing aircraft by the introduction of a parallel hybrid power train [17][20] to resizing of the aircraft with similar parallel power train [18][23], and, for some, significant transformation of the propulsion architecture [19][21][22][21]. Most of the studies looked at parallel hybrid or serial parallel, a few to turboelectric. Still, significant divergences appear between studies on the potential benefit of HEP, with a range from almost no benefit [21] to high fuel burn reduction (over 25%) [19][22]. From these studies, it is difficult to infer a conclusion regarding an actual clear benefit from hybridization. At least, battery specific energy at the upper bound of the assumptions range, plus reduced mission range seem to be required (from this point of view, it is noticeable to see that most authors converged on battery specific energy below 500 Wh/kg at pack level). Retrofitting existing aircraft does not yield any fuel burn reduction per passenger.

In the context of the NOVAIR European project (part of Clean Sky 2), NLR and TU Delft investigated parallel hybrid propulsion for a SMR aircraft [25]. Parallel hybrid propulsion was used to downscale the main turbofan engines of an A320 class aircraft projected to 2035 technology level. Electric power was added to the turbofans only during take-off and climb. The battery specific energy was 500 Wh/kg. For this study performed at a conceptual level, the fuel burn reduction was 7% compared to the reference “A320-2035” configuration (which exhibited a quite ambitious fuel burn reduction of 30% compared to the current A320neo) with an associated 3% reduction of the energy consumption. Thanks to hybridization, the turbofans were downscaled by 13.3% with a power split (ratio of electric power to thermal power) of 17% during take-off and 15% during climb.

For a similar type of mission (although NASA qualifies the concept as a regional aircraft), 180 passengers for a typical range of 750 nm (design range 2500 nm), the SUZAN concept [26] explores turboelectric distributed propulsion with 16 distributed electric fans at the trailing edge under the wing (a configuration close to DRAGON of ONERA). A noticeable originality of the concept is the use of 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 added in combination with the turboelectric system to optimize the performance and sizing of the turbofan, while a large single use battery is used only in engine out scenarios for an emergency landing. Initial performance estimates show a block fuel reduction of about 27% over the 750 nm mission compared to a 2005 baseline aircraft, which however infers a much lower reduction compared to a 2035 conventional reference aircraft.

Lents & al. (UTRC) performed, at conceptual level, a large screening of parallel hybrid turbofan propulsion (PHTP) for single aisle aircraft [24]. 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 were explored for the hybridization strategy from 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. Finally, all configurations were close to each other, with a benefit about 5% compared to the baseline.

The CENTRELINE European project pursued the investigation of the BLI tail fan driven by an electric motor supplied by electric generators implemented on the main turbofan engines of the aircraft [27]. The study was performed for long-range aircraft, 6500 nm, with 340 PAX at M 0.82. The final configuration featured a 10 MW electric engine to drive the BLI tail fan and one 3.67 MW generator installed on each main turbofan engines. Power transmission used a DC link voltage of 2640 V. Quite detailed analyses and modelling were performed during the project. Performances were evaluated compared to a conventional reference configuration based on 2035 technology progress. The final fuel burn reduction was 3.2%. 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.

Finally for longer range aircraft (SMR or long range), none of the recent studies in the literature evidenced strong benefit of hybridization.

IV. The IMOTHEP project

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 is 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. Such integrated approach is key for HEP. In effect, hybridization does not bring benefit per se for fuel burn reduction (it adds to the aircraft mass and does not necessarily increase propulsive efficiency), but through the synergies that can be developed between the airframe, some aircraft functions (e.g. control) and the propulsion system, or through the increased number of degrees of freedom for propulsion sizing and optimization.

IMOTHEP relies 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 are investigated in the technology work packages of the project with a twenty-year timeframe perspective. In return, these technological studies provide performances estimates, based on actual preliminary design, for the components of the power train, which feed the performance assessment of the aircraft. Two subsequent design loops are planned within the project, with an increasing level of fidelity, to assess the achievable performances and refine the components' requirements. Through vehicle's performances and sensitivity studies, the analysis will allow to identify key technological enablers, as well as technology gaps for HEP, and will provide 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, will support the elaboration of a development roadmap that constitutes the ultimate goal of IMOTHEP (Figure 2).

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 is on SMR and regional missions, which represent the bulk of current flights and a significant share of aviation's emissions[8]. Table 1 lists the corresponding specifications that were established with Airbus and Leonardo at the beginning of the project. They represent a compromise between market's needs and orientations, and initial guess regarding hybrid aircraft feasibility.

[8] From Schäfer[28], 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.

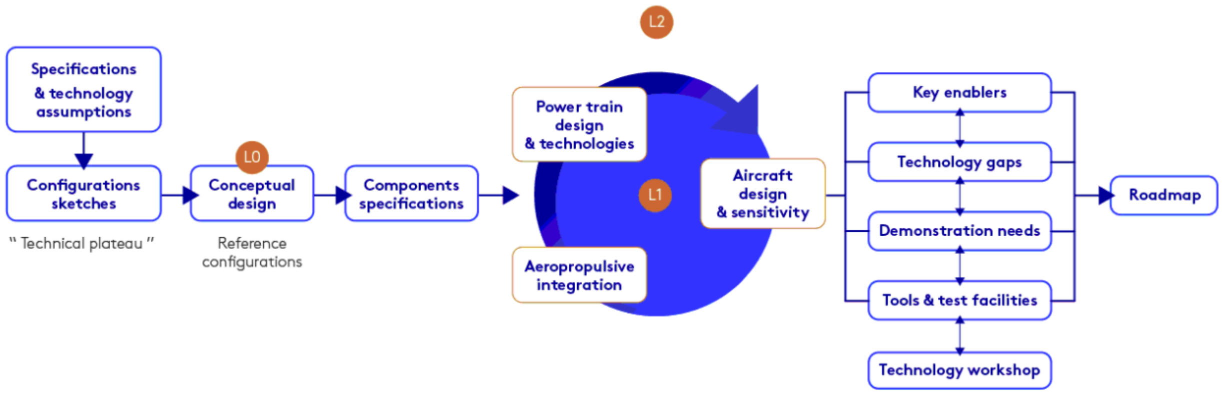

Figure 2: IMOTHEP's methodological approach

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	>= 1200 nm (typ. 800 nm)

The project has 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 allows 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.

Table 2: Initial aircraft configurations for IMOTHEP concepts studies

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

For regional, the conservative configuration explores 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 builds on earlier studies concluding that such parallel hybrid architecture is best suited for the shortest ranges. The radical regional investigates 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).

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 configuration is a blended winged-body (BWB), using massively distributed turboelectric propulsion, designed to make a maximum use of airframe boundary layer ingestion. The conservative configuration is an evolution the DRAGON configuration proposed by ONERA within CleanSky2. It 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 also uses a turboelectric power train.

Hybridization can be envisioned with different types of fuel, from drop-in fuels[9] to liquid hydrogen. Since the focus of IMOTHEP is on the hybrid electric power chain, the project considered only drop-in fuels. For electric systems, the primary focus is on conventional conductivity, but superconductivity is also investigated at both system level and component level, because superconductivity could be a game changer, especially for applications with the highest power.

Technology investigations cover the whole power train from energy generation to thrust generation, including the general electric architecture of the system. The goal is to investigate preliminary designs based on the specifications stemming from the configuration design and on primary technology assumptions for 2035[10]. The project is also dedicating efforts to the aerodynamic integration of the propulsion system. This is instrumental for a careful optimization of the propulsion integration to the airframe but also for a correct evaluation of the performances. This is 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 3 provides a global view of the technical scope covered in IMOTHEP.

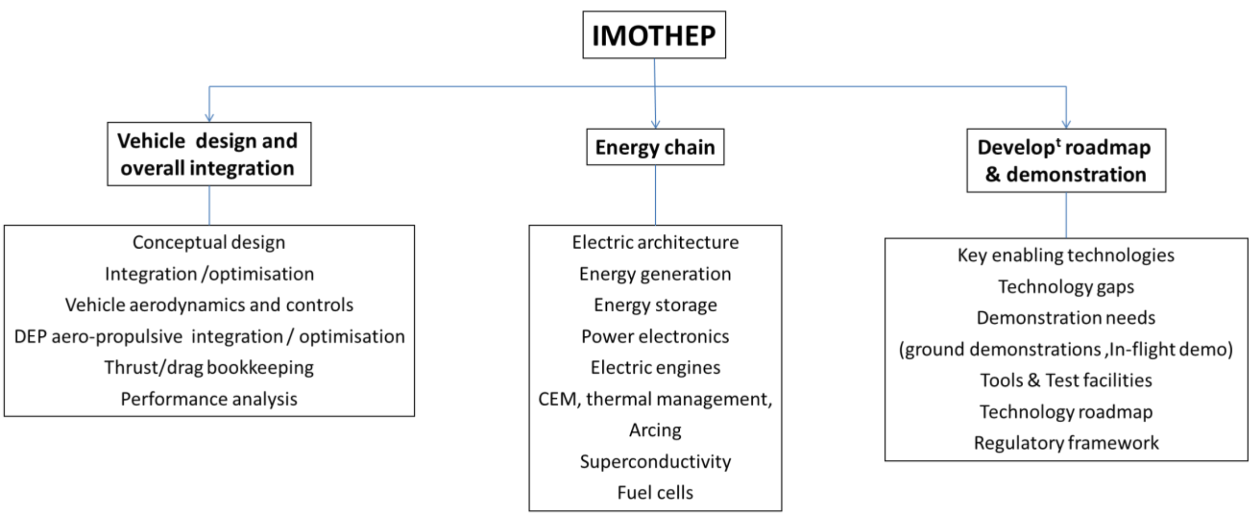

Figure 3: Technical scope of IMOTHEP

[9] 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.

[10] Technology at TRL 6 in 2035 for an entry into service EIS by 2040.

V. Results from configuration studies

The IMOTHEP project is still running and complete results are not yet available. However, it achieved significant progress and interim results already provide interesting trends and preliminary conclusions. This section details the outcomes obtained to date from configurations studies.

Two complete design loops have been performed to date. The first one, preliminary design, used technology assumptions for the various subsystems and electric components based on projection to 2035 from the literature or from IMOTHEP experts' judgement. It provided the initial aircraft configurations and a low fidelity assessment of their performances. Moreover, it allowed defining the specifications for all the components of the power train, which were then studied to provide a new set of characteristics and models based on an actual design. This new set of data and models was integrated in the second design loop and performance evaluation of the aircraft configurations, offering a consolidated assessment of the potential for fuel burn reduction.

Such assessment requires a clear definition of the comparative reference for 2035. IMOTHEP devoted a particular attention to setting a series of 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 [29]. A first reference used primarily for the validation of design tools ("REFX") is an existing aircraft: the ATR 42-600 for the regional and the A320neo for the SMR. A reference aircraft ("REF") is then obtained by deriving the previous REFX for IMOTHEP's TLARs 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 at TRL 6 in 2035 for an entry into service in 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 CO_2 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[11], are beyond the scope of IMOTHEP. The tentative targets for IMOTHEP is 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 is also defined, which does not use hybrid propulsion but conventional turbofan, in order to isolate the specific contribution of the unconventional aerodynamic shape.

Noise is also an important environmental impact for the assessment of new technologies, with a critical impact on societal acceptance. Therefore, IMOTHEP will assess noise impact for the different configurations in its final step but, at this early stage of design, does not include it as an optimization parameter.

Regional conservative configuration

The Regional-Conservative, further referred to as REG-C, 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 fuel burn reduction potential was mostly sensitive to the battery specific energy, 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.

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[11] Also in case of the use of sustainable aviation fuels, the climate impact depends on the actual GHG emissions of the fuel on the full life cycle.

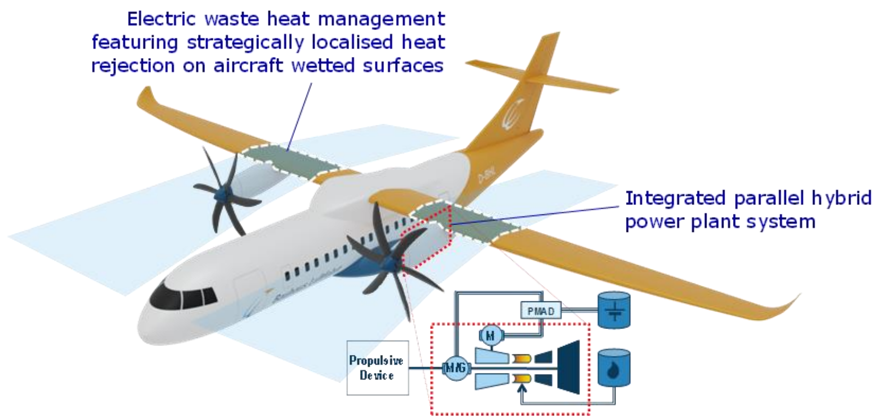


Figure 4: Regional conservative (REG-C) configuration (source Bauhaus Luftfahrt)**.**

The concept was further refined in the next design loop (Loop 1) [30]. Based on a review of last developments in batteries, a more ambitious specific energy of 405 Wh/kg (1C, pack level) was selected. Batteries are positioned 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. 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 energy, 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 (Hp) of 15% (which corresponds to a ratio of electrical power assistance to engine shaft 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. 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. Supplying energy to the non-propulsive systems with an all-electric aircraft represents a significant part, about 40%, of the battery use and mass. This suggests exploring other options for non-propulsive systems.

Regional radical configuration

The Regional-Radical configuration, further referred to as REG-R, resulting from the preliminary design loop (L0) is illustrated in Figure 5.

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 was 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 hybridization. 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, also referred to as "plug-in" configuration.

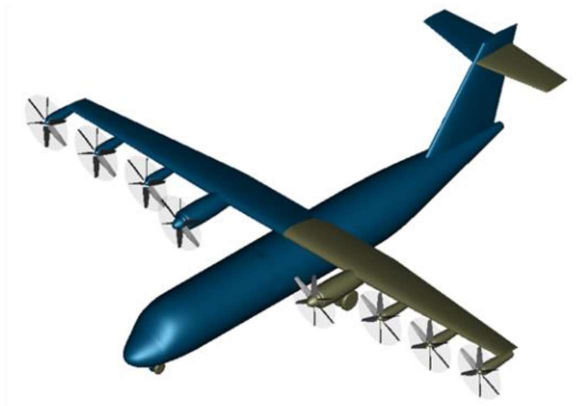


Figure 5: REG-R initial configuration with distributed electric propulsion

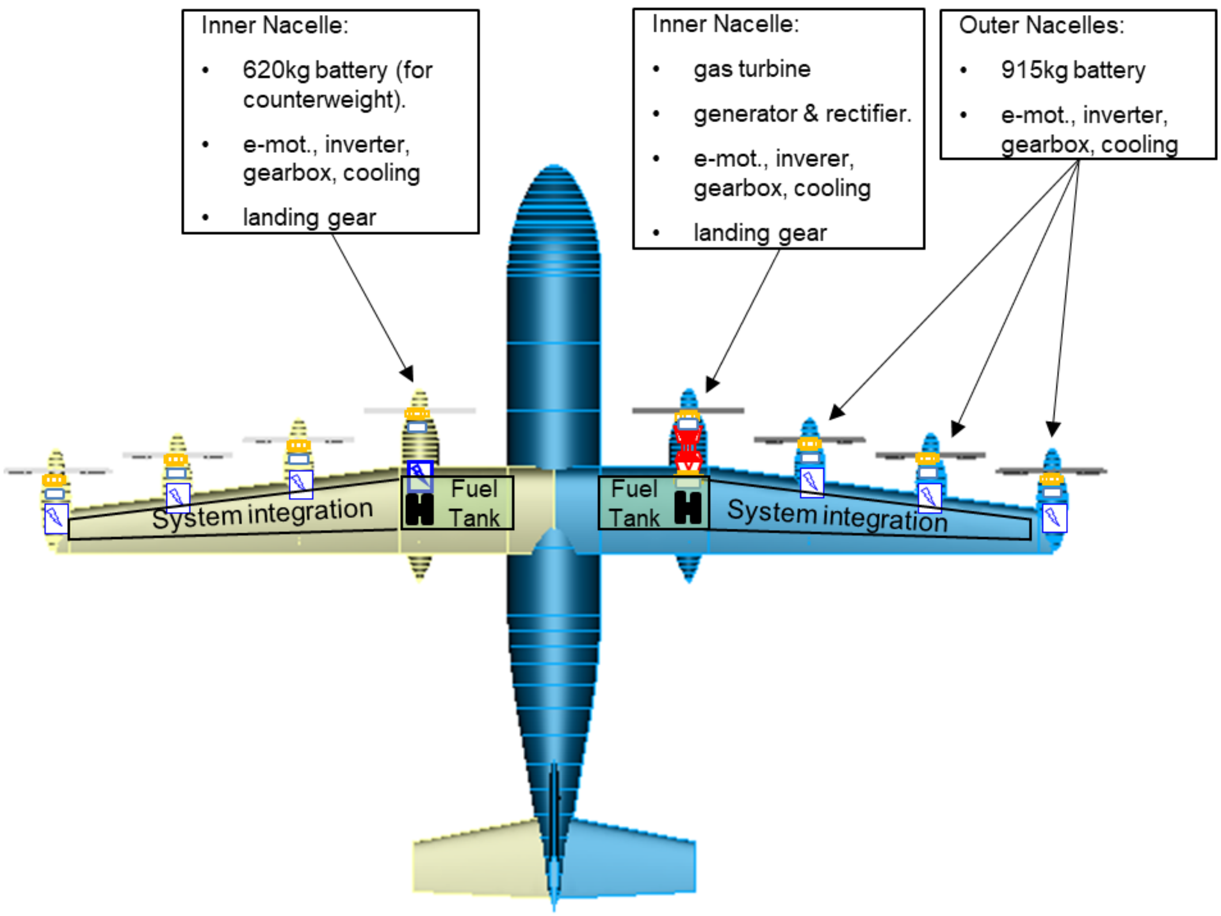


Figure 6: New REG-R configuration for second design loop (L1) (source DLR)

The new configuration (Figure 6) still uses distributed electric propulsion and wing-tip propeller [31]. 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 a 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-R 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. Sensitivities on batteries energy density, between 404 Wh/kg to 556 Wh/kg (extreme assumptions from the battery performance review performed within IMOTHEP) mostly affected the MTOM of the aircraft (-16.5% to + 21.3%) with a limited influence on the block energy (-2.1% to +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 are also sensitive to the propulsive efficiency of the electric power train but not to the specific power of the electric propulsion unit (EPU). 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.

SMR conservative configuration

The SMR-Conservative configuration, further referred to as SMR-C, builds on the previous DRAGON configuration designed by ONERA within Clean Sky 2 [32] 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).

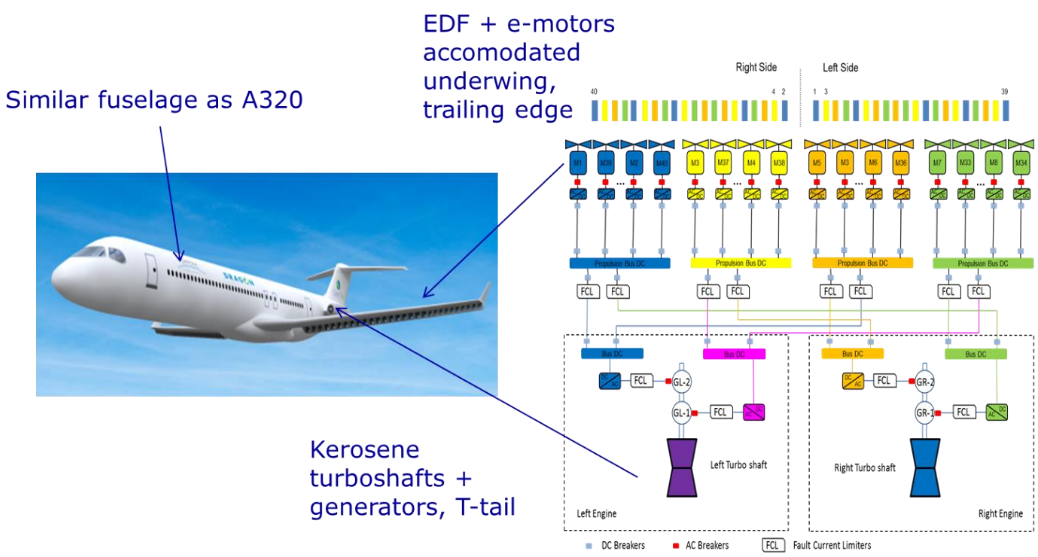


Figure 7: SMR-C turboelectric DRAGON configuration (source ONERA)

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 hybridization and the energy transmission losses [33]. 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 (integrated 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%). 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. 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.

SMR radical configuration

As the SMR-C, the radical SMR, SMR-R, uses a turboelectric architecture [29]. The initial design in Loop 0 accommodated 18 electrically driven fans distributed on the upper side of a 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. To separate the respective benefits from hybridization 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-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. 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 [34], was introduced (Figure 8). 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. This is planned in the last design loop of IMOTHEP.

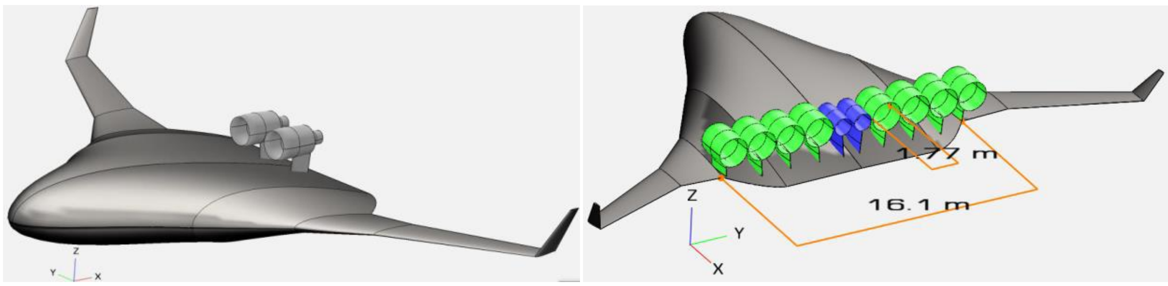


Figure 8: SMR-R configuration (source NLR/ONERA)

(left "0HEP" aircraft, right HEP configuration - turbogenerators in blue and electric fan in green)

VI. Investigation of the electric power train

The specifications of the electrical systems studied in IMOTHEP directly come from the configuration studies, which have defined different classes of systems depending on the configuration (Table 3.

Table 3: Characteristics of electrical subsystems for IMOTHEP configurations

Configuration	Architecture	Total elec. power (kW)	Motor unit power (kW)	Generator unit power (kW)	DC Voltage
REG-C	parallel	2000	1000	n.a.	540
REG-R turboelectric	turboelectric	1800	300	900	800
REG-R plug-in	Plug-in (elec / turboelec)	2245	300	2245	800
SMR-C	turboelectric	22000	820	11000	3000
SMR-R	turboelectric	22000	2400	10900	3000

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.

For most IMOTHEP configurations, energy generation makes use of a turbogenerator. 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 for the electrical machines was carried out, including trade-offs on geometries, materials, electro-magnetic technologies, weight, loading, integration/coupling etc. Table 4 provides a snapshot of the performances obtained for the different classes of generators using permanent magnets synchronous technology. Performance are compared to the state of the art and to projection to 2035 retrieved from literature or experts' judgement. A major issue for the generators is cooling, which will require heat exchangers that raise integration and mass challenges.

Table 4: Performances obtained for electric generators

Parameter	IMOTHEP	SoA 2020	Projection to 2035
Power density (kW/kg)	~12 (1 MW) ~10 (11 MW)	5-10 (<250 kW) 10-15 (1 MW)	20 - 25
Efficiency (%)	*~ 98%*	95	98
Rotational speed (x1000 rpm)	24,5 (1 MW) 9.5 (11 MW)	5-20 (<250 kW) 5-15 (1 MW)	5 -30

For batteries, the rapid evolution of the technologies makes difficult to project performances to 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 requirements for an aircraft. IMOTHEP performs investigations on Gen4 all-solid state Lithium anode (ASS-LA) batteries, combining an experimental study on coin cell samples with numerical modelling of ASSLA using electrochemical simulation [35]. The experimental study provides electrochemical and physical parameters from the developed ASS-LA cells to the numerical study, which is used to optimize cell design and performances. 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 9).

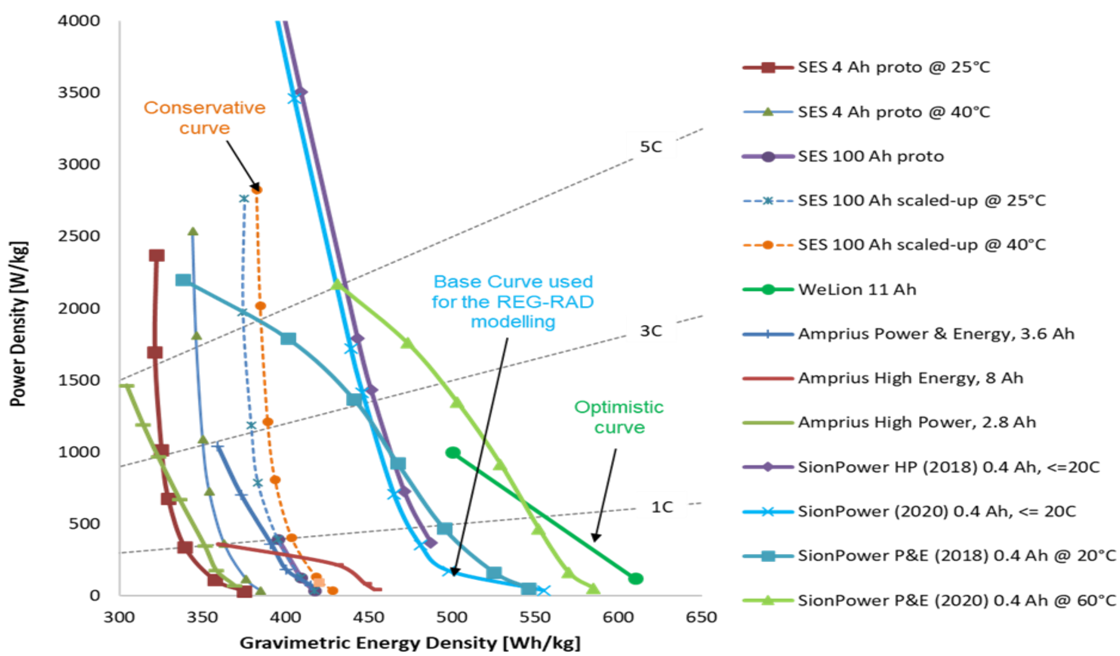


Figure 9: synthesis of recent developments in batteries performances

As for generator, the project carried out design activities on electric motors taking into account the specifications from the aircraft studies. Proposed configurations are permanent magnet synchronous machine with inner rotor. Liquid cooled and air-cooled were both investigated for a range of temperature in the engine: a usual one (180°C), a limit value (220°C) and a challenging one (300°C). The analysis also considered direct drive and integrated drive option with a gearbox. The highest performances can only be reached with liquid cooling, while increasing the operating temperature increases the specific power of the machine, at the expense of the slight impact on efficiency. For the SMR-R, the integral drive architecture of the EPU can increase by 25% the specific power. Performances beyond the state of the art could already be obtained with conservative technology assumptions (Table 5).

Table 5: Performances obtained for electric motors (SMR case, direct drive)

Motor specifications	Cooling	Spec. power kW/kg	Efficiency %	SoA	Projection 2035
0.82 MW 5700 rpm	Air cooled (180°C / 300°C)	6.1 / 8.5	98.94 / 98.66	6 kW/kg 95 % ≤ 500 kW	[11 – 17] kW/kg 98 % MW class
	Liquid cooled (180°C / 300°C)	12.9 / 16.6	98.00 / 97.74		
2300 kW 3100 rpm	Liquid cooled	6.5	98.12		

The analysis also encompassed power electronics with DC/AC inverters and DC/DC converters, as well as the electric wiring interconnection system (EWIS). The later represents a particular challenge for the most powerful SMR configurations. Preliminary sizing of cables was achieved using the usual rules and constraints prioritization (temperature, volume, weight and losses). The impact of the distribution voltage was analyzed for the considered electric architectures. For regional configurations, the analysis showed that increasing voltage from 540 V to 800 V for REG-C, and from 800 V to 1500 for the initial REG-R, allowed reducing the cable masses by 30 to 50%. For the SMR configuration, it was not possible to consider distribution voltage bellow 2000 V (Table 6).

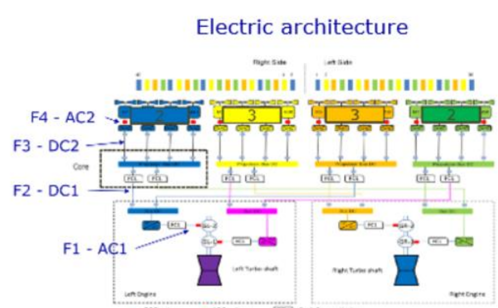
Table 6: Influence of DC distribution voltage on EWIS

3000 V

ID	Core material	Wire Gauge	Number of wires	Linear mass density	Efficiency	Equivalent diameter of the power line
F1	Copper	#0000	18	26 kg/m	99.96 %	143 mm
F2	Aluminium	#0000	8	4 kg/m	99.97 %	69 mm
F3	Aluminium	#0000	6	3 kg/m	99.94%	62 mm
F4	Aluminium	#0	12	3 kg/m	99.96 %	81 mm

1000 V

ID	Core material	Wire Gauge	Number of wires	Linear mass density	Efficiency	Equivalent diameter of the power line
F1	INFEASIBLE – T cable > Tmax					
F2	Aluminium	#0000	20	9 kg/m	99.9 %	195 mm
F3	Aluminium	#0000	16	8 kg/m	99.83%	163 mm
F4	Aluminium	#0	24	11 kg/m	99.98 %	130 mm



VII. Observations, challenges and perspectives

The preliminary design loop of IMOTHEP (Loop 0), performed at conceptual level with low fidelity models suggested 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. The explanation could be a larger potential for increasing of propulsive efficiency in case of configurations using turbofan instead of propellers. However, the introduction of the outcomes of the components studies[12] in subsequent Loop 1 did not confirm this initial conclusion and did no longer evidence any benefit from hybridization for the SMR configurations. Yet, these results were obtained with conservative technology assumptions for the design of the electric components. Loop 1 results showed 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). From this point of view, superconductive technologies, could emerge as a key enabler by allowing significant mass reduction of electric systems. Regarding the regional aircraft, the turboelectric option is no longer considered as a promising one and was dropped from the IMOTHEP roadmap. Remaining options are the parallel hybrid systems and the fully battery powered electric aircraft with thermal

[12] Some subsystems still require better modelling in the configuration design. This is in particular the case for the TMS.

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). For parallel hybrid however, high batteries' performances and a limited mission range seem required for HEP to bring a fuel burn reduction. From all the investigated configurations, the REG-R, a fully electric concept for short ranges using a thermal range extender for longer missions, emerges as the most promising solution.

Recent publications reviewed in section III do not strongly contradict these findings: for parallel hybrid, the benefit seems limited to short mission and high battery performances also. For SMR, the potential benefit of HEP does not seem to exceed 5 to 7%, for low fidelity evaluations, which is consistent with the early findings of IMOTHEP in Loop 0. The experience from IMOTHEP and other project is however, that refined analysis tends to decrease the performances compared to conceptual low fidelity design.

From a technology perspective, IMOTHEP and other studies suggests the development of classes of system for the regional and SMR respectively (although this may depend on the respective definition of regional and SMR, which can change with market's evolution), as detailed in Table 7.

Table 7: 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

* The highest value corresponds to IMOTHEP plug-in configuration

Table 7 clearly evidences the technological step between the regional and SMR missions. 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. 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…). However, 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 and would induce 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.

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-R 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, one can infer 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.

Beyond the performances of the electric systems, cooling and thermal management emerged as a particularly critical issues for both the design of the SMR 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 [36]. 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. 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. The integration of a heat exchanger is also an issue. 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.

The regional configurations heavily rely on batteries, for which high specific energy is a key requirement. Nonetheless, additional aspects need to be underlined. 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 synchronized with the aircraft maintenance schedule while mitigating obsolescence. Last, certification of batteries is an important topic.

VIII. Conclusion

A major question at the origin of IMOTHEP was to assess the potential of HEP for reducing aircraft fuel burn and to identify concepts that best benefit from hybridization. For the SMR aircraft, even if some consolidation is still needed by the end of the IMOTHEP project, current results do not conclude on an actual potential benefit of hybridization for this category of aircraft. In addition, hybridization of this class of aircraft would represent a huge technological step for the development of electric systems. This is even truer 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, 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 offers 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 does not look interesting, while the conclusions for parallel hybrid are lukewarm. From our analyses, at least, significant battery performances are required and the benefit, which would not exceed 10%, is mainly achievable on short-range missions. It is noticeable however that an industrial interest is still manifest for this kind of solution as demonstrated by announcements from GE or Prat & Whitney. 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 requires 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 on-going and will enable, on the one hand, to refine the key issues and critical enablers for the REG-R configuration, and on the other hand to consolidate the confidence in the conclusions regarding SMR by refining the aggressive SMR-R 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 article, it might bring some further insight, especially in the gap analysis used as entry for the roadmap.

Acknowledgments

This project has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No 875006.

Authors thank all the contributors to the project from the 29 partners of the consortium (see www.imothep-project.eu).

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