Perspectives of hybridization for commercial aircraft: the lessons learned from the IMOTHEP project

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Hybrid electric propulsion

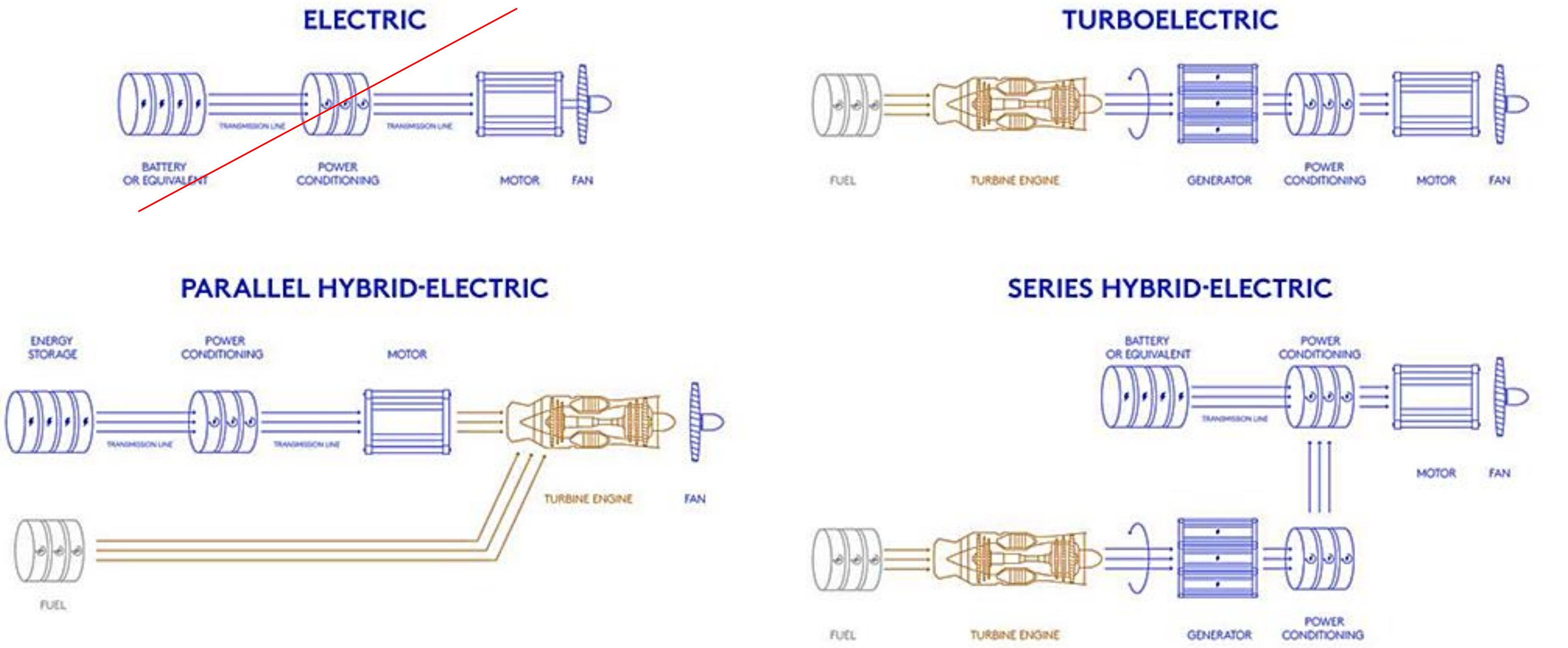
- **What is it ?**
  - Basically the combination of thermal and electric energy sources with thermal and electric motors for the propulsion of aircraft
  - Also some time extended to the use of fuel cells as energy sources
- **What for ?**
  - An attempt to reduce aircraft fuel burn and CO_2 emissions in the context of aviation's effort to reduce its climatic impact
  - An idea that emerged and developed during the 2010's
- **Why not simply electric?**

Because batteries capabilities limit fully electric propulsion to small aircraft

➢ A 500 Wh/kg battery allows the flight of a 40-50 PAX aircraft on 200 nm

Hybrid electric propulsion

- **Multiple architecture options**



Hybrid electric propulsion

- **But how does it reduce fuel burn ?**
  - **Hybridization does not improve efficiency per se**
    - Additional mass of electric systems and sources
    - Introduction of additional losses in the power chain (e.g. turboelectric)
    - No automatic improvement of propulsive efficiency
  - **Benefit of hybridization is to be obtained through:**
    - Energy substitution ⇨ Parallel hybrid : energy stored in the battery
    - Enlarged design space ⇨ more degrees of freedom for propulsion optimization and integration
    - Possibilities of synergies between airframe, aircraft control and propulsion

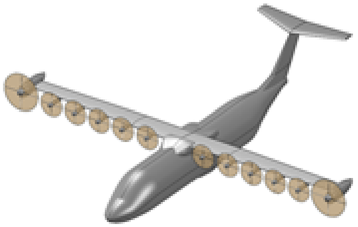
    ⇨ ***Distributed electric propulsion, boundary layer ingestion, use of propulsion for control…***

    ⇨ ***Strong interdependency and synergy between aircraft configuration and propulsion architecture***

Hybrid electric propulsion

➢ **Numerous possible architectures and aircraft configurations**

NASA Pegasus
Parallel hybrid

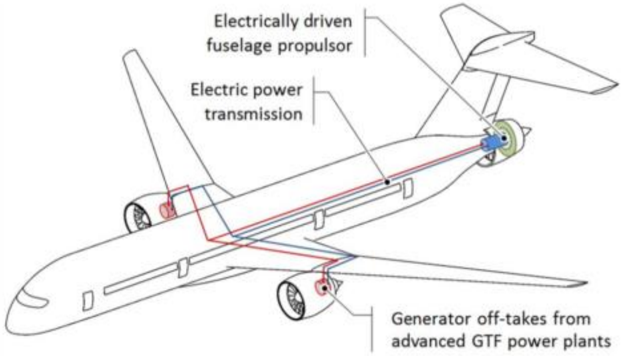


ONERA/SAFRAN
Distributed propulsion blown wing

EPS ECO150-300
Distributed propulsion

NASA N3-X
DEP + BLI +
Superconductivity

Boeing Sugar Volt
Electrically Assisted turbofan

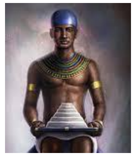


CENTRELINE (H2020)
BLI turboelectric tail-fan

ONERA DRAGON
Distributed propulsion

NASA SUZAN
Distributed propulsion +BLI tail-fan

The IMOTHEP project



Imhotep - Egyptian architect, doctor and philosopher
A great and innovative builder…

- **A Horizon 2020 project (CINEA)**
- **Rationale:**
  - **What could be the actual benefit of hybrization ? For which missions?**
  - **Willingness to perform an analysis with a consistent set of assumptions and design approaches**

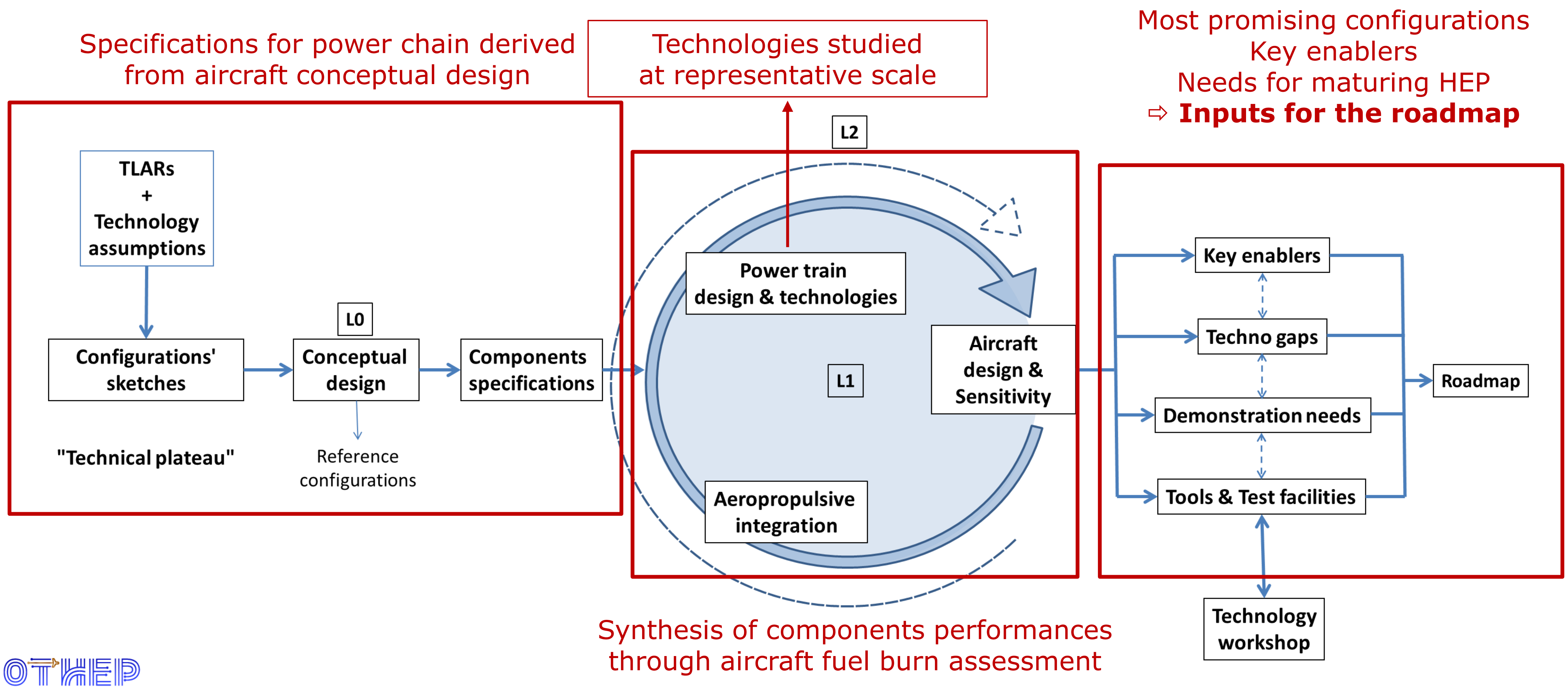
- **Objectives : achieving a key step in assessing potential benefits of HEP for emissions reductions of commercial aircraft**
  - Identifying propulsion architectures & aircraft concepts benefiting from HEP
  - Investigating technologies for HE power train architecture and components
  - Analysing required tools, infrastructures, demonstrations and regulatory adaptations for HEP development
  - Synthesising results through the elaboration of the development roadmap for HEP

IMOTHEP project

- **Four-year research project (2020-2024)**
  - Coordinated by ONERA
- **29 partners**
  - **9 European countries + 2 international partners from Canada**

IMOTHEP's methodological approach

- **Investigating hybrid power train in close relation with its integration on a representative configuration of aircraft**



IMOTHEP GETTING HYBRID ELECTRIC

Project's scope & targets

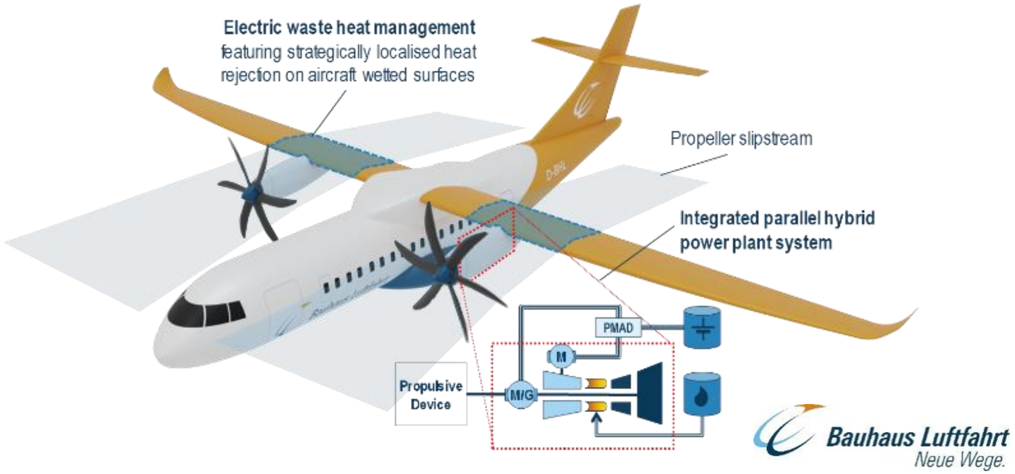
- **Reference missions**
  - **Short/medium range:** minimum segment for a significant impact on aviation emissions
  - **Regional:** more accessible, potential intermediate step toward SMR

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

  ➢ **Two configurations studied per mission: a "conservative" one and a "radical one"**

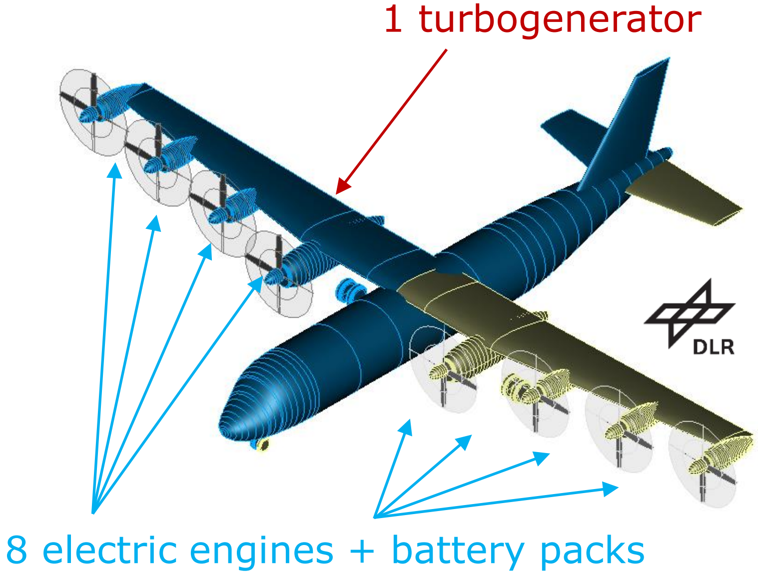
  - **EIS: 2035+**
- **Technological scope**
  - Central focus on thermal hybrid with drop-in fuel
  - Conventional conductivity + exploration of superconductivity as a potential enabler
- **Ambition :** 10% more emissions reductions than Clan Sky 2 targets with conventional technologies
  ➢ **Assessment against "baseline" aircraft:** 2014 reference aircraft adapted to TLARs and projected to 2035
- *Note : micro-hybridization for operative assistance to UHBR or USF not in the scope of IMOTHEP*

Highlights on IMOTHEP configurations

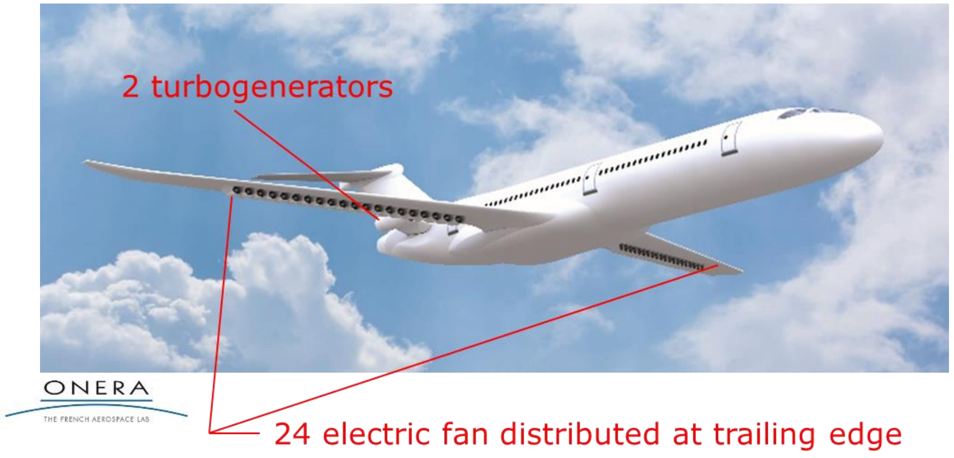


- **Regional conservative : parallel hybrid**
  - Combined electric assistance to shaft and core cycle
  - Up to 1 MW electric assistance to turboshafts
  - 2670 kg of batteries (405 Wh/kg, pack level)
  - 540 DC voltage
  - Heat rejection on aircraft wetted surfaces

- **Regional radical : distributed electric propulsion**
  - ➢ **Initially : Pure turboelectric propulsion ➩ abandoned**
  - ➢ **"plug-in" :** fully electric over 200 nm + range extender for 600 nm
  - 8 x 300 KW electric motors
  - One 2345 kW generator
  - 6115 kg of batteries (360 Wh/kg)
  - 800 V DC voltage

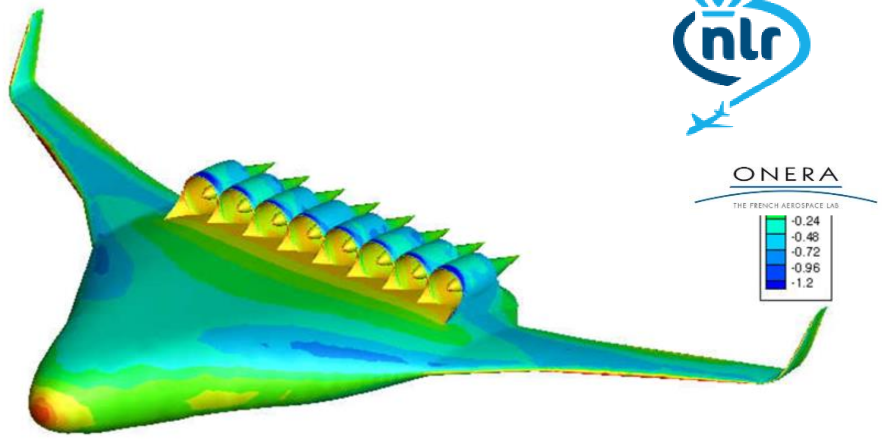


Highlights on IMOTHEP configurations



- **SMR conservative : turboelectric DEP tube & wings**
  - 24 electric fans, 820 kW each
  - 2 turbogenerators : 2 x 11 MW
  - 3000 V DC voltage

- **SMR Radical: turboelectric + DEP + BLI + BWB**
  - 8 electric fan, 2400 kW each
  - 2 turbogenerators : 2 x 11 MW
  - 3000 V DC voltage



Different classes of electric systems for HEP

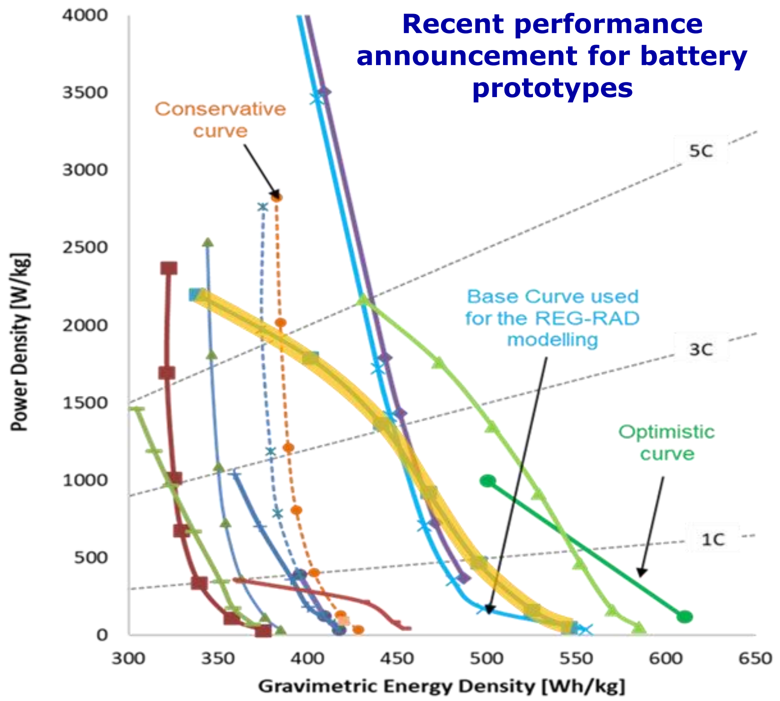
From configurations studies:

	Regional	SMR
Distribution	< 1 kV	~3 kV
Electric motor	0.3 to 1 MW	~1 to 10 MW
Generator	~1 MW / 3 MW* * Regional "plug-in"	~5 MW / 10 MW
	TRL 6 by 2030	TRL 6 after 2035

- **Clearly set a much higher challenge for SMR regarding:**
  - distribution and associated issues (insulation, arcing, discharge…)
  - electric machines
    - *Benefit from DEP for reducing motors' power level*
  - *Generator might also be challenging for our regional radical configuration*
- **Longer time horizon to develop hybrid SMR technologies**

Energy generation - Batteries

- **Assumptions based on industry announcement + existing battery roadmaps**
- **Primary performance parameter: specific energy** (SE, Wh/kg)
  - IMOTHEP assumptions : **475 - 545 Wh/kg** (cell), cell-to-pack **0.74**
  - Expectations by 2030+: up to 600 Wh/kg (cell, 2C)*
    - Significant variations in batteries' performance projections over the duration of IMOTHEP
    - **Li-ion battery R&D mostly for road transport**
      - Aviation gaining importance



Year	2023	2030(+)
Battery technology	Gen3	**Adv. Gen4c ASSB**
Cell GED [Wh/kg]	250 - 290	**500 - 600**
Packaging efficiency	70-82%	**85-90%**
Pack GED [Wh/kg]	200 - 238	**~500(+)**

* Battery with moderate power (*type for regional aircraft)*
450 Wh/kg for high power cells (8-10C) (e.g. for eVTOL)
Power requirement: moderately high for HE REG-CON (≤3C) and E REG-RAD (~1.5C)

Source: AIT

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Energy generation – Electric generator

- **Specification**

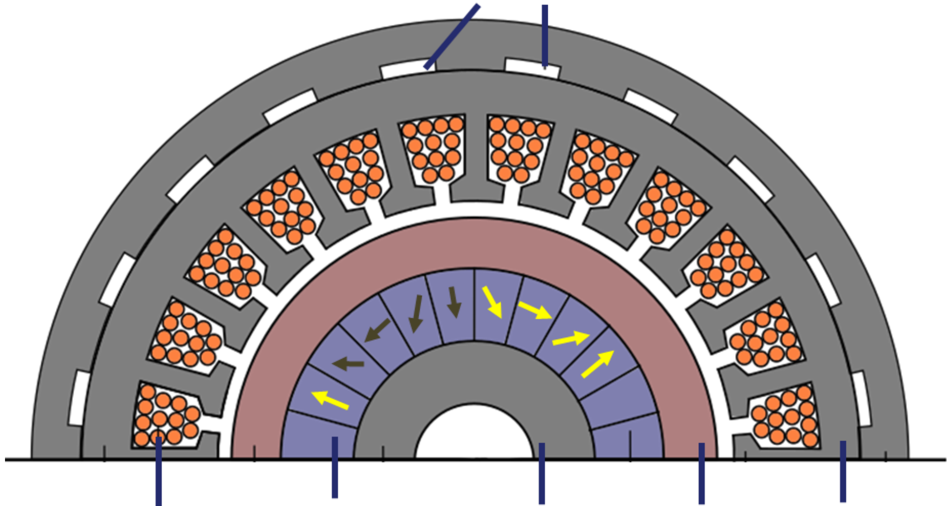
  Regional radical: 2,25 MW – 15000 rpm

  SMR : 5,74 MW – 8000 rpm (x4) (max power)

- **Technological Assumptions**
  - Oil cooling of the generator (T_{oil} ~ 80°C) : end-winding spray + channels on the external surface
  - Halbach PMs to reduce the inductance and improve THD
  - Frequency limited to 1,5 kHz (fundamental)

➢ ***"Medium" aggressive technology assumptions***

(SoA + technology at TRL 6 by 2030)



	Rated power (kW)	Rated speed (rpm)	Rated efficiency (%)	Active mass (kg)	External diameter (m)	Power density (kW/kg)	SoA 2020 (kW/kg) (1 MW)	Projection 2035 (litterature)
REG-RAD	2250	15000	98,7	124,0	0,343	~ 9	10 – 15 kW/kg η = 0.95	20 - 25 kW/kg η = 0.98
SMR	5740	8000	98,8	325,2	0,576	9 -13		

Source: U. Lorraine

Electric motors

➢ **Choice of best classes electric components**
- Electrical Machines (EM) = Permanent Magnet Synchronous Machine (PMSM)
- Power Electronics (PE) = Two-Level Inverter with SiC Power Modules
- Liquid cooling

Aircraft	Motor specification	Tmax	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		

Results from Conservative Approach = SoA + First mature technologies by 2030
➔ If disruptive assumptions introduced: +95% specific power @EPU level

Electrical wiring interconnection system (EWIS)

➢ **SMR radical case**

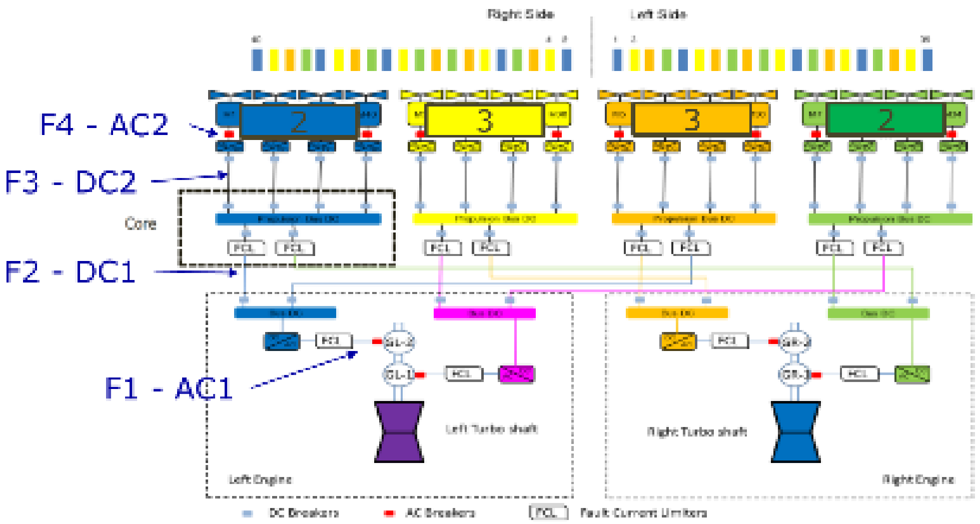
3000 V

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

Electric architecture



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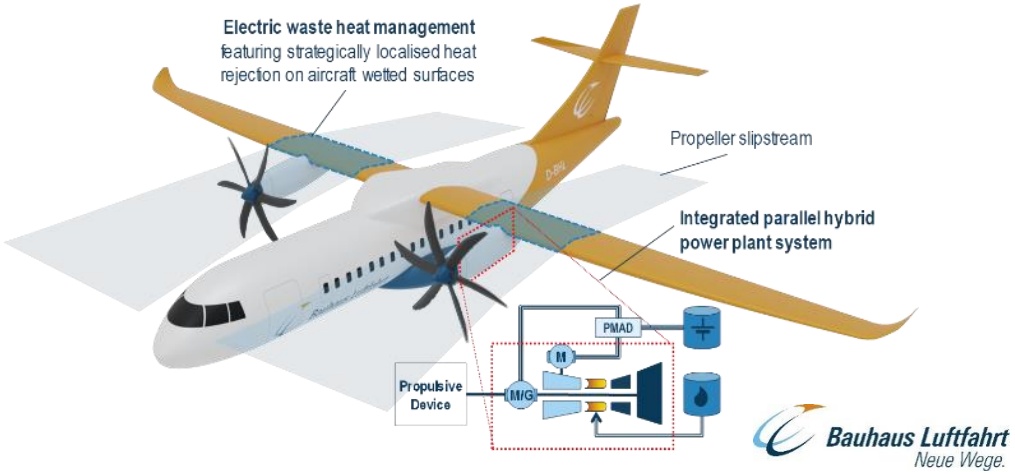
Outcomes for electric power train studies

- **Safe and operable electric architectures could be designed for all configurations**
  - ➢ Yet for DEP architecture, reliability issues in operation could be encountered for conservative assumptions on components' reliability
- **For most electrical components, design could be identified (at paper level) that surpasses SoA and approach projection for 2035**
- **Cooling of generators and motors with their electronics is key (TMS)**
  - ➢ Call for the highest possible efficiency for electrical machine
    or alternatively, electrical machines that withstand high temperatures (300°C)
  - ➢ Optimal design for cooling solution and consequences on aircraft performances? ⇨ system level
- **Feasibility of cabling is a major issue**
  - Regional (800 V): mostly size and integration issues
  - SMR (3 kV) :
    - no possible extrapolation from current installation rules and guidelines
    - insulation solution to ensure lifetime duration ?
    - numerous issues for protection devices partial discharge, arcing, breaking capacities
    - integration issues

Configurations studies : regional aircraft



- **Regional conservative : parallel hybrid**
  - 2670 kg of batteries (408 Wh/kg, pack)
  - Up to 2 x 1 MW electric assistance – 540 V DC
  - MTOW : +30% vs "baseline aircraft"
  - **9.6% fuel reduction over a 200 nm typical mission**
  - But **6% increase on design mission** (600 nm)
  - **Battery specific energy is the main driver**
  - Limited benefit expected from electric system improvement

- **Regional radical :**
  - **Turboelectric not promising ⇨ move to electric + range extender**
  - 8 x 300 KW electric motors - One 2345 kW generator – 800 V DC
  - 6115 kg of batteries (360 Wh/kg)
  - **60% block energy reduction over 200 nm** (fully electric)
  - **36% fuel burn reduction over 600 nm** (with extender)
  - Efficiency gain from electric chain + configuration-specific optimization
  - Not too sensitive to battery specific energy

Configuration studies: regional aircraft

- **Complementary observations from literature survey** (end 2022)
  - Mostly parallel hybrid + some turboelectric
  - Still strong divergences between studies regarding the potential benefit of HEP
  - Convergence of assumptions on batteries on "reasonable" values (≤ 500 Wh/kg pack)
  - **Difficult to infer from this survey an clear benefit of HEP**
  - At least, **battery energy density at the upper bound** of the assumptions range + **reduced mission range** seem to be required for parallel hybrid

    ⇨ **Consistent with IMOTHEP findings**

Conclusions for regional aircraft

- **Turboelectric:** improvement of propulsive efficiency brought by distributed electric propulsion is not sufficient to compensate mass increase
- **Parallel hybrid:** best suited for short range (typically 200 nm)
    - ➢ fuel burn reduction limited to 10 or 15% on 200 nm with assumptions on batteries' specific energy at the upper end of current expectations for the next decade

– **Hybrid "plug-in"** (thermal range extender) : **most promising configuration**

– **Main enablers:**

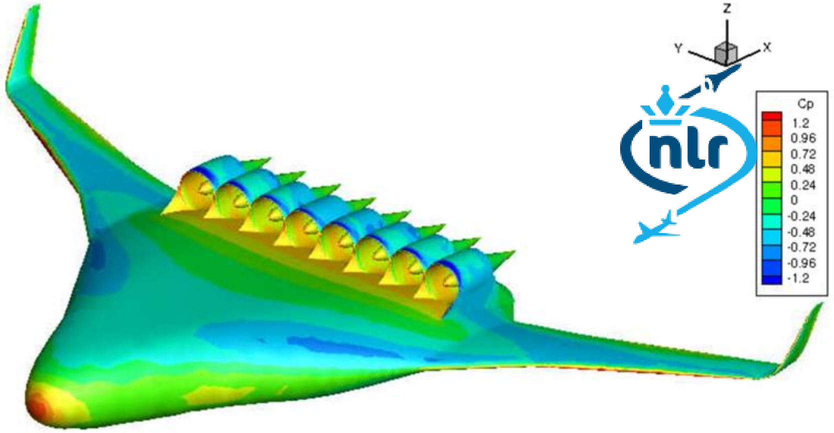
  - Batteries (in particular specific energy)
  - Limited sensitivity to electric system performances (specific power, efficiency, etc.)
  - Critical point : cabling feasibility (mostly volume and installation constraints)

Configuration studies : SMR aircraft

- **SMR conservative : turboelectric DEP tube & wings**
  - 24 electric fans, 820 kW each
  - 2 turbogenerators : 2 x 11 MW
  - 3000 V DC voltage
  - MTOW : +10% vs "baseline aircraft"

ONERA
THE FRENCH AEROSPACE LAB

- **SMR Radical: turboelectric + DEP + BLI + BWB**
  - 8 electric fan, 2400 kW each
  - 2 turbogenerators : 2 x 11 MW
  - 3000 V DC voltage



- ***For both configurations:*** **No benefit from hybridization**
  - Refined analysis negated initial benefit (6 to 11%) from conceptual studies
    - ***DEP increases propulsion efficiency but does not compensate increased weight and losse***s
  - **Strong influence of turboshaft SFC**
  - Limited expectation from electric systems performances improvements (under consolidation)
  - Huge technological step due to high power / high voltage electric power chain

Configuration studies: SMR aircraft

- **Complementary observations from literature survey**

  - **CENTRELINE** (H2020): partially turboelectric + BLI tail fan
    - ➢ Modest 3.2% fuel burn reduction compared to reference 2035
  - **NOVAIR** (CS2):parallel hybrid assistance to turbofan with downsizing
    - ➢ 7% FB reduction (3% block energy reduction, bat: 500 Wh/kg pack) – ***Conceptual study***

  - **NASA SUZAN**: turboelectric + DEP + BLI tail fan
    - ➢ Fuel burn reduction < 7% (w.r.t. 2035 reference conventional aircraft)
  - **UTRC** (Lens & al.): configuration screening of parallel hybrid (conceptual)
    - ➢ All configurations close to each other with max fuel burn reduction of ~5%

❖ *General remark:* refined analysis tends to decrease benefits compared to conceptual Low-Fi design

Conclusions for SMR aircraft

- **Perspective of benefit looks rather modest for all configurations**
  - Modest benefit at conceptual level not likely to be confirmed by refined HiFi studies
  - **Promising configuration still to be identified for investigated TLARS**
  - **Or TLARs and aircraft operations to be revisited**
  - Not clear from IMOTHEP studies whether improved performance of electric systems could change the conclusion (under consolidation but sensitivity is low)
  - Potential benefit from superconductivity to be investigated by the end of the project
- **Huge technological challenges associated to high voltage (~ 3 kV)**
  - Major disruption with aviation current electrical system (< 540 V)
    - Partial discharges, space charges skin effects, etc.
    - Design and integration issues: heating, arcing, cable size and bending radius, etc.
    - Step increase in electric machine power

Toward a roadmap for hybrid electric propulsion

- **From IMOTHEP results, primary focus on regional aircraft**
  - For SMR, more exploratory research needed on TLARs + fleet scenarios + configurations
- **Configurations : plug-in and parallel hybrid**
  - Share a number of similar technologies
  - **Primary focus on "scope 1 technologies":** up to 1 kV and 1 MW
    - Caveats:
      - Higher power (3 MW) to be targeted for generators
      - Feasibility of 800 V distribution may be an issue for integration

Note: ***fuel cell based systems, not studied, but possibly important part of the roadmap***

Toward a roadmap for hybrid electric propulsion

- **Batteries : key enabler**
  - Primary KPI: specific energy (Wh/kg) ⇨ cell chemistry but also integration (cell-to-pack)
  - Also key: safety (ASSB), chemistry/cell design suitable for aviation and certification
- **Electric motors: mature and demonstrate IMOTHEP techno and design level**
  - IMOTHEP configurations not much sensitive to motor specific power
  - Key requirements : cooling (key role of efficiency), reliability and life time
- **Electric generators: need to push the technology toward aggressive design**
  - Potential benefit from improved performance compared to IMOTHEP techno level
  - Key requirements : high DC voltage, cooling (key role of efficiency), reliability
- **Power electronics: design component packages suitable for flight conditions**
  - Components suitable for 800 V power distribution announced by 2025/2026
- **EWIS: mature, develop & certify cables, contactors, protection & breakers for 800V**
  - + Research needs on fault arc detection
  - ❖ Integration of cables remains in key issue
- **Thermal management: key role of components' efficiency and max operating T**

Conclusions

- **Final conclusions and roadmap from IMOTHEP available in June 2024**
  - ➢ Final refinements and consolidation going-on on radical configurations
  - ➢ Roadmap to be completed
- **Trends for the potential and applicability of HEP have been identified**
  - For SMR :
    - potential of HEP not confirmed at this stage for considered TLARs
    - the huge technology step pushes hybrid SMR to a longer term
  - For regional aircraft, technological solutions have been identified
    - Most convincing configuration is full electric + range extender
    - No revolutionary development seems required by 2035 for the targeted applications
      - ➢ *Yet wiring remains an issue*

THANK YOU !

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IMOTHEP team at work

Team workshop,
Eurocontrol, Sept. 2022

Team workshop,
ONERA, Oct. 2023

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