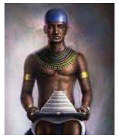
IMOTHEP: toward a roadmap for the development of hybrid electric propulsion

Ph. Novelli, ONERA – Project coordinator

12th EASN International Conference– 18/10/2022

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

IMOTHEP's top level ambition



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

"Investigation and Maturation of Technologies for Hybrid Electric Propulsion"

- **H2020 project (**Call 2019 “Mobility for Growth” - "towards a hybrid/electric aircraft")

- **Achieving a key step in assessing potential benefits of HEP for emissions reductions of commercial aircraft**
- **Building the overall European development roadmap for HEP**

- **First level objectives**
  - 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 (2020-2023)**
  - Coordinated by ONERA
- **29 partners**
  - **9 European countries + international partners from Canada**
- **10.4 M€ EC funding** (+ contribution of international partners)

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

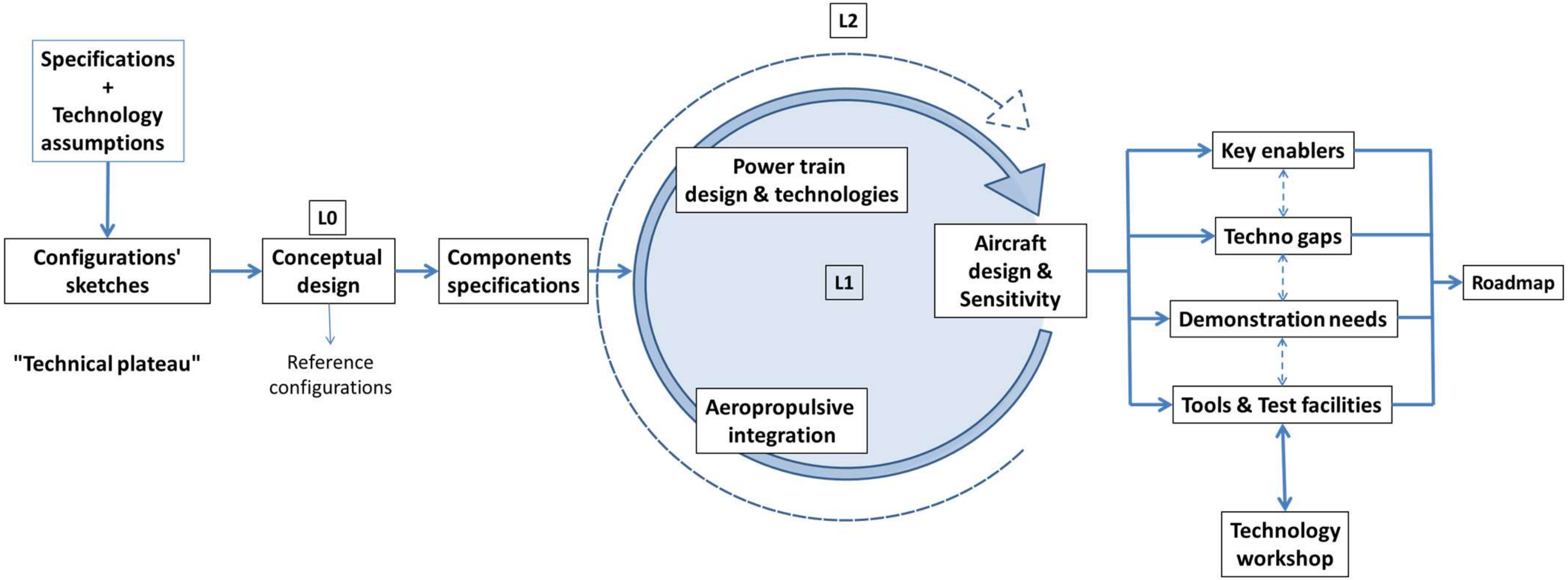
Mission	PAX	Speed	Range
Regional	40	Mach 0,4	600 nm (typ. 200 nm)
SMR	150	Mach 0,78	>= 1200 nm (typ. 800 nm)

  - EIS: 2035+
- **Technological scope**
  - Central focus on thermal hybrid with drop-in fuel
    + some investigations on fuel cells at conceptual level (aircraft + fuel cell specific issue for aircraft)
  - Main focus on conventional conductivity
    + Exploration of superconductivity as a potential enabler
- **Ambition :** reaching 10% more emissions reductions than Clan Sky 2 targets with conventional technologies

IMOTHEP GETTING HYBRID ELECTRIC

IMOTHEP's methodological approach

A highly integrated approach from representative configurations to components investigation



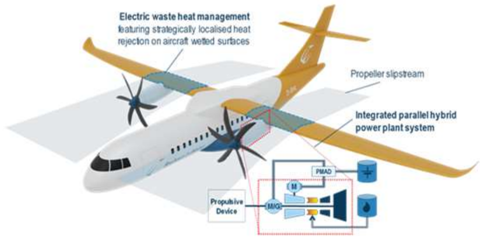
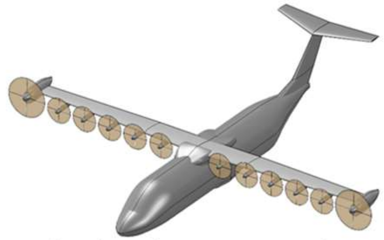
➢ **Design loop L0 and L1 achieved – L2 initiated**

IMOTHEP GETTING HYBRID ELECTRIC

Project's supporting configurations

- Build-on / complement previous studies (e.g. CS2, CENTRELINE, etc.)
- Explore a range of architectures with consistent assumptions

Initial supporting configurations

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

- *Note : micro-hybridization for operative assistance to UHBR or USF not in the scope of IMOTHEP*

Project's technical scope

IMOTHEP

- **Vehicle design and overall integration**
  - Conceptual design
  - Integration /optimisation
  - Vehicle aerodynamics and controls
  - DEP aero-propulsive integration / optimisation
  - Thrust/drag bookkeeping
  - Performance analysis
- **Energy chain**
  - Electric architecture
  - Energy generation
  - Energy storage
  - Power electronics
  - Electric engines
  - CEM, thermal management,
  - Arcing
  - Superconductivity
  - Fuel cells
- **Develop^{t} roadmap & demonstration**
  - Key enabling technologies
  - Technology gaps
  - Demonstration needs
  - (ground demonstrations ,In-flight demo)
  - Tools & Test facilities
  - Technology roadmap
  - Regulatory framework

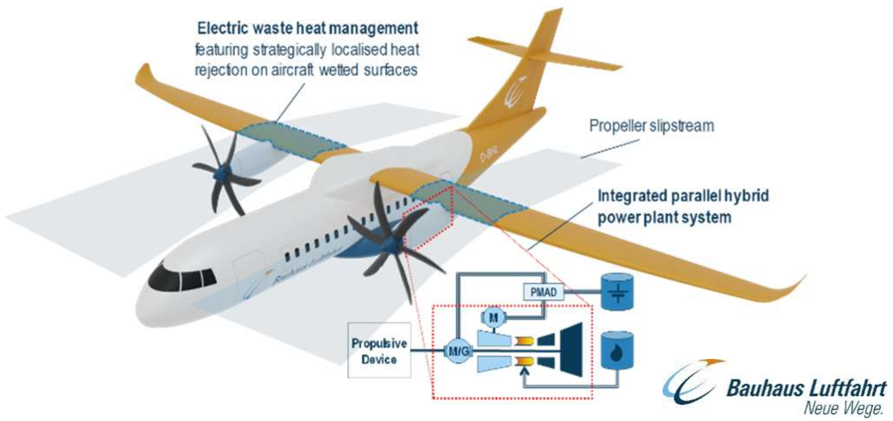
TRL 2 to 4 conceptual studies

Work achieved to date

- **First design of all components of the power chain for all configurations**
- **Electric architecture and power management definition for all configurations**
  - ✓ Failure case analysis performed
- **Integration of electric systems definition in configuration studies (L1)**
- **Preliminary definition and modelling of thermal management system**
  - ➢ Not yet integrated in configuration design
- **Aeropropulsive integration**
  - – Propeller design and integration investigations
  - – Fan and inlet design for BLI thrusters
- **Performance analyses for all configurations**
  - + First sensitivities
- **Investigation of certification issues initiated**

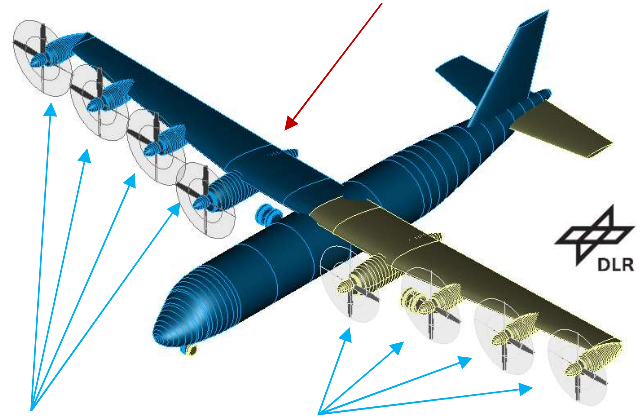
➢ *Please, note detailed presentation on regional aircraft at IMOTHEP session on Thursday*

Highlights on IMOTHEP configurations



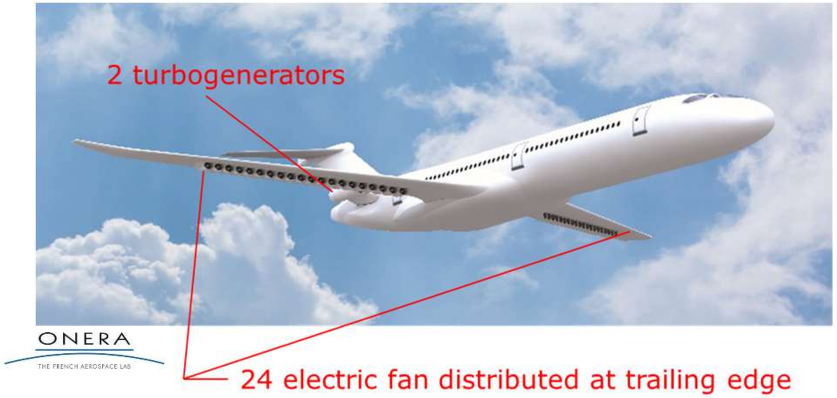
- **Regional conservative : parallel hybrid**
  - Combined electric assistance to shaft and core cycle
  - Up to 1 MW electric assistance to turboshafts
  - 2670 kg of batteries (405 Wh/kg, pack level)
  - 540 DC voltage
  - Heat rejection on aircraft wetted surfaces

- **Regional radical : electric + range extender**
  - ➢ **Pure turboelectric propulsion abandoned**
  - ➢ **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



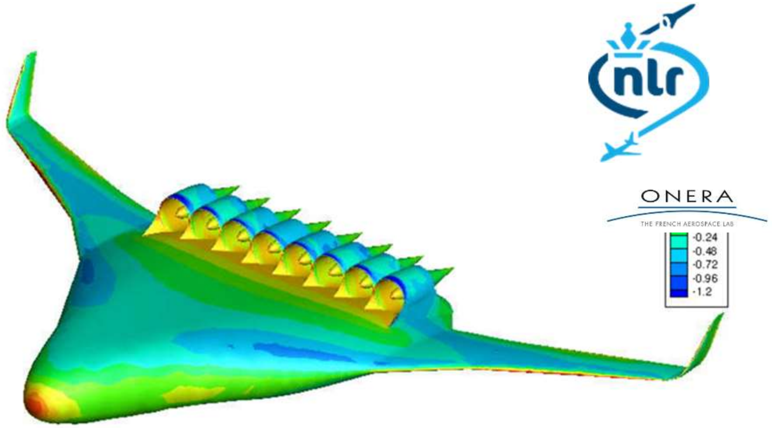
IMOTHEP
GETTING HYBRID ELECTRIC

Highlights on IMOTHEP configurations



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

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



Different classes of electric systems for HEP

From configurations studies:

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

* Reg-RAD plug-in configuration

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

Highlights on electric components studies

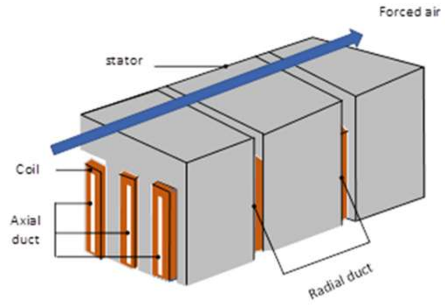
Electrical motors (SMR case)

- **First step: design for aircraft requirements based on conservative technologies**
  - Permanent Magnet Synchronous Machine (PMSM), inner rotor
  - Optimized for both electromagnetic and thermal aspects
  - Investigation of air and liquid cooling for different acceptable temperatures
- **Preliminary performance results:**

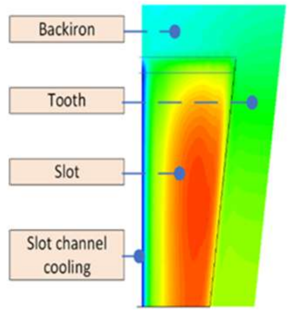
Motor specification	Cooling	Spec. power kW/kg	Efficiency %	SoA	Projection 2035
0.82 MW / 5700 rpm	Air cooled (180°C / 300°C)	6.1 / 8.5	98.94 / 98.66	6 kW/kg 95 % ≤ 500 kW	[11 – 17] kW/kg 98 % MW class
	Liquid cooled (180°C / 300°C)	12.9 / 16.6	98.00 / 97.74		
2300 kW / 3100 rpm	Liquid cooled	6.5	98.12		

IMOTHEP

Literature
+ expert guess



a) *Advanced air cooling configuration*



b) *Oil cooling configuration*

Cooling options
(U. Nottingham)

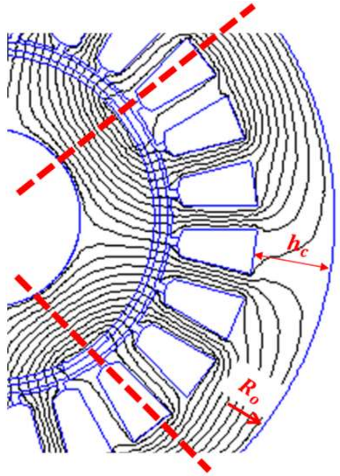
Highlights on electric components studies

Electric generators (SMR case)

- Generator designed in close connection with power turbine definition
- 11 MW machines, 8500 to 9500 rpm
- Permanent magnets synchronous machine
- Advanced materials & aggressive cooling methods (liquid cooling)

➢ **Preliminary performance results**

Parameter	IMOTHEP L1	SoA 2020	Projection 2035
Power density (kW/kg)	**~10 kW/kg** (11 MW)	5-10 (<250 kW) 10-15 (1 MW)	20 - 25
Efficiency (%)	*99%* (11 MW)	95	98
Rotational speed (x1000 rpm)	**9.5** (11 MW)	5-20 (<250 kW) 5-15 (1 MW)	5 -30



❖ **Major issue : cooling** (3% of 11 MW converted in heat)

➢ Mass and integration challenges of required heat exchangers

Highlights on electric components studies

EWIS : influence of DC distribution voltage (SMR radical case)

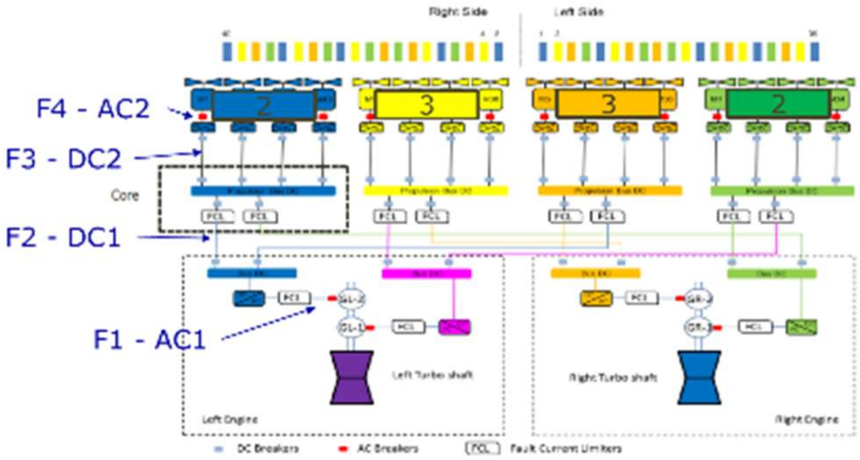
3000 V

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

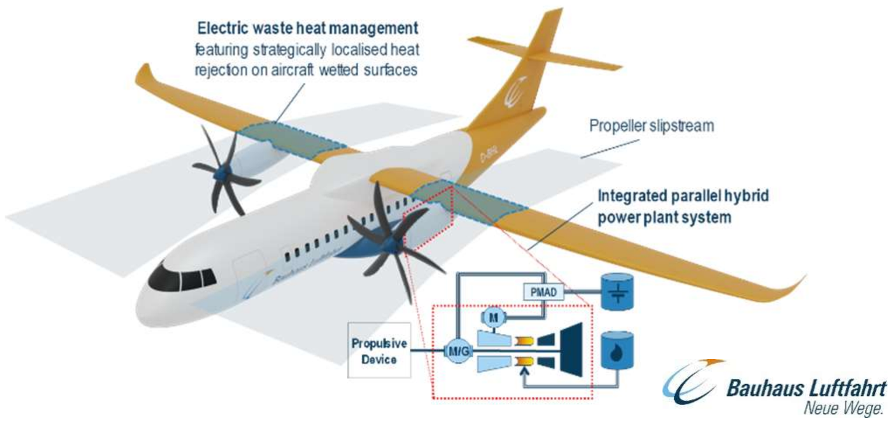
Electric architecture



Some major challenges with electric architecture

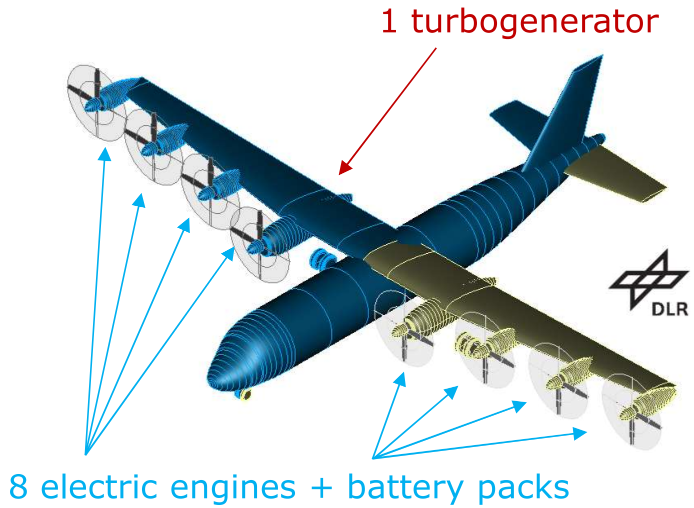
- **Feasibility of high voltage cabling**
  - No clear extrapolation from current 540 V cables' design & installation guidelines
    - ➢ Need for modelling & experimental approaches for high voltage
  - Which insulation solutions to ensure life duration above 1 kV ?
  - Many issues, also for protection device: partial discharge, arcing, breaking capacity...
  - Integration issue
- **Cooling and thermal management : critical for SMR**
  - High power generators cooling
  - Components' operative temperature ⇨ need for control
  - Distributed low grade heat
  - Use of ram-air is a significant factor in aircraft design
    - ➢ Closely linked with configuration
    - ➢ Impact on drag and mass difficult to assess
    - ➢ Need for a parametric model difficult to establish

Preliminary outcomes from configuration studies

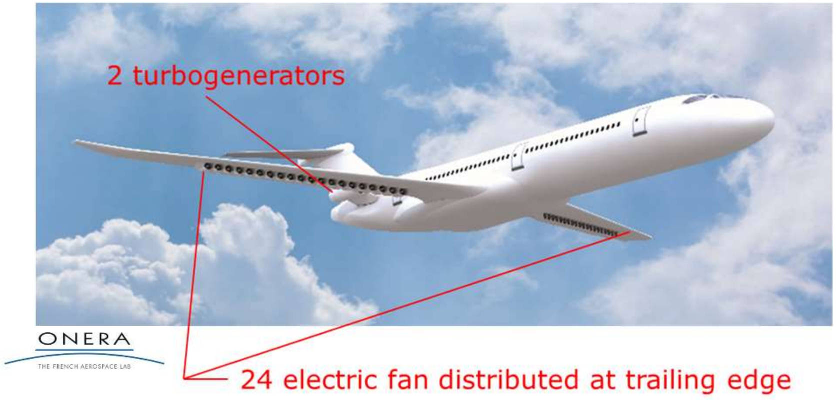


- **Regional conservative : parallel hybrid**
  - MTOW : +30% vs "baseline aircraft"
  - **9.6% fuel reduction over a 200 nm typical mission**
  - But **6% increase on design mission** (600 nm)
  - **Battery specific energy is the main driver**
  - Limited benefit expected from electric system improvement

- **Regional radical : electric + range extender**
  - **60% block energy reduction over 200 nm** (fully electric)
  - **36% fuel burn reduction over 600 nm** (with extender)
  - Strong benefit of efficiency gain from electric chain + configuration-specific optimization
  - Not too sensitive to battery specific energy

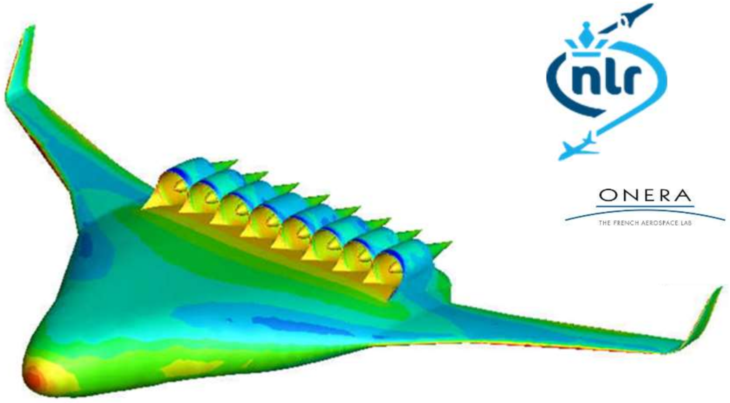


Preliminary outcomes from configuration studies



- **SMR conservative : turboelectric DEP tube & wings**
  - MTOW : +10% vs "baseline aircraft"
  - **No benefit obtained from hybridization**

- **SMR Radical: turboelectric + DEP + BLI + BWB**
  - **No benefit obtained from hybridization compared to the BWB with two turbofans**



> ***For both configurations:***
> - Strong influence of turboshaft SFC
> - Some conservative assumptions for electric components' design

Preliminary conclusions from configuration studies

- **Regional aircraft**
  - Purely turboelectric architecture not perceived as promising
  - Parallel hybrid requires high battery assumptions + reduced mission range
    - *A result that looks consistent with other studies from the literature*
  - The **"plug-in" hybrid with range extender** exceeds IMOTHEP's fuel burn reduction targets ⇨ **Studies in loop 2 to further consolidate the configuration**
  - Batteries are a key component for regional
- **SMR aircraft**
  - **Perspective of benefit looks rather modest for all configurations**
    - Also true for other configurations from literature
  - **At least require aggressive technology solutions** for electric systems

General remark: Refined analysis tends to decrease benefits compared to conceptual Low-Fi design

Conclusions

- **Preliminary analysis to be refined in project "Loop 2"**
- **Ways and benefits for SMR remain unclear and longer term**
  - Huge technology step
  - No clear promising configuration
  - ➢ *Need to further investigate key enablers (superconductivity ?)*
- **An interesting configuration was identified for regional**
- **A step-by-step incremental approach to increasing level of power seems reasonable although technologies are not necessarily scalable**
  - ➢ ***Short term focus on regional***
- **Battery is a key component for the regional configurations studied in IMOTHEP**
  - Will benefit from general research on chemistry
  - But need to check suitability of announced technology for aircraft
    - ➢ Fast charge / discharge
    - ➢ Life duration
    - ➢ …

⇨ **Specific formulation and design may be required**

THANK YOU !

Contact points for any question:

- Project Coordinator
  - Philippe NOVELLI (ONERA)
  - Email: philippe.novelli@onera.fr
  - Office: +33 1 80 38 69 14

- PMO
  - Peggy FAVIER (L-UP)
  - Email : peggy.favier@l-up.com
  - Office: +33 4 78 41 44 47
  - Mobile: +33 6 75 64 10 78

- www.imothep-project.eu

At IMOTHEP team workshop in Eurocontrol, Sept. 2022

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

IMOTHEP
GETTING HYBRID ELECTRIC