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HYLENA project (HYdrogen eLectrical Engine Novel Architecture)

HYDROGEN-POWERED SOLID OXIDE FUEL CELL - GAS TURBINE SYSTEM FOR AERONAUTICAL APPLICATION

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Abstract

HYLENA will investigate, develop and optimize an innovative, highly efficient integrated hydrogen powered, electrical aircraft propulsion concept for short and medium range. It will achieve significant climate impact reduction by being completely carbon neutral with radical increase of overall efficiency.

The full synergistic use of:

a) an **electrical motor** (as the main driver for propulsion),
b) a **contoured hydrogen fueled SOFC stacks** (geometrically optimized for nacelle integration),
c) a **gas turbine** (to thermodynamically integrate the SOFC),

will act as an enabler for hydrogen aviation and will allow for efficient and compact engine concepts.

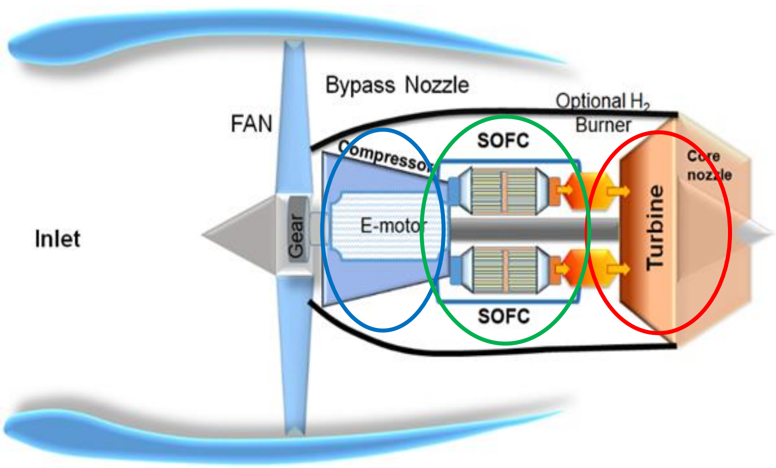

Figure 1: General HYLENA concept

This disruptive propulsion system will be called HYLENA concept.

HYLENA aims to evaluate and demonstrate the feasibility of a “game changing” engine type which integrates Solid Oxide Fuel Cells (SOFC) into a turbomachine, in order to utilize the heat generated by the fuel cells on top of its electrical energy. The combination of e-motor, turbomachine and contoured SOFCs fueled with H_2 will deliver high overall efficiency and performance versus state-of-the-art turbofan engines. Indeed, HYLENA Figures of Merit consist of minimizing CO_2 emission; negligible NO_X and an unmatched overall efficiency versus state-of-the-art turbofans which corresponds to an outstanding performance increase. It will also enable to extend the flight range for the same fuel tank size.

The HYLENA project will deliver:

1. On SOFC cell level: Experimental investigations on SOFC cell technologies and identification of the most promising one(s) for aeronautical applications;
2. On SOFC stack level: Studies and tests to determine the most compact/ light/ manufacturable way of stack integration;
3. On thermodynamic level: Cycles simulations of the proposed novel HYLENA concept architecture and down selection of the most performing one;
4. On engine design level: Exploration, through resilient calculation and simulation, of the best engine design, sizing and overall components integration;
5. On overall engine efficiency level: Demonstration that HYLENA concept can reach very high efficiency levels with limited weight and complexity;
6. On demonstration level: A decision dossier for a potential ground test demonstrator to prove that the HYLENA concept works in practice during a second phase in the continuity of this project.

Keywords: CINEA, Solid Oxide fuel cell, gas turbine, Electrical motor

1. Abbreviations and Acronyms

Acronym	Signification
AIRBUS or AI	When not specified includes all entities AI SAS, AI-Fr and AI-D
ALM	Additive Layer Manufacturing
AM	Advanced Material
AS	Air Supply
BHL	Bauhaus Luftfahrt e.V.
CAEP	Committee on Aviation Environmental Protection

CAJU	Clean Aviation Joint Undertaking
CFD	Computational Fluid Dynamics
CRT	AIRBUS Central R&T
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DMP	Data Management Plan
DMU	Digital Mock-Up
EASA	European Aviation Safety Agency
EAEG	European Aviation and Environment Working Group
ECAC	European Civil Aviation Conference
e-Motor	Electrical Motor
FAA	Federal Aviation Administration
FC	Fuel Cell
GT	Gas Turbine
GTD	Ground Test Demonstrator
HYLENA concept	New Integrated e-Motor-SOFC-GT-Engine
INP	Institut National Polytechnique
IPR	Intellectual Property Rights
ICAO	International Civil Aviation Organization
LUH	Leibniz University Hannover
SMR	Short and Medium Range aircraft
SOFC	Solid Oxide Fuel Cell
TMS	Thermal Management System
TUD	Technical University of Delft
UGA	Université Grenoble Alpes
WP	Work Package

2. HYLENA project overall description:

The HYLENA methodology covers on:

- SOFC cell level: experimental investigations on new high-power density cell technologies
- SOFC stack level: studies and tests to determine the most light-weight and manufacturable way of stack integration
- Thermodynamic level: engine cycle simulations of novel HYLENA concept architectures
- Engine design level: exploration, through resilient calculation and simulation, of the best engine design, sizing and overall components integration
- Overall engine efficiency level: demonstration that HYLENA concept can reach an outstanding overall efficiency increase compared to state-of-the-art turbofan engines
- Demonstration level: a decision dossier for a potential ground test demonstrator to prove that the concept works in practice during a second phase following the initial HYLENA project.

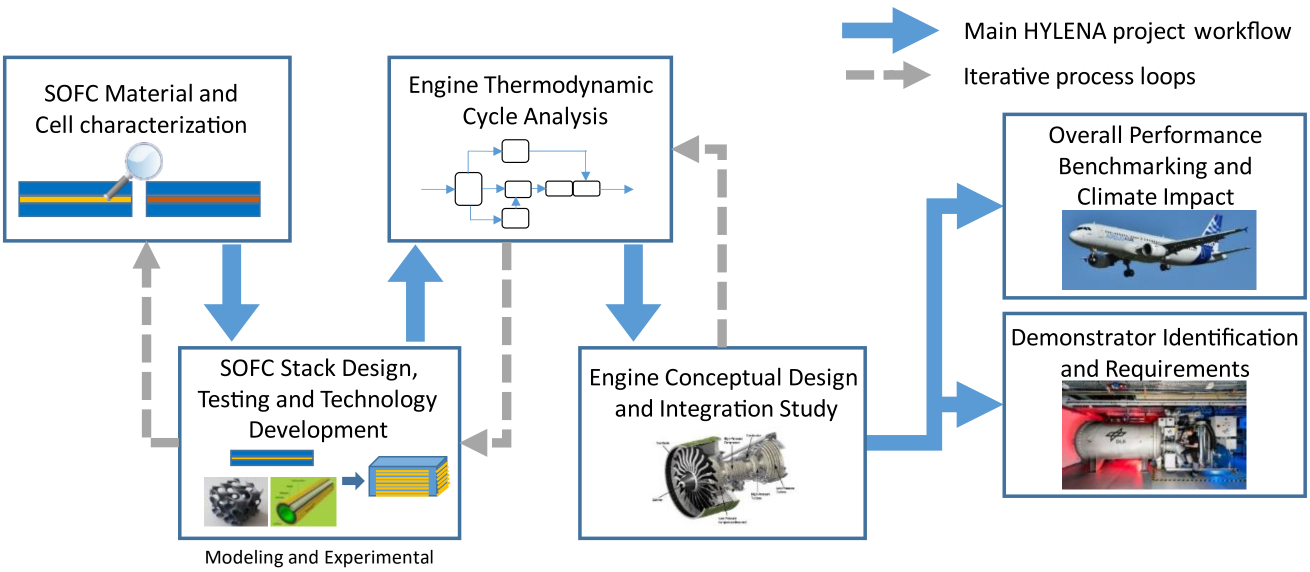

Figure 2: HYLENA structure

3. HYLENA consortium:

The HYLENA consortium consists of one of the biggest aircraft manufacturer (AIRBUS), three major European universities (TUD, LUH, GRENOBLE INP - UGA) and two internationally recognized research institutes (DLR, BHL) . The HYLENA consortium is ideally suited and fully committed to reach the project outcomes. In addition, the consortium has established a strong advisory board with stakeholders from various relevant areas to ensure further exploitation to the market and the society.

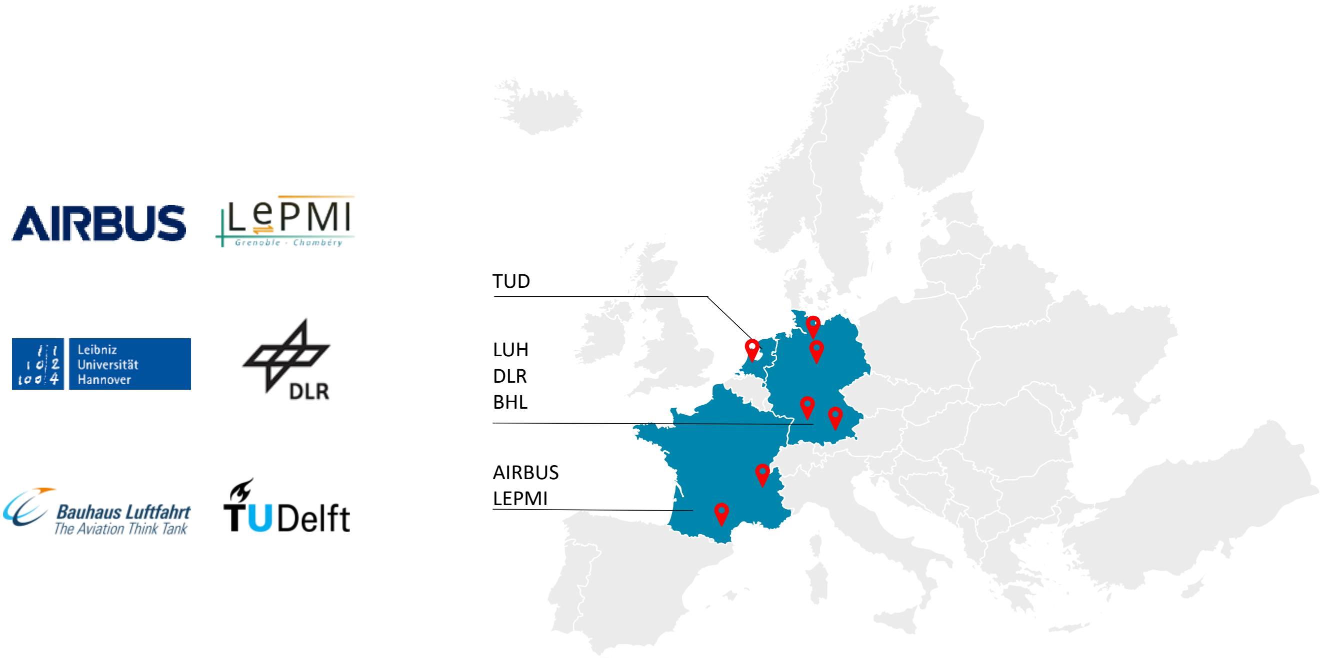

Figure 3: HYLENA partnership overview

4. HYLENA timeline:

As stated above, this project will focus on the SOFC System Study and concept formulation as well as detailed integration performance studies during the project duration of 3.5 years.

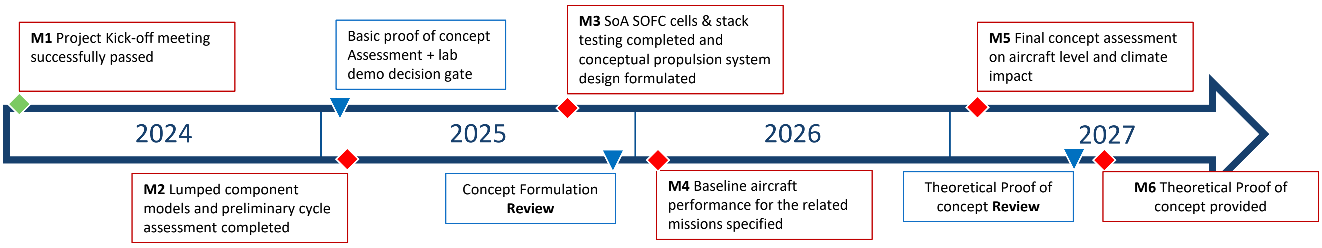

Figure 4: HYLENA timeline

Pending the outcomes of this project stated as phase I, a Phase II will be proposed and will be dedicated to demonstrator definition, manufacturing, assembly and testing with results and final performance assessment.

5. HYLENA Work package description:

HYLENA will focus on the following key aspects:

- Efficiency: HYLENA will study the thermodynamically optimized architectures for integrated e-motor-SOFC-GT concepts and their performance.
- Flexibility: The HYLENA concept engine is a combined cycle which can adapt to different operation modes in an efficient way and can be compatible with different fuels on top of hydrogen due to the high temperature fuel cell. It will be designed for short and medium-range aircrafts, but can later on be adapted to helicopters and urban air mobility, if integration is successful.
- Emissions: Efficient operation in all flight modes enables low block fuel consumption and emission.

As stated in chapter 2, we have defined 6 different WPs to fulfill these goals on top of management and communication/dissemination:

5.1 WP1: SOFC material and cell characterization

The study in WP1 focuses on the electrochemical performance analysis and durability of button cells at atmospheric pressure. The data obtained will serve as input parameters for modeling the SOFC stack for WP2. The activities of WP1 are split into three main tasks:

- The first task involves characterization of cell efficiency and power density using State-Of-the-Art Materials as a function of operating conditions.

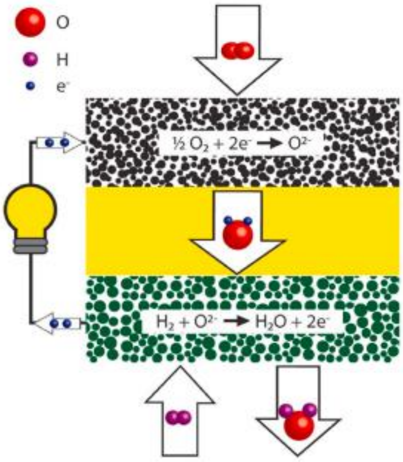

Figure 5: SOFC cell typical electrochemical reaction

- The second task concerns the implementation of Advanced electrolyte and cathode Materials in button cells and the optimization of cell efficiency, power density and lifetime.
- The last task deals with Investigation of an optimized material architecture for SOFC cells.

Figure 6: different types of micro-SOFC

5.2 WP2: SOFC stack design, testing and technology development

WP2 bridges the gap between WP1 and WP3. The aim of this work package is to investigate the heart of the system, the SOFC. The investigations are to be realized both experimentally and simulatively. First and foremost, existing SOFC cell and stack concepts are to be simulated and validated with experimental data. An experimental setup is available for this purpose, which can also be pressurized. The far more challenging goal of this work package is to develop models for a future stack generation that are experimentally supported at cell level. Of course, the gravimetric but also the volumetric power density, which is a decision criterion for civil aviation, should be mentioned first and not least.

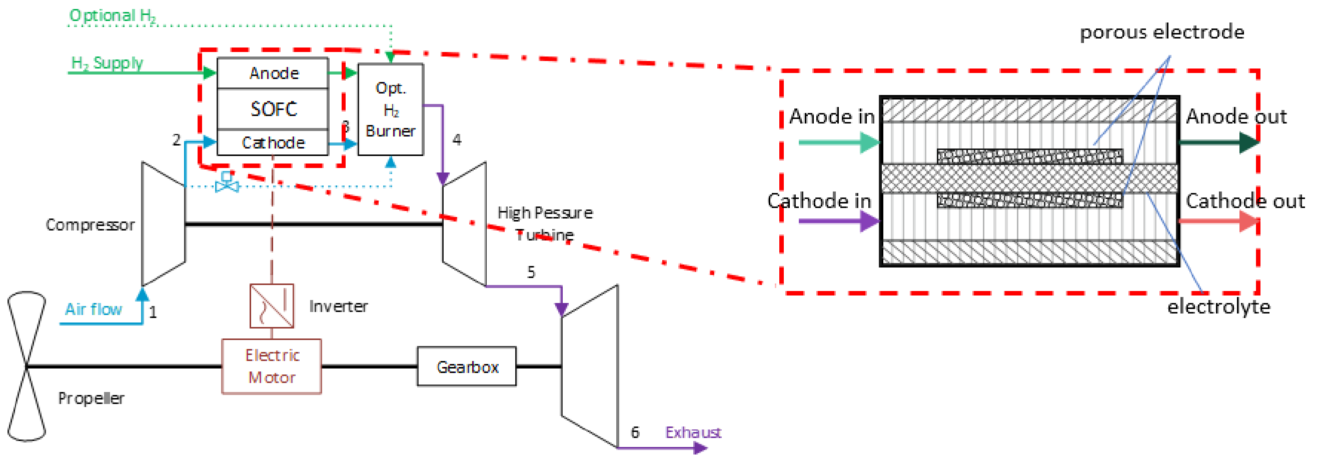

Figure 7: SOFC stack at the core element of the system

As part of the investigations, however, further multi-physical investigations are also carried out to examine the robustness and vibration behavior. The simulations are topped off with investigations in CFD, for example for the SOFC itself, but also for the surrounding components such as the manifolds. Thanks to the close cooperation with WP1, the life cycle of the cell and stacks can also be simulated and analyzed depending on the framework conditions. The bridge to WP3 is built by embedding the experimentally validated models in the simulation environment of WP3 in order to investigate the behavior of the SOFC, both state of the art and future, in the system context. The multiphysically investigated SOFC system and the SOFC model validated in terms of power density provide the basis for the other phases of the HYLENA project, which are much more experimentally oriented.

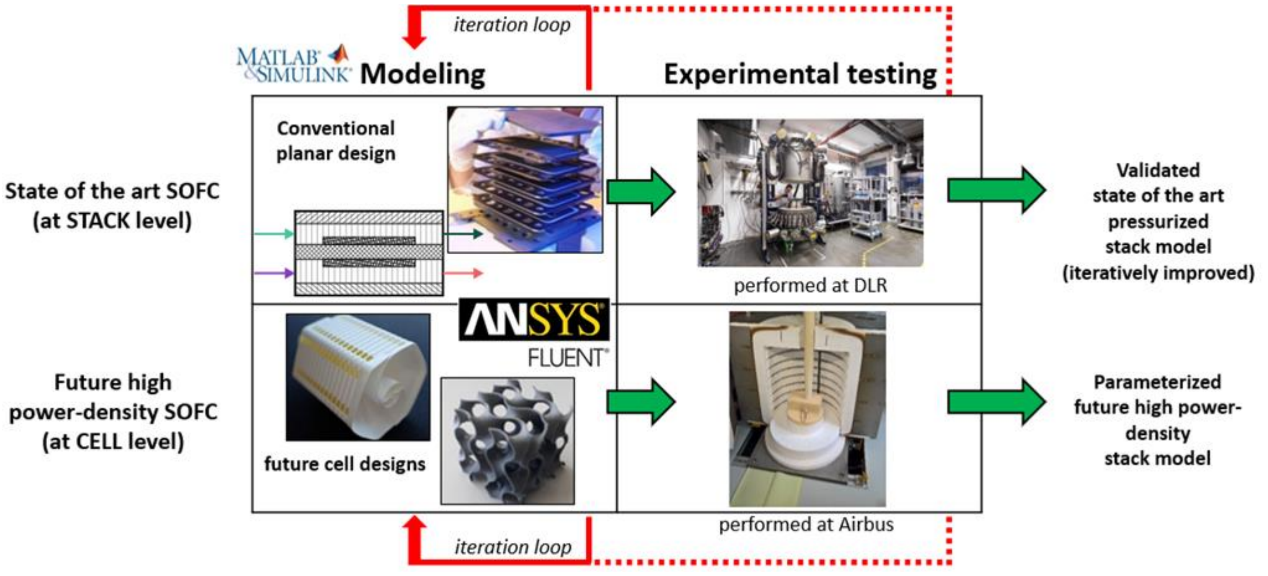

Figure 8: Two-fold approach from WP2

5.3 WP3: Engine Thermodynamic Cycle analysis

To realize an SOFC-GT engine for aeronautical applications, the well-known Brayton cycle with its compressor, combustion chamber and turbine has to be extended by the SOFC (Fig. 9, left). With the consideration of an additional after-burner, this results in a second heat source in the T-s diagram (Fig. 9, right). In addition, electrical components such as inverters and electric motors, as well as heat-exchangers, are required to operate the propulsor and to provide the proper operating conditions for the SOFC itself. These standard components and the constraints imposed by the boundary conditions, e.g. temperature at the SOFC anode and cathode inlet and temperature gradient, lead to a wide range of possible cycle constellations to realize an SOFC-GT engine. In WP3, these possible cycles will be investigated in terms of their feasibility and usefulness as an aero engine from a thermodynamic point of view.

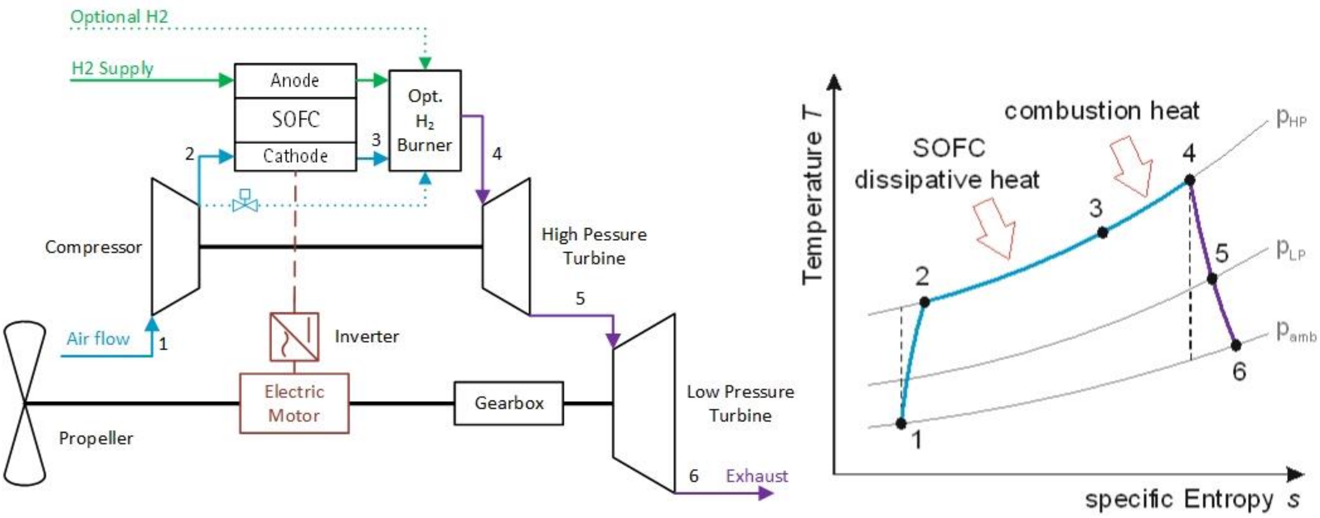

Figure 9: Schematic figure of one HYLENA-concept (left) and the T-s-diagram of a SOFC-Brayton-Cycle (right)

Starting with an intensive literature screening and the definition of possible HYLENA concepts, WP3 will - analogous to the SOFC in WP2 - model the remaining system components as turbomachinery, electric motor or heat-exchanger as first lumped steady-state components. With these components, the wide range of defined HYLENA concepts will be investigated in a steady-state mode for cruise, take-off, and top-of-climb conditions. This thermodynamic exploration study will search for the optimal thermodynamic cycle taking into account, for example, the energetic efficiency, load flexibility and thermal robustness. To save time and computational resources, the study is divided into three sections (Fig. 10). First, an initial down-selection of the wide range of HYLENA concepts will be performed with the lumped component models and generic thermodynamic assumptions. As the research progresses, the components will be refined and modelled in more detail. With these models, off-design and part-load studies can be performed, which, together with the input from the adjacent work packages, will lead to a more detailed geometry and flow arrangement as well as to a more profound knowledge of pressure and heat losses. With the results of the initial exploration study, and later with the more detailed models, an in-depth thermodynamic exploration study will be conducted to identify the most promising concepts for aerospace applications.

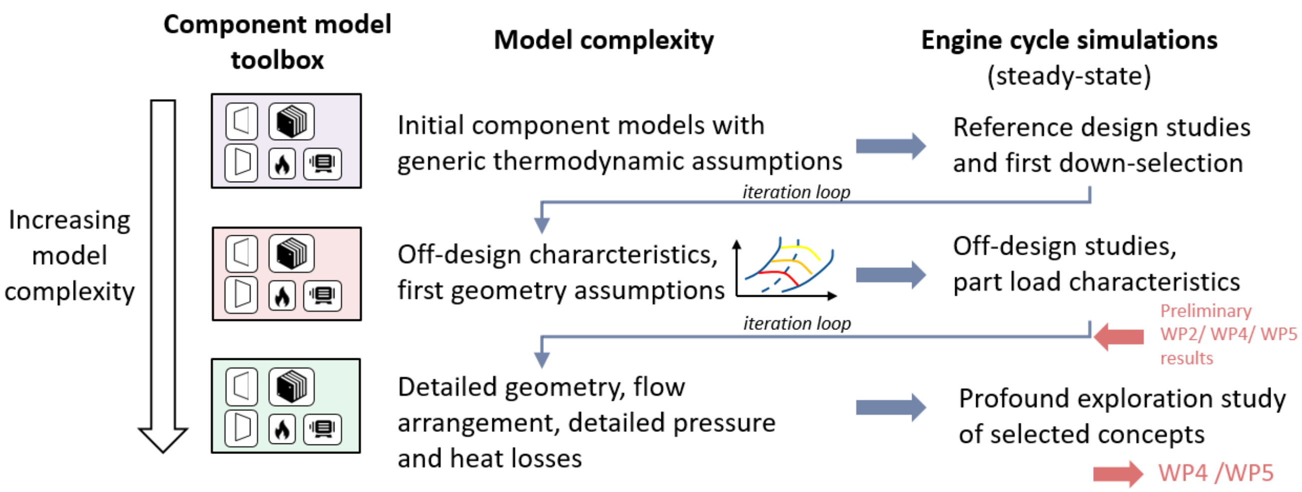

Figure 10: Component modelling in WP3

5.4 WP4: Engine conceptual design and integration

The overall target of WP4 is to perform the engine conceptual design, size the propulsion system and integrate mechanical and electrical components into the overall propulsion system assembly. Specifically, the objectives include exploring conceptual design possibilities for the HYLENA concept, sizing the propulsion system components in terms of mass and geometries and finding integration solutions for the sized components to provide a best-and-balanced conceptual design. Additionally, WP4 involves assessing scaling characteristics, providing key data for further evaluation at overall aircraft level (WP5) as well as delivering a digital mock-up (DMU) of the HYLENA concept to enable the creation of a physical 3D-printed mock-up in WP7.

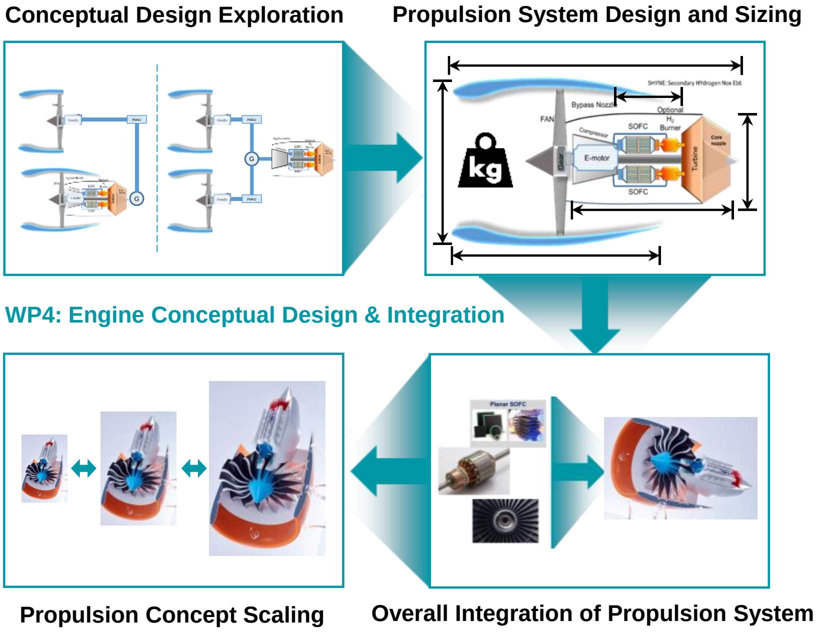

Figure 11: Overall HYLENA conceptual design and integration approach in WP4

The work involves several tasks:

- The first task focuses on conceptual design exploration, including identifying different HYLENA concepts, conducting preliminary assessments, and selecting concepts based on expert judgment. These concept ideas would include different integration options for the SOFC and other key components of the propulsion system. Furthermore, different options for the usage of the electric output power will be investigated.
- The second task involves propulsion system design and sizing, such as adapting and extending the SOFC models from WP3, determining balance-of-plant components, and estimating mass and geometric parameters of the SOFC, turbomachinery and other electrical components. In addition, the preliminary design and sizing of the thermal management system (TMS), which depends on the heat utilization of the overall system, will be performed.
- In a subsequent step the overall integration of the propulsion system, including determining the best overall integration approach of the key propulsion system components and sketching the flow path layouts is covered. Based on this, the geometric arrangement of the HYLENA concept will be derived, resulting as an input for the 3D-printed mock-up in WP7.
- Finally, the last task in WP4 analyses the scaling characteristics of the overall propulsion system with a focus on the SOFC system, to outline the overall potential of the HYLENA concept for different aircraft application cases. For this, sizing heuristics of the key components will be derived and included in the overall sizing methodology in order to make statements with regards to the propulsion system performance and weight at different power classes.

5.5 WP5: Overall Performance bench-marking and climate impact

WP5 aims to benchmark and assess the HYLENA concept aircraft system, evaluate its off-design performance, transient behavior, and emissions, and propose a redesigned aircraft for post-2035 deployment. The comparison will be made against the Airbus 320 neo, an appropriate benchmark for short to medium range (SMR) flights. A key focus is on the off-design and transient behavior of the aircraft's propulsion system. SOFCs are noted for their higher electrical efficiencies compared to low-temperature counterparts, and the high-temperature heat they generate is further utilized in the proposed Turbo-FC engine. The engine must provide the required power efficiently across various flight modes, including take-off, landing, and handling transient load demands. Current SOFC technology faces constraints related to operating temperature gradients, fuel and airflow adjustments, and fuel utilization, which are compounded by their large thermal mass. The proposed hybrid Turbo-FC engine, while offering enhanced operational flexibility, necessitates the development of strategies for off-design operation and a sophisticated control system to enhance transient behavior. The Turbo-FC configurations selected in previous work packages (WP3 and WP4) will undergo dynamic modeling to simulate off-design performance under selected flight modes and conditions. These models will help develop appropriate hybridization strategies and simulate transient behavior at crucial points in the flight envelope, such as start-up, shutdown, and various failure scenarios. This iterative process aims to converge on a configuration capable of delivering the required power efficiently throughout all phases of flight.

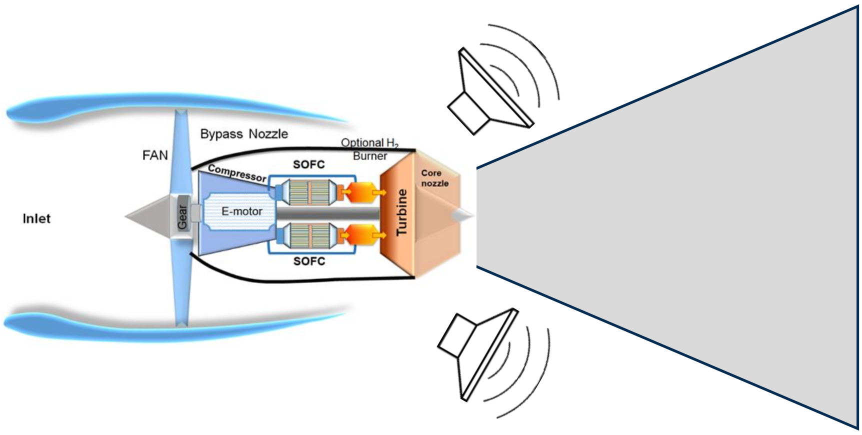

Figure 12: Environmental impact of this new Engine will be a key driver

In parallel, the climate impact analysis will focus on the emission characteristics of the SOFC-GT system, which significantly differ from conventional gas turbine engines. Hydrogen-powered SOFCs eliminate carbon emissions and NOx but produce higher levels of water vapor. Additionally, the system's efficiency and atmospheric conditions may lead to persistent contrail formation, which has a strong impact on climate. If equipped with combustion chambers, the SOFC-GT system may emit limited amounts of NOx, leading to ozone formation and methane depletion in the upper troposphere and lower stratosphere, thus affecting the climate. Using the state-of-the-art climate response model AirClim, a scenario-based study will assess the overall climate impact associated with these emission changes. The study will define scenarios that include demand forecasts and various technology, operations, and fuel options, with the 'business-as-usual' case serving as a baseline for comparison. The impact of water vapor, contrail formation, and NOx emissions will be quantified using appropriate climate metrics.

5.6 WP6: Demonstrator identification and requirements

The objective of WP6 is to perform the technical assessment and planning for the design, construction and testing of a demonstrator test rig for Phase II that could follow this project.
The scope of this demonstrator will be to combine an SOFC with a gas turbine and compressor on ground testing facilities with hardware-in-the-loop emulation for flight conditions under pressurized operational conditions.
In particular this demonstrator is planned to enable to:

- confirm the feasibility, steady state and transient performance of the chosen concept
- validate and recalibrate the performance and mass models that were developed during this project (Phase I) and analyzing the deltas and differences between simulation and experiment
- explore the manufacturing, operations, controls and wear potential issues of the concept

The demonstrator will therefore enable to proof the basic concept and reach higher maturity level of the HYLENA concept.

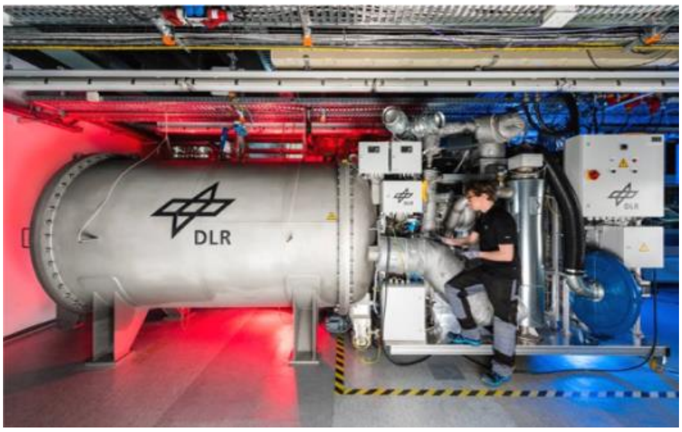

Figure 13: Picture of the hybrid SOFC-MGT emulator at DLR

In order to reach these above objectives, WP6 will address the following tasks:

- Define the requirements to be met by the demonstrator.
- Compile an assessment derived from the WPs 1 through 5, in order to provide a preliminary demonstrator architecture proposal.
- Elaborate a testing plan to indicate the main parameters that define a successful demonstration.
- Preparation of a decision dossier to evaluate the feasibility of a Phase II project, including preliminary studies, a project plan and estimated budget.

6. Conclusion

HYLENA project aims to at least measure the gap between what can be foreseen today in terms of fully integrated eMotor-SOFC-GT engine architecture and a potential airborne Engine application.

We remind that this project will address the following objectives:

- Confirm the expected **high level of efficiency** of the concept engine and its operability all over the flight profile, in steady state and transient operations.
- Accurately and reliably estimate the **thrust, fuel consumption, emissions, weight** and **volume** of the concept engine over the flight profile on several pertinently selected architectures
- Assess the **scalability** of the concept from small regional to Large Passenger Aircraft/Long Range
- Explore the means to address the thermodynamic, architecture, integration and technological challenges
- Define a **Roadmap** giving a fair overview of the evolution of SOFC-GT technology and of its overall Figures of Merit over the next years

In particular, the core study of this project (stated as phase I) will focus on the SOFC stack. Taking into account all the progress currently made on SOFC, it might be possible with some creativity to overcome the gravimetric density issue required to deal with weight constraints.

At the end, the project will confirm the potential overall efficiency we could expect for a typical SMR or regional aircraft application and in parallel open the way to a follow-up project (phase II) with the objective to:

- Develop different physical concepts of SOFC stacks and test them to characterize the best arrangement with regards to different Figures of Merit
- Develop a physical SOFC-GT engine lab test demonstrator

This phase II will enable to confirm the way forward taken on SOFC stack as well as the overall HYLENA feasibility study that is the aim of HYLENA (phase I).

7. Acknowledgment & disclaimer

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9. Copyright Statement