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DESIGN OF A HYBRID TURBO-ELECTRIC PROPULSION (HTEP) WITH FUEL CELLS FOR A REGIONAL AIRCRAFT WITH 80 SEATS. DEMONSTRATION AND VERIFICATION OF SOME SOLUTIONS FOR HTEP ECCOMAS CONGRESS 2024

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Key words: Hybrid turboelectric propulsion, regional aircraft, hydrogen, hybridization level, critical technologies.

Summary. The study is based on the idea that the type of energy supply (hydrocarbon or hydrogen fuel) for the gas turbine and electric engines will determine the design of a hybrid turbine-electric system with "fuel cells" for a regional aircraft with a capacity of up to 80 seats and a range of up to 1,000 km.

INTRODUCTION

This paper is based on research conducted in the EFACA (Environmentally Friendly Aviation for all Classes of Aircraft) project funded by the European Commission through the Horizon Europe Programme (Grant Agreement n° 101056866), inserted on the Climate, Energy and Mobility cluster. EFACA aims to promote a greener and more environmentally friendly aviation sector by developing new technologies through the use of electric and hybrid thermoelectric propulsion systems and new sustainable fuels in order to combat climate change by 2050 (www.efaca.eu).

GENERAL PART

New programs are currently being set up and existing programs are being actively pursued to develop new engine elements and components that will run on alternative fuels (biofuels, synthetic fuels, electric fuels), synthetic fuels blended with kerosene, gaseous or liquid hydrogen. The results of the application of these hydrogen technologies are expected to be on board aircraft by 2030.

A number of general conclusions can be drawn from an analysis of the scientific and technical information of currently available on the development of hybrid technologies for aviation applications:

- In commercial aviation, hydrogen or hydrogen-based fuel mixtures are selected as an alternative fuel for existing and future aircraft. In any case, hydrogen will be on board the aircraft and burned in the combustion chamber. However, hydrogen itself can be stored and used in two forms: in cryogenic form or as a synthetic fuel.

- For small and general aviation, the use of hydrogen as a fuel instead of kerosene (or an additive to the combustion chamber workflow) is not advisable. This is due to use hydrogen on board such aircraft significantly adds weight to the structure and equipment (storage tanks, boost equipment and hydrogen supply). Therefore, for such aircraft, it is advisable to use a powerplant (PP) with battery.
- PP for regional aircraft (RA) (with a capacity of 50-90 passengers) using fuel cells (FC) or batteries are the most energy efficient, environmentally friendly and economical option for the shortest distances. For short-haul aircraft (90-120 passenger capacity) hybrid PP (hydrogen for gas turbine engine or/and FC) is best suited.
- Long-haul hydrogen-powered aircraft are technically and theoretically possible, for example, the Airbus A380 project with a hydrogen engine. However, such projects are too expensive. Currently, a more efficient option for such aircraft is the use of synthetic fuels. A fundamentally different aircraft design (a combination of wing-fuselage) may be able to change the trend in favor of hydrogen. However, such aircraft may appear at least in 20 years.

In order to reduce the environmental impact of aviation, new methods and techniques are being developed to create hybrid powerplants based on the following technologies:

– the use of battery and turboelectric circuits (hybrid technologies),
– direct combustion of hydrogen or hydrogen mixtures in the combustion chamber,
– the use of hydrogen fuel cells to power electric motors.

The analysis of the directions of development of hybrid PP shows that the creation of hybrid turbo-electric propulsions (HTEP) involves several ways:

- Gas turbine engine (GTE) using hydrogen in the combustion chamber. The architecture of the PP includes the existing GTE with an improved combustion chamber and new fuel lines. Significant changes will be made to the airframe design and its fuel storage and distribution systems.
- GTE and electric engine (EE), combined by a common gearbox to drive the propeller. The use of electrical power depends on the operating conditions of the GTE, the flight conditions of the aircraft and its flight profile. This approach requires an energy distribution unit on board the aircraft.
- GTE and a separate EE, which is powered by battery or fuel cell energy.

Further analyses of the design and development process for regional aircraft using HTEP based on the application of FC will be considered through the lens of the objectives of the EFACA project Work Package 7:

- Methodologies for the co-design of aircraft electrical components and their energy management strategies.

- Energy benefits, impact of hybridisation on weight and volume of propulsion system and aircraft.

- Real aircraft flight profiles used to derive a hybridised power supply strategy for the PP.

In view of the above, the issue of determining the integration characteristics of the airframe-hybrid propulsion system is relevant and will have an impact on both the configuration of the

HTEP and the aircraft in general.

The next stage of the work was a review and analysis of the main parameters and criteria for optimising hybrid powerplants, which allowed us to identify the main directions for further research:

– to evaluate the layout scheme of the HTEP as part of the aircraft, indicators and criteria should take into account the quantitative characteristics of the accumulation and consumption of electricity and power of the GTE at each stage of the flight;

– performance indicators of the HTEP as part of the aircraft should take into account the quantitative distribution of electricity from energy sources to consumers;

– application of criteria and performance indicators of HTEP as part of the aircraft generally depends on the aircraft concept (purpose, number of passengers, flight range, number, and location of engines) and does not depend on geometric and weight data of the aircraft.

Thus, based on the review of scientific and technical information on the definition of the main indicators and criteria for optimizing the HTEP with electric motors and FC as part of aircraft the main conclusions are drawn:

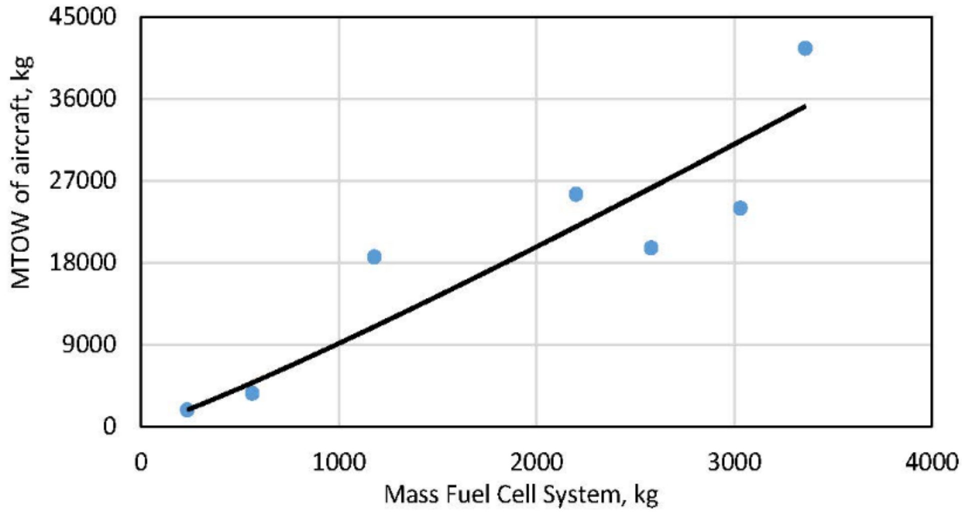

Figure 1: Approximation of the power system mass with FC on board of the aircraft from MTOW

An important aspect for assessing the characteristics of aircraft from HTEP is the strategy for managing the supply of electricity and heat throughout the flight cycle. The degree of hybridisation determines the size of the power plant components, and the operating strategy determines the level of energy efficiency. Thus, the power management strategy will be defined according to the intended flight profile and subsystem size constraints.

The design of a hybrid electric aircraft requires a comparison of the performance of the aircraft with the conventional configurations of existing aircraft designed for the same flight profile. Otherwise, an incorrect comparison of configurations may lead to an overestimation of the advantages of a hybrid electric aircraft.

The overall architecture of the HTEP should be optimised to select the best energy management strategy compatible with the selected airframe configuration and flight profile.

The study shows that a multi-criteria evaluation is required to optimise the HTEP- aircraft system, so that, for example, the evaluation should not only be based on mass or economic performance, but should also take into account the objectives of greenhouse gas emission reduction programs and the level of technological maturity of the system components.

Finally, the criteria and indicators presented below were selected, although it is clear that this list may be modified and/or supplemented in the course of further research.

Characteristics of HTEP as part of a regional aircraft:

- The degree of energy hybridization for HTEP:
- Payload Range Energy Efficiency Indicator (PREE):
- Technology Readiness Level (TRL).

Operational characteristics of the regional aircraft:

Maximum Payload Weight / Maximum Take-off Weight (MTOW);

Economic characteristics of the regional aircraft:

- Fuel consumption per flight cycle;
- The cost of 1-hour flight.

Environmental characteristics of the regional aircraft

- Emission Index (EI);
- Estimated CO_2 emission indicator, which will be adapted for schemes using hydrogen.

The evaluation criteria selected based on the results of the study will make it possible to determine the optimum power supply scheme for the HTEP with FC as part of a regional aircraft.

A preliminary concept of RA with HTEP has been formed and preliminary requirements for HTEP with electric motor and fuel cell have been defined by ANTONOV`s company. In our study, at the first stage of work, the same power distribution between GTE and EE is assumed for all variants: 80 per cent to 20 per cent in cruising mode and 75 per cent to 25 per cent in take-off mode. This is the minimum power distribution required to achieve the 30% emissions reduction required by international environmental programs: 12 per cent through the latest GTEs plus 20 per cent by replacing approximately 20 per cent of kerosene energy with FC hydrogen energy.

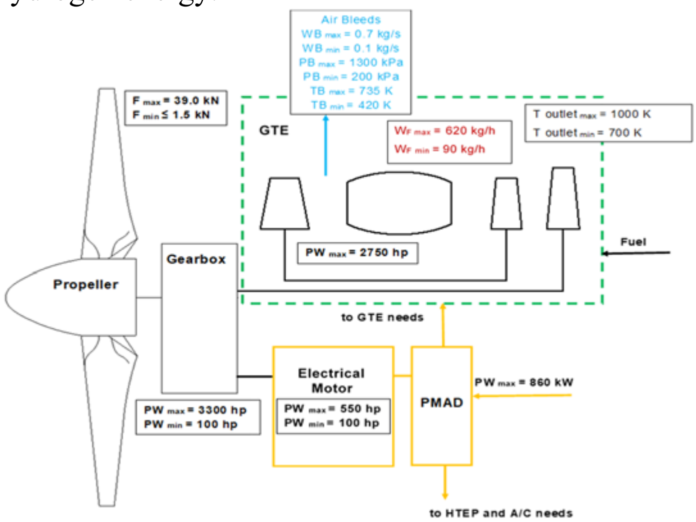

Figure 2: A common part for all HTEP power supply schemes

The HTEP variants differ in the way the GTE and the EE are powered (illustrated in Figure 2). Further work will be to find the optimum system variant, considering that hydrogen can be used both as a fuel for the GTE and as well as for fuel cells, which allow the electric motor to be operated at the same time. Based on the above scientific and technical information, the following energy concepts for HTEP are presented.

At the initial stage, preliminary calculations were performed for the determination of the ranges of the main parameter values of the system components (such as GTE, electric motor, fuel cells, fuel tanks, evaporators, etc.), which are necessary for the further shaping of the image of energy supply systems for HTEP.

In addition, in further studies, all schematic solutions adopt a general propulsion concept including a propeller driven by a gearbox combining GTE and EE.

Based on the IVCHENKO's experience in the design and development of aircraft GTE, parametric calculations were carried out to select the parameters of the main components of the GTE and the design scheme of the engine was selected. In addition, the possibility of using engine air bleeds in the FC module (preliminary engine air bleeds parameters are given in the diagrams), as well as the use of water from the FC for injection into the GTE cycle, will be investigated in the course of further research.

Further research will be conducted based on the strong conviction that the HTEP power supplies will determine the design, dimensions and mass of the propulsion system and the RA in general. Four energy supply schemes have been adopted for further work:

The scheme in which kerosene for GTE and hydrogen from the aircraft tank are used is accepted as a basic one for further calculations and comparison of parameters and characteristics (illustrated in Figure 3).

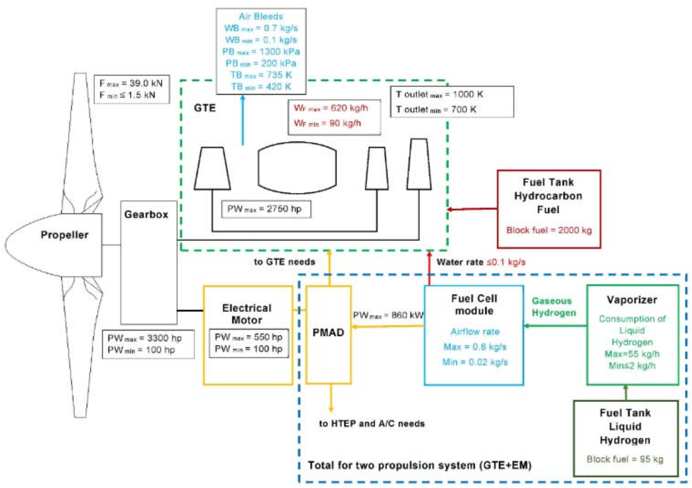

Figure 3: Scheme 1. Using liquid hydrogen and jet fuel

The reduction of pollutant emissions is contingent upon the degree of hybridisation of the aircraft propulsion system for all considered schemes (with the exception of the using of hydrogen as fuel for the GTE).

For all schemes using FC it is necessary to develop reliable systems to ensure its operation (air supply with appropriate pressure and temperature, heat supply/dissipation for the FC module, supply of reaction mass, removal of reaction products).

The principal advantage of Scheme 2 (illustrated in Figure 4) is the near-zero emission of greenhouse gases, which reduces the carbon footprint. However, this is offset by the increased emission of NOx and the large system volume.

Concurrently, all schemes utilising liquid and gaseous hydrogen are associated with inherent safety concerns pertaining to the flammability and explosion risks inherent to their storage and transportation.

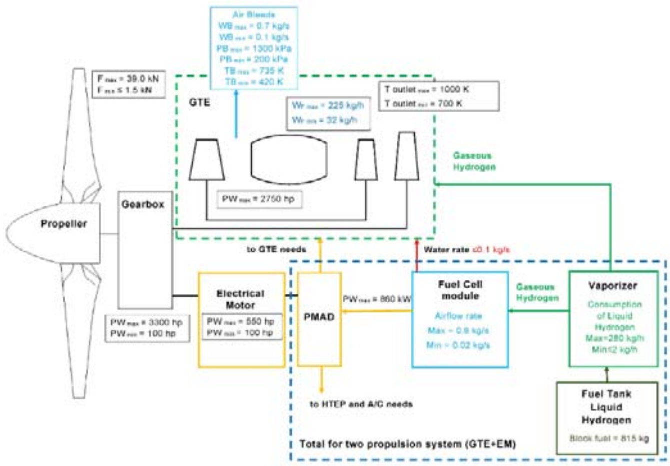

Figure 4: Scheme 2. Using liquid hydrogen

The next scheme under consideration involves the production of gaseous hydrogen for FC module operation from hydrocarbon fuel in a cracking reactor. The capacity of the reactor is selected with consideration given to the production of hydrogen block fuel, which in turn necessitates an increase in the hydrocarbon fuel tank (See Figure 5.).

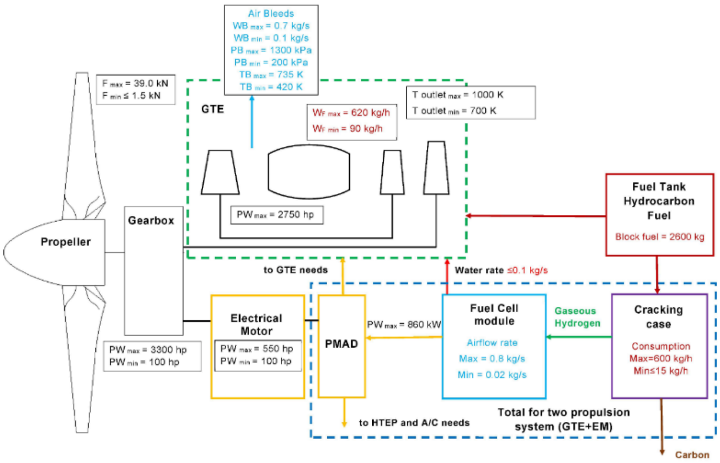

Figure 5: Scheme 3. Using jet fuel to produce hydrogen on a board

In addition to the advantages previously enumerated, it can be posited that the absence of liquid hydrogen tanks on board in this scheme significantly enhances safety.

At the same time, it is necessary to develop a system of reaction product removal for this scheme.

The following scheme illustrates the generation of electrical energy by the FC module from hydrocarbon fuel. The consumption of hydrocarbon fuel will further determine the overall efficiency of the process.

In addition to the aforementioned disadvantages, it is necessary to develop a system for removing reaction products, given that solid carbon (soot) is a by-product and that the design of this type of fuel cell is a complex and expensive process.

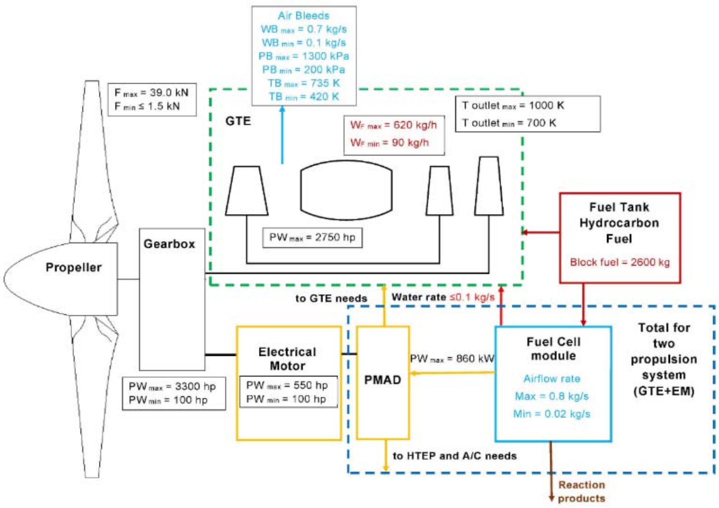

Figure 6: Scheme 4. Using jet fuel and generating electric energy in a fuel cell

The data presented allows for an understanding of the conceptual schemes themselves, as well as a preliminary assessment of the values of the main parameters necessary for further research in order to create requirements for the elements of the HTEP.

The presented data permit an understanding of the essence of concepts, and allow for the preliminary estimation of the values of the basic parameters necessary to define the requirements of the elements of HTEP. A general comparison of the schemes is presented in Table 1.

Table 1: Total table of scheme comparision

Scheme	1	2	3	4
Type of propulsion system	GTE+EE			
Fuel	JF+LH stored	LH stored	JF (H2 to produce on board)	JF
Propulson weight	medium	low	high	high
System volume	medium	high	low	low

To date, the HTEP generic requirements have been developed and constitute a fundamental document for all EFACA consortium partners. They provide a set of input data and requirements necessary for the conceptual design of HTEP components in an 80-seat regional aircraft. The deliverable presents the environmental parameters that are dependent on the adopted operating range of the regional aircraft (temperature, pressure and overloads acting on the aircraft). In addition, a set of individual requirements is established for each system component, including the results of the development of that component.

The conceptual design of the HTEP components (GTE, FC, EE, vaporiser, cracking reactor) is still under development. Each component of the system possesses its own distinctive features.

For instance, when developing a GTE, it is essential to consider the distinctions between the GTE necessitated by a HTEP and that required by a conventional GTE. Such differences include the injection of water (from the FC module) into the GTE duct and its influence on the characteristics of the blade machines (compressors and turbines), which depends on the thermophysical properties of the reaction mass. It is also necessary to consider the characteristics of hydrogen combustion within the GTE combustion chamber. Consequently, a correction must be introduced that is dependent on the thermophysical properties of the reaction products, which are influenced by its chemical composition (kerosine or hydrogen).

With regard to the vaporiser and cracking reactor concepts, the potential utilisation of air and GTE combustion products in the operational process of hydrogen production and evaporation is currently under investigation. (The potential utilisation of the combustion products of a gas turbine engine as a heat carrier). It is crucial to highlight that during the hydrogen production process (in the cracking reactor), one of the reaction products is solid carbon (soot). This presents a significant issue in the development of the system for the removal and storage of reaction products.

The conclusion of the initial phase of our research is the formation of the HTEP concept as a unified entity, encompassing all its components. It is important to note that the HTEP layout will be structured around four schemes for its energy supply.

The next stage of the study will involve determining the aircraft characteristics for each of the schemes and selecting the optimal power supply scheme for HTEP as a part of RA.

The final output of work package 7 of the EFACA project is the definition of the HTEP component requirements that will form part of the roadmap for the development of a regional aircraft with hybrid propulsion.

For all scheme options considered in Work Package 7 of the project, the propulsion system includes an air propeller driven by a gearbox combining GTE and EE. The feasibility of this concept will be assessed in Work Package 1 (First TRL3 demonstration bench-test of novel gearbox combining inputs from turbine and electrical engines).

EFACA's WP1 project will carry out a bench test of TRL3, a new transmission combining inputs from a gas turbine and an electric engine. The concept demonstrator is under development and includes:

1 – AI-450C-2 turboprop engine, PW=550 kW,
2 – gearbox,
3 – electric engine with permanent magnets, PW=110 kW,
4 – propeller pitch governor,
5 – external AC power supply, 380 V or a lithium-ion polymer battery,
6 – charger,
7, 8, 9, 10 – contactors
– AI-P800V7 air propeller, PW=700 kW,
– frequency converter

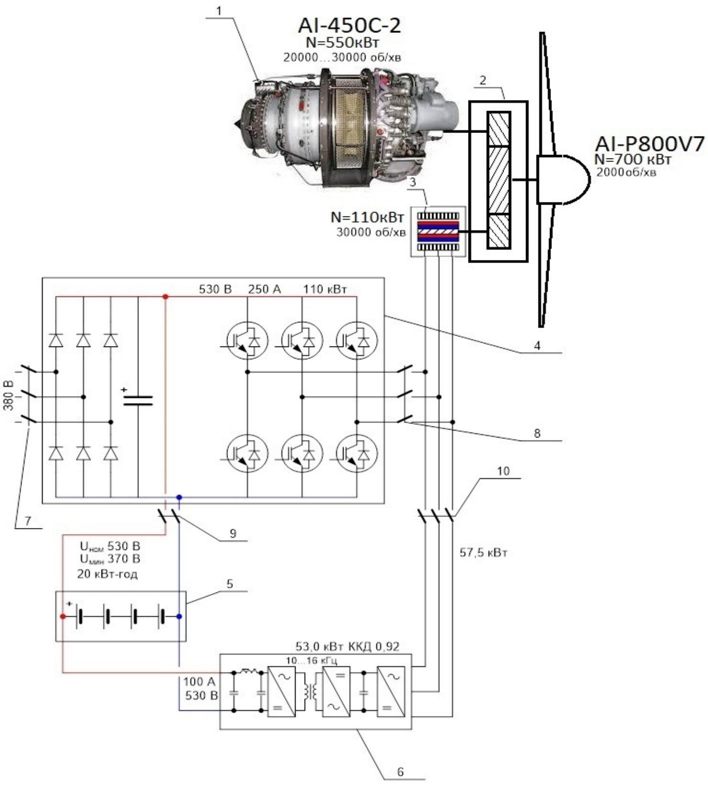

Figure 7: Requirement development for test bench of demonstrator reduction gear

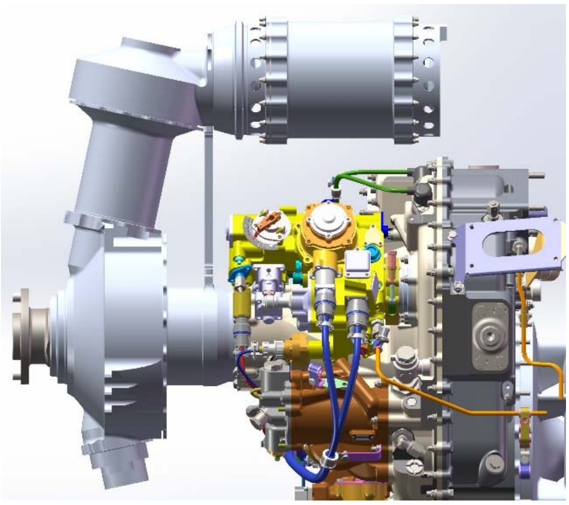

Figure 8: Reduction gear layout

Currently, the detailed layout of the gearbox connecting the GTE and EE has been developed (See Figure 8.), the maximum power of the EE has been selected (20% of the power of the GTE according to the degree of hybridisation of WP7), and the further development of the EE is underway.

Further work is planned as part of the project to test the demonstrator to confirm the performance of the combining gearbox at different powerplant ratings (joint and separate operation of GTE and EE, operation at different levels of 'hybridisation').

To complete all the tasks in Work Package 1, it will be necessary to prepare a dedicated test bench (Figure 9), purchase all the necessary components, manufacture an electric engine and a combined gearbox, develop software to control the GTE and EE to ensure the combined operation of these engines, install all the components of the bench and perform adjusting of all the systems, including the installation of an air propeller with propeller pitch governor. Conduct tests of the gearbox demonstrator as part of the overall hybrid turboelectric system on standard operating ratings of a typical turboprop engine and compare the results obtained with the requirements for the HTEP in Work Package 7. Conclude on the performance of the concept and the possibility of its implementation in the HTEP of an 80 seat regional aircraft with a range of 1,000 km of demonstrator reduction gear.

Figure 9: Preparation of the test bench for HTEP

CONCLUSIONS

- The objective of this study is to assess the validity of the hypothesis that the type of power supply (hydrocarbon or hydrogen fuel) for a hybrid turboelectric system with ‘fuel cells’ will determine the design of a regional aircraft with a seating capacity of up to 80 seats and a range of up to 1,000 km. In other words, the impact of the integration characteristics of the airframe-hybrid propulsion system on both the HTEP configuration and the aircraft as a whole will be determined.
- The study indicates that a multi-criteria evaluation is necessary to optimise the HTEP-aircraft system. This evaluation should not be based solely on mass or economic performance, but should also consider the objectives of greenhouse gas emission reduction programmes and the level of technological maturity of the system components.
- The data obtained in the study permit an estimation of the potential for the creation of diverse power supply schemes for HTEP, along with an assessment of their respective advantages and disadvantages. Furthermore, the data permit the identification of the optimal power supply system for HTEP as a part of a regional aircraft.
- The overarching objective of this research is to establish the concept of HTEP as a unified entity integrated into the propulsion system of regional aircraft. Consequently, the findings of this research will inform the development of a regional aircraft with a hybrid propulsion system.
- As a result of the HTEP preliminary design, the optimum power of the EE was selected to be 20% of the GTE power. The EE operates in all phases of the flight mission, from taxiing to take-off and landing. This solution allows a significant reduction in CO2, NOx and noise emissions.
- It is expected that as a result of the new gearbox demonstrator tests as a part of the

whole hybrid turboelectric propulsion on standard operating ratings of a typical turboprop engine, it will be possible to prove the operability of such a scheme of HTEP with higher power, including for an 80-seat regional airliner with a range of 1,000 km. The recorded characteristics of the basic parameters of the HTEP demonstrator will form the basis for the verification of the HTEP parameters of an 80-seat aircraft.