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ENFICA-FC: Preliminary Survey & Design of 2-Seat Aircraft Powered by Fuel Cells Electric Propulsion

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[Abstract] The main objective of the ENFICA-FC project (ENvironmentally Friendly Inter City Aircraft powered by Fuel Cells), funded by European Commission, is to develop and validate the use of a fuel cell based power system for propulsion of more/all electric aircraft. The fuel cell system will be installed in a light sport aircraft which will be flight and performance tested as a proof of functionality and future applicability for inter city aircraft.

A feasibility study will be carried out to provide a preliminary definition of new forms of commuter aircraft propulsion systems that can be obtained by fuel cell technologies. In parallel, a two-seat electric-motor-driven airplane powered by fuel cells will be developed and validated by flight-test.

The high efficiency two-seat existing aircraft Rapid 200, manufactured by Jihlavan Aircraft, was selected over more than 100 light sport aircrafts and will be used for the conversion from internal combustion engine. The fuel cell system and the electric motor will be integrated on board. The following items shall be pursued:

- **A fuel cell system shall be designed, built and tested in laboratory ready to be installed on board for flying. (provided by Intelligent Energy).**
- **A high efficiency brushless electric motors and power electronics apparatus for their control shall be designed and manufactured ready to be installed on board for flying**
- **Efficiency greater than 90% would be obtained by an optimised aerodynamic propeller design.**
- **A study of the flight mechanics of the new aircraft will be carried to verify the new flight performance.**
- **Flight test bed of the aircraft capable of remaining aloft for one hour will be the main goal of the project to validate the overall high performance of an all electric aircraft system.**

The ambitious results will be to present, in a public event within the scheduled time (Summer 2009), the flight test bed of the aircraft capable of remaining aloft for one hour to validate the overall high environmental performance of an all electric aircraft system.

NOMENCLATURE

AC, DC	=	alternating or direct current	AMU	=	aircraft management unit
AR	=	aspect ratio	b	=	wing span
C	=	shaft torque	C_D	=	drag coefficient
C_L	=	lift coefficient	COTS	=	component off-the-shelf
E	=	aerodynamic efficiency	FC	=	fuel cell
h	=	flight altitude	MTOW	=	max take-off weight
n	=	load factor	OEM	=	empty weight
P, P_{FC}	=	power, power at fuel cell	P_r	=	required power
R	=	blade radius	mac	=	mean aerodynamic chord
S	=	wing area	T_{prop}	=	propeller thrust
V	=	aircraft velocity	W	=	weight
V_{stall}	=	stall speed	η_{FC}	=	fuel cell efficiency
W/S	=	wing loading	λ	=	advance ratio
Ω	=	propeller angular velocity	ρ	=	air density
χ	=	torque coefficient (or power coefficient)	τ	=	thrust coefficient

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I. INTRODUCTION

Rapidly emerging hydrogen and fuel cell power based technologies can now be exploited to initiate a new era of propulsion systems for light aircraft and small commuter aircraft. In addition, these technologies can also be developed for the future replacement of on-board electrical systems in larger 'more-electric' or 'all-electric' aircraft.

The Earth global warming is also becoming a major source of problem for the population and societal stakeholders, and is a key issue for the overall transportation system growth, including aeronautics.

During the combustion of kerosene in today's engines, carbon dioxide (CO2) and water (H2O) are produced. Additionally lesser amounts of sulphur dioxide (SO2), carbon monoxide (CO), nitrogen oxide (NOX) and unused hydrocarbons (HC) are also emitted. The last three substances are considered to be greenhouse gases. Large emission of NOx is produced by engine at airport flight phase. Furthermore the engine technology used in the majority of the general aviation aircraft is decades old. Of the 170,000 piston-powered aircraft flying in USA, most were originally certificated to burn only leaded fuels. Although of less entity, similar situation is also valid for EU.

Although the public health dangers of *alkyl lead* compounds, have been greatly reduced since the ban on leaded automotive fuels, the annual use of hundred million litres of leaded aviation gasoline still presents significant hazards to individuals who may come in contact with the raw fuel.

ENFICA-FC will directly target the **massive reduction of noise and emission developing a new environmental friendly aircraft concept. This great effect will have a strong direct positive impact on the quality of life and health of the Citizens.**

The cardinal advantages are **low noise and low emissions** particularly important for commuter airplanes that usually takeoff and land from urban areas. The possibility to takeoff and land within the **noise abatement regulations** set for small airfields, in urban areas and near population centres, will allow the use of these airfields during the late night hours when the noise abatement regulations are even more stringent. Other advantages of this commuter all electric aircrafts are: high reliability, low maintenance and only slight reduction in engine performance due to altitude.

Fuel cells are energy conversion devices that convert the chemical energy of a fuel and oxidant directly into electrical energy through an electrochemical combination of hydrogen and oxygen (from the air). Apart from electricity the only by-products are heat and pure de-ionised water. There is no combustion and there are no moving parts within the fuel cell. Fuel cells offer: clean, efficient, reliable, quiet and safe systems, which present a wide range of possible applications. Fuel cells provide continuous power as long as fuel and oxidant are supplied. When operated on hydrogen, the by-products of the fuel cell reaction are heat and water. In order to appreciate the advantages, a hydrogen fuel storage system with gravimetric efficiency of 6% provides a Mass Specific Energy of 1100 Whr/kg, compared to 140 Whr/kg for a rechargeable Lithium Ion battery. The fuel cell engines using hydrogen as fuel has an efficiency of approximately 60% compared to 30% using an Internal Combustion Engine (ICE).

For **aeronautics applications**, fuel cell system power density, defined as the power output per unit weight, is a critical parameter. Based on a one-to-one replacement of the current propulsion system with a fuel cell system, it is estimated that nearly a 20-times increase in power density (20 kW/kg) is required to enable all-electric flight of a large commercial aircraft.

Two main fuel cell types are actually under consideration for aircraft applications: PEM (Proton Exchange Membrane) and SOFC (solid oxide fuel cells). Each of these systems offers distinct advantages as well as issues associated with their use in aircraft propulsion applications.

Hydrogen has the advantage that, in principle, there is an unlimited supply of it, although it is fixed in the form of water. Energy has to be used to extract hydrogen from water to make it useable. With a regenerative energies - a closed loop is created with its combustion: water-hydrogen-water. While the combustion value for kerosene is around 42,800kJ/kg, it is 120,000kJ/kg for hydrogen. Hydrogen contains three times as much energy per kg, which in turn means that only a third as much fuel has to be carried to cover a certain range. However, the significantly lower density of hydrogen causes problems with the fuel tanks unless pressurised gas will be used. Hydrogen can be stored in a tank or generated via reformer of a hydrocarbon; hydrogen fuelled propulsion can be exploited trough different routes:

- Fuel cell (which supplies electricity to an electromagnetic motor)
- Internal Combustion Engine H_2ICE
- Turbine
- Hybrid (Internal combustion engines, electromagnetic motor and batteries)

Boeing is currently developing a feasibility study for applying fuel cell technologies for reducing noise and emissions of large transport aircrafts; several applications are foreseen in APU and several sub-systems applications [1].

Boeing is also developing, and will later test, an electrically powered demonstrator airplane as part of a study to evaluate environmentally friendly fuel cell technology for future Boeing products. The airplane manufacturer is working with Boeing's new Research and Technology Center in Madrid, Spain, (including Intelligent Energy (UK), Diamond Aircraft Industries (Austria), the Spanish companies Sener and Aerlyper, and Advanced Technology Products (ATP, USA), the Polytechnic University of Madrid & the Polytechnic University of Catalonia) to modify a small, single-engine airplane (Super Dimona) by replacing its engine with fuel cells and an electric motor that will turn a conventional propeller.

A research was carried out by the Foundation for Advancing Science and Technology Education's (FASTec, USA); **FASTec** sponsored a research on designing, building, and testing a safe airplane, powered by DC electricity from Fuel Cells and advanced rechargeable batteries. The Electric Airplane, or Eplane, was manufactured around an all-carbon DynAero Lafayette III, which was powered by an advanced electric motor supplied by UQM Corp. No any news are available about aircraft flight test.

Airbus is currently coordinating the EU funding project **CELINA** (Fuel **CEL**l Application **I**n **N**ew Configured **A**ircraft)[2]. A feasibility study is being carried out by several partners with the objectives to: Generate basic requirements for fuel cell power system integration with regard to safety, certification, maintenance and installation; Investigate hydrocarbon reforming; Design a fuel cell system including all subsystems; Study the operational behaviour of the fuel cell system on board of an aircraft; Integrate the Fuel Cell System in an un-pressurised zone of an aircraft; Investigate a system concept covering the interaction between fuel cell system and electrical network

The **ENFICA-FC** has been selected for co-funding by the European Commission in the Aeronautics and Space priority of the 6th Framework Programme. The main objective of the **ENFICA-FC** project is to **develop and validate the use of a fuel cell based power system for the propulsion of more/all electric aircraft**. The fuel cell system will be installed in a selected aircraft which will be flight and performance tested as a proof of functionality and future applicability for inter city aircraft. Through this project, the research and industrial Consortium partners will focus on developing and providing operational zero-pollution solutions to the immediate needs of aircraft services. The project will bring together key industrial and academic players in the design and development and validation of intercity aircraft together with fuel cell expertise for propulsion systems and hydrogen storage. The overall budget is 4.5 M€, of which 2.9 M€ will be funded by the European Commission [**http://www.enfica-fc.polito.it/**].

The ambitious project main objective is to develop, and validate by flight test-bed, the use of a fuel cells system as a power source for a more/all electric aircraft propulsion in order to eliminate or drastically reduce the pollutant emission and external noise, with respect to combustion engine or turbo-prop powered vehicles. NO OTHER PROJECT FUNDED BY European Commission will give such ambitious results and it will be presented on ground and in flight in a public event within the scheduled time.

The ENFICA-FC consortium, coordinated by Prof. G. Romeo of Politecnico di Torino, consists of 10 partners representing the whole value chain with aircraft manufacturers (IAI, Evektor and Jihlavan Airplanes), Fuel cells Power system producer (Intelligent Energy), hydrogen distribution (Air Product), research Institutes (Brno University of Technology, Politecnico di Torino, Université Libre de Bruxelles and University of Pisa) as well as a SME in the field of administrative management (Metec). Within the course of the 3 years **ENFICA-FC** project, which was launched on October 2006, two key objectives will be realised:

1) A feasibility study will be carried out to provide a preliminary definition of new forms of aircraft power systems that can be provided by fuel cell technologies (APU, Primary electrical generation supply, Emergency electrical power supply, Landing gear, De-icing system, etc); also Safety, certification & maintenance concepts shall be defined as well as a Life Cycle Cost evaluation.

In defining the Inter-City aircraft systems that can be powered by fuel cell technologies, the feasibility study will take into account the performance improvements of future generation fuel-cells and will thereby show the technical (and performance) advantages that could be obtained in contrast to existing conventional systems.

In addition, the feasibility of an **all-electric propulsion inter-city aircraft** (10-15 seat), completely powered by fuel cells, will be studied in order to assess the impact that a more silent and less polluting aircraft will have in being able to takeoff and land from congested urban areas using short airfields.

2) By the end of the project **an electric-motor-driven two-seat airplane powered by fuel cells will be developed and validated by flight-test at a public event.**

An existing and certified high efficiency two-seat aircraft design will be modified. The fuel cell system and the electric motor will be integrated on board.

- A fuel cell unit and a high efficiency brushless electric motors and power electronics apparatus for their control shall be designed, built and tested in laboratory prior to installation on board for flight;

•Efficiency greater than 90% would be obtained by an optimised aerodynamic propeller design and the flight mechanics study of the new aircraft will be carried out to verify the new flight performance.

•Flight testing of the aircraft capable of remaining aloft for at least one hour will be a major goal of the project to validate the overall high performance of an all electric aircraft system.

The feasibility of the project is dependent on several key-enabling technologies such as fuel cell stack, fuel cell system, hydrogen fuel storage and a safe airport hydrogen-fuelling infrastructure. Another important consideration is that it should demonstrate the path to future economic viability.

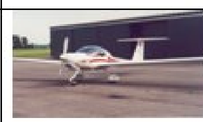
The activity carried out by our research group on the transformation of the two-seat aircraft into a fuel-cell powered aircraft shall be presented in this report.

II. SELECTION OF THE MOST SUITABLE AIRCRAFT AND DESCRIPTION OF CURRENT PROPULSION SYSTEM AND PERFORMANCE

The main objective of the ENFICA-FC project is to develop and validate the use of a fuel cell based on power system for propulsion of more/all electric aircraft.

Since newly developed propulsion system is still limited in terms of available power output, only airplanes in Ultra-light, VLA or LSA categories may be found suitable for conversion into an electric motor driven aircraft powered by fuel cells. A database of candidates has been established by available informations found on websites, including basic information such as geometrical characteristics, performances and costs.

The statistical analysis contains basic parameters of more than 125 airplanes [3-6]. The majority of aircraft is from the ULTRALIGHT category, supplemented by several VLA and LSA airplanes [7-8]. Airplanes highlighted in the graphs include: EV-97 Eurostar, Rapid 200 (airplanes produced by consortium members) and Super Dimona HK-36 (airplane selected by Boeing for Fuel Cell application) [1].

	Rapid 200 (KP-2U)	EV-97 Eurostar	Super Dimona HK 36
Certification	UL-2	UL	VLA
Description			
Max. take-off weight [kg]	450	450	770
Empty weight [kg]	285	269	555
VNE [km/h]	265	270	
Cruise (75%) [km/h]	200	200	185
Max. level speed [km/h]	240	245	261
Stall speed [km/h]	48	65	68
Rate of climb [m/s]	6,5	5,5	4,9
Wing area [m^2]	11,85	9,84	15,3
Wing span [m]	9, 90	8,10	16,33
Take off run [m]	100	145	190
Landing run [m]	90	90	
G-Limit	+4g/-2g	+6g/-3g	
Max. glide ratio	1:14 - 1:18	1:10	1:27
Total tank capacity [l]	64	65	80
Current engine	Rotax 912 (59 kW)	Rotax 912 (59 kW)	Rotax 912 S (74 kW)
Produced by	Jihlavan	Evektor	Diamond

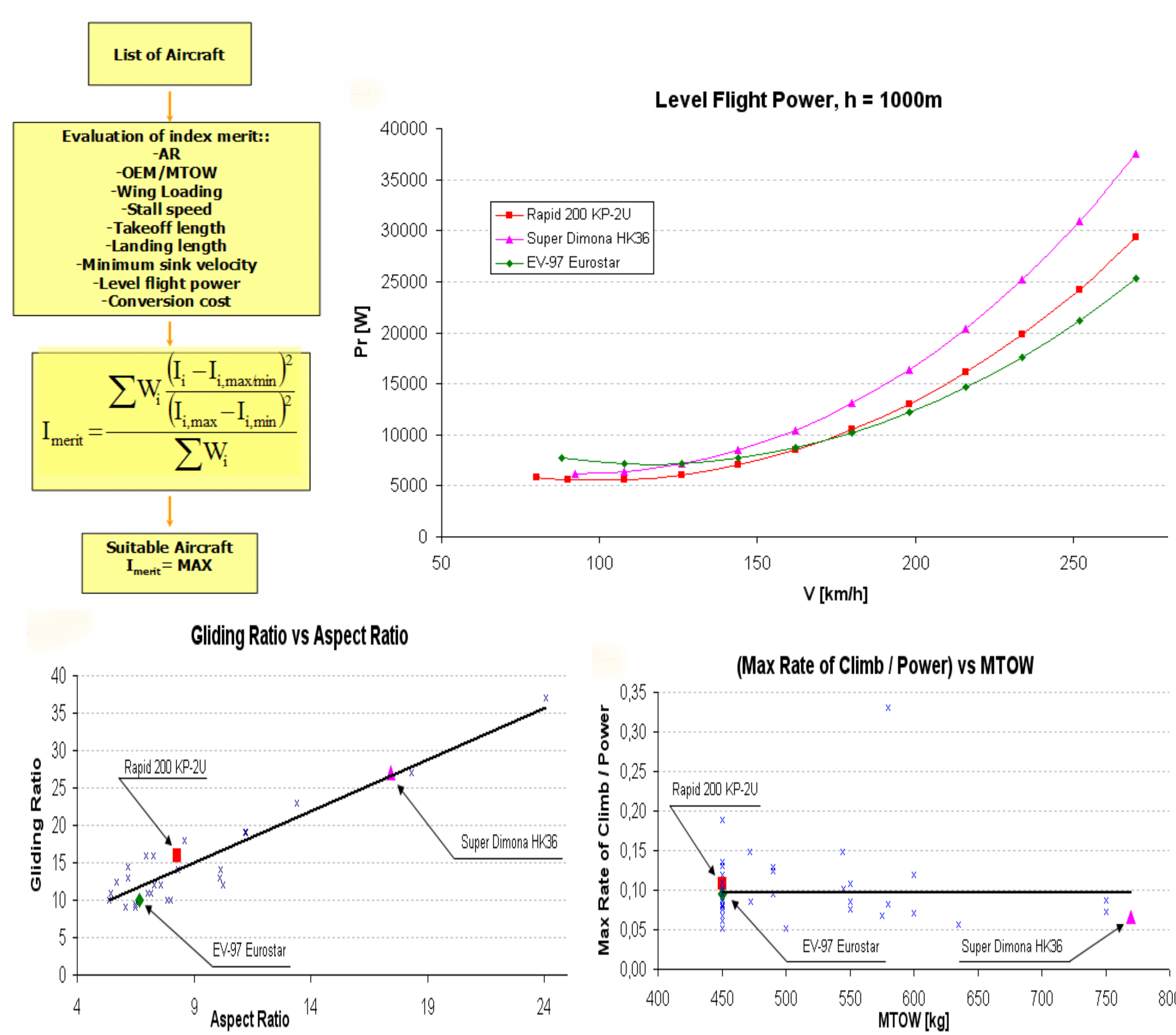
Several basic parameters were investigated for each airplane: a) Dimensions of the most important parts of the airplane; b) Weights and Loads; c) Performance; d) Engine type; e) Landing gear type; f) Price; g) Low wing vs. high wing concept; h) Airframe material; i) Aircraft Category.

Assessment of suitable airplanes was realized in 4 logical steps:

- Weight – performance characteristics
- Aerodynamic characteristics
- Cabin volume and weight available for the conversion
- Technological simplicity of the conversion

Since overall data-bank has more than 125 airplanes, it was necessary to select a limited number of aircraft for the detailed analysis. These airplanes should be considered as suitable candidates for conversion into fuel cell powered aircraft. The procedure identifies each aircraft through nine parameters: 1) Aspect Ratio; 2) Operative Empty Weight / Maximum Take-Off Weight ratio; 3) Wing Loading; 4) Stall speed; 5) Take-Off Length; 6) Landing Length; 7) Minimum sink speed; 8) Minimum required power for Level Flight; 9) Conversion Cost;

In order to consider all the parameters concurring in the selection procedure, a multi-criteria analysis has been used. Calculation is based on 65 Aircrafts, selected from ultra-light category. A total merit index has been carried out (based on the evaluated parameters) and used to compare different aircrafts (Fig.1).



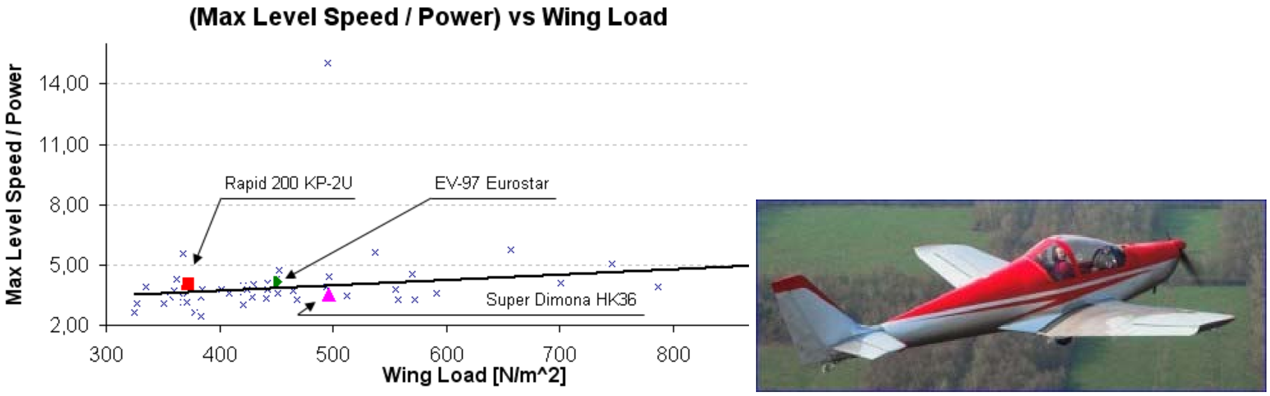


Fig. 1 - Selection Procedure and comparison of several parameters between selected aircrafts – Rapid 200

The weights (from 1 to 3) given to each partial index have been based on the evaluated parameters: for the conversion analysis, the minimum sink speed, the minimum power at level flight and the conversion cost are very important parameters [9].

A multi-criteria analysis has been introduced to perform a preliminary selection of aircrafts suitable for conversion. This analysis comprises four major aspects: characteristics, performance, technology and cost. The index merit results have shown Rapid 200 as a possible good candidate for conversion as because of the good performance as well as the advantage to be a Partner's Aircraft (JIHLAVAN Airplanes). The second Partner's Aircraft EV-97 Eurostar have shown, for the specific application, a slightly lower value of the index merit.

A. Comparison between Rapid 200 KP-2U and EV-97 Eurostar powered by electric engine

Flow chart of how the fuel cells will be fed and the handling of heat and power distribution is shown in figure 2.

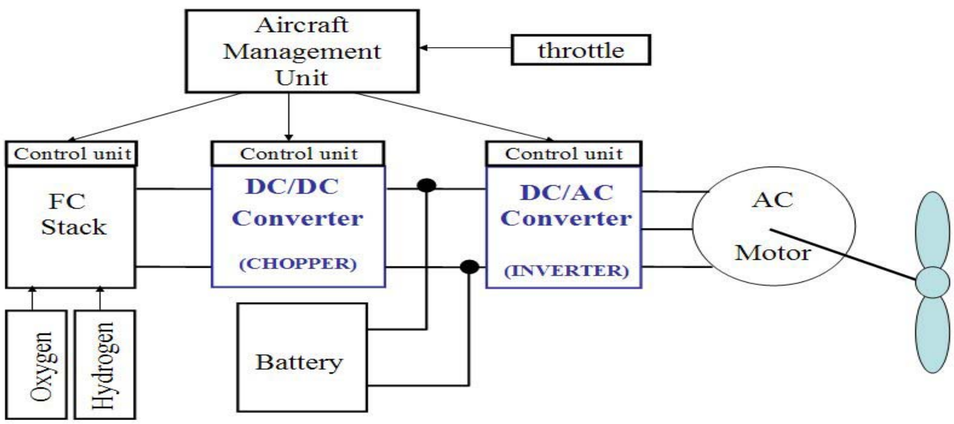


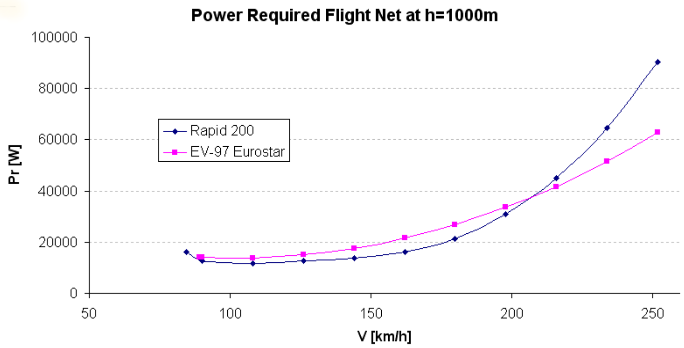
Fig. 2 – Overview on Propulsion System Power Electronics

The engine weight was changed with the new energy system. This includes: a) Battery; b) Fuel cell system; c) H2 system; d) DC/DC converter; e) DC/AC converter

The power should be provided from fuel cell stack for 20 kW and an additional 20 kW from batteries. The battery pack should work for about 15 minutes, for boosting the aircraft during take-off and initial climb from 0 to 1000 m.

The overall system (motor + batteries + inverter + converter) should weight not more than 120 kg. A hypothetical mission profile includes take-off, climb from the sea level to an altitude of 1000 m (with a medium climbing ratio of 2,5 m/s), level flight at 1000 m at about 144 km/h, descent and landing. The total mission time is about 1 h.

Power required for level flight is an important parameter because, for the electric plane, a lower power is required in this flight conditions (Fig. 3). A level flight at 1000m was supposed. It is interesting the power required between 100 km/h and 170 km/h: in this range Rapid 200 KP-2U shows a slightly lower value of the power required for level flight. At 144 km/h, the net power required for level flight from Rapid 200 is 14 kW and from EV-97 is 18 kW; while the power required at fuel cell + battery system is 18 kW for Rapid 200 KP-2U and 23 kW for EV-97 Eurostar.



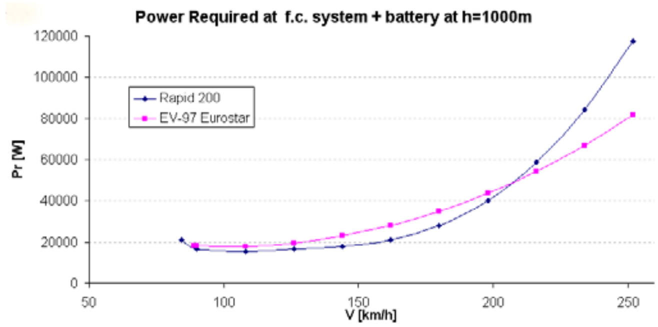


Fig. 3 – Power required for level flight (net and gross)

The low power required at low velocity (about 144 km/h) for a level flight has been evaluated an important parameter for the selection. Also very important parameters have been: the possibility to landing without engine, in case of an engine failure, and the lowest stall speed is a major point in flight safety (it is the most important factor in landing distance).

III. PRELIMINARY CHOICE, BASED ON ALL AVAILABLE DATA, OF A COTS ELECTRIC DRIVE (MOTOR AND INVERTER)

The principal objective is the design and manufacture of the electrical propeller drive system from the converter through to the propeller, ready to be installed in the two-seater aircraft for flight-testing. At present the whole Power Supply Drive system is envisaged to consist of:

- A fuel cell producing about 20-22kW
- Batteries producing about 20kW at take off and climbing
- A DC/DC converter system managing fuel cell and batteries
- A DC/AC inverter driving the electric drive motor
- An Aircraft Power Management Unit and Distribution.

The energy management strategies and the coordination between the converter and the fuel cell system will be implemented on the aircraft power management unit or on the control unit of the fuel cells system.

The work will be de-risked as far as possible by investigating if it is possible to easily purchase the required high efficiency items using COTS (commercial off-the-shelf). This philosophy will be applied to the inverter, electric motor and propeller systems.

It's quite crucial the study and realisation of the Aircraft Power Management Unit and Distribution interfaced between fuel cell system, converter, inverter and throttle, with employment of algorithms of control and management. The demanded control system must be able to carry out also functions of supervision of the entire process in the successive phases of integration. It should be shaped according to an architecture that answers the requirement of the appropriate applications, as far as the various meaningful aspects.

Some possible configurations for the electric power plant for the ENFICA-FC are investigated. The FC stack and the hydrogen storage system are considered as self-standing systems. The rest of the power plant includes the battery pack, the DC/DC converter, the inverter, the electric motor, the propeller and the power control unit. The FC stack will be able to deliver 20 kW of maximum continuous power until there is hydrogen stored in the tank. The battery pack has to guarantee others 20 kW of maximum continuous power for a limited time period (15 minutes), during take-off, climb and, in case of emergency, for landing in safety, which means that the pack should be able to storage 5 kWh. In the following paragraphs some possible system configurations are presented with an analysis of every component excluding the FC stack and the hydrogen tank.

Single systems which compose the electrical power plant are analyzed from the point of view of efficiency and weight requirements. The most important point is to find the system that satisfies all our requirements, without exceeding in weight, and possibly already off the shelf.

A. Battery pack specification

The main problem of this sub-system is the weight: the complete battery pack with all the sub-systems needed to properly work should weight less than 50 kg. This means an energy density of the battery pack of at least 100 Wh/kg. The only of battery which could provide such an energy density is the lithium-ion; these batteries have some safety problems (especially if discharged too much) and needed to be controlled cell by cell. The most critical phase in the battery cycle is during the charge because thermal run-away phenomena could occurs. However, since the charge of the battery will be done on ground it could be controlled and should be perfectly safe. The following requirements shall be satisfied:

- capability to deliver 20 kW constant power for 15 m at a temperature between 20 and 40 °C; recharge is made on the ground, from a power supply outside the airplane, in a narrow temperature range (say 20-40°C).
- maximum total weight, including Battery Management System (BMS), 52 kg (50 kg highly desired). For safety reasons it is mandatory to have supervisory BMS that adds weight to the system.
- voltage range: a voltage span during battery operation located within the window 200-300V is preferable.
- Expected cycle-life should be at least 400 cycles.
- The energy density at a 15-minute discharge is lower than the nominal energy density of batteries, normally computed at a 2-hour or 3-hour rate.

The considered battery system is composed by several modules in series and the connections between modules add weight. Detailed analysis is still under way to attain a more precise evaluation of the battery weight and to determine how to operate to compensate for the higher battery weight, acting on other electric system components.

B. Electronic converters (chopper and inverter)

The inverter has the purpose of transforming electric power into the mechanical power needed by the propeller for the given mission profile. This may be obtained in several different ways, e.g. imposing the mechanical power, or rotational speed, or torque, delivered by the motor. For instance, in case a speed control is chosen, the inverter will make the motor operate at the given speed, and the corresponding torque will be function of the air speed relative to the aircraft and the aircraft angle relative to a horizontal plane.

The chopper has the purpose of defining the power exchanges with the FC stack. For a given battery voltage and stack voltage/current curve, the power flow is a function of control variable of this device (its duty-ratio).

This device also must be interfaced with the Aircraft Management Unit (AMU) that determines the power to be delivered by the stack as a function to the pilot commands.

DC/DC Converter. A DC/DC converter is used to transform DC current with certain characteristics (of voltage and current) in DC current with different characteristics. Since the FC stack and the batteries have an output voltage which depends from the time, such a component is necessary to stabilize the input characteristics in the DC/AC inverter.
Regardless of the configuration selected, the total weight of the DC/DC converters should be equal or less of 15 kg and should have efficiency equal or higher than 95%.

DC/AC Inverter. As for DC/DC converter, regardless of the configuration selected, the total weight of the DC/AC inverters should be equal or less of 15 kg and should have an efficiency equal or higher than 95%.

C. Electric Motor

The electric motor should have the following characteristics:

- Angular velocity between 1500 and 2500 r.pm.
- Efficiency higher than 95%.
- Maximum continuous torque less or equal 250 Nm.
- Weight: less or equal 30 kg.

At the moment three producers have been contacted: Drivetek (CH), Phase motion (IT) and PML (UK). Electric motors form Phase motion and PML are normally liquid cooled while Drivetek could design an air cooled engine, also if it seems that liquid cooled engines could provide better efficiency.

Phase Motion, an Italian industry, has a widely catalogue of electric motors used for several applications. The proposed solution is a frameless brushless motor (Fig. 4), which consist of separately a supplied three phase stator and a rotor unit. It provides: a) the highest torque density available today for direct drive; b) the least weight. c) the rotor unit is suitable for direct assembly inside the structure of the machine.

From the general aircraft propulsion scheme shown, it is clear that:

- o FC stack failure or Chopper failure or Battery failure implies the loss of half the propulsion power (20 kW). To avoid total loss of propulsion power the AMU must be designed to manage the event of a FC stack or chopper failure in such a way that this does not cause any system block.
- o The inverter failure implies the loss of all the propulsion power (20/40 kW). For increasing the system realibility, the possibility of splitting this device into two independent units is being considered, although its implications in terms of cost, weight, space occupation, control complexity.

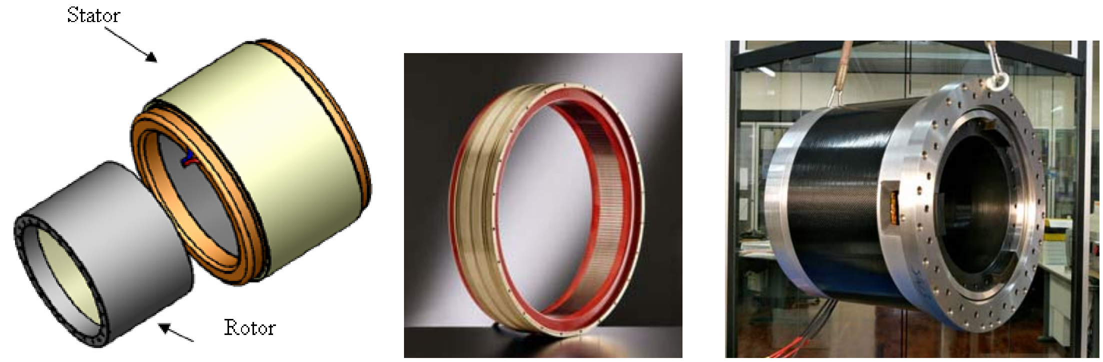


Fig. 4 - *Frameless Motor;* ***Stator*** ***Rotor***

IV. DESIGN OF OPTIMAL PROPELLER

The results of an optimized propeller for the ENFICA-FC project are presented. Two algorithms were used: the first allows for the determination of the geometric characteristics of the maximum efficiency propeller for a given operative condition and profile distribution along the blade. The output of this first analysis is the chord and twist angle distributions along the blade, together with its efficiency, torque and thrust for the operative condition. The second algorithm allows for the evaluation of the propeller efficiency, torque and thrust for a given geometry when the blade pitch and operative condition are changed. Both algorithms were developed by the Politecnico of Torino and have been validated by comparison with experimental data [10].

Two coefficients, thrust coefficient and torque coefficient, have been defined,:

$$\tau = \frac{T}{\rho \Omega^2 R^4} \qquad \chi = \frac{C}{\rho \Omega^2 R^5} = \frac{P}{\rho \Omega^3 R^5} \quad \text{since} \quad P = C \cdot \Omega$$

(torque coefficient could also be written as function of power consumed by the propeller at the shaft)

Another dimensionless parameter is introduced, the so called advance ratio: $\lambda = \frac{v}{\Omega R}$

The design of the optimized blade has been carried out in two different conditions: cruise (case A) and climb (case B). The two designs are then compared. In both cases, the design of the optimized blade requires the a priori knowledge of the number of propeller blades: the analysis is carried out for 2 and 3 blades.

The optimization algorithm uses an aerodynamic theory based on classical results obtained from the integration of vortex theory, wing theory and momentum theory [11, 12]. A compressibility correction is used introducing a semi-empirical factor which corrects the lift and drag coefficients. Experimental code validation is illustrated in Ref [13]. The evaluation of the aerodynamic performance of the propeller and its optimisation requires the detailed knowledge of the airfoil used for the blades which should provide the values of drag and lift coefficients as function of the angle of attack and Reynolds number. A ClarkY profile is selected for the first iteration of propeller design. An aerodynamic database has been created as function of the angle of attack [-10° /+25°] and Reynolds number [from 10^3 up to 5×10^6].

The following parameters are adopted for designing the blade in cruise condition:

h=1000m; V= 40m/s; Ω=2000rpm; T=340N; R=0.8m; blade=2

The chord and twist angle distributions versus the dimensionless radius for a blade optimized for the cruise conditions are shown in figure 5. In these conditions the efficiency of the propeller reaches the 90%. The optimal collective pitch angle is equal to 22.8 deg.

Using the second algorithm[10], it's possible to evaluate the behavior of the propellers outside the design condition. The propeller is considered fixed-blade: the collective pitch angle is fixed and equal to the optimal one. This means that when the flight condition changes, the angular velocity of the propeller (and so the angular velocity of the engine) has to change. However, also different collective pitch angles have been taken in account.

Thrust and Torque coefficient and Efficiency versus advance ratio are also plotted in Figure 5.

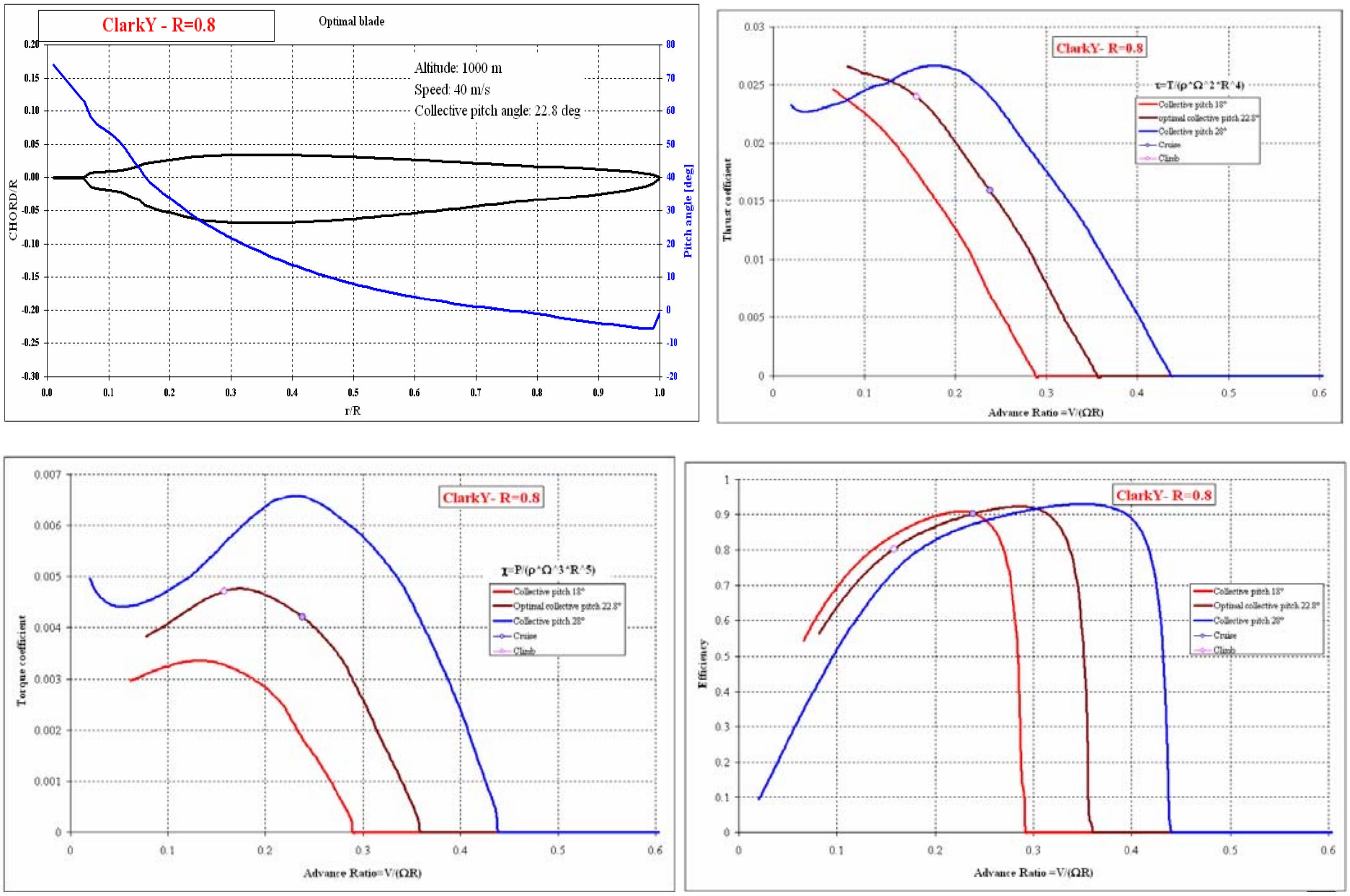


Fig. 5 - Blade optimized for the cruise conditions. Chord and twist angle distributions versus dimensionless radius. Thrust and Torque coefficient and Efficiency versus advance ratio.

Many other optimum propeller were designed; differences between propellers are quite light; however, the two blades propeller seems to have a slight advantage in term of weight and it is easier to built and cheaper then a three blades one. The analysis has shown the hypothetical possibility to obtain a 90% efficiency propeller for cruise condition and about 80% for climb condition. This results are quite good if compared with the maximum theoretical efficiency that it's possible to reach in such conditions.

V. PRELIMINARY PERFORMANCE AND ANALYSIS OF THE AIRCRAFT STABILITY

Starting from the basic empty weight configuration and adding the new electric and energy system, the new aircraft Centre of Gravity (CG) position would be determined in an attempt to maintain it within the conventional value.

When possible the solutions suggested by the energy system provider shall be maintained; however, since the CG & flight performances shall depend from the FCS system, it should be necessary to carry an interaction process in order to maintain or improve the best performances of the aircraft. The preliminary 3D drawing of the aircraft as well the analytical study of CG and flight performances of the aircraft have been started.

A flight dynamic analysis has been performed, in the preliminary design phase, to have a first estimation of the airplane Handling Qualities and a rigid mathematical model has been therefore used to describe the flight dynamics of the aircraft [14,15]. The approach used to analyse the dynamic behaviour of the airplane has been to use the uncoupled, linearised equations of motion solutions. A Matlab-Simulink flight dynamic software has been developed to solve out the equations. For each flight condition, after the trim conditions have been determined, it is possible to obtain the aircraft response to any step impulse of flight control surfaces. The following data has to be supply to the software: MTOW, S, mac, b, aircraft Inertia moments, aircraft aerodynamic polar and aerodynamic derivatives.

A maximum weight of 550 kg has been considered for a preliminary analysis of the aircraft stability. Two flight conditions have been considered: cruise and climb; a steady flight at 1000m at an average velocity of 40 m/s and a climb flight to 500m at an average velocity of 30 m/s, with a ramp angle of 4,0 deg. In both cases, the response of the aircraft at a flight control impulse has been evaluated at 1 deg impulse of elevator, for the longitudinal stability, at 1 deg impulse of aileron and of rudder for the lateral/directional stability. Eingenvalues, damping and frequencies for the longitudinal and lateral/directional stability are determined.

Longitudinal Stability. The assumptions made in the analysis are that the effects of lateral motion on the aerodynamic and propulsion forces and moments associated with the lift L, drag D and thrust T forces are negligible. Of course, in the model linearization, we also assume that the motion of the vehicle is undergoing small changes in the variables ΔV (airspeed), $\Delta\alpha$ (angle of attack), Δq (pitch rate) and $\Delta\theta$ along with small inputs in the elevator deflection control $\Delta\delta e$. Characteristic roots of the longitudinal model are given by the eigenvalues of the system matrix considering a steady flight at 1000 m.

We can distinguish two basic modes: the phugoid mode and the short-period mode. The phugoid mode is the one that has the longest time constant and is usually lightly damped. Responses of the aircraft that are significantly affected by the phugoid mode are the velocity and the pitch attitude. There is very little response seen in the angle of attack when the aircraft is excited in the phugoid mode. The short-period mode is displayed in the motion of the airplane $\Delta\alpha$ and Δq. It has a relatively short time constant (hence the name short-period). In most situation, this mode is relatively well damped. All the longitudinal modes (short and long period) are stable (Fig. 6a).

Lateral Stability. The assumptions made in the analysis are that the effects of longitudinal motion on the aerodynamic and propulsion forces and moments associated with the lift L, drag D and thrust T forces are negligible. Hence, the motion in the lateral axis is decoupled from the longitudinal dynamics. The lateral dynamic model is described by a set of 4 linear ordinary differential equations in the variables $\Delta\beta$ (side slip angle), Δp (rolling angular velocity) Δr (yaw angular velocity) and $\Delta\phi$ (bank angle). There are 3 modes associated with the lateral motion analysis:

The spiral mode is a slow mode that is associated with a real root depicting predominantly motion in the roll attitude. Its value is significantly affected by the damping in roll from the term CLp (i.e. rolling moment due to roll rate). In cruise condition this mode may even be unstable; but since it is a very slow mode, the pilot can interact and correct satisfactorily for the spiral instability. The Dutch-roll mode is an oscillatory mode with significant components in the yaw and the roll variables. The roll mode is usually associated with a real root which is very stable. The motion is predominantly in roll rate p and settles down quite quickly.

Shown in Figures 6b are time responses in the lateral motion to a separately applied impulse input at the aileron control surfaces. One lateral mode is not stable but it has an high period, which means that it could be easily controlled The same result was obtained for directional modes.

As expected, the aircraft has a stable behaviour in cruise condition, but it needs to be controlled by the pilot, especially in the lateral manoeuvres. In climb conditions, the aircraft is stable in its longitudinal plane, but it's not stable in its lateral plane: however, since the period of its unstable modes is very high, it could be easily controlled.

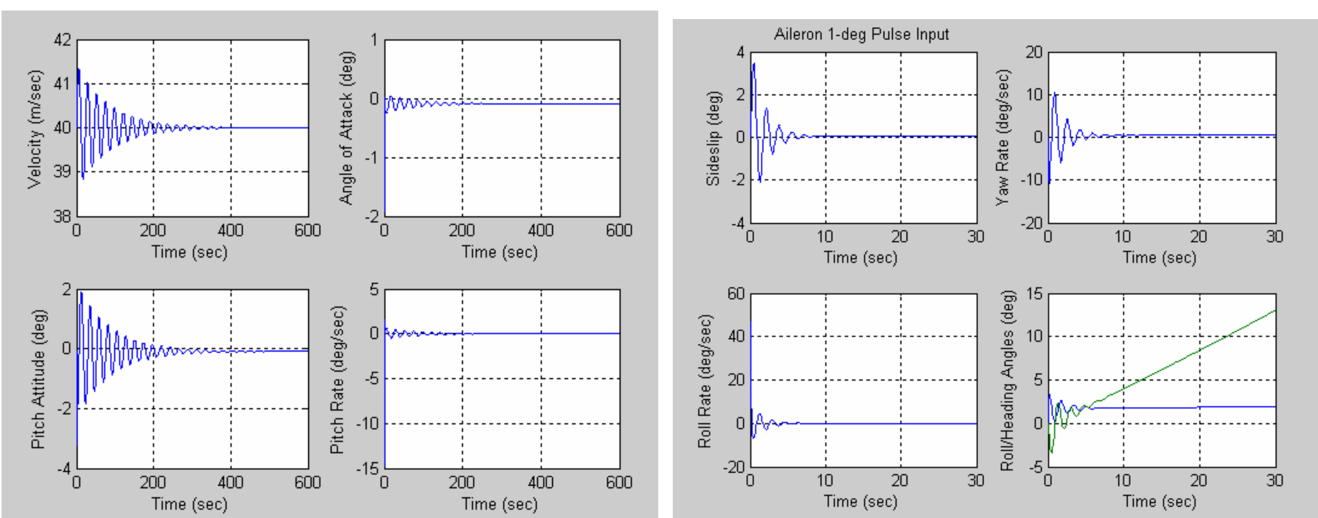


Fig. 6 – a)Response of the aircraft at 1 deg impulse of elevator; b)Response of the aircraft at 1 deg impulse of aileron.

VI. PRELIMINARY PARAMETRIC SIZING

A preliminary parametric analysis has been carried out to analyze which improvements would be possible in the future in the overall system as efficiency and performances of few elements will be increased. At moment only two parameters have been take into account: H2 tank storage efficiency and power density of the fuel cell stack.. The parametric sizing has been carried out considering a typical mission profile (take-off, climbing, cruise, descent) (Fig. 7).

The results of this preliminary analysis affects three parameters: the volume occupied from the power plant (batteries, converter, inverter, FC stack and the electric engine), the payload and/or the cruise time improvement (endurance improvement). In the future, other parameters will be included in this analysis, such as the fuel cell efficiency (constant at the moment), the electric engine power density, the batteries power density and so on.

The piston engine and the normal fuel tank of the Rapid will be substituted with an electric power plant composed by a H2 tank, a fuel cell stack, a DC/DC converter, a Li-Ion battery pack, a DC/AC inverter and an electric engine. Data from COTS components have been considered; using this data it's possible to evaluate the power required at the FC stack and batteries.

Battery energy density (including battery management unit)	100	Wh/kg
Battery average density	2000	kg/m3
Power distribution power density (converter, inverter)	2500	W/kg
Power distribution system average density	2000	kg/m3
Engine weight	35	kg
Engine volume	0.028	m3
Maximum power at the FC output	20000	W

COTS Components data

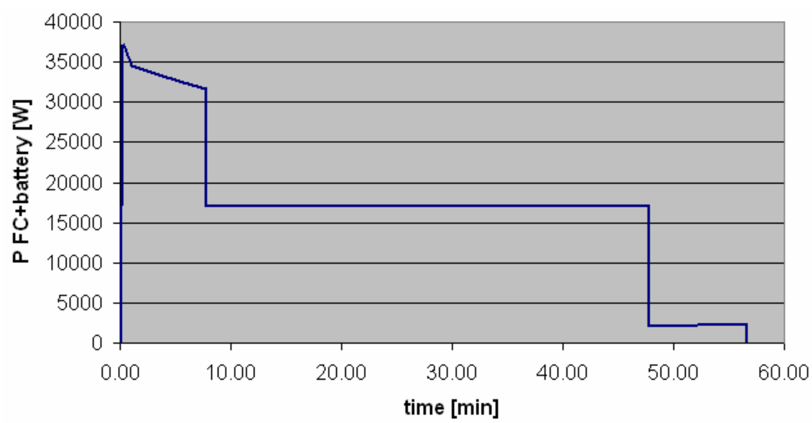


Fig. 7 - Power required at the FC stack and batteries

As it's possible to notice, since the maximum power at the FC stack is 20kW, the battery have to supply the remaining required power during the take-off and the climb phase. It appears that the battery have to supply a maximum continuous power of 17 kW (during the take-off). For security reasons, it was assumed that the battery have always to supply the maximum continuous power. Using this information and considering 5 minutes of battery reserve for security, the battery pack is designed.

The power distribution system (inverter, converter and power management unit) is designed, considering a peak power of the system of 40 kW (at the FC and battery output). A weight of 36 kg is expected for inverter, converter and PMU with a volume of about 0.017 m^3

It is possible to extrapolate the power required only from the FC in the different mission phases (notice that when the power required at the power plant is greater than 20 kW, the power supplied from the FC is 20 kW. In the other case, the FC supplies all the power required). Using this data and assuming the FC efficiency constant, the H2 [kg] needed is evaluated with the following equation:

$$m_{H2} = \frac{P_{FC} \cdot t}{32166.67 \cdot \eta_{FC}} \qquad \text{(t expressed in hours)}$$

A 4% reserve is considered. With this assumptions the H2 mass for the basic mission results of 1.15 kg.

Two parameters have been considered: the H2 tank storage efficiency and the fuel cell power density. The H2 tank storage efficiency is the ratio between the H2 mass [kg] and the tank mass [kg]. Apart these two parameters, the storage pressure [atm] has been changed in order to evaluate the power plant volume (Fig. 8a). For a certain storage pressure, there is a strong reduction in the power plant volume for values of the FC power density bounded between 200 and 1000 W/kg. After 1000 W/kg the slope of the curve decreases and there is not a great gain in volume. On the other hand, for a fixed FC power density, the volume of the system decreases with the storage pressure; however, from values of 200 atm, this reduction is quite low.

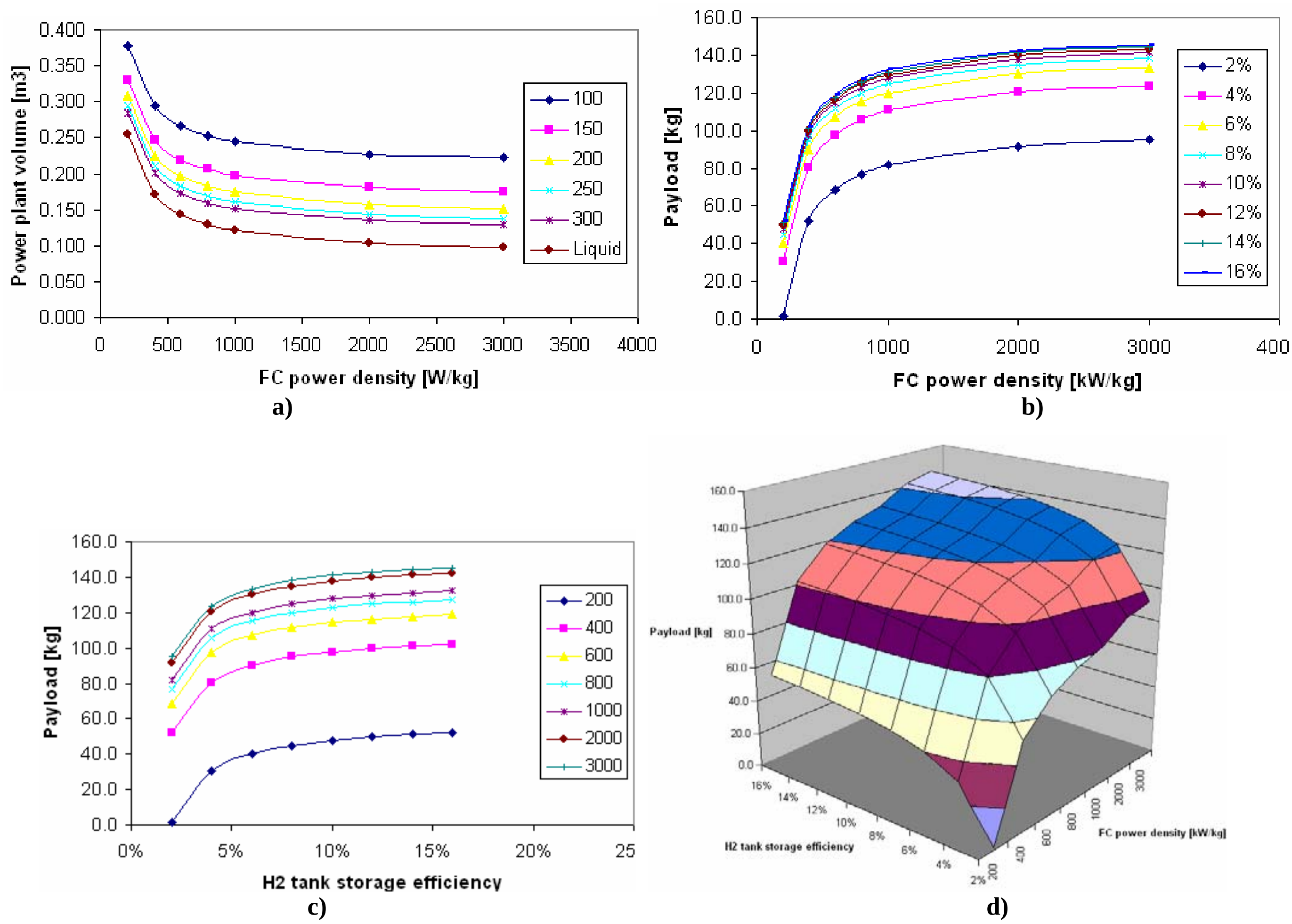


Fig. 8 – a) Power plant volume vs FC power density (function of storage pressure – atm);
b) Payload vs FC power density (function of H2 tank storage)
c) Payload against H2 tank storage efficiency for different FC power density [W/kg]
d) Payload against storage efficiency and FC power density

The aircraft payload is analysed, as function of the H2 tank storage efficiency and the fuel cell power density (Fig. 8b). The payload increases with both parameters. It seems that exists a limit: for FC power density greater than 3000 W/kg the payload increase is negligible. The some phenomena occur for H2 storage efficiency greater than 16%.

Another interesting point is that the slope of both curves changes drastically in the considered range of values: from FC power density greater than 1000 W/kg the payload increase is very light. Instead, for FC power density lower than 1000 W/kg, the payload rise up very fast. In case of the H2 tank storage efficiency dependence, change of slope occurs for the 6% (Fig. 8c). Finally, the dependence between the three different parameters are reported in Fig. 8d.

The increase in the aircraft cruise endurance is analysed as function of H2 tank storage efficiency and of fuel cell power density. It has been introduced the hypothesis that all the available payload is used to increase the H2 storage on board.

The cruise time as function of FC power density grows with the storage efficiency in a linear way but it has an asymptotic behaviour versus the FC power density. It exists a limit: for FC power density greater than 1500 W/kg the payload increase is negligible. It appears that in this case it's more convenient to increase the H2 storage efficiency than the FC power density (Fig. 9a, 9b). Finally, the dependence of the three parameters is reported in Fig. 9c.

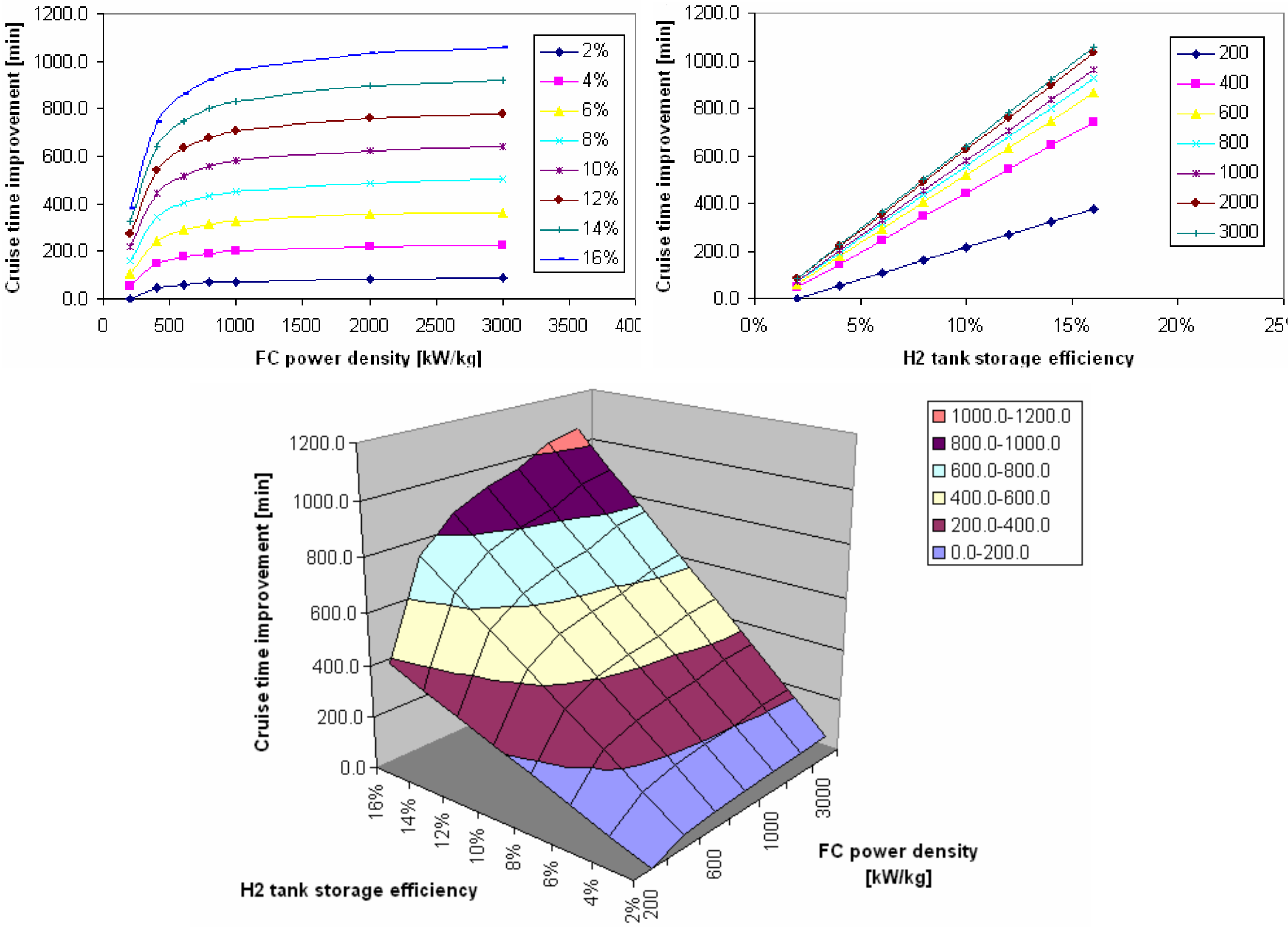


Fig. 9 – a) Cruise time vs FC power density for different storage efficiency [%]
b) Cruise time vs storage efficiency for different FC power density [W/kg]
c) Cruise time vs storage efficiency and FC power density

Some interesting results have been obtained from this preliminary parametric sizing, although at the moment only two parameters (FC power density and the H2 tank storage efficiency) were considered. In particular, it has been shown that future developments in FC technology and storage tank could drastically improve the aircraft performances, even surpassing the piston engine powered one.

However, it's necessary to consider also other parameters, such as the FC efficiency, the power plant (converter, inverter, batteries and engine) power density and the position of the various component inside the aircraft and how they influence the balance and stability.

CONCLUSIONS

A statistical analysis has been presented in this report from the survey of more than 100 airplanes. Three airplanes have been highlighted in the analysis: EV-97 Eurostar and Jihlavan Rapid200 (airplanes produced by consortium members) and Super Dimona HK36 (airplane produced by Diamond Aircraft and selected by Boeing for Fuel Cell application). On the strength of the comparison between these aircrafts, Rapid 200 has been considered the aircraft with the best characteristics for the conversion into electric-motor-driven airplane powered by fuel cells. The low power required at low velocity (about 144 km/h) for a level flight has been evaluated an important parameter for the selection.

A preliminary design of the general aircraft propulsion system (brushless electric motors, inverter, converter, and battery stack) has been completed, based on components-off-the-shelf elements, showing very high efficiencies in front of very low weight; however, several precautions has to be taken into consideration to assure safety operation of each element and than reliability of the system.

A new preliminary aircraft Centre of Gravity (CG) position has been determined, starting from the basic empty weight configuration and adding the new electric and energy system, in an attempt to maintain CG within the conventional value. Since the CG & flight performances shall depend from the several FC elements position, an interaction process is in progress in order to maintain or improve the best performances of the aircraft. The preliminary 3D drawing of the aircraft as well the analytical study of CG and flight performances of the aircraft have been started. A mathematical model has been therefore developed to describe the flight dynamics of the aircraft to obtain a first estimation of the airplane Handling Qualities. As expected, the aircraft has a stable behavior in cruise condition but it needs to be controlled by the pilot, especially in the lateral maneuvers. More precise evaluation will be made when the CG position of the modified aircraft will be evaluated in more detail.

A preliminary optimized propeller analysis has also been performed on the propeller considered separately from the remain structure. The analysis has shown the hypothetical possibility to obtain a 90% efficiency propeller for cruise condition and about 80% for climb condition. A CFD more detailed analysis is being started to include the effect of nacelle and venting to determine the actual propeller efficiency.

The preliminary parametric sizing carried as function of FC power density and of the H2 tank storage efficiency has been shown that future developments in FC technology and storage tank could drastically improve the aircraft performances, surpassing the piston engine powered one. However, it's necessary to consider also other parameters, such as the FC efficiency, the power plant (converter, inverter, batteries and engine) power density and the position of the various component inside the aircraft and how they influence the balance and stability.

The manufacturing or acquisition of all the elements (aircraft structure, FC system, power supply drive, power management unit, etc.) are being acquired by the several partners composing the ENFICA-FC consortium aiming to the assembling in the aircraft for a first flight test in Summer 2009.

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