1. Introduction
Aviation emissions are growing faster than any other sector and they risk undermining the progress achieved through emission cuts in other areas of the economy. Rapidly emerging hydrogen and fuel cell based technologies could be developed for future replacement of on-board electrical systems in larger ‘more-electric’ or ‘all-electric’ aircrafts. Primary advantages of deploying these technologies are low emissions and low noise (important features for commuter airplanes which takeoff and land in urban areas).

The ENFICA-FC (Environmentally Friendly Inter City Aircraft powered by Fuel Cells) project led by Politecnico di Torino in the Aeronautics and Space priority of the EU Sixth Framework Programme (FP6) carries out a feasibility study on more-electric inter-city aircraft to provide a preliminary definition of new forms of systems that can be obtained by fuel cell technologies (Auxiliary Power Unit, Primary electrical generation supply, Emergency electrical power supply, Landing gear, De-icing system, etc). Three aircraft types have been taken into consideration: Air Taxi (5 seats), Small Commuter (9 seats) and Regional Jet (32 seats).

Due to its potential capability of being fed by various high-density fuels (e.g. jet fuels), their high efficiency and their heat recovery capability, it has been established that a SOFC-based system could be one of the systems which efficiently suit the needs of the on-board systems of more-electric aircrafts.

After the definition of a mission profile and the characterization of the power consumption of the electrical and non-electrical loads of three kinds of transport aircraft, the design of a SOFC-based and a hybrid SOFC/µGT energy system as well as the simulation of complete missions have been performed. Preliminary estimations on size and weight of these new systems have been carried out. Possible and realistic improvements for reducing the weight of the overall SOFC system with current and near-future technology are analyzed. The obtained results are discussed.

2. Typical mission load profile: considerations about SOFC utilisation
When considering a SOFC generator, some of the loads of a more electric aircraft, which are supposed to be covered with electricity, can be treated in fact as thermal loads (just like it is done currently with the traditional heat engines) because SOFC systems are suited for operating in CHP configuration with temperature of the exhaust gases around 250°C up to 300°C. This is an advantage over other fuel cell systems like PEM, in which the waste heat is not very useful because it is available at low temperatures (nearly 60°C).

If some loads are supplied directly with the exhaust recovered thermal power, the total electric load to be covered by the fuel cell generator is reduced. It reduces also the system’s size and mass, critical aspects when it comes to aeronautical applications. The feasibility of converting some of the electric loads directly as thermal loads has been studied taking into account a typical heat recoverable value which is around 50% of the electric power in real operating SOFC systems [2]. The more practical use for the recovered thermal power is heating the passenger’s cabin. Since the generator must follow the load profile along the mission, at some points (low electrical load) the thermal power recovered from the stack is not enough for covering the thermal load. It has been hypothesized an integrated system in which gas-to-gas heat exchangers are upstream electric heaters so, when needed, part of the thermal load is covered directly with an electric power surplus (otherwise, the heat need could be covered by a after burner increasing the SOFC exhaust temperature).

The maximum electric power to be provided by the SOFC generator is reduced in the case of the Regional Jet and the Small Commuter due to the heat recovery. The whole mission profile is then modified, dissipating thermal power or integrating thermal and electric power depending on the single mission phase. As regards the Air Taxi, the current heating system of this aircraft is fed with heat recovered from the main engine without affecting its performance so no heat recovery from the stack has been hypothesized.

An alternate solution for increasing the overall efficiency of the system is integrating a bottoming cycle composed of a micro gas turbine fed with the exhaust gas from the SOFC [3]. Operating
conditions of the stack (pressure and temperature) are changed in order to satisfy the inlet conditions of the gas turbine and extra fuel is consumed in a after burner. This solution has been analyzed only for the Regional Jet in which the size of the gas turbine is not too small.

3. Mission simulations

Through a 0-D computer-based model of a complete SOFC Stack (planar, anode-supported cells) and BoP [4,5], the main operation variables of the system during each phase of the typical mission as well as the fuel consumption have been calculated. The nominal power of the system, and therefore the stack sizing (number of cells, BoP), have been estimated on the basis of the maximum gross electrical load along the mission, taking into account also the power consumed by the air compressor in the worst-case scenario (highest altitude, highest load). Natural Gas has been considered as fuel.

![Figure 1. Fuel Consumption during Typical Mission (Regional Jet). (The dotted line represents the case in which no heat recovery is considered and all the heating is supplied electrically)](image)

In the case of the Regional Jet, it has been also analyzed the case in which air from the passengers’ cabin is used for feeding the stack, significantly reducing the power for air compression and with it the gross electric power output of the stack as well as its size and weight. Human breath does not affect the performance of the stack [5]. For this type of aircraft it has also been considered the use of a hybrid SOFC/µGT system. The operating pressure of the stack is increased to allow the exhaust expansion throughout the turbine. The stack operating temperature is increased by reducing the flow rate of excess air (with a positive effect on the air compressor consumption). The inlet temperature of the turbine is reach in a post combustion chamber.

![Figure 2. SOFC-based electrical system (a: only SOFC; b: hybrid SOFC/µGT)](image)
4. Preliminary Weight Estimations

Four main blocks compose the system: SOFC Stack and BoP, Air Compressor, Fuel Storage and Heat Recovery System. The weight and volume of these components have been estimated separately and added for obtaining the overall weight which can be compared to traditional power supply systems. As regards the Regional Jet, a block representing the Gas Turbine has been added.

From literature and direct measurements (SEM analysis) thickness and composition of the anode, cathode, electrolyte and interconnect, as well as the geometrical characteristics of the cell, have been found. Known the geometry and density of each layer, the weight of a single cell can be calculated. It has been taken into account the rest of the components that constitute the Balance of Plant. Weight and volume of these elements have been estimated according to their geometry and material.

Fuel consumption has been obtained from the performed mission simulations (see Figure 1). It has been hypothesized the use of commercial ‘Type 3’ Tanks, considering CNG at two pressure levels (200 and 350 bar) and the LNG solution. The Air Compressor and the Heat Recovery System has been estimated on the basis of existing commercial units. The same approach has been employed for the Gas Turbine and the post combustor.

System’s weight is separated in the analyzed blocks, as can be seen in Figure 3 (Regional Jet). It can be then determined what block accounts for a larger fraction of the overall weight for studying possible improvements on the components of the block. In this case, for instance, the weight of the internal vessel and the internal insulation could be reduced by employing innovative and lighter materials, lightening the BoP.

In planar SOFC, most of the weight of the stack is given by the interconnection plates between the cells (Crofer-22). In fact, about 30% of the overall weight of the planar SOFC system corresponds only to interconnect. The impact of this component can be reduced by changing its composition or modifying its thickness. A realistic near-future improvement could be reducing the interconnect thickness to 0.5 mm.

Once the analysis has been performed, estimated weight can be compared to that of the traditional power supply systems of the Regional Jet, Small Commuter and Air Taxi: 264, 70 and 25 kg, respectively. Simultaneous immediate and near-future improvements in all blocks have been considered and weight has been recalculated (see Figure 4). Estimated weight of the hybrid SOFC/μGT system has been included in just for the Regional Jet.
Conclusions

Due to their useful high temperature exhaust gas, the use of SOFC is advantageous over other FC systems like PEM, making it possible to reduce the nominal electric power and therefore the size and weight of the fuel-cell-based APU for more-electric aircraft when operating in combined heat and power configuration. Moreover, and better, SOFC can be integrated with a gas turbine bottoming cycle to reduce the fuel consumption and weight of the overall system.

SOFC’s fuel flexibility, that is, their potential possibility (with material improvements) to use hydrocarbons and high energy-density fuels, including jet fuel, represents a big advantage since no significant modifications should be made to current fuel storage and distribution systems and there is no need for large and complex hydrogen storage tanks to be incorporated into the aircraft.

A SOFC-based electrical system with current technology would be heavier than traditional systems in the three analyzed aircraft types. However, some realistic improvements with current and near-future technology would reduce the weight of the overall SOFC system making it possible to compare it with traditional-technology systems; this especially in small transport aircraft like the Air Taxi and the Small Commuter.

As regards the Regional Jet, the hybrid SOFC/µGT solution seems to be a good choice in terms of efficiency and mass of the overall system. Practical applicability of this configuration is, nevertheless, yet to be proved.

Many aspects should still be analyzed, and improvements of the fuel cells and fuel storage systems would need yet to be made before this technology could be able of competing with traditional and long-proven technologies (since security and reliability of every component is a major issue when it comes to aeronautics). Some characteristic conditions of aeronautical applications are new in the field of fuel cells, for long employed in stationary power production and automotive applications.

References