FUEL CELL APU'S IN COMMERCIAL AIRCRAFT – AN ASSESSMENT OF SOFC AND PEMFC CONCEPTS

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Abstract

Future aircraft will have to deal with a set of stricter and new technical, operational and economical requirements towards in-flight and on ground power generation for primary and secondary aircraft systems. The reduction of fuel consumption, noise and exhaust emissions calls for new technologies, of which fuel cells show a high potential for future realization because of the unmatched efficiency and environmental performance.

Basically, two types of fuel cells, i.e. low temperature PEMFCs and high temperature SOFCs, seem to be technically feasible to enter the market in the coming 10 to 20 years. Considerable differences in performance, possible concepts and integration into the aircraft favor the one or the other. According to dedicated fuel cell concepts, simulations have been modeled to obtain results which form the basis for a general assessment of compatibility with major aircraft systems in more electrical aircraft architectures.

Additionally, integration concepts have been investigated to determine potentials for an optimal location of the concepts.

1 General Introduction

1.1 Aircraft System Architectures

Along with basic economic and operational requirements towards aircraft from operators, who demand inter alia for low operating cost and high reliability, other factors, like more stringent noise and emission standards, are formulated by airports, councils or authorities. This drives the aircraft to higher efficiency and productivity on the one hand and compliance with its environment on the other. In this sense, aircraft systems undergo an evolution towards such characteristics with great impact on the form of energy they are powered with. The clear trend to substitute pneumatically and hydraulically driven aircraft systems by electrical ones is reasoned by the high share of symbiotic effects of combining subsystems electrically, its flexibility and interoperability here from as well as the light infrastructure, thus providing the promising outlook that the overall aircraft efficiency and reliability will improve (see for example EU funded research projects like "Power Optimized Aircraft POA" [1]). The aircraft system concept behind this is the more electric aircraft (MEA), which completes to an all electric aircraft (AEA) if all systems are electric. The transition is already being realized at aircraft of the new generation, for example the A380 with electro-hydraulic and electro-mechanical actuators for secondary flight control systems, and is to be continued with in development aircraft like the 7E7, envisaged to operate with an electric ECS.

However, the higher number of electrical consumers as well as specific consumers with extremely high electrical load profiles (e.g. electric ECS, flight control systems, landing gears) means a much higher demand for electrical power, not comparable to existing amounts of nowadays aircraft. In case of an AEA, maximum electrical power demand can exceed the order of 1MegaWatt (MW) for very large airplanes like A380 or B747. But MEA already have peak demands in excess of 500 kilowatt (kW) for airplanes like the B777 or A330/340.

However, current approaches exclusively use main engine mounted generator technologies. With increasing electric power requirements, it is a doubtfull, if generator size can grow with this pace, charging the aircraft's main engines, and thus propulsive efficiency considerably. Additionally, with the well-known limitations in available space and prevailing temperature in and on the aircraft main engine, generators are limited as well and will hardly be able to solely comply with serving the aircraft as the primary electrical supply system. In addition, the customer requirement for higher overall efficiencies is not met satisfactory with this conventional approach, as the thermodynamic efficiency of combustion engines, and thus that of generators, is limited to a technical maximum. Nowadays thermodynamic engine performance is at around 50% efficiency, electric efficiency is accordingly lower at the design point [2]. The problem can only be dealt with by a new and integrated approach.

1.2 Use of Fuel Cells

Fuel cells can offer solutions for these requirements with their main advantages: higher fuel efficiency, lower to nil emissions, direct current generation, decentralization of power generation and potential water recovery. Automotive industry here is a pacemaker particularly for low temperature fuel cells.

Electrical power load profiles and dynamics of aircraft systems have a major impact on the choice of type of fuel cell in the first place, and on the type specific concepts in the second place as well.

Different sources describe the potential implementation of fuel cell types in aircraft [3, 4, 5]. But deciding are not only the characteristics of the type of fuel cell. With regard to new system architectures, more emphasize will be addressed to interoperable and cross-fertilizing aspects between the fuel cell and aircraft systems to fully exploit the realizable and feasible development range.

1.3 Motivation and Aim

The paper is motivated by the current discussions at aircraft manufacturers and system suppliers, who try to identify the type of fuel cell with the strategically most robust technology for future applications on an overall aircraft context, regardless of obvious advantages in fuel efficiency, useable water, environmental effects or technology readiness.

Therefore, the aim of the investigation is to focus on an assessment of different fuel cell concepts which substitute the conventional APU by a full-time fuel cell power unit in a MEA environment. Basically, concepts of two fuel cell types are being investigated: The high temperature (1000°C) Solid Oxide Fuel Cell (SOFC) and the low temperature (90°C) Polymer Electrolyte Membrane Fuel Cell (PEMFC).

According to results from thermodynamic MATLAB / Simulink simulations for a given electric power requirement and flight mission, the assessment provides a general overview about the performance regarding fuel efficiency as well as a comparison of produced water and other beneficial spin-offs, forming the foundation for potentials of integration into the aircraft. Benefits and drawbacks of every single system concept are qualitatively evaluated and subsumed in the assessment, focusing on dedicated evaluation criteria for the fuel cell system, its allocation and integration in the aircraft.

1.3 Conditions of Investigation

Comprising the conditions of the investigation, the following technical scenario has been developed to serve as foundation for the research. Time horizon for technology readiness is assumed to be 2015, stipulating that any aircraft program launched at that date could benefit from fuel cell technology an entry into service some 4 to 5 years later.

Fuel cell systems are especially beneficial for long range aircraft, like the Airbus A330/340 or Boeing 777 series. These aircraft have been chosen to function as a platform for research. According to the power requirements and characteristics of these aircraft, the future electric power demand of a MEA is displayed. An overview is given in figure 1, where the dedicated MEA scenario for this study is pictured. Taking into consideration all electric systems, peak demands are around 560kW. In table 1, the respective power demands have been compiled from different sources, indicating the order of magnitude of system power and compared to today's as well as to the AEA scenario. The 'in-flight demand' shows the maximum required power provided at the same time (i.e. generally in flight), defining the design point of the system, whereas the 'total demand' is the sheer sum of demands of all electric consumers in the aircraft.

In the calculated scenario it is assumed, that pneumatic power is generally not supplied by the main engines anymore, assigning power supply of the ECS with cabin pressurization and temperature regulation, as well as ventilation of systems to electric driven compressors.

Main Electrical Consumers	Conventional System Architecture		MEA System Architecture		AEA System Architecture		System Power [kW]
	active else than in flight	active in flight	active else than in flight	active in flight	active else than in flight	active in flight	
Auxiliary Hydraulic Pumps		(X)		(X)		(X)	(60)
Fuel Pumps		X		X		X	10
Ice & Rain Protection		X		X		X	10
Lighting		X		X		X	15
Commercial loads		X		X		X	25
Avionics		X		X		X	10
Galleys		X		X		X	75
Cargo Doors			X		X		15
Flight Controls						X	80
Landing Gear						X	25
Engine Starter			X		X		350
Wing Anti Ice						X	200
ECS				X		X	400
Total demand [kW]	145 (205)		910 (960)		1215 (1275)		
In-flight demand [kW]	145 (205)		560 (720)		850 (910)		

Figures interpolated from different sources for A330 and 777, rounded to 5kW, figures in ( ) depict systems active in emergency only

Table 1. Composition of System Powers

However, hot and compressed air for wing anti ice system is still delivered by the main engines, as it consumes large amounts of energy, but operates at comparably short times during flight. This would enlarge the 'in-flight demand', and thus the size of the system considerably, whereas benefits from relieving the main engines are small in relation to the total mission. Hydraulic power is only substituted to a limited extend, as these systems need a high power density and redundancy which is not the strength of electric systems. Until 2015, only secondary flight controls and cargo doors are substituted.

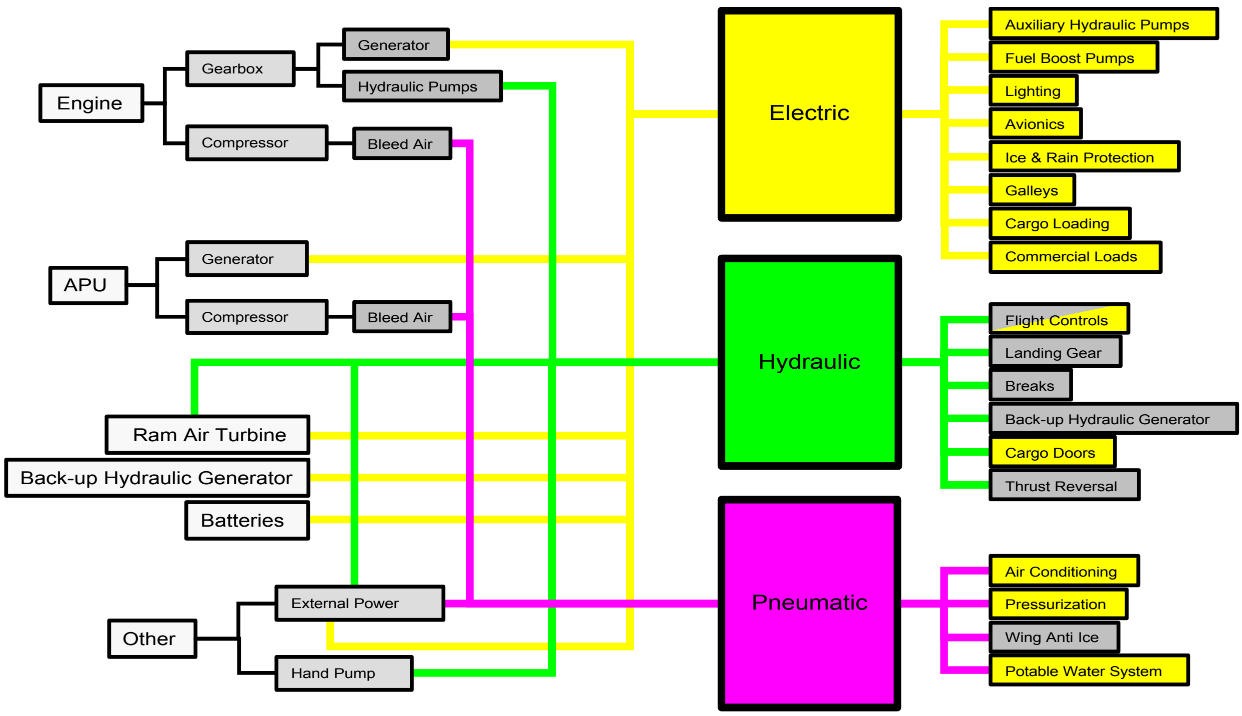

Fig. 1. Energy Supply (left) and Consumers (right) with Future Electric Systems (yellow) According to the Scenario

PEMFC and SOFC can be operated with either ambient or cabin air. All concepts are fuelled by kerosene, which has to be reformed to obtain hydrogen, as hydrocarbon fuels stay to be much cheaper available than hydrogen from renewable resources. With various possibilities at hand to convert diesel or kerosene, steam reforming has been selected. It provides highest hydrogen conversion and the maximum electric efficiency for fuel cell systems. This is in line with other studies as well (for example [6]).

As a consequence of stricter environmental regulations, sulphur contents in kerosene have been reduced dramatically. However, desulphurization still has to take place on ground at the airport (mobile systems on fuel trucks) to clean kerosene largely from sulphur.

To compare the results with previous studies [5], total fuel cell system power has been aligned to 370kW to mainly support the all electric ECS. Results can be scaled to higher powers appropriately.

2 Fuel Cell Performances

Assessing the system solely for efficiency to generate electric power, both the SOFC and PEMFC are shortly described in the following. As compiled from [7], the table shows a rough oversight of general characteristics of both types of fuel cells. With a future development status, it is assumed, that both types have similar power and volumetric stack power densities.

	PEMFC	SOFC
Electrolyte	Ion Exchange Membranes	Ceramic
Operating Temp.	80°C - 100°C	600-1000°C
Charge Carrier	H^+	O^{2-}
Reforming process for HC-fuels	External	partial external pre-reforming, partial stack-internal
Prime Cell Components	Carbon based	Ceramic
Catalyst	Platinium	Perovskites / Nickel
Robustness against poisoning	Highly sensitive to CO, UHC, S	Sensitive to S
Product H_2O Management	Evaporative	Gaseous Product
Product Heat Management	Process Gas + Independent Cooling Medium	Internal Reforming + Process Gas
H_2O effluent at	Air side	Fuel side
System efficiency	> 40%	> 75% (hybrid SOFC)
Response to load change	Quick, dynamic system behaviour	Slow, static system behaviour
Maturity	First operational test series in automotive industry	Breadboard units for mobile application

Table 2. Comparison of PEMFC and SOFC systems

2.1 SOFC

As presented in [5], the schematic overview describes a hybrid SOFC (fuel cell and gas turbine components). With a stack entry pressure of over 3.5 bar and a stack temperature between 800°C and 1000°C, heat energy can be recovered by the turbine, driving the compressor and generator.

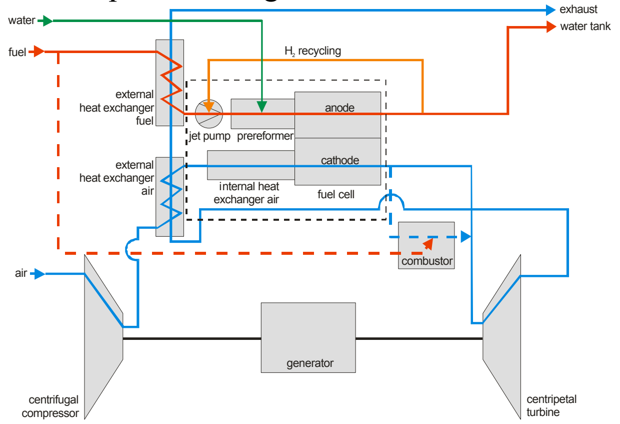

Fig. 2. SOFC System Overview

Average system efficiencies for a 12 block hour mission are at over 75% for the cabin air concept and slightly lower than 70% for the ambient air concept.

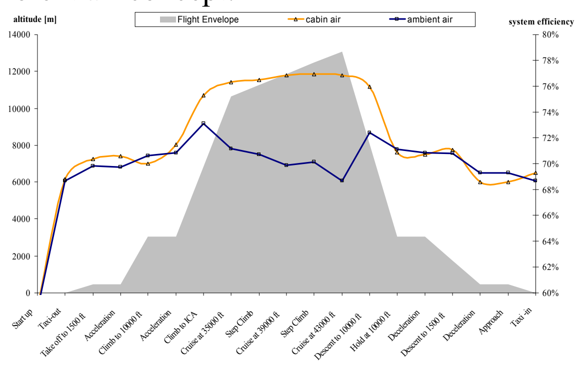

Fig. 3. SOFC System Performance

Assuming total water recovery of the electrochemical reaction in the fuel cell, 70% is used for the reformation process and 30% is saved as net water generation in the aircraft tanks. An advantage is that water is produced at the fuel side (here anode), and thus air flow quality is not hindered by condensers and cooling traps.

For comparison with the PEMFC system, the used and generated power of single components is given hereunder.

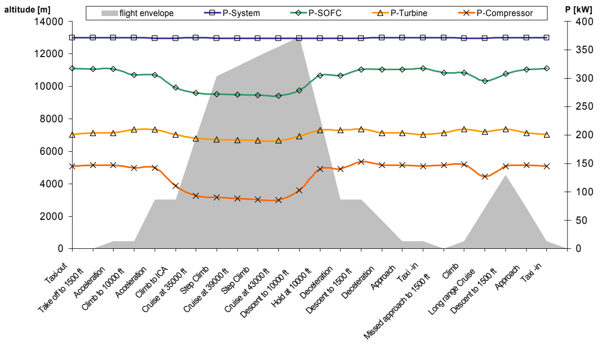

Fig. 4. SOFC System Component Powers

A pre-design of the system shows the integrated concepts of fuel cell, heat exchangers and gas turbine. Even though many subsystems support the SOFC, there is no extensive cooling system, reforming system or gas clean up required.

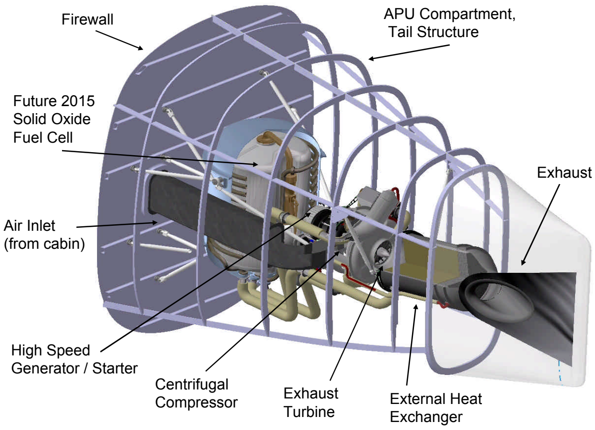

Fig. 5. SOFC System Pre-Design

Even if system weight is about 2.75 times higher than that of a super efficient future conventional APU, mass balance reveals a benefit for missions longer than over two and a half hours with full net water recovery and four and a half without any net water recovery.

2.2 PEMFC

The system concept of the PEMFC is mirroring a comparable composition as in automotive industry, characterized by a much larger number of subsystems, responsible for reforming of kerosene, clean-up processes, temperature controlling of mass flows and recovery of water. The system is regulated to operate at 90°C with 1 to 1.5 bar in the fuel cell. First limitations come up with the compression of the air. For all flight conditions, the given pressure range of 1 to 1.5 bar in the fuel cell suites very well with air temperature PEMFC requirements, both for cabin and ambient air. Going beyond 1.5 bar, air is heated up too much from compression effects and has to be cooled, without significant fuel cell performance increase at higher pressures. Higher temperature PEMFCs, which have a different electrolyte and operate at 130°C to 150°C, would enhance thermal stability, integration and robustness, but have not been simulated here.

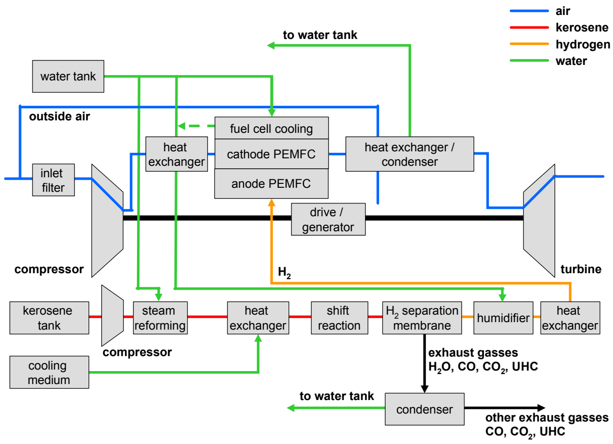

Fig. 6. PEMFC System Overview

To reduce electric power from the fuel cell for the compressor, air is expanded through a turbine. In contrary to ground conditions, where actually no recovery takes place, a substantial part is recovered during cruise, especially if the system is supplied with cabin air. This relieves the fuel cell and improves overall efficiency.

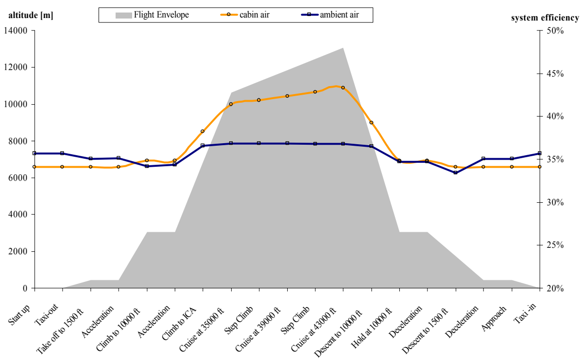

Fig. 7. PEMFC System Performance

The system behavior in figure 7 shows the difference at higher altitudes. The cabin air concept has its peak efficiency at about 44%, whereas with ambient air and pressure recovery in the inlet efficiency is around 37%. For a 12 hour mission, efficiencies are 41.7% respectively 36.7%. The difference in efficiency at ground conditions is mainly due to the temperature, which is higher in the aircraft cabin than the international standard atmosphere ISA at zero meter altitude. It is obvious, that the steam reforming unit consumes large amounts of energy to heat the mass flows of kerosene and water in the reforming reactor to 800°C. Heat is produced by combustion of kerosene in the reactor. It is included in the energy diagram with roughly 150kW and effects system efficiency considerably.

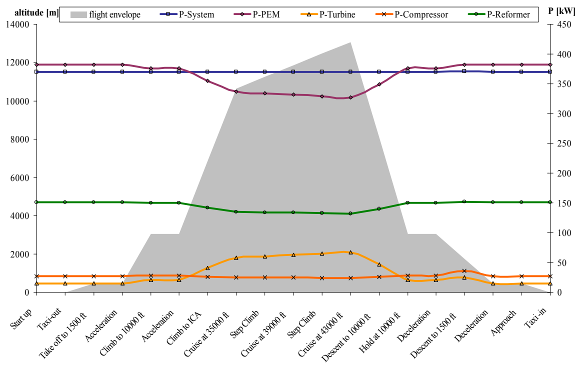

Fig. 8. PEMFC System Component Powers

Especially in the dry cruise environment, it is vital for the fuel cell to be humidified. Due to the electro-osmotic water drag, the membrane dries at the anode increasing its resistance. The back diffusion of water from the cathode to the anode through the thin membrane results in a net water transport of nearly zero. Thus it is important to humidify the incoming anode gas, the hydrogen [7, 8].

Water is released at the cathode air side. For water recovery, this means that the air has to be cooled down near to 0°C, which affects efficiency of the small turbine there after.

2.3 Performance Comparison

There are specific advantages for both systems. While SOFCs have outstanding efficiencies and potential for water recovery, PEMFCs are reacting quickly to load changes and are much more mature. However, for application with kerosene, there are significant drawbacks on the side of the PEMFC. Beside the high amount of energy, also large volumes of water (steam to carbon ratio of 3) have to be used to prevent coking of kerosene. Unlike as with the SOFC, the PEMFC has to separate the reforming process from the fuel cell, requiring heat exchangers for water recovery both after the fuel cell and after the reformer. Without these, water would be used rather than produced and an additional weight penalty would come from the water to be carried along for reformation. The SOFC has both the kerosene reforming and the electro-chemical reaction in the anode mass flow, requiring only one heat exchanger for water recovery.

To comply with the demand of 370kW, the PEMFC system needs a larger fuel cell stack with at least 400kW, whereas the stack of the SOFC stays about 20% below this figure. With similar stack power densities, the system weight of the PEMFC is estimated to be about 50% higher, mainly triggered by the larger fuel cell as a result of the lower system efficiency, the more complex reforming system and the required heat exchangers.

Generally, both systems produce water in the same order of magnitude, which is reasoned by the similar electric efficiency. Because of the required higher PEMFC stack power, however, the system generates almost 15% more water. As described in [5], a mass balance constituted from the basic system weight together with fuel consumption and water generation results in the following diagram.

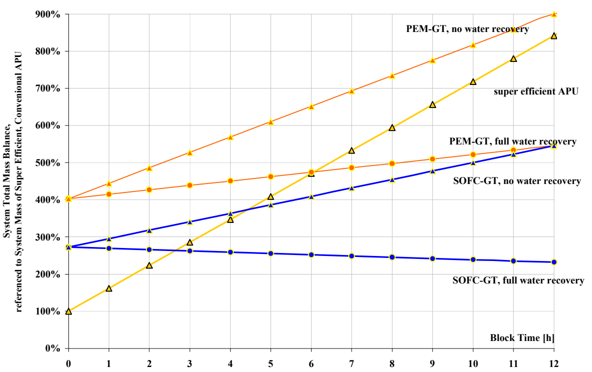

Fig. 9. Mass Balance Comparison of Fuel Cell Systems

Fuel and net water masses vary with the operation mode influenced by block time and required power profile. Produced mass of net water has a positive effect and, therefore, is subtracted in the balance. According to the degree of water recovered, the system performs within the cone of full and no net water recovery. At a given block time, balance depicts the sum of system mass plus mass of consumed fuel minus mass of regained water.

Hybrid SOFC systems with full net water recovery show always highest efficiencies, but with regard to block times longer than 5 hours, PEMFC systems with full net water recovery are outperforming the super efficient conventional APU with assumed 30% efficiency as well. One of the future crucial factors therefore is, to which extend water can be recovered to have an optimum compromise between system complexity, weight and efficiency benefit.

To be mentioned is that in case of a direct hydrogen supply without reforming process, the PEMFC gains considerably upon the SOFC. Still behind the SOFC with efficiencies of almost 50% for ambient and 60% for cabin air, maturity and system dynamic might outweigh and, thus, favor the PEMFC.

3 System Integration Concepts

With regard to future developments in both systems and power generation, qualitative concepts of fuel cell integration are proposed to identify optimal allocation in the aircraft. Factors driving this decision can be the distance of power generation to systems (power losses, weight for cables, tubes, etc.), integration with regard to fire safety, flexibility or symbiotic effects with other systems.

The figure points out, where the different electric consumers are located. It is obvious, that most of this power is in the centre of the aircraft.

Systems with a relatively stable power demand are the ECS, avionics, ice and rain protection systems (if activated) and the fuel pumps, the other main systems, landing gears, engine starters, galleys and flight controls, have partially high dynamics with quick run-up and shut down times, or short high load levels. Along with other concepts, the ones proposed were favored most. All low temperature electric systems need fire shielding, whereas high temperature systems require explicitly fire compartments. All concepts operate with cabin air, as recovery of cabin pressure has benefits for efficiency.

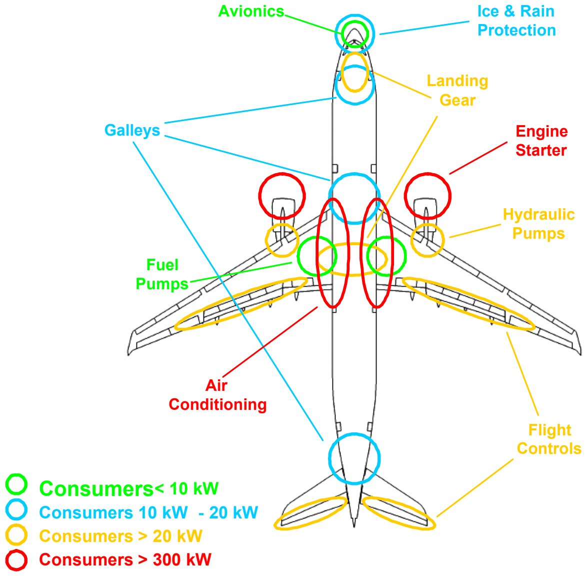

Fig. 10. Location of Main Electric Consumers

Even though wing anti ice systems are powered pneumatically, concepts have been assessed which make use of heat in the fuel cell systems. Maximum pressure and temperature for the anti ice air flow is today limited by the condition for an auto-ignition of fuel in case of a leakage or other damage. The nominal temperature of the bleed air for anti-icing is about 190-230°C and the pressure is at 2.1 bar in cruise. The hot air is supplied to the inner surface of the wings leading edges through ducts and dumped over board after heating the structure.

3.1 Concept 1

With a PEMFC as main electric power supplier in the center of the aircraft and the reformer unit in a fire compartment, distances to major consumer are minimized. The continuously operating ECS is electrically driven by the fuel cell. The wing anti ice systems can utilize heat from the reforming unit, as mass flows have to be cooled down thereafter. The additional air is delivered from the cabin, which is further compressed and led through the heat exchanger at the reforming unit. However, this would require additional power of about 150kW.

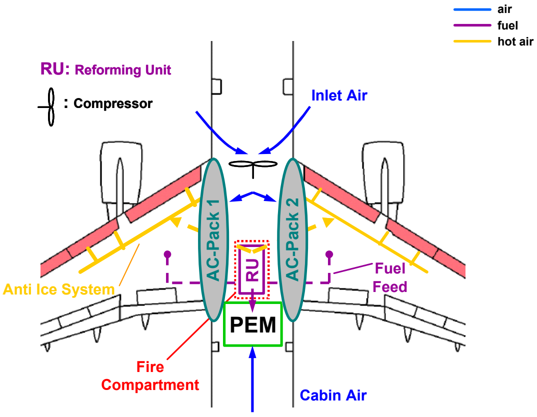

Fig. 11. Concept 1: PEMFC in Aircraft Center

Large dynamic loads from engine start or landing gear deployment or retraction are fully supported by the fuel cell and the power management system. The system's location could be either direct in the wing root, or by occupying parts of the pressurized cargo compartment. Air is taken from the recirculation and mixing plenum of the ECS.

3.2 Concept 2

Similar to concept 1, with reformers located at the engines, heat from the engines can be used to reduce required reactor power to heat kerosene and water. Additionally, necessary infrastructure is available (fuel lines, thermal shielding) and easy access for maintenance is provided. However, there is only limited space in the nacelle and in the engine. Reformers could be integrated into the engine, implying that engine development has to be coordinated with suppliers for the fuel cell APU system.

Wing anti ice is provided either conventionally by the engine or from an integrated heat exchanger using reformer heat.

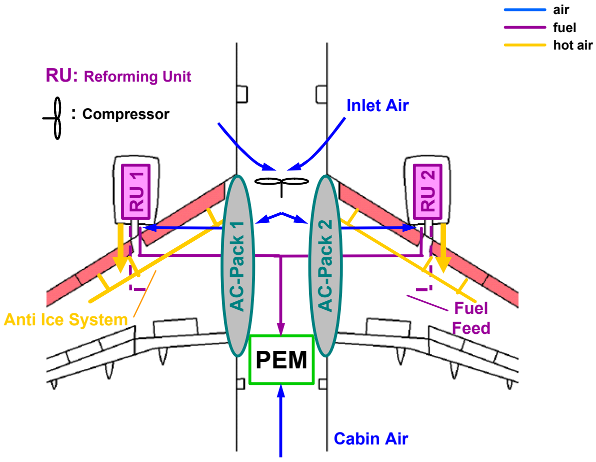

Fig. 12. Concept 2: PEMFC in Aircraft Center, Reformer at Engines

3.3 Concept 3

SOFC integration is realized in the wing root, following the same arguments as of concept 1 and 2. However, additional batteries would have to secure short power demands for system run-ups. Also, the SOFC has to be placed in a fire compartment. An advantage is that the hot exhaust can optionally be used for wing anti ice by an additional blower.

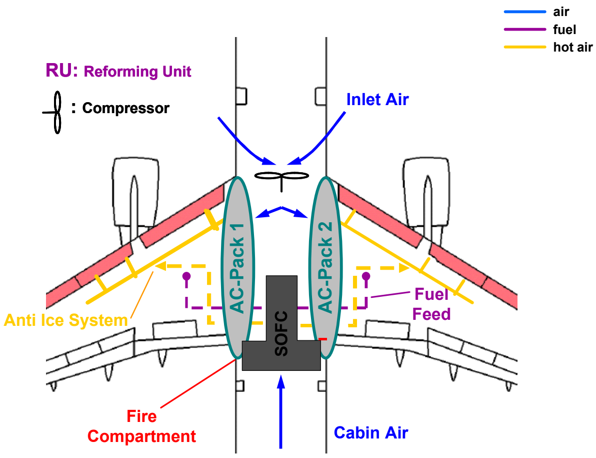

Fig. 13. Concept 3: SOFC in Aircraft Center

In emergency, the hybrid SOFC concept assures additional heat from the combustor of the gas turbine components, which is normally used to expedite the start-up of the system. Again, air is taken from the recirculation and mixing plenum of the ECS.

3.4 Concept 4

A combination of a cabin air supplied SOFC in the tail of the aircraft and PEMFC in the aircraft center is described with concept 4. A basic, stationary electric high power is provided for ECS, engine starter or landing gears with the SOFC, whereas dynamic loads are covered by the PEMFC. To have most symbiotic effects, reforming is performed for both systems in the SOFC. As an open system on the anode (fuel) side, gas utilization typically is around 80%, leaving 20% unused hydrogen to be used by the PEMFC which is filtered by metallic membrane technology (see for example [9]). This means, that available power from the PEMFC is between 15% and 20% of the SOFC power. Resulting in higher PEMFC efficiency, the complete fuel cell system has comparable performance as a single hybrid SOFC system.

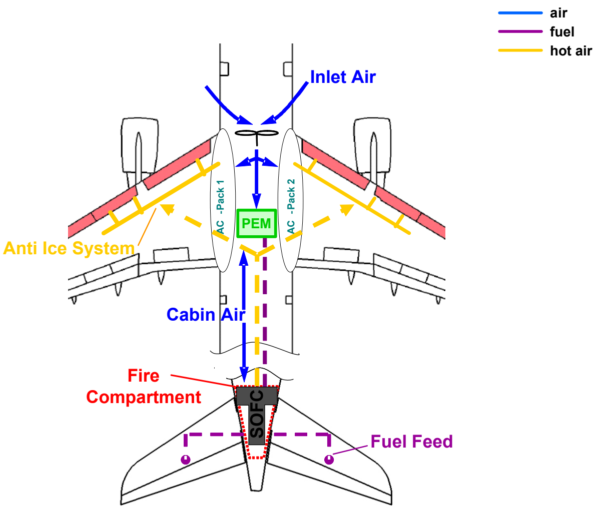

Fig. 14. Concept 4: SOFC in Aircraft Tail, PEMFC in Aircraft Center

For a 370kW system with a 315kW SOFC stack, about 60kW is coming from the PEMFC. System benefits with other systems, like wing anti ice, are comparable with the SOFC of concept 3. Existing fire compartments can be used.

Drawbacks have to be addressed in power transmission through long wires which have to be insulated and encased in EMC-compatible casings. Longer tubes incorporate higher system weights.

4 Assessment of Concepts

A relative assessment according to weighted evaluation criteria pointed out the most promising concept with regard to type of fuel cell and integration into the aircraft. The following factors show the order of relevance: fuel efficiency, system weight, water recovery, system size, maturity, system complexity, compliance with power demands, effects of location in the aircraft and interaction with aircraft systems. Deliberately there is no appraisal of cost, as systems will only qualify if cost of ownership (system price) as well as cash operational cost (fuel efficiency, maintenance, dispatch reliability) is in an adequate, commercially viable relation. The weighted results are displayed in figure 15.

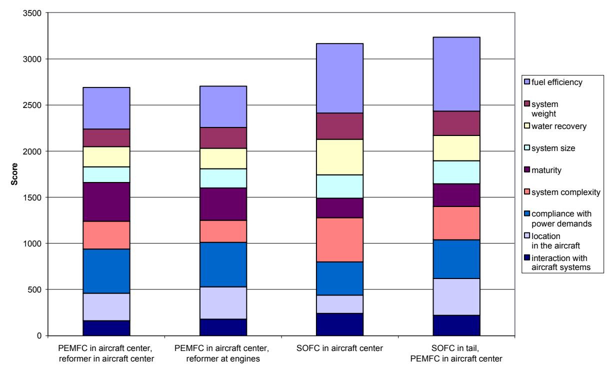

Fig. 15. Weighted Score of Fuel Cell Systems

From a technical point of view, concepts with hybrid SOFCs seem to exhibit important advantages, like performing with outstanding efficiency and offering the most robust and simple system. The reaction on dynamic loads is a concern, which can be met by either batteries or a PEMFC. Even though two different fuel cell systems are integrated, which increases complexity, it contributes to system performance. As a consequence, the combination implies benefits of both types of fuel cell in one and scores best.

However, fuel cells, and particularly as application in aircraft, have low maturity. Despite of current research in mobile applications, SOFC are in arrears compared to PEMFC. With regard to a medium term future, PEMFC would be the first system to obtain experience with this new technology in aircraft.

For the longer term and with progress in miniaturization and serial production, SOFC offer the higher potential.

Means for water recovery will also play a major role. The chart with non-weighted, direct scores show low values, as larger heat exchangers to extract water or steam from those mass flows spoil the mass balance on aircraft level.

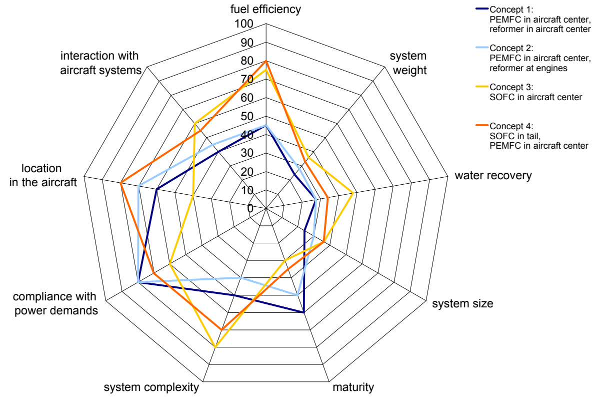

Fig. 16. Direct Score of Evaluation Criteria

5 Conclusions

In the future, aircraft system architectures will change to more electric configurations. Parallel to stricter requirements towards fuel efficiency and environmental compliance, new means for auxiliary power generation have to be found, as current electric efficiencies are bound to the thermodynamic efficiencies of internal combustion engines.

Fuel cells give a promising outlook to be a next step towards these aims. Two different types are identified to have the potential for commercialization. These are the low temperature PEMFC with pressure recovery and the high temperature SOFC as a hybrid with a gas turbine unit. All systems are fueled with kerosene, implying that on-board steam reformation is generating the required hydrogen.

Comparison of the two types has been performed both quantitatively on a fuel cell system level and qualitatively on an aircraft integration level. Concepts with the SOFC generally show much higher system efficiencies and thus potential to substitute conventional APU systems. At the same time, water recovery is a key element in the performance of the entire system.

Yet, dynamic loads are addressed much better by PEMFCs, which also have a higher maturity level. Assessing different integration concepts, it resulted that a combination of both fuel cells would suite best to the requirements from a technical point of view with the SOFC being located in the tail of the aircraft and the PEMFC in the center. Focusing on longer-term entry into service dates after 2020, the SOFC possibly can catch up the development head start of the PEMFC, leading to a high efficient auxiliary power unit.

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