

USAGE POTENTIAL OF FUEL CELLS FOR MANNED/UNMANNED AIR VEHICLES: DEVELOPMENTS, CURRENT STATUS

Meryem Gizem SÜRER¹, İsmail SARIKAYA², Hüseyin Turan ARAT³

^{1,2}Department of Mechanical Engineering, İskenderun Technical University, Hatay/TURKEY

³Department of Mechatronics Engineering, İskenderun Technical University, Hatay/TURKEY

Corresponding author: Meryem Gizem SÜRER, e-mail: meryemsurer.mfbel7@iste.edu.tr

REFERENCE NO	ABSTRACT
FCEL-07	Fuel cells are the most popular source of power for electric air vehicles in terms of being greener, more reliable and higher efficient. Although fuel cells have considerably superior properties, there are some problems to be solved, such as hydrogen storage, high cost and low flight endurance. Therefore, more researches are needed to solve these problems with developing technology. Purpose of this paper is to provide an overview of applications of hydrogen fuel cells in air vehicles. Therefore, the usage of hydrogen fuel cells like APU and propulsion application, advantages and working principles are presented and their challenges are determined. The latest research activities, hydrogen storage methods with challenges are analyzed and the developments of fuel cell powered air vehicles are discussed. As a result, this review is important in terms of compiling the latest technology for air vehicles, as well as fuel cell applications in large aircraft.

Keywords:
PEMFC/SOFC
Hydrogen storage
APU application
UAV propulsion system

1. INTRODUCTION

Risk of depletion of jet fuels and increasing harmful gas emissions depending on the growth of air transportation, have led future planes to become more electric. However, increasingly electrification of aircraft provides many advantages such as efficiency, reliability, low vibration, low thermal and noise signature... etc.[1]. Although electricity can be supplied with batteries, fuel cells, solar batteries and ultra-capacitors [2], fuel cells (especially PEMFC and SOFC) are the most promising power source for air vehicles [3].

Fuel cells produce electricity from the chemical energy contained in the fuel with electrochemical reaction by breaking molecular bonds in one step [4-6]. However, an energy storage device such as a battery is required next to the fuel cells to provide longer durability in air vehicles [7]. Fuel cell / battery systems, especially PEMFC/ lithium ion battery, are the most common choice in electric flight [7]. While conventional lithium batteries allowing 60-90 min durability, can provide specific energy of 150-250 Wh / kg, a fuel cell based system provides higher specific energy [3]. For example, combination a fuel cell with a pressurized hydrogen fuel tank (with 6% weight fraction) can provide a specific energy in excess of 800-1000 Wh/kg

[3]. The similarities and differences of fuel cells and the batteries have been expressed by [1, 8] and the comparative characteristics of li-ion batteries and fuel cells are listed in table 1.

When it comes to advantages and disadvantages of fuel cells compared to internal combustion engine; Aktaş [2] listed as;

- Fuel cells are more efficiently than internal combustion engines. (For instance, Hepperle [9] analysed typical on-board conversion chains with typical component and total efficiencies for a conventional turboprop, a conventional turbofan, a battery powered system and fuel cell powered system. He determined that the efficiency was 39% for turboprop, 33% for turbofan, 73% for battery powered system and 44% fuel cell powered system.)
- Fuel cells produce only water as by-product. Thus, they are greener than internal combustion engine burning conventional fuel.
- Hydrogen is a renewable energy source that can be produced from water and again converted back into water. However, hydrogen usage comes with

the difficulties of producing, transporting, distributing and storing.

- Most of fuel cells operate silent compared to internal combustion engines.
- Low temperature fuel cells are ideal for military applications since they have low heat conduction.
- Fuel cell based vehicles have longer refuelling time and shorter driving range.
- Fuel cell technology is a new technology being developed and its production is currently expensive [2].

Table 1. Some comparatively characteristics of li-ion batteries and fuel cells.

Properties	Li-ion battery	Fuel Cells
Energy density (Wh/L)	200–500[10] 200 – 400[11]	500–3000[10]
Specific energy (Wh/ kg)	75-200[10] 60-200[11] 120–200[12]	800–10.000[10]
Specific power (W/kg)	150–315[10] 500-2000[13]	500+[10]
Power density (W/L)	1300- 10.000[11]	500+[10]
Power rating (MW)	0–0.1 [10]	0-50 [10]
Life time (years)	5-15[10]	5-15[10] 20+ [14]
Daily self-discharge (%)	0.1–0.3[10]	Almost zero[10]
Discharge efficiency (%)	85[15]	59[15]
Cycling times (cycles)	1000- 10.000[10] 500 – 10 ⁴ [11]	1000+[10] 20.000+[14]
Cycle efficiency (%)	90-97[10]	20-50[10] 45-66[16]
Suitable storage duration	Minutes- days[10]	hours - months[10]
Power capital cost (\$/ kW)	1200– 4000 [10]	10,000+[10]
Energy capital cost (\$/kW h)	600–2500 [10] 2770– 3800 [17]	15[15]
Maturity	Developed	Developing

In addition to the above, Sürer and Arat [1] pointed out some of the disadvantages of fuel cells that need to be improvement compared to combustion engine. These can be listed as late response to transient loads, greater

volume requirement for a given power and smaller specific power [1].

Fuel cells have two major areas of usage on aviation: instead of jet engines in small air vehicles for propulsion and instead of gas turbine APUs (Auxiliary Power Unit) in large air vehicles [18-19]. Detailed information on the usage application of fuel cells in micro/macro air vehicles is given in section 3. In this review, the usage applications of fuel cells in air vehicles, advantages and working principles are presented and their challenges are determined. The latest research activities, hydrogen storage methods with challenges are analyzed and the developments of fuel cell based air vehicles are discussed. As a result, this review is important in terms of compiling the latest technology for manned / unmanned air vehicles.

2. FUNDAMENTAL PRINCIPLE OF FUEL CELLS

A fuel cell consists of a fuel electrode (anode), an oxidant electrode (cathode) and an electrolyte sandwiched between them. The electrodes have porous material that is coated with a layer of catalyst [4]. Fuel cells mainly have 6 different types. However, the most commonly used fuel cells for propulsion and APU applications in aviation are SOFC and PEMFC.

2.1. Polymer Electrolyte Membrane Fuel Cells (PEMFC)

During the operation of the PEMFC, hydrogen on the anode side is electrochemically oxidized. Then, the protons (H^+) formed here are carried along the separating membrane. On the cathode side, oxygen is electrochemically reduced and forms water (H_2O) with protons coming from the anode [20]. The general working principle of PEMFC is illustrated in figure 1.

The efficiency of a PEMFC varies between 40-60% and achieves the highest efficiency at partial loads [1]. Numerous test flights aimed at research and demonstration has proved suitability of PEMFC usage on UAV [3]. Thus, PEMFCs are the most promising choice on electric air vehicles [1, 3].

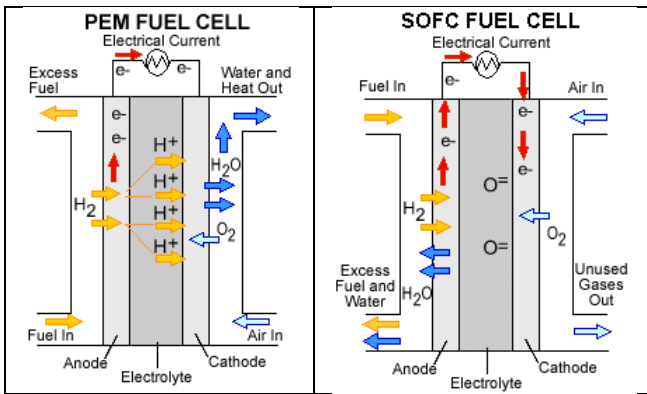


Figure 1. Basic schemes of PEMFC and SOFC [21].

Features that make PEMFC suitable for flight can be counted as: low working temperatures, partly higher power density, rapid response to load changes, good load following ability, and short warm-up time [3, 22]. However, PEMFCs are not without challenge. Especially, the use of expensive platinum catalysts and membranes used in PEMFC is a significant drawback in terms of cost [23]. In addition, usage of PEMFCs requires hydrogen of high purity as fuel [22].

2.2. Solid Oxide Fuel Cells (SOFC)

While ion movement at the other fuel cells is seen from anode to cathode, this movement at SOFC is executed from cathode to anode by O_2^- ions [24]. On the anode, hydrogen is divided into protons and electrons by high heat and electrons pass through an external circuit to the cathode. The oxygen gas in the air supplied to the cathode combines with the electrons to form O_2^- ions. These O_2^- ions formed pass through the electrolyte and combine with hydrogen at the anode and produce water and electricity. The main chemical reaction in this fuel cell is the combustion of water [24]. Principal structure of SOFC is given in figure 1.

Table.2 The properties of mostly used fuel cells on aviation for propulsion and APU application [1, 3]

Fuel cell	Fuel	Operation temperature (°C)	Efficiency (%)	Stack specific power (W/kg)	System specific power (W/kg)	Reactions
PEM	Hydrogen	30-100	40-60	>500	>150	Anode: $H_2 \rightarrow 2H^+ + 2e^-$ Cathode: $\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$
SOFC	Hydrocarbon	500-1000	30-50	>800	>100	Anode: $H_2 + O_2^- \rightarrow H_2O + 2e^-$ Cathode: $\frac{1}{2} O_2 + 2e^- \rightarrow O_2$

SOFCs operate high temperature between 600- 1000 C and this situation comes with both advantages and disadvantages [3]. For example, this high temperature allows SOFCs to use hydrocarbon fuels that increase fuel availability and reduce storage requirements [3]. But, due to high temperature; SOFC cannot rapid respond to changes in load. Because, it takes time to heat the SOFCs and reach the operating temperature [1]. In the study by done [22], the advantages and disadvantages of SOFC are listed.

While the PEMFCs have an output power up to 50-250 kW (67-335 hp), the SOFCs also have an output power up to 100kW (134hp) [25]. The comparative characteristics of the PEMFC and SOFC are given in table 2.

3. FUEL CELL APPLICATIONS ON AVIATION

3.1. Propulsion Application

Fuel cells are commonly used as propulsion system in UAVs for military purposes (such as reconnaissance, battlefield monitoring, ordnance delivery... etc) and civilian purposes (such as search and rescue operations, geological surveying...etc.)[7]. However, the first use of fuel cells on manned aircraft was in 2008 for a two-seat aircraft [26].

Generally, propulsion system of UAV is divided into four elements. These include: energy source (chemical fuels, electricity, solar energy, hydrogen... etc), storage media (tanks, batteries, capacitors, metal hydrides...etc), mechanical energy converter (internal combustion engine and fuel cell + electric motor) and lift/thrust converter (rotor, fan, propeller, jet engine...etc)[27].

For example, in the propulsion system shown in fig. 2, hydrogen as a energy source, hydrogen tank as a storage medium, fuel cell + electric motor as a mechanical energy converter, and propeller as a lift/thrust converter were selected [27].

Hybridization of fuel cells and batteries is the best propulsion solution in UAV in terms of endurance [8]. In ENFICA-FC research project, internal combustion engine of two seat Rapid 200 aircraft is replaced with an electric propulsion system [28]. Figure 3 shows a propulsion system with fuel cell proposed for this aircraft. This hybrid fuel cell-battery power system basically consists of a FC stack (about 20-22 kW power generation), a pack of batteries (20 kW power generation at take off), two DC-DC converter, a DC/AC inverter and brushless motor [28]. Fuel cells and batteries are used to get propulsion as primary power source and secondary power source, respectively. DC-DC boost converter which steps up a low- voltage DC come from the fuel cell and battery is used to get a desired voltage value at the input of the DC/AC inverter. The inverter also converts the DC to a three-phase variable voltage and variable frequency power for getting changes in the speed and torque of the electric machine [28].

3.2. APU application

APU, feeding a number of subsystems such as lubrication system, fuel system, fuel heating system, ignition system, air system, thermostat system, cooling system, indicator system, fire warning and extinguishing system, electrical system; is a small scale gas turbine and consists of compressor, turbine, combustion chamber and gear box [29]. According to the models and series of APUs,

compressor and turbine stages can be in various numbers [29].

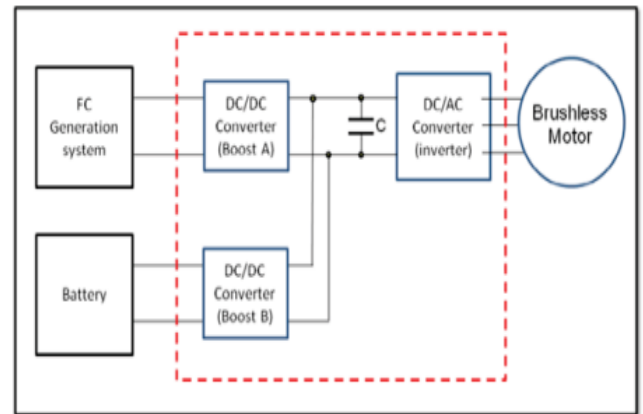


Figure 3. Schematic View of modified Propulsion Assembly done by ENFICA-FC research project [28].

APU's have the same mechanical properties as the main engines, but the control systems are more advanced and automatic running gas turbine motors[29]. APU also burns jet fuel and produces emissions and noise [30]. Current gas turbines APUs operate at 15 % load cycle efficiency and cause 20 % of the aircraft emissions [30]. In addition, according to research done by Zurich airport, the APU is responsible for emission of 18 % NOx and significant amount CO [31].

The suitability of the usage of fuel cells instead of APUs has been encouraged by several projects such as Airbus (CELINA project), Boeing and NASA (NEXCAP project) [30]. Especially PEMFC, SOFC are most promising candidate for APU application [32]. The DOE has published that fuel cell APU in aircraft could reduce in a 2-5% in the total amount of fuel used by the U.S. Air Force, saving 1 million to 3 million barrels of jet fuel [33]. Nasa jointly with Delphi and Boeing conducted a research on hybrid FCAPU development for large, 305-seat commercial aircraft (Boeing 777) [34].

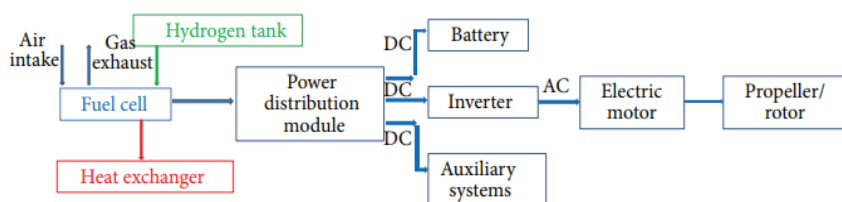


Figure 2. An exemplary fuel cell and electric motor based UAV propulsion system [27].

The hybridization of SOFC / GT has been selected in this work because it works more efficiently than separate cycles. The FCAPU was planned to get the following minimum target for the 305-seat research aircraft: design power output of 440 kW, peak system power output of 438 kW in flight, lifetime of 40,000 h, less than 880 kg of system weight [34]. The system structure of the proposed hybrid fuel cell APU for this work is shown in Fig.4.

4. HYDROGEN STORAGE ON FUEL CELL APPLICATION

The methods of hydrogen storage are basically divided into two sections as physical storage (compressed H₂ tank, liquid H₂ tank) and chemical storage (metal hydrides, carbon nanotubes, glass microspheres, chemical hydrides) [1]. Among these storage methods, the most common storage methods used in aviation research for fuel cells application are compressed H₂ storage, liquid H₂ storage and chemical hydrides storage. Although other storage methods require more development, all storage methods have problems to be solved [1]. At the beginning of these problems, hydrogen comes in low volumetric energy density [35]. Hydrogen, which has a upper heating value of 143 MJ/kg all of the existing fuels in terms of mass energy density, has the lowest density of volumetric energy with 0.0108 MJ/L in gaseous state [35]. Numerous studies have been conducted to overcome these problems and to efficiently store the hydrogen. Research on metal hydride, carbon nanotubes and glass microspheres was compiled by [1, 35-38]

1. Compressed H₂ Storage

Hydrogen is stored by pressurizing due to its low density [1]. In this storage method in which storage pressure varies from 35 to 70 MPa [3], hydrogen gas density increases as pressure increases [38]. Although very high pressures make fuel filling difficult, the advantages of this method are the rapid filling releasing rate is possible and the easiness of technology[1]. However, the method of pressurizing hydrogen is a simpler, more economical and more efficient method than other methods, but the storage weight is a significant problem for especially air vehicles [35, 37]. In order to solve this problem, fiber-composite structures with lightweight in certain proportions and high mechanical strength are used in new technology high pressure tanks [35]. On the other hand, the amount of energy used to compress hydrogen to high pressures which varies depending on the circuit and system efficiency, is an issue to consider in cost evaluations [35].

4.2. Liquid H₂ Storage

For large scale storage, hydrogen should be stored in liquid form which requires but very low temperatures not high pressure [3]. The density of liquid hydrogen (70.8 g / L) at 20 K temperature and 1 atmospheric pressure is about two times the density of hydrogen gas (38.7 g / L) at 700 bar pressure [35]. However, since liquid hydrogen tanks can be made much lighter and smaller in volume than high-pressure gas tanks, the weight problem of gas storage is solved [35].

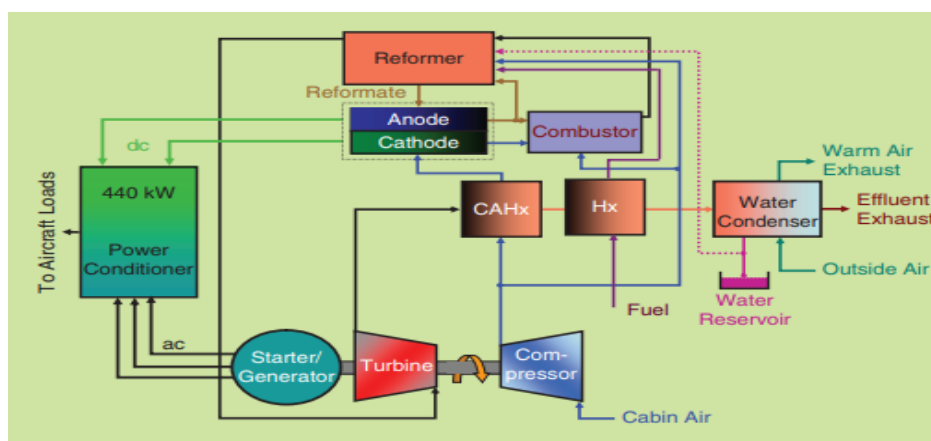


Figure 4. Proposed hybrid fuel cell APU [34].

Due to the usage experience on spacecraft and higher density under lower pressure, hydrogen stored in liquefied form is considered to be the easiest way to apply to aviation [37]. Gong and Verstraete [3] specified that according to research conducted by the NRL (Naval Research Laboratory), using liquid hydrogen instead of compressed gas on UAV may provide an increase in flight time from 26 to 72 hours [3]. Liquefied storage has many advantages compared to gas storage, but there are still problems to need solve for its widespread use in aviation. Liquefaction of hydrogen with very low values such as critical temperature of 33 K and liquefaction temperature of 20 K is relatively difficult and requires special techniques [35]. Because liquid hydrogen is stored at very low temperatures (21 K), it is practically impossible to completely prevent the heat transfer from the surrounding to fuel tank and the evaporation of hydrogen [35]. In addition, fuel system components such as liquid fuel pumps, fuel lines, heat exchangers, filters, valves will be needed [37].

4.3. Chemical hydrides

Methods in which the host material is chemically converted during use or hydrogen is obtained from different chemicals during use are classified as chemical storage [35]. Chemical hydrides with higher energy density have begun to attract attention as they contain light elements [1]. But, the very high temperatures required for thermal decomposition of hydrogen from chemical hydrides make this method unpractical. At the same time, investigations (catalyst etc.) continue to reduce the decomposition temperature of these hydrides [35]. Sodium borohydride (NaBH_4) and ammonia borane are the most investigated chemical storage compounds for UAVs [1]. Advantages of sodium borohydride include: stable reaction, rapid reaction at ambient temperature, low hydrolysis heat, and a more stable and easy to handle fuel source compared to liquid or compressed hydrogen [1].

5. DEVELOPMENT OF FUEL CELL BASED AIR VEHICLES








In this section, projects which are related with fuel cell powered aircraft were given in historical order. Detailed information on these projects is shown in table 3.

6. CONCLUSION

Due to factors such as increasing energy consumption and emissions, a lot of areas containing energy are in the way of electrification. Air transportation also is the stage of transition from gas turbine to electric propulsion. Despite the fact that the first fuel cell based UAV was built in 2003, for the first time after 13 years the 4-seat fuel cell based manned aircraft test flight successfully completed. This means that there are many problems that need to be solved for electrification in air vehicles. Most of the research projects focus on PEMFC because it is the most promising candidate that obeys future aviation strategies and application (minimizing emissions, high efficiency... etc.); this situation requires effective production and storage of hydrogen. However, storage system with the desired characteristics and enough endurance cannot be achieved for enabling fuel cells to be used extensively in large and small-scale all aviation. Therefore, there are many studies to solve these problems and new methods (such as hybridization) are being developed. Although the usage of fuel cells as primary energy sources for commercial aircraft requires a great deal of time and technological suitability, they are currently being developed primarily in UAVs and are seen as an important candidate.

In this review, the usage applications of fuel cells in air vehicles like propulsion, APU, hydrogen storage are given in detail. Advantages and working principles of these applications are presented and their challenges are determined.

Table 3. Examples of the development of fuel cell based aircraft in historical order.

Prototype	Aircraft Name	Year	Fuel Cell Type	Fuel Type	Hydrogen Storage	Test Flight Time	Explanatory
	ScanEagle (UAV/Insitu) [39-40]	2017	PEM	Hydrogen	Compressed hydrogen	8+ hr.	<ul style="list-style-type: none"> ●Length:1.55 m ●Wingspan: 3.11 m ●Max. takeoff weight:22 kg ●Max. speed:41.2 m/s ●Max.flight altitude: 5,944 m (19,500 ft). ●1.3 kW fuel cell system
	HY4 (first four-seat passenger aircraft/DLR) [41]	2016	PEM	Hydrogen	Compressed hydrogen (4,300-5,800 psi)	10 min.	<ul style="list-style-type: none"> ●Length: 7.4 m ●Wingspan: 21.36 m ●Max. takeoff weight: 1,500kg ●Max. speed: 200km/h ●80 kW power output ●HY4 can achieve a range of between 750 and 1500 kilometers.
	Ion Tiger (UAV-NRL) [42]	2013	PEM	Hydrogen	Cryogenic liquid hydrogen	48 hr.	<ul style="list-style-type: none"> ●Wingspan: 5.18 m ●Weight: 16.78kg ●Max. payload: 2.25kg ●Power: 550W (0.75hp)
	Stalker XE (UAS- Boeing, Lockheed Martin, Adaptive Materials Incorporated) [43-44]	2011	SOFC	Propane	Small propane fuel storage tank	8+ hr.	<ul style="list-style-type: none"> ●Wingspan: 12 ft ●Max. takeoff weight: 22 lbs ●Max. speed: 45mph ●Max.flight altitude: 15,000 ft ●Payload: Up to 5.5 lbs
	Rapid 200-FC (Manned-known as ENFICA-FC) [45]	2010	PEM	Hydrogen	Compressed hydrogen (350 bar)	45 min.	<ul style="list-style-type: none"> ●Wingspan: 10 m ●Max. speed: 150 km/h ●Total weight: 550kg ●20 kW two fuel cell system
	Ion Tiger (UAV-NRL) [42]	2009	PEM	Hydrogen	Compressed hydrogen (5,000 psi)	26 hr.	<ul style="list-style-type: none"> ●Wingspan: 5.18 m ●Weight: 16.78kg ●Max. payload: 2.25kg ●Power: 550W (0.75hp)
	Antares DLR-H2 (First manned aircraft with fuel cell solely/DLR) [46-47]	2009	PEM	Hydrogen	Compressed hydrogen	5 hr.	<ul style="list-style-type: none"> ●Wingspan: 20 m ●Max. takeoff weight:875 kg ●Max. speed:170 m/s ●Fuselage length:47.4 m ●Range : 750 km ●Max 33 kW fuel cell power and up to 52% fuel cell efficiency.

	First fuel cell manned airplane (Boeing-two seat) [26]	2008	PEM	Hydrogen	Compressed hydrogen (350 bar)	26 to 28 min.	<ul style="list-style-type: none"> ●Wingspan: 16.3 m ●Max.flight altitude: 3500 ft ●Max. speed:100 m/s ●Max. 24 kW gross fuel-cell system power
	Endurance (UAV- University of Michigan) [48-49]	2008	SOFC	Propane	Small propane fuel storage tank	10 hr.	<ul style="list-style-type: none"> ●Wingspan: 1.524 m
	Blended wing-body (BWB) MAV (KAIST) [50]	2007	PEM	Hydrogen	Sodium borohydride	5+ hr.	<ul style="list-style-type: none"> ●Energy density of the total system: 1,000 W.hr/kg ●PEMFC was fabricated by stacking 24 cells that have 3.8 cm² active areas.
	HyFish (UAV/DRL) [49,51]	2007	PEM	Hydrogen	Compressed hydrogen	0,25 hr.	<ul style="list-style-type: none"> ●Length: 1.3 m ●Wingspan: 1 m ●Total weight: 5 kg ●Max. air speed: 200 km/h
	PUMA (UAV/ AeroVironment) [49,52]	2007	PEM	Hydrogen	Sodium borohydride	9 hr.	<ul style="list-style-type: none"> ●Length: 1.4 m ●Wingspan: 2.8 m ●Empty weight: 5.9 kg ●Speed: 37 to 83km/h ●Max.flight altitude: 500ft
	Georgia Institute of Technology and Colorado State University (UAV) [3,49]	2006	PEM	Hydrogen	Compressed hydrogen	0.75 hr.	<ul style="list-style-type: none"> ●Wingspan: 6.58 m ●Takeoff weight: 16.4 kg ●1.3 kW fuel cell system ●A 500 W 32-cell PEMFC stack
	Spider Lion(UAV/NRL) [49,53]	2005	PEM	Hydrogen	Compressed hydrogen (4500 psi)	3 hr	<ul style="list-style-type: none"> ●Wingspan: 2.2 m ●Weight: 2.5 kg ●Max 110 W fuel cell system
	Global Observer(UAV/ AeroVironment) [49]	2005	PEM	Hydrogen	Liquid hydrogen	24 hr.	<ul style="list-style-type: none"> ●Wingspan: 15.24 m
	Hornet (MAV/ AeroVironment) [49,54]	2003	PEM	Hydrogen	Sodium borohydride	0,25	<ul style="list-style-type: none"> ●Wingspan: 0,381 m

Nomenclature

PEMFC: Polymer Electrolyte Membrane Fuel Cell
SOFC: Solid Oxide Fuel Cell
FC: Fuel cell
APU: Auxiliary Power Unit
FCAPU: Fuel Cell Auxiliary Power Unit
GT: Gas Turbine
UAV: Unmanned Aerial Vehicle
UAS: Unmanned Aerial System
DC/AC: Direct Current/ Alternative Current
DOE: US Department Of Energy
CELINA: Fuel Cell Application In A New Configured Aircraft
NEXCAP: Next Generation Clean Aircraft Power and Propulsion
ENFICA: Environmentally Friendly Intercity Aircraft
NASA: National Aeronautics and Space Administration
NRL: Naval Research Laboratory
DLR: Deutsches Zentrum für Luft- und Raumfahrt
MAV: Micro air vehicle
H₂: Hydrogen
H₂O: Water
NO_x: Oxides of Nitrogen
CO: Carbon Monoxide
CO₂: Carbon Dioxide

References

[1] Sürer, M., Arat, H., State of art of hydrogen usage as a fuel on aviation. *European Mechanical Science*, Vol. 2, No.1, 2017, pp. 20-30.
[2] Densu, A., DA-II electric-powered sport aircraft utilizing fuel cell and liquid hydrogen technologies, master theses, 2010, University of Tennessee.
[3] Gong, A., & Verstraete, D., Fuel cell propulsion in small fixed-wing unmanned aerial vehicles: Current status and research needs, *International Journal of Hydrogen Energy*, Vol. 42, No. 33, 2017, pp. 21311-21333.
[4] Sharaf, O. Z., & Orhan, M. F., An overview of fuel cell technology: Fundamentals and applications. *Renewable*

and Sustainable Energy Reviews, Vol. 32, 2014, pp. 810-853.

[5] Ward, T. A., & Jenal, N., Design and initial flight tests of a hydrogen fuel cell powered unmanned air vehicle (UAV). *ECS Transactions*, Vol.26, No.1, 2010, pp.433-444.

[6] Williams, M. C., Fuel cell handbook. EG&G Technical Services, National Energy Technology Laboratory, 2004, US Department of Energy.

[7] Mobariz, K. N., Youssef, A. M., & Abdel-Rahman, M., Long endurance hybrid fuel cell-battery powered UAV, *World Journal of Modeling and Simulation*, Vol. 11, 2015, pp. 69-80.

[8] Osenar, P., Sisco, J., Reid, C., Advanced Propulsion for Small Unmanned Aerial Vehicles, *White paper*, 2017.

[9] Hepperle, M., Electric flight-potential and limitations, 2012, German Aerospace Center, Institute of Aerodynamics and Flow Technology.

[10] Chen, H., Cong, T. N., Yang, W., Tan, C., Li, Y., & Ding, Y., Progress in electrical energy storage system: A critical review, *Progress in Natural Science*, Vol. 19, No.3, 2009, pp. 291-312.

[11] International Electrotechnical Commission, Electrical energy storage white paper, *Geneva, Switzerland: International Electrotechnical Commission*, 2011, pp. 1-78.

[12] Du Pasquier, A., Plitz, I., Menocal, S., & Amatucci, G., A comparative study of Li-ion battery, supercapacitor and nonaqueous asymmetric hybrid devices for automotive applications, *Journal of Power Sources*, Vol. 115, No. 1, 2003, pp. 171-178.

[13] Hadjipaschalis, I., Poullikkas, A., & Efthimiou, V., Overview of current and future energy storage technologies for electric power applications. *Renewable and sustainable energy reviews*, Vol. 13, No. 6-7, 2009, pp. 1513-1522.

[14] Smith, W., The role of fuel cells in energy storage. *Journal of Power Sources*, Vol. 86, No. 1-2, 2000, pp. 74-83.

[15] Shoenung SM, Characteristics and technologies for long- vs. short-term energy storage: a study by the DOE energy storage

systems program, Technical report. SAND2001-0765, Sandia National Laboratories, *United States Department of Energy*, Published March 2001.

[16] Schaber C, Mazza P, Hammerschlag R., Utility-scale storage of renewable energy. *Electr J*, Vol. 17, 2004, pp.21–9.

[17] Rastler D. Electricity energy storage technology options: a white paper primer on applications, costs, and options, *Electric Power Research Institute (EPRI)*, Technical report, Published December 2010.

[18] Spencer, K. M., Martin, C. A., Investigation of potential fuel cell use in aircraft, *Institute for defense analyses*, 2013.

[19] Wu, S., & Li, Y., Fuel cell applications on more electrical aircraft. *In Electrical Machines and Systems (ICEMS), 17th International Conference on*, 2014, pp. 198-201, IEEE.

[20] PEM Yakıt Pili Bileşenleri, <https://muhendisbeyindefteri.wordpress.com/2016/11/28/yakit-pili-bilesenleri/> [Accessed in January 2018]

[21] <http://earthsci.org/mineral/energy/fuelcell/fuelcell.html> [Accessed in January 2018]

[22] Aguiar, P., Brett, D. J. L., & Brandon, N. P., Solid oxide fuel cell/gas turbine hybrid system analysis for high-altitude long-endurance unmanned aerial vehicles, *International journal of hydrogen energy*, Vol.33, No.23, 2008, pp. 7214-7223.

[23] Hydrogen Fuel Cell Engines and Related Technologies. Module 4: Fuel cell engine technology, U.S. DOE. 2001, <https://energy.gov/eere/fuelcells/downloads/hydrogen-fuel-cell-engines-and-related-technologies-course-manual> [Accessed in January 2018]

[24] <http://biyokure.org/yakit-pilleri-yazi-dizisi-9-kati-oksit-yakit-pilleri/10101/> [Accessed in January 2018]

[25] Righi, H., Hybrid electric aircraft, Doctoral dissertation, 2016, Mississippi State University,

[26] Lapeña-Rey, N., Mosquera, J., Bataller, E., & Ortí, F, First fuel-cell manned aircraft. *Journal of aircraft*, Vol. 47, No. 6, 2010, pp. 1825-1835.

[27] González-Espasandín, Ó., Leo, T. J., & Navarro-Arévalo, E., Fuel cells: a real option for unmanned aerial vehicles propulsion. *The Scientific World Journal*, 2014. DOI: 10.1155/2014/497642.

[28] Innocenti, M., Pollini, L., Mati, R., & Sani, L., Design of an all-electric propulsion system and control management for a general aviation aircraft. In *AIAA Atmospheric Flight Mechanics Conference*, Chicago, Illinois, 2009, pp. 5932.

[29] Coşkun, N., APU'nun teknik özellikleri ve sivil havacılıkta kullanımı, 2016, Bitirme ödevi, Erciyes Üniversitesi Sivil Havacılık Yüksek Okulu.

[30] Extern, G. A. E. S., 2006, GAES project: Potential Benefits of Fuel Cell Usage in the Aviation Context.

[31] Friedrich, K. A., Kallo, J., Schirmer, J., & Schmitthals, G, Fuel cell systems for aircraft application. *ECS Transactions*, Vol. 25, No.1, 2009, pp. 193-202.

[32] Friedrich, K. A., & Henne, R. Auxiliary Power Unit (APU) Application, Tagungs-CD H2Expo 2006

[33] Elitzur, S., Rosenband, V., & Gany, A., On-board hydrogen production for auxiliary power in passenger aircraft, *International Journal of Hydrogen Energy*, Vol. 42, No. 19, 2017, pp. 14003-14009.

[34] Rajashekara, K., Grieve, J., & Daggett, D., Hybrid fuel cell power in aircraft, *IEEE Industry Applications Magazine*, Vol.14, No.4, 2008, pp. 54-60.

[35] Kaya, N., Hidrojen kullanan turbofanlı bir insansız hava aracının ekserjetik sürdürülebilirlik analizi, 2015, doktora tezi, Anadolu Üniversitesi.

[36] Hwang, H. T., & Varma, A., Hydrogen storage for fuel cell vehicles, *Current Opinion in Chemical Engineering*, Vol. 5, 2014, pp.42-48.

[37] Şenel, K., Hidrojenin yakıt olarak uçaklarda kullanımı. yüksek lisans tezi, Eskişehir Osmangazi Üniversitesi, Fen Bilimleri Enstitüsü, 2007.

[38] Colozza A. J., Hydrogen Storage for Aircraft Applications Overview, 2002, Analex Corporation, Brook Park, Ohio.

- [39] <http://articles.sae.org/15568/>
[Accessed in January 2018]
- [40] <http://www.ballard.com/about-ballard/newsroom/news-releases/2017/12/22/ballard-launches-next-generation-fuel-cell-system-for-drones-expands-insitu-flight-testing>
[Accessed in January 2018]
- [41] <http://www.aerospace-technology.com/projects/hy4-aircraft/>
[Accessed in January 2018]
- [42] <http://www.naval-technology.com/projects/ion-tiger-uav/>
[Accessed in January 2018]
- [43] <https://www.lockheedmartin.com/us/products/stalker-uas.html>
[Accessed in January 2018]
- [44] <http://www.airforce-technology.com/projects/stalker-xe-unmanned-aerial-system-uas/> [Accessed in January 2018]
- [45] http://www.enfica-fc.polito.it/content/download/246/1105/version/1/file/Press%20New%201st%20Flight%20Test_v4/index.pdf [Accessed in January 2018]
- [46] http://www.dlr.de/dlr/en/desktopdefault.aspx/tabid-10203/339_read-8244#/gallery/12336 [Accessed in January 2018]
- [47] <https://www.evhangar.com/aircraft/poc-aircraft/antares-dlr-h2/>[Accessed in January 2018]
- [48] <http://evworld.com/news.cfm?newsid=19751> [Accessed in January 2018]
- [49] Fuel Cells and Other Emerging Manportable Power Technologies for the NATO Warfighter – Part II: Power Sources for Unmanned Applications, STO Technical report,2014,
- [50] Kim, T., Shim, H., & Kwon, S., Micro aerial vehicle powered by a micro PEM fuel cell and sodium borohydride hydrogen source, *Proc Power MEMS*, 2007, pp. 285e8.
- [51] <http://www.dlr.de/tt/Portaldata/41/Resources/dokumente/institut/elchemenergietechnik/HandoutHyFish-e.pdf> [Accessed in January 2018]
- [52] <https://www.airforce-technology.com/projects/avincpumaeuav/>
[Accessed in January 2018]
- [53] Stroman, R., Kellogg, J. C., & Swider-Lyons, K., Testing of a PEM fuel cell system for small UAV propulsion. *Power*, Vol.60, No 80,2000.
- [54] Bradley, T.H., Parekh,D.H, Design, applications and commercialization of fuel cell powered aircraft, National Hydrogen Association Conference – Sacramento, 2008.