IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

International Journal of Heat and Technology
Vol. 41, No. 1, February, 2023, pp. 259-264
Journal homepage: http://iieta.org/journals/ijht

# Design and Construction of a UAV for High Atmosphere Flight Powered by Hydrogen Fuel Cell

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7th AIGE-IIETA Int. Conf. and 16th AIGE Conf.-SPECIAL ISSUE

https://doi.org/10.18280/ijht.410129

**Received:** 1 February 2023
**Accepted:** 15 February 2023

***Keywords:***
*volcanic emissions, unmanned aerial vehicle, hydrogen, fuel cell*

**ABSTRACT**

The need to improve the quality of monitoring and forecasting of volcanic gases and ashes dispersion, which frequently contaminate the airspace close to volcanoes, has led to the development of a modeling chain for the forecasting of atmospheric conditions and air quality. It provides airport companies with information aimed at increasing flight safety, together with decision support tools to adopt, in case of risk, measures for their temporary closure. For the validation of the model on a regional scale, in particular for the area surrounding the Etna volcano in Italy, measurement campaigns on gases and ashes, on the ground and at altitude, are necessary, the greatest difficulty of which consists in the height of the volcanic plume (7-14 km). To this end, the work presents the design and construction of an innovative UAV (Unmanned Aerial Vehicle) prototype, a fixed-wing aircraft powered by hydrogen fuel cells, equipped with sensors for detecting the emitted substances, flying at high altitudes (above 3,000 m) and piloted beyond the pilot's visual line of sight (BVLOS). The UAV can have useful applications for the territory observation, control and management (prevention of natural disasters), for first aid and others, targeting markets in aeronautics, transports, health care.

## 1. INTRODUCTION

The gases and lithic particles emitted into the atmosphere during the explosive activity of a volcano affect altitudes up to several km in height (7-14 km for Etna) and contaminate the airspace, representing one of the biggest risks for air traffic.

It is consequently necessary to improve the quality of monitoring and forecasting of their dispersion, providing airport management companies with information increasing their operations, functionality and safety, together with decision support tools to adopt, in the event of risk, measures for temporary airport ban or closure.

Integrated modeling chains such as WRF-Chem [1], including a meteorological model (Weather Research and Forecasting model, WRF) coupled with an atmospheric pollutant dispersion and transport one (Chemistry), are adopted in the aim; they require for validation at a regional/local scale measurements on the ground and in the volcanic plume, difficult to carry out due to its high temperature, pressure and altitude: for Etna volcano area (Italy) object of the study such quote is 7-14 km.

To this end, the work presents the design and construction of an innovative fixed-wing UAV prototype powered by hydrogen fuel cell [2, 3], equipped with sensors for detecting the emitted substances, that will be piloted beyond the pilot's visual line of sight (BVLOS) to carry out measurements inside the non-eruptive volcano plume, between the craters at 3.2 and 4-5 km altitude.

The fuel cell is suitable in terms of weight/power ratio, occupation and energy density [4-6]: compared to a battery with the same weight it has autonomy 3-4 times higher; moreover, hydrogen shows environmental sustainability and energetic performances: 1 kg provides 33.3 kWh gross of losses, with minimum occupancy if compressed [7-11]. Fuel cells address multiple power sectors and applications across stationary [12], transports [13] and portable, ranging from micro [14, 15] to large power plants.

## 2. PROJECT OF THE FUEL CELL POWERED UAV

### 2.1 Structure and materials

The design characteristics of the UAV prototype, a single engine model with variable pitch propeller, are: maximum tangency altitude 5,000 m, minimum payload 2 kg and flight autonomy at operating altitude up to 10 hours.

Firstly, the UAV mass in flight order and the wing area necessary for sustenance were estimated, defining the most appropriate concept, for which the operating/minimum speeds and the required power have been assessed.

Comparisons of various aerodynamic profiles and different main wing configurations were carried out through CFD software, determining geometries, optimal aerodynamic configurations and fuselage dimensions in relation to the load (sensors and power supply).

The identified airfoils showed excellent efficiency at the relevant altitudes.

The design was carried out through 3D CAD/CAM software (Figure 1).

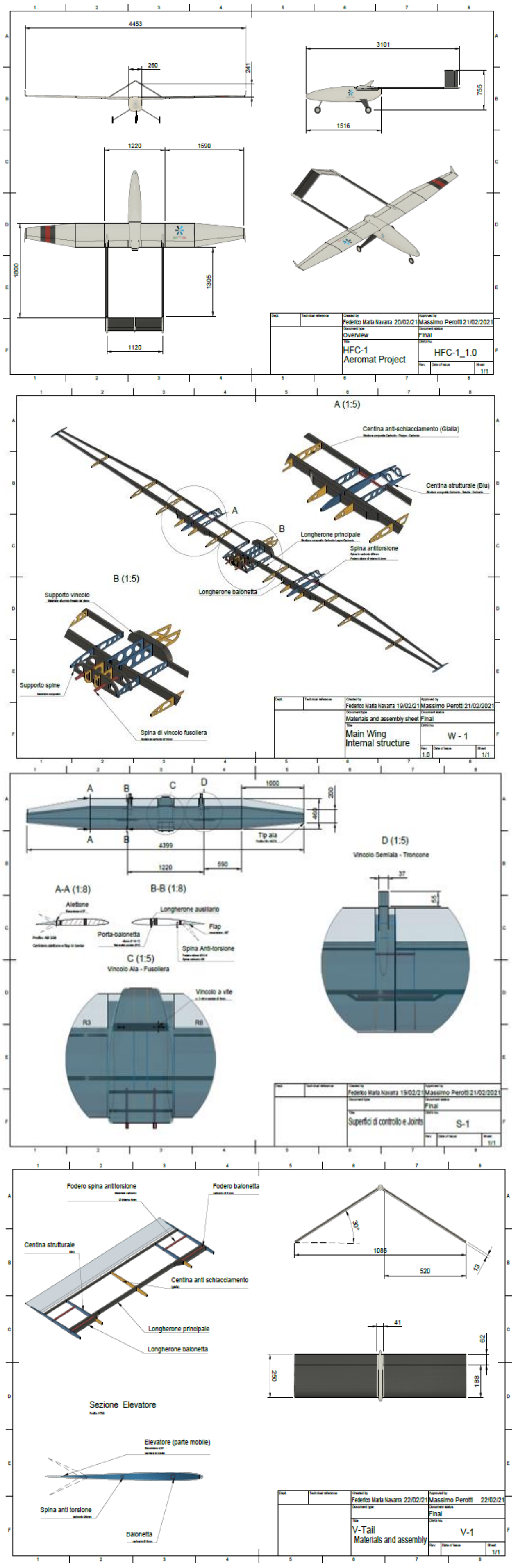


**Figure 1.** Overview and components of the projected UAV

Structural parts are made of composite materials: carbon fibers, kevlar and glass, subjected to heat treatment to optimize mechanical characteristics. Wings, control surfaces and fuselage are in fiber/foam/fiber sandwich, while in spars, ribs and frames the foam core is replaced with wood. Wings are coated with a film in abrasion resistant material to minimize abrasion damages caused by sharp prismatic micro-powders and hydrodynamic friction.

The design included the characterization of the propulsion system, made in abrasion resistant material, the landing gears of the frames, the on-board electronics, the pilotage and remote control, the traceability, safety, data transmission systems, including the ground station for the telemetry and flight commands communication and the management of flight planning. The system was equipped with ADS-B (Automatic Dependent Surveillance - Broadcast) systems and stroboscopes.

### 2.2 Power system

The electric power supply system is based on two integrated technologies, fuel cell and batteries, respectively for the cruise and take-off phases: since consumption is greater at take-off and peaks, it is more convenient to use a high power LiPo battery for the short take off (less than 1 min.) and peak (2 min.) times. As the fuel cell delivers power with a response time of tens of seconds, the battery is also necessary for starting; in turn it will be loaded by the fuel cell itself. Fuel cells use hydrogen and need oxygen or air.

**Table 1.** Technical characteristics of the fuel cell package

| | | |
|---|---|---|
| Maximum continuous power | | 800 W |
| Maximum peak power | | 1400 W |
| Output voltage | | 19.6 V – 25.2 V |
| Fuel cell power module | Dimensions | 196x100x140 mm |
| | Mass | 930 g |
| Hydrogen regulator | Mass | 250 g |
| | Maximum regulator pressure | 350 bar |
| | Output pressure | 0.5 – 0.25 bar |
| | Maximum cylinder mass | 10 kg |
| Hybrid battery | Dimensions | 125 x 30 x 40 mm |
| | Mass | 300 g |
| | Capacity | 1800 mAh |
| | Emergency flight time | 2 minutes |
| Environmental operating conditions | Operating temperature | 5°C-35°C |
| | Maximum altitude | 3,000 m |
| | Storage temperature | -10°C-70°C |
| | System lifetime | 100 hours |
| Other features | Internal data storage | SD Card |
| | Communication port to fuel cell | UART |
| | Output electrical connector | XT-60 |

The use of pure oxygen instead of air has a prominent influence on its power density and efficiency, which increases of 20% [16], but oxidizes its metal parts, so air, eventually mixed with maximum 30% oxygen, is preferred; we used pure air also in order to limit weight. At the considered quotas air is very thin, but the selected fuel cell is able to work without additional oxygen, the loss of efficiency due to oxygen lack being compensated by power oversizing. Table 1 shows the technical characteristics of the fuel cell package (fuel cell, hydrogen regulator and tank), depicted in Figure 2.

The cell has a suitable form factor, low weight and integrability for telemetry and remote control; a DC/AC converter matches the voltage to the load. Figure 3 shows the power supply (fuel cell + battery) power trend and Figure 4 the fuel cell power reduction above 3,000 m. Two 800 *W* fuel cells connected via power path module, air-cooled, have been used to obtain the 1,600 *W* design power. Their consumption $FC_c$ is:

$$FC_c = \frac{P}{\eta \times HEC}$$

where P is the design power, $\eta$ the fuel cell efficiency (0.56) and *HEC* the hydrogen energy content (33.3 *Wh/g*). It results:

$$FC_c = \frac{1600\ W}{0.56 \times 33.3\ Wh/g} = 85.8\ g/h$$

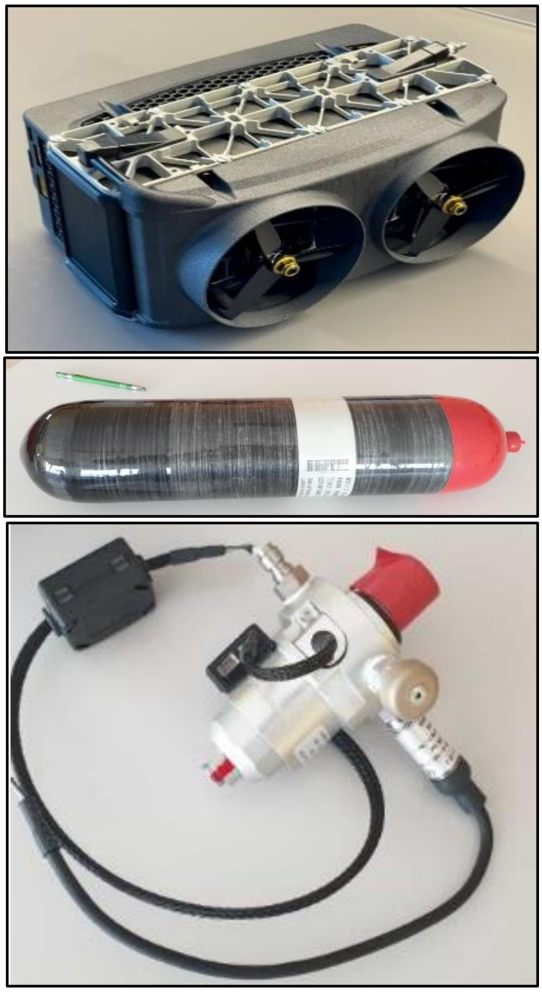

**Figure 2.** Fuel cell package (fuel cell, tank and hydrogen regulator)

The 9 *l* hydrogen tank volume allows a high autonomy, 6-12 *h* in dependence on altitude: higher at the bottom, with a significant decrease with height. At the involved altitudes the temperature is extremely low (every 100 m altitude increase it drops by 1°C) and being the fuel cell functionality > 0°C, due to its humid membranes and to water produced in the chemical reaction, it must be thermally insulated in order to maintain the heat generated. Moreover, since carbon fiber is very electrostatic and could react with hydrogen, both tanks and fuel cells are electrostatically isolated through a *Faraday* cage of a conductive material (*Cu, Al*).

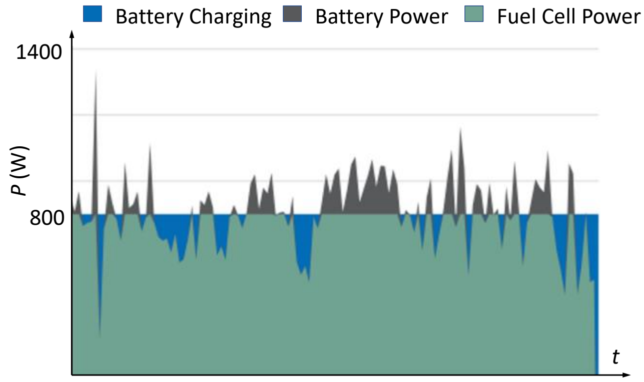


**Figure 3.** Power supply (fuel cell + battery) power trend

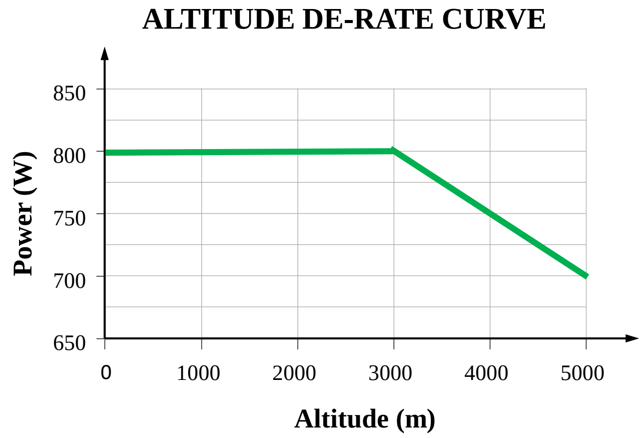


**Figure 4.** Fuel cell power reduction with altitude

### 2.3 Hydrogen storage

A comparison among solid and gaseous storage (metal hydrides and compressed hydrogen) in terms of weight, energy density and cost was effected. Solid storage occurs as metal hydride of an alkaline (*Na* or *Li*) or alkaline earth (*Ca*) metal: a solid compound forms when hydrogen under pressure (25-100 bar) diffuses occupying the interionic space in the crystal lattice of the metal.

Systems based on sodium hydrides (*NaH*) were analysed, exploiting their reaction with water. It is strongly exothermic and proceeds quickly: to control it, hydrogen is stored in pellet form, encapsulated in plastic containers cut into thin slices that, immersed in water, react releasing hydrogen and metal hydroxide (*NaOH*) as by-product, that can be recycled by reforming hydrogen.

The operating temperature range is -40°C - +60°C. Energy densities are greater than those obtainable with compressed hydrogen and comparable to those referred to liquid one. Further advantages are cost, small footprint, stability and safety due to low pressures, as well as low weight [17]. However, due to the critical issues of the process (the heat released and the cartridge disposal via methane, not feasible at the site) the gaseous storage has been preferred.

### 2.4 Hybrid photovoltaic - Fuel cell power

To increase autonomy a UAV must have a low weight: its heaviest component, the battery, drastically affects the flight time. For small-sized aircrafts, where the space is the key factor, it is interesting to adopt a hybrid fuel cell/photovoltaic power: PV panels offer a favorable power/surface ratio (350 W/m$^2$) [18], allowing flight times 8-10 times longer compared to batteries [19]. Integrating the solar panels in the wings UAV weight would increase only 1-2% and thickness 1-2 mm.

During the day, in full sunlight, panels would produce energy to guarantee the flight or the accessories supply and the battery charge [20-23] (Figure 5). The double junction *Tandem* cells [24] in thin film in *Gallium Arsenide* (*Ga-As*) [25] better exploit the light absorption spectrum obtaining high efficiencies (32%).

They have a mass of 240 g/m$^2$, can be integrated into carbon fiber and fiberglass and lend themselves to a transparent coating, ensuring protection from atmospheric events. Further possibility would be the solar powering of an electrolyser to obtain hydrogen for fuel cell supply, so that during the day the UAV would operate indefinitely. Solar power will be considered as a future development of the project.

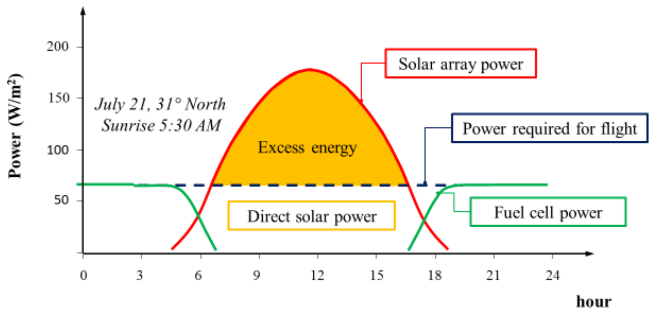


**Figure 5.** Sources of the power rates

## 3. THE SCALE MODEL

Preliminarily to the construction of the UAV prototype a scale model with a wingspan of 299 cm (70% of the real prototype) was created to carry out configuration and proof tests aimed to verify the aerodynamic design solutions provided by mathematical simulations (Figure 6).

The model allowed to make functional variations, to identify and correct errors of wings unbalance/deviation, defining the optimal collection. As concerns its aerodynamic surfaces, the wings were made of materials (foam) other than those of the full-scale prototype, very expensive.

Except for the fuel cell, which is replaced by a lithium-ion battery, the model is equipped with the same electronics and avionics as the full scale one and integrates an open-source system for flight management. Telemetry system reaches 40 km distance in straight line. The UAV can perform missions in complete autonomy in all phases (take-off, flight, landing). It is equipped with a parachute landing system, is completely demountable and transportable.

Abrasion tests were conducted on the wings since the simulation showed that the empty wing, hit by the microparticles of the volcanic plume, resonated at very low frequencies (800 Hz) and the generated vibrations could cause a crisis in the computer controlling the UAV position. To prevent this the wings were filled with material absorbing vibrations, so that the central part of the aircraft, containing both the communications control center and measurement sensors, was suspended and isolated from vibrations.

**Figure 6.** Components and prototype of the scale model

Static and frame quality tests were executed; in this aim a first versions of the scale model, with a wingspan of 286 cm (65% of the final prototype), materials and construction techniques of the model aircraft, was constructed. Bench tests were aimed to verify the functionality and efficiency of all systems (propellers, engine, front wheel, static load, connection link at ground level). 6 dynamic configuration and proof tests followed, performed with different take-off settings (center of gravity, weight, elevator trim, flap, flight mode) and weather conditions (coverage, cloud base, visibility, wind), also under loss of signal or generating a failsafe event. Stability, tuning of the auto-pilot, flight controller setting were tested, also forcing critical flight conditions and executing automatic flight missions. The space required for take-off/landing is 20 m. The prototype took off and landed without complications. 2 more test flights were effected on a final version of the model, with a wingspan of 299 cm (70% of the full scale one), different from the first one in construction techniques and valuable materials used, confirming the results.

## 4. THE FULL-SCALE MODEL

To realize the full-scale model the project was adapted after the results obtained from the tests on the scale model.

Table 2 shows its characteristics: having dimensions > 3 m the full-scale model belongs to the certified class; its prototype is reported in Figure 7.

**Table 2.** UAV project data and characteristics

| | | | |
|---|---|---|---|
| Flight altitude | maximum tangency altitude | | 5,000 m |
| Geometric characteristics | wingspan | | 4,400 mm |
| | length | | 2,400 mm |
| | maximum section | | 1,450 mm |
| | maximum chord | | 500 mm |
| Weight | maximum take-off weight | | 15 kg |
| Payload | minimum | | 2 kg |
| Material | composite | | carbon fibers, kevlar and glass |
| Propulsion | motor | | brushless with variable pitch propeller |
| Power supply | hybrid | cruising | hydrogen fuel cell |
| | | at take-off | Li-Po batteries |
| | power | fuel cell | 1,600 W |
| | | battery (peak) | 1,650 W |
| | cruising | | 375 W |
| | uphill | | 750 W |
| | at take off | | 1,500 W |
| Tank | high pressure hydrogen | | 9 l |
| Speed | cruising | at operating altitude | 61 km/h |
| | | at sea altitude | 93 km/h |
| | at take off | | 50 km/h |
| | in stall | | 12 m/s |
| | in vertical ascent | | 5 m/s |
| Time | take-off | | 30 s – 1 min |
| | ascent to operating altitude | | 20 min |
| Autonomy | at operating altitude | | up to 10 h |

**Figure 7.** Prototype of the full-scale model

The UAV is equipped with gas and particle sensors, a gas analyzer with constant flow air intake for $SO_2$ measurements and a particle counter with optical sensor.

Static and bench load tests have been conducted on the variable pitch propulsion system, defining the power curve. The dynamic testing at high altitude (3,000-6,000 m) on the UAV piloted in BVLOS mode (beyond pilot's visual line of sight) have been carried out also through the forcing of critical flight conditions and the execution of automatic flight missions, verifying operation in suboptimal atmospheric conditions. The space required for take-off and landing is 70 m. Telemetry reaches 200 km in straight line.

## 5. CONCLUSIONS

Volcanic ash and gases which contaminate the airspace close to volcanoes represent one of the greatest risks for air traffic. The need to improve the quality of monitoring and forecasting of such phenomena has led to the development of forecasting models of atmospheric conditions and air quality, consisting of integrated modeling chains composed of a meteorological model (*Weather Research and Forecasting model, WRF*) coupled to an environmental model of dispersion and transport of atmospheric pollutants (*Chemistry*).

They provide airport management companies with information aimed at increasing flight safety, airport functionality and operation, acting in event of risk as support tools to adopt measures for the temporary airport ban or closure. For the validation and commissioning of the models on a regional scale, in the study particularly for the area surrounding the Etna volcano (Italy), measurement campaigns on gas and ashes, on the ground and at altitude, are necessary, the greatest difficulty of which consists in the height of the volcanic plume (7-14 km). Once validated, the model will be submitted to the *National Civil Aviation Authority* (in Italy *ENAC*) to obtain aeronautical certification and possible introduction in the international procedure.

To this aim, the work presents the design and construction of a prototype of UAV powered by hydrogen fuel cell, equipped with sensors for detecting the emitted substances, which will be used to carry out measurements inside the non-eruptive plume, between the craters at altitudes of 3.2 and 4-5 km, piloted in BVLOS (Beyond pilot's visual line of sight) mode. The UAV could anyway be used in a wider field, including the territory observation, control and management (prevention of natural disasters), targeting markets in the aeronautics, transport, first aid sectors, etc.


## ACKNOWLEDGEMENTS

This work is to be framed within the Research and Development Project "Use of innovative technologies, materials and models in the aeronautical field (AEROMAT)", *National Operational Program Research and Innovation 2014-2020*.


## REFERENCES


[1] Grell, G.A., Peckham, S.E., Schmitz, R., McKeen, S.A., Frost, G., Skamarock, W.C., Eder, B. (2005). Fully coupled "online" chemistry within the WRF model.

Atmospheric Environment, 39(37): 6957-6975. https://doi.org/10.1016/j.atmosenv.2005.04.027
[2] Sujit, P. B., Saripalli, S., Sousa, J.B. (2014). Unmanned aerial vehicle path following: A survey and analysis of algorithms for fixed-wing unmanned aerial vehicless. IEEE Control Systems Magazine, 34(1): 42-59. https://doi.org/10.1109/MCS.2013.2287568
[3] Bang, S., Kim, H., Kim, H. (2017). UAV-based automatic generation of high-resolution panorama at a construction site with a focus on preprocessing for image stitching. Automation in Construction, 84: 70-80. https://doi.org/10.1016/j.autcon.2017.08.031
[4] González-Espasandín, Ó., Leo, T.J., Navarro-Arévalo, E. (2014). Fuel cells: A real option for unmanned aerial vehicles propulsion. The Scientific World Journal, Article ID: 497642. https://doi.org/10.1155/2014/497642
[5] Lapeña-Rey, N., Blanco, J.A., Ferreyra, E., Lemus, J.L., Pereira, S., Serrot, E. (2017). A fuel cell powered unmanned aerial vehicle for low altitude surveillance missions. International Journal of Hydrogen Energy, 42(10): 6926-6940. https://doi.org/10.1016/j.ijhydene.2017.01.137
[6] Lei, T. (2021). Energy management system and strategy for a fuel cell/battery hybrid power. In Unmanned Aerial Systems (pp. 289-313). Academic Press.
[7] Momirlan, M., Veziroglu, T.N. (2005). The properties of hydrogen as fuel tomorrow in sustainable energy system for a cleaner planet. International Journal of Hydrogen Energy, 30(7): 795-802. https://doi.org/10.1016/j.ijhydene.2004.10.011
[8] Marchenko, O.V., Solomin, S.V. (2015). The future energy: Hydrogen versus electricity. International Journal of Hydrogen Energy, 40(10): 3801-3805. https://doi.org/10.1016/j.ijhydene.2015.01.132
[9] Ball, M., Weeda, M. (2015). The hydrogen economy–vision or reality? International Journal of Hydrogen Energy, 40(25): 7903-7919. https://doi.org/10.1016/j.ijhydene.2015.04.032
[10] Dincer, I., Rosen, M.A. (2011). Sustainability aspects of hydrogen and fuel cell systems. Energy for Sustainable Development, 15(2): 137-146. https://doi.org/10.1016/j.esd.2011.03.006
[11] Hoffmann, P. (2001). Tomorrow's energy: Hydrogen, fuel cells and the prospects for a cleaner planet. Cambridge, Massachusetts: The MIT Press. https://doi.org/10.1017/S1466046602251261
[12] Marino, C., Nucara, A., Pietrafesa, M. (2015). Electrolytic hydrogen production from renewable source, storage and reconversion in fuel cells: The system of the "Mediterranea" University of Reggio Calabria. Energy Procedia, 78: 818-823. https://doi.org/10.1016/j.egypro.2015.11.001
[13] Mori, D., Hirose, K. (2009). Recent challenges of hydrogen storage technologies for fuel cell vehicles. International Journal of Hydrogen Energy, 34(10): 4569-4574. https://doi.org/10.1016/j.ijhydene.2008.07.115
[14] Carbone, R., Marino, C., Nucara, A., Panzera, M.F., Pietrafesa, M. (2019). Electric load influence on performances of a composite plant for hydrogen production from RES and its conversion in electricity. Sustainability, 11(22): 6362. https://doi.org/10.3390/su11226362
[15] Büchi, F.N., Freunberger, S.A., Reum, M., Delfino, A. (2005). On the efficiency of $H_2/O_2$ automotive PEM fuel cell systems. Proc. of 3rd Eur. PEFC For. File B091.
[16] Carbone, R., Marino, C., Nucara, A.F., Panzera, M.F., Pietrafesa, M. (2019). A case-study plant for a sustainable redevelopment of buildings based on storage and reconversion of hydrogen generated by using solar energy. ArcHistoR, 6(12): 596-615. https://doi.org/10.14633/AHR184
[17] Ouyang, L.Z., Qin, F.X., Zhu, M. (2006). The hydrogen storage behavior of Mg3La and Mg3LaNi0. 1. Scripta Materialia, 55(12): 1075-1078. https://doi.org/10.1016/j.scriptamat.2006.0
[18] Sharma, S., Jain, K.K., Sharma, A. (2015). Solar cells: in research and applications—a review. Materials Sciences and Applications, 6(12): 1145. https://doi.org/10.4236/msa.2015.612113
[19] Gadalla, M., Zafar, S. (2016). Analysis of a hydrogen fuel cell-PV power system for small UAV. International Journal of Hydrogen Energy, 41(15): 6422-6432. https://doi.org/10.1016/j.ijhydene.2016.02.129
[20] Townsend, A., Jiya, I.N., Martinson, C., Bessarabov, D., Gouws, R. (2020). A comprehensive review of energy sources for unmanned aerial vehicles, their shortfalls and opportunities for improvements. Heliyon, 6(11), e05285.
[21] Chu, Y., Ho, C., Lee, Y., Li, B. (2021). Development of a solar-powered unmanned aerial vehicle for extended flight endurance. Drones, 5(2): 44. https://doi.org/10.3390/drones5020044
[22] El-Atab, N., Mishra, R.B., Alshanbari, R., Hussain, M.M. (2021). Solar powered small unmanned aerial vehicles: A review. Energy Technology, 9(12): 2100587. https://doi.org/10.1002/ente.202100587
[23] Rajendran, P., Smith, H. (2018). Development of design methodology for a small solar-powered unmanned aerial vehicle. International Journal of Aerospace Engineering, 2018. https://doi.org/10.1155/2018/2820717
[24] Liu, N., Wang, L., Xu, F., Wu, J., Song, T., Chen, Q. (2020). Recent progress in developing monolithic perovskite/Si tandem solar cells. Frontiers in Chemistry, 8: 603375. https://doi.org/10.3389/fchem.2020.603375
[25] Ma, C., Park, N.G. (2020). A realistic methodology for 30% efficient perovskite solar cells. Chem, 6(6): 1254-1264. https://doi.org/10.1016/j.chempr.2020.04.013