NEW FUEL CELL TECHNOLOGIES EXTEND MISSIONS FOR VERTICAL TAKE-OFF AND LANDING UNMANNED AERIAL VEHICLES

James Sisco,*† Phil Robinson,‡ and Paul Osenar§

Vertical Take-Off and Landing (VTOL) drones have seen widespread adoption recently due to the operational flexibility provided by multirotor platforms. However, mission duration remains a significant challenge. To date, fuel cell use in VTOL systems has been limited to demonstrations. While fuel cells exhibit very high energy density (the amount of energy stored for a given weight), they have typically been limited in power density (how quickly that energy can be delivered) compared to batteries. Recent developments in the fuel cell industry – largely driven by portable defense applications – have resulted in new fuel cell technologies which provide both the energy density and power density needed to effectively prolong VTOL drone missions by a factor of three over the best batteries. These technical advances are explored, along with the tradeoffs that unmanned aerial system (UAV) manufacturers and users must examine to determine if fuel cell power might make sense for a given platform and mission. The discussion will include some of the challenges associated with retrofitting existing platforms, as well as factors affecting fuel choice (fuel cells can use not only hydrogen, but also hydrogen-bearing compounds for fuel), safety, and ground station equipment. Design information is provided for UAV designers and users interested in significantly increasing mission durations beyond those that can be achieved using batteries for a wide range of VTOL multi-rotor drone platforms.

INTRODUCTION

Although they have been historically used by the military, unmanned aerial vehicles (UAVs), also known as drones, have also recently become significant tools in the consumer and commercial sectors. According to recent reports, the U.S. Pentagon now has some 7,000 aerial drones, compared with fewer than 50 a decade ago.** Currently, these unmanned systems are being used primarily in the role of intelligence, reconnaissance, and surveillance (ISR) from hand-launched to passenger airplane-sized systems, with the capability to carry significant payloads.

In June 2016, the U.S. Department of Transportation’s Federal Aviation Administration finalized the first operational rules for routine use of small UAVs, opening the door to expanded commercial uses. The new regulations streamline the process to legally operate a UAV in U.S.
airspace and create the opportunity for as many as 600,000 commercial drones to be flying in the United States within the next year. Internationally, Teal Group estimates there were 2.25 million UAVs produced for civil applications and operating around the world in 2016.

Small UAVs, with a gross take-off weight of less than 25 kg, are dominating the commercial uses. There are significant gains to be had with UAVs performing the dull, dirty or dangerous operations previously performed by larger platforms with humans in the cockpit. However, with the growing interest in UAVs and their potential for a host of military, commercial and civilian applications, limitations in the current state-of-the-art power systems are coming to light. Particularly in the small, multi-rotor drone UAV space, batteries have been used exclusively for power production. Battery technology will limit the use and efficacy of UAV systems as the platforms continue to evolve and their capabilities expand, requiring gains in autonomy and range.

An alternative technology, hydrogen fuel cells, has come to the forefront as a solution to these challenges. First demonstrated in military fixed wing UAVs, fuel cell systems now have proven reliability, durability, and range, opening doors to commercial and civilian applications. Fuel cell-powered systems offer improved operational duration relative to their battery counterparts, with the same benefits of an all-electric power system such as: high throttleability, low thermal and noise signature, payload/motor flexibility, and zero emission operation.

The applicability of fuel cell-based power systems specifically to multi-rotor VTOL drones with a gross takeoff weight (GTOW) of 3-25 kilograms is discussed. Fuel cell design considerations and sizing information are provided to assist drone developers in assessing the operational benefits of fuel cell power systems for their unique platform; a fuel cell system will not be the appropriate power solution for every application. Based on the current state of the art technology, fuel cell power systems can provide at least two times the flight duration of the best available batteries on many VTOL drone platforms.

FUEL CELL PLANT OVERVIEW

The most widely used fuel cell (FC) technologies are proton exchange membrane (PEM) and solid oxide (SO). While both PEMFC1 and SOFC2 technology have been applied in fixed UAV applications, the current state of the art in PEMFC technology is most promising for VTOL UAV platforms due to its higher specific power and power density, relatively low operating temperature (<80ºC or <175ºF), and quick start-up time.

A PEMFC system, or plant, consists of the following primary components: 1) fuel cell stack, 2) air delivery subsystem, 3) hydrogen management subsystem, 4) thermal management subsystem, and 5) control electronics. Often components 2) through 5) are lumped together and classified broadly as balance of plant (BoP) components; these are all supporting components, but essential to fuel cell plant operation. These key PEMFC BoP components are schematically illustrated for a liquid-cooled PEMFC system in Figure 1 along with key external systems such as the hydrogen storage/feed system, and hybrid power management system.

Each fuel cell plant manufacturer incorporates their own unique design methodologies in each subsystem, but all fuel cell power systems must contain these core components and subsystems.

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2 http://www.uasmagazine.com/articles/1573/uas-numbers-of-the-future
2 http://www.ultra-fuelcells.com/Data/Pages/184889ed47b46bde534d47356bad3d8f-90203A-PDS-D245XR.pdf
The following sub-sections outline the functionality and technologies incorporated in each of the PEMFC subsystems, and how they influence system operation and performance.

![Fuel Cell Stack Diagram](image)

**Figure 1.** Liquid-cooled PEMFC operational flow diagram indicating critical internal and external subsystems and components. Green = air/cathode, Pink = hydrogen/anode, Blue = coolant, Red/Black = power.

### Fuel Cell Stack

The core of a PEMFC system is the fuel cell stack. A fuel cell stack consists of two primary components: 1) the bipolar plate (cathode and anode flow fields), and 2) the membrane electrode assembly (MEA). A single cell of the fuel cell stack is created by stacking a cathode bipolar plate, a MEA, and an anode bipolar plate as shown in Figure 2. The MEA consists of two porous, catalyst-coated electrodes (cathode and anode) that are layered upon either side of an proton conducting membrane. The bipolar plates are electrically conductive and facilitate the supply of oxygen (cathode) and hydrogen (anode) to the MEA via integral flow passages.

Figure 2 illustrates the electrochemical reaction that occurs within a PEMFC. On the anode side of the cell, platinum catalyst within the MEA’s electrode layer separates the hydrogen’s negatively charged electrons from positively charged ions (protons). The protons move through the membrane to toward the cathode. The electrons from the anode side cannot pass through the membrane and as a result are forced around the membrane through an external electrical load before returning to the cathode side of the cell; the resultant flow of electrons is a useful electrical current. At the cathode side of the cell, the catalyst within the MEA’s electrode layer facilitates the re-combination of the

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protons and electrons along with supplied oxygen to produce water and heat.

Much like a battery cell, the core cell (cathode bipolar plate/MEA/anode bipolar plate) of the PEMFC is repeated in series combinations to customize its electrical output characteristics; this assembly is referred to as the fuel cell stack. The number of cells placed electrically in series defines the stack voltage output. The cell active area is the metric typically used to describe the current capacity of the fuel cell stack. An exemplary PEMFC voltage-current (V-I) curve is shown in Figure 3 illustrating typical variation of cell voltage with current density (mA/cm²). True stack V-I curve behavior is dependent upon construction and operating conditions, but can often be tailored to specific customer requirements.

The fuel cell stack is physically bracketed by current collectors that serve as the main power terminals, and structural end plates that support clamping hardware, such as tie rods or straps, that provide mechanical compression to maintain stack alignment and seal integrity. A wide range of stack compression and sealing approaches exist in the industry and some lead to higher stack specific power than others.

### Air Delivery Subsystem

For a UAV application, oxygen is supplied to the fuel cell by driving ambient air through the flow channels in the cathode bipolar plates thereby exposing air to the MEA. The fuel cell air flow requirement increases with increasing load demand. The type of air mover incorporated into the air delivery system is dictated by the air flow rate requirements and pressure drop characteristics of the fuel cell stack (more details in a subsequent section) and can range from low speed axial fans, similar to what might be found in a personal computer, to high speed blowers. The air mover is most often driven by an electric motor and so imposes a parasitic load on the fuel cell system affecting the net power output of the system. As with any air mover the flow rate will be reduced with increasing density altitude; this will impact the performance of the fuel cell (more details in a subsequent section). The air mover is also the loudest component in the fuel cell plant, but is typically quieter than the spinning rotors of a multi-rotor drone.

It is important to note that PEMFC stack performance is sensitive to air humidity levels. Generally speaking, fuel cell performance increases with increasing air relative humidity (RH); for this reason, some fuel cell plants will incorporate an air humidification system to facilitate more stable performance and operation over a wider range of environmental operating conditions. In weight sensitive applications, like a UAV, a passive humidifier is often used that exchanges water produced through fuel cell electrochemical reactions and transported in the cathode exhaust stream with the dry incoming air stream from the air mover. Water not transported to the incoming air stream is exhausted to the external environment. Any humidification scheme will impose a pressure drop penalty on the cathode side of the system and depending on the chosen air mover, may not feasible in all fuel cell configurations (more details in a subsequent section).

Depending on the application and the operating environment some fuel cell air delivery subsystems may also incorporate a filtration system including a range of filter elements; again pressure drop is a consideration making such filtration infeasible for certain systems.
Hydrogen Management Subsystem

Since the hydrogen is stored in limited quantities onboard the UAV, any hydrogen that is not consumed to produce power will reduce the allowable flight duration of the vehicle. Ideally, the fuel cell stack would be operated to completely consume all the hydrogen within the stack without exhausting to the environment (the rate of hydrogen consumption varies with stack load). However, complete consumption of stored hydrogen in this manner is difficult due to: 1) water accumulation and 2) diluent build-up.

In all PEMFC stacks, a portion of the water produced through electrochemical reactions will be transported from the cathode side of the stack to the anode side through the MEA. Depending on the hydrogen source, some water may also be delivered to the stack with the incoming hydrogen. Excess liquid water on the anode side of the stack can lead to performance reduction, so the hydrogen management system must provide a method to periodically remove this water. Diluents, such as nitrogen, are also present in any hydrogen source, and may build up over longer periods of time on the anode side of the stack acting to reduce hydrogen partial pressure and stack performance. The hydrogen management system must also provide a means to periodically vent these diluents, as well as built-up water, from the anode side of the stack to the external environment.

A hydrogen management subsystem is incorporated into the fuel cell plant to manage these issues and ensure that the stored hydrogen utilized as efficiently as possible for power generation. The hydrogen management system typically consists of valves and/or pumps that are used to recirculate the unconsumed hydrogen, clear water, and vent diluents. The components typically require electric power to operate and impart a slight parasitic load on the fuel cell system. Each fuel cell system manufacturer incorporates a unique hydrogen management subsystem design.

A common metric used to quantify the hydrogen consumption efficiency of the fuel cell plant is utilization; it is defined as the ratio of theoretical hydrogen consumed by the fuel cell to actual hydrogen delivered to the fuel cell plant. PEMFC hydrogen management systems have been demonstrated to provide hydrogen utilization levels of greater than 99% in flight systems. In more common terms this translates to lower fuel consumption rates and lower brake specific fuel consumption.

Thermal Management Subsystem

The thermal efficiency of a PEMFC stack is approximately 50%; so, roughly speaking, for every watt of electrical power generated a watt of waste heat is produced by the system. A complication is that PEMFC MEA is temperature sensitive and must operate below about 80˚C to prevent irreversible degradation. For this reason, all PEMFC systems incorporate a thermal management system to regulate the fuel cell stack temperature during operation. The method of thermal management is a distinguishing feature for PEMFC systems and can have a strong impact on system metrics, environmental ruggedness, and reliability. In general, two types of thermal management techniques are most often employed: 1) air and 2) liquid cooling; these are described in detail below.

Air-Cooled. One method of PEMFC stack thermal management is accomplished via air-cooling. In this approach, the stack is designed to accommodate sufficient air flow for stack thermal management as well as power production. The air side of an air-cooled stack must serve the dual role of a fuel cell cathode and heat exchanger; as such, compromises are made in materials of construction, fabrication techniques, and flow path design to provide this dual functionality while maintaining reasonable stack size and weight for UAV applications. The air flow demand of an air-cooled stack is more than 15 times greater than that required for power production alone.
To accommodate this high flow rate while minimizing pressure drop, the hydraulic diameter of cathode flow channels are relatively large and are exposed to the external environment; for this reason, stacks incorporating this approach are often referred to as “open-cathode” stacks. Typically, large diameter axial fans are employed as the air mover in air-cooled systems due to their high volumetric flow capacity.

A benefit of an air cooled configuration is the simplicity of the air delivery and thermal management subsystems; a single air mover provides the oxygen for power production and the air for cooling. From a fluidic standpoint, the system operates open loop, i.e. the air is not recycled, and closed loop feedback control for the air mover is provided by a temperature measurement on the stack. As a result, the balance of plant components required to implement an air-cooled system are minimal and the overall system weight, at equivalent power output, tends to be lower than liquid-cooled systems. These characteristics have led to early implementation of air-cooled PEMFC systems, such as the EnergyOr EPOD EO-310-XLE shown in Figure 4, in multi-rotor UAV applications.

At equivalent power output capacity, air-cooled stacks tend to be larger in size and weight than liquid-cooled stacks as the requirement for large air flow channels drives the need for large cathode bipolar plates. The low pressure capacity of the large fans used in these systems makes inclusion of a humidification and/or filtration system difficult and this narrows the environmental conditions under which the system may operate, although advances in MEA technology have improved tolerance to low humidity conditions. The design compromises employed in air-cooled stack construction for UAV applications limit its performance and operability in challenging conditions; such as at high-density altitude or in extreme environments.

**Liquid-Cooled.** The second most used method of PEMFC thermal management is liquid-cooling. In this approach, a liquid coolant is circulated through the fuel cell stack to regulate its temperature. The stack cathode and/or anode plates are designed to include flow channels to distribute the coolant throughout the fuel cell stack; these channels can be quite small due to the coolant’s high heat capacity relative to air. A pump is typically used to circulate the coolant in a closed loop system; heat is rejected by delivering the coolant to an external heat exchanger/radiator. Closed loop feedback control for the pump (and in some cases a radiator bypass valve) is typically provided by a fuel cell stack temperature measurement; the pump (and valve) will add a small parasitic load. Depending on expected environmental operating conditions the coolant could be deionized water (above freezing) or an antifreeze/water mixture (below freezing) similar to that used for automobile windshield wiper fluid.

A liquid-cooled thermal management system is more complex than an air-cooled system in that it adds a coolant control subsystem and external radiator to the BoP; for this reason, a liquid-cooled system is often heavier than an air-cooled system at equivalent power output capacity. A liquid-cooled system also adds maintenance operations around coolant selection and filling.

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* http://www.energyor.com/products/detail/epod-310
A major benefit of a liquid-cooled, or closed cathode, system is that it separates the air streams required for power production and heat rejection; as a result, the fuel cell stack and heat exchanger may be designed to be more compact and more robust. Since the heat exchanger is not required to be co-located with the fuel cell stack it may utilize more conventional materials and design methodologies and be placed in a more optimal location on the UAV to leverage freestream airflow; this also allows for tighter integration into the airframe that may lead to overall weight savings. The low fuel cell air flow requirement of a liquid-cooled design also opens up more fuel cell stack air mover options, such as high pressure capacity blowers, that enable the incorporation of humidification and filtrations systems into the fuel cell plant. These air movers also provide greater flow control and are better able to compensate for altitude effects. All of these characteristics make liquid-cooled systems more robust to environmental extremes than air-cooled systems. These characteristics have led to the implementation of liquid-cooled PEMFC systems in fixed wing UAV platforms, such as the 500 W system shown in Figure 5 developed by Protonex Technology Corporation, a wholly owned subsidiary of Ballard Power Systems.

Control Electronics

The fuel cell plant control electronics board serves as the brains of the system controlling BoP components and performing system health maintenance tasks in accordance with load demand and operating conditions. Fuel cell manufacturers will typically incorporate a customized electronics board into the plant that contains a central processing unit (CPU) running custom software for BoP control, DC/DC power converters to drive BoP components, and analog-to-digital (AD) converters for data acquisition. The control board is powered by the fuel cell itself, but may require external power input, via a small parallel battery, for startup. The control board is typically small and lightweight. Often fuel cells are hybridized with secondary batteries that may require the incorporation of power management electronics; these electronics will be discussed in a subsequent section.

Fuel Cell Plant Metrics

For VTOL multi-rotor applications the power demand required by the platform dictates the fuel cell plant size and weight; as a result, the fuel cell plant specific power (W/kg) and power density (W/L) are critical sizing metrics. As outlined above fuel cell plant metrics will vary based upon the type of fuel cell plant employed, air- or liquid-cooled, but general ranges of performance may be provided for each type of system to assist multi-rotor platform designers. The published metrics for the current state of the art in air- and liquid-cooled PEMFC plants marketed for UAV applications are summarized in Table 1; the stated metrics include the fuel cell stack and BoP components including control electronics (and independent heat exchanger in the case of liquid-cooled systems).
As stated above, and confirmed in Table 1, the air-cooled fuel cell plants developed by HES Energy Systems* and MMC† for commercial applications provide higher specific power (300-440 W/kg) and power density (130-170 W/L) than the liquid-cooled plants developed by Protonex for military applications at similar rated power output capacity (280-300 W/kg and 100 W/L). Ballard Power Systems, in collaboration with Protonex, is currently developing a promising 400 W air-cooled fuel cell plant for UAV applications; preliminary estimates put system metrics at 520 W/kg and 190 W/L. The stack incorporated into Ballard’s 400 W UAV power system is based upon mature Ballard FCgen®-1020ACS stack technology (shown in Figure 6‡) originally developed for backup power applications, but has refined to be ultra-lightweight, with specific power estimated at almost 2,000 W/kg, using new plate manufacturing technologies. Technology advancements continue to be made that will lead to future reductions in plant weight, volume, and ruggedness for both air- and liquid-cooled systems that will improve fuel cell plant metrics for future UAV systems.

Table 1. UAV PEMFC plant specific power and power density metrics.

<table>
<thead>
<tr>
<th>System</th>
<th>Vendor</th>
<th>Cooling</th>
<th>Power Output (W)</th>
<th>Weight (kg)</th>
<th>Volume (L)</th>
<th>Specific Power (W/kg)</th>
<th>Power Density (W/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A-200*</td>
<td>HES</td>
<td>Air</td>
<td>200</td>
<td>0.7</td>
<td>1.6</td>
<td>310</td>
<td>130</td>
</tr>
<tr>
<td>A-500*</td>
<td>HES</td>
<td>Air</td>
<td>500</td>
<td>1.4</td>
<td>3.0</td>
<td>360</td>
<td>170</td>
</tr>
<tr>
<td>A-1000*</td>
<td>HES</td>
<td>Air</td>
<td>1,000</td>
<td>2.3</td>
<td>6.0</td>
<td>440</td>
<td>170</td>
</tr>
<tr>
<td>H1†</td>
<td>MMC</td>
<td>Air</td>
<td>1,800</td>
<td>5.2</td>
<td>7.8</td>
<td>340</td>
<td>230</td>
</tr>
<tr>
<td>400 W</td>
<td>Ballard</td>
<td>Air</td>
<td>360</td>
<td>0.7</td>
<td>1.9</td>
<td>520</td>
<td>190</td>
</tr>
<tr>
<td>500 W</td>
<td>Protonex</td>
<td>Liquid</td>
<td>500</td>
<td>2.0</td>
<td>5.6</td>
<td>280</td>
<td>100</td>
</tr>
<tr>
<td>1200 W</td>
<td>Protonex</td>
<td>Liquid</td>
<td>1,200</td>
<td>4.0</td>
<td>12.0</td>
<td>300</td>
<td>100</td>
</tr>
</tbody>
</table>

HYDROGEN STORAGE OVERVIEW

As discussed in the preceding sections, PEMFC systems consume hydrogen fuel; therefore, any fuel cell-based UAV power system must include a hydrogen storage and delivery system onboard. Various means for storing the hydrogen fuel onboard the UAV have been evaluated. Liquid hydrogen is densest of all storage options, but cryogenic storage necessitates the use of tanks that require special handling and materials to contain and keep the fuel cool, and to prevent waste via “boil-off.” The added complexity and weight of liquid hydrogen storage often precludes it from use on small UAV systems. The most promising hydrogen storage approaches for VTOL UAV applications are described below.

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* https://media.wix.com/ugd/047f54_8483372175ef4e1aa43edbe62aae68e.pdf
Compressed Hydrogen Storage

Compressed hydrogen storage systems have been demonstrated in hundreds of prototype fuel cell vehicles and are available commercially at low production volumes. To achieve meaningful storage density, compressed hydrogen is typically stored at pressures ranging from 350-700 bar (5,000-10,000 psi). Carbon composite overwrapped pressure vessels (COPV) are typically used provide a lightweight and structurally sound storage solution. Current state of the art COPV tanks, with lightweight polymer liners (Type IV) capable of high cycling, are able to achieve a hydrogen mass fraction of approximately 5-6%, hydrogen mass/(hydrogen + tank mass), and a hydrogen volume fraction of about 80-85%, hydrogen volume/(hydrogen + tank volume) over the 350-700 bar range.

Compressed hydrogen can be produced in large “central production” plants and transported to the point of end-use, in high-pressure gas cylinders, and stored until use. Hydrogen may also be produced in smaller “distributed production” facilities, very near or at the point of end-use. Hydrogen required to operate a UAV system can be generated on-site and on-demand using available water and a portable electrolyzer. An electrolyzer is driven by electrical power that can be supplied by a photovoltaic array to provide a net-zero energy solution, or a ground-based generator; by this approach, the system is multi-fuel capable, including JP-8.

The anode side operating pressure of most PEMFC systems may range from 0.5 to 2 bar above local ambient (7 to 30 psig) depending on the manufacturer. In compressed hydrogen systems, a mechanical pressure regulator is typically employed to reduce the hydrogen supply pressure from the high levels in the storage tank to safe fuel cell operating levels. A range of commercial-off-the-shelf (COTS) pressure regulators are available that provide the appropriate flow capacity and outlet pressure ranges for storage pressures in the 350-410 bar range, but customized designs are typically necessary to enable integration up to 700 bar.

Chemical Hydride Storage

Another convenient way to store hydrogen for smaller UAV platforms is through the use of chemical hydride cartridges. In general, a chemical hydride can store hydrogen at low pressure with minimal packaging. Chemical hydrides may also provide more volumetrically efficient hydrogen storage than compressed hydrogen. Hydrogen is liberated from the chemical hydride using a processing subsystem that can add cost and complexity relative to a compressed hydrogen system. Typically these systems run at low pressures, so the weight of the containment structure is significantly reduced relative to compressed hydrogen.

Sodium borohydride (SBH), which has a large hydrogen content, is a commonly used, readily available, and cost-effective chemical hydride. SBH is most often stored in a water based solution that is non-flammable. By pumping the sodium borohydride solution over a catalytic reactor, the hydrogen is liberated as needed by the fuel cell system. This system is completely load-following and can be ramped to full output in 3-5 seconds. Similarly, hydrogen production can be idled instantaneously without loss of hydrogen. The chemical hydride system is packaged as a cartridge that can be installed prior to flight. Once primed on the ground, the system interfaces with the fuel cell to provide hydrogen as needed. Once completed the cartridges can be discarded or returned for remanufacturing.

http://www.hypercompeng.com/Products
In chemical hydride systems, the hydrogen supply pressure to the fuel cell is regulated to safe operating levels through control of the hydrogen liberation process. In the case of an aqueous SBH system, a pump is typically used to control the rate of SBH flow to the reactor to maintain a constant hydrogen supply pressure for the fuel cell.

**Hydrogen Storage System Metrics**

For VTOL multi-rotor applications the energy demand required by the platform dictates the hydrogen storage system size and weight; as a result, the fuel storage system specific energy (Wh/kg) and energy density (Wh/L) are critical sizing metrics. The energy storage metrics will vary based on the type of hydrogen storage media employed, compressed gas or chemical hydride, but general ranges of performance may be provided for each method to assist multi-rotor platform designers. In general, the larger the energy requirement for the application, the larger the percentage of storage system weight and volume the storage media becomes, and the better the hydrogen storage metrics. The theoretical specific energy of compressed hydrogen is approximately 20,000 Wh/kg while the specific energy for SBH, a representative chemical hydride, can range from about 800-1,300 Wh/kg depending on fuel formulation. The theoretical energy density of compressed hydrogen ranges from about 460-780 Wh/L (assuming 350-700 bar storage pressure) and for SBH ranges from about 810-1,270 Wh/L. These metrics assume hydrogen at standard conditions (25°C and 1 bar) and fuel cell operation at 0.75 V/cell and 99% hydrogen utilization.

The fluid metrics above indicate that compressed hydrogen is a far superior storage media from a mass standpoint, while SBH, and other chemical hydrides, provide great volumetric storage metrics; however, practical considerations limit both of these approaches. A comparison storage metrics for various hydrogen storage methods is found in Table 2 including compressed hydrogen and several chemical hydride cartridge variants, such as the Protonex SBH fuel cartridge, shown in Figure 7, and the HES Energy Systems Aeropack L-Series liquid chemical hydrides.* The chemical hydride cartridge metrics shown in Table 2 include the weight of the containment structure, fuel processing subsystems, and the fuel itself.

Table 2 shows that the weight of the COPV tank reduces the achievable specific energy drastically from the theoretical limit, but the practical specific energy attainable with compressed hydrogen, 1,000 Wh/kg or more, is higher than available chemical hydrides at a similar total energy capacity. Table 2 also shows that chemical hydrides provide energy densities comparable to or better than low pressure (close to 350 bar) compressed hydrogen; chemical hydrides may offer a competitive hydrogen storage solution for volume constrained applications. Compressed hydrogen stored at 700 bar provides the best energy density metrics of all available storage options at about 360 Wh/L. It should be noted that practical use of 700 bar hydrogen will require added ground infrastructure to compress hydrogen beyond the levels typically produced by electrolyzers (limited to 130-350 bar) or those contained in standard gas cylinders (typically limited to about 410 bar).

* https://media.wix.com/ugd/047f54_18f6b9d95c7c40c8859787879c130417.pdf

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Figure 7. Protonex 1100-1400 Wh SBH fuel cartridges.
Table 2. Comparison of hydrogen storage metrics.

<table>
<thead>
<tr>
<th>Storage System</th>
<th>Vendor</th>
<th>Energy Capacity (Wh)</th>
<th>Weight (kg)</th>
<th>Volume (L)</th>
<th>Specific Energy (Wh/kg)</th>
<th>Energy Density (Wh/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressed H(_2) (350 bar, 25°C, 1250 Wh)</td>
<td>N/A(^\wedge)</td>
<td>1250</td>
<td>1.1</td>
<td>3.4</td>
<td>1130</td>
<td>360</td>
</tr>
<tr>
<td>Compressed H(_2) (700 bar, 25°C, 1250 Wh)</td>
<td>N/A(^\wedge)</td>
<td>1250</td>
<td>1.2</td>
<td>2.2</td>
<td>1040</td>
<td>560</td>
</tr>
<tr>
<td>Chemical Hydride Cartridge Type 1(^\ast)</td>
<td>HES</td>
<td>900</td>
<td>1.6</td>
<td>2.3</td>
<td>560</td>
<td>390</td>
</tr>
<tr>
<td>SBH Cartridge (Formulation Range)</td>
<td>Protonex</td>
<td>1100-1390</td>
<td>2.1-2.2</td>
<td>3.8</td>
<td>500-660</td>
<td>290-370</td>
</tr>
</tbody>
</table>

\(^\wedge\)Estimated based on current COPV state of the art.

BATTERY HYBRIDIZATION

Often the best power system solution includes both fuel cells and batteries with appropriate power management electronics. Generally, batteries have better power density (power per unit weight) than PEM fuel cells. In contrast, PEMFC systems typically provide higher energy density than batteries, assuming long enough flight duration. The attributes of both these systems can be combined in a hybrid propulsion system to good effect, although it does increase the complexity, see Figure 8. The power management electronics monitors the battery state of charge and the fuel cell output relative to the vehicle and payload requirements. In periods of high power demand, power is supplied both by the fuel cell and the battery. In periods of low demand, some of the fuel cell power will recharge the battery. Once the battery is fully charged, the fuel cell system can be directly output to the vehicle load.

For a VTOL UAV system, one hybridization approach would be to size the fuel cell system to provide sufficient power for hover plus some overhead power to provide a reasonable battery recharge rate. A small lithium polymer (LiPo) battery could be incorporated to provide additional power output for lift-off and climb to increase the platform climb rate and maneuverability. The battery could then be re-charged while hovering and in forward flight when the power demand is lower. Hybridization can also be useful in managing diverse payload power requirements including payloads that might traditionally overwhelm other power sources.

![Figure 8. Example UAV fuel cell/secondary battery hybridization scheme.](image-url)
MULTI-ROTOR UAV POWER SYSTEM STATE OF THE ART

The majority of multi-rotor VTOL UAV power systems in the Group 1, less than 9 kg (20 lb), and Group 2, 9.5 to 25 kg (21 to 55 lb), are based upon rechargeable lithium battery technology. The attractiveness of batteries in these platforms is based on the simplicity and scalability of the approach, which requires minimal power system knowledge to implement. While these battery-based systems are sufficient for many consumer hobbyist applications, the energy density of batteries limits the platforms’ range and endurance for commercial uses. Battery technology is receiving considerable attention with steady improvements in capacity, but even optimistic projections for capacity will not meet many of the UAV use cases contemplated. Additionally, as has been highlighted by several recent events, the quest for improved battery energy density often sacrifices some level of stability and, ultimately, safety.

Battery Metrics

Currently available multi-rotor VTOL UAV systems are often packaged with rechargeable LiPo batteries of varied series (S)/parallel (P) cell arrangements depending on the application and platform. The exceptionally high maximum continuous discharge rate capacity (in some cases greater than 25 times nominal capacity) provided by LiPo cells are ideally suited for the high power demand during vertical take-off and hover in multi-rotor platforms. LiPo cells also provide a relatively high energy capacity for a rechargeable cell; at nominal discharge rate, state of the art LiPo technology is capable of providing specific energy on the order of 150-200 Wh/kg depending on manufacturer, packaging, and discharge capacity. The energy density of a LiPo pack is approximately 325-450 Wh/L, again depending upon pack configuration.

The goal for multi-rotor UAV power system design is to maximize flight time by providing the necessary power at the lowest weight possible. A complicating factor in the design of a LiPo-based power system is that its effective energy capacity decreases with increasing average discharge rate above its nominal rating; defined as 1C where ‘C’ equals the nominal capacity of the cell (in Ah). As an example, one would not expect to achieve the rated energy capacity of a given LiPo cell while operating, on average, at a 5C rate even if the cell possessed a 25C maximum continuous discharge rating. As a result, battery pack sizing for multi-rotor UAV systems requires detailed knowledge of discharge characteristics. Often, designers will incorporate parallel arrangements of cells to increase current output capacity without sacrificing energy capacity; for instance, a parallel arrangement of two strings of 5 Ah rated cells will increase the nominal discharge rate of the 2P system to 10 Ah (2x).

The LiPo battery pack voltage is dictated by the number of series arranged cells, 3.7 V/cell nominal, and is typically configured to achieve a bus voltage for the platform that meshes with the voltage input requirements for electric motor controllers, avionics, and payload hardware. A 6S arrangement (22.2 V nominal) is typical for many VTOL multi-rotor platforms, although some larger platforms employ 12S arrangements (44.4 V nominal).

Battery Sizing Example

As an example, consider the DJI Matrice 600 Pro VTOL hex-copter drone. The baseline battery configuration for the Matrice 600 Pro is a 6S6P arrangement of 4.5 Ah LiPo cells providing a total nominal discharge rate of 27 Ah and a nominal power output of 600 W; the maximum continuous discharge rating of the pack is not advertised in the DJI literature. The total nominal en-

* http://www.dji.com/matrice600-pro/info#specs
The energy capacity of the pack is about 600 Wh at a total weight of approximately 3.6 kg providing a specific energy of 168 Wh/kg. The weight of the platform is stated at 9.5 kg, including batteries but no payload, with a maximum gross takeoff weight (GTOW) of 15.5 kg, with 6 kg payload. Neglecting battery weight the system core structure, propulsion, and avionics components weighs about 5.9 kg. The system incorporates six 21-inch diameter rotors with matching electric motor and electronic speed controller (ESC).

The rotor/motor/ESC combination used in the Matrice 600 Pro is stated to provide 1800 to 2500 g thrust under sea level operation; which translates to about 10.5 to 8.7 g/W of power loading. Assuming a 10.5 g/W loading in hover at a 9.5 kg GTOW, the total nominal propulsive power draw is estimated at about 905 W, or about 1.5C. DJI states that the vehicle can fly for 32 minutes (with 10% capacity remaining) at 9.5 kg; at 905 W this translates to about 483 Wh realized battery capacity. At a 15.5 kg GTOW and 8.7 g/W loading the total power draw would be about 1780 W, or around 3C. At 15.5 kg the stated flight time is 16 minutes; at 1780 W this translates to about 475 Wh. Given the estimated 1.5C to 3C nominal operating range of the battery pack, it is not surprising that the computed effective energy capacity (482 and 475 Wh) is largely constant between the two vehicle configurations; this suggests appropriate battery cell selection for the platform. This illustrative example provides a basis for fuel cell power system sizing in the following subsection.

### Table 3. Summary of advertised PEMFC powered multi-rotor platforms.

<table>
<thead>
<tr>
<th>Platform</th>
<th>Vendor</th>
<th>Number of Rotors</th>
<th>GTOW (kg)</th>
<th>Payload (kg)</th>
<th>Endurance (hr)</th>
<th>FC Rated Power (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H2QUAD 400†</td>
<td>EnergyOR</td>
<td>4</td>
<td>N/A</td>
<td>None</td>
<td>3.8</td>
<td>1000</td>
</tr>
<tr>
<td>H2QUAD 1000‡</td>
<td>EnergyOR</td>
<td>4</td>
<td>N/A</td>
<td>1.0</td>
<td>2.0</td>
<td>1500</td>
</tr>
<tr>
<td>HyDrone 1550§</td>
<td>MMC</td>
<td>6</td>
<td>18.5</td>
<td>None</td>
<td>2.5</td>
<td>1800</td>
</tr>
</tbody>
</table>

**MULTI-ROTOR UAV FUEL CELL POWER SYSTEM SIZING**

A number of multi-rotor UAV fuel cell power systems have been advertised recently illustrating the readiness of PEMFC technology and its capability to increase platform endurance; some examples are shown in Figure 9. Detailed technical information pertaining to the demonstration platforms are limited, but have centered on the use of customized quad- and hex-rotor configurations as shown in Figure 9. Many of the demonstrations were focused on proof of concept and so did not incorporate a sizable payload (in some cases, no payload at all). The majority of the fuel cell multi-rotor demonstrations have incorporated air-cooled PEMFC plants running on compressed hydrogen, including each system outlined in

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‡ [http://www.energyor.com/products/detail/h2quad-400](http://www.energyor.com/products/detail/h2quad-400)
Figure 9. The reported flight durations of these systems range from 2 to almost 4 hours; a substantial improvement over the 0.3 to 1 hour flight endurance provided by current battery powered multi-rotor platforms.

The characteristics of the COTS DJI Matrice 600 Pro multi-rotor platform may again be used as an illustrative example; in this case, to summarize the capability that a fuel cell may provide to a multi-rotor platform. As outlined in the previous subsection, the maximum GTOW of the Matrice 600 Pro is 15.5 kg and its core weight is 5.9 kg, leaving 9.6 kg for the fuel cell power system and payload. At a GTOW of 15.5 kg it was estimated that the platform requires about 1800 W of power for hover. If it is assumed that about 20% overhead power (about 360 W) would be needed in addition to the hover power for climb capability, the total required fuel cell power output requirement becomes about 2,200 W. Using the Ballard 400 W air-cooled fuel cell power system metrics summarized Table 1 (520 W/kg), assuming six systems are incorporated into the vehicle to provide 2,200 W capability, the weight of the fuel cell plant would be 4.2 kg; subtracting this from the 9.6 kg allowable weight leaves 5.4 kg for the fuel storage system and payload. The estimated volume of the fuel cell plant would be about 11.6 L (190 W/L).

Table 4. Estimated metrics with payload capacity for Ballard air-cooled PEMFC on 15.5 kg GTOW, 21-in rotor diameter hex-copter. Battery metrics provided for comparison.

<table>
<thead>
<tr>
<th>Payload Weight (kg)</th>
<th>H₂ Weight (kg)</th>
<th>Tank + H₂ Weight (kg)</th>
<th>Total FC Weight (kg)</th>
<th>Total Energy (Wh)</th>
<th>Energy Specific (Wh/kg)</th>
<th>Energy Density (Wh/L)</th>
<th>Endurance (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.32</td>
<td>5.2</td>
<td>9.6</td>
<td>5465</td>
<td>569</td>
<td>213</td>
<td>182</td>
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<td>1.3</td>
<td>0.24</td>
<td>3.9</td>
<td>8.3</td>
<td>4089</td>
<td>493</td>
<td>185</td>
<td>136</td>
</tr>
<tr>
<td>2.4</td>
<td>0.17</td>
<td>2.8</td>
<td>7.2</td>
<td>2916</td>
<td>405</td>
<td>152</td>
<td>97</td>
</tr>
<tr>
<td>3.6</td>
<td>0.10</td>
<td>1.6</td>
<td>6.0</td>
<td>1645</td>
<td>274</td>
<td>104</td>
<td>55</td>
</tr>
<tr>
<td>0.0</td>
<td>9.6 (6S16P)</td>
<td></td>
<td></td>
<td>1600</td>
<td>168</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>1.3</td>
<td>8.3 (6S14P)</td>
<td></td>
<td></td>
<td>1394</td>
<td>168</td>
<td>46</td>
<td></td>
</tr>
<tr>
<td>2.4</td>
<td>7.2 (6S12P)</td>
<td></td>
<td></td>
<td>1210</td>
<td>168</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>3.6</td>
<td>6.0 (6S10P)</td>
<td></td>
<td></td>
<td>1008</td>
<td>168</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>6.0</td>
<td>3.6 (6S6P)</td>
<td></td>
<td></td>
<td>605</td>
<td>168</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

Endurance estimates are provided in Table 4 based upon the notional fuel cell system described above assuming a range of payload weights and assuming hover at a steady 1,800 W power draw. For the purposes of these calculations, a compressed hydrogen fuel storage system was assumed incorporating a Type IV COPV, a 6,000 psi hydrogen storage pressure, and a 0.25 kg pressure regulator. The results indicate that endurance levels of over one hour may be achieved with a payload weight of 3 kg or less. For comparison, if additional batteries were installed on the platform creating 6S10P, 6S12P, and 6S14P configurations weighing 6.0, 7.2, and 8.3 kg respectively, the effective payload capacities would be 3.6, 2.4, and 1.3 kg. In these configurations, the battery based system would provide 34, 40, and 46 minutes of flight time respec-
tively, while in the fuel cell configuration the flight times would be 55.97, and 136 minutes; that equates to over 2 hours flight time with a 1.3 kg payload. Based on these results, the fuel cell system would provide 1.6x, 2.4x, and 3.0x increases in flight time over battery based systems at 3.6, 2.4, and 1.3 kg payload capacities respectively.

While the preceding results are encouraging it would be preferable to accommodate larger payload capacity on the vehicle while providing high endurance to show a more significant improvement over existing platform capabilities. The best way to improve system metrics would be to reduce the fuel cell plant weight, which frees up more weight allotment for payload. An approach that has been used to reduce fuel cell plant weight on VTOL platforms is to decrease the hover power requirement by increasing the rotor blade diameter; hover power scales roughly with the rotor diameter, all else being equal. A drawback of increasing the rotor blade diameter is that the vehicle must necessarily become larger; this would incur a slight weight penalty and could also impact mission capabilities. Additionally, with a larger rotor the vehicle loses some agility and maneuverability.

An example of a fuel cell powered hex-rotor vehicle that is comparable to the DJI Matrice 600 Pro that leverages large diameter rotors is the MMC HyDrone 1550, which incorporates six 29-in diameter rotors. Despite that fact that the HyDrone 1550 is a slightly heavier platform than the Matrice 600 Pro at 18.5 kg maximum GTOW, it incorporates an air-cooled fuel cell, the MMC H1 fuel cell, rated to 1,800 W. As described in the Matrice 600 Pro sizing exercise above it was estimated that a 2,200 W fuel cell was necessary for that 15.5 kg platform. Another benefit of reducing the hover power requirement is that the fuel cell hydrogen consumption rate is decreased; this acts to increase endurance for equivalent stored hydrogen mass.

For illustration purposes, if it is assumed that the Matrice 600 Pro were outfitted with 29-inch diameter rotors at the same 15.5 kg maximum GTOW the hover power requirement would be about 72% of that at a 21-in rotor diameter, or about 1,300 W. Adding a 20% overhead capacity, the ideal fuel cell power output for such a platform would be about 1,560 W. Rounding up to 1,600 W using the same 520 W/kg specific power estimate (in this case, equating to about four 400 W systems), the fuel cell plant weight for such a system would be estimated at about 3.1 kg. At 190 W/L the volume of the system would be estimated at 8.4 L. The core weight of the modified platform is assumed to increase by 0.5 kg to 6.4 kg due to the larger, heavier rotor blades and correspondingly longer, heavier frame arms. This leaves about 6.0 kg for fuel storage and payload, a 0.9 kg increase over the 21-in rotor configuration.

Endurance estimates are provided in Table 5 based upon the notional fuel cell system described above assuming a range of payload weights assuming hover at a steady 1,300 W power draw. As in the prior sizing exercise, a compressed hydrogen fuel storage system was assumed incorporating a Type IV COPV, a 6,000 psi hydrogen storage pressure, and a 0.25 kg pressure regulator. The results indicate that in the larger rotor configuration platform endurance levels of over four hours may be achieved with a payload weight of about one kilogram or less. The fuel cell endurance capability is compared to that of a battery based system at payload masses of 1.9, 3.1, and 4.3 kg in Table 5 assuming additional parallel cells were installed on the platform creating 6S12P, 6S10P, and 6S8P configurations weighing 7.2, 6.0, and 4.8 kg respectively. The comparison shows that the fuel cell system increases estimated platform endurance by 3.4x, 2.8x, and 1.9x at payload masses of 1.9, 3.1, and 4.3 kg respectively. The endurance estimates summarized in Table 4 and Table 5 are also plotted against payload weight in Figure 10.
Table 5. Estimated metrics with payload capacity for Ballard air-cooled PEMFC on 15.5 kg GTOW, 29-in rotor diameter hex-copter. Battery metrics provided for comparison.

<table>
<thead>
<tr>
<th>Payload Weight (kg)</th>
<th>H₂ Weight (kg)</th>
<th>Tank + H₂ Weight (kg)</th>
<th>Total FC Weight (kg)</th>
<th>Total Energy (Wh)</th>
<th>Energy Specific (Wh/kg)</th>
<th>Density (Wh/L)</th>
<th>Endurance (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
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<td>6108</td>
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<td>282</td>
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<tr>
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<td>7.2</td>
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<td>568</td>
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<td>3.1</td>
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<tr>
<td>4.3</td>
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<td>4.8</td>
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<tr>
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<td>1495</td>
<td>168</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.9</td>
<td>7.2 (6S12P)</td>
<td>1210</td>
<td>168</td>
<td>56</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1</td>
<td>6.0 (6S10P)</td>
<td>1008</td>
<td>168</td>
<td>47</td>
<td></td>
<td></td>
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<tr>
<td>4.3</td>
<td>4.8 (6S8P)</td>
<td>806</td>
<td>168</td>
<td>37</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>5.5</td>
<td>3.6 (6S6P)</td>
<td>605</td>
<td>168</td>
<td>28</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The preceding sizing exercises are meant to provide an illustration of the capability provided by a fuel cell power system on a multi-rotor VTOL UAV platform based on projected capability of new fuel cell technology. Recent advances in PEMFC plant and hydrogen storage technology have positively impacted fuel cell power system metrics and may be leveraged to improve platform capability in the near term. More comprehensive PEMFC trade studies and design analyses should be conducted in collaboration with platform developers to determine the optimal power system configuration for their application.

Figure 10. 15.5 kg max GTOW multi-rotor endurance variation with payload weight with fuel cell and battery power system configurations including effect of rotor diameter.
CONCLUSION

Proton exchange membrane fuel cell power systems are an attractive alternative to current battery-based power system solutions for a range of VTOL multi-rotor UAV systems in the 3-25 kg range. Fuel cell-powered systems offer improved operational duration relative to their battery counterparts, with the same benefits of an all-electric power system such as high throttleability, low thermal and noise signature, payload/motor flexibility, and zero emission operation. Air-cooled PEMFC plants provide a lightweight, compact system that provides great performance under most operating conditions. Liquid-cooled PEMFC plants provide consistent performance even under severe environmental conditions, but at the expense of some weight and volume. Compressed hydrogen offers a readily available, inexpensive, high specific energy fuel storage solution for PEMFC systems particularly for larger VTOL multi-rotor UAV platforms, while chemical hydrides provide a high energy density solution for smaller fuel cell powered VTOL UAV platforms. The endurance benefits provided by fuel cell power systems will vary from platform to platform. In most cases, the overhead weight of the fuel cell plant, which does not provide useful energy without fuel, will limit the payload capacity relative to a battery only solution; for the same reason, the greatest endurance improvements may be found on larger, Group 2 VTOL UAV platforms. At equivalent vehicle GTOW and payload weight, fuel cell power systems are generally able to increase flight endurance by two to three times that provided by state of the art rechargeable batteries. Continued advancements are being made in PEMFC technology that are pushing fuel cell performance and reducing system weight that will further improve system capability for future VTOL multi-rotor UAV platforms.

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REFERENCES
