Drone Refueling

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10/1/2018

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Executive Summary

In June 2016, the U.S. Department of Transportation's Federal Aviation Administration (FAA) finalized the first operational rules for routine use of small UAVs, opening the door to expanded commercial uses. The new regulations have streamlined the process to legally operate a UAV in U.S. airspace. As of January 2018 over one million drones had been officially registered with the FAA; this includes over 122,000 drones registered specifically for commercial uses.[1] Internationally, Teal Group estimates there were 2.25 million UAVs produced for civil applications and operating around the world in 2016.[2]

The current commercial drone market is growing at an exponential rate with industry just beginning to grasp the full potential and use cases for drones. Some of the big hurdles facing the growing drone market are Beyond Visual Line of Sight (BVLOS) regulation, optimizing return on investment in the different drone market segments and finding technology enablers that allow industry to effectively manage and utilize fleets of drones rather than individual platforms.

Ballard, an experienced leader in clean and efficient hydrogen power, is working closely with industry to bring energy-dense hydrogen fuel cell capabilities to the commercial drone market to drastically improve operational flight time of industrial drones, enabling markets dependent on cost effective BVLOS and heavy lift operations.

To make fuel cells a reality for the drone economy, Ballard recognizes the need to address the big question of "Where does my hydrogen come from?" Fuel cell system metrics speak for themselves as a capability enabler but they are only relevant if customers have easy and cost effective access to "hydrogen on demand".

This paper touches on the current state of fuel cell UAS technology and takes a deeper dive into the economics and logistics of providing hydrogen to drone operators in the field. Different hydrogen generation technologies will be discussed and evaluated.

The Demand for Drones

Today's commercial inspection drones carry heavier, more capable sensors able to image and identify pipeline leaks, bolt corrosion, stockpile size, crop infestation and many other industry-specific metrics. These small unmanned aircraft can inspect with higher resolution and more cost effectively than manned airplanes, helicopters, or ground based inspection teams. The prospect of incorporating drone inspection into industrial management practices can at the same time reduce the risk of human fatality and accidents, equipment damage and other liabilities.

Drone use is being explored for inspection and evaluation in every major market from oil and gas pipeline infrastructure to crop fields and wildfires. Although each market segment has very different operational needs and requirements they all share a common theme: Reducing cost and/or human risk. Inspection operations that typically require helicopters or manned planes come with high operating expenses, human safety risk and operational inconsistency due to uncontrollable events such as bad weather. These operations are a primary target for drone use across all industries. Although the human is still in the loop to control an unmanned vehicle, operators are on the ground rather in the air, and aircraft accidents are dramatically less costly.

In conjunction with improving human safety factors, operational cost of ownership plays a big role in stimulating drone use. The per-flight-hour expense of planes and helicopters used for aerial inspection often exceeds $250+/Hr and operationally requires significant capital expenditure to implement and sustain.[3] Compounding vehicle platform and maintenance costs are the expenses of hiring pilots and operators.

Other inspection operations optimal for drone use that do not utilize planes and helicopters often require close human inspection in hard to reach and/or dangerous locations. The inspection of towers and industrial tanks, bridges, transmission lines, and nuclear power plants are examples that incur huge cost and safety risk getting operators to the point of inspection. Many of these operations require weeks or months to execute, making routine and regular inspection impossible.

Drone Flight Duration

Cost savings and risk reduction are important drivers of drone adoption, but drone platforms are also able to provide expanded capability beyond the current state of the art. The user community continues to identify new ways to use these novel platforms and cost models continue to be refined in the process. Key drivers in reducing drone operation costs include man power reduction, such as single person management of multiple drones, improved lifetime and resilience of drone platforms, and enhanced performance in sensors, analytical software and drone capabilities. As drone applications expand, so too will the size, capability, and power draw of their sensors/payloads; this also puts added stress on the batteries and IC engines providing them power. There is a growing demand for more power and longer, more reliable flight duration than batteries and IC engines are unable to provide.

A typical battery powered commercial UAS can provide a mere 20-35 minutes of operational flight time and less in hot or high-elevation environments. Such limited flight duration makes it difficult to carry out any detail oriented tasks and nearly impossible to carry out BVLOS operations. During a typical operation, field service operators can spend a similar amount of time in-between flights unloading spent batteries, loading fresh batteries and charging drained batteries. A productive day of drone flights currently yields only about 8 flights with much of the day spent maintaining the power system while the drone is grounded. Managing the logistics of current battery operated drones is difficult as fleet size grows. Power system logistics can reduce drone operational effectiveness by 50% and put a significant annual cost burden on operations due to the maintenance and transportation of large quantities of lithium ion/polymer batteries and/or engine maintenance and overhaul schedules. Although power system logistics do not make drones cost prohibitive for all, they severely limit the cost savings potential of drones as business try to scale and grow.

Hydrogen Fuel Cell Solution

To fill the growing power capability gap, Ballard has brought to the forefront of the drone market the hydrogen fuel cell. First demonstrated in military fixed wing UAVs over 10 years ago, fuel cell systems have proven reliable, durable and able to drastically expand flight times of industrial drones typically operating on batteries, opening doors to commercial and civilian applications. Fuel cell-power 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. Relative to internal combustion engine-powered systems, fuel cells provide reduced acoustic signature (up to 2x), limited altitude derating (10% at 15 kft), and reduced maintenance (5x increase in time before overhaul).

Critical to the integration of a hydrogen fuel cell power plant into an unmanned aerial system is the supporting hydrogen infrastructure, including the onboard storage tank, ground refueling hardware, and fuel sourcing/generation scheme. Within each category, there are several options to choose from, the selection of which depends upon the particulars of the UAS air and ground operational approaches. The following sections aim to provide an overview of mature hydrogen infrastructure technologies ready for integration with hydrogen fuel cell power system as aid for UAS designers and operators.

Hydrogen Consumption

UAS hydrogen consumption can be broken out into two categories: 1) flight consumption, and 2) ground consumption. Flight consumption is the amount of hydrogen required to power the aerial vehicle for its designed flight mission; it dictates the amount of hydrogen that must be carried on board the aircraft and, ultimately, the storage tank size and weight. Ground consumption is the amount of hydrogen required to power a fleet of air vehicles; it dictates the total amount of hydrogen that will be consumed per day during operations and, consequently, the capacity of ground refueling and storage/generation hardware.

There are a wide range of flight missions and fleet operational schemes in use throughout industry and to give a sense for scale and application, two notional operational schemes will be discussed to include Group 1 (< 9.1 kg) and Group 2 (9.5-25 kg) UAS. Scheme 1) assumes the use of a large multi-rotor vehicle, on the order of 10-15 kg, requiring approximately 1.1-1.5 kW continuous power draw for hover. Past studies have shown that a fuel cell could power such a vehicle for approximately 1-2 hours using compressed hydrogen.[4] Scheme 2) assumes the use of a fixed-wing vehicle, on the order of 20-25 kg, requiring 550-750 W for cruise. It is estimated that a fuel cell could power such a vehicle for approximately 6-8 hours using compressed hydrogen. For both schemes it is assumed that fleet operational requirements call for continuous 24 hour operations. To guide hydrogen consumption estimates for each of these scenarios, Table 1 includes a list of relevant, off-the-shelf UAV PEMFC systems from Horizon Energy Systems (HES) and Ballard Power Systems that may be utilized for these classes of vehicles. It should be noted that fuel cell hydrogen consumption rate varies with power draw, typically reaching a minimum level at approximately 25-50% of maximum power output.[5]

For Scheme 1) assuming 1.3 kW continuous draw, using the information from Table 1, it is estimated that the hydrogen consumption rate is about 79 g/hr, making the flight consumption 79-157 g and the ground consumption 1.9 kg over a 24 hour period. For scheme 2) assuming 650 W continuous draw it is estimated that the hydrogen consumption rate is about 41 g/hr, making the flight consumption 246-328 g and the ground consumption about 1 kg. The hydrogen consumption metrics of each scenario are summarized in Table 2, showing the very different scales in flight and ground consumption levels that must be factored in when selecting hydrogen infrastructure; these will be referenced throughout the paper.

Table 1. UAV PEMFC plant fuel consumption metrics.

System	Vendor	Fuel Cell Cooling	Maximum Power (W)	H_2 Consumption @ Max Power (g/hr)	Specific H_2 Consumption (g/kWh)
Aerostack-500[6]	HES	Air	600	38	63
Aerostack-1000[6]	HES	Air	1,300	75	58
FCAir-600[7]	Ballard	Liquid	650	41	63
FCAir-1200[7]	Ballard	Liquid	1,300	82	63

Table 2. Baseline UAS operational schemes and estimated H_2 consumption metrics

Scheme	1: 10-15 kg Multi-Rotor UAS	2: 20-25 kg Fixed Wing UAS
Power Requirement	1.1 – 1.5 kW	550 – 750 W
Flight Duration	1-2 hr	6-8 hr
H_2 Consumption Rate	79 g/hr @ 1.3 kW	41 g/hr @ 650 W
Flight Consumption	79 – 157 g	246 – 328 g
Flight Energy Capacity	1.3 – 2.6 kWh	3.9 – 5.2 kWh
Ground Consumption	1.9 kg over 24 hrs	1.0 kg over 24 hrs

Hydrogen in Flight

A drone power system is evaluated based on energy density and factors in the size and weight burden absorbed during platform integration. For IC engines and fuel cells, system energy density must include the power system, fuel and fuel tank. To achieve meaningful storage density of hydrogen fuel required for drone use, compressed hydrogen is typically stored at pressures ranging from 350-700 bar (5,000-10,000 psi). Compressed hydrogen storage systems of such levels have seen dramatic improvement and investment in recent years, stemming from wide scale deployment in fuel cell cars. Scaled down tanks and system components that meet the needs of unmanned aircraft have now become available commercially at low production volumes and are safe for vehicle use.

Carbon composite overwrapped pressure vessels (COPV) are typically used provide a lightweight and structurally sound hydrogen 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.[8]

Type IV polymer tanks are used for onboard fuel storage because of their extreme light weight. The tanks are not typically used for ground storage because polymer liners are permeable to hydrogen and will slowly bleed pressure over the course of days to weeks; this is perfectly acceptable for UAV applications where expected storage time is on the order of hours. For long term storage applications, aluminum lined (Type III) COPV tanks are used to provide an impermeable containment structure; however, a Type III tank is substaintially heavier than a Type IV tank of equivalent storage volume. Type III tanks are able to achieve hydrogen mass fractions of approximately 3-4%.

A number of design specifications have been defined both within the U. S. and internationally that outline structural requirements under different applications and use scenarios. In particular, these guidelines must be adhered to if the flight UAV tank is intended to be transported with hydrogen under pressure. Example specifications include the Canadian Standards Assocation (CSA)/American National Standards Insitute (ANSI) Hydrogen Gas Vehicle 2 (HGV 2) standard and the European Union's (EU) Regulation (EC) No. 79; these both deal specifically with hydrogen powered motor vehicles and their hydrogen storage systems. Requirements for UAV hydrogen storage systems are not yet well defined, but may be modeled after these existing specifications.

Figure 1. a) 4.7 L and b) 9 L Type IV compressed H_2 COPVs.

The 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 up to the 350-400 bar (5,000-6,000 psi) range, but customized designs are typically necessary to enable integration up to 700 bar.

Ground Hydrogen Generation and Storage

Critical to the integration of a hydrogen fuel cell power plant into an unmanned aerial system is the supporting hydrogen infrastructure, including the onboard storage tank, ground refueling hardware, and fuel sourcing/generation scheme. Within each category, there are several options to choose from, the selection of which depends upon the particulars of the UAS air and ground operational approaches.

The infrastructure necessary to support ground-based hydrogen fueling depends upon a number of factors including: 1) on-board storage method, compressed or liquid, 2) ground hydrogen consumption, 3) operational mobility requirements, and 4) operational accessibility (grid power, water, transportation infrastructure, etc.). The considerations, technologies, and trades involved in selecting an approach to re-fuel hydrogen-based fuel cell systems are discussed in the remainder of the paper.

Blow Down

The most straightforward method of re-fueling a compressed hydrogen COPV tank is by filling from a higher pressure, higher volume compressed hydrogen source. An example schematic of this so-called "blowdown" fill approach is shown in Figure 2. In this scheme, a standard, high pressure gas cylinder, such as a 6,000 psi (400 bar) bottle available from most industrial gas suppliers, or a high pressure 5,000-10,000 psi (350-700 bar) COPV tank, similar to that which might be used for motive fuel cell applications, is used to provide a high pressure, high volume hydrogen source. The source is connected to the flight COPV tank through a: 1) pressure regulator, to set the flight tank fill pressure, 2) a control valve, to isolate the flight tank, and 3) a quick-disconnect fitting, to enable quick removal of the flight tank from the system.

Over the range of temperatures that the blowdown fill process might be expected to occur, hydrogen possesses a negative Joule-Thomson coefficient; meaning that it will warm as it expands into the flight hydrogen tank. The flight tank internal temperature must be monitored during the fill process to ensure that it does not heat the tank beyond the recommended limits of the composite overwrap; the commonly established COPV temperature limit for filling is 85˚C, see SAE J2601. The rate of heating increases with the rate of fill and so in some cases, typically for large tanks (> 10 L), the room temperature fill rate may be restricted due to thermal considerations. Alternatively, as shown in Figure 2, a chiller may be installed in the fill line to cool the hydrogen as it expands into the hydrogen tank to counteract the Joule-Thomson effect. However, given that the tanks required for the UAV missions described in this paper are relatively small, it is believed that <5 minute fill times are achievable under room temperature conditions.

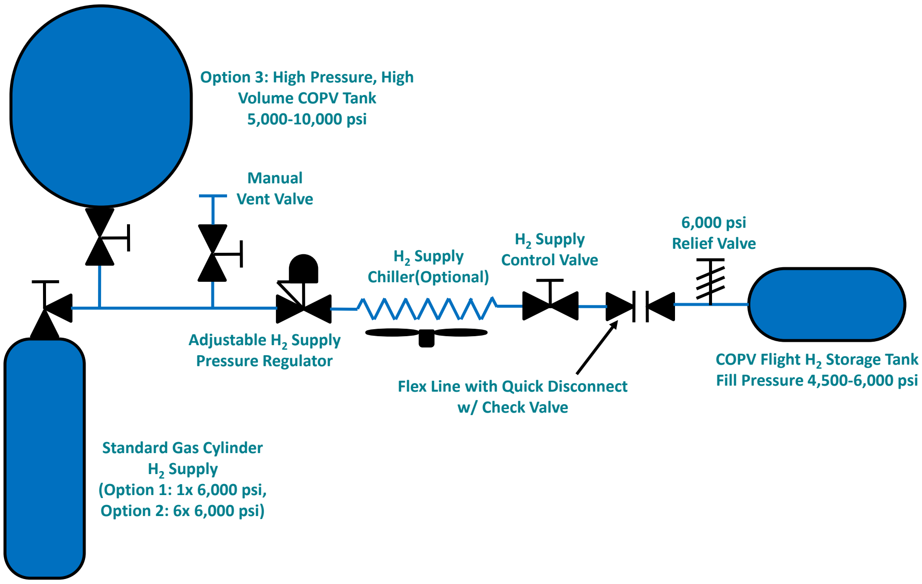


Figure 2. Example compressed hydrogen COPV flight tank fill scheme from high pressure, high volume sources.

It is also important to note that after the fill process is completed the hydrogen will cool, lowering the tank pressure; as a result, the flight tank should be filled to a pressure slightly above the intended fill pressure, approximately 5-10%, to ensure that the intended hydrogen capacity is achieved for flight.

In the blowdown fill scheme, the source pressure will drop as the flight tank is being filled, so the source maximum pressure and total volume should be selected appropriately to achieve the intended maximum flight tank fill pressure. The source must be replaced or re-filled once its pressure has dropped to that of the intended flight tank pressure. Multiple gas cylinders or COPV tanks may be ganged together in this approach to increase the source volume.

Most U.S.-based industrial gas suppliers, such as Praxair, Air Liquid/Airgas, Linde, etc., offer standard 6,000 psi (400 bar) hydrogen gas cylinders of a range of purity levels. For fuel cell applications, it is recommended that the purity be 99.97% hydrogen or better to meet SAE J2719 (standard industrial grade hydrogen, 99.95%, will not meet this requirement). These cylinders, even at higher purity, will be delivered to most accessible locations, although lead times will vary with location (often on the order of 2-5 working days). These suppliers will also typically offer a six-pack of 6,000 psi cylinders for operations consuming high volumes of hydrogen. A standard 6,000 psi (400 bar) hydrogen gas cylinder contains approximately 484 standard cubic feet (13.7 std. m^3) of hydrogen,[9] equating to approximately 1.13 kg.

As the proliferation of hydrogen fuel cell automobiles, buses, and material handling equipment continues, so will access to high pressure hydrogen fueling stations. A typical hydrogen fueling station will provide hydrogen at 10,000 psi (700 bar), and sometimes also 5,000 psi (350 bar), at fill rates much higher than would be required for UAV tank filling. For instance, the Toyota Mirai contains two COPV tanks, 60 and 62 L respectively that may be filled to a total capacity of approximately 5.0 kg of hydrogen in about 5 minutes;[10] this is more than 15 times the largest UAV flight tank capacity defined in this paper. A Mirai-like COPV tank could be filled at such as station and used as a high pressure, high volume hydrogen source for UAV tank filling.

As described previously, 6,000 psi is assumed to be the target flight tank fill pressure for UAV applications. A drawback of the blowdown fill scheme is that the source pressure and volume limits the achievable flight tank fill pressure. For the purposes of this discussion, it is assumed that the UAV operator can still meet mission requirements with a 25% reduction in on-board stored hydrogen mass resulting from hitting a fill pressure lower than the target; this works out to a fill pressure of approximately 4,500 psi (300 bar).

With a lower pressure limit defined, the operational schemes defined previously may be used to illustrate the usable hydrogen that both standard gas cylinders and high pressure, large volume COPV tanks may provide for flight operations. Figure 3 plots the variation in the pressure of these hydrogen source tank options with the amount of hydrogen withdrawn. Overlaid on the plot is the defined flight and ground hydrogen consumption of the two operational schemes defined in

Table 2.

Figure 3 shows that a single 6,000 psi gas cylinder may be sufficient for one or two flights under Scheme 1, but is insufficient to meet the minimum pressure requirement for Scheme 2 for a single flight. A six-pack of 6,000 psi cylinders can meet a full 24 hour demand of Scheme 2 operations, and about 18 hours (1.4 kg) of Scheme 1 operations. A 10,000 psi, 60 L automobile fuel cell hydrogen tank can meet a 24 hour demand of Scheme 2 operations, but only about 12 hours (1.0 kg) of Scheme 1 operations. The automobile tank can also support flight tank fills to 6,000 psi (0.7 kg) for several flights (4-8) in Scheme 1 or two flights in Scheme 2. It should be noted that at 4,500 psi, approximately 80% of the starting hydrogen remains unused in the gas cylinder sources while about 55% remains unused in the automobile COPV tank.

These results suggest that a blowdown operation may be sufficient for both Scheme 1 and 2 assuming that the operator is willing to sacrifice some flight time to enable a relatively simple re-fueling approach. An automobile COPV or a six-pack of gas cylinders offer a means to support 24 hour operations under Scheme 2, but would require re-filling or replacement daily. None of the source options explored here meet all the demands of Scheme 1, but an automobile COPV or a six-pack of gas cylinders would be sufficient to support daylight operations.

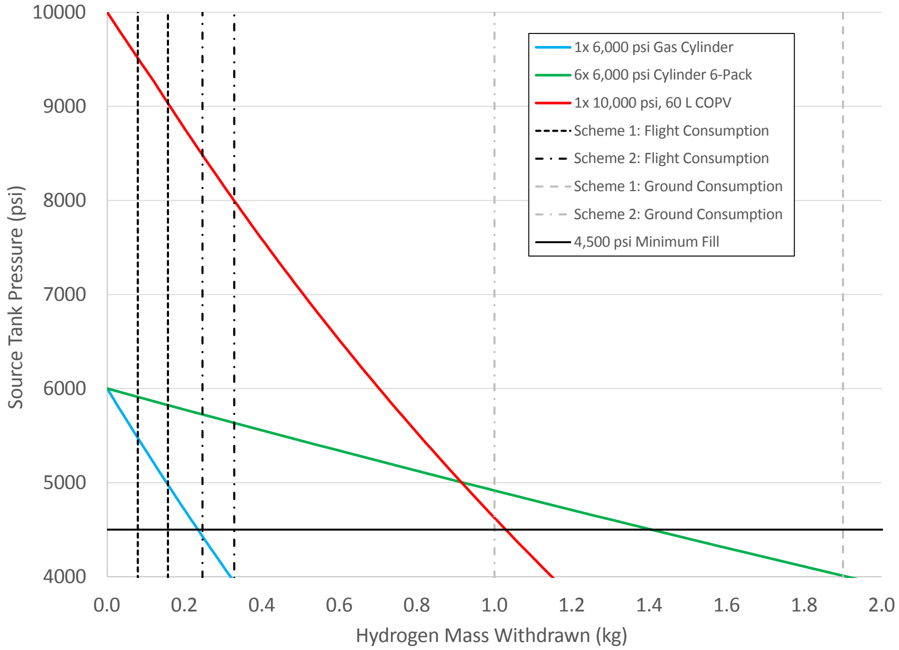


Figure 3. Variation in source tank pressure with hydrogen mass withdrawal.

Boost Compression

The preceding section illustrated that a blowdown refueling approach is viable for the operational schemes discussed, but may limit the achievable flight time and leaves much of the hydrogen unused in the source container(s). A method to overcoming these limitations is to integrate a boost compressor between the hydrogen source and the flight tank to increase the supply pressure to the design target and nearly exhaust the source. An example schematic of the system is shown in Figure 4. The system layout is identical to that shown in Figure 2 for the blowdown scheme, but includes a boost pump upstream of the hydrogen pressure regulator.

Although represented simplistically in Figure 4, the boost pump is a sophisticated mechanical system that typically employs positive displacement, in some cases multi-stage, to provide high compression, typically on the order of 10:1. The pump is typically driven by an electric motor, although pneumatically-driven models also exist; various AC voltage options may be available depending upon specifications. A complete boost pump system will typically include safety devices such as inlet and exit pressure switches, pressure relief valves, and temperature overload protection. The working fluid is heated during the compression process and so the pump will also contain a cooling system to regulate pump head temperature (typically liquid coolant with fan and radiator for heat rejection). Analog or electronic control interfaces are also available. As with any positive displacement device, regular maintenance (interval dependent on design specifics) is required to replace lubricants, seals, belts, and filter elements. Notable vendors of off-the-shelf and customizable high pressure (up to 10,000 psi), hydrogen boost pumps include Hydraulics International, Inc (HII) and PDC Machines, see Figure 5.

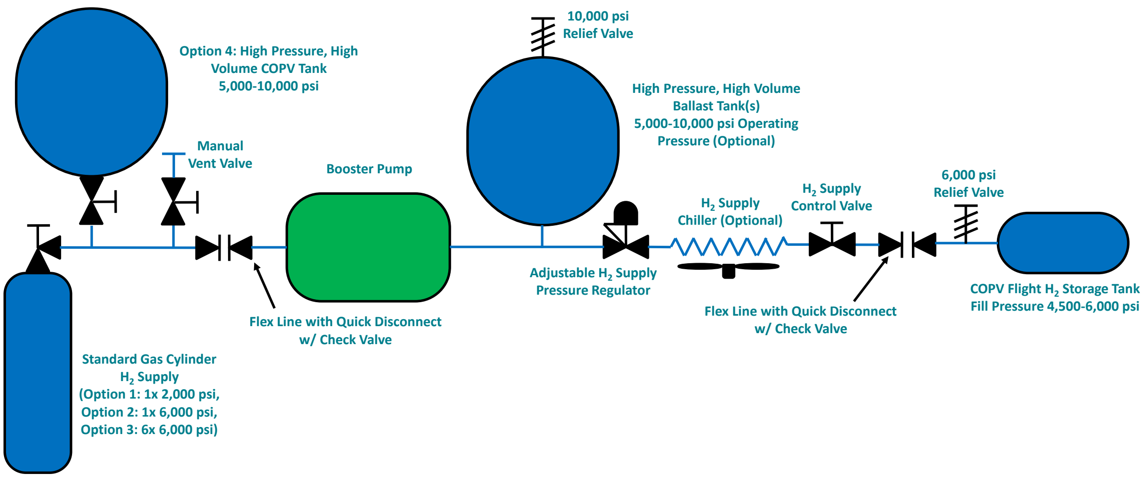


Figure 4. Example compressed hydrogen COPV flight tank fill scheme from high pressure, high volume sources through boost compressor.

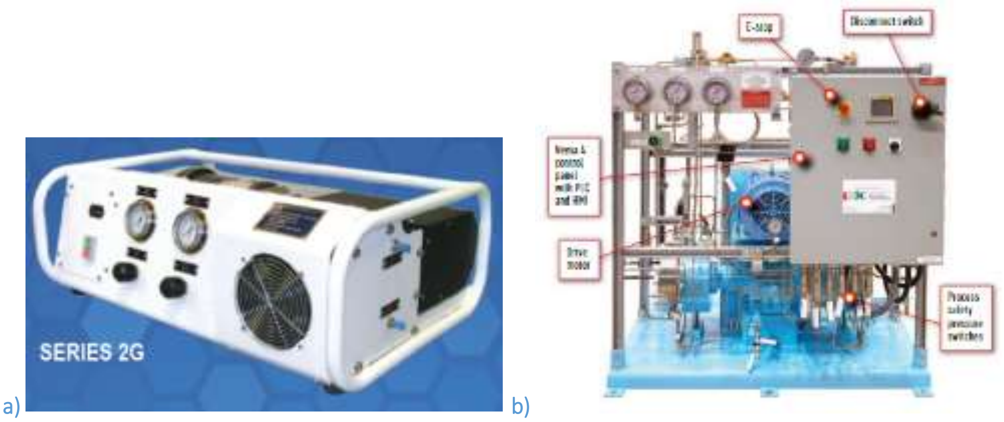


Figure 5. Commercially available high pressure, hydrogen boost pumps from a) Hydraulics International, Inc.[11] and b) PDC Machines.[12]

From a refueling system design standpoint, the key metrics for the boost pump are the achievable output pressure and flow rate. Boost pumps capable of 6,000-10,000 psi (400-700 bar) output pressure, such as those in Figure 5, are readily available and so meet the target flight tank pressure requirement defined previously. Additionally, the systems in Figure 5 provide hydrogen output flow capacities of up to 1.5-3 kg/hr (300-600 sLpm) and so provide more than enough capacity to meet the 24 hour demands defined by Schemes 1 and 2 in

Table 2. The systems in Figure 5 operate using electric motors ranging from 2 to 10 hp (1.5 to 7.5 kW).

It is also important to determine whether the pump flow capacity is sufficient to fill the flight tanks directly. If it is assumed that, for ease of operations, the tank fill process should take no longer than 5 minutes, then the required pump flow capacity should range from 0.95-1.9 kg/hr for Scheme 1 and 3.0-3.9 kg/hr for Scheme 2. These results show that the boost pump flow capacity may be insufficient for Scheme 2 options if longer fill times are not acceptable (for reference, a 10 minute fill time would reduce flow requirements to 1.5-2.0 kg/hr for Scheme 2 fitting within off-the-shelf pump specifications). To circumvent a potential flow capacity limitation, high pressure ballast tanks could be incorporated into the system downstream of the boost pump and be charged between flight tank fills. The flight tank could then be filled from the ballast tanks via a blowdown operation as described in the preceding section. Since the ballast tank would be part of the ground equipment, it could be larger and heavier than a flight tank to enable multiple fills and high pressure storage up to 10,000 psi (700 bar).

A major benefit of a boost pump refueling approach is that it broadens the range of hydrogen sources that may be utilized in a UAV flight operation. For example, a standard 2,400 psi (165 bar) gas cylinder, which is often more readily available than a 6,000 psi cylinder, may be used to fill flight COPV tanks to target pressure. A standard 2,400 psi (165 bar) hydrogen gas cylinder contains approximately 196 standard cubic feet (5.5 std. m^3) of hydrogen, equating to approximately 0.46 kg. Since the boost pump operates at a limited compression ratio, it is also important to consider the usable hydrogen available from a given source even with a boost pump. Assuming a compression ratio of 10:1 (approximate rule of thumb for the pumps under consideration), a boost system will be able to drain a source to 600 psi while still achieving the 6,000 psi flight tank target pressure, and will meet the minimum flight tank pressure of 4,500 psi while draining a source down to 450 psi.

Table 3. Usable hydrogen from common sources via blowdown and boost compression refueling schemes.

Hydrogen Source	Usable Hydrogen (kg)			
	Blowdown to 6,000 psi	Blowdown to 4,500 psi	Boost to 6,000 psi	Boost to 4,500 psi
1x 2,400 psi Gas Cylinder	N/A	N/A	0.33	0.37
1x 6,000 psi Gas Cylinder	N/A	0.23	0.99	1.02
6x 6,000 psi Gas Cylinder Six Pack	N/A	1.41	5.94	6.15
10,000 psi, 60 L Automobile COPV	0.70	1.03	2.12	2.17

Table summarizes the estimated usable hydrogen available in both the blowdown and boost refueling approaches assuming flight tank fill to 6,000 and 4,500 psi using the commonly available hydrogen sources described in this paper. The estimates in Table show that the boost pump provides the greatest benefit, over 4x increase in usable hydrogen, for the 6,000 psi gas cylinder configurations. The boost pump enables a single, 6,000 psi gas cylinder to support a full day of Scheme 2 operations (1 kg) at target flight tank fill pressure. Similarly, the boost pump enables a single 6,000 psi six-pack to support approximately six days of Scheme 2 operations (6 kg) and three days (5.7 kg) of Scheme 1 operations at target flight tank fill pressure.

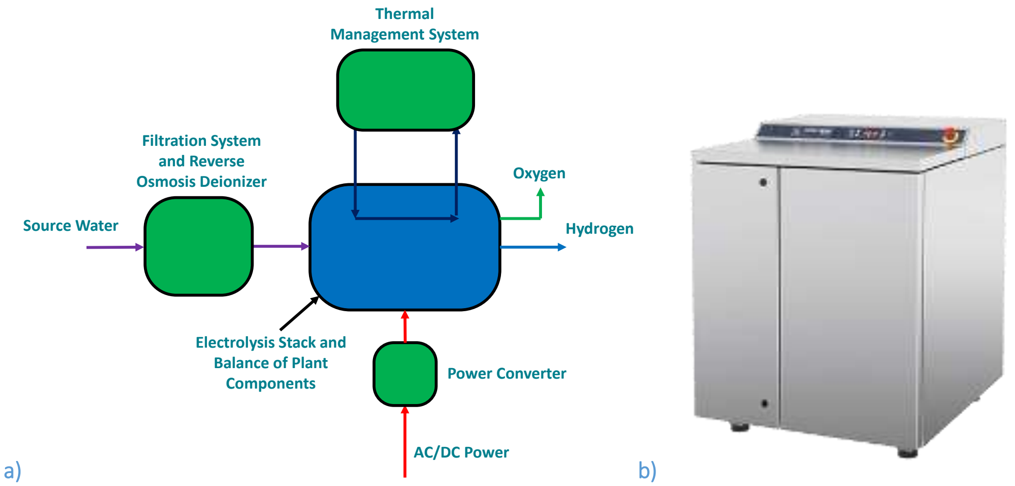
The boost pump also increases the usable capacity of the 10,000 psi automobile COPV by 2x, enabling the approach to support a single day of Scheme 1 operations (1.9 kg) or two days of Scheme 2 operations (2.0 kg). Additionally, the boost pump enables the use of a 2,400 psi gas cylinder to support two to four Scheme 1 flights or one Scheme 2 flight at target flight tank pressure; this may be sufficient to support daytime flight operations in some cases.

These results suggest that incorporation of a boost pump system into a ground refueling infrastructure can significantly increase hydrogen capacity, to several days, under both Schemes 1 and 2. Additionally, the system provides consistent fill pressure to the target flight tank fill level of 6,000 psi. The drawbacks are that the system becomes more expensive, larger and heavier (although still transportable in a standard pick-up bed or small trailer), and requires electrical power input (up to 10 kW estimated depending upon configuration). Like the blowdown scheme, the boost pump approach is also dependent upon availability of outside hydrogen sources.

Electrolysis

The refueling schemes detailed in the preceding sections relied upon the use of hydrogen sources located external to the UAV operating infrastructure. On-site hydrogen generation offers a means to operate independently and generate hydrogen as needed for flight operations. The most effective way to generate hydrogen for onsite operations is through electrolysis of water via an electrolyzer; a technology that has been used in industrial applications for 125 years. An electrolyzer consumes electrical energy creating hydrogen (and oxygen) from water through an electrochemical reaction (reverse reaction of a fuel cell).

The primary components of a typical electrolyzer system are shown in Figure 6a and an example of a complete field ready product is shown in Figure 6b. Core to the electrolyzer is an electrolysis stack with internal thermal management and power electronics. Critical to operation is a deionization (Usually reverse osmosis) and filtration system to treat and prepare incoming water. With the right filtration unit, tap water or treated gray water can be used making the system more optimal for austere use.



a) b)

Figure 6. a) Schematic of a typical electrolyzer system, and b) Proton OnSite S Series electrolyzer.

In data tracked by the U.S. Department of Energy (DOE), electrolyzers have been shown to be the most reliable piece of major equipment at hydrogen fuel stations. Proton exchange membrane (PEM) electrolyzers have high reliability with low ongoing maintenance costs and frequency. Electrolyzers are inherently scalable and are commercially available in small, appliance-size equipment that is well-suited for distributed hydrogen production. An example of a commercially available system that provides hydrogen capacity sufficient to meet the needs of Scheme 1 and 2 from

Table 2 is the Proton OnSite S Series electrolyzer, shown in Figure 6b. The S Series systems can provide 1.1 to 2.3 kgH_2/day while consuming 3.5 to 7 kW on average in a package about the size of a washing machine.[13] The water consumption rate needed to support the hydrogen generation rates outlined above is quite low at approximately 11 to 23 L/day (3 to 6 gal/day).

Commercially available electrolyzers typically operate below 500 psi (35 bar); for instance, the S Series provides hydrogen at 200 psi (14 bar). An electrolysis-based hydrogen re-fueling system for a UAV operation would require a boost compressor to increase the flight tank fill pressure to the 4,500 to 6,000 psi (300-400 bar) target. The system would be similar in setup to that described in the preceding section except that the electrolyzer would serve as the hydrogen source, as shown in Figure 7. Since small, portable electrolyzers, such as the S Series, produce hydrogen at relatively low rates (0.05 to 0.10 kg/hr), the system would be unable to directly fill the flight tanks in a 5-10 minute time frame. A high pressure ballast tank is necessary in an electrolyzer refueling system to facilitate rapid flight tank filling through a blowdown process. The electrolyzer would likely need to run continuously to charge up the ballast tank.

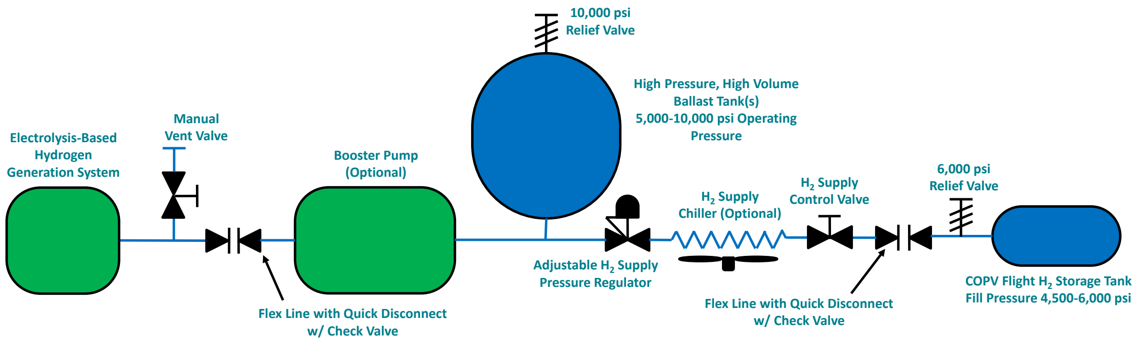


Figure 7. Example compressed hydrogen COPV flight tank fill scheme from an electrolyzer through a boost compressor.

An alternative design in development, at Proton OnSite and other companies such as HyET Hydrogen, is an electrolyzer stack that produces hydrogen at high pressure; current development systems are targeting 5,000 to 10,000 psi (350-700 bar). A system with this design is more efficient and reliable than using a lower pressure electrolyzer with a high compression ratio boost pump, and could be less costly given the lower part count. A low compression ratio boost pump may still be needed in this configuration if low electrolyzer hydrogen production rates necessitate the use of a ballast tank.

Regardless of the pressure achieved through electrolysis, power for the system could be supplied by the existing generator system that runs the UAV ground control station, a vehicle auxiliary power unit (APU), or a renewable energy source, such as solar power. An integrated water purification system would allow the use of potable water or pretreated gray water based on existing reverse osmosis and de-ionization technology.

An electrolysis-based refueling system offers a mature approach to on-site hydrogen generation that would make a UAV hydrogen refueling infrastructure independent of outside hydrogen sources. Commercial electrolysis technology has the capability to meet the daily hydrogen demands of operational Schemes 1 and 2, but requires a boost compressor or advanced electrolysis technology to meet pressure needs and a high pressure ballast tank to meet anticipated fill rate requirements. Since the system consumes water and electricity it may be easily integrated within existing infrastructure in established commercial locations. In more austere environments, renewable energy or hydrocarbon-fueled generators may be used to power the system, and local water sources may be used to drive hydrogen production. The capital cost for setting up an electrolysis-based system would be high, but the recurring cost would be low given the input requirements and limited maintenance.

Liquid Hydrogen Storage

The current state-of-the-art in liquid cryogen (<123 K; −238 °F) storage technology is the vacuum jacketed dewar with multi-layer insulation (MLI) between the inner and outer shells. Vacuum eliminates convective heat transfer while MLI slows the rate of radiation heat transfer. Shell materials typically consist of thin gauge stainless steel or aluminum, the mass fraction of cryogen to tank ranges from 6% for 1 kg tanks to 15% for 8 kg tanks.[14]

While metal vacuum jacketed tank technology has been successfully demonstrated by the Naval Research Laboratory's 15 kg Ion Tiger UAV,[15] this configuration is less suitable for use in smaller UAVs and can be improved upon for use in larger UAVs. The traditional vacuum jacketed design was developed for long term storage of cryogenic liquids by minimizing boil-off, however, airborne UAVs will typically require a constant flow of hydrogen gas to fuel the propulsion system. Consequently, engineering the boil-off rate to match nominal fuel cell consumption reduces mass by relaxing insulation requirements. Storage mass can be reduced by using polymers in lieu of metals. Polymers have not historically been used as a material for cryogenic storage dewars because mass was not an issue, and polymers become brittle at cryogenic temperatures. The new design paradigm founded on additive manufacturing and novel polymer composites has enabled the development of the next generation of cryogenic storage tank that will offer increased thermal performance and reduced mass compared to the status quo. This technology, although progressing, is still in a state of early development and will not be ready for routine commercial use for some time.

A comparison of liquid hydrogen tank metrics is shown in Table , including design figures for a 5 L tank currently in development by Protium Innovations LLC. Also in Table are estimated metrics for two smaller tanks incorporating Protium design features. Table indicates that the benefits of liquid hydrogen are more fully realized at larger hydrogen storage mass/volume. At lower volumes the mass is very similar to compressed hydrogen technology; however the volume is substantially lower due to the high storage density of liquid hydrogen.

Table 4. Comparison of liquid hydrogen tank metrics.

Tank	Vendor	Tank Water Volume (L)	Tank Weight (kg)	Stored H_2 (g)	H_2 Weight Percentage (%)
5 L[a]	Protium	5.0	3.3	300	8.3
2.9 L[b]	Protium	2.9	2.2	175	7.4
1.7 L[b]	Protium	1.7	1.7	100	5.6

[a] Currently in development [b] Engineering estimates

Conclusion

In UAV applications, hydrogen-fueled PEMFC power 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. Relative to internal combustion engine-powered systems, fuel cells provide reduced acoustic signature, limited altitude derating, and reduced maintenance.

Key to realizing the benefits of PEMFC systems in UAVs are lightweight and rugged on-board hydrogen storage components and portable, reliable, and easy-to-use ground based refueling systems. Multiple storage and refueling approaches are currently in-use and available that leverage mature technologies. Selection from these options requires knowledge of hydrogen demands at the flight platform and fleet operation levels. A representative VTOL multi-rotor (10-15 kg) application scenario, Scheme 1, was defined requiring 79-157 g of hydrogen per flight and a daily consumption of 1.9 kg to assist in assessing these options. Similarly, a representative fixed wing (20-25 kg) application scenario, Scheme 2, was defined requiring 246-328 g per flight and 1 kg per day.

High pressure compressed hydrogen provides a straightforward hydrogen storage method using mature COPV tank technology. Storing hydrogen on-board the aircraft at high pressures (400 bar target) in plastic-lined COPV tanks enables storage mass fractions approaching 6% and specific energy of about 1,000 Wh/kg in Scheme 1. Lightweight cryogenic liquid hydrogen tank technology that enables more stringent boil-off control is maturing. Hydrogen mass fractions of 8-10% are achievable with liquid hydrogen tank technology and analysis shows that it is better suited for higher energy applications, like Scheme 2, were it is estimated to achieve about 1,300 Wh/kg.

Portable compressed hydrogen refueling may be accomplished through several methods reliant on hydrogen sourced from outside vendors. Blowdown filling from a high pressure, high volume source is the most straightforward approach, but provides limited control of the flight tank pressure and leaves a large residual quantity of hydrogen in the source container. This refueling approach is best suited for short, intermittent flight operations of a day at a time. Boost compressor filling from a high volume source at a wider pressure range enables tight control of the flight tank pressure and significantly reduces residual hydrogen, but adds complexity through the addition of the compressor. A boost compression system could be transported on the bed of a pickup truck, and is best suited for multi-day (consecutive) flight operations.

Alternatively, hydrogen may be generated on site by feeding water and electricity to an electrolyzer and using a boost compressor to increase pressure for flight tank filling. High pressure electrolyzers are in development that may reduce the size of, or eliminate altogether, the boost compressor by supplying hydrogen at flight tank storage pressures. An electrolysis-based system makes the hydrogen fueling operation independent of outside hydrogen sources, but adds complexity due to the array of components required for operation and has high up-front cost. An electrolysis-based refueling system could be transported on a small two-wheeled trailer or in a box truck, and is best equipped for week (or more) long flight operations.

Liquid hydrogen refueling can be accomplished through blowdown filling from a high volume cryogenic dewar sourced from outside vendors. A general drawback of liquid hydrogen filling is that significant hydrogen is lost through the tank chilling process that is integral to the flight tank filling procedure, but this approach is suitable for either one-day or multi-day flight operations. On-site liquefaction of hydrogen can be accomplished through the use of a cryocooler using outside compressed hydrogen sources or via electrolysis-based generation. Adding liquefaction increases the complexity of the system and the up-front cost, but the system is portable via a trailer or box truck and is best suited for extended (week or more) flight operations.

This paper has shown that there is no clear catch-all hydrogen storage or refueling solution for all PEMFC powered UAV systems; each approach provides distinct benefits. The choice will be unique for each UAV application depending on the mission and fleet requirements, flight operation duration, portability needs, operating location(s), and budget. It is hoped that this paper has provided a sufficiently detailed overview to assist current and future PEMFC power system operators in finding the path that is best for their unique situation.

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