Impact of Hydrogen Powered Drones on Advanced Air Mobility

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In this paper, we examine the key features of hydrogen-powered drones in comparison with battery-powered drones on the basis of working principles, energy density, fight duration, payload, and commercial-off-the-shelf availability. The impact of hydrogen-powered drones on Advanced Air Mobility is then investigated. Currently, small drones run using the power from LiPo batteries, while the current state of battery energy density is not ideal for long-duration and large-payload drones. Hydrogen fuel cells have great potential to overcome these drawbacks thanks to hydrogen's significantly higher energy density than LiPo batteries. While this may be promising for drone enthusiasts, the current state of hydrogen-powered drones is still in the infancy stage of research and development.

I. Introduction

A. Motivation

As time passes, humans have been striving to make the world a better place. As we currently stand, we have an issue that has been addressed, and initiative has already been taken in order to solve it. Greenhouse gases are increasing in our atmosphere due to pollutants. The emission problem has been exposed and we as a society are already working to fix this issue with new technology set to minimize emissions as a result of the Net-Zero Coalition. Net-zero essentially means cutting all greenhouse gases that are polluting the air. Since the 1800s, Earth has seen an increase in temperature of 1.1°C (about 2°F). The Paris Agreement, adopted in 2015, wants to limit global warming to below 2°C, preferably below 1.5°C. To ensure Earth does not exceed the 1.5°C threshold, we are currently trying to implement zero-emission by 2050. Since the United Nations Framework Convention on Climate Change, signed in 1992, we have seen an increase of 60 percent in carbon dioxide (CO_2) emissions from both energy and industry. In order to prevent further climate change damage, there are a few objectives that need to be completed. By the year 2030, we expect to see a 45 percent reduction in global greenhouse gas, as well as an annual $4 trillion dollar investment in clean energy. By 2040, electricity generation with net-zero emissions is supposed to account for 50 percent of our energy consumption globally [1] [2] [3]. At this point in time, hydrogen-based fuels have great potential to be very well used everywhere which brings us to our motivation to look into hydrogen-powered drones in future aviation.

Currently, the majority of the clean drones being used are battery-powered. Although they can be efficient, there are drawbacks to using these types of drones. The number one issue has to be the short flight time. This limits the uses of the drone, as it cannot be doing certain tasks for too long. It takes a great amount of energy to lift the drone, and the energy stored in the batteries tends to run out quickly [4]. On top of that, the payload for battery-powered drones is relatively small. When comparing battery-powered drones and hydrogen-powered drones, hydrogen-powered drones exceed in a way that battery-powered drones do not. Hydrogen-powered drones use hydrogen fuel cells, which significantly extend the flight time due to higher energy density and make it more efficient. The flight time for battery-powered drones is one of its major drawbacks. There are occasions when a drone is needed for a long period of time, but the battery runs out before it can complete its task. Hydrogen-powered drones, however, are more expensive at the current stage since there are not too many of them and they are relatively new.

B. Background

The first hydrogen-powered drone reported in the literature was built by DOOSAN [5], a South-Korean company. The drone delivered face masks to those on remote islands in 2020 amidst the global pandemic. The drone also carried

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on 2hr flights that cover vast distances up to 80 km to monitor offshore pipelines. The prototype by DOOSAN then garnered three different offspring. The first is the DS30 which is very similar to the prototype. The second is the DT30 which is smaller and is used for more general purposes with a flight time of 2.5 hours. The last offspring is the DT30N which is the largest model of the drone thus far.

Shortly after the success of the DOOSAN Drones, a company out of Singapore called H3 Dynamics [5] joined the race with test flights of their drone being held in Tokyo, Japan in 2020. Even Toyota helped in the manufacturing by supplying electronics to be used on the drones. H3 Dynamics hopes to continue its future endeavors in unmanned aerial vehicles by producing drones to deliver cargo, then gradually move into manned aerial vehicles by building a hydrogen-powered drone that carries a single passenger.

Currently, hydrogen-powered drones are still in the infancy stages of research and development. With time they have great potential to outnumber the amount of battery-powered drones; due to hydrogen's superiority when comparing flight duration. Hydrogen is still also a relatively new source of alternative fuel. Currently, hydrogen-powered drones are relatively much more expensive than battery-powered drones, thus making them unattainable to the general public.

Hydrogen is one of earth's most abundant elements, however, it usually appears in compounds such as water and methane. This makes the production sophisticated and leads to hydrogen gas being primarily used as a catalyst in the welding process [6]. The energy, automotive, and aerospace industry urge to jump into the hydrogen-powered industry to support their sophisticated fuel source. With time hydrogen technologies will evolve and become more accessible making the products cheaper and more readily available which is currently a big bottleneck.

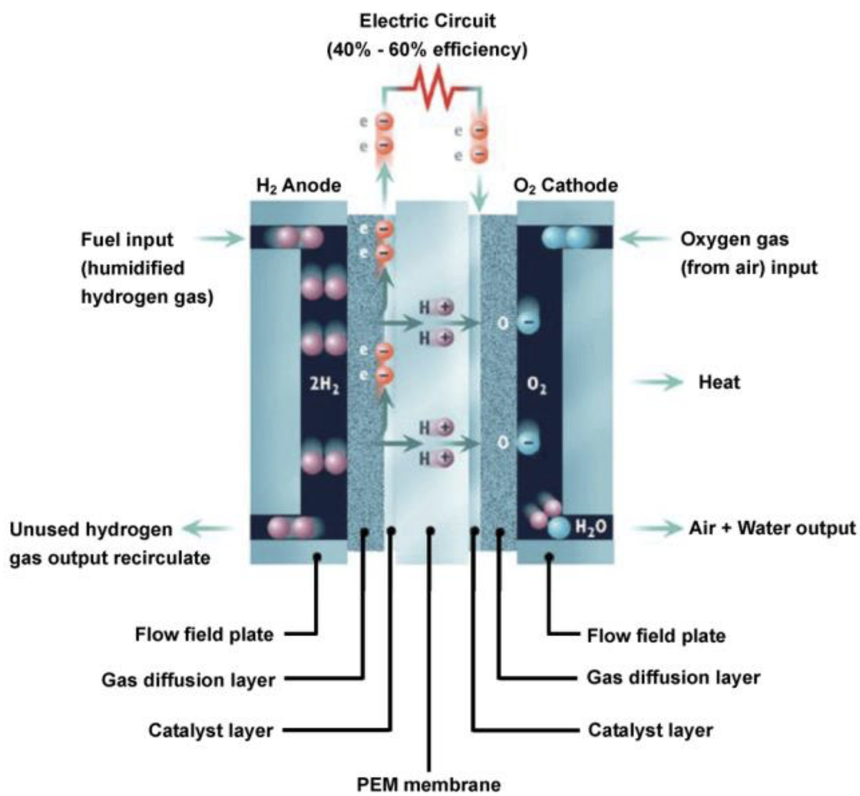

Fig. 1 Operation of a fuel cell [7].

C. Contribution

In this paper, we summarize and visualize the collected information for hydrogen-powered drones and compare it with battery-powered drones. Furthermore, we summarize and visualize the differences between all of the hydrogen-powered drones that are currently on the market. We look into these comparisons from various perspectives, such as energy density, max payload, cost, and flight duration. We hope this work would help readers to gain a quick understanding of the key significance of hydrogen-powered drones and their differences versus battery-powered drones, and compare existing off-the-shelf hydrogen-powered drones to each other for drone selection. Eventually, we bring our insights about the impact of hydrogen-powered drones on Advanced Air Mobility (AAM).

D. Structure

The remaining of the paper is structured as follows. Section II presents how hydrogen is produced and then converted into energy on a drone. Section III gives insight into the comparison between battery-powered drones and hydrogen-powered drones by showcasing the difference between the energy densities, speed, rate of recharging, etc. Section IV presents key aspects of hydrogen production. Section V compares off-the-shelf hydrogen-powered drones to each other. Section VI introduces the concept of AAM and summarizes the impact of hydrogen-powered drones on AAM.

II. Working Principle of Hydrogen Powered Drones

A. Energy generation by hydrogen

The energy can be generated by hydrogen in a fuel cell, as shown in Fig. 1. A fuel cell is a device that intakes in hydrogen and oxygen and produces electricity. It has two plates, a catalyst, and an electrolyte. When operating the fuel cell, the hydrogen atoms want to go to the cathode. However, hydrogen is made of one proton and one electron. The electrolyte only allows positive atoms to pass, whereas atoms need to be equalized in order to work. The fuel cell has a wire that passes the catalyst and cathode. This then creates an electrical current which makes a reaction between oxygen and hydrogen to form water and power the motor [7].

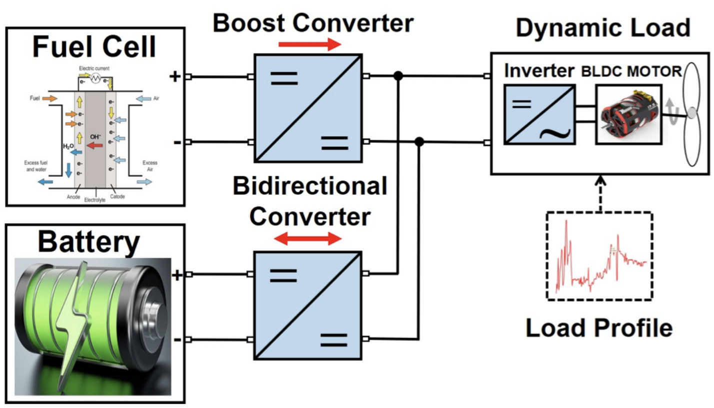

Fig. 2 Hybrid power supply system topology [8].

B. Energy conversion to power drone motors

Hydrogen is converted into electricity by a hydrogen fuel cell which utilizes a catalyst made of a compound of materials; primarily platinum, to take hydrogen as an input and provide water and electricity as an output. When using a hydrogen drone the power supplies a fuel cell, boost converter, dynamic load, bidirectional converter, and battery, as shown in Fig. 2. These power supplies cooperate with each other as the fuel cell produces the electricity and then passes it through the boost converter. The boost converter is used to set up inputs and works by storing energy in the inductor that then is used to load it with higher voltage. Then it goes through the dynamic load, used as a live load that changes the direction, magnitude, position, and structure. After it goes through the bidirectional converter it can be converted to DC current for the power supplies. Then the battery provides the electricity to make the power drone motors function. More information about how the energy is converted to electricity can be found here [8].

C. Cost of hydrogen cells

A hydrogen drone costs around $6,800 [9]. The materials that the hydrogen drone uses are the fuel cell and hybrid battery along with a hydrogen tank. A fuel cell's primary material is the catalyst that is made of platinum. This material is expensive since it's the main factor in how the fuel cell separates the protons and the electrons. A hybrid battery powering the drone's propellers helps the drone be up in the air for a long period of time. A hydrogen tank cost about 16 dollars per gallon [10]. However, hydrogen is more efficient than gasoline. When buying a hydrogen drone there are many considerations on what makes this drone so expensive as opposed to the battery drones. It's important to consider that the price of a Hydrogen Fuel Cell can be greatly decreased by looking into cheaper catalysts instead of using rare earth metals such as platinum.

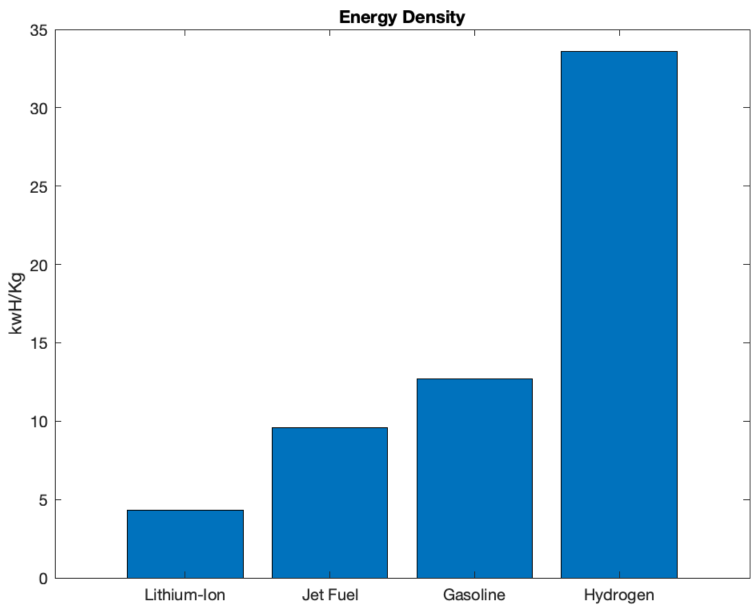

Fig. 3 Bar chart shows the difference in energy density between hydrogen-powered and other energy sources.

III. Characteristics of Hydrogen

A. Energy density of hydrogen- and battery-powered drones

The most prominent advantage of using hydrogen as a viable clean energy source is the superior energy density compared to other energy sources. Hydrogen has an energy density of 33.6 kWh/kg which is about 3 times more dense than gasoline and 6 times as dense as a lithium-ion battery [11–13], as shown in Fig. 3. Furthermore, Figure. 3 shows the energy density between hydrogen-power and LiPo battery drones in terms of flight duration versus power/energy system weight fraction.

B. Rate of electricity recharging vs. fuel cell refueling

The advised charging rate of an energy cell is between 0.5 C and 1 C. Lithium Ion batteries go through 4 stages when charging as shown in Fig. 5. This process has a charge between 2 to 3 hours. For fuel cells, refueling is fast and quite simple. For a hydrogen-powered car, it takes no longer than 3-5 minutes to refuel. It is similar to refueling a car with gasoline [14, 15].

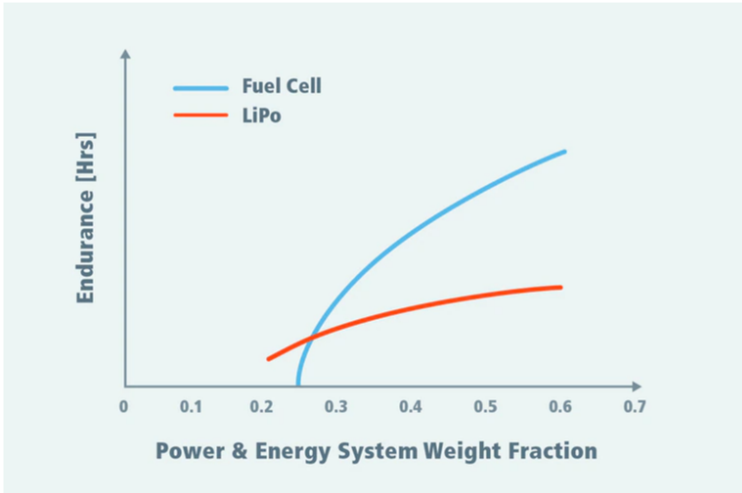

Fig. 4 Energy density comparison: hydrogen fuel cell vs. lithium batteries [13].

C. Impact of temperature on hydrogen-powered and battery-powered drones

For electricity-powered drones, low temperatures will decrease the voltage of the batteries, while high temperatures can also affect the drone. Hydrogen generates electricity through chemical reactions. If the temperature surrounding the drone is too high, the heat will affect these chemical reactions and it will reduce the flight time as well as the life of the battery. Hydrogen-powered drones have a higher endurance when it comes to temperature. They are capable of flying in temperatures that are both higher and lower than battery-powered drones [16–18].

IV. Hydrogen Production

Hydrogen can be produced by many methods, as shown in Fig. 6. These methods include renewable energy, nuclear, fossil fuels, natural gas, and electricity for electrolysis. Production of hydrogen can be categorized by color based on the way it is manufactured. Brown hydrogen comes from non-renewables, red hydrogen from nuclear processes, and green hydrogen from renewables. Red hydrogen production is very promising as this form of producing hydrogen is very clean and can be done very cheaply. Mitsubishi is currently developing a plant that will take water and Iodine-sulfate as the input and output Hydrogen [19].

A. Electrolysis Hydrogen Production

Electrolysis hydrogen production is currently the most widely used form of hydrogen production. It encompasses two different types of hydrogen production which are brown and green hydrogen production. The color stems from where the energy for electrolysis is obtained. To produce 1 kilogram of hydrogen, through water electrolysis, with an effective electrical efficiency of about 70-80% we need 50-55 KWh of electricity. The amount of water that is needed is about 2.4 gallons, which is approximately 9.1 kilograms [20]. Brown hydrogen production is redundant due to the fact that more emissions are created to get less energy out in the end. However green hydrogen production is more environmentally friendly as the energy needed for the electrolysis process is obtained by utilizing solar power, wind power, etc... thus the byproducts of green hydrogen production are oxygen and hydrogen as the water molecules are split apart.

B. Hydrogen Cost

Hydrogen production through water electrolysis costs about $16/kg in the U.S. [21], however, this price is said to drop drastically in the near future with the Hydrogen Shot Program. Extensive research is being done to find newer, cheaper, and more efficient ways to develop hydrogen to make it a mainstream medium of energy. The "1 1 1 Hydrogen Shot Program", sets the goal to make 1 kilogram of hydrogen cost 1 dollar in one decade.

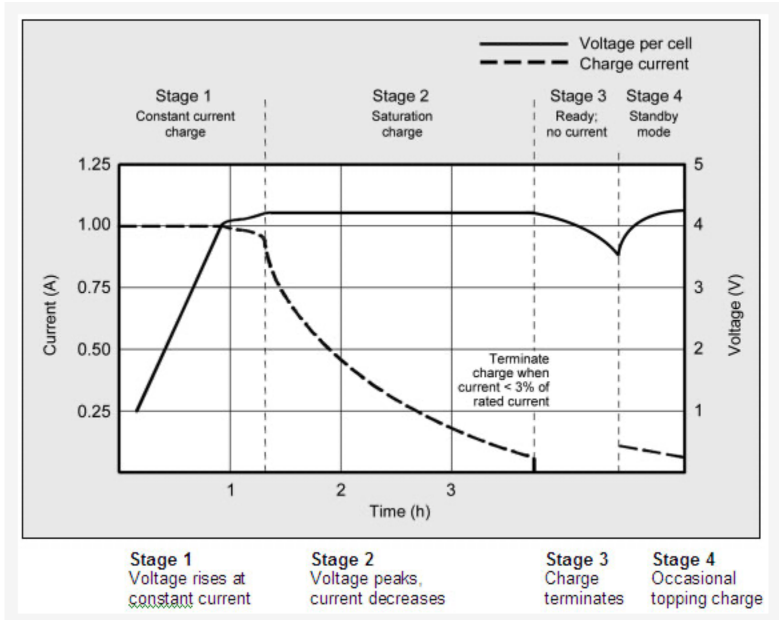

Fig. 5 Charge stages of a lithium-ion [14]

C. Hydrogen Distribution

On the distribution side, there are challenges as most hydrogen is being produced near areas of operation. There is currently work being done to convert oil & gas pipelines as well as create new pipelines to directly pump hydrogen in liquid form to areas of operation, in this case to vertiports and airports [22]. Storage of hydrogen currently is very dangerous in containment due to the immense amount of pressure needed to keep hydrogen in its liquid state even more so with all the energy that is packed within hydrogen [23]. Research is being done on storing hydrogen as ammonium which contains one nitrogen atom with four hydrogen atoms attached [24]. There are certainly drawbacks to this solution as it is also highly toxic but it can be stored in its liquid form a lot easier than hydrogen itself. There is certainly a lot of work to be done with the hydrogen supply chain, but there are many different researchers and companies that see the benefits of hydrogen as a clean energy source and will very likely expedite the process.

V. Commercial-Off-the-Shelf Hydrogen-Powered Drones

Hydrogen-powered drones are currently in their infancy stages as there are few options actually out on the market currently. We present five hydrogen-powered drones in this section and it can be seen that the growth within the market did not exist until the early 2020s. Fig. 7 displays the key aspects of each drone side by side.

A. BSHARK Narwhal 2

BSHARK is a high-end drone company out of China, and they have created a true marvel in the drone industry, the Narwhal 2, which is a quadcopter. The drone has a lightweight carbon-fiber body that is fire/dust/water resistant which was heavily emphasized in the marketing of the drone. The drone weighs in at 6.6 kg while due to that low weight the drone's max payload suffers a max payload of only 1 kg. However, due to the high power density provided by the hydrogen fuel cell, the drone can fly up to 33,000 ft, which is the highest altitude allowed for drones to fly before they become a hazard to air traffic. In other words, the drone definitely has capabilities in the range department. In fact, the drone can fly up to 30 km away from the controller before the connection which is done through WIFI/4G/3G thus allowing the drone to really fly off the beaten path. With the connectivity capabilities paired with the complex environment autonomous flight algorithm, this drone can be easily utilized for many different purposes such as search and rescue, surveillance, etc. The reason this drone is a true marvel to the hydrogen-powered drone industry is because of its price. The listed price for this drone is 6,800 U.S. dollars. However, this is a huge improvement to what's already out on the market by cutting the price by over 50 percent in just a little over the 2-year time frame that hydrogen-powered

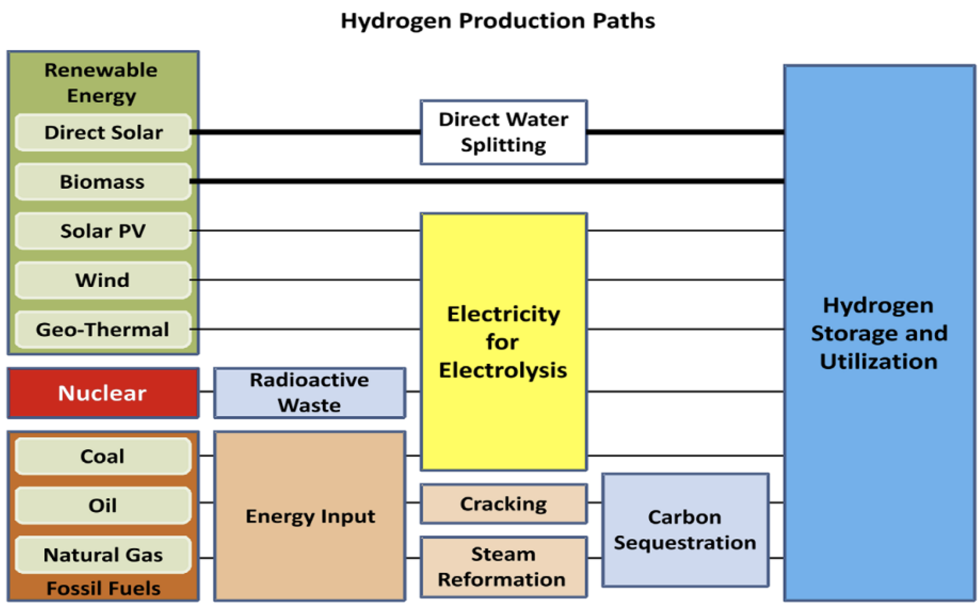

Fig. 6 Hydrogen Production Paths [6].

drones have been out on the market. The drone is very durable and easy to use for consumers, this added to the reasonable price point if one is on the market for specifically a hydrogen-powered drone. One disadvantage is the low payload capacity when compared to similar drones on the market, thus making this drone good for smaller payloads such as cameras [9, 25, 26].

B. DOOSAN DS30W

Doosan DS30W is the second generation of DS30 drones manufactured by the South Korean company, Doosan Mobility Innovation. Doosan recently won the 2020 CES Best Innovation award for their original Doosan DS30 drone, but have made modifications to the original design since then. The DS30W has eight motors and is measured at 1850 mm x 1850 mm x 815 mm. The DS30W can hold two different sizes of DP30M2S H2 fuel cells weighing either 6.9 kg or 12.7 kg with the addition of the fuel tank. In total, the drone weighs 21.9 kg (with a 10.8 L fuel cell) or 20.9 kg (with a 7 L fuel cell). The DS30W can carry a payload up to 3 kg (which is 2 kg less than the original DS30) and has a max takeoff weight of 24.9 kg. The fuel cell can produce 2.7 kW on a single charge, which allows the drone to travel for up to 2 hours and 80 km without a payload. The DS30W also has wind resistance of up to 12 m/s. Unfortunately, because this generation of drones is so new, there is not much information about the speeds that it can reach and the maximum altitude. No information on the cost of this drone is available without contacting the company directly [5, 27–29].

C. Carrier H6 Hydrone

The Carrier H6 Hydrone is a hydrogen-powered drone manufactured by Harris Ariel, an American Unmanned Ariel Vehicle Company. This drone is a hexacopter with a diagonal wheelbase of 1590 mm which is about 1.6 m across thus making it a sizeable drone. The drone itself without the fuel cell is 8.5 kg the fuel cell weighs 6 kg making the total drone weigh 14.5 kg. The max payload of this drone is good when compared to other drones with a payload of 5 kg. The drone has the longest flight time with no payload at just about 3 hours. As for the flight time while carrying the max payload the drone can only fly for an hour and 30 minutes. Figure 8 displays a graph comparing payload to flight time. The peak speed of the drone is 15 m/s. The carrier H6 has a maximum power capacity of 2.4 kw when paired with the 50 V output to fly for long distances. The Carrier H6 has an exceptional flight time with and without payload when compared to its counterparts. Along with that, the max payload is also very good. This drone can also be configured with scientific sensors, this allows the drone to be used on a more sophisticated level such as research. The drone can be configured with Lidar sensors in order to capture and analyze the motion of the drone. Furthermore, the drone has a built-in algorithm that accounts for flight in high wind speed environments [30, 31].

Drones	Max Payload	Cost	Self-weight	Flight Duration
BSHARK Narwhal 2	1 kg	$6,800 USD	6.6kg	120 minutes
DOOSAN DS30W	3 kg	N/A	12.7 kg	120 minutes
Carrier H6 Hydrone	5 kg	N/A	8.5 kg	180 minutes
Skylle 1550	10 kg	$10,000 USD	6.5 kg	80 minutes

Fig. 7 Comparison of the selected hydrogen-powered drones in terms of max payload, cost, self-weight, and flight duration.

D. Skylle 1550

The Micro MultiCopter company based in China has also put their Skylle 1550 drone on the market at §9999.99. This drone has six motors and comes in two different sizes, portable (700 mm x 700 mm x 300 mm) and standard (400 mm x 730 mm x 300 mm). The drone has a weight of 6.5 kg without batteries or payload but can carry a payload of 10 kg and a max takeoff weight of 21 kg. The Skylle 1550 does have one of the shortest flight times at 80 minutes without a payload. Although it can only fly for a short period of time, it can climb up to 5 km at a speed of 4 m/s and cruises at 15 m/s. The Skylle 1550 also has a control range of 10 km which allows it to be used for forest fire prevention as well as power line inspection [29].

E. Research on the build of hydrogen-powered drones

A research team out of the University of California Irvine is working on building their own hydrogen-powered drone [32]. The team has spent around $2600 dollars in their efforts in building a hexacopter, which is much less expensive than the off-the-shelf hydrogen-powered drone mentioned before. As the prices of hydrogen fuel cells go down gradually over time, the cost of constructing personal hydrogen-powered drones would go down.

VI. Impact of Hydrogen-Powered Drones on Advance Air Mobility

A. Advanced Ariel Mobility

Advanced Air Mobility (AAM) is NASA's vision for the safe development of aerial transportation using never before seen vertical takeoff and landing (VTOL) aerial vehicles [34]. This will consist of the transportation of cargo and people. AAM will cover travel across local, regional, intraregional, and urban areas. This will completely reshape the way we view transportation. Morgan Stanley estimates that AAM will be a 1.8 Trillion dollar industry within the next 30 years. AAM has three main pillars: the Automated Flight and Contingency Management (AFCM) subproject, the High-Density Vertiplex (HDV) subproject, and the National Campaign subproject. Fig. 9 outlines the plan for commercialization of AAM Outlined by Deloitte.

The AFCM subproject focuses on the research and development of collaborative and responsible automated piloting. The goal of AFCM is to achieve UAM maturity level 4, which implies that the VTOLs can safely transport through areas of medium traffic and complexity while using a collaborative and automated response. Thus the main goal of this subproject is to enable virtual piloting and some automated piloting which reduces the need for skilled pilots. This is beneficial considering the number of vehicles and will surely surmount the number of skilled pilots.

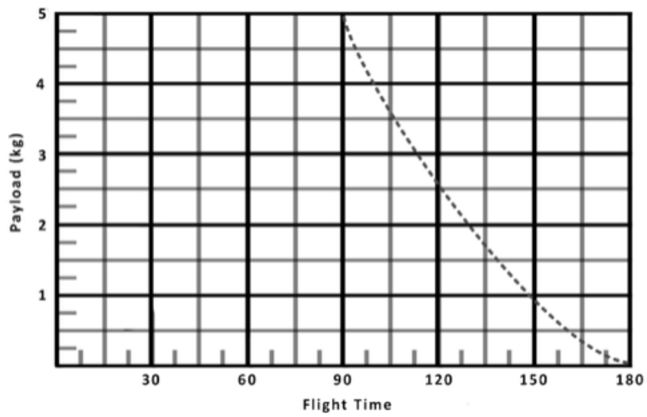

Fig. 8 Relation between the flight duration vs. the Payload for the H6 Hydrone. [30]

The HDV subproject is the research and development for the areas in and near vertiports. A vertiport is an airport specifically for VTOL vehicles. This is an important pillar because the air traffic near vertiports will be very dense, leading to many complications in the airspace around vertiports. Furthermore, research needs to be done to estimate the amount of electricity that needs to be produced to sustain the influx of electricity needed to power these new vehicles. This is a significant issue considering states that are waning off of fossil fuels are already struggling to keep up with the demand for electricity (e.g., California).

The National Campaign subproject is in place to spread the word about NASA's AAM project to convince the public that this technology is ready and safe to be deployed. This subproject will also spread the word about AAM, enticing people to use this new mode of transportation giving this project meaning.

While AAM seems like a great idea on the surface, there are certain limitations such as mentioned before, the need for more power. With the influx of electricity needed the electrical grid will have a hard time keeping up with demand. This is where hydrogen power can be of great benefit. Hydrogen delivers higher power density within the vehicle allowing for more flights between fill-ups and is another clean alternative to electricity only producing water as a byproduct.

B. Roadmap to Sustainable Hydrogen Aircraft for AAM

Air travel is known to be one of the safest methods of traveling thanks to how safe aircraft are. Aircraft are always being optimized to ensure nothing goes wrong with them. However, as technology continues to develop, aircraft are not just transporting people from one place to another, but it is being used for many different purposes, especially with drones which can be used for many different small tasks. The problem with all these aircraft we currently have is that it emits greenhouse gases. In 2019, all aviation accounted for about 2% of global emission [35]. Our goal by the year 2050 is to eliminate all greenhouse gas emissions. By doing this, we need to resort to other types of fuels to power all our forms of transportation, including aviation. This is where the image of hydrogen-powered aircraft comes in. Hydrogen-powered aircraft will not emit greenhouse gases, and we are working our way to meet the demands of lowering emissions and completely getting rid of them by 2050.

Hydrogen-powered aircraft are as safe as jet-fuel aircraft. They are essentially the same, but with hydrogen, you will not have any carbon emissions which is extremely good for the environment and to achieve the net zero emissions by 2050 we desire. As of right now, the cost of hydrogen is higher than other energy sources, which is a huge drawback in making it our primary source of fuel. Furthermore, there are several challenges in the clean production of hydrogen energy as it is still a relatively new form of energy. Liquid hydrogen has 2.8 times more energy than energy fuel per kilogram. Although this is the case, we still need a way for us to safely store hydrogen which has been a challenge, for both hydrogens in its gaseous and liquid form. When combining the weight of fuel and tank, jet fuel accounts for about 78 percent of its total weight, while hydrogen only accounts for about 18 percent of the total weight. If we manage to increase the percentage of hydrogen fuel, we will be one step closer to using it as our primary source of fuel for aviation thanks to its energy density. The potential of hydrogen fuel is high, and it will be extremely beneficial.

Hydrogen-powered drones have a lot of potential for use in AAM as they will ease the stress of the need for electricity

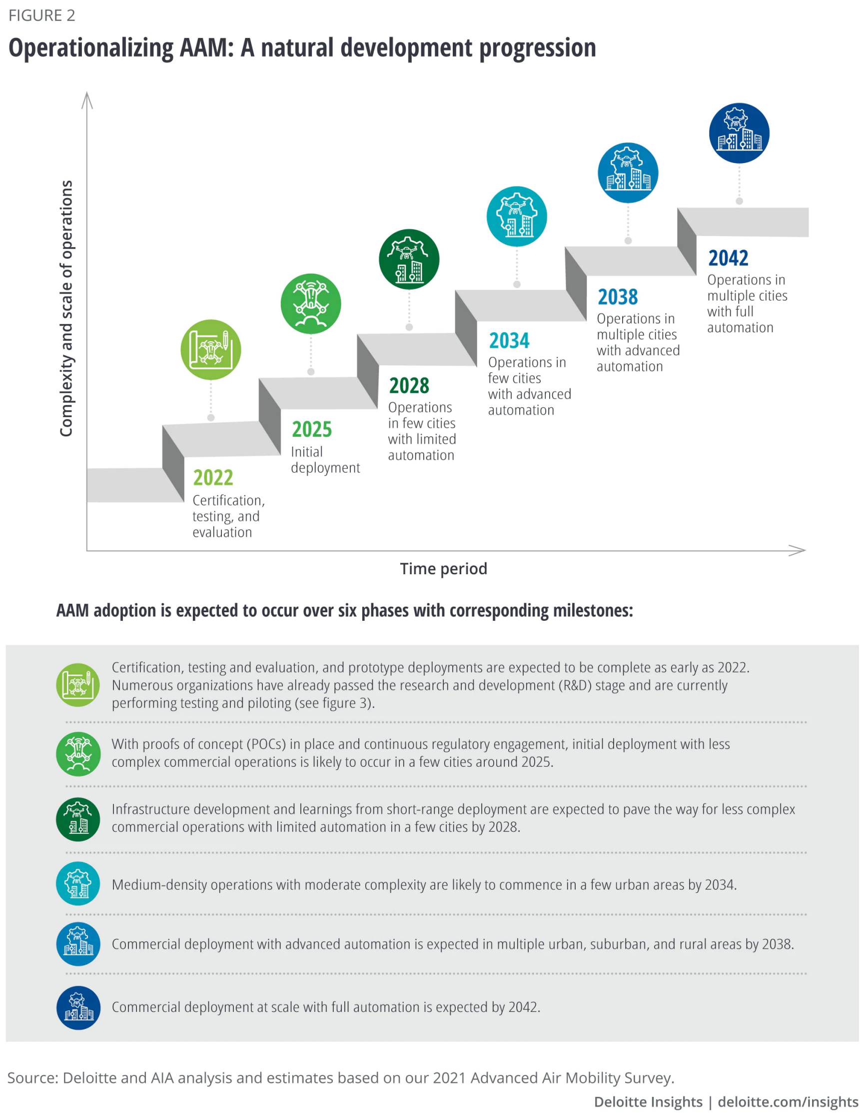

Fig. 9 Plan for Advanced Ariel Mobility's Commercialization. [33]

going to vertiports. This will expedite the process of AAM due to the fact that the aviation industry does not have to wait for the power grid to catch up to the imminent electricity demand increase. Another advantage to hydrogen-powered drones is the increase in energy density as stated before one fuel up for a hydrogen-powered drone will last on average 3 times longer than one charge of the electric drones. Yet another advantage of using hydrogen-powered drones is the short fill-up times as they don't need time to recharge. Hydrogen-powered drones fuel up similar to a car running on petroleum. While hydrogen-powered drones have a lot of upsides for AAM there are still drawbacks. One such drawback is the need for innovation in the industry, there is only a handful of hydrogen-powered drones on the market and they are small-scale and extremely expensive. Thus there needs to be more development in the hydrogen-powered drone industry before there can be widespread use in the aviation industry.

VII. Conclusion

Hydrogen-powered drones have proven to have great potential in future technology and further breaking boundaries in the aviation industry. The energy density of a hydrogen-powered drone highly exceeds that of a Lithium-ion battery drone. This in turn drastically increases the flight duration of a hydrogen-powered drone. Furthermore, hydrogen as a power source is still new, remaining a lot of places for research to make it a cheaper and more readily available power source. This is huge due to the fact that the United States has kept a net-zero coalition in the back of their minds. Currently, hydrogen-powered drones are very sparse and hard to come by making the technology expensive and hard to get information about. However, we have already seen dramatic price drops in hydrogen-powered drones further proving that the technology has immense room to grow for the future of energy, transportation, and aviation.

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