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Prospects and Challenges of Propulsion Technologies of Unmanned Aerial Vehicles: A Review

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Abstract

This review paper discussed the different types of propulsion technologies for unmanned aerial vehicles (UAVs). In it, several UAV propulsion systems were investigated, with particular emphasis on internal combustion engine (ICEs)-powered propulsion systems and electrically powered propulsion systems. The characteristics and working principles of these propulsion systems and challenges were discussed in this paper. Also, the methods in which future generations of UAVs can perform better have been discussed particularly with regards to endurance characteristics, power-to-weight ratios, and environmental wise. Similarly, the relevance of future UAV propulsion systems, which is a hybrid of the two major propulsion systems (ICEs and electric systems), giving a yield for high endurance, long-range, and durability, is discussed.

Keywords: P/W ratio, PV Cell, GTE, Hybrid Power Systems, Hydrogen Fuel Cell

1.0 INTRODUCTION

Unmanned Aerial Vehicles (UAVs) are aircraft that can be operated autonomously and remotely from the ground without an onboard pilot [1]–[3]. The idea to use a mechanism that can fly without a person on board has always been in the researchers' mind. Ever since the inception of UAV technology, it has been considerably advanced, and major developments in safety, and reliability have been achieved [4],[5]. UAVs are increasingly used today, both commercially and by the military. The latter usage includes security and surveillance, search and rescue missions, detection of floating mines and coastal defences, and detection of naval artillery. While the commercial use ranges from agriculture to remote sensing, wildlife, photogrammetry, and sales delivery among others [4], [6]. The most important benefits of UAVs over manned aircraft are, they are proven to be cheap, have less operational cost and lessen the danger of a pilot's life [7].

However, the increasing use of UAVs creates a necessity to resolve several problems which consist of both constructional and operational problems [8], [9]. The propulsion system of any aircraft in many regards determines its performance [10], [11]. Thus, to overcome operational and constructional challenges, a reliable and certifiable propulsion system that meets the requirements of the UAV mission profiles is required [14]–[16]. Moreover, the right choice of the light propulsion system and a power source that can endure long-range is inevitable today [15], [16]. This is to reduce the contribution of greenhouse gases by the propulsion systems using fossil fuels. This is one of the major tasks while designing any aircraft. So, in the design of UAV, it is pertinent to recognize the impact of the propulsion system operation on the environment. Depending on the tactical role, endurance, speed, range, payload, and size of a UAV are critical. Various types of propulsion systems are employed in UAVs; nonetheless, the piston and electric engines are the most widely used [13].

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The payload to some extent plays role in determining the propulsion system used on the UAV and hence affecting its overall operations. Again, the type of payload on the UAV and its performance requirement is driven by the operational needs of the UAV. UAVs payloads range from a simple subsystem comprising of an unstabilised video camera having a mass of 200 g to a payload with a mass of 272 kg [10], [17]. The later payload mass can be seen for instance in the MMIST CG-10 Snowgoose UAV. Therefore, this paper aims to review various types of propulsion systems employed on UAVs: internal combustion engine, hydrogen fuel-cell based hybrid, and solar power propulsion systems. The paper is organized as follows: Section 2 gives a general overview of the various types of propulsion systems for UAVs. Section 3 presents challenges and future trends in UAV propulsion systems while concluding remarks are presented in Section 4.

2.0 UAV PROPULSION SYSTEMS

2.1 Internal Combustion Engines (ICEs)

An ICE works by transforming heat energy into torque through explosions of air-fuel mixture inside a confined space known as a combustion chamber [18]. ICEs could be reciprocating, rotary, or gas turbine types as discussed in the proceeding subsections.

i. Reciprocating engines

Reciprocating engines are one of the propulsion systems used in powering most UAVs [1]. The power created by reciprocating engines arises due to an explosion that happens in the engine combustion chamber as a result of the combustion of the air-fuel mixture [19]. The reciprocating engines are mostly piston engines, and could either be two or four strokes working with either petrol, methanol, or diesel as fuel [1], [20]. The reciprocating engines rely on a repeating pattern of intake, compression, combustion, and exhaust to function known as the four-stroke cycle. The first step is the intake, in which air-fuel mixture is injected into the engine cylinder. Next is the compression of the air-fuel mixture by the piston to the top of the cylinder. This puts pressure on the mixture, and the spark plugs or enough hot air in the case of compression ignition engine ignites the mixture. This ignition expands the mixture of gases and pushes the piston down, creating energy. Waste is released in the last step – exhaust – and the cycle begins again. The torque produced by the engines is a result of the connection of the crankshaft to the piston [21].

a) Two-stroke engine

The two-stroke engine is a common power source for small and medium-sized UAVs, which has extensive applications in civil and military [1], [22]. In a two-stroke engine, the start of the intake and the compression strokes are developed to happen at the same time, and likewise the combustion and exhaust strokes [1], [15], [22]. This makes a two-stroke engine complete a power cycle after every revolution of the crankshaft, only in two piston strokes [1], [18], [19].

This large power boost gives the two-stroke reasonable benefits when compared to other engines. Since these engines are in general lightweight, they have a high power-to-weight ratio making them attractive for many uses including a propulsion system for UAVs weighting up to 50 kg [7]. Fig. 1 shows a two-stroke piston engine. It is worth mentioning that two-stroke engines are mostly air-cooled, and no lubrication is required since oil is mixed with the fuel.

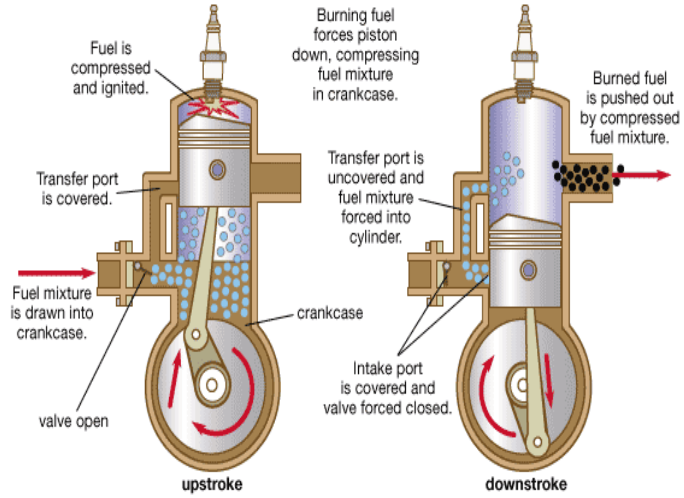

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Figure 1: The working principle of a 2-stroke engine [23]

One of their deficiencies is that most of these engines work at a very high temperature which reduces their durability because most of them are air cooled and the temperature of the burning air-fuel mixture goes as high as 3316^{o}C. Again, oil is burned during the engine's operation which is the reason why they exhaust more fumes than other ICEs [8].

Additionally, most two-stroke engines run on a carburetted system in which the amount of fuel released is reliant on the amount of air vacuumed into the cylinder. This is tricky for UAVs required to operate at lightweight high altitudes consisting of less oxygen per unit of air resulting in incomplete combustion and thus, lower fuel efficiency. This required the use of a fuel injection method that uses a sensor to measure the quantity of oxygen in the intake air and releases fuel accordingly to obtain complete combustion as opposed to the carburetted system [8], [15].

Today, several UAVs in action run on carburetted two-stroke engines such as the Marine Corps' Pioneer, the Navy's Neptune UAV, and the XPV-1-term used by the United States Special Operations Command (SOCOM) [7], [15].

b) Four-stroke engine

Propeller propulsion systems with two- and four-stroke piston engines are commonly used for the propulsion of UAVs [1], [15]. Four-stroke engines are described by greater efficiency and longevity due to an effective cooling system. The four strokes as mentioned refer to the intake, compression, combustion, and exhaust strokes that take place during two crankshaft rotations per working cycle of the spark and compression ignition engines respectively [1], [7], [15]. Figure 2 presents the four-stroke cycle of a four-stroke engine. Thus, a four-stroke engine fires once every two revolutions.

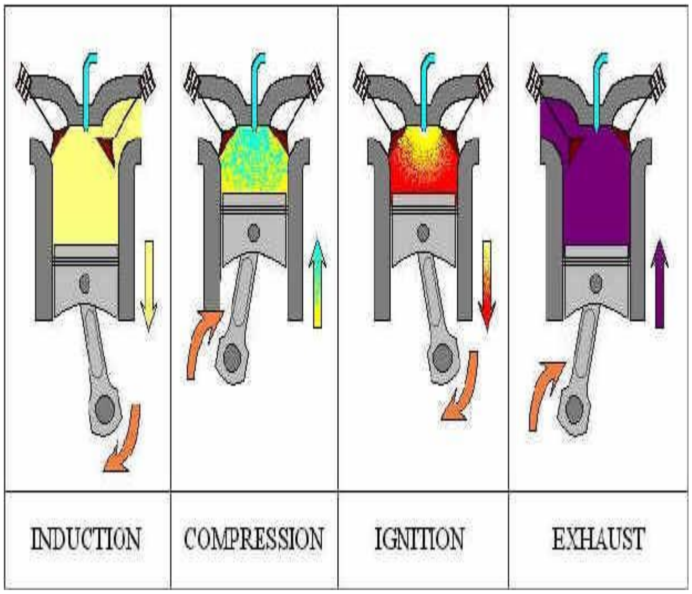

Figure 2: Cycle of a 4-stroke engine [24]

The four-stroke engine has a separate lubrication system; thus, it is likely to abate a fuel-oil mixture, which leads to lessening the production of exhaust emissions [19]. However, these engines have more weight because of added moving components. Furthermore, the four-stroke engines are louder and less powerful [7], [15].

Generally, reciprocating engines have issues linked to weakness of crankshaft, the vibration of systems because of the engine, failure of seals that results in power losses, and reduced reliability. Such technical concerns are linked to operating temperature and airborne communication barriers through the noise created by the engine. Also, the most important concerns existing for smaller UAVs are their greater emissions of carbon dioxide and a low fuel economy [4]. In instances where electronic fuel injectors (EFIs) are used, there is an improved fuel efficiency.

ii. Wankel engine

The Wankel engine is a different type of ICE that uses a rotary movement instead of reciprocation to produce work [7], [15], [18]. It has four strokes that take place inside the oval-shaped casing [18], as shown in Fig. 3. The Wankel engine uses a rotor as a substitute for a piston to complete the four cycles. With its three peaks in contact with the housing always, the rotor creates three separate air pockets that go through intake, compression, combustion, exhaust stages in that same chamber as the rotor rotates. The lubrication is similar to that of a two-stroke engine [7], [13]. A great benefit of using Wankel engines in aviation is their small size, simpler, lighter, and have fewer number of moving parts in contrast with piston engines with equivalent power output [19]. Also, their fast response to throttle movement offers greater reliability and a smooth flow of power. Their application in the UAV shows an increase in development; the US Army uses the Wankel engine in Shadow 200 [7].

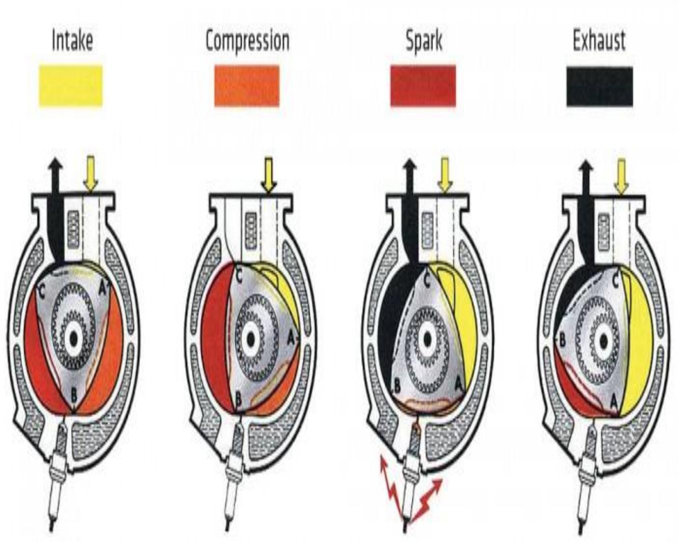

Figure 3: Wankel engine [25]

The foremost gain of using this engine is that it has a lesser frontal area compared to a piston engine of equivalent power, therefore, making the design of the nose easy [7], [13], [15]. However, it is very challenging to produce it to meet the global emission standards. Also, its cost of manufacturing is high since the number of engines produced is less than equivalent to the piston engines. Additionally, they typically have less fuel economy compared with piston engines as the thermodynamic efficiency of the engine is reduced by the long combustion-chamber shape and low compression ratio

[7].Table 1 compares some of the characteristics of two-stroke, four-stroke, and rotary engines

Table 1: Comparison between two- and four-stroke reciprocating engines

	Particular	Four-stroke engine	Two-stroke engine
1.	No of power stroke	One stroke for every 1 revolution of crankshaft	One stroke for every 2 revolutions of crankshaft
2.	Power for the same cylinder volume	Large (about 1.5 times of 4 stroke)	Small
3.	Construction & cost	Simple, cheap	Complicated, expensive
4.	Fuel consumption	High (about 15% more)	Little
5.	Removal of exhaust gases	Difficult	Easy
6.	Durability	Poor	Good
7.	Stability of operation	Low	High
8.	Changeability of rpm	Low (with small flywheel)	High (with large flywheel)
9.	Lubrication	Using fuel, mixed with lubricating oil	Equipped with an independent lubricating oil circuit
10.	Oil consumption	Little	Much
11.	Self-weight and size	Suction & exhaust is noisy but other working is noiseless	Suction & exhaust is noiseless but other working is noisy
12.	Self-weight and size	Light & small	Heavy & large

iii. Gas turbine engine (GTE)

From the viewpoint of propulsion type, piston engines have steadily given way to GTE in the aviation industry ever since the end of World War II. A GTE is an ICE working in a highly dynamic manner, putting in work to process air-fuel mixture in a manner that produces a high-velocity thrust as the output [13]. The engine is divided into two units; the front unit having the intake and compressor whereas the second unit has the combustion chamber and the turbine. The hot gases from the combustion chamber propel the turbine, which is joined with the compressor by a shaft and thus, the turbine propels the compressor for another cycle, in addition to thrust produced [1], [7], [15], [26]. The produced thrust is the momentum change of inlet and outlet gases. A GTE is widely applied in various aircraft types because of its actual benefits in the thrust-weight ratio [8], [9]. However, it is a relatively complex structure which makes it more challenging for the realization of lightweight design [9]. Small GTEs suffer from the lack of ability to loiter at low enough speed without using a rotary-wing UAV, but even then the high specific fuel consumption, mostly for small GTEs, is generally unreasonable [9]. The GTE is classified as turbofan, turbojet, turboshaft, and turboprop [13], as shown in Fig. 4. The turbofan and turbojet engines are generally denoted as jet engines [1]. These propulsion systems possess upthrust at high speeds and high altitudes, better than propeller-driven options. This makes them fit for UAVs flying at equivalent airspeeds greater than 200 kt and at Mach>0.6. For the propulsion of small UAVs, jet engines generating a thrust of 15–30 N and weighing about 2 kg are used [9], [15]. Two distinguished UAVs that employ turboprop engines are the General Atomics MQ-9 Predator B and the IAI Heron TP. Northrop Grumman X-47A and B, Boeing X-45C and Phantom Ray, General Atomics Avenger, BAE Taranis, Dassault Filur, and Saab Sharc, among others, use jet propulsion [1].

It is noteworthy that extensive discussion on the different classifications of these GTEs is beyond the scope of this paper. However, it is worth mentioning that expensiveness, difficult systems, high-speed rotation, and working at high temperatures are some drawbacks of GTEs [13].

2.2 Hydrogen Fuel-Cell Based Hybrid Power Systems

The depletion of fossil fuels, the effect of global warming, and the need to reduce greenhouse emissions/pollutants from aircraft have led to research in unconventional propulsion systems like hybrid electric systems and solar power [5], [27], [28]. The latter will be discussed in the proceeding section. Today’s hydrogen fuel-cell-based hybrid power systems are considered a technology to advance the range and endurance of electrically-powered UAVs [1], [29]. Fuel cells are electrochemical devices that constantly generate electrical energy and remain functional if fuel and oxidizers are delivered. It functions by converting chemical energy stored in hydrogen to electrical energy utilizing oxidants [1], [7], [15]. Hydrogen fuel-cells have a considerably better specific energy than competing electric propulsion power sources, zero CO_2 emissions, reduced noise, less vibration, and low thermal signatures [12], [29]. In addition, in systems driven by reciprocating and jet engines, fuel only adds about 18-25% of energy to propulsion, whereas in fuel cell-powered propulsion, this effectiveness is in the region of 44%. Though not in regular operation, fuel cells can offer 3 times more endurance than battery-equipped UAVs [12].

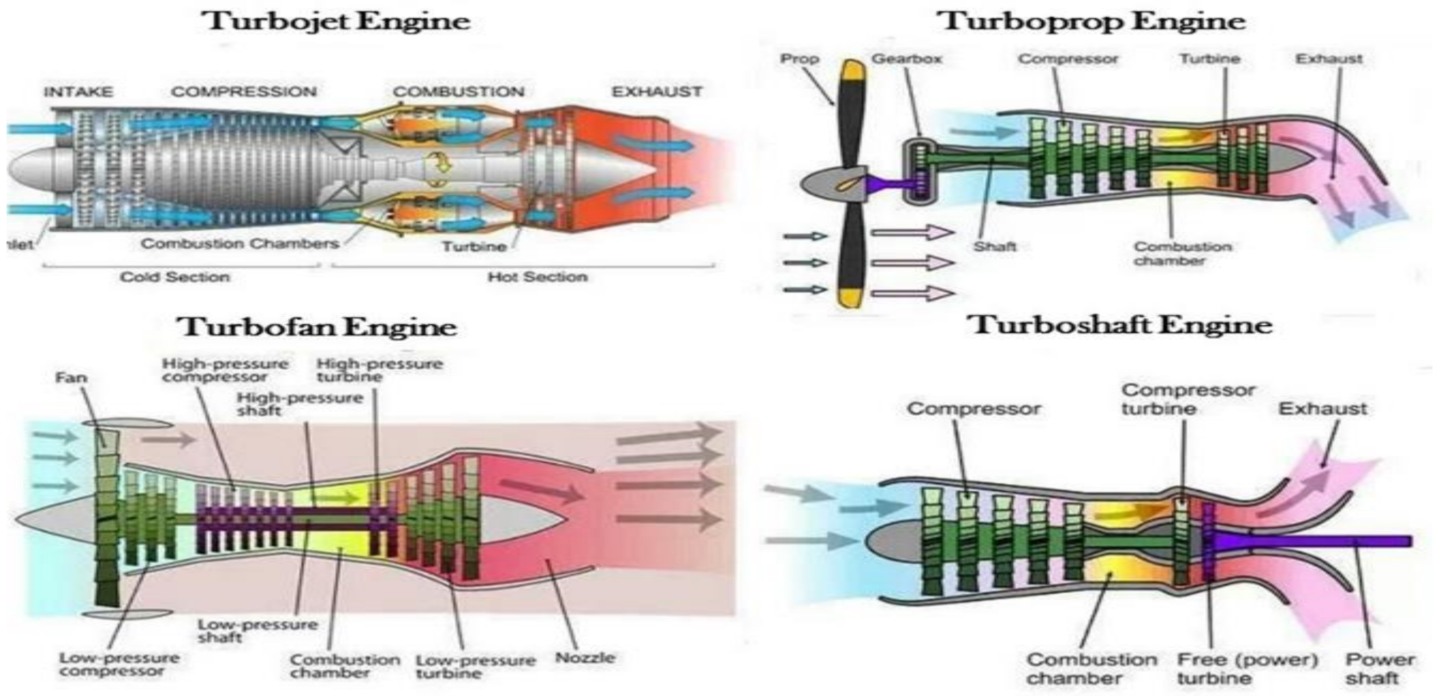

Figure 4: The four different types of GTEs [13]

The shortcomings of hydrogen fuel-cell-based hybrid power systems include cost, the sensitivity of the electrode catalyst to poisoning, and the safety concerns on storage of hydrogen among others [4], [7], [15], [29]. The most common type of fuel cell designed to power UAVs is the proton exchange membrane fuel cell (PEM) [1]. This type of fuel cell was used in Oklahoma State's Pterosaur aircraft to power an unmanned aircraft distance world record with an efficiency of 41%, joint with hydrogen to offer an energy density of 7402 WH/lb. If it were not for the overly heavy storage of hydrogen gas, pressurizing hydrogen lessens the energy density to 395 WH/lb, which is still remarkable [9].

As a means to improve UAVs propulsions system, a hybrid system of ultracapacitor, battery, and hydrogen fuel cell was proposed and implemented using a test flight by Gong & Verstraete, 2018 [29]. They showed how supercapacitors can provide a load smoothing effect for the UAV on fuel cells when the flight is in a dynamic condition. This shows that as we go into the near future where high endurance UAVs are required, hybrid systems of distributed power will be the best choice because of the ability to transit between two or more integrated power systems. In comparison to the electric power generation system and the conventional gasoline, the hybrid power systems have a low environmental impact, minimum fuel consumption, increased distributive power, and high redundancy [30]. In the hybrid system for energy storage, which comprises batteries and supercapacitors, they both complement power generation [23] making the hybrid system the best in consideration for high endurance UAVs as shown in Fig. 5.

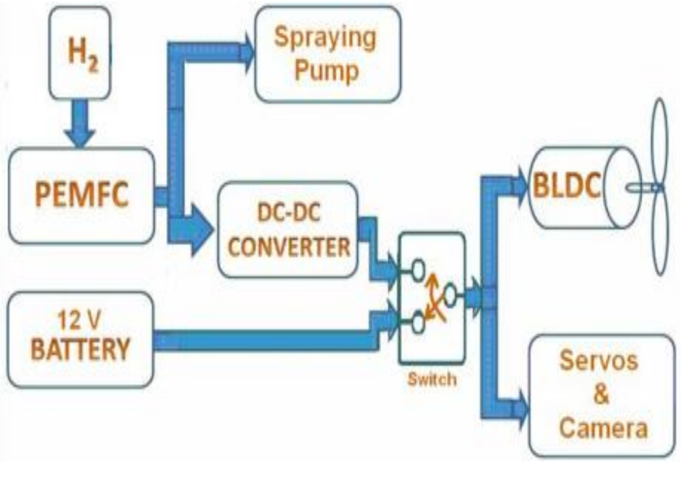

Figure 5: Hybrid fuel-cell battery hybrid power system [31]

2.3 Solar Powered Propulsion System

In line with the global trend on green energy, electric-powered hybrid reconnaissance vehicles have already been commercialized, and even electric-powered aircraft are under development [5]. Solar UAVs have the benefits of being environmentally friendly, with great flight altitude, resilient stability, wide coverage area, and exceptional load capacity [23]. The solar-powered aircraft power system portion comprises photovoltaic (PV) cells, rechargeable batteries, and a maximum power point tracker (MMPT). Photovoltaic cells are categorized based on materials for solar cell processing and are grouped as follows: crystalline silicon, thin-film, organic/polymer, hybrid photovoltaic cell, and a dye-sensitized photovoltaic cell. Even though solar-powered UAV has lots of benefits, it correspondingly faces pronounced worries in design, particularly in the two aspects which include the intensity of force and deformation on wing root. The extreme force on the wing root will cause the failure of the wing root beam material, while excessive deformation of the wing will ruin the aerodynamic performance of the wing and damage the battery, which will have an impact on the endurance of the aircraft [23]. And so, in the design of a solar UAV, given its operational desires, the overall weight, flight speed, lift-drag ratio of the UAV can be determined first, and then a load of storage battery and the solar cell can be calculated [23]. In Figure 6, the photovoltaic (PV) cells used, possessing 30% to 40% energy conversion efficiency which is considerably high for the proper functioning of a propulsion system for a solar powered UAV. It is combined with the Artificial Neural Network – a smart algorithm used as the MPPT. This algorithm gives a fast response and has a high partial shading efficiency. Connected to the MPPT is the rechargeable Li-Air battery having the ability for long endurance flights [32], [33].

The most critical aspect to remember in rechargeable batteries is the energy capacity. In terms of battery technology, Li-air batteries can provide energy to a variety of applications, most notably solar-powered aircraft, and electric vehicles, owing to their high theoretical energy densities, which average 11680 Wh/kg (Watt-hour per kilogram) when compared to current batteries. This is shown in Figure 7 with the energy properties of different battery types indicating the effectiveness the combination of PV cells, MPPT and Li-Air will give in the nearest future. With advancements in technology, an effective powered system for solar-powered aircraft applications has been proposed. Today, solar-powered aircraft (UAVs) have the capability of continuous flight, high altitude, and long endurance, enabling them to be used in intelligence, surveillance, and reconnaissance (ISR) and relay communication, hazard warning, rescue and evaluation, agricultural surveillance, and other applications.

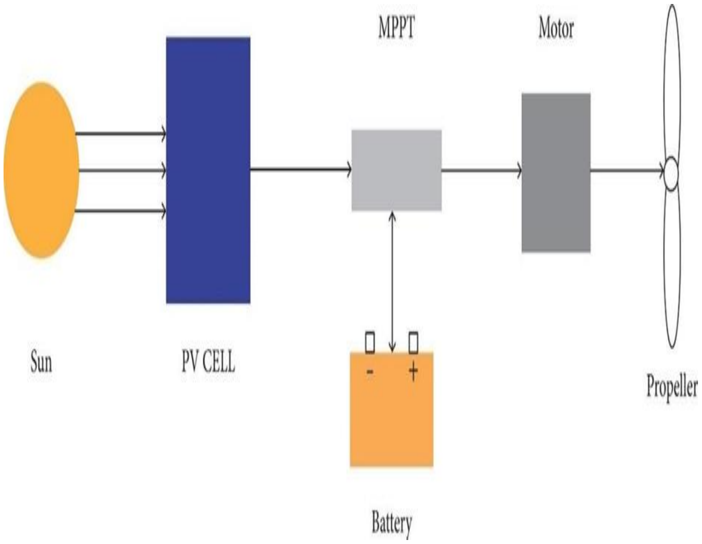

Figure 6: MPPT controller in a solar-powered aircraft application [32]

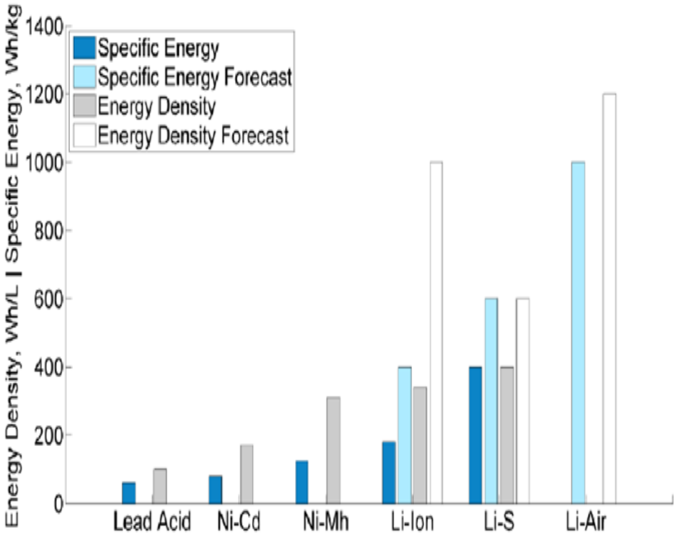

Figure 7: Energy properties of different battery types [18]

Solar aircraft will soon be able to take advantage of emerging technology. The performance of thin-film solar cells has improved dramatically as technology has progressed. Multi-junction solar cells have high-efficiency levels, ranging from 40% to 50%. Quantum dots are another type of solar cell that increases the bandgap value to absorb a large amount of light from the solar spectrum and generate sufficient charges from a single photon [32]. All of this increases the solar cell's effectiveness. Table 2 illustrates how different PV cells and batteries are used in solar-powered aircraft and how they are mounted while

Table 3 compared various propulsion systems employed on UAVs.

Table 2: Application and installation of different PV cells and batteries on solar-powered aircraft [32]

Name	Year	Photovoltaic			Battery	
		PV Cell	Efficiency (%)	Power (W)	Battery	Specific energy (Wh/Kg)
Sunrise I	1974	Monocrystalline	11	400	Li-ion polymer	145
Sunrise II	1975	Monocrystalline	16.1	600	Li-ion polymer	145
Gossamer Penguin	1983	Monocrystalline	13.2	660	Nickel Cd	50
Solar Challenger	1981	Monocrystalline	13	250	Nickel Cd	50
Sky Sailor	2004	Monocrystalline	18	84	Li-ion polymer	172.8
So-Long	2005	Monocrystalline	18	220	Li-ion	220
Solar Impulse I	2009	Monocrystalline	18	240	Li-ion polymer	240
Zephyr 7	2010	Amorphous Silicon	19		Lithium sulphur	400-600
Solar Impulse II	2014/2016	Monocrystalline	18	260	Li-ion	260

Table 3: Comparison of propulsion systems

System Classification	System	Operations		Design	Weight	Pollution	
		Fuel Efficiency	Durability			Noise	Environmental
Conventional Propulsion System	2-Stroke reciprocating engines	Low	Low	Simple	Light	High	High
	4-Stroke reciprocating engines	High	High	Complex	Heavy	Low	Low
	Wankel engine	Low	Very High	Very Simple	Light	High	High
	Gas Turbine Engine (GTE)	Average	Very High	Complex	Heavy	High	High
Unconventional Propulsion system	Hydrogen Fuel-Cell Based Hybrid Power Systems (Electric Propulsion)	Average	Medium	Complex	Average	Low	None
	Solar Powered	Nil	High	Simple	Heavy	None	None

3.0 CHALLENGES AND FUTURE TRENDS

A two-stroke reciprocating piston engine has both higher propulsive efficiency and fuel-saving in low and medium flight speed conditions compared to a GTE. Thus, making it a superior choice for small and medium-sized UAVs [9]. Four-stroke engines have superior efficiency equated to others but are affected by the power-to-weight (P/W) ratio, which is a major deciding factor in selecting a propulsion system for UAVs. Though the two engines serve current UAV operations, a small number of areas could use some advancement. Since stealth is a critical requisite for UAVs, lessening engine noise is necessary. Similarly, increasing the engine's fuel economy is important, since the fuel weight is the main part of the total aircraft mass [7], [15]. The stringent global demand for cleaner energy as a result of the fall in fuel prices, global warming, and the need to reduce pollutants/emissions from aircraft have resulted in research on unconventional propulsion systems like hybrid electric systems and solar-powered systems. Hybrid engines provide the best from both worlds (gasoline and electric) as they offer superior efficiency, better power, and fuel economy. However, the major drawback of hybrid engines is the increase in weight due to the need to carry batteries as well as fuel [7]. Also, the complex systems of the solar-powered aircraft demand effective energy management throughout flight making the cost of operations relatively high when compared to the IC engines [33], [34]. Looking into the future, ICE will continue to be a major source of a propulsion system for most vehicles, as shown in Figure 8.

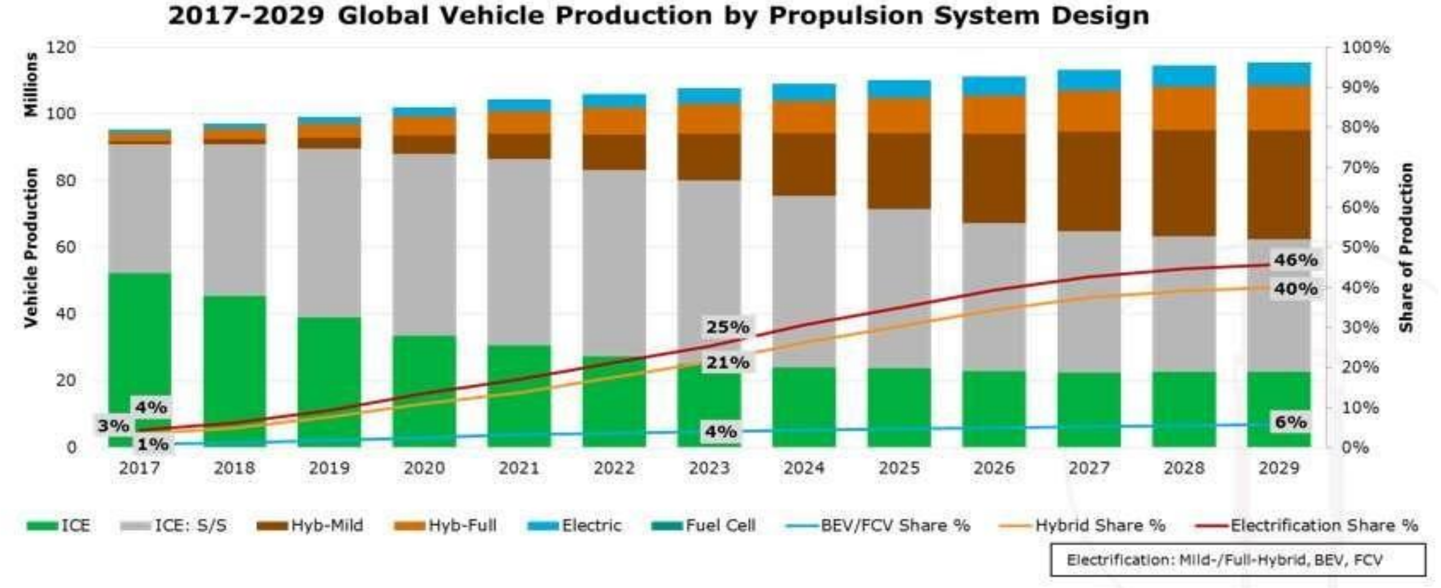

Figure 8: Projected global vehicle production by propulsion system design [35]

4.0 CONCLUSION

The study of UAV's propulsion technology is discussed in this paper with a focus on the prospects and challenges of different UAV propulsion technologies. In this study, the propulsion system is grouped into Conventional and Unconventional propulsion systems where the engines are used in the first and the second is a hybrid system with potentials of future combinations. Through the study, the discovery of the efficiency and relevance of the conventional systems together with the potentials of the unconventional as a combination with the former makes the prospects of long-range and endurance of the UAVs feasible.

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