

Review

# Hybrid Propulsion Systems for Remotely Piloted Aircraft Systems

Mithun Abdul Sathar Eqbal, Nuwantha Fernando , Matthew Marino and Graham Wild \* 

School of Engineering, RMIT University, Melbourne, VIC 3000, Australia;

mithun.abdul.sathar.eqbal@student.rmit.edu.au (M.A.S.E.); nuwantha.fernando@rmit.edu.au (N.F.);

matthew.marino@rmit.edu.au (M.M.)

\* Correspondence: graham.wild@rmit.edu.au; Tel.: +61-3-9925-8051

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**Abstract:** The development of more efficient propulsion systems for aerospace vehicles is essential to achieve key objectives. These objectives are to increase efficiency while reducing the amount of carbon-based emissions. Hybrid electric propulsion (HEP) is an ideal means to maintain the energy density of hydrocarbon-based fuels and utilize energy-efficient electric machines. A system that integrates different propulsion systems into a single system, with one being electric, is termed an HEP system. HEP systems have been studied previously and introduced into Land, Water, and Aerial Vehicles. This work presents research into the use of HEP systems in Remotely Piloted Aircraft Systems (RPAS). The systems discussed in this paper are Internal Combustion Engine (ICE)–Electric Hybrid systems, ICE–Photovoltaic (PV) Hybrid systems, and Fuel–Cell Hybrid systems. The improved performance characteristics in terms of fuel consumption and endurance are discussed.

**Keywords:** remotely piloted aircraft systems; unmanned aerial systems; hybrid electric propulsion; internal combustion engine; photovoltaic cell; fuel cell; electric motor

## 1. Introduction

One of the ultimate goals present in the aviation industry is to operate perfectly “sustainable” aircraft to facilitate operations while reducing reliance and cost on fossil fuels. The concept of sustainability is two-fold and comprises economic sustainability and environmental sustainability. To this end, the airliner of the future is likely to be an all-electric aircraft which has the capability to be autonomously operated. These two facets (all electric and autonomous) remove two of the most significant costs in the aviation industry, fuel and flight crew [1]. This then goes towards achieving the goal of economic sustainability. Furthermore, by eliminating the need for fuel, the environmental impact from the aviation industry is also significantly reduced as the majority of emissions from aviation come directly from burning fuel. There needs to be incremental change in the evolution of aircraft in the aviation industry to develop and promote the benefits of aviation sustainability. The lack of current development is driven by (1) the industry’s conservative approach utilizing proven safe and reliable systems, and (2) minimal profit margins in the industry appear to some extent to limit required investment into revolutionary technologies. Evolutionary steps towards all electric aircraft have provided incremental means to develop a stream of alternative propulsion technologies. This is clearly seen in the automotive industry. Hybridization of automobiles has made way for technology development and acceptance of hybrid vehicles. One may expect that hybrid-propulsion systems for aerospace application will develop in the same manner and become an essential entity in the aviation industry.

The advent of the unmanned aviation industry has inadvertently helped the evolution of manned aviation by providing small scale but practical test beds for the iteration of aerospace technologies.

The associated cost of the design and development life cycle means that unmanned aircraft can readily make use of novel and innovative technologies. The rate of development and application into unmanned systems results in more innovation at shorter time scales. This of course further drives and grows the unmanned aviation sector. The rapid growth of unmanned aviation is essential to support the growth and expansion of the larger-scale commercial market. Currently, the market value of the unmanned aircraft market (in 2016) is estimated at \$8.5 billion with projections of exponential growth (at 7.6% per annum) to \$12 billion by 2021 [2]. While unmanned aircraft in the past have commonly been associated with negative press with various news outlets reporting on predator drones launching hellfire missiles [3], it is becoming increasingly common to think of the almost ubiquitous quadrotor aircraft and their many developing applications. These applications include mail, package, and pizza delivery [3], as well as the ever-expanding photography and videography sectors. There are also applications that require unmanned aircraft to achieve long endurance times and thus are specialty products that require specific expertise to operate legally [4]. Another identified growth sector is mining and agricultural survey applications. These two industries can involve the monitoring of exceptionally large areas, and hence any aircraft utilized needs to be capable of flying for many hours. When factoring in payload requirements (sensors for the surveying), the current energy density of batteries means electric multi-rotor aircraft have limited usefulness in these long-endurance missions. The increase in range and endurance could lie in the hybridization of the electric and internal combustion (IC) engine system to provide means to progress the technology and introduce it to the larger aviation industry.

The aim of this work is to review the general propulsion methods available to unmanned or remotely piloted aircraft systems (RPAS) and to present the current efforts into increasing the endurance of electric aircraft with the use of hybrid configurations. The hybrid configurations investigated and discussed in this work include the internal combustion engine (ICE) and conventional electric hybrid, the ICE and photovoltaic (PV) hybrid, and the fuel-cell hybrid. To support and understand of each of these, the constituent propulsion systems are also described. The objective of this work is to present the associated improvements in performance characteristics in terms of fuel consumption and endurance of hybrid RPAS.

## 2. The Existing Propulsion Systems

### 2.1. Battery Powered

Electric propulsion is a popular system for small and micro RPAS [5,6]. Electric propulsion is known to have a favorable electrical and mechanical efficiency while being reliable due to the simple mechanics and reduced moving parts compared to IC engines [7–10]. These systems are further divided into active and passive systems, which depend on the type of bus connection between the electric machine and the battery [9]. This is very similar to all other kinds of electric vehicles and has the following components [5].

- propeller,
- electric motor,
- energy source,
- optional gear box,
- electric power converter,
- plugs,
- connectors, and
- optional cooling system.

However, in an all-electric vehicle, the propulsion systems account for as much as 60% of vehicle density [11], with the battery pack contributing the most [12]. This is primarily due to low energy densities of the batteries, and is the limiting factor in vehicle endurance. Research in battery technology

has been essential in improving battery energy density for various applications [13–15]. It has been reported that the calculated overall efficiency of a full battery-powered aircraft can be 73% when considering the individual efficiencies of each component (battery (100%), controller (98%), electric motor (95%), gear box (98%), and propeller (80%)) [12]. There are multiple research efforts promising better battery technologies, including: Lithium-Air (Li-O<sub>2</sub>), Lithium-Sulphate (Li-S), Zinc-Air (Zn-O), Aluminium-Air (Al-Air), Magnesium Ions, and Graphene [16]. Although the improvement of the efficiency of system components results in a more efficient propulsion design, energy density and battery technology remains the crucial element in the success of electric aircraft. These battery technologies will be used in the first instance on unmanned aircraft before any certification onto manned aircraft.

Table 1 shows the current battery specific energy density, as well as the predicted increases for the future, and the theoretical maximum achievable. Also, since the specific energy is the energy per kilogram, Table 1 is indicative of the potential to reduce the overall weight and improve the performance of the RPAS. At present, most RPAS use Li-Ion batteries because they are a proven, reliable, and available battery technology [17,18].

**Table 1.** Specific energy of current and future chemical battery systems.

System	Specific Energy (Wh/kg)		
	Theoretical <sup>1</sup>	Current	Expected in 2025 <sup>1</sup>
Li-Ion	390	240 <sup>2</sup>	250
Zn-air	1090	442 <sup>3</sup>	500
Li-S	2570	375 <sup>4</sup>	1250
Li-O <sub>2</sub>	3500	362 <sup>5</sup>	1750

<sup>1</sup> Source: [12]. <sup>2</sup> Source: [19]. <sup>3</sup> Source: [20]. <sup>4</sup> Source: [21]. <sup>5</sup> Source: [22].

## 2.2. Fuel-Cell Powered

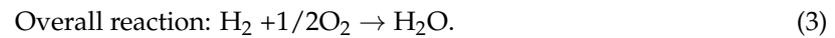
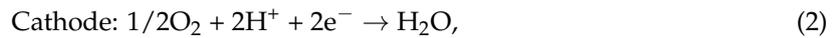
A fuel cell is an electrochemical cell that converts chemical energy into electrical energy through an electrochemical reaction and is classified according to the kind of electrolyte it utilizes. These include [23]:

- Polymer Electrolyte Membrane fuel cell or Proton Exchange Fuel cell (PEM),
- Direct Methanol Fuel Cells (DMFC),
- Alkaline fuel cells,
- Phosphoric acid fuel cells,
- Molten Carbonate fuel cells, and
- Solid Oxide Fuel Cell (SOFC).

The main competitors for fuel cells utilized within the aviation industry are PEM, SOFC, and DMFC.

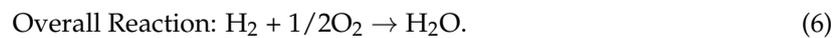
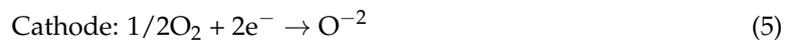
### 2.2.1. Proton Exchange Fuel Cell

Proton exchange fuel-cells are the most commonly used fuel cell for aerial systems [24]. They directly produce direct current (DC) electric current, operate at low temperatures, and water is the only emission (when utilizing hydrogen) [25,26]. These fuel-cells are light-weight, have comparatively higher energy density than SOFC and DMFC, and they can respond to high load changes; as such, these fuel-cells make the most favorite choice for RPASs [23,24]. However, there is still a drawback with the PEM fuel-cell when exposed to fast load changes, which reduces the life span of the already expensive fuel-cell membrane [27]. The efficiency of a typical PEM ranges between 40 and 60% [23,28,29], and the power output ranges between 100 watts and several kilowatts. The overall chemical reaction of the PEM is given as:



### 2.2.2. Solid Oxide Fuel Cell

The SOFC is also referred to as a high-temperature fuel cell, since it operates between temperatures ranging from 600 to 1000 degrees Celsius [23]. This allows for potential for use in cogeneration or combined cycle applications where heat exchange is used to further improve efficiency [30]. This high temperature tends to give the flexibility of using a much denser propane fuel and gives advantage over the fuel storage space when compared to the PEM, where the less-dense hydrogen needs a heavier storage area [24]. This is a significant advantage in aircraft and aviation in general where weight is a critical factor. The efficiency of SOFCs ranges between 25 and 50% [23]. The overall chemical reaction of the SOFC is given as:



CO and hydrocarbons, such as CH<sub>4</sub>, can also be used as fuels in an SOFC. At the high temperatures within the cell, this gives:



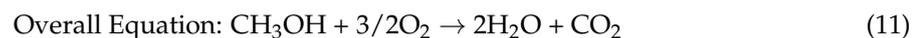
or in the case of natural gas:



The reduction reaction occurs at the cathode (air electrode) at 1000 degrees Celsius, while fuel oxidation occurs at the anode. The anode should be porous to conduct fuel and transport the products of fuel oxidation away from the electrolyte and fuel-electrode interfaces [23,28]. The SOFC is the second most commonly utilized fuel cell behind the PEM in aerospace applications.

### 2.2.3. Direct Methanol Fuel Cell

The DMFC is similar to the PEM, operates at low temperature between 20 and 90 degrees Celsius, and uses methanol as a fuel. This fuel cell has less power density than the SOFC and PEM; however, the advantage of the system is the use of a denser methanol fuel that is liquid in contrast to the gas state of the hydrogen and propane, which require bulkier gas storage systems [24]. In general, liquid fuel systems are simpler to use in aerospace vehicles as storage conforms to the aircraft structure and is not geometry-dependent. The overall chemical reaction of the DMFC is given as:

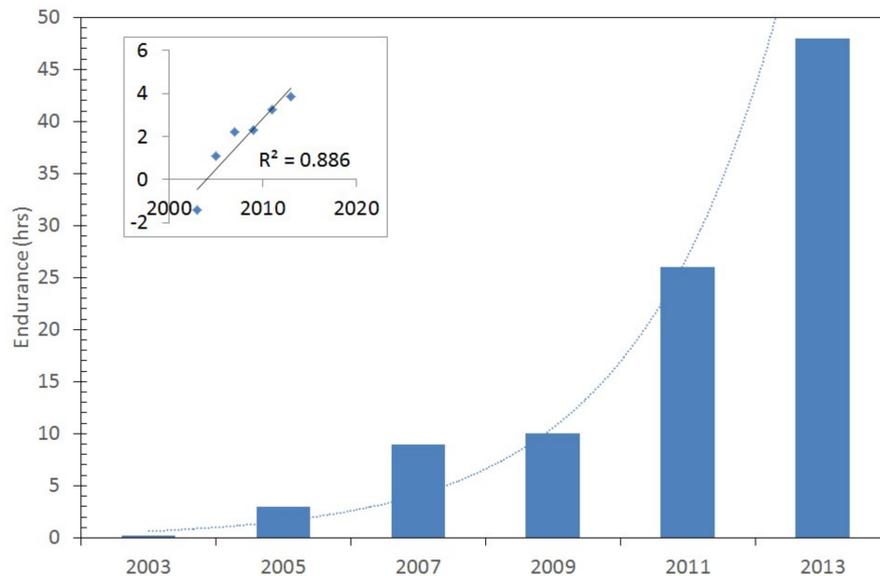


The major disadvantage of the DMFC systems is that the efficiency is 20–30% [23]. Also, as indicated in Equation (9), CO<sub>2</sub> is also produced as an emission byproduct.

### 2.2.4. Fuel-Cell Powered RPAS and Endurance

Figure 1 shows the increase in RPAS fuel-cell “efficiency” relative to endurance for a 10-year period between 2003 and 2013. The first fuel-cell powered Unmanned Aerial System UAS was flown in 2003. Over the decade, advances of various technologies have increased the overall endurance from the 15 min (2003) to 48 h [24]. This represents a significant increase in the endurance capability of RPAS

systems. A mission endurance of 48 h is sufficient for most RPAS applications, excluding those that require persistent on loitering mission scenarios. All of the given RPAS use PEM fuel-cell technology, where the highest endurance RPAS use a fuel cell with liquid hydrogen as fuel [31].



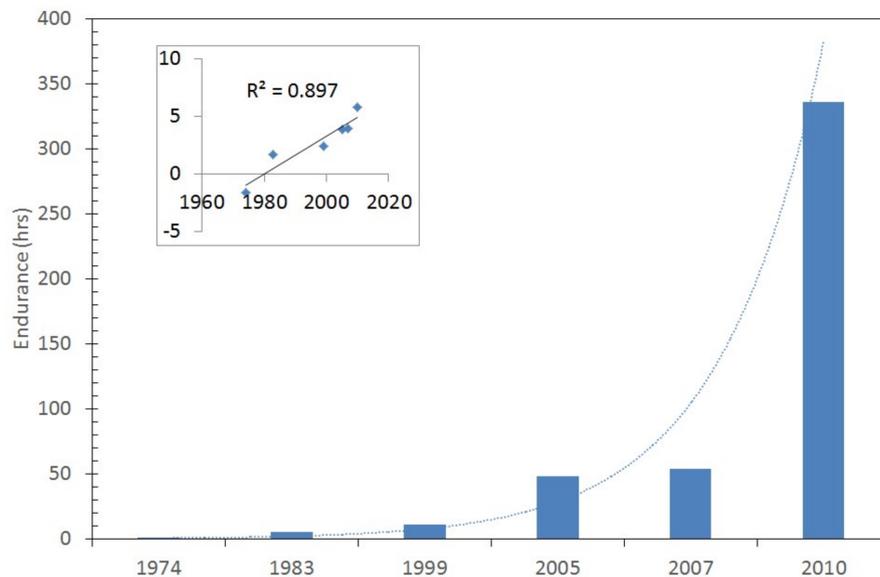
**Figure 1.** Endurance of various fuel-cell powered aerial vehicles as developed over time. The overlaid exponential trend is statically significant at the 99.7% confidence level and is given in the inset.

### 2.3. Photovoltaic-Powered

Some long-endurance aircraft utilize photovoltaic cells which convert solar energy into electrical energy. The cells are made into solar panels and can be integrated into the wings of an aircraft. A solar cell system usually comprises a form of energy storage, such as batteries, to supply extra energy to the propulsion system or to store excess harvested energy away until it is operationally needed. Solar panels use a photovoltaic process to convert radiative solar energy to electrical energy through Photovoltaic Cells (PVs) [32,33]. These PV and battery systems are well-suited for High Altitude Long Endurance (HALE), and the system needs a larger wing surface area to accommodate the PV panels. Li-ion and Lithium polymer batteries are the most common batteries that are used in conjunction with PV. Endurance is reliant on the availability of solar activity (sun light) [34]. Solar panels for aerospace application are typically expensive due to geometry and weight requirements [35]. Improving the efficiency of individual components can improve the overall efficiency. For example, high Power Conversion Efficiency (PCE), weight, flexibility, mechanical resilience, and operational stability can all improve the overall efficiency of a PV system [36]. There are promising materials that will improve these conditions; these include advanced silicon [37], ultrathin kesterites [38], organic and inorganic semiconductors [36,39], organo-lead halide perovskites [40,41], and improved PCE [42]. There is further research investigating the implementation of PV panels with high power-to-weight ratio solar cells [36]. Such panels inhibit flexible material properties, allowing for a flexible wing design which would absorb turbulence and reduce aircraft perturbation. Furthermore, it would allow shape conformity to maximize the PV-occupied wetted area and solar power yield.

Figure 2 shows the increase in endurance of solar-powered aerial vehicles over almost 40 years, starting with research from 1974 through to 2010 [43,44]. Advances in PV technology and materials and battery technology contribute significantly to this [44]. The trend suggests that solar-based propulsion endurance has increased over the years by many orders of magnitude. Specifically, in 1974 the endurance was just 20 min [45]. In 2010, the endurance was recorded as 336 h, 22 min, and 8 s. So, from 1974 to 2010 there has been an increase by a factor of 1009, that is, 3 orders of magnitude in

less than 40 years. The goal of persistent loitering with solar-powered aircraft is clearly achievable. However, the limitations are in terms of available payload for useful operations.



**Figure 2.** Endurance of solar aerial vehicles as developed over time. The overlaid exponential trend is statically significant at the 99.6% confidence level and is given in the inset.

#### 2.4. Internal Combustion Engine

Internal combustion engines represent the traditional form of propulsion for aviation. For aviation, it currently stands as the most common form of propulsion system. Piston engine technologies are more popular for general aviation aircraft, including larger long endurance unmanned aerial vehicles (UAVs). Gas turbine engines are another form of ICE engine with widespread use in commercial aviation. Both of these engine types can be divided into further sub-types.

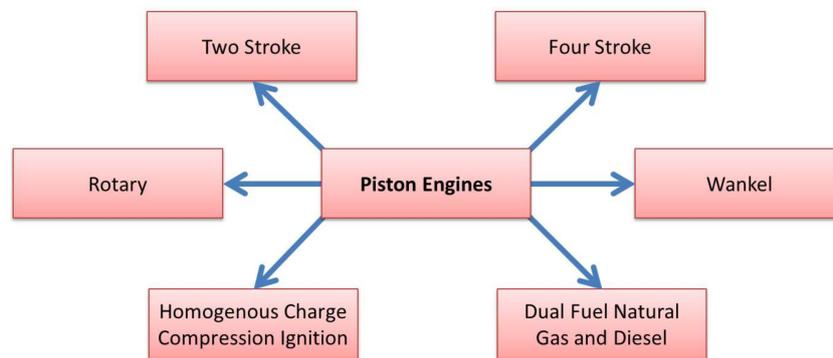
##### 2.4.1. Piston Engine

The piston engines that are popular in remotely piloted aircraft are further classified into [46]:

- Two-stroke,
- Four-stroke,
- Wankel,
- Homogenous-charge ignition engine, and
- Dual fuel engine.

These engine classifications are illustrated in Figure 3. Two stroke engines are commonly air cooled, light-weight, and do not need any additional lubrication as the oil and fuel is mixed. Two-stroke engines have a high power-to-weight ratio, are well-proven technology, and are efficient. Some shortcomings of piston engines include the inherent noise, limited altitude ceiling, and carbon-based emissions [47]. Four stroke engines are heavier than the two stroke engines and have a lower power-to-weight ratio than a two stroke engine; however, four stroke engines have greater efficiency and a longer expected lifespan. The Wankel engine is also a four stroke engine; it has a working part which resembles the reuleaux triangle with slightly convex sides. This part in the Wankel engine performs the four-strokes cycle in an oval-like housing [46]. Wankel engines have a higher power-to-weight ratio but produce less torque. A homogenous-charge compression ignition engine combines both the advantages of diesel and petrol engines and the ignition occurs naturally through compression (similar to a diesel engine) rather than ignition through a spark plug. Dual-fuel and

high-compression engines work on a similar principle to a diesel engine where it can be fired by multiple fuels. It is capable of reducing nitrogen oxide emissions by 66% [46].



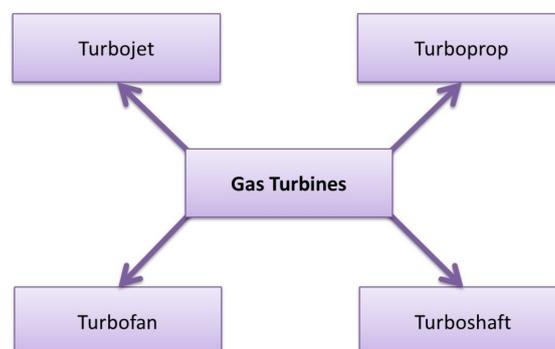
**Figure 3.** Classification of Piston Engine.

#### 2.4.2. Gas Turbine Engine

Gas turbines are divided into:

- turboprop,
- turbojet,
- turbofan, and
- turboshaft.

These engines work on the Brayton cycle principle. The turbofan and the turbojet are referred to as thrust-producing engines, while the turboshaft and the turboprop are referred to as power-producing engines. Figure 4 illustrates the division of the gas turbine into these four subcategories. Gas turbine engines are mostly used in high-endurance and high-altitude RPAS. This requirement is suited to the gas turbines' superior efficiency. The major advantage of the gas turbine engine is a very high power-to-weight ratio; however, a major drawback is the high fuel consumption at non-optimum conditions or conditions not favorable to the engine. These often occur in low-speed and idling scenarios. Due to high turbine combustor temperatures, emissions, such as nitrogen oxides and unburnt hydrocarbons, can be produced by a turbine engine. With low fuel efficiency comes high mission cost, and as with piston engines, there are environmental issues associated with the operation of gas turbine engines [48].



**Figure 4.** Types of gas turbine engine.

### 3. Hybridization

A hybrid system integrates the advantage of different systems to create a more efficient system. The advantages of hybrid electric propulsion (HEP) systems include fuel saving, efficiency, and

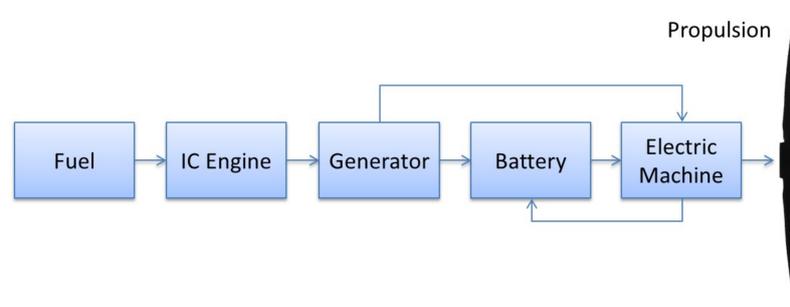
less pollution [49]. The advantages of the hybrid system over the conventional systems have been previously studied in terms of the drive train efficiency [50] and the electric power system [51]. In both studies, favorable increases in efficiency are reported.

### 3.1. Types of Hybrid Using Internal Combustion Engine

The first major type of hybrid propulsion system is the EM-Electric generator system combined with an ICE. This is the most common type of Hybrid system and is utilized in land, water, and aerial vehicle applications. These ICE-HEP systems are referred to as heavy hybrid systems and are the most extensively studied in the literature. These are classified according to architectures or system configuration, and these classifications are not limited to ICE-based HEP systems; they are applicable across all hybridization models [52].

#### 3.1.1. Series Configuration

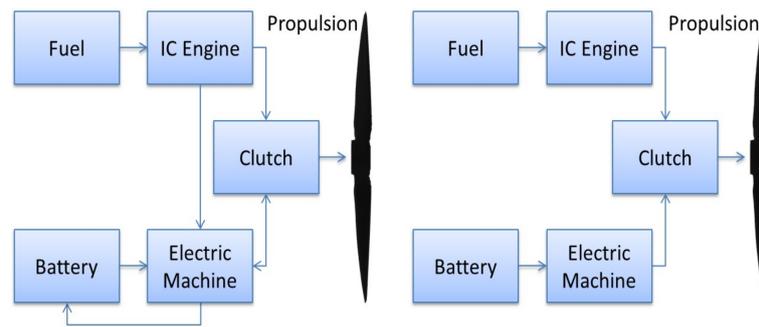
In a series configuration, the propeller is directly driven by an electric machine, which is illustrated in Figure 5. Note that although the term propeller is used here and throughout the discussion, this could easily be a fan or other piece of turbomachinery used for propulsion. The chemical energy of the fuel is converted into mechanical energy and then into electrical energy by a generator and finally stored in batteries. Then, the stored energy is fed into the electric machine that turns the propeller to produce propulsive power. This electrical energy can be stored in the battery or can be directly used to run the electric machine. Even though this is the simplest configuration, the multiple energy conversion paths result in significant energy loss [53,54]. The series configuration is much heavier, and is best suited for low-speed and high-torque applications. This system was first successfully used in a flight test a DA36 E-star. The manufacturer, Diamond Aircraft, indicates a potential 25% decrease in fuel consumption. The series configuration has been shown to be unsuitable for RPAS/UAS applications, where it was estimated that a small UAV would result in an 8%, or 2.5 lb (1.13 kg), weight penalty for a 30-lb (13.61 kg) UAS [55].



**Figure 5.** A possible series configuration energy flow chart. IC: internal combustion.

#### 3.1.2. Parallel Configuration

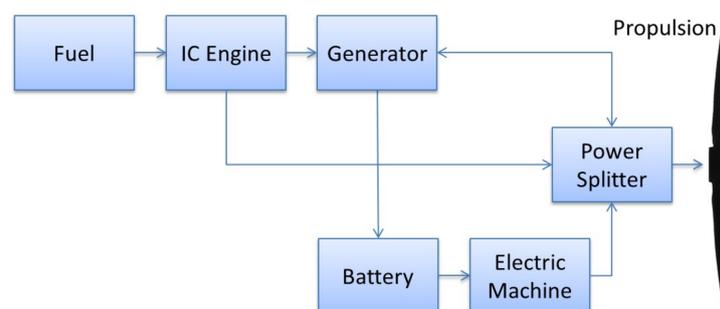
In a parallel configuration, the propeller can be driven either by the ICE, the electric machine, or a combination of both as shown in Figure 6. Both the ICE and the electric machine are connected through a mechanical clutch to the propeller that can either be in the path of the ICE or the electric machine, and can either engage or disengage according to the mode of operation. Alternatively, the ICE can drive both the propeller and electric machine as a generator to generate electricity and thereby charge the battery. This configuration is commonly used in hybrid land vehicles [56–58]. The major limitation of the parallel configuration is that the direct coupling to the propeller transmission limits the energy efficiency [59].



**Figure 6.** Parallel configuration energy flow chart, with (left) and without (right) the ability of the IC engine to drive the electric machine and hence recharge the battery.

### 3.1.3. Series/Parallel Configuration

The final configuration is the series/parallel, which is the combination of a series and parallel configuration together; this configuration can also be referred to as a power-split configuration. The propeller, electric machine, generator, and ICE are all connected to a planetary gear that is also connected to the propeller. The ability to combine two power sources effectively improves the overall design of a power-split configuration and can result in fuel efficiency improvements while reducing emissions. Such a design can introduce complexities into the cost and control strategies that are required for its operation [60]. Unlike the clutch system of the parallel configuration, the power-split configuration does not include a clutch to transfer the mechanical energy to the propeller. This device is complex and heavy and is not practical for use in either manned or unmanned aircraft. As such, the power-split configuration is mostly used in land vehicles [61]. Figure 7 illustrates the flow of energy in the various possible paths for the power-split configuration.



**Figure 7.** Series/parallel or power-split configuration energy flow chart.

## 3.2. Fuel-Cell Hybrid

In a fuel-cell only system, the electrical energy produced by the fuel cell is directly used to power the electric machine. Similarly, in a battery-only system, energy from the battery is used to power the electric machine. Finally, we could consider a photo-voltaic system, where the electrical energy produced by the solar cell is directly used to power the electric machine. It is then possible to consider combinations of these three systems.

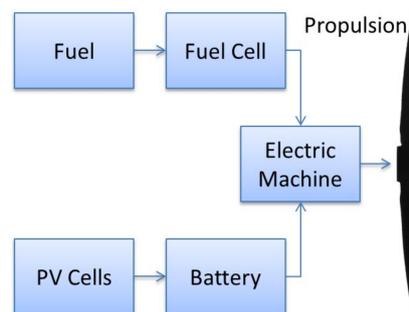
### 3.2.1. Fuel-Cell–Battery

The low-energy density of a conventional battery for aircraft is unfavorable due to the inherent weight of their design [31]. In a fuel-cell–battery hybrid system, the low-power density of a fuel-cell system [62–64], in addition to the current electric power storage limitation of batteries [65], are both overcome by their use in combination. This allows the fuel-cell system to help achieve better fuel

economy and performance while part of the load is powered from the batteries or super capacitors [66]. Such combination systems have shown improvement; for example, a Li-Po battery combination with a fuel cell shows an improvement in battery stack by over 7% relative to the fuel-cell-only system [67]. Other research shows a flying time increase from 470 to 970 min [26]. Another study outlined that the fuel-cell–battery combination could reduce fuel consumption by up to 3% by exploiting the efficiency of the fuel cell at part-load [24]. A fuel-cell–battery with hydrogen sourced from sodium borohydride demonstrated effective improvements to UAS endurance and this was validated through flight tests [68]. This hybrid system is mostly used by integrating a battery into the stack system to improve endurance. An example of this has shown an increase in stack efficiency of the hybrid by 7% [67]. Another example [69] has shown that a passive hybrid system could improve the efficiency of the fuel-cell system over 50%.

### 3.2.2. Fuel Cell-PV-Battery Hybrid

In the fuel-cell, PV, and battery hybrid system the combination consists of a fuel-cell, PV cells, and battery storage all utilized in tandem. In this three-part system, the three components can be combined in series and parallel in many different combinations to give a resultant hybrid system. There have been a few systems put forward in the literature. For example, the design put forward by Zafar and Gadalla [70] showed an increase in flight time of up to 10,670 s (2.96 h) from a conventional propulsion system time of 8286 s (2.3 h), which is an increase of 2384 s (0.66 h). Figure 8 shows a potential configuration of a three-part hybrid system utilizing a fuel-cell, PV cells, and batteries, similar to that in [26]. Figure 8 shows a typical PV–fuel cell hybrid system that uses a parallel configuration for the power sources. The system is connected to an electric machine that drives the propeller, where the electric machine can be powered either from a battery or the fuel cell.

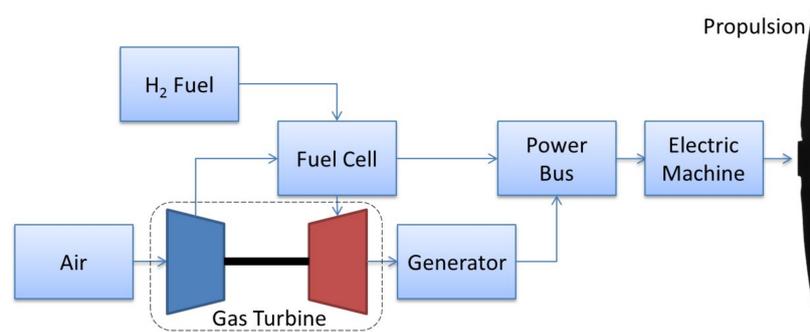


**Figure 8.** Configuration of a potential fuel-cell + photovoltaic (PV) + battery hybrid system. In this example, the PV system is in series with a battery system, which are both in parallel with a fuel-cell system.

### 3.2.3. Fuel-Cell Gas Turbine Hybrid

A fuel-cell gas turbine hybrid system uses a combination of a turbine engine-generator setup and a fuel-cell to produce power; specifically, the application of an SOFC fuel cell has been demonstrated. Here, the hybrid system may utilize a heat-recovery method [71,72]. This hybrid approach showed that such a system could achieve an improvement of up to 66.3% if the three-stack system was utilized [71]. This system is illustrated schematically in Figure 9.

Figure 9 shows an architecture of a fuel-cell—gas turbine hybrid. The system consists of a gas turbine and fuel-cell system that is connected to an electric machine that drives a propeller. The main fuel source is liquid hydrogen that is supplied to the fuel cell. The waste heat from the fuel cell is routed to an electric gas turbine generator and works with the principle of topping cycle heat recovery. Electric power from both sources is fed into a distribution network in a parallel architecture. The electric power distribution network supplies the power needed for operations, namely aircraft propulsion, the control system, and operational activities, such as radar and imaging.



**Figure 9.** A fuel-cell and gas turbine hybrid system. In this example, both the fuel cell and gas turbine are generating electricity which is then used to power an electrically driven propeller.

### 3.3. ICE–PV Hybrid

The ICE and PV system is a specific type of hybrid system which is utilized to improve endurance. Specifically, the hybrid system utilizes PV cells to run the electric motors connected to the propeller during times when sufficient sun light is available, and the ICE is utilized otherwise. This model design has been implemented [34] with the goal of increasing the functionality of the aircraft (mission potential in terms of payload, etc.), but at the expense of a limited fuel supply such that the ultimate endurance is less than a PV–battery hybrid-powered aircraft. This is because when there is insufficient sunlight, the “hybrid” system will need to power the aircraft, and if this is dependent on a limited substance then there will be an ultimate limit to the endurance. In contrast, a PV–battery system can be engineered such that sufficient energy harvest during the day can power the aircraft continuously.

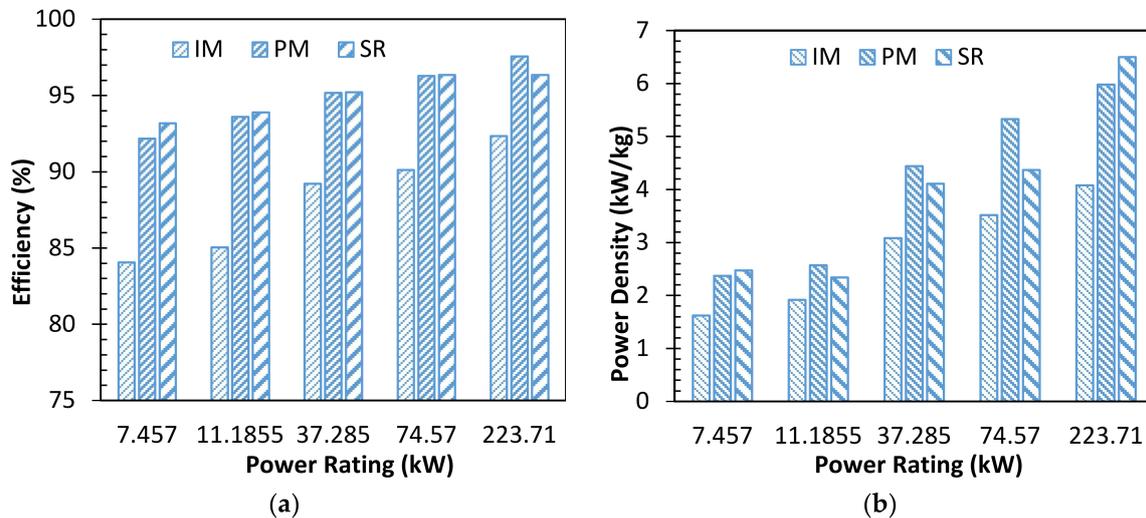
### 3.4. Electric Machine Technology

The present power generation technology in commercial aircraft consists of a separately mounted synchronous generator driven off by a Constant Speed Drive (CSD) ensuring 400 Hz supply at varying engine speeds as demanded by flight conditions. The synchronous generator has been proven to be reliable [73]; however; the need for a CSD penalizes the overall power density of the package. In RPAs, the power levels are lower than those of civil aircraft. It is generally considered that at low gear power transfer levels, the gear box power density is low [74] and as a result it can be inferred that use of a gearbox in mechanical power transmission at low power levels, such as those of RPASs, will achieve uncompetitive low power densities. Therefore, the need for a direct drive configuration of engine and electrical machine seems to be an obvious choice. Recent trends in more-electric aircraft (MEA) and all-electric aircraft (AEA) have also moved towards the direct integration of an electrical machine with an engine [75,76]. Alternative types of electrical machines and power electronic converters that offer low weight and high reliability have been studied for this purpose [77,78]. The authors of [79] compare permanent magnet (PM), switched reluctance (SR), and induction machines (IM) over a range of power levels and speed of 9000–10,000 rpm.

Figure 10 summarizes the study presented in [79]. The induction machine is found to be lower in efficiency and power density according to [79]. From Figure 10, it can be seen that at low power levels below 10 kW as required for RPASs, the power density of the induction machine is considerably lower than that of PM or SR machines. At power levels below 10 kW, both the SR and PM machines offer very similar performance. However, the SR machine requires a higher peak power rating of the power electronic converter. At power levels for RPAS systems, this peak power requirement may not pose a significant disadvantage and remains to be studied in detail.

The power density is also a function of the rated speed at which the electrical machine is designed. The authors of [80] show that for a range of 50 kW to 200 kW PM machine designs, the increase in designed surface rotor speed from 25 m/s to 200 m/s results in an increase in power density approximately from 1.8–2 kW/kg to 3.5–4 kW/kg. A similar study on SR machines remains to be

investigated. However, a review on high-speed machines undertaken by the authors of [81] shows that at speeds above 50,000 rpm, the surface PM machine achieves higher merit compared to other machines. Therefore, for a given RPAS system the selection of either the PM or SR machine technology depends on the power requirement and speed.



**Figure 10.** Efficiency (a) and Power density (b) comparison of induction machines (IM), permanent magnet (PM) machines, and switched reluctance (SR) machines at different power levels designed for a rated speed in the neighborhood of 10,000 rpm [79].

#### 4. Discussion

The major findings of this review are provided in Table 2. The four principal hybrid systems with applications to RPAS or UAVs have been identified:

- ICE parallel hybrid,
- ICE series hybrid,
- Fuel-cell hybrids, and
- PV hybrids.

Table 2 also identifies some of the key factors associated with each of these hybrid propulsion systems.

The concept of a turbo-electric hybrid system may be valid for use in the RPAS/UAS domain. Due to the high-rotational speeds of current turbine technologies, higher system power densities can be achieved with the use of high-speed machines and by elimination of mechanical gearing. The PM machine and the SR machines have been found to be the two candidates for application in RPAS systems. Various studies in the literature have shown that high RPM energy extraction from the turbo shaft is possible and will reduce the design complexity while reducing mechanical losses [82]. Excess energy extraction from a free turbine stage coupled with a battery-storage system may also hold benefits; however, increases in weight due to batteries is the obvious shortfall of the concept. Improvements in battery technology and improvements to energy density are ongoing. Energy storage through the use of light-weight supercapacitors may solve the issue of temporary energy storage and also have the advantage of a fast release for times of high-thrust requirements. The benefits of specific systems, outlined in Table 2, are universal when applied; however, weight, design, and mission requirements must be taken into consideration. The top-level requirements of an aircraft's power system are always driven by power-to-weight ratios. When expanding into hybrid system options, weight considerations must be applied as more components are added to the overall system. A reduction and simplification of the power system is commonly favorable. Systems that do not use

batteries for energy storage would be desirable; however, this is not commonly the case for electric aircraft. Utilizing solar panels on aircraft wings have been a popular and well-researched area as the power source is readily available from the sun; however, solar activity and time of day restrict the operational envelope of the aircraft. It is unclear at this stage which system, either a series or parallel, will be more favorable for use in RPAS. The mission requirements of each RPAS system is different as they perform different missions. If an RPAS is required to fly at night with a required range and endurance, then solar panels are not optimal. On the contrary, a day-time operation RPAS will see endurance benefits by harvesting energy from the sun. The scale of RPAS in which a hybrid system will be implemented is also a determining factor, as larger RPAS and UAS operate in a more aerodynamically efficient Reynolds number and can carry more weight relative to smaller aerial vehicles. Hybrid systems may in fact hold the key in larger drone scales.

**Table 2.** Comparison of different hybrid systems and percentage of improvement.

Model	Percentage of Improvement
Parallel Hybrid	- [83] 40% less fuel consumption
	- [84] with a patent: Fuel consumption reduction (rule-based controller during one-hour and three-hour Intelligence Surveillance And Reconnaissance (ISR) missions is 54% and 22% less)
	- [59] Increases in efficiency by 6.5% compared to engine only
	- [85] Improvements in endurance by 13%
	- [86] 12% improvement in total efficiency
Series Hybrid	- [87] Endurance improvement of 23.7 h at cruise speed (by comparison, a UAS using a commercial gasoline SI engine was predicted to have an endurance of 15.1 h)
	- [60] 2006-HYPERSTAR 25% decrease in fuel consumption
Fuel cell Hybrid	- [71] Pp to 66.3% when a three stack system is used
	- [88] Increase the endurance by 300%
	- [89] Increase the efficiency by 3%
	- [67] Increased in stack efficiency of a fuel cell by 7%
PV hybrid	- [34] Up to 20% of the daily input can be fed through PV
	- [26] Fuel cell–PV (470 to 890 min for baseline conditions) i.e., is up to 90%

## 5. Conclusions

This study has highlighted fundamental technologies to facilitate the development of long-endurance RPAS. Many current studies have outlined the benefit of isolated components to improve the efficiency of a propulsion system. The study attempts to review the way these technologies can be combined to form hybrid systems in multiple configurations. Of these many systems identified in the literature, those of specific interest in the design and development of unmanned aircraft have been detailed, including the potential benefits of each. Some case examples of these systems have been included, and are used to demonstrate the potential improvements in performance, specifically in terms of endurance. Further research is required to understand which system may provide the most benefit for the various scales and types of RPAS and UAS currently on the market, and this paper provides some visibility on hybridization and its benefits in the domain of RPAS.

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