Heliyon 6 (2020) e05285

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

A comprehensive review of energy sources for unmanned aerial vehicles, their shortfalls and opportunities for improvements

Ashleigh Townsend [a,*], Immanuel N. Jiya [b], Christiaan Martinson [c], Dmitri Bessarabov [c], Rupert Gouws [a]

[a] *School of Electrical, Electronic and Computer Engineering, North West University, Potchefstroom 2520, South Africa*
[b] *Department of Engineering and Science, University of Agder, 4879 Grimstad, Norway*
[c] *HySA Infrastructure Center of Competence, Faculty of Engineering, North West University, Potchefstroom 2520, South Africa*

ARTICLE INFO

Keywords:
Aerospace engineering
Electrical engineering
Energy
Electric power transmission
Fuel cell
Energy storage technology
Hydrogen energy
Fuel technology(FC)
Lithium-polymer (Li-Po)
Super-capacitor (SC)
Unmanned aerial vehicle (UAV)

ABSTRACT

Unmanned Aerial Vehicles were first introduced almost 40 years ago and their applications have increased and diversified substantially since then, in both commercial and private use. One of the UAVs main issues when it comes to mobility is that the power sources available are inadequate, this highlights an area for improvement as the interest in drones is on the increase. There exist many different types of power supplies applied to UAVs, however each has their own limitations and strengths that pertain to weight contributions, charging and discharging times, size, payload capabilities, energy density and power density. The aim of this paper is to review the main power sources available for UAVs, determine their shortfalls, compare the power sources with each other and offer suggestions as to how they can be improved – hence identifying where the gap lies for developing better alternative power sources.

1. Introduction

As the world becomes more reliant on technology, the requirement for autonomous and more mechanized operations, that remove the possibility of human error, is also increasing [1]. Operations involving visual condition inspections, in areas inaccessible by humans, necessitate stealth, safety considerations and viability, which in turn requires that the object used for such a purpose be quiet and small [2]. Autonomous motorized vehicles offer these characteristics, however, they are limited with regard to mobility as they require a surface to operate on and such surfaces are often unavailable. This brings in the added requirement of a vehicle that does not require an operating surface, one that is aloft, shifting the focus to unmanned aerial vehicles (UAVs).

UAVs can be relatively small, very mobile and quiet, with the top of the line ranges tending to be less affected by external influences such as wind direction or speed changes. On top of all these benefits they also have a wide range of applications; however, the smaller UAVs do not solve the mechanization issue fully as they have one predominant flaw, the power supply is inadequate [3]. The larger drones, such as those predominantly used in military applications, offer the advantage of adequate (and in many cases more than adequate) power supplies, however this advantage makes them much larger, less mobile and quite noisy. The aspect of an adequate power supply is imperative as it leads to a long flight endurance, it is also important that the drone be very mobile and minimally affected by the surrounding environment [4].

In recent years the requirement for UAVs in different areas of application, whether commercial, recreational or public, has increased tenfold, currently this demand is mainly consumed by military use but it is expected to exponentially shift to more of the recreational and public use [5, 6]. One major application is in the use of criminal, theft and poaching surveillance [7]. There is also a very big market for the use thereof for scientific monitoring purposes (water sampling, landslides and volcanic activity) as well as for transmission line surveillance [8, 9, 10, 11].

Combustion engines currently remain one of the favored power supplies for most military and commercial UAVs, however, electrical systems offer a higher efficacy and tend to be more reliable, with the added benefit of having low to no greenhouse gas emissions and low noise [2]. This is why electrical systems for UAV applications are becoming more prevalent. The field of electrical systems extends to

---

[*] Corresponding author.
E-mail address: ashleighktownsend2@gmail.com (A. Townsend).

https://doi.org/10.1016/j.heliyon.2020.e05285
Received 14 February 2020; Received in revised form 8 June 2020; Accepted 14 October 2020

batteries, fuel cells (FCs) and solar power, amongst others, these systems will be further discussed in the paper. All of the mentioned electrical systems utilize a battery (generally to increase the energy density of the system during peak energy requirements), however, batteries do not offer an energy density much higher than that of the main power source, as they have high power densities but low energy densities. Therefore, the addition of the battery can increase the endurance of the system and its peak power capabilities, but it does not increase them to the desired point and therefore still drains both of the power supplies during these instances considerably, still limiting the flight pattern of the system.

Ever since drones have come into the picture many creators have been assessing and re-evaluating the efficiency thereof and more specifically the options to increase the flight time [12, 13]. Two main options exist, change the power source in a way that increases the capacity thereof or refuel the power source sporadically [14]. The latter option requires an external refueling station. This in itself presents more limitations: the drone will be required to land periodically and refuel – decreasing actual usable flight time; the stations will be required along the flight path – limiting the path, decreasing mobility and increasing complexity; finally, this method increases overall costs unnecessarily.

The first mentioned option has many more possibilities that can be much simpler and more cost effective than the last, such as: increasing the capacity of the power source by replacing it with a larger one (or a different type of power source) or combining the existing power source with another to exploit the benefits of the combination. All of the options [15] have their advantages and disadvantages and these will further be discussed in this paper. This paper will briefly discuss the three main types of drones, giving more detail about their main power sources and the shortcomings thereof, focusing on possible solutions in the form of hybrid systems and how they can affect each drone type.

2. Types of UAVs

Before the different power sources are discussed, the two main types of UAVs (shown in Figure 1) will be briefly discussed. There are two main types of UAVs, rotary-wing types and fixed-wing types. The former consists of a body that travels using multiple rotors and the latter has the look of a general aircraft having a fixed wing on either side of the body.

The rotor-craft types tend to be more popular since they can take-off and land vertically, thus not requiring a launcher or runway, they can hover and are very agile making them best suited for more precision maneuverability applications. However, these types of UAVs require more mechanical and electronic complexity leading to more complicated maintenance, decreasing operational time and increasing costs. Rotary-wing types also have the disadvantage of smaller load capabilities, increasing power requirements, decreasing operational duration and increasing costs even further.

Fixed-wing types have the advantage of a much simpler structure, compared to rotary types, allowing for simpler maintenance and more efficient aerodynamics, decreasing operational costs and increasing flight time. The fixed wings also give the craft a natural gliding ability, decreasing power consumption, while the aircraft itself can carry larger loads for longer distances using less power, once again decreasing costs and increasing efficiency. The disadvantages of this type include the necessity of a runway or launching device for takeoff and landing, they need to be in a constant forward motion and can thus not hover as a rotary type can and they tend to be much larger and bulkier in comparison. These all decrease the maneuverability of the UAV [16].

Amongst all the rotary- and fixed-wing drones exists a unique type of drone that combines both drone types. As a combination it provides the stability and maneuverability of a rotary-wing drone with the long flight range of a fixed-wing drone. Furthermore, no runway or additional equipment is required for take-off, [17]. An example of the combination drone can be seen in Figure 2. All three types have respective applications suited to their advantages and disadvantages and there also exists many different power sources used in these drones.

3. UAV power sources

There are many different power sources available on the market, such as batteries, solar power, FCs, combustion engines, etc., most of which can be applied to drones. Over the years some of these power sources have been disregarded as they have more disadvantages than advantages regarding the specific application, some of these include having a too large weight or size, being restricted to specific movements or simply not having a large enough energy density. Most power sources are defined using their respective energy- and power densities.

The power density refers to the amount of power the source can provide at a specific instance, whereas the energy density refers to the energy that can be stored within the source, therefore how long that amount of power can be delivered. With reference to the Ragone plot from [18] super capacitors (SCs) have a large power density (80–75 000 W/kg) but a small energy density (0.09–0.10 Wh/kg), allowing them to be able to provide a large amount of power but for a short period of time. FCs have a large energy density (200–3 000 Wh/kg) but a low power density (1.5–20 W/kg), thus allowing them to provide an average (low) amount of power for an extended period of time. Li-ion capacitors fall in the middle providing a comparably large amount of power (power density, 1 000–55 000 W/kg) over an arguably long period of time (energy density, 18–350 Wh/kg) [18].

In order to determine the shortcomings of the different UAVs available on the market some more in-depth research into the different power sources is required. This section will mainly focus on the main types of power sources used in drone applications.

3.1. Batteries

There are many different types of batteries used onboard UAVs, each of which has its respective advantages and disadvantages. The types include: Lead acid (Pb-acid), Nickel cadmium (NiCad), Nickel Metal Hydride (NiMH), Alkaline, Lithium Polymer (Li-Po), Lithium Ion (Li-ion), Zinc Oxide (Zn-O_2), Lithium-air (Li-air) and Lithium-Thionyl-chloride (Li-$SOCl_2$) [19]. The most common batteries for drones are Li-Po and Li-Ion. Li-$SOCl_2$ – batteries have two times higher energy density per kg

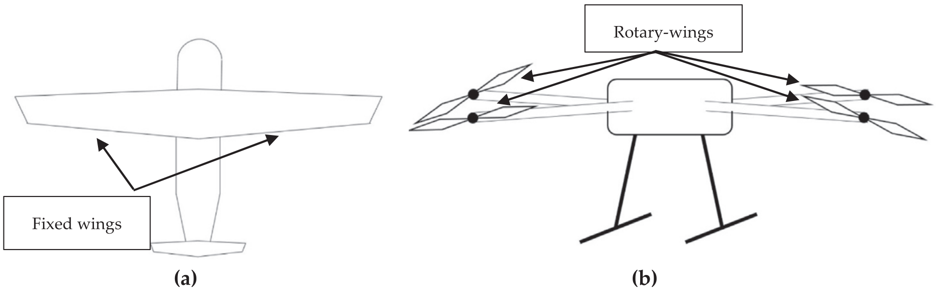

Figure 1. Drone types. Above (a), fixed wing drone, and above (b), rotary-wing drone.

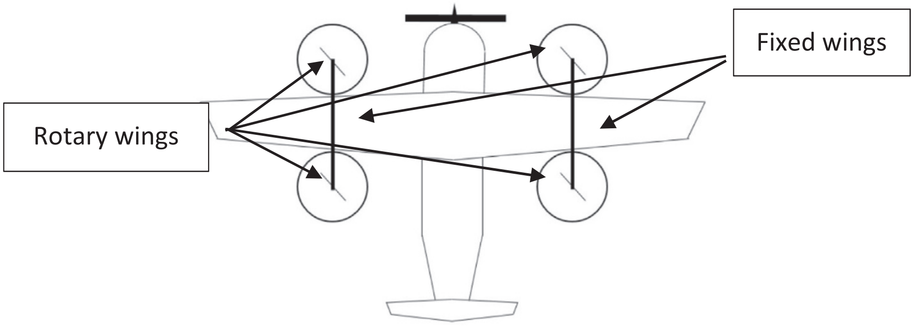

Figure 2. Transition type drone.

compared to the aforementioned and Li-air batteries can be up to seven times higher, however, they are unfortunately not so widely available and are much more expensive than Li-Po and Li-ion. Another variation of Li-batteries, Lithium sulphur (Li-S), also offer a higher density compared to Li-ion at a reduced cost making them the obvious choice to replace Li-ion batteries in the near future.

The most suitable type of battery is determined by comparing the power density, energy density, weight, volume, cycle life, cost, safety and maintenance (to name a few criteria) of the different options. Each of the criteria affect different aspects of the drone, power density affects the acceleration capabilities, energy density determines the range, cycle life determines how often the battery will need to be replaced, weight and volume affect the range of the system and cost affects availability [20]. Pb-acid, NiMH and Li-ion batteries are the most popular for electric vehicles (EV) applications as they are capable of meeting the requirements of EVs.

Li-ion batteries are able to deliver high energy and power per unit of battery mass; they are also lighter and more compact than the other rechargeable batteries. Other advantages include high energy efficiency, no memory effects and a comparably long cycle life. The one major shortcoming of these batteries is the cost which is significantly more than the other two [21].

Li-air batteries could cause a significant increase in the range of EVs as they have a very high energy density, almost comparable to that of gasoline. They can hold 5–10 times the energy of a Li-ion battery, with the same weight, or twice the energy for the same volume. For comparison they have an estimated energy density of around 2000–3500 Wh/kg, which is much higher than any other known battery. A small lithium-air battery has already been designed with a 600 mAh/g density compared to the 100–150 mAh/g density of a Li-ion battery of the same size [22, 23]. Amongst all of these advantages lie a few disadvantages, a rechargeable version of this battery presents a challenge as they have a very limited number of recharge/discharge cycles, they have a very slow recharge rate and they are extremely dangerous if water vapor is present in the oxygen, as lithium reacts violently with this.

Table 1, below, compares the energy-/power -densities and usable life of the mentioned battery types. For cost comparisons between the different types to be relevant it is necessary to choose a reference point, chosen as the capacity of the battery, namely: 2 Ah. Due to availability the closest values to this chosen value were used and in the case of the Zn-O_2 battery, the largest value was used. The sites where the respective battery-ratings where obtained are referenced below the table.

Li-Po batteries are preferred over most other batteries in portable devices and electric transportation (EV and their hybrid counterparts) due to their superior energy density, power-to-energy balance and long cycle life [20, 24, 25].

The main advantages of battery powered drones relate to being capable of charging almost anywhere, transported generally without limitations and easily recharged by simply replacing the battery pack. The disadvantages include small amounts of recharge cycles and comparably low energy densities.

3.2. Hydrogen FCs

As renewable fuel vehicles become more popular, alternative power sources to batteries are being investigated, one of which has to do with FCs. FCs can be divided into different categories, i.e., Proton Exchange Membrane (PEM) FC (also known as *Polymer electrolyte fuel cell* [36]), Phosphoric Acid FC (PAFC), Solid Acid FC (SAFC), Alkaline FC (AFC), High temperature FC (HTFC) and Electric storage FC (ESFC).

A PEMFC operates in a similar manner to that of a battery, there are two electrodes, an anode and a cathode, separated via a membrane and

Table 1. Comparison of different characteristics of different battery types (combined from [20, 22, 23, 24, 25, 26]).

	Battery Type								
	Pb-acid	NiMH	Li-ion	NiCad	Alkaline	Li-Po	Zn-O_2	Li-air	Li-$SOCl_2$
Nominal cell voltage (V)	2.1	1.2	3.6–3.85	1.2	1.3–1.5	2.7–3	1.45–1.65	2.91	3.5
Energy density (Wh/kg)	30–40	60–120	100–265	40–60	85–190	100–265	442	11 140	500–700
Power density (W/kg)	180	250–1000	250–340	150	50	245–430	100	11 400	18
Cycle life	<350	180–2000	400–1200	2000	NA, non-rechargeable	500	100	700	NA
Charge/Discharge efficiency (%)	50–95	66–92	80–90	70–90	45–85	90	60–70	93	6–94
Self-discharge rate (%)	3–20	13.9–70.6	0.35–2.5	10	<0.30	0.3	0.17	1–2	0.08
Rating	12 V	12 V	3.6 V	12 V	1.5 V	3.7 V	1.4 V	N/A	3.6 V
	2 Ah	2 Ah	2 Ah	1.8 Ah	2.2 Ah	2 Ah	300 mAh		2.2 Ah
Costs (US$/Wh)[*]	0.6975	0.8546	0.9361	2.6778	1.6727	2.3095	0.3095	N/A	0.5492
TRL[**]	9	9	9	9	9	9	9	6	9

[*] Available for purchase on 18/05/2020 [27, 28, 29, 30, 31, 32, 33, 34], relative for comparison.

[**] Technology Readiness Level, [35].

connected using an electrolyte. A fuel is supplied to the anode and an oxidant to the cathode, which then reacts with the electrolyte as well as with each other causing electrons to flow in the external circuit from the one electrode to the other inducing a voltage. This chemical process produces two types of byproducts, one from the fuel and one from the oxidant. A hydrogen FC has a fuel of hydrogen and oxidant of air, thus producing water and air as byproducts. These FCs have an energy density of up to 150 times that of a Li-Po battery. In recent advancements a hand-launchable fixed-wing UAV has been developed that is capable of a 10 h flight with a distance of 500 km. Another drone design uses the hollow structure of its body to store hydrogen instead of air allowing the elimination of the weight contributed by the usual storage of the hydrogen [37]. For the implementation of hydrogen FCs in vehicles the FCs are required to have a high power density, rapid response to loads and a hydrogen supply infrastructure. PAFCs use hydrogen as the fuel and liquid phosphoric acid is the electrolyte [38]. This FC has a few drawbacks including: the phosphate ion being absorbed at the catalyst surface hindering the electrochemical reaction, an acid loss when operated at high temperatures for extended periods of time, the platinum catalyst particles migrating and forming larger particles on the electrode reducing the active surface thereof and at high voltages a gradual carbon corrosion becomes present [39].

SAFCs utilize a solid acidic material as the electrolyte. Solid acids are chemical intermediates between salts and acids, at low temperatures they act like salts, while at higher temperatures they undergo a phase transition to act like acids. This increases conductivity and allows for increased efficacy of the FC. The electrolyte of the PEMFC is a water-based acidic polymer membrane (constantly in the liquid state) whereas the SAFC has an acid that transitions from solid to liquid when required. This type of FC can function using hydrogen gas obtained from a variety of different fuels, increasing their areas of application [40, 41].

AFCs are one of the first developed FC technologies and have a liquid potassium hydroxide (KOH) solution as electrolyte [42]. This FC is advantageous as it has a high efficiency, lower costs and a simple structure, however their shortfalls include quite a short operating life due to the KOH eroding the FC parts and purified oxygen is required in the system as it is very intolerant to carbon dioxide [42].

HTFCs have two main types, Solid oxide FCs (SOFC) and Molten carbonate FCs (MCFC). The former uses a solid ceramic inorganic oxide as the electrolyte [43]. The latter uses a mixture of molten potassium and lithium carbonate as the electrolyte [44], but is irrelevant to the use in UAVs and will not be further discussed. SOFCs are not limited to the more common flat shape and are often in the shape of a rolled tube, they only operate at high temperatures allowing for the use of more inexpensive catalysts and can be run on a variety of fuels, without the need of purification [45]. The final FC is the ESFC which is a conventional battery that includes the use of hydrogen and oxygen as alternative inputs for charging the battery.

PEMFCs require relatively low operating temperatures while maintaining high efficiency, power density and rapid response to load changes, which makes them the preferred variation for EVs or other applications requiring a light weight power source that is small in size [46, 47, 48, 49]. FCs used onboard drones contain a buffer (Li-Po) battery that is used to supplement the power when peak power is required. This allows the FC to have a longer usage time per flight as it isn't drained during the peak power instances. However, these batteries cause the system to be heavier and decrease the life of the aircraft as batteries have a limited cycle life. This cycle life is less than that of the FC. Another issue is that the FC constantly recharges the battery once it is depleted below its optimal voltage, which then decreases the overall range of the FC.

Advantages of FCs on drones include no direct pollution, no sound, large energy density and an almost instant recharge. Disadvantages are related to the size being significantly larger than conventional battery-powered drones, operating costs are dependent on the availability of hydrogen gas [50] and the size of the hydrogen gas tank limits the build of the drone. The hydrogen tank needs to be taken into consideration when balancing the drone keeping in mind that the weight decreases as the tank empties.

3.3. Combustion engine

Both petrol and diesel engines fall under the term combustion engines and consist of relatively the same components, an engine block containing (amongst others) a combustion chamber, pistons, fuel injectors, and an intake and exhaust valve. A two stroke engine, the most commonly used combustion engine, consists of two strokes and four stages, intake, compression, power and exhaust. One of the main differences between petrol and diesel engines is that the former have spark plugs, whereas the latter do not require this due to diesel self-igniting when under extreme pressure. Diesel engines sometimes require a glow plug to heat up the diesel before it enters the chamber as diesel engines can have complications when starting in cold weather. Other differences include petrol engines having a faster rotational speed compared to diesel as they have lighter pistons, connecting rods and crankshaft (lower compression ratios) and due to petrol igniting easier than diesel. However, petrol engines have lower efficiency than diesel engines; this includes thermal efficiency [51].

Kerosene, Methanol, Ethanol and LPG Propane are all variations of the petrol-powered solutions available and some of them have a remarkable performance, one performance of a gasoline-powered fixed wing UAV being more than 20-hours with one full tank of gasoline [51]. The weight of the drone is continuously decreased in flight due to the weight of the fuel decreasing, therefore increasing the range. Diesel engines have the highest effective efficiency of all the combustion engines, they can also operate on a variety of fuels, some of which have higher energy densities and are safer for the environment and the external system requires lower voltages allowing for better environmental adaptability [52, 53]. Diesel engines are in general more robust than petrol engines but this also leads them to be heavier and bulkier which is counterproductive when used onboard a drone.

The advantages of combustion engine drones comprise of longer flight times, robustness, small, light-weight and having a good specific fuel consumption. The disadvantages comprise of being heavier compared to battery-powered drones and require more complex maintenance [54].

3.4. Solar power

The conversion of sunlight into electricity is most commonly done by converting light into electric current through the photovoltaic (PV) effect. This current is then either directly used or stored in a battery and the battery provides power to the system. There are two main technologies used for solar power, PV systems or concentrated solar power (CSP). The former being a direct conversion of sunlight into electricity and the latter being used to make steam that allows a turbine to generate electricity [55, 56, 57]. Solar panels are generally used onboard fixed-wing drones as they require a large surface for the panels, but they can also be used to extend the range of a rotor-type drone (used to assist the main power of the rotor-type). Solar powered drones are quiet, have low operational costs, low maintenance costs and an excellent carbon footprint, however, in order for them to be efficient a large area is required for the panels, therefore increasing the size of the drone tremendously and the panels also require sunlight to operate.

3.5. Summary of power source shortfalls

Under each of the respective power sources mentioned above a description was given with some of the main advantages and disadvantages thereof. In this section the shortfalls of each power source will be elaborated on in order to highlight where there is room for improvement, this is summarized in Table 2, below.

3.6. Comparison of main power sources

Each of the power sources in the previous section have their advantages and disadvantages, these will be discussed in this section with specific emphasis on the following aspects, specific energy, flight time, weight, payload capability, recharge/discharge time and cost. For this comparison the most common power sources used in drones will be assessed. The Li-Po battery drone will be assessed for the battery variation as they tend to give the best results [64] and are the most common battery used in drones at present.

In order to compare the sources sufficiently a reference point of the payload capability of around 5 kg for each drone has been chosen, this allows for a more sensible comparison between the sources. It is worthy to be noted that the flight time of the combustion engine- and FC-powered drone is dependent on the size of fuel tank. The above-mentioned aspects are summarized in Table 3 below.

In order to compare the different drones a basis of reference will be required. In this paper that basis will be the ratios of flight time to weight, payload to flight timr, payload to weight, flight time to cost and flight time to recharge time. These values are laid out in Table 4. For the first ratio a value larger than 1 is preferred and the larger the better as this indicates that the UAVs flight time is less affected by the weight thereof, therefore, fewer losses. The second ratio prefers values smaller but closer to 1 as this reflects a good flight time while still including a payload capability, which is beneficial as it can have a wider field of application. Values above 0 for the third ratio show that the UAV is capable of carrying a weight above its own, again increasing the field of application thereof, the larger – the better. For the fourth ratio it is desired that the drone have a large flight time and a smaller comparable cost as this indicates good value for money, therefore a value closer or larger than one is desired. And for the final ratio it is preferred that the flight time be much larger than the recharge time as this indicates very good efficiency and once again allows the UAV to be applied into many more fields, thus a value larger than 1 is desired.

The bold formatted values indicate where the best value was obtained for each ratio, thus from examining the results it seems that the combustion drones are the best option. Batteries have the best payload to flight time ratio while the other ratios lag far behind the other power sources. Hydrogen FCs come in second compared to Combustion as they have the best flight time to weight ratio and were either second or third best for all the other ratios. This allows FCs to lean towards being the better option for use onboard drones as FCs only fall behind when it comes to cost. They are quite light, have a great flight time, can carry a large payload to weight ratio and recharge very quickly, this allows them to have many more applications than most of the other options. Hydrogen FC powered drones are mainly limited when it comes to cost, size of the fuel tank and acquisition of the hydrogen fuel. Table 5 summarizes the content of section 3.1 of this paper.

Some of the advantages and disadvantages of each power source have been listed as well as the possible combinations for each source. The main criteria to determine the efficacy of each source pertain to flight time, peak power, size, noise, charge/discharge rate and the amount of combinations each source can be a part of. Each source was given a rating out of 4, 4 being the worst and 1 being the best, just to compare the sources against each other. These values were estimated from either the literature of each power source or from Table 3. From the table, batteries are the best when only considering size as they lack in all other categories, hydrogen FCs seem to be a good option as they are top 3 in all categories, combustion engines are a good option if size and noise are not a problem and solar panels are the largest option and have the lowest peak power.

Hydrogen FC drones function with the use of a buffer battery essentially making them a hybrid system. This battery is usually a Li-Po battery and solves, to a degree, the problem of bad peak power performance. However, as mentioned in this paper, Li-Po batteries take long to recharge, have a short cycle life and a low power density. Although this increases the efficiency of the FC, it, to an extent, also decreases the overall life time of the FC and does not offer such a large increase in the overall power density of the system. This opens a window for further investigation into solving the power density problem, to be discussed in the next section.

3.7. Possible solutions to improving flight time

There are some possible solutions to improve the flight time of drones powered by these different power sources, i.e.

1. Wireless charging techniques, which include, Gust- soaring, PV arrays, Laser and Battery dumping
2. Electro-magnetic field (EMF) -based techniques
3. Wireless charging techniques, which include, Gust- soaring, PV arrays, Laser and Battery dumping
4. Hybridization

The first three techniques pertain to battery powered drones or drones containing batteries. The fourth technique can be applied to all the mentioned power sources and will therefore be the only solution discussed further.

3.7.1. Hybridization

Hybrid systems contain two or more types of power sources, generally one is used to generate the other or one is preferred and the other is used at specific times to improve efficacy. The principle behind this is that one of the power sources has more advantages than the other in normal conditions, whereas the other provides specialized advantages which are beneficial at certain times during operation. This helps improve the energy and fuel efficiency of the system [69, 70, 71]. From section 3.1 it is evident that some of the power sources have advantages over the others and vice versa. There are disadvantages of some of the sources that can be resolved or improved by using alternate sources. This is where the concept of hybridization comes into consideration. By combining two or more power sources their advantages can be combined and their disadvantages can be minimized. However, special attention needs to be given to the method of hybridization.

There are generally five categories of hybrid vehicles, parallel (PH), mild parallel (MPH), power split or series parallel (SPH), series (SH) and plug in hybrid (PIH). PH can function using either of the sources used in the hybrid or one individually; when both are used the use is split equally. MPH prefers the use of one and uses the other when assistance is

Table 2. Summary of the shortfalls of each power source.

Power source	Shortfall
Batteries	Low recharge cycles; low energy density; low flight time in comparison; recharge period significantly longer than others; dangerous to the environment and/or operators; limited flight time thus limited applications [58, 59, 60].
Hydrogen FCs	Larger size; limited by availability of hydrogen gas and gas tank size; quite expensive; lower energy efficiency compared to batteries due to complex power management requirements [61]; hydrogen extraction process increases refuel time [62];
Combustion engine	Heavier; larger size; noisy; complex maintenance;
Solar power	Large surface required for solar panels; requires sunlight; much heavier than others; significantly larger cost than others; maximum power point tracking (MPPT) algorithm is required [63].

Table 3. Comparison of the different characteristics of various power sources.

Product name*	Li-Po Battery	Hydrogen FC	Gasoline	Solar
	DJI Matrice 600	BMPower 1 kW	Yeair!	Airbus Zephyr 8
Specific energy (Wh/kg)	9.99	646	2600	435
Flight time (min)	20	250	120**	20 160
Weight (kg)	10	6.5	4.9	60
Payload (kg)	5	5	5	5
Recharge/discharge time (min)	92	Refuel time	Refuel time	Constant recharge via panels
Cost (USD from 2019 figures)	5699	13 410	1 550	3 000 000

* obtained from online sources on 18/05/2020 [65, 66, 67, 68].

** For comparison 1.5 L tank is chosen, which yields 5 kg payload.

Table 4. Comparison of power source ratios.

	Ratios				
	$\frac{\textit{Flight time (min)}}{\textit{Weight (kg)}}$	$\frac{\textit{Payload (kg)}}{\textit{Flight time (min)}}$	$\frac{\textit{Payload (kg)}}{\textit{Weight (kg)}}$	$\frac{\textit{Flight time (min)}}{\textit{Cost (USD)}}$	$\frac{\textit{Flight time (min)}}{\textit{Recharge time (min)}}$
Battery	2	**0.25**	0.5	0.003509	0.217391
Hydrogen FC	**38.46154**	0.02	0.769231	0.018643	<250
Combustion	24.4898	0.041667	**1.020408**	**0.077419**	<120
Solar	5.6	0.014881	0.083333	0.000112	**<336**

The bold formatted values indicate the best value obtained for each ratio.

required. SPH can utilize both in varying ratios, i.e. 100% of both or 60% one and 40% the other; therefore one can regulate the efficiency. Generally SPH also only uses the one power source, either when assistance is required or when the power requirements are really low in order to decrease fuel usage. SH uses the one power source (electric power) as its main power source and utilizes the other (petrol/diesel generator) to recharge the main source, thus the second power source is not connected to the main power system. PIH uses the main power source permanently and uses grid power via a plug to recharge, thus avoiding the use of the combustion engine for this purpose. The use of the combustion engine is then up to the discretion of the driver, making this option the more pure of the five [72, 73, 74, 75, 76].

The type of hybrid method used depends on many aspects including, cost, availability, user preference and application. Some areas in the world are far from a reliable source of energy, therefore utilizing renewable energy sources becomes imperative, but these sources tend to have low energy density and poor stability. To combat this, the renewable source is combined with something of a less renewable nature or another renewable source [77]. Another advantage of hybrid systems can be the reduction in one's carbon footprint. In order to meet the needs of both energy and power, hybrid power supplies are becoming more popular. A couple of these hybrid power supplies, solar hybrids, gasoline-electric hybrids, plug-in hybrid electric (PHE) and hybrids containing SCs, are explained further below.

Solar Hybrid systems include the combination of PV and CSP systems with each other or other forms of power generation such as diesel, wind or biogas. This hybridization allows the system to modulate power output depending on the demand or to reduce fluctuations caused by the solar power [78]. Solar power-hybrid drones deliver astonishing endurances. Tethered systems also fall under these types of drones. These are systems that allow an unlimited flight time within the small radius. These types of UAVs are used more for military or industrial application and are therefore not of interest for this paper.

Gasoline-Electric Hybrids are mainly used for regenerative breaking, dual power or less idling. As the vehicle slows down for breaking the energy is used to recharge the batteries, depending on the driving circumstances the power can be divided between the dual sources or the vehicle can be shut off and restarted easier using an electric motor when the vehicle comes to a stop [79]. For UAV applications these types combine the quick reactions of an electric motor with the advantages of gasoline powered flight. Plug in Hybrid Electric (PHE) systems use a combustion engine to supplement the electric engine when the battery levels are too low. The electric motor is powered mainly using PV-arrays. The main shortcoming to this hybrid system is the necessity of the combustion engine [80].

Table 5. Summary of information presented regarding power sources.

Power source	Advantages vs. Disadvantages	Possible Combinations	Flight time	Peak power	Size	Noise	Charge/ discharge rate
Batteries	Smaller, light weight. Cannot supply peak power demands.	Hydrogen FC Solar panel S/HCs	4	2	1	3	4
Hydrogen FC	No pollution, quieter, fast recharge. Larger size, cannot supply peak power demands, operating costs subject to hydrogen availability.	Batteries S/HCs	2	3	2	1	1
Combustion engine	Robust. Heavy, bulky, limited to fixed wing type drone.	Solar Electric	3	1	3	4	2
Solar panels	Quiet, low operational and maintenance costs. Larger size due to panel space requirements, limited to fixed wing type drone.	Batteries Laser	1	4	4	2	3

Table 6. Comparison of different hybrid solutions.

Method	Advantages	Disadvantages
Solar hybrid	Reduces fluctuations present in pure solar power, high flight time.	Limited flight range and application.
Gasoline electric hybrid	Quick reaction of electric motor, long endurance of combustion engine.	Complex circuitry, bulky, pollution.
Plug in hybrid	Relies mainly on solar thus more efficient.	Pollution, bulky, complex circuitry.
FC and SC hybrid	Eco-friendly, high energy and power density.	Bulky, reliant on hydrogen availability, initially expensive.
Li-ion and SC hybrid	High energy and power density, longer endurance.	Limited by recharge rate and cycles of batteries.

A capacitor consists of electrodes (anode and cathode) separated by an electrolyte [81]. The variations of capacitors are differentiated through the type of electrodes and electrolyte used. Electrostatic capacitors store charges through dielectric polarization, their energy density is not very high, however the power density is, making them good for applications requiring short duration, high efficiency and high output power. SCs can be classified into two categories, double layer capacitors (DLC) and electrochemical capacitors (EC). The former involves a separation of charges at the interface of the electrodes and the electrolytes; the capacitance is proportional to the area of the electrode material. The latter functions on the principle of fast Faraday redox reactions, therefore relying on high reversible redox reactions occurring on the electrodes surface or inside the electrodes to produce the specific capacitance. The breakdown potential of the electrolyte limits the voltage of the capacitors to a maximum of 3 V; therefore a series connection is required to increase the working voltage, which simultaneously reduces the effective capacitance.

The SC is based on the high working voltage of an electrolytic capacitor and combines the electrolytic and ECs to have the best features with a high working voltage, specific capacitance and energy density [81]. SCs have the advantage of fast charging, large power density and a long cycle life with the main disadvantage being their low energy density. Their advantages make them the best suited option for supplementing another power source requiring an increase in peak power. SCs have the capability to deliver quick bursts of energy during peak power demands and store energy and excess power that would otherwise be lost. They have a much lower energy density than batteries but are great at supplementing these power shortages [82, 83, 84, 85].

The uses of SCs on drones are still in the initial stages of implementation and as such there are very limited resources detailing the efficiency thereof. The charge and discharge of SCs occurs very quickly compared to batteries, they have high power density, and almost unlimited recharge cycles. On the other hand they can be large and bulky, must be used to supplement main power supply and cannot efficiently function as the main power source. The use of SCs on drones is usually in the supplementation capacity, they are used as a secondary source to supplement the primary source when peak power is required and as such there are many different hybrid systems containing SCs.

An aluminum air FC (AAFC) can be combined with super capacitors to form a power source. AAFCs have a higher energy density than most other batteries, but have a lower power density, therefore on its own, the AAFC is not a viable driving source of power. As mentioned above, SCs have a high power density, fast charge and discharge, but a poor energy density. This makes them ideal for supplementing the AAFC. There are three stages in power supply of this system, stage 1 involves only the use of the AAFC when there is a low power demand, stage 2 uses both AAFC and SC for larger power demands and stage 3 is one that occurs continuously, known as regenerative breaking, where the SC is charged through the use of energy that is usually lost when the system idles [86].

The Li-ion battery has many advantages over other batteries including, high voltage, light weight, low self-discharging and long cycle life. The shortcoming of Li-ion batteries is that if they are used in a high power demand application, their performance in terms of weight, cost and lifetime degrades tremendously. By adding the SCs, the battery can satisfy the average power demands while the SCs satisfy the peak power demands during acceleration or breaking [87].

3.7.2. Comparison of hybrid solutions

By comparing the different hybrid methods laid out in this section it will be possible to determine how relevant and also how efficient they are. This comparison of the advantages and disadvantages of each is done in Table 6, below. According to Table 6, FC and SC hybrids have the best advantages and have more desirable disadvantages when compared to the other hybrid methods, Li-ion and SC hybrids come in close second as they have the difference of the disadvantage of a limited cycle life when compared to the FC and SC hybrid. The other hybrid methods are also very advantageous however they have the downfall of being quite a bit larger and more complex than the last two.

4. Conclusion

UAVs are fast becoming a ubiquitous resource for industrial and commercial use as they offer many technological and safety advantages. However, in order for the areas of application to expand, the power supply system needs to be upgraded to increase its endurance. There are many different power sources for drones, each with their own advantages and disadvantages, some more than others, depending on the application. Presently the most popular power sources are combustion engines, FCs and batteries.

The aim of this paper was to review the different power sources currently available for UAVs, to determine their shortfalls and what solutions currently exist to address these shortfalls. The review has been done to help highlight the shortcomings pertained to the specific sources. From this the following conclusions can be made:

4.1. Power sources

- Combustion engine powered drones offer the best characteristics across the board, their biggest downfall being their pollution aspect.
- Solar systems, although extremely eco-friendly with a preferable flight time, are much more expensive than the other options.
- If the cost could be justified by the advantages, hydrogen fuel cells offer a great alternative to combustion engines as they have a large flight time, low weight and considerably quick refuel time. They are also very eco-friendly.
- SCs have inverse advantages and disadvantages as compared to the other power sources.

4.2. Possible solutions

- Most of the solutions increase complexity of the system.
- The top solutions are FC and SC hybrids and Li-ion and SC hybrids.
- Hybrid systems allow for the reduction of a power source's shortfalls by combining it with another power source that has those aspects as advantages. This allows the user or designer to decide which disadvantages can be tolerated.

Combustion engines are robust but much heavier and have a limited application due to them being mainly applied to fixed-wing types. FCs and batteries offer a large flight time and a larger range since they are more maneuverable but both struggle to supply peak current when required and the supply thereof drains the source at a drastic rate.

Hybrid systems tend to offer a very good advantage over all other systems. They can utilize more than one power source in order to acquire the specific advantages that each power source has to offer. These systems also tend to eliminate small issues such as prolonged charging time, short flight times, poor peak power supply, etc. The most common power source used in hybrid systems is SCs, as they tend to have advantages that overcome the disadvantages of the other power sources.

It was found that the flight time of drones can be improved by implementing a hybrid system. This system however would need to be comparable in weight and size, to an existing drone, while increasing the efficiency in order to be an improvement on the current systems. Hydrogen FC are effectively a hybrid system as they contain Li-Po batteries, but Li-Po batteries have many disadvantages when it comes to their use in drones, they have low energy density, short flight time, comparably long recharge time, they can be hazardous to the environment and have a limited life span compared to the other power sources. As SCs have a high energy density, short recharge period and almost infinite cycle life, they seem to be the obvious replacement for the Li-Po battery in this system but further research is required into how they affect the efficacy of the FC system in drone applications.

Declarations

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Funding statement

This work was supported by Hydrogen South Africa (HySA).

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

[1] Q. Zhai, K. Meng, Z.Y. Dong, J. Ma, Modeling and analysis of lithium battery operations in spot and frequency regulation service markets in Australia electricity market, IEEE Trans. Ind. Informat. 13 (5) (Oct. 2017) 2576–2586.

[2] Z.F. Pan, L. An, C.Y. Wen, Recent advances in fuel cells based propulsion systems for unmanned aerial vehicles, Appl. Energy 240 (February) (2019) 473–485.

[3] M. Alwateer, S.W. Loke, N. Fernando, Enabling drone services: drone crowdsourcing and drone scripting, IEEE Access 7 (2019) 110035–110049.

[4] L. Tang, G. Shao, Drone remote sensing for forestry research and practices, J. For. Res. 26 (4) (2015) 791–797.

[5] M. Alwateer, S.W. Loke, A.M. Zuchowicz, Drone services: issues in drones for location-based services from human-drone interaction to information processing, J. Locat. Based Serv. 13 (2) (2019) 94–127.

[6] L. Ruan, et al., Energy-efficient multi-UAV coverage deployment in UAV Networks : a game-theoretic framework 15 (October) (2018) 194–209.

[7] A. Claesson, et al., Drones may be used to save lives in out of hospital cardiac arrest due to drowning, Resuscitation 114 (2017) 152–156.

[8] S. Loke, M. Alwateer, V. Abeysinghe, Virtual space boxes and drone-as-reference-station localisation for drone services: an approach based on signal strengths, 2016.

[9] A. Shukla, X. Huang, H. Karki, Autonomous Tracking and Navigation Controller for an Unmanned Aerial Vehicle Based on Visual Data for Inspection of Oil and Gas Pipelines, 2016.

[10] M. Bacco, et al., Smart Farming: Opportunities, Challenges and Technology Enablers, 2018, pp. 1–6.

[11] G. Ding, Q. Wu, L. Zhang, Y. Lin, T. Tsiftsis, Y.-D. Yao, An amateur drone surveillance system based on cognitive internet of things, IEEE Commun. Mag. 56 (2017).

[12] J. Lee, et al., Constructing a Reliable and Fast Recoverable Network for Drones, 2016, pp. 1–6.

[13] S. Yoo, et al., Poster, 2015, pp. 275–277.

[14] J. Zhou, B. Zhang, W. Xiao, D. Qiu, Y. Chen, Nonlinear parity-time-symmetric model for constant efficiency wireless power transfer: application to a drone-in-flight wireless charging platform, IEEE Trans. Ind. Electron. (2018) 1.

[15] M. Lu, M. Bagheri, A. James, T. Phung, UAV wireless charging: a review, reconceptualization, and extension, IEEE Access (May 2018).

[16] A. Sato, H. Naknishi, Observation and measurement in disaster areas using industrial use unmanned helicopters, in: 12th IEEE Int. Symp. Safety, Secur. Rescue Robot. SSRR 2014 - Symp. Proc., 2014, pp. 1–5.

[17] A. A. Cc., Afridrones, Afridrones.com, 2019 [Online]. Available: https://afridrones.com/.

[18] V. Aravindan, J. Gnanaraj, Y. Lee, S. Madhavi, Insertion-type electrodes for nonaqueous Li-ion capacitors, Chem. Rev. 114 (Jul) (2014).

[19] S. Ci, N. Lin, D. Wu, Reconfigurable battery techniques and systems: a survey, IEEE Access 4 (Jan) (2016) 1.

[20] K. Rajashekara, Present status and future trends in electric vehicle propulsion technologies, Emerg. Sel. Top. Power Electron. IEEE J. 1 (Mar. 2013) 3–10.

[21] C. Vidal, S. Member, O. Gross, R. Gu, P. Kollmeyer, A. Emadi, xEV Li-ion battery low-temperature effects — review 68 (5) (2019) 4560–4572.

[22] F. Wagner, B. Lakshmanan, M. Mathias, Electrons to go: electrochemistry and the future of the automobile, J. Phys. Chem. Lett. - J PHYS CHEM LETT 1 (Jul. 2010).

[23] E. Karden, S. Ploumen, B. Fricke, T. Miller, K. Snyder, Energy storage devices for future hybrid electric vehicles, J. Power Sources 168 (May 2007) 2–11.

[24] T. Kim, W. Qiao, L. Qu, Power electronics-enabled self-X multicell batteries: a design toward smart batteries, IEEE Trans. Power Electron. 27 (11) (2012) 4723–4733.

[25] J. Meng, G. Luo, F. Gao, Lithium polymer battery state-of-charge estimation based on adaptive unscented Kalman filter and support vector machine, IEEE Trans. Power Electron. 31 (Jan. 2015) 1.

[26] M. Song, et al., Improved charging performances of Li2O2 cathodes in non-aqueous electrolyte lithium-air batteries at high test temperatures, ICMREE 2013 - Proc. 2013 Int. Conf. Mater. Renew. Energy Environ. 2 (82604132222) (2013) 513–515.

[27] R. Components, FG20201 lead acid battery - 12V, 2Ah [Online]. Available: https://za.rs-online.com/web/p/lead-acid-batteries/8431308/. (Accessed 18 May 2020).

[28] R. Components, RS PRO 12V NiMH AA rechargeable battery pack, 2000 mAh [Online]. Available: https://za.rs-online.com/web/p/rechargeable-battery-packs/7770400/. (Accessed 18 May 2020).

[29] R. Components, Samsung 3.6V 18650 lithium-ion battery, 2000mAh [Online]. Available: https://za.rs-online.com/web/p/speciality-size-rechargeable-batteries/8182992/. (Accessed 18 May 2020).

[30] R. Components, RS PRO 12V CS NiCd rechargeable battery, 1800mAh [Online]. Available: https://za.rs-online.com/web/p/rechargeable-battery-packs/1253427/. (Accessed 18 May 2020).

[31] R. Components, RS PRO 1.5V alkaline AA battery [Online]. Available: https://za.rs-online.com/web/p/aa-batteries/7442199/. (Accessed 18 May 2020).

[32] R. Components, RS PRO 3.7V Wire Lead Terminal Lithium Rechargeable Battery, 2000mAh." .

[33] R. Components, "RS Button Battery, PR44, 1.4V, 11.6mm Diameter." .

[34] Mantech, "LITHIUM CELL/BATTERY AA 3V6 2.2AH 14x50." .

[35] NASA, Technology Readiness Level Definitions, 1989, p. 1.

[36] S.A. Kalogirou, Industrial process heat, chemistry applications, and solar dryers, in: Solar Energy Engineering, Elsevier, 2014, pp. 397–429.

[37] DroneII, Drone energy sources [Online]. Available: https://www.droneii.com/drone-energy-sources. (Accessed 30 July 2020).

[38] S. Ganguly, S. Das, K. Kargupta, D. Bannerjee, Optimization of performance of phosphoric acid fuel cell (PAFC) stack using reduced order model with integrated space marching and electrolyte concentration inferencing, Computer Aided Chem. Eng. 31 (2012) 1010–1014.

[39] V. Kumar, R. Rudra, S. Hait, P. Kumar, P.P. Kundu, Performance trends and status of microbial fuel cells, in: Progress and Recent Trends in Microbial Fuel Cells, Elsevier, 2018, pp. 7–24.

[40] S. Haile, D. Boysen, C. Chisholm, R. Merle, Solid acids as fuel cell electrolytes, Nature 410 (May 2001) 910–913.

[41] S. Haile, C. Chisholm, K. Sasaki, D. Boysen, T. Uda, Solid acid proton conductors: from laboratory curiosities to fuel cell electrolytes, Faraday Discuss 134 (Feb. 2007) 17–39, discussion 103.

[42] M. Uzunoglu, M.S. Alam, Fuel-cell systems for transportations, in: Power Electronics Handbook, Elsevier, 2018, pp. 1091–1112.

[43] S. Dharmalingam, V. Kugarajah, M. Sugumar, Membranes for microbial fuel cells, in: Microbial Electrochemical Technology, Elsevier, 2019, pp. 143–194.

[44] M. Steilen, L. Jörissen, Hydrogen conversion into electricity and thermal energy by fuel cells, in: Electrochemical Energy Storage for Renewable Sources and Grid Balancing, Elsevier, 2015, pp. 143–158.

[45] C. Thanomjit, Y. Patcharavorachot, A. Arpornwichanop, Design and Thermal Analysis of a Solid Oxide Fuel Cell System Integrated with Ethanol Steam Reforming, 2012, pp. 287–291.

[46] V. Mehta, J. Cooper, Review and analysis of PEM fuel cell design and manufacturing, J. Power Sources 114 (Feb. 2003) 32–53.

[47] O. Mohammed, D. Lowther, M. Lean, B. Alhalabi, On the creation of a generalized design optimization environment for electromagnetic devices, Magn. IEEE Trans. 37 (Oct. 2001) 3562–3565.
[48] F. Barreras, A. Lozano, L. Valiño, C. Marin, A. Pascau, Flow distribution in a bipolar plate of a proton exchange membrane fuel cell: experiments and numerical simulation studies, J. Power Sources 144 (Jun. 2005) 54–66.
[49] G.Y. Jeon, et al., PEM (proton exchange membrane) fuel cell bipolar plates, in: Proceeding Int. Conf. Electr. Mach. Syst. ICEMS 2007, 2007, pp. 1891–1893.
[50] A. Gong, R. Macneill, D. Verstraete, J. Palmer, Analysis of a Fuel-Cell/Battery/Supercapacitor Hybrid Propulsion System for a UAV Using a Hardware-In-The-Loop Flight Simulator, 2018.
[51] T. Hodgkinson, Long live the senses, Cult. Critiq. 104 (1) (2019) 192–201.
[52] K. Grote, B. Bender, D. Göhlich, Dubbel – Taschenbuch für den Maschinenbau, 25th ed., Springer, 2018.
[53] K. Reif, Dieselmotor-Management im Überblick, second ed., Springer, 2014.
[54] A. Jammer, C. Support, and C. Relay, "Non Sensitive Information – Releasable to the Public ANNEX B NATO Unmanned Aircraft Systems - Operational as Determined via Open-Source (Public) Documents (HALE and MALE Systems Are Presented in Bold) Non Sensitive Information – Releasable to the Publ," Nation, pp. 1–9.
[55] Y. Liu, X. Ning, Al/Al 2 O 3 interface : a first-principle study, Comput. Mater. Sci. 85 (April) (2014) 193–199.
[56] B. Lojek, History of semiconductor engineering, Hist. Semicond. Eng. (2007) 1–387.
[57] L. Fraas, L. Partain, Solar Cells and Their Applications, second ed., 2010, pp. 581–611.
[58] D. Verstraete, K. Lehmkuehler, K.C. Wong, Design of a fuel cell powered blended wing body UAV, Adv. Aerosp. Technol. 1 (2012) 621–629.
[59] T. Donateo, A. Ficarella, L. Spedicato, A. Arista, M. Ferraro, A new approach to calculating endurance in electric flight and comparing fuel cells and batteries, Appl. Energy 187 (Feb. 2017) 807–819.
[60] L.W. Traub, Range and endurance estimates for battery-powered aircraft, J. Aircraft 48 (2) (Mar. 2011) 703–707.
[61] Y. Wang, K.S. Chen, J. Mishler, S.C. Cho, X.C. Adroher, A review of polymer electrolyte membrane fuel cells: technology, applications, and needs on fundamental research, Appl. Energy 88 (4) (Apr. 2011) 981–1007.
[62] G. Rhoads, T. Bradley, N. Wagner, B. Taylor, D. Keen, Design and flight test results for a 24 hour fuel cell unmanned aerial vehicle, in: 8th Annual International Energy Conversion Engineering Conference, 2010.
[63] L. Peng, S. Zheng, X. Chai, L. Li, A novel tangent error maximum power point tracking algorithm for photovoltaic system under fast multi-changing solar irradiances, Appl. Energy 210 (Jan. 2018) 303–316.
[64] Y. Chen, D. Baek, A. Bocca, A. Macii, E. Macii, M. Poncino, A Case for a Battery-Aware Model of Drone Energy Consumption, 2018.
[65] D. Store, Matrice 600 pro. [Online]. Available: https://store.dji.com. (Accessed 18 May 2020).
[66] BMPower, BMPower Range of products [Online]. Available: https://bmpower.us/. (Accessed 18 May 2020).
[67] Yeair!, Yeair! Is the next generation quadcopter solution [Online]. Available: https://yeair.de/features/. (Accessed 18 May 2020).
[68] Sinovoltaics, Top 8 solar powered drone (UAV) developing companies [Online]. Available: https://sinovoltaics.com. (Accessed 18 May 2020).
[69] K. Rajashekara, Power Electronics for the Future of Automotive Industry, in: PCIM, 2002.
[70] A. Emadi, K. Rajashekara, S. Williamson, S.M. Lukic, Topological overview of hybrid electric and fuel cell vehicular power system Architectures and configurations, Veh. Technol. IEEE Trans. 54 (Jun. 2005) 763–770.
[71] B. Chen, X. Li, S. Evangelou, Comparative Study of Hybrid Powertrain Architectures from a Fuel Economy Perspective, 2018.
[72] M. Yilmaz, P. Krein, Review of battery charger topologies, charging power levels, and infrastructure for plug-in electric and hybrid vehicles, Power Electron. IEEE Trans. 28 (May 2013) 2151–2169.
[73] A. Emadi, Y. Lee, K. Rajashekara, Power electronics and motor drives in electric, hybrid electric, and plug-in hybrid electric vehicles, Ind. Electron. IEEE Trans. 55 (Jul. 2008) 2237–2245.
[74] P. Bajec, D. Voncina, D. Miljavec, J. Nastran, Bi-directional power converter for wide speed range Integrated Starter-Generator 2 (2004).
[75] L. Chedot, G. Friedrich, J.-M. Biedinger, P. Macret, Integrated starter generator: the need for an optimal design and control approach. Application to a permanent magnet machine, Ind. Appl. IEEE Trans. 43 (Apr. 2007) 551–559.
[76] A. Jain, S. Mathapati, V.T. Ranganathan, V. Narayanan, Integrated starter generator for 42-V powernet using induction machine and direct torque control technique, Power Electron. IEEE Trans. 21 (Jun. 2006) 701–710.
[77] M. Chen, L. Huang, J. Yang, Y. Lyu, Design and Simulation of Multi-Energy Hybrid Power System Based on Wave and Wind Energy, 2017.
[78] D. Kraemer, L. Hu, A. Muto, X. Chen, G. Chen, M. Chiesa, Photovoltaic-thermoelectric hybrid systems: a general optimization methodology, Appl. Phys. Lett. 92 (Jun. 2008) 243503.
[79] S.D. Shah, Electrification of Transport and Oil Displacement: How Plug-Ins Could lead to a 50 Percent Reduction in US. Demand for Oil, Jan. 2009, pp. 22–44.
[80] H. Fathabadi, Plug-in hybrid electric vehicles (PHEVs): replacing internal combustion engine with clean and renewable energy based auxiliary power sources, IEEE Trans. Power Electron. 1 (Jan. 2018).
[81] J.-Y. Zou, L. Zhang, J.-Y. Song, Development of the 40 V hybrid super-capacitor unit, Magn. IEEE Trans. 41 (Feb. 2005) 294–298.
[82] R. Lu, C. Zhu, L. Tian, Q. Wang, Super-capacitor stacks management system with dynamic equalization techniques, IEEE Trans. Magn. 43 (1) (2007) 254–258.
[83] A. Burke, M. Miller, Comparisons ultracapacitors and advanced batteries for pulse power in vehicle applications: Performance, Life Cost EVS 19 (Jan. 2002) 855–866.
[84] L.J. Deal, Department of energy 3 (April 2013) (1982) 203–204.
[85] A. Burke, The Present and Projected Performance and Cost of Double-Layer Pseudo-capacitive Ultracapacitors for Hybrid Vehicle Applications, 2005.
[86] Y. Zhang, Y. Mo, Z. Yang, An energy management study on hybrid power of electric vehicle based on aluminum air fuel cell, IEEE Trans. Appl. Supercond. (Sep. 2016) 1.
[87] T. Mesbahi, F. Khenfri, P. Bartholomeus, P. moigne, Combined optimal sizing and control of Li-ion battery/supercapacitor embedded power supply using hybrid particle swarm-Nelder-Mead algorithm, IEEE Trans. Sustain. Energy 8 (Jan. 2016) 1.