

Review

Power Sources for Unmanned Aerial Vehicles: A State-of-the Art

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Abstract: Over the past few years, there has been an increasing fascination with electric unmanned aerial vehicles (UAVs) because of their capacity to undertake demanding and perilous missions while also delivering advantages in terms of flexibility, safety, and expenses. These UAVs are revolutionizing various public services, encompassing real-time surveillance, search and rescue operations, wildlife assessments, delivery services, wireless connectivity, and precise farming. To enhance their efficiency and duration, UAVs typically employ a hybrid power system. This system integrates diverse energy sources, such as fuel cells, batteries, solar cells, and supercapacitors. The selection of an appropriate hybrid power arrangement and the implementation of an effective energy management system are crucial for the successful functioning of advanced UAVs. This article specifically concentrates on UAV platforms powered by batteries, incorporating innovative technologies, like in-flight recharging via laser beams and tethering. It provides an all-encompassing and evaluative examination of the current cutting-edge power supply configurations, with the objective of identifying deficiencies, presenting perspectives, and offering recommendations for future consideration in this domain.

Keywords: UAV; power supply; battery swapping; laser beam inflight charging; tethered UAV; batteries; battery systems; materials of batteries; efficiency; duration; hybrid power system; energy management system



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1. Introduction

An unmanned aerial vehicle (UAV), also referred to as a flying robot or drone, possesses the ability to operate independently or under remote control for specific missions [1]. In recent times, UAVs have garnered considerable attention as a result of advancements in microprocessors [2,3] and artificial intelligence (AI) [4–7], sensors [8–14], and the design [15–18] and manufacturing process [16–20], facilitating the creation of intelligent UAVs. The term “intelligent UAVs” refers to these drones’ capacity to operate autonomously or semi-autonomously, making real-time decisions based on data from their sensors and AI algorithms. These intelligent UAVs can adapt to changing environments, navigate with precision, and perform tasks with a level of autonomy that was once reserved for science

fiction [21]. Moreover, the UAV wireless charging system represents a significant departure from conventional cable-based charging methods. This innovation has attracted substantial interest in the field [22], as it offers a promising alternative to traditional charging mechanisms, further enhancing the appeal of UAV technology. These technologically advanced UAVs offer a multitude of benefits, including cost efficiency and exceptional maneuverability, leading to their utilization in diverse military and civilian domains such as mine clearance, surveillance, delivery services, wireless connectivity, and agriculture [23,24]. It is crucial to highlight that UAVs have significant advantages over UGV operational requirements [25], but UGVs are preferred for heavy-load missions due to their ability to carry substantial payloads [26]. Prominent multinational corporations are making substantial investments to enhance UAV capabilities and expand their application spectrum. Nowadays detection techniques improve safe and reliable UAV operations due to fault detection methods [27]. It is estimated that the market value of UAVs will reach a staggering USD 127 billion by 2022 [28,29]. This surge is propelled by remarkable advancements in microprocessors, artificial intelligence (AI), sensors, design, and manufacturing processes. Recent statistics and trends underscore their growing significance, as UAVs have become integral in numerous real-world applications. For instance, in 2021, the global drone market was valued at USD 22.5 billion, and it is projected to reach a staggering USD 42.8 billion by 2026 [28,29]. These numbers reflect not only the market's explosive growth but also the increasing adoption of UAVs across various sectors. From precision agriculture to search and rescue missions, surveillance, and even package delivery services, the ubiquity of UAVs is a testament to their versatile and dynamic role in modern society.

UAVs exhibit diverse features and configurations that are tailored to meet specific mission demands. Consequently, the literature provides multiple classifications that emphasize various parameters [30,31]. In terms of their physical structure, UAVs can be classified into distinct categories such as fixed-wing, rotary-wing, flapping-wing, hybrid, or balloon configurations. When considering their dimensions, UAVs come in different sizes, including mini, micro, and nano variations. The North Atlantic Treaty Organization (NATO) has established a classification system for UAVs, grouping them into three classes based on their maximum take-off weight (MTOW). Each class is further divided into subcategories, which take into account factors such as altitude and mission radius [32].

Electric UAVs are favored for their advantageous characteristics, such as their reliability [33], reduced noise, disturbance rejection [34] and thermal signatures [35,36], high efficiency [5], absence of pollutant emissions, self-starting capabilities, and advanced control mechanisms that enable exceptional maneuverability. For instance, electric UAVs have excelled in urban environments where noise and emissions regulations are stringent. They are being utilized for tasks like monitoring traffic, delivering medical supplies, or capturing aerial footage with minimal disruption. On the other hand, internal combustion engine (ICE)-based UAVs offer longer endurance due to the high power and energy densities of ICE. Thus, ICE-based UAVs, with their extended endurance, still have their place in missions requiring long flight durations, such as search and rescue operations in remote areas or the surveillance of large, sparsely populated regions. The choice between electric and ICE-based UAVs often depends on the specific demands of the mission and the environmental considerations [35]. However, they necessitate an auxiliary starting motor, involve more complex control demands [37], and generate high acoustic and thermal signatures. Some researchers [38,39] have explored hybrid architectures that combine electric motors with ICE to harness the advantages of both engine types. Nevertheless, the depletion of fossil fuels and the growing concerns regarding greenhouse gas (GHG) emissions have diminished the appeal of thermal engines, prompting the adoption of electric propulsion as a sustainable technology across various sectors, including transportation [40]. International policies and market trends that aim to phase out ICE vehicles [41] are expected to extend to UAVs in the foreseeable future, fostering the development of environmentally friendly devices. The shift away from ICE in UAVs, particularly for tasks that do not require extensive endurance, can be attributed to these factors.

Batteries serve as the primary source of electric power, but their flight durations in UAVs are limited by their low energy density and long-lasting charging time [41] similar to all unmanned types of unmanned vehicles [42]. These challenges are common to various types of unmanned vehicles. In addition to energy density and charging time concerns, the safety of battery energy storage systems has become a paramount consideration, especially in light of the increasing use of electric vehicles [43]. Monitoring the state of charge (SOC) and battery temperature has proven to be instrumental in enabling comprehensive decision-making within the system, ultimately enhancing safety and performance. Furthermore, batteries may not offer the required power response for rapid maneuvers due to their slow power dynamics. To address these limitations, supercapacitors present a suitable option for balancing the constraints imposed by batteries [44]. It should be noted that flight endurance can be improved through aerodynamic optimization during the UAV design phase [45]. Recent advancements in battery technology have slightly extended endurance to approximately 90 min using lithium polymer (LiPo) batteries [46]. However, increasing the number of batteries becomes impractical due to weight and space limitations. One of the key challenges is the limited energy density of batteries, which constrains the amount of energy that can be stored within a given weight and volume [47]. This limitation impacts the flight duration and payload capacity of electric UAVs, making it a critical consideration in mission planning. Additionally, batteries exhibit slow power dynamics, meaning they may not provide the rapid power response required for sudden maneuvers or emergencies. These challenges are central to the quest for improving the endurance and overall capabilities of electric UAVs [22]. To enhance UAV endurance, additional power sources must be employed to supplement batteries while adhering to weight and space constraints. In this regard, fuel cells offer a promising solution due to their high specific energy and near instantaneous refueling capability. They can typically achieve up to five times higher energy density than LiPo batteries, significantly enhancing the endurance of hybrid UAVs [48]. It is worth mentioning that many existing electric UAVs utilize fuel cells as their primary power source. Supercapacitors can also contribute to the power supply process due to their high-power density and rapid response to peak power demands during UAV take-off and sudden maneuvers. They excel in providing high power density, enabling electric UAVs to execute swift maneuvers and respond promptly to changing flight conditions. Additionally, supercapacitors boast a longer cycle life, meaning they can endure a higher number of charge and discharge cycles without significant degradation. The combination of batteries and supercapacitors in a hybrid system capitalizes on the strengths of both technologies, optimizing energy storage and delivery for UAVs. Fixed-wing UAVs have the advantage of incorporating solar cells and harnessing solar energy, which can reduce fuel consumption and greatly enhance endurance when combined with an energy storage system [49].

Therefore, in order to achieve longer endurance for UAVs, it becomes necessary to employ hybrid power supply systems that combine multiple power sources. The selection of the power supply system structure is crucial and depends not only on the characteristics of the power sources but also on the specific mission requirements of the UAV. To effectively manage the distribution of power among the onboard power sources and ensure optimal performance and efficiency for the intended mission, the implementation of an energy management system (EMS) is essential. An EMS is a sophisticated control system that plays a pivotal role in efficiently managing the distribution of power among the UAV's onboard power sources. It employs a combination of current and voltage sensors for monitoring power flow, converters for regulating the power source outputs, and a processing unit responsible for executing the adopted power management strategy. The EMS ensures that power is allocated optimally, enabling the UAV to meet its specific mission requirements. In addition to hybridization, there are alternative techniques available to extend the endurance of battery-based UAVs. These techniques include battery swapping [50,51], in-flight recharging using laser beams [52–55], and tethered UAVs [56–58]. Battery swapping involves replenishing depleted batteries of a UAV during its mission by

utilizing ground stations located at specific locations. In-flight recharging utilizes a laser beam transmitted from a generator at a ground station to provide light power, enabling recharging without the need for landing. Tethered UAVs have the advantage of unlimited endurance as they receive a continuous power supply through connection lines that link the UAV to a ground-based power supply station.

Numerous review papers in the literature have extensively covered various aspects of UAVs. These include topics such as fuel storage and generation in small fixed-wing UAVs [41], the classification, advancements, and research trends in small-scale UAVs [58], the classification and design challenges of UAVs [30], path planning algorithms for fixed-wing UAVs [59], the guidance, navigation, and control of rotorcraft unmanned aircraft systems [60], and the modeling and control of quadrotors [61]. However, the specific focus of this review is centered on the energy aspect of UAVs. Its objective is to provide a comprehensive and critical assessment of the existing power supply structures [62] and their corresponding energy management systems. This review will not only identify any existing gaps but also provide valuable recommendations and prospects to guide future research in this field.

2. Unmanned Aerial Vehicle (UAV)

Prior to discussing the various power sources, it is important to provide a brief introduction to the two main types of UAVs, as illustrated in Figure 1. These types are rotary-wing UAVs and fixed-wing UAVs. Rotary-wing UAVs are characterized by a body structure that incorporates multiple rotors for propulsion. In contrast, fixed-wing UAVs resemble conventional aircraft, featuring fixed wings on either side of the body. Rotary-wing UAVs, also known as rotorcraft types, have gained popularity due to their ability to perform vertical take-off and landing, eliminating the need for a runway or launcher. They are capable of hovering in the air and exhibit exceptional agility, making them well-suited for precise maneuvering tasks. However, the design of rotary-wing UAVs involves mechanical and electronic complexities, resulting in more intricate maintenance procedures, reduced operational time, and increased costs. Additionally, rotary-wing UAVs generally have lower payload capacities, higher power requirements, shorter operational durations, and even higher costs.



Figure 1. Two types of drones: (a) fixed-wing drone, (b) rotary-wing drone.

Fixed-wing UAVs present several advantages over rotary-wing UAVs. They possess a simpler structure, leading to easier maintenance and improved aerodynamics, resulting in reduced operational costs and increased flight time. The presence of fixed wings enables natural gliding capabilities, leading to lower power consumption. Additionally, fixed-wing UAVs can carry larger payloads over longer distances with less power, enhancing efficiency and cost-effectiveness. However, they require a runway or launching device for take-off and landing, lack the hovering capability of rotary-wing UAVs, and tend to be larger and bulkier, compromising maneuverability. In addition to rotary-wing and fixed-wing UAVs, there is a unique type of drone that combines the characteristics of both. This hybrid drone

offers the stability and maneuverability of a rotary-wing drone along with the extended flight range of a fixed-wing drone. Importantly, it does not require a runway or additional equipment for take-off. Figure 2 provides an illustration of this combination drone. Each type of UAV—rotary-wing, fixed-wing, and hybrid—has its own applications that align with their respective advantages and disadvantages. Moreover, various power sources are employed in these drones.

Rotary-wing UAVs are highly versatile, excelling in tasks that require precision and agility, such as surveillance, search and rescue, and monitoring. They are ideal for stable and controlled aerial observation in confined spaces and urban environments. On the other hand, fixed-wing UAVs are preferred for endurance and long-range missions, making them suitable for tasks like precision agriculture, mapping, wildlife tracking, border patrols, and high-speed data collection in expansive areas. The choice between these UAV types depends on the specific mission requirements and operational constraints.

The unmanned aerial vehicle (UAV) platform, depicted in Figure 2, comprises several essential components. Firstly, there is an onboard flight control system encompassing processing units that handle various tasks, including implementing guidance, navigation, and control (GNC) algorithms, collecting and analyzing in-flight data, establishing communication with the ground station, and planning mission activities. Secondly, a propulsion system is integrated, which consists of multiple elements such as power supply sources, speed controllers, converters, energy management systems, motors, and propellers. These components work together to generate the required thrust and control the UAV's speed. Thirdly, the UAV is equipped with sensors that enable autonomous flight by providing crucial feedback and accurate measurements about the surrounding environment. Lastly, there is the payload, which includes additional equipment necessary for specific missions. This may comprise actuators, cameras, radar systems, or other specialized tools and instruments [63].

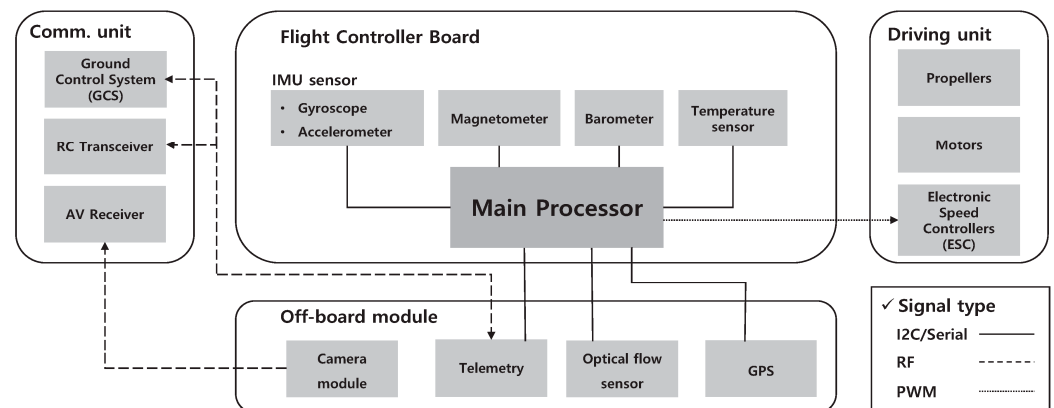


Figure 2. A typical UAV block diagram [64].

The propulsion system of a UAV plays a critical role as it consumes a significant portion of the onboard power. Its main purpose is to convert stored electrical energy into mechanical power, which propels the UAV through the motor propeller system called a propulsion unit. In fact, the propulsion system can constitute more than half of the total weight of the UAV. Figure 3 provides a typical schematic diagram of a UAV propulsion system. The power from the onboard sources is supplied to the DC bus through unidirectional and bidirectional converters, allowing for battery charging and discharging. These converters enable control over the power flow and receive control signals from the energy management system (EMS), which manages power distribution. Among the various motor types utilized in small UAVs, the brushless DC (BLDC) motor is widely preferred. This motor type offers significant advantages, including high efficiency and power density [65], as well as features such as high speed, favorable torque characteristics, reliability, ease of control via electronic speed controllers, ESCs, and long lifespan [66]. While induction motors are cost-effective

and robust, they have limitations such as relatively low efficiency, cooling challenges, and lower torque output.

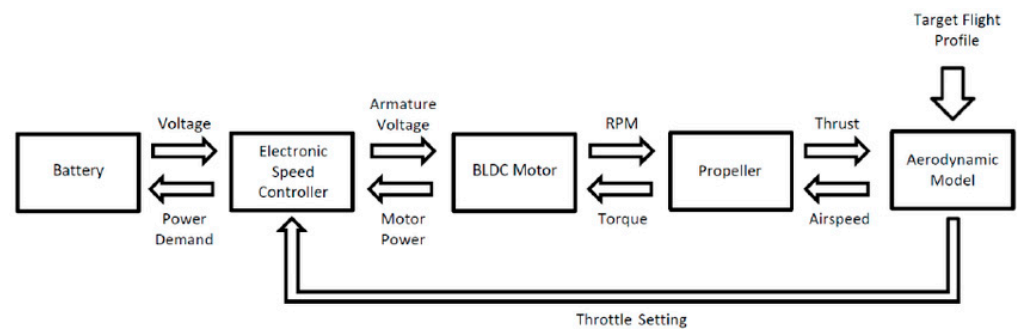


Figure 3. UAV propulsion system block diagram.

2.1. Unmanned Aerial Vehicle (UAV) Power Sources

Gas turbine engines have been widely used in aircraft propulsion systems due to their favorable power-to-weight ratio [67] and extended operational duration [30]. Gas turbine engines operate on the principle of air compression, combustion, and exhaust propulsion. They intake air, compress it, mix it with fuel for combustion, and then release the high-velocity exhaust gases to produce thrust. These engines are known for their high power-to-weight ratio, making them suitable for fast and agile UAVs. However, their optimal performance is limited to high-power ranges [68], typically above 100 hp [69]. As a result, they are not suitable for small-scale UAV applications, as they exhibit drawbacks such as inefficiency in fuel consumption, low overall efficiency, and high noise levels [70]. In contrast, the internal combustion engine (ICE) has traditionally served as the cornerstone of aircraft propulsion systems [71,72]. These engines are characterized by their energy density, making them suitable for long-endurance missions in UAVs. Compared to electric motors (EMs), ICEs offer advantages in terms of higher fuel energy and power densities, enabling longer flight times and larger payload capacities, which are crucial factors in flight missions. However, the multi-step energy production process in ICEs results in decreased system efficiency [56]. EMs are the preferred choice for UAVs due to their distinct characteristics, including minimal thermal and acoustic signatures, well-established electronic control systems, adaptability to automatic control, self-starting capabilities [37], cost-effectiveness, and higher reliability, which minimizes the risk of crashes caused by motor shutdown or failure. It should be noted that electric propulsion systems may encounter electronic speed controller (ESC) failures due to issues such as overheating and melting of the ESC casing. One potential solution to mitigate this problem is duplicating components [73].

A research paper [37] introduced a novel hybrid power propulsion prototype for unmanned aircraft systems (UAS), aiming to combine the advantages of thermal and electric engines. Although simulation results showed a 13% improvement in endurance, the system was considered complex and not environmentally friendly. Other researchers [73] have also discussed hybrid parallel powertrain architectures using electric motors (EMs) and internal combustion engines (ICEs). However, the incorporation of ICEs in UAVs is currently not the preferred solution due to limitations in fuel usage and endurance optimization. Therefore, this section will solely focus on electric propulsion-based UAVs and provide a critical evaluation of available electric power sources for UAV applications. Additionally, alternative supply strategies including swapping, laser beam inflight recharging, and tethered UAVs will be discussed, particularly for UAVs relying on a single power source.

2.2. Battery-Based Supply Techniques

2.2.1. Battery-Powered Unmanned Aerial Vehicles (UAVs)

Battery power is widely utilized in small UAVs, especially quadrotors, as it offers simplicity and flexibility to the propulsion system [71]. Battery-based platforms, particularly those using lithium batteries, such as LiPo batteries, are popular in hobbyist and

commercial applications due to their flight time capabilities and cost effectiveness. However, the endurance of small battery-powered UAVs is limited by the weight constraints of the battery pack, typically allowing for a maximum flight time of around 90 min using LiPo batteries [46]. LiPo batteries are preferred for small UAVs due to their lightweight nature and relatively high specific energy. In fact, LiPo batteries power the majority of micro aerial vehicles weighing less than 2 kg and with a length below 100 cm [30].

In selecting the appropriate battery technology for a given UAV application and mission, various characteristics such as specific energy, energy density, and specific power are taken into consideration. Table 1 provides detailed information on these characteristics for four different battery technologies, aiding in the battery technology selection process [44]. Additionally, in a specific study, different battery technologies were assessed based on the state of charge (SOC) for a particular mission, further emphasizing the importance of considering mission requirements when choosing battery technologies [58].

Table 1. Comparison of different batteries with their characteristics [57,58].

Characteristics	Ni-Cd	Ni-Mh	LiPo	Li-S
Specific energy (Wh/kg)	40	80	180	350
Energy density (Wh/L)	100	300	300	350
Specific power (W/kg)	300	900	2800	600

Ref. [74] focused on examining the factors that affect the performance of UAVs powered by batteries. Mathematical equations were developed to assess the UAV's range and endurance, taking into consideration the discharge conditions of the battery. The study establishes relationships to estimate the range and endurance of battery-powered aircraft, considering battery discharge rate and voltage drop effects. The research demonstrates that the Peukert effect can enhance range and endurance, particularly when battery capacity significantly exceeds current demand. Conversely, when the current draw approaches the battery's nominal capacity, effective capacity decreases. In situations with geometric constraints and a fixed battery weight as a fraction of the total aircraft weight, increasing battery capacity can lead to reduced performance due to higher power requirements and current draw.

One of the main challenges encountered by electric vehicles relying on battery power, including UAVs, is the limited autonomy they possess. Extensive efforts have been devoted to enhancing the performance of batteries in order to prolong operational duration and enable extended missions for electric vehicles. Despite the advancements made in battery technology, the specific energy of current batteries still poses limitations on the endurance and range of UAVs, which may not meet the requirements of numerous UAV applications. Additionally, improvements in energy density can have implications for the stability and safety levels [75]. To tackle these limitations, various solutions have been proposed in the existing body of literature. Fuel cells have emerged as a promising alternative due to their higher specific energy. Furthermore, numerous existing UAVs employ a hybrid configuration in their power supply, utilizing multiple energy sources such as batteries, fuel cells, solar cells, and supercapacitors. In practice, hybrid configurations integrate various power sources, such as batteries, fuel cells, solar cells, or generators, to work in harmony. The energy management system (EMS) plays a crucial role in optimizing power distribution among these sources to achieve enhanced efficiency and endurance [76].

The advantages of hybrid configurations over single-source systems are numerous. They offer improved endurance, as different sources can complement each other. For example, batteries can provide immediate power for take-off, while fuel cells or generators can sustain operations for longer durations. They enhance reliability by providing redundancy—if one source fails, others can take over. Additionally, hybrid systems can be more environmentally friendly, using cleaner energy sources in combination with traditional ones [76,77].

2.2.2. Swapping Method Algorithm

The technique known as swapping is employed to recharge the batteries of a UAV while it is in the midst of its mission. This process involves the exchange of depleted batteries with fully charged ones, which can be performed either autonomously or with human intervention. A specific type of swapping, called hot swapping, enables the immediate replacement of a depleted battery with a fully charged one, allowing the UAV to maintain power and continue its operation without interruption. Subsequently, the UAV can return to its assigned operational area and resume its tasks. By deploying multiple UAVs and coordinating their actions, a multi-agent system can ensure uninterrupted coverage of a specific area [34]. To successfully carry out a swapping operation, three important conditions must be fulfilled: (1) the presence of a ground recharge station where UAVs can land for battery charging or replacement, (2) a group of UAVs capable of continuous operation, and (3) a management system that facilitates cooperation among the swarm of UAVs. Figure 4 illustrates the techniques of swapping and hot swapping.

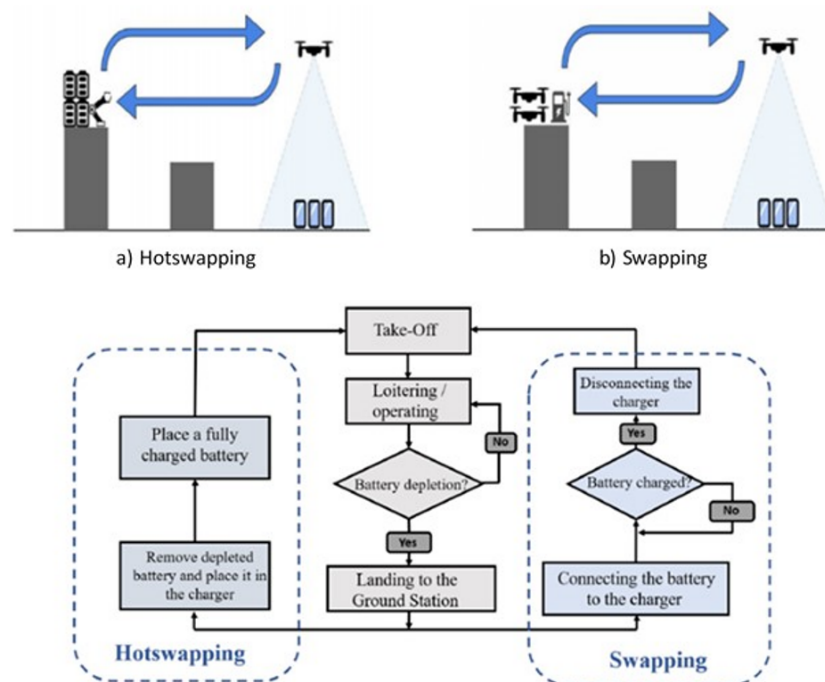


Figure 4. The swapping and hot swapping algorithms.

In the infrastructure network for UAVs, ground stations (GS), are strategically placed in various locations, such as cities or along connecting paths between cities. These GS can be installed on different structures like cell towers, streetlights, rooftops, power poles, or standalone pylons. As part of this infrastructure, battery swap stations are established, which consist of several components including ground electronics, an onboard circuit, a landing frame, and a contact mechanism. The batteries can be recharged through contact-based pathways or by utilizing inductive coupling. The docking platforms at the swap stations can be powered through a combination of power lines, large batteries, and solar cells, especially for stations located in remote areas.

There was also research that developed a multi-rotor aerial prototype specifically designed for long-duration missions using the swapping approach. The main goal of their study was to ensure the uninterrupted operation of the airborne platform by monitoring the battery’s state of charge (SOC). Their concept involved having three quadcopters in a rotating system, with one quadcopter always in a loiter position. When the SOC of a quadcopter drops below a predetermined threshold, it is replaced by another quadcopter, allowing the former to return to the ground station for battery charging. This cycle continues until all batteries are depleted or the mission is completed. The number of batteries required

for sustainable operation depends on the discharge time and the duration needed for charging, rather than the number of UAVs. However, a larger number of batteries increases the system's resilience and reliability [34–36].

However, it is important to mention that the process of battery swapping and charging on the launch platform was not automated and still relied on human intervention. Additionally, the field test conducted in the study did not involve specific missions that required the use of sensors; instead, only static loitering was performed. In a separate study, researchers conducted an economic comparison of battery refilling and recharging platforms. They developed three stations based on axiomatic design principles, which allowed them to analyze and establish relationships between cost, complexity, and coverage levels [78]. This analysis provided valuable insights into the various factors associated with the implementation of battery refilling and recharging platforms.

The comparison between refilling and exchange stations has indicated that refilling stations are suitable for low-coverage scenarios, while exchange stations are preferable when higher coverage levels are required. In [79], research was conducted on a comparison of battery charging and replacement systems using a Petri net model. A Petri net model is a mathematical tool used to model and analyze systems with concurrent processes, making it relevant in designing efficient battery management systems. The authors also discussed in detail the design options for autonomous swapping stations, aiming to achieve precise UAV positioning for swapping regardless of landing errors. However, it is worth noting that the estimated swap time in their study was approximately one minute, which is relatively long compared to other studies. Moreover, the system was not fully operational, as certain modules were not prototyped or tested. In a separate study [57], a ground recharge station was designed for battery-powered quadrotor helicopters, and an algorithm was implemented to reduce the battery recharge duration. It can significantly reduce downtime and enhance the efficiency of quadrotor helicopters in applications like search and rescue, surveillance, delivery services, agriculture, infrastructure inspection, environmental monitoring, film production, and security. The proposed autonomous charging process utilized safer electrical contacts and a balancer specifically designed for swarm applications. It is important to mention that similar to the majority of the conducted studies, no experiments or flight tests were performed, and the study did not consider battery lifetime as a factor.

An automated refueling station for small-scale UAVs was designed and implemented in a study [80] to enable long-duration autonomous missions with multi-agent UAV systems. The study developed a planning and learning algorithm and tested it in a 3 h persistent flight involving 3 UAVs and over 100 battery swaps. The battery recharger mechanism used a linear sweeping motion, resulting in a simple and robust design. However, the cost of the system was not taken into account, and it should be noted that increasing the number of batteries and UAVs could potentially lead to a more expensive and complex system to manage. In a study [81], a swapping system based on online algorithms for energy management, UAV health monitoring, and accurate landing was proposed. The system utilized a servo-based lift for battery swaps and placed the batteries onto a horizontally mounted hexagonal mat for charging. However, this swap mechanism introduced power losses in the UAVs. While individual tests were conducted for all the components, the entire system was not tested as a whole. In another study [82], an autonomous docking platform was designed using active infrared imaging. The system operated during both day and night and incorporated a camera and an infrared filter to achieve high-precision landing.

In a study [73], a hardware platform was introduced featuring a dual-drum structure for efficient hot swapping of batteries. The platform included a buffer of eight batteries, and experimental work provided insights into the average time required for battery swapping. A flight test was conducted, focusing on a search and track mission with communication constraints. However, the maximum operational time achieved for this mission using the developed station with three quadrotors was approximately 70 min. In a recent paper [83], the focus was on cyclically repeated missions, such as aerial delivery services. They

proposed the use of mobile battery swapping stations (MBS) that would move to designated swapping points according to a preset timetable. UAVs could then join the appropriate station for battery replacement and cargo loading/unloading. The study addressed the optimization of the number of UAVs and the distance traveled by proposing a declarative model for routing UAVs and MBS. However, it should be noted that this approach is applicable to only a limited range of missions, and the feasibility of mobile swapping stations may vary. The study primarily focused on the routing task, and no specific experiments related to swapping were conducted. Table 2 provides a critical analysis of the various swapping approaches discussed in the literature.

Table 2. The critical evaluation of available swapping studies [78–80,84].

Main Contribution	Advantages	Limitations
An aerial prototype utilizing multiple rotors designed for surveillance missions of extended duration by employing battery health monitoring.	The hardware prototype enables uninterrupted operation by taking into account battery health considerations.	The system does not include autonomous swapping, and its operation is managed using a laptop instead of an embedded controller.
The design, testing, and construction of an autonomous ground recharge station were carried out, incorporating a balancer and safer electrical contacts.	A hardware platform was developed that enabled autonomous swapping, utilizing an embedded controller. An optimization algorithm was implemented to minimize the recharge duration.	Although no flight test was conducted, the hardware platform focused on autonomous swapping and did not consider battery health as a factor in its design.
A planning and learning algorithm was developed and tested during a 3 h long persistent flight involving 3 UAVs and over 100 battery swaps.	The design and hardware implementation of an automated refueling system was carried out, and flight tests were conducted to evaluate its performance.	The discussion of system cost and the consideration of landing accuracy were not included in the analysis.
An automated swapping mechanism was implemented, incorporating online algorithms for energy management, vehicle health monitoring, and accurate landing. The system aimed to optimize the swapping process by efficiently managing energy resources, monitoring the health of the vehicles, and ensuring precise landing during the swapping operation.	The constructed platform is designed to sustain the continuous operation of a single UAV indefinitely. It incorporates algorithms for precision landing, ensuring accurate and safe landing during the swapping process. Additionally, the platform includes battery health tracking algorithms to monitor and manage the condition of the batteries, optimizing their performance and lifespan.	The entire system, including all its components and functionalities, was not tested as a whole. While individual tests were conducted for specific aspects of the system, such as precision landing and battery health tracking, a comprehensive test involving the complete system was not performed.
A design for an autonomous docking platform was developed, incorporating the use of active infrared imaging. The system utilized a combination of a camera and an infrared filter to achieve precise and accurate docking between the unmanned aerial vehicle (UAV) and the docking platform. The active infrared imaging technology enabled the system to operate effectively both during the day and at night, enhancing the reliability and versatility of the docking process.	A hardware platform was created to enable accurate and fast swapping of components, specifically targeting an impressive swapping time of 8 s. The platform was designed to operate seamlessly during both daytime and nighttime conditions, ensuring its usability in various environments and lighting conditions. This capability allows for continuous and efficient operations, minimizing downtime and maximizing the overall efficiency of the system.	No flight tests were conducted to evaluate the performance of the hardware platform. Additionally, the study did not focus on discussing the specific improvements in endurance achieved through the implemented technology.

Table 2. Cont.

Main Contribution	Advantages	Limitations
<p>A dual-drum structure was implemented in the hardware platform to enable fast and efficient hot swapping. This design feature allows for the quick replacement of batteries, enhancing the efficiency of the swapping process.</p>	<p>A flight test was conducted to evaluate the performance of the system, taking into account communication constraints. During the test, the system was assessed under real-world conditions, considering limitations in communication capabilities. This provided valuable insights into the system's performance and effectiveness in scenarios with communication constraints.</p>	<p>The study did not include tracking the health of the vehicle or monitoring its condition. Additionally, the experiments conducted had a maximum mission time of only 70 min. Therefore, the study did not focus on monitoring and assessing the overall health and performance of the vehicle throughout extended missions.</p>
<p>A declarative model was proposed to optimize the routing of a multi-agent system consisting of UAVs and mobile battery swapping stations (MBS) for delivery missions. The model aimed to efficiently plan the routes and schedules of UAVs and MBS to ensure timely battery replacements and loading/unloading of goods. However, it is important to note that the study primarily focused on the routing aspect and did not involve specific experiments or tests related to the functionality and feasibility of mobile battery swapping stations in the context of delivery missions.</p>	<p>The study focused on optimizing the distance traveled and the number of UAVs in the context of the proposed multi-agent system with mobile battery-swapping stations. The goal was to find an optimal configuration that minimizes the overall distance traveled by the UAVs and maximizes the efficiency of the system. By optimizing these factors, the study aimed to enhance the performance and cost-effectiveness of the system. However, it should be noted that the feasibility and practicality of implementing the proposed optimizations were not specifically tested or evaluated in the study.</p>	<p>The study presented computational results related to the optimization of the traveled distance and the number of UAVs in the context of the multi-agent system with mobile battery swapping stations. However, it did not include experimental validation or testing of the proposed techniques. The focus of the study was on computational modeling and analysis, providing insights into the potential benefits of the proposed optimizations. The specific details and mechanisms of the swapping technique were not discussed in the study, as it primarily concentrated on the computational aspects of routing and optimization.</p>
<p>The study aimed to achieve precise UAV positioning after landing with minimal error. The researchers focused on developing techniques or algorithms that would ensure accurate positioning of the UAVs after the landing process. By minimizing the positioning error, they aimed to enhance the overall performance and efficiency of the system. However, it is important to note that the specific methods or approaches used to achieve precise UAV positioning after landing were not detailed in the information provided.</p>	<p>The research focused on achieving precise UAV positioning for swapping operations, regardless of any errors that may occur during the landing process. The objective was to develop techniques or strategies that would ensure accurate and reliable positioning of the UAVs during swapping, even if the initial landing had some degree of error. By addressing this challenge, the researchers aimed to enhance the efficiency and effectiveness of the swapping process, enabling seamless battery replacement and continuous operation of the UAVs. However, specific details about the methods or approaches employed to achieve precise positioning in the presence of landing errors were not provided in the given information.</p>	<p>The study reported a relatively long swapping duration, indicating that the process of replacing batteries in the system took a considerable amount of time. However, it should be noted that the entire system, including all its components and functionalities, was not tested as a whole. This means that while certain aspects of the swapping process may have been examined or validated individually, the complete integration and performance of the system were not assessed through comprehensive testing. As a result, the overall efficiency and effectiveness of the swapping mechanism, as well as its potential limitations or drawbacks, remain uncertain and require further investigation or evaluation.</p>

2.2.3. Laser Beam Inflight Recharging

The swapping approach has shown promise in extending the operational time of battery-powered UAVs by utilizing ground stations for battery replacement or recharging. However, an alternative approach that has been proposed is wireless recharging, as discussed in the previous literature [51,85]. This method involves a ground station equipped with a primary power source, which generates a laser beam transmitted to the UAV while it is in flight. The UAV has an embedded optical receiver that converts the light into electricity, effectively powering the UAV. With wireless recharging, UAVs can remain airborne indefinitely without the need to land for battery recharging. When recharging is necessary, the UAV can access an aerial power link area to receive energy. This approach enhances

safety by eliminating risks associated with take-off and landing. Laser transmitters can be strategically positioned on tall building rooftops to ensure an unobstructed laser beam path, or they can be installed on a mobile station, as depicted in Figure 5. This establishes a radiative link between the UAV and the nearest energy source, enabling fast power transfer. Companies like LaserMotive (Washington, DC, USA) have developed working prototypes capable of transferring hundreds of watts of power [54]. Furthermore, experiments described in [53] have demonstrated the feasibility of this technique, achieving flight times of over 12 h for a quadcopter. Wireless recharging offers the potential for continuous operation and extended flight durations, addressing limitations associated with battery capacity and swapping cycles. However, further research and development efforts are necessary to optimize the technology and overcome challenges related to power efficiency, safety, and scalability.

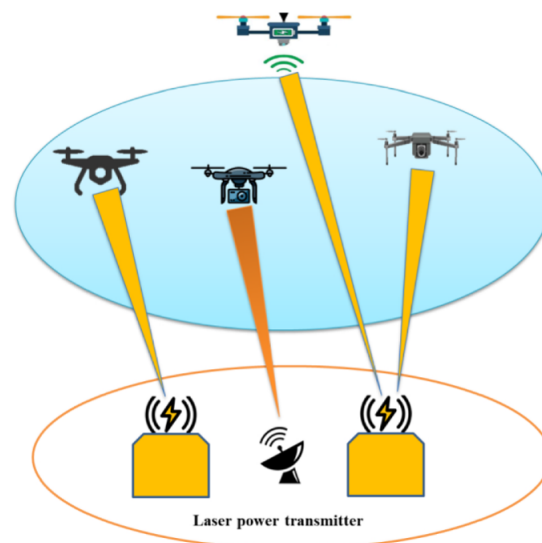


Figure 5. A laser-powered UAV inflight charging system [54,58,68].

While the laser beam inflight recharging approach offers potential benefits, it also introduces certain constraints and considerations that need to be taken into account. One such constraint is the need for UAVs to operate at reduced heights and within a limited area to maintain a reliable power transfer from the laser transmitter. This limitation is influenced by regulations, such as those imposed by the FAA, which set a maximum altitude of 400 feet for small UAVs weighing less than 26 kg. Compliance with these regulations is crucial for safe and legal operations. Another consideration is that each UAV utilizing laser beam inflight recharging requires its own dedicated laser transmitter. This can pose limitations on the number of UAVs that can be deployed in a given area, as multiple transmitters would be needed to support a larger fleet. Additionally, the individual transmitters can significantly increase the overall cost of implementing the laser beam inflight recharging system [34]. Therefore, the scalability and economic feasibility of this approach should be carefully evaluated before widespread adoption. It is important to conduct a comprehensive assessment of the operational and regulatory aspects, as well as the economic implications, when considering the integration of laser beam inflight recharging for UAVs. This evaluation should involve a careful balance between the benefits of extended flight time and the potential limitations and costs associated with this technology. By addressing these considerations, researchers and industry professionals can make informed decisions regarding the practical implementation of laser beam inflight recharging in UAV operations.

2.2.4. Tethered UAVs

Tethered UAVs offer a unique solution for achieving unlimited autonomy by connecting to a power supply station through tethering lines. This eliminates the need for

frequent recharging or battery replacement, enabling long-duration missions. Typically located on the ground, the power supply station continuously provides electricity to the UAV through the tethering lines, ensuring uninterrupted operation. Traditionally, copper wires have been used for the tethering lines of UAVs. However, there is a growing trend toward using fiber optic technology in this domain. Fiber optic cables allow for the transfer of kilowatts of power using high-intensity light, offering several advantages over copper wires. Optics-based power transfer reduces detectability by eliminating electrical signatures and significantly reduces both the payload weight of the UAV and the weight of the power lines compared to copper wires. In fact, fiber technology can reduce weight by up to eight times. Furthermore, power losses in fiber optic cables are minimal, making them more efficient for high-altitude operations.

Tethered UAVs have found applications in various fields. For instance, in maritime pollution monitoring, a tethered UAV can be deployed on a ship to detect oil spills in the sea, preventing contamination of the shoreline [57]. In data-gathering applications, tethered UAVs equipped with sensors can be utilized to collect information in specific areas [58]. However, one limitation of tethered UAVs is the restricted operating area imposed by the length of the connecting cable, which prevents the UAV from flying far from its ground station. To overcome this limitation, in some cases, a moving vehicle is used to carry the prime power source, allowing the UAV to cover a larger area. In missions requiring extremely long endurance, such as monitoring nuclear power plants, tethered UAVs can be deployed to provide continuous aerial surveillance for days or even months, as long as the tethered cable provides a continuous power supply [55]. Prototypes of tethered UAVs have been designed and successfully demonstrated in outdoor environments, showcasing the feasibility and potential of this technology. The use of fiber optic cables in tethered UAV systems presents unique advantages in terms of weight reduction, power efficiency, and reduced detectability, making them an attractive option for extended-duration missions in various applications.

2.3. Fuel Cell Powered UAVs

Hydrogen-powered UAVs offer significant benefits compared to traditional battery-powered UAVs, particularly in terms of flight duration and refueling time [86,87]. LiPo batteries, commonly used in UAVs, have a specific energy of up to 250 Wh/kg. In contrast, a fuel cell system with a compressed hydrogen tank can provide a specific energy of up to 1000 Wh/kg, allowing for much longer flight times [46,48]. This substantial increase in specific energy enables hydrogen-powered UAVs to fly for hours instead of just a few minutes.

Furthermore, refueling hydrogen-powered UAVs is nearly instantaneous compared to the time-consuming recharging process required for batteries. While batteries need a significant amount of time to recharge and replenish their energy, refueling a hydrogen-powered UAV involves simply replacing the depleted hydrogen tank with a fully charged one. This enables quick turnaround times and continuous operation. These advantages make hydrogen-powered UAVs highly desirable for applications that require extended flight durations and rapid refueling, such as long-range surveillance, mapping, and monitoring missions. However, it is essential to consider the infrastructure needed for hydrogen storage, transportation, and refueling, as well as the safety considerations associated with handling hydrogen gas [88]. Proper safety protocols and infrastructure development are necessary to ensure the efficient and secure use of hydrogen-powered UAVs. Thus, a comprehensive comparison of battery-based supplying techniques is presented in Table 3 for a better understanding on their advantages and limitations.

Table 3. A comparison between battery-based supplying techniques [54,58,78–80].

Power Supplying Technique	Advantages	Limitations and Drawbacks
Swapping	<p>Hydrogen-powered UAVs offer the advantage of unlimited operating time, making them a viable option for long-range missions. Unlike battery-powered UAVs that require multiple battery packs or frequent recharging, hydrogen-powered UAVs rely on a single energy source, namely hydrogen fuel. This significantly reduces the weight and complexity of power management systems.</p>	<p>The use of a ground station (GS) in the context of battery-powered UAVs can introduce certain challenges and considerations. While a GS can provide benefits, such as battery charging or swapping capabilities, it also brings along some limitations that impact operational efficiency.</p>
	<p>With a hydrogen fuel cell system, the UAV can continuously generate electrical energy by combining hydrogen and oxygen, producing water vapor as a by-product. This continuous power generation eliminates the need for carrying multiple batteries or landing for recharging, allowing the UAV to operate for extended periods without interruption.</p>	<p>One of the major concerns is the increased cost associated with deploying and maintaining a GS. As the number of batteries and UAVs in operation increases, the infrastructure and resources required for the GS also need to scale accordingly. This can result in higher costs for equipment, maintenance, and operational management.</p>
	<p>The reduction in weight and complexity of power management systems brings several benefits. Firstly, the overall weight of the UAV is reduced, enabling increased payload capacity or longer flight durations. Secondly, the simplified power management system decreases the risk of component failures and improves overall reliability. Moreover, the reduced complexity also simplifies maintenance and servicing, contributing to more efficient operations.</p>	<p>Another challenge is the coordination and cooperation between UAVs and the GS. Efficient communication and synchronization are essential for smooth operations. UAVs need to interact with the GS to initiate battery charging or swapping processes, which requires effective communication protocols and coordination algorithms. Failure in communication or synchronization can disrupt operations and lead to inefficiencies.</p>
	<p>These advantages make hydrogen-powered UAVs particularly suitable for long-range missions where endurance and uninterrupted operation are crucial. Applications such as aerial surveillance, environmental monitoring, and remote sensing can greatly benefit from the extended operating time and reduced power management requirements of hydrogen-powered UAVs.</p>	<p>Autonomous swapping, which involves landing and battery-changing operations, can introduce additional issues. Precise UAV positioning during landing is crucial to ensure safe and accurate battery swapping. Any errors or discrepancies in landing can affect the efficiency and reliability of the swapping process. Designing and implementing robust algorithms and mechanisms to achieve precise positioning and seamless battery-changing operations is a complex task.</p>
	<p>However, it is important to consider the infrastructure for hydrogen storage, transportation, and refueling, as well as safety considerations associated with handling hydrogen gas. Proper infrastructure development, safety protocols, and regulations are necessary to support the widespread adoption of hydrogen-powered UAVs and ensure their safe and efficient operation.</p>	<p>Furthermore, autonomous swapping systems need to address concerns related to the compatibility of different UAV models and battery types. Ensuring that the swapping mechanism is compatible with a wide range of UAVs and batteries adds complexity to the system design and may require customization or adaptation for different configurations.</p>
		<p>Overall, while the concept of a ground station and autonomous swapping holds promise for extending UAV operational time, it is important to address the challenges associated with cost, cooperation between UAVs and the GS, and the technical issues related to landing and battery-changing operations. Thorough planning, system design, and testing are necessary to achieve efficient and reliable autonomous swapping systems in practical applications.</p>

Table 3. Cont.

Power Supplying Technique	Advantages	Limitations and Drawbacks
Laser beam charging	<p>The concept of wireless refueling offers significant advantages for UAVs, including the potential for unlimited operating time and extended mission durations. With this approach, UAVs can receive a continuous supply of power without the need to land or swap batteries. This eliminates the limitations imposed by battery capacity and enables persistent missions.</p>	<p>While wireless refueling using laser beams offers potential benefits for UAVs, there are certain constraints and considerations that need to be addressed. One of these constraints is the necessity of a ground station (GS) equipped with a laser transmitter to provide power to the UAVs. This means that the UAVs need to operate within a certain range of the GS to maintain a reliable power transfer. This range limitation can restrict the operating area of the UAVs and may not be suitable for missions that require long-range coverage or operations in remote areas.</p>
	<p>By utilizing a wireless power transfer system, UAVs can remain in the air while receiving power from a ground station or an aerial power link area. This continuous power supply ensures that the UAVs can operate without interruption, effectively extending their operating range and mission capabilities.</p>	<p>Another constraint is related to the operating heights of the UAVs during laser beam recharging. In order to maintain a consistent power transfer, the UAVs typically need to operate at reduced heights, which can be influenced by regulations and safety considerations. For instance, the Federal Aviation Administration (FAA) sets maximum altitude restrictions for small UAVs, limiting their operating height to 400 feet. Compliance with these regulations may further restrict the altitude range for UAVs using laser beam refueling.</p>
	<p>The use of a single energy source in wireless refueling simplifies the power management system of the UAV. There is no need to manage multiple batteries or swap them out, reducing the weight and complexity associated with power management. This streamlined approach enhances the overall efficiency and reliability of the UAV system.</p>	<p>Obstruction of the laser beam is another consideration. The laser beam used for refueling needs a clear path between the GS and the UAV. This means that obstacles such as buildings, trees, or other structures can obstruct the beam, potentially interrupting the power transfer. Careful planning and positioning of the GS and the UAVs are required to minimize the risk of obstruction and ensure a reliable power supply.</p>
	<p>Wireless refueling also eliminates the need for UAVs to land, reducing the risks and challenges associated with take-off and landing operations. This improves safety and minimizes potential damage or wear and tear on the UAVs during landing and take-off maneuvers.</p>	<p>Furthermore, the range of laser beams used for wireless refueling is typically limited compared to the range of traditional propulsion systems. This can impact the operational range of the UAVs, especially for missions that require long-distance coverage or operations in remote areas.</p>
	<p>With unlimited operating time and extended range, wireless refueling opens up possibilities for a wide range of applications. UAVs can be deployed for persistent surveillance, long-range mapping, remote sensing, and other missions that require continuous operation over extended periods.</p>	<p>Overall, while wireless refueling using laser beams offers advantages, such as extended flight duration and continuous operation, the necessity of a GS, constraints related to operating heights and beam obstruction, and reduced range need to be carefully considered when evaluating its suitability for specific UAV missions. Proper planning, regulatory compliance, and technological advancements are necessary to overcome these constraints and fully leverage the benefits of laser beam refueling for UAVs.</p>
	<p>However, it is important to note that wireless refueling is still an emerging technology, and further research and development are needed to optimize its efficiency, safety, and scalability. Challenges such as power efficiency, regulatory considerations, and infrastructure requirements must be addressed to fully realize the potential of wireless refueling for UAVs.</p>	

Table 3. Cont.

Power Supplying Technique	Advantages	Limitations and Drawbacks
Tethered UAVs	<p>Wireless refueling using laser beams offers the potential for unlimited operating time for UAVs without the need to land. By utilizing a single energy source, such as a ground station equipped with a laser transmitter, the UAVs can receive a continuous and uninterrupted power supply while in flight. This eliminates the need for frequent battery changes or recharging, allowing for persistent operation and extended mission durations.</p>	<p>While wireless refueling offers the advantage of unlimited operating time and eliminates the need for landing or battery replacement, it comes with certain limitations. One of these limitations is the necessity of a ground station (GS) to provide the power supply or laser transmitter. The GS serves as the central hub for supplying power or transmitting the laser beam to the UAV in flight.</p>
	<p>In addition to providing power, wireless refueling also enables safe and effective data transfer between the UAV and the ground station. Along with power, the laser beam can be used to transmit data and communication signals, ensuring seamless connectivity and information exchange between the UAV and the ground control.</p>	<p>Additionally, wireless refueling methods often have constraints related to the operating area of the UAV. For example, laser beams used for power transfer may have a limited range or be affected by obstructions, such as buildings or other objects that can block or interfere with the transmission. This can restrict the operational altitude and area of the UAV, requiring it to operate within a specific range from the GS to maintain a consistent power supply.</p>
	<p>The ability to operate continuously and receive power and data transfer wirelessly offers several advantages. It enables UAVs to perform long-duration missions without interruption, making them suitable for applications that require persistent surveillance, monitoring, or data gathering. It also reduces the logistical challenges and risks associated with manual battery replacement or refueling operations, as the UAVs can remain in the air and operational throughout their mission.</p>	<p>Another concern with wireless refueling is the potential for UAV damage in case of tethering loss. In some cases, UAVs may be tethered to the power source or laser transmitter through physical connections, such as cables or beams. If the tethering connection is lost or severed, it can lead to a sudden loss of power or disruption in the energy transfer, which may result in the UAV losing control or experiencing a sudden shutdown. This can potentially lead to damage to the UAV or compromise the mission's success.</p>
	<p>Moreover, wireless refueling contributes to increased safety by eliminating the need for frequent take-offs and landings, which can be risky maneuvers for UAVs. The continuous operation and avoidance of landing procedures minimize the chances of accidents or incidents during mission execution.</p>	<p>To mitigate these limitations and concerns, careful planning, system redundancy, and safety measures need to be implemented. This may involve the use of backup power sources or redundant laser transmitters to ensure uninterrupted operation and minimize the risk of power loss. Additionally, thorough risk assessments and safety protocols should be in place to prevent or mitigate potential damage to the UAV in case of tethering loss or system failures.</p>
	<p>Overall, wireless refueling with a single energy source provides UAVs with the capability for unlimited operating time, persistent operation, safe data transfer, and reduced reliance on ground-based support. These advantages make it an attractive solution for various applications where extended flight durations, continuous operation, and efficient data transfer are essential.</p>	<p>Overall, while wireless refueling offers advantages, such as unlimited operating time and no landing requirements, it is important to consider the necessity of a GS, the limitations on operating area, and the potential risks associated with tethering loss. Proper planning, robust systems, and safety measures can help address these concerns and ensure the efficient and safe operation of UAVs using wireless refueling methods.</p>

In a study [89], a comparison of various battery types (Li-ion, Ni-Cd, Ni-Mh) and fuel cells was conducted, considering criteria such as energy and power densities, discharging characteristics, temperature effects, efficiency, and endurance. However, it is important to note that flight tests were not conducted to evaluate the actual behavior, capabilities, and performance of these power sources in real flight conditions. Figure 6 in the study presents a comparison of specific power versus specific energy for batteries, fuel cells, and supercapacitors. It indicates that fuel cells demonstrate higher specific energy compared

to other power sources, which makes them a promising option for achieving extended endurance in UAVs while maintaining a given weight [57]. Nevertheless, it should be acknowledged that fuel cells may have lower energy density compared to lithium batteries due to the additional volume required for hydrogen storage in the form of a tank.

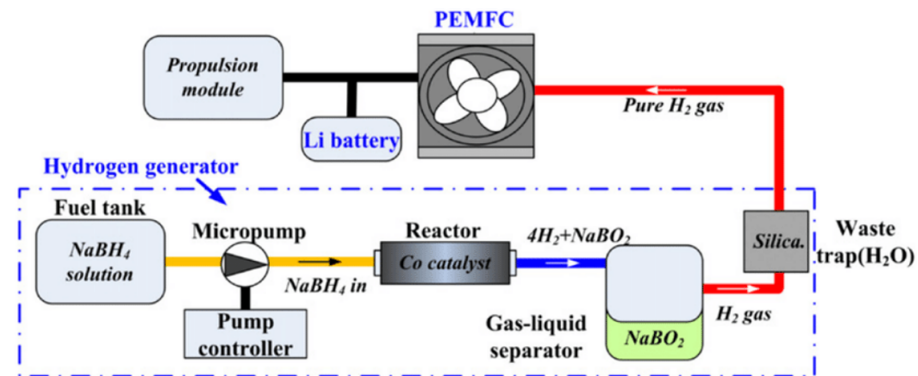


Figure 6. The fuel cell system auxiliaries.

In a separate study, the development of a UAV for mobile crane inspection was explored, with a focus on proton exchange membrane fuel cells [90] and lithium-ion batteries [91]. The research involved an economic analysis and a life cycle assessment to compare the two power sources. One of the main conclusions drawn from the study was that from a commercial standpoint, fuel cells, being a niche product, tend to be more expensive compared to lithium-ion batteries. This fact emphasizes the trade-offs between fuel cells and batteries in terms of specific energy, energy density, cost, and commercial viability. The selection of the appropriate power source for UAV applications relies on specific requirements, mission profiles, and considerations such as flight endurance, weight limitations, cost constraints, and the availability of infrastructure.

2.3.1. Fuel Cell Efficiency Issues

The process of electricity generation from fuel cells involves certain elements. Fuel cells can achieve an efficiency level of up to 60% [89]. However, this efficiency is lower compared to lithium batteries, which can exceed 90%. One of the reasons for the lower efficiency of fuel cells is the presence of auxiliary equipment required for the operation of the fuel cell stack. These auxiliary components add complexity to the system and can contribute to energy losses, thus reducing overall efficiency [80]. Additionally, the onboard hydrogen generation system, which is necessary for fuel cell operation, can also introduce complexity and potentially decrease efficiency. While fuel cells may have lower efficiency compared to lithium batteries, they offer advantages in terms of specific energy and longer operational duration. While proton exchange Membrane fuel cells (PEMFCs) hold promises for enhancing the endurance of drones and hydrogen–lithium composite energy storage systems prove adaptable to specialized working conditions, certain challenges must be addressed for their large-scale commercialization. Notably, PEMFCs require higher power and current densities to meet the demands of commercial applications. However, at elevated operating current densities, issues such as the accumulation of liquid water in the Gas Diffusion Layer (GDL) can lead to flooding and impede gas diffusion, resulting in a rapid degradation of cell performance [92]. Consequently, the improvement of water management capabilities is imperative to unlock the full potential of PEMFCs and achieve better cell output performance. The choice between fuel cells and batteries depends on specific application requirements, taking into account factors such as flight endurance, weight limitations, cost considerations, and the availability of infrastructure. The cost of implementing fuel cells in drones varies based on factors such as fuel cell type, size, and specific application requirements. While fuel cells offer advantages in terms of extended endurance and reduced environmental impact, their cost is a significant consideration in

the adoption of this technology. Cost reduction efforts, advancements in research and development, and economies of scale are expected to make fuel cells more cost-effective in the future. The decision to use fuel cells as the primary means of power generation and energy supply in drones will depend on the specific drone applications, regulatory support, competition with evolving battery technology, and a comprehensive evaluation of the total cost of ownership, taking into account initial purchase, maintenance, and operational costs.

2.3.2. Fuel Storage

Hydrogen has a low density at standard temperature and pressure, which poses a challenge for storing a sufficient amount of fuel for UAV missions. The low density means that hydrogen tanks need to be bulky to accommodate the required amount of fuel, which can impact the size and weight of the UAV. In addition to the size and weight considerations, safety is also a significant concern when it comes to storing hydrogen. Pure hydrogen cannot be stored under extremely high pressure and low temperatures due to safety reasons. Therefore, alternative techniques are employed for hydrogen storage in UAVs.

The three main techniques currently used for hydrogen storage in UAVs are as follows:

- 1 **Compressed hydrogen gas:** Hydrogen gas is stored in tanks under high pressure. This method allows for easier storage and refueling compared to other techniques. However, it requires high-pressure tanks, which can add weight and volume to the UAV.
- 2 **Liquid hydrogen:** Hydrogen is stored in a liquid state at very low temperatures. This method provides a higher energy density compared to compressed gas storage. However, it requires specialized cryogenic storage systems and insulation, which can add complexity and weight to the UAV.
- 3 **Chemical hydrogen generation:** Hydrogen is generated onboard the UAV through chemical reactions, such as the reaction between a metal hydride and water. This method offers the advantage of generating hydrogen as needed, eliminating the need for storing large quantities of hydrogen. However, it requires additional components and can have limitations in terms of hydrogen generation rate.

Table 4 in the referenced study likely provides a detailed analysis of the advantages and drawbacks of each hydrogen storage technique in UAV applications, allowing for a comprehensive comparison and evaluation of the different options.

Table 4. Comparison between compressed and liquid hydrogen storage [80,89].

	Compressed H ₂	Liquid H ₂
Properties	The most commonly used method for hydrogen storage in UAV applications is high-pressure storage. Hydrogen is stored at pressures ranging from 35 to 70 megapascals (MPa). At these high pressures, the density of hydrogen increases, reaching approximately 42 kg/m ³ at 70 MPa	Hydrogen has a density of approximately 71 kg/m ³ at 1 bar and a temperature of −252.87 °C, which is extremely low. To store hydrogen in its liquid form, a thermal insulation system is necessary to maintain such low temperatures. While hydrogen storage has benefits for large-scale applications, it can be challenging on a smaller scale. The liquefaction process requires extremely low temperatures, making it costly and energy intensive. It is more practical for large-scale production and distribution systems rather than small-scale applications.

Table 4. Cont.

	Compressed H ₂	Liquid H ₂
Advantages	<p>High-pressure storage offers several advantages. It is a relatively simple method, requiring a pressure vessel to contain the hydrogen gas. The storage mass penalty, or the additional weight of the storage system, is relatively low compared to other storage methods. Additionally, high-pressure storage allows for rapid refueling capability, enabling quick turnaround times for UAV operations.</p> <p>However, there are certain drawbacks to high-pressure storage. One significant disadvantage is the low storage efficiency. The energy required to compress hydrogen to high pressures results in energy losses, reducing the overall storage efficiency. This can impact the range and endurance of the UAV.</p>	<p>There are several advantages to using hydrogen as a fuel despite its low density. One advantage is its high energy density, which means that a relatively small volume of hydrogen can store a large amount of energy. This high energy density enables longer flight durations and increased operational efficiency for UAVs.</p> <p>Hydrogen storage also offers improved safety compared to other fuel options. Hydrogen is non-toxic and non-polluting, and it dissipates rapidly in the event of a leak. However, safety measures are still necessary due to its flammability and the potential for embrittlement of materials in the presence of hydrogen.</p>
Disadvantages	<p>Safety risks are also a concern with high-pressure storage. The high pressures involved in the storage process increase the potential for leaks or ruptures, which can be hazardous. Proper safety measures and precautions must be in place to mitigate these risks.</p> <p>Another consideration is the larger volume required for high-pressure storage systems. The pressure vessels need to be sized to accommodate the required amount of hydrogen at the specified pressure. This can increase the overall size and volume of the UAV, affecting its aerodynamics and payload capacity.</p> <p>In summary, high-pressure storage is a commonly used method for hydrogen storage in UAVs. It offers simplicity, low storage mass penalty, and rapid refueling capabilities. However, it has drawbacks such as low storage efficiency, safety risks, and the need for larger storage volumes. These factors should be carefully considered when selecting the appropriate storage method for UAV applications.</p>	<p>Handling and transporting hydrogen in its liquid form can be difficult due to the low temperatures involved and the need for specialized storage and transportation infrastructure. Additionally, the weight of the storage tanks can be significant, impacting the overall weight of the UAV.</p> <p>In summary, while hydrogen offers advantages, such as high energy density, improved safety, and the potential for long-duration flights, there are challenges associated with its low density, high liquefaction energy requirements, impractical small-scale production, and the need for careful handling and storage. These factors must be carefully considered in the design and implementation of hydrogen storage systems for UAV applications.</p>

2.4. Hybrid Power Sources (Fuel Cell and Battery)

Fuel cells face limitations when used as the sole power source for UAVs. Their time constant is relatively long, typically in the range of seconds, due to the requirements of fuel and air supply facilitated by pumps, valves, and compressors. This sluggish response is primarily attributed to the mechanical characteristics of the pumps, flow delay, thermodynamic properties, and the effect of capacitance [93]. Consequently, when there are significant fluctuations in current demand, there is a potential risk of fuel shortage,

which can negatively impact the fuel cell system's lifetime, reliability, and efficiency [94]. To tackle these challenges, researchers have explored the integration of fuel cells with batteries to form hybrid power supply systems, which have emerged as a promising solution. By harnessing the strengths of both power sources and mitigating their weaknesses, hybrid systems can deliver enhanced performance and efficiency for UAV propulsion [48,95,96]. The battery can swiftly provide power for sudden changes in demand, while the fuel cell can supply sustained power for extended durations. This approach enables superior power management, heightened system dependability, and overall improved UAV performance.

In a hybrid UAV propulsion system, the battery plays a crucial role in supplying power during high-demand maneuvers, like take-off and climbing. Its higher power density, quicker response time, and greater efficiency make it well-suited for such tasks compared to a fuel cell. On the other hand, the fuel cell takes over as the primary power source during cruise or descent phases, providing sustained power and also recharging the battery to maintain its state of charge (SOC) above a certain threshold. To evaluate the performance of hybrid UAV propulsion systems, researchers have employed hardware-in-the-loop (HIL) simulations. These simulations analyze the behavior of each power source in various test scenarios, considering factors such as endurance and hydrogen consumption.

The role of the battery in the hybrid system has been extensively considered in studies, such as [63]. These experiments have specifically focused on analyzing the battery's performance during different flight mission phases and under varying demands. Additionally, ref. [75] provides a comprehensive characterization of the hybrid propulsion system using diverse mission profiles and speeds. However, it should be noted that these studies mainly concentrated on passive power-splitting methods and did not delve into the development of an active energy management strategy. The implementation of an energy management strategy is a crucial aspect of hybrid UAV propulsion systems. It involves actively regulating the power flow between the fuel cell and battery to optimize the overall performance, efficiency, and longevity of the system. This strategy determines the appropriate utilization of each power source based on the prevailing flight conditions, load requirements, and the battery's state of charge. By employing intelligent power management algorithms, the hybrid system can achieve enhanced efficiency and prolong the UAV's mission endurance. Table 5 in this review paper offers a comprehensive comparison between batteries and supercapacitors, providing a detailed analysis of their characteristics and performance. Moving forward, Table 6 provides a comprehensive overview of the advantages and disadvantages associated with batteries and supercapacitors, aiding in the assessment of their suitability for various applications. Lastly, Table 7 is dedicated to a thorough comparison of diverse power supply configurations, facilitating a nuanced understanding of the various options available for power delivery in different contexts. These tables, with their respective data and insights, play a pivotal role in elucidating key aspects of energy storage and power supply solutions.

Table 5. Comparison between batteries and supercapacitors [48,95,96].

Type	Energy Density (Wh/kg)	Power Density (W/kg)	Cycle Life (Times)	Efficiency (%)
Lead-acid battery	30–40	200–300	300–400	75
Ni-MH battery	60–80	800–1500	1000	75
Li-ion battery	100–120	600–2000	1000	90
Supercapacitor	4–15	1000–100,000	100,000	85–98

Table 6. Batteries and supercapacitor advantages and disadvantages.

Type	Advantages	Disadvantages
Lead-acid battery	Affordable, rapid discharging rate, and high recyclability.	Inadequate performance in low-temperature conditions.
Ni-MH battery	High energy density, quick charging and discharging, and extended lifespan.	Pronounced self-discharge rate, the necessity for a cooling system, and higher manufacturing expenses.
Li-ion battery	Elevated voltage, superior energy density, lightweight, durable cycle life, minimal self-discharge, absence of memory effect, and eco-friendly.	Reduced lifespan in high-temperature environments, susceptibility to overcharging and over-discharging, and stringent security requirements.
Supercapacitor	Swift charging and discharging capabilities, absence of pollution, and remarkability.	Limited energy density.

Table 7. Comparison of power supply configurations.

Energy Sources	Architecture	Advantages	Limitations and Drawbacks
Thermal energy	Gas turbine engine	Impressive ratio of power to weight, coupled with extended duration of operation.	Extremely poor fuel efficiency and elevated noise levels.
	ICE	Exceptionally high power and energy densities, extended endurance, and significant payload range.	Decreased efficiency, thermal and acoustic signatures, greenhouse gas emissions, and high fuel costs.
One electrical source	Battery	Significant energy density and storage (rather than generation), resulting in a rapid response to power demand.	Limited power density, decreased endurance, and prolonged recharging time with the presence of a “memory effect” in certain battery types. To enhance autonomy, additional batteries need to be added, leading to increased weight and cost.
	Fuel cell	Significant energy density and, instant refueling without the presence of a “memory effect,” allowing for increased autonomy using more fuel within the same stack, resulting in weight reduction.	Due to the process of energy generation, there is a slower response to power demand in fuel cells. Additionally, auxiliary equipment, such as compressors and regulators, are required for their operation. Challenges related to the lack of hydrogen distribution infrastructure, issues with hydrogen storage, safety concerns, and the high cost of hydrogen production are also present.

Table 7. Cont.

Energy Sources	Architecture	Advantages	Limitations and Drawbacks
Hybrid power supply	Fuel cell and battery	The high energy and power densities of the hybrid power supply result in increased endurance and faster response time. This allows for efficient energy generation and storage, enhancing the overall performance of the system.	The use of a hybrid power supply system leads to an increase in weight, as additional components, such as controllers and converters, are required to manage the system. This introduces added complexity to the UAV, further contributing to the overall weight.
	Fuel cell, battery, and solar cells	The inclusion of an additional energy source in a hybrid power supply system results in improved endurance for the UAV. This extra source provides clean and readily available energy, which leads to a decrease in energy costs and saves on hydrogen usage.	Large UAV wings are necessary for the implementation of a hybrid power supply system. However, this configuration is not suitable for rotary-wing UAVs. Additionally, an energy storage device is required to store and manage the energy generated by the system. The hybrid system also necessitates the use of an energy management system (EMS) and Maximum Power Point Tracking (MPPT) to optimize the power flow and ensure efficient operation.
	Fuel cell, battery, and supercapacitor	The hybrid system consisting of a fuel cell, battery, and supercapacitor offers several advantages. It provides very-high-power density, enabling efficient and rapid charging. It also contributes to reduced weight and minimized fluctuations in the direct current (DC) bus. The system exhibits a very long lifetime, thanks to its reduced internal resistance, and experiences minimal heat loss. These features make the hybrid system highly desirable for various applications, ensuring optimal performance and reliability.	The integration of an energy management system (EMS) is essential in the hybrid system, which includes a fuel cell, battery, and supercapacitor. The EMS plays a crucial role in coordinating and regulating the power flow between these components. It ensures efficient utilization of the energy sources, manages charging and discharging processes, and maintains the stability of the system. Additionally, the voltage regulation of the supercapacitor is necessary to ensure its proper operation and prevent any voltage-related issues. The EMS and supercapacitor voltage regulation contribute to the overall performance and reliability of the hybrid system.

3. Conclusions

The primary focus of this research paper is to examine and evaluate the energy aspects of onboard propulsion systems in UAV platforms. By conducting a comprehensive review and analysis of different power supply architectures and energy management strategies, the objective is to establish a foundation for the development of high-performance UAV propulsion systems. This assessment aims to facilitate the assessment of trade-offs and considerations when selecting suitable power sources for UAVs.

Relying solely on a single power source can be limiting for UAVs, as different power sources exhibit diverse performance characteristics under varying operating conditions. Therefore, the integration of hybrid power sources with complementary capabilities is increasingly recognized as a standard approach for designing UAV electric power systems. The selection and sizing of hybrid power sources depend on the specific mission requirements and associated weight/duration constraints of the UAV.

By comparing and analyzing various power supply architectures and energy management strategies, this research paper aims to contribute to the advancement of efficient and reliable UAV propulsion systems. The objective is to enable UAVs to operate optimally in different mission scenarios, enhance overall performance, extend mission durations, and improve the adaptability of the propulsion system to changing operating conditions.

Therefore, some key points regarding the advantages and limitations of different power sources for UAV propulsion systems are highlighted. Combustion engines, although robust, are typically heavier and more commonly used in fixed-wing UAVs. On the other hand, fuel cells (FCs) and batteries, such as lithium polymer (Li-Po) batteries, offer longer flight times and greater maneuverability. However, they may struggle to supply peak current when required and can deplete their energy rapidly. Hybrid systems, which combine multiple power sources, offer significant advantages over single-source systems. By leveraging the specific strengths of each power source, hybrid systems can address issues such as prolonged charging times, short flight durations, and limited peak power supply. Supercapacitors (SCs) are commonly used in hybrid systems due to their ability to overcome the drawbacks of other power sources. SCs have high energy density, short recharge periods, and virtually unlimited cycle life, making them a promising replacement for Li-Po batteries in hybrid systems.

Hydrogen fuel cells, often incorporating Li-Po batteries, can be considered a type of hybrid system. However, Li-Po batteries present several disadvantages in drone applications, including low energy density, short flight times, long recharge times, environmental hazards, and limited lifespan compared to other power sources. SCs, with their high energy density, short recharge periods, and long cycle life, offer a potential solution as a replacement for Li-Po batteries in hybrid systems. Further research is necessary to evaluate the impact of SCs on the effectiveness of fuel cell systems in drone applications. Overall, the implementation of hybrid systems with SCs shows promise in improving the flight time and efficiency of UAVs. To truly advance current systems, hybrid systems need to be comparable in weight and size to existing drones while providing enhanced performance and addressing the limitations of single-source power systems. Further research and development are required to optimize the integration and performance of hybrid power systems in UAV applications.

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