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Review

Status and Development Prospects of Solar-Powered Unmanned Aerial Vehicles—A Literature Review

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Abstract: Solar-powered unmanned aerial vehicles are fixed-wing aircraft designed to operate solely on solar power. Their defining feature is an advanced power system that uses solar cells to absorb sunlight during the day and convert it into electrical energy. Excess energy generated during flight can be stored in batteries, ensuring uninterrupted operation day and night. By harnessing the power of the sun, these aircraft offer key benefits such as extended flight endurance, reduced dependence on fossil fuels, and cost efficiency improvements. As a result, they have attracted considerable attention in a variety of military and civil applications, including surveillance, environmental monitoring, agriculture, communications, weather monitoring, and fire detection. This review presents selected aspects of the development and use of solar-powered aircraft. First, the general classification of unmanned aerial vehicles is presented. Then, the design process of solar-powered unmanned aerial vehicles is discussed, including issues such as the structure and materials used in solar-powered aircraft, the integration of solar cells into the wings, the selection of appropriate battery technologies, and the optimization of energy management to ensure their efficient and reliable operation. General information on the above areas is supplemented by the presentation of results discussed in the selected literature sources. Finally, the practical applications of solar-powered aircraft are discussed, with examples including surveillance, environmental monitoring, agriculture, and wildfire detection. The work is summarized via a discussion of the future research directions for the development of solar-powered aircraft. The review is intended to motivate further work focusing on the widespread use of clean, efficient, and environmentally friendly unmanned aerial vehicles for various applications.

Keywords: unmanned aerial vehicles (UAVs); solar-powered vehicles; solar-powered UAVs; aircraft; fixed-wing aircraft; drones; SUAVs

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1. Introduction

Nowadays, the use of unmanned autonomic vehicles, including unmanned ground vehicles (UGVs) [1], unmanned surface vehicles (USVs) [2], unmanned underwater vehicles (UUVs) [3], and unmanned aerial vehicles (UAVs) is continuously growing. UAVs play an important role in various activities, environments, and specific areas such as precision agriculture, infrastructure, environmental monitoring, video surveillance, topography, etc. In agriculture, UAVs play a crucial role in precision farming by allowing farmers to monitor the crop health, optimize irrigation, and detect pest infestations. In the construction industry, UAVs are utilized for site surveying, progress tracking, and 3D mapping, improving project management efficiency and reducing the overall costs. In the military sector, UAVs soar strategically above the battlefield and beyond for surveillance and reconnaissance, combat support, force protection, electronic warfare, precision strikes, training, and testing.

Despite the many advantages of UAVs, a major limitation is still the range of the drones, which can only carry a mass-limited amount of energy. Thus, the energy autonomy of UAVs is a crucial direction in the field of aerospace, given the possibility of continuous operation. In response to this problem and the need for alternative energy sources, particularly solar energy, work is underway on solar-powered fixed-wing aircraft. Solar-powered UAVs are unmanned, fixed-wing aircraft designed to operate solely on solar power. Their defining feature is an advanced power system that utilizes solar cells to absorb sunlight during the day and convert it into electrical energy. Excess energy generated during flight can be stored in batteries to ensure uninterrupted operation during the day and night. The amount of excess energy depends on factors such as sunlight intensity, weight, wing area, and efficiency [4].

Solar-powered UAVs are characterized by low wing loading, low speed, and low power consumption, which demand high efficiency and reliability from the propulsion system. To ensure efficient operation, solar-powered UAVs are typically equipped with four main components: the airframe, the propulsion system (including the engine, controller, gearbox, propeller, and thrust control mechanism), the power system (comprising the battery, controller, and solar module), and onboard equipment. As solar-powered UAVs use only electric motors as the power source device, they offer the advantages of high range and endurance, low cost, and high energy utilization [5]. Moreover, solar power reduces the carbon footprint associated with their operations, aligning with the sustainability goals. This is caused by the fact that the typical carbon footprint of PV systems is approximately 14–73 g CO_2-eq/kWh, which is 10 to 53 orders of magnitude lower than the emissions reported from burning oil [6]. Moreover, the carbon footprint of the UAVs could be reduced by a further order of magnitude by using novel manufacturing materials, both in the case of PV systems and other materials (for example, flax fibers can replace carbon fibers). The general scheme of an electric propulsion system for solar-powered UAVs is shown in Figure 1. The discussed electric propulsion system consists of a PV panel, a battery management system (BMS), a DC bus, an inverter, and a motor. The BMS protects the battery from overcharging and over-discharging. The DC bus serves as a central hub, connecting all the power sources and storage devices. The inverter converts DC power to AC for specific components. The energy generated by the PV panel is directed to the battery, the DC bus, or both, depending on the level of solar irradiation and the battery's state of charge. An energy management system (EMS) regulates the power distribution by collecting voltage and current data from the power source, battery, and DC bus. Another key component is the electronic speed controller (ESC), which includes bridge inverter circuits and a microprocessor-based speed controller. The speed controller generates pulse width modulation (PWM) signals based on the control strategy, reference signals from the flight controller, and precise motor feedback. For small UAV applications, brushless direct current (BLDC) motors are commonly used in conjunction with fixed-pitch propellers to generate the required thrust efficiently [7].

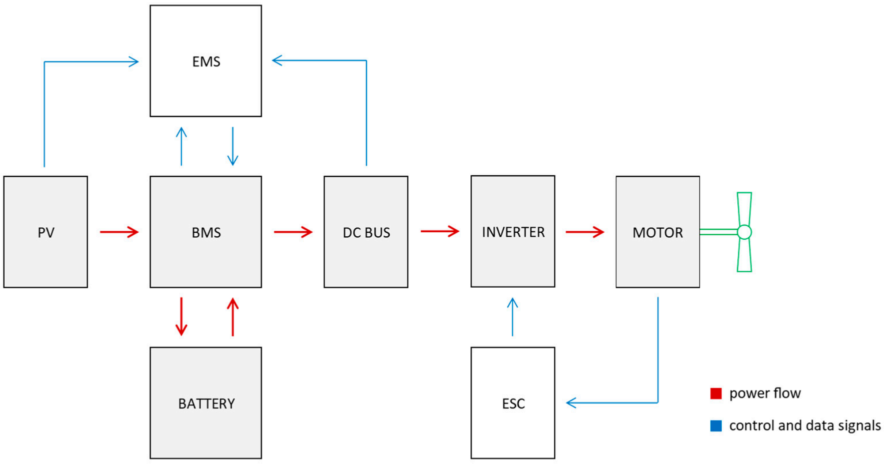


Figure 1. General scheme of an electric propulsion system for solar-powered UAVs.

Over the years, numerous attempts have been made to utilize solar cells to enhance the flight time of UAVs. The first solar-powered UAV, Sunrise I, was developed in 1974 [8]. Due to its damage, the improved Sunrise II was constructed and tested one year later [9]. The next interesting constructions, Gossamer Penguin and Solar Challenger, were developed in the 1980s, while in 1997, Pathfinder reached a record of 21.5 km, and, in 2018, Zephyr demonstrated capabilities like 14 continuous days of flight [10,11]. In the period 2012–2013, Solar Impulse achieved significant multi-day and intercontinental flights [12]. Nowadays, various aircraft characterized by numerous up-to-date technical solutions have been developed and discussed in the worldwide literature. The work aims to summarize the actual achievements in the field of developing solar-powered UAVs, along with a discussion of the most significant challenges associated with their implementation for selected commercial applications. These challenges have been grouped according to the subsequent steps involved in the development of solar-powered UAVs, including the design of the structure and materials used in solar-powered aircraft, the integration of solar cells into the wings, the selection of appropriate battery technologies, and the optimization of energy management to ensure their efficient and reliable operation. The general information on the above areas is supplemented by the presentation of the results discussed in the selected literature sources. Finally, the practical applications of solar-powered UAVs are discussed, with examples including surveillance, environmental monitoring, agriculture, and wildfire detection. The work is summarized via a discussion of the future research directions for the development of solar-powered UAVs, followed by brief conclusions. Consequently, the important contributions of the paper are as follows:

- A synthetic description of the UAV categories is presented, including classification based on the size, range, and application of aircraft, classification based on the types of propulsion systems, as well as classification based on the geometry and materials used.
- Structural and material issues in the development of solar-powered UAVs are discussed, providing an overview of the key challenges associated with the design process of this type of aircraft.
- The methods of integration of solar cells in solar-powered UAVs are discussed, and the improvements in solar cell technologies are briefly described.
- The selection of energy storage technology for solar-powered UAVs is discussed, along with a brief comparison of the selected battery types.
- The energy management in solar-powered UAVs is presented with a primary focus on optimizing their energy efficiency.

- Selected applications of solar-powered UAVs are discussed, providing an overview of the practical usability of these units.
- The emerging future research directions for the development of solar-powered UAVs are outlined.

2. Methodology

This review aims to provide a comprehensive analysis of the general aspects related to the development of solar-powered UAVs. To ensure its credibility and clarity, a systematic approach was adopted for selecting and analyzing the literature.

2.1. Criteria Applied to Ensure the Credibility and Clarity of the Review

The literature was primarily retrieved from established academic databases, including Scopus, Web of Science, ScienceDirect, IEEE Xplore, and EBSCO. The literature found in these databases was supplemented by using data obtained from carefully selected websites related to the discussed topic. The following criteria were applied to refine the results:

- peer-reviewed journal articles and conference proceedings were preferred (137);
- articles published in the last 10 years were primarily considered (in total 128, including 87 articles published in the period 2020–2025 and 41 articles published in the period 2015–2019);
- articles from well-established editorial sources were mainly cited, including Elsevier, MDPI, Wiley, Springer Nature, IEEE, Frontiers, and IOPscience.

2.2. The Main Stages of the Literature Review Process

The review covers a wide time range, with a focus on recent publications to capture the state of the art. A limited number of studies from earlier periods were selected to provide essential context. The literature review process involved several stages:

- titles and abstracts were first reviewed to assess their relevance to the topic under consideration;
- full-text articles were examined to identify scientific and technical contributions, methodologies, and findings relevant to the topic;
- the key findings were categorized into themes and then included in the relevant sections.

2.3. Limitations of the Review

The following limitations were identified during the process of collecting literature sources and preparing the review:

- a number of industry-specific enhancements and military applications were excluded due to the proprietary nature of certain technologies;
- the review focuses on articles written in English and may overlook contributions written in other languages;
- the reliance on keyword searches may inadvertently exclude some relevant studies due to the variations in terminology.

3. General Classifications of Unmanned Aerial Vehicles

Drones come in various configurations tailored to their mission profiles and operational requirements. They are classified according to various parameters, including size, range, and application. Considering the size of drones, the following classes can be distinguished: very small UAVs (including micro or nano UAVs), mini UAVs, medium UAVs, and large UAVs. The very small UAV class comprises extremely compact and lightweight UAVs designed to resemble insects, ranging in size from that of a large insect to approximately 30–50 cm in length. Their small size makes them suitable for surveillance and biological warfare applications. The mini UAV class applies to drones with at least one dimension ranging from 0.5 m to 2 m. Many aircraft classified in this category are based on the fixed-wing model, and most are hand-launched by throwing them into the air. The medium UAV class includes drones that are too heavy for a single person to carry but remain smaller than a light aircraft. These UAVs typically have a wingspan of 5–10 m and carry payloads of 100–200 kg. Finally, the large UAV class refers to the large drones mainly used by the military for combat operations. Taking into account the classification according to their range and endurance, drones can be divided into close range UAVs (range of 5 km, endurance time of 20–45 min), close-range UAVs (range of 50 km and endurance time of 1–6 h), short-range UAVs (range of 150 km or longer and endurance times of 8–12 h), medium-range UAVs (super-high speed and a working radius of 650 km), and long-range UAVs (endurance of 36 h and a working radius of 300 km) [13]. Furthermore, drones have a wide range of applications across various sectors, including military, commercial, surveillance and security, agriculture, delivery and logistics, and research. Due to their differing requirements, they employ significantly different technological solutions. Drones dedicated to military missions can be utilized for real-time battlefield monitoring, covert operations, and border security patrols, equipped with high-resolution cameras, infrared sensors, and radar. They must meet stringent operational requirements, including stealth and low detectability, secure and resilient communications, multi-domain capabilities, weather resilience, and environmental adaptability, as well as a high payload capacity required for the implementation of advanced sensors. On the other hand, in the commercial sector, drones can be utilized for aerial photography and videography, as well as for infrastructure and construction inspections, including various building inspections, 3D mapping, and site planning. In the delivery and logistics sector, drones are utilized for e-commerce delivery, medical supply delivery, and warehouse inventory management, particularly with the use of indoor UAVs. Surveillance and security applications include, among others, border and coastal surveillance, private security, asset protection, and anti-poaching and wildlife protection. In the agricultural sector, drones can be utilized for precision farming, including crop health monitoring with multispectral imaging, soil moisture analysis, and automated pesticide and fertilizer spraying, as well as for livestock monitoring and environmental conservation. Finally, when considering the scientific applications of drones, notable examples include activities such as environmental and climate research (including tracking weather patterns, monitoring glaciers and ice melt, and assessing the air quality), space and atmospheric exploration, as well as archaeological and geographical studies. The general classification of UAVs, based on their size, range, and application, is illustrated in Figure 2.

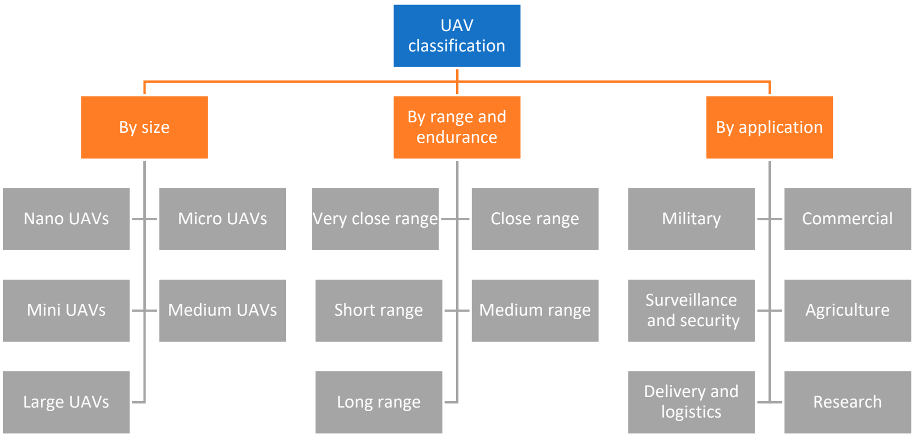


Figure 2. UAV classification based on their size, range, and application [14,15].

Another important consideration is geometry. The three main geometries are rotary wing, fixed wing, and a combination of fixed and rotary wing called vertical takeoff and landing (VTOL) drones [16]. UAVs also differ in the materials used in their construction, the propulsion systems, and the complexity and cost of the control system [14]. UAVs are typically composed of metals, composites, and plastics. Metals (including aluminum, titanium, and steel) are popular for their strength and durability. On the other hand, composites (typically a resin combined with fibers such as carbon fiber or Kevlar) have higher strength-to-weight ratios, allowing for increased payload capacities. In the case of plastic, additive manufacturing technologies, often referred to as 3D printing, enable rapid prototyping and fast production. Each material has its own set of benefits and challenges [17,18]. Considering the various propulsion systems, UAVs typically employ three primary propulsion systems: fuel, fuel–electric hybrid, and all-electric. The classification of UAV propulsion systems by energy type is shown in Figure 3.

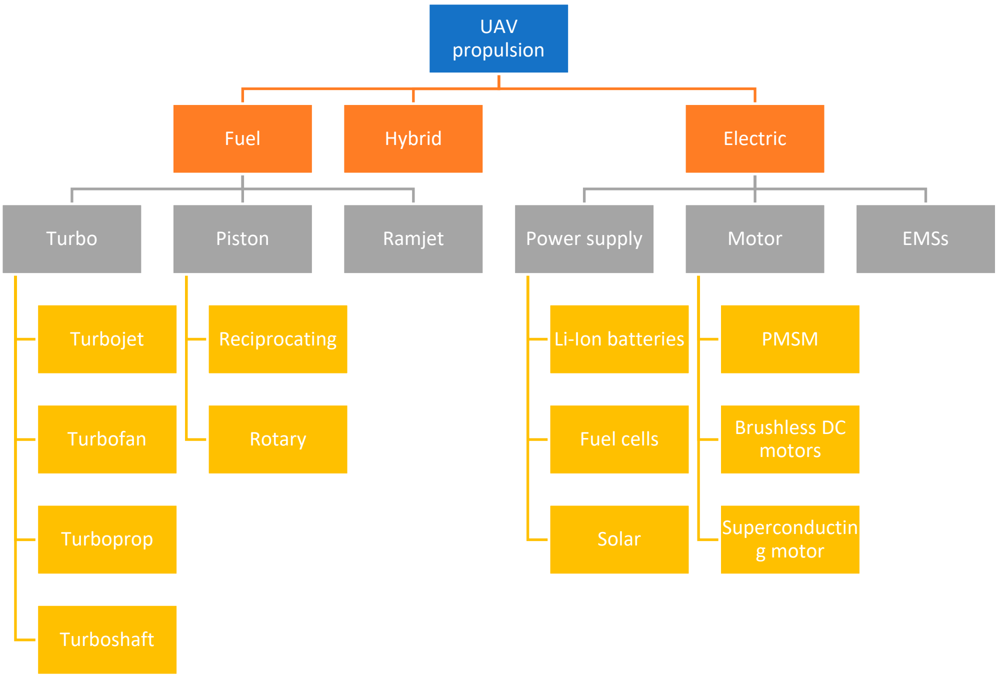


Figure 3. UAV classification based on the types of propulsion systems [5].

In addition to the classifications discussed above, other works have introduced further classifications of UAVs. For example, Watts et al. [19] classified drones for civil, scientific, and military purposes based on characteristics such as size, endurance, and capabilities. The proposed classification includes Micro Air Vehicles (MAVs), Nano Air Vehicles (NAVs), VTOL, Low Altitude, Short-Endurance (LASE), Low Altitude, Long-Endurance (LALE), Medium Altitude, Long-Endurance (MALE), and High Altitude, Long-Endurance (HALE). Cavoukian [20] categorized drones into three main types, including MAVs, Tactical UAVs (TUAVs), and Strategic UAVs (SUAVs). Generally, different mission requirements have led to the development of various types of UAVs. In this context, UAVs can be considered as horizontal takeoff and landing (HTOL), VTOL, hybrid model (tilt-wing, tilt-rotor, tilt-body, and ducted fan), helicopter, heli-wing, and unconventional types [21]. Only the selected solutions discussed above can be considered for incorporating solar cells into the power supply. These options are presented in the next sections of this paper, which is organized as follows: Section 4—Structural and material issues in the development of solar-powered UAVs, Section 5—Integration of solar cells in solar-powered UAVs, Section 6—Selection of energy storage technology for solar-powered UAVs, Section 7—Energy management in solar-powered UAVs, Section 8—Selected applications of solar-powered UAVs, Section 9—Future research directions for the development of solar-powered UAVs, and Section 10—Conclusions.

4. Structural and Material Issues in the Development of Solar-Powered UAVs

The structure and construction materials have a significant influence on the durability and range of solar-powered UAVs. To achieve extended flight endurance, fixed-wing UAVs are preferred over multi-rotor UAVs [22]. There are several reasons for this. First, fixed-wing UAVs can maintain flight with minimal power input by gliding, unlike multi-rotor drones that require continuous thrust to stay airborne. They are also more stable in strong winds than multi-rotor drones and can realize high-altitude and long-endurance missions. Additionally, fixed-wing UAVs have large wingspans, which provide a greater surface area for solar cells. However, the integration of solar cells into the wings affects the aerodynamics, including induced drag, lift, and overall flight efficiency. The induced drag is inversely proportional to the aspect ratio (AR), which means that wings with a higher AR (i.e., longer, narrower) reduce the induced drag. Consequently, high AR wings naturally have low induced drag, so the addition of solar cells has no significant effect. Additionally, when evenly distributed, solar cells can act as microlaminar flow modifiers, enhancing the lift-to-drag ratio in certain cases. On the other hand, solar cells add weight, requiring more lift generation, which in turn increases the wingtip vortices and can cause higher induced drag. This effect is more pronounced in low-power UAVs. Another potential drawback can occur if the solar cells are not flush with the wing surface. In such cases, solar cells can disrupt the laminar airflow, leading to localized flow separation and increased drag. Poor integration can also increase form drag and reduce the efficiency. To overcome the challenges such as wing deformation due to a high aspect ratio, flight control difficulties, and aeroelasticity issues, most solar-powered UAVs have adopted a conventional layout in recent years [23]. The design issues, including structures, systems, propulsion, aerodynamics, and system integration for solar-powered aircraft were reviewed by Abbe and Smith [24]. When designing a solar-powered UAV, the first step is determining the total weight, flight speed, and lift-to-drag ratio based on the mission requirements. Once these parameters are established, the weight of the storage battery and solar cells can be calculated. On the other hand, the relationship between the wing's produced lift and drag should be studied when considering the wing's geometry. Considering a constant wing area, the higher the aspect ratio (AR), the greater the wingspan. This increase in the wingspan reduces the wing portion affected by wingtip vortices, thus reducing the lift losses and decreasing the induced drag component [25]. Additionally, the wing's shape affects the distribution of lift along its span. Rectangular wings are easier to manufacture but generate excessive induced drag, while elliptical wings offer optimum aerodynamic performance but are complex and expensive to manufacture. The wing taper ratio provides a compromise between these two designs, striking a balance between efficiency and practicality [26]. On the other hand, since most wing surfaces have some degree of curvature and bending during flight, stresses can be induced in the solar arrays. In this context, Scheiman et al. [27] studied solar cell cracking from wing integration through the array assembly process to flight. The authors used photoluminescence to assess the wing stresses by optically identifying cell crack propagation.

In general, many authors have published works explaining the design process of solar-powered UAVs [28,29]. For example, Shiau and Ma [30] investigated the aerodynamic performance design based on a mass parameterization approach, as well as the design of a solar power management system featuring a microcontroller-controlled buck–boost power converter. The aircraft mass was parameterized as a function of two key performance factors: wing reference area and cruise speed. A fitness function was then formulated to link the optimization problem to a genetic algorithm. The algorithm was then used to identify the optimal configuration for minimizing the energy consumption. Based on the optimization results, a solar-powered UAV was designed and constructed. The proposed approach was validated through successful ground and flight tests, and the UAV made its maiden flight in Taiwan in August 2012. The aerodynamics and design of a UAV powered primarily by solar cells were also investigated by Escobar-Ruiz et al. [31]. The design process was divided into three key phases: conceptual design, preliminary design, and computational fluid dynamics (CFD) analysis of the aircraft. The conceptual design was developed based on the specifications of the area covered by the solar cells, determining the minimum area required for their placement. The empennage and fuselage were designed using aerodynamic calculations to achieve the optimum glide angle and ensure static stability during the glide phase. A preliminary model was created based on the conceptual design, followed by an aerodynamic analysis using CFD to evaluate the lift generated by the UAV. Performance tests were also performed on the solar cells with a polymer-based coating. This coating reduced the weight and allowed seamless integration into the UAV platform. Furthermore, Ilhan and Calik [32] conducted studies focused on searching for the conceptual design methodology, emphasizing the complex interplay of factors such as aerodynamics, structural analysis, and performance requirements in solar-powered UAV design. They discussed the crucial aspects, including solar irradiation, weight analysis, and aerodynamic parameters, during the design process. The proposed UAV design incorporated monocrystalline silicon solar cells, lithium batteries, and Maximum Power Point Tracking (MPPT) technology. The authors concluded with a detailed weight estimation, aerodynamic parameters, and a conceptual design that envisions a solar-powered UAV capable of sustained flight. Dinca et al. [33] proposed a solar-powered UAV configuration called "Newsolar", which sacrifices high aerodynamic efficiency for a larger surface area available for the solar cells. In this way, the amount of energy available on board the UAV was increased, and the UAV structure became more robust for the same wingspan. The potential performance of this new configuration was studied using an onboard energy balance. It was found that the distance covered by "Newsolar" in this mission was 67% greater than that of the glider configuration. The overall configuration of "Newsolar" is illustrated in Figure 4.

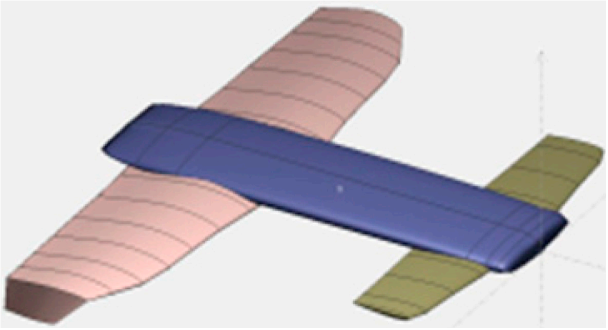
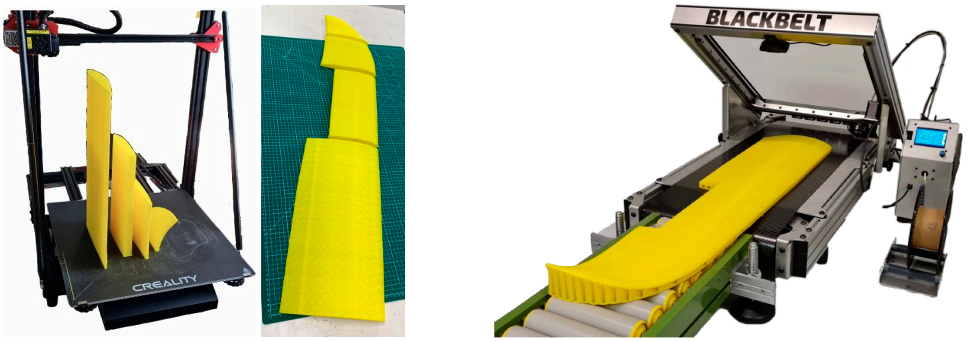


Figure 4. The overall configuration of "Newsolar" [33].

Garcia-Gascon et al. [34] described the conceptual design and manufacturing process of SolarÍO, a solar-powered aircraft developed using additive manufacturing technologies. For the prototype's production, a specialized 3D printer with a moving belt-like bench—which allows the production of parts without Z-axis limitations—was evaluated. The results demonstrated the potential of additive manufacturing as an innovative production method for small aircraft, highlighting its future relevance in the aerospace industry as new materials and more efficient manufacturing processes continue to be developed. Figure 4 illustrates the difference between the wing generated by the conventional 3D printer (Figure 5a) and the wing manufactured using the Z-infinite printer (Figure 5b). In the first case, the wing parts were joined together using an adhesive. Consequently, the joints may be critical points of bending stress. On the other hand, there are no joints in the second case where the wings were printed as a whole part.



(**a**) (**b**)

Figure 5. Wing generated in the conventional 3D printer (**a**) and the wing manufactured using the Z-infinite printer (**b**) [34].

Considering the various optimization attempts, Li et al. [35] proposed a general optimization design method for a solar-powered UAV, with a primary focus on planning the propulsion system. Considering the typical mission requirements, the key design variables (such as wing area, aspect ratio, and design mission date) were incorporated to minimize the aircraft weight. The findings indicated that prioritizing propulsion system planning in the optimization process significantly reduces the energy storage battery's electricity demand and substantially lowers the overall weight of the solar-powered UAV. Hou et al. [36] established a mathematical model for multi-objective optimization of a solar-powered UAV, utilizing a multi-objective genetic algorithm to optimize the design. For aircraft with a large, flexible structure, a comprehensive design method for load, stiffness, and strength based on the load configuration was proposed. In the early design stage, the cross and coupling effects of each subsystem were comprehensively considered, and the load, mass, stiffness, and other design factors were carefully evaluated. Then, by adjusting the mass and stiffness distribution of the structure to reduce the load, the overall performance of the aircraft was improved. Bakar et al. [37] utilized a genetic algorithm to optimize the design of a solar-powered UAV for a specific altitude, cruise speed, and static margin. The study focused on developing an airfoil tailored to these flight conditions while considering the overall performance and weight estimation. The proposed mass estimation model was based on the structural layout, design parameters, and materials commonly used in similar UAV fabrications. The optimized UAV configuration had a total mass of 7.08 kg, with a battery mass of 3.4 kg. The airfoil featured a smooth surface with a thickness of 9.7% and a camber of 4.6%. Additionally, longitudinal and lateral control systems were developed using an inner–outer loop strategy, incorporating an LQR controller for longitudinal stability and a PID controller for lateral control. Al Majarfi et al. [38] designed a solar-powered UAV with the intention of doubling the endurance of any aircraft by incorporating solar cells and operating at an altitude of 100 m and speed of 35 km/h. The solar system was installed on the UAV airframe, which had a specially designed wing. The study was conducted using the eCalc website, mathematical equations, as well as MATLAB and Multisim software to assess the system's performance. Jashnani et al. [39] explored the impact of the altitude and payload mass as independent parameters influencing the size and design of solar-powered UAVs. Two distinct models were introduced to estimate the available solar power (one for low altitudes below 2.5 km and another for high altitudes). The dedicated model was developed to simulate the power and propulsion system over 24 h of continuous operation. The authors presented data from the tests performed and changes that can be made to improve the design. Another example of the analyses related to solar-powered UAVs from the point of view of determining the possible payload was presented by Montagnier et al. [40]. In the case discussed, the wing's mass was minimized by utilizing composite materials and tolerating a high degree of flexibility. The optimization showed the existence of the UAV in a cruise speed versus lift coefficient diagram. This yielded an optimal solution with a payload of approximately 4% of the total mass, 817 kg, for a wingspan of 69 m. Oktay et al. [41] conducted studies to increase the maximum lift-to-drag ratio (E_{max}) of TUAVs by implementing innovative small-scale aerodynamic modifications. The aircraft was developed at the Faculty of Aeronautics and Astronautics at Erciyes University and featured both passive and active morphing capabilities. To enhance E_{max}, the nose cone and tail cone were redesigned, and an active flow control system was integrated into the wings. These aerodynamic modifications resulted in a significant improvement in the UAV's maximum lift-to-drag ratio. Jaszczur et al. [42] analyzed the aerodynamic parameters of the initial model of the solar-powered UAV designed by AGH Solar Plane, including lift, drag, and airflow breakup analysis. During the study, four new wings' geometries were created. CFD simulations were used to investigate the flattening of the upper surfaces for the attachment of solar cells. It was found that the flattening of the wing caused by the flat PV cells reduced the lift-to-drag ratio (CL/CD). However, a significant decrease was observed for the three- and five-flat variants, while the six-flat variants were very similar to the non-flat result. The results of the mathematical modeling were validated in an aerodynamic tunnel using the Particle Image Velocimetry (PIV) method. Taking into account all the analyses, several recommendations were made for the further development of the proposed aircraft. The prototype of the constructed vehicle, known as "Franek", is illustrated in Figure 6.

Figure 6. An overall configuration of solar-powered UAV constructed [43].

Harasani et al. [44] outlined the design features of the Sun Falcon, a solar-powered UAV capable of continuous daytime flight, with enhancements planned for nighttime operation. A key consideration in the design process was the critical role of airfoil selection, as the Reynolds number for such UAVs is significantly lower than that of conventional vehicles. Considerations included the camber curvature and wing area, which needed to accommodate solar cells while ensuring the structural integrity and efficiency in varying weather conditions. From the two options considered, the SD7037 airfoil was ultimately selected due to its superior geometry and camber line, which enabled the optimal integration of the solar panels, as well as improved takeoff performance and a higher cruise lift-to-drag (L/D) ratio. Furthermore, Guo et al. [45] proposed an integrated design methodology that considers both the propulsion system and the UAV structure. The study included an aerodynamic layout design, performance evaluation, and the fabrication and assembly of a prototype for flight testing. The wing area was determined based on the power generation of a single solar panel and wing loading. The airfoil design was accomplished using Profili 2.21 software, taking into account the low speed and low thrust-to-weight ratio characteristics of solar-powered UAVs. The body and tail design was performed to achieve the best aerodynamic performance. The assembled UAV is shown in Figure 7. The results highlighted the effectiveness of this approach in enhancing the efficiency of the UAV's solar-powered propulsion system.

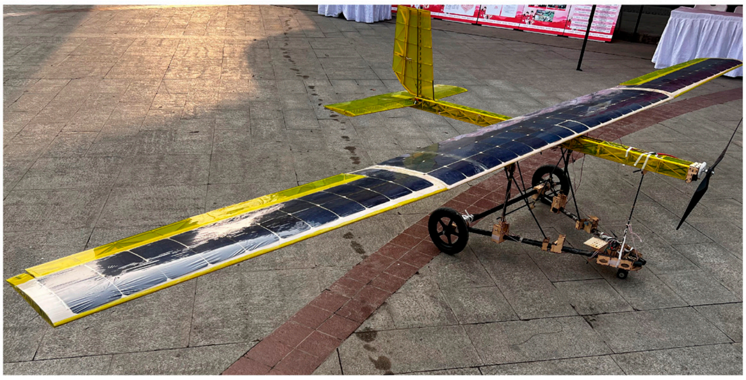


Figure 7. An overall configuration of solar-powered UAV constructed by Guo et al. [45].

Thipyopas and Warinthis [46] developed small solar-powered UAVs for low-altitude operations. Their study involved analyzing different solar cell technologies and evaluating the aircraft performance to determine the optimal design configuration for efficient flight within the target operational wind speeds of 0–5 m/s. They also investigated high-angle-of-attack landings to assess the feasibility of short landings in confined areas. Calculations and flight tests showed that setting the aileron deflection to −30 degrees enabled a deep stall trajectory, allowing a controlled descent without damaging the aircraft. Hong et al. [47] developed a solar-powered UAV designed for low-altitude, long-endurance flight. The proposed aircraft was constructed using commercially available materials and components. It featured a 4.7 m wingspan and a T-tail configuration. During conducted flight tests, the endurance of 21 h and 50 min was achieved, marking a record in Taiwan. Although the full-day flight objective was not fully realized, the results highlight the UAV's potential for extended endurance with further design and operational efficiency refinements. The authors in Ref. [48] presented the development process of a small, 6.9 kg, hand-launchable, low-altitude, solar-powered UAV that completed an 81 h continuous flight, establishing a new world record for flight endurance among all aircraft with a mass below 50 kg. The results from this flight show that AtlantikSolar achieved a minimum state of charge of 39%, an excess time of 6.8 h, and a charge margin of 6.2 h. Oettershagen et al. [49] presented the conceptual design, development, and flight testing of *AtlantikSolar*, a 5.6 m wingspan solar-powered LALE UAV. An enhanced conceptual design methodology was introduced to improve the aircraft's resilience to local meteorological disturbances such as clouds and wind, ensuring sustained flight. The development of the airframe, avionics hardware, state estimation, and control methods for autonomous operations was described in detail. Moreover, the authors described flight tests that included a 12 h battery-powered flight to simulate night-flight conditions, demonstrating the UAV's capability for extended endurance missions. Salazar et al. [50] conducted a study to optimize the use of solar energy to power a fixed-wing UAV. The use of tools such as FoilSim III for analyzing aerodynamic profiles with a low Reynolds number, including the DAE-5 Profile, N-60 Profile, and the Selig Profile (profiles Sa7038, S4083, and SG604), ensured the efficient integration of solar cells without compromising the in-flight maneuverability. Furthermore, the use of MATLAB software for simulating different trajectories and analyzing the energy behavior during battery loading and unloading enabled the analysis of the aircraft's flight behavior under various flight conditions. Alsahlani et al. [51] highlighted the importance of finding a minimum feasible weight solution in the context of HALE solar-powered UAVs. As these aircraft operate at high altitudes, it is even more crucial to optimize their total mass, which, as mentioned before, directly impacts the energy needed to operate in the air. The authors mentioned the lightweight composite materials widely used in UAV structures, such as carbon fiber incorporated in Helios, Pathfinder, Qinetiq Zephyr, and X-HALE. Liller et al. [52] described the concept of a battery-free, solar-powered aircraft, emphasizing the reduction in power consumption by minimizing the weight of the UAV. The authors presented the design of a tail constructed from a carbon-fiber-reinforced polymer tube, which keeps the tail connected to the fuselage while maintaining a minimal weight. In general, the further development of lightweight composite materials and advanced structural technologies can play a critical role in improving the performance of solar-powered UAVs. The integration of carbon fiber composites (characterized by a high strength-to-weight ratio, enabling weight reduction while maintaining structural strength), graphene (ultra-light, conductive material that improves the solar cell efficiency and heat dissipation), aerogels (extremely light, insulating material that improves the thermal resistance in high-altitude UAVs), Kevlar composites (characterized by high durability and impact resistance, and used for rugged UAVs in military and extreme environments), and 3D-printed polymers (customizable and lightweight materials that enable rapid, weight-optimized UAV prototyping) can revolutionize the design of solar-powered UAVs. These materials, combined with carefully selected solar cells and batteries, along with an optimized energy management system, enable longer flight endurance, increased energy efficiency, and enhanced structural resilience.

5. Integration of Solar Cells in Solar-Powered UAVs

The next step in developing solar-powered UAVs is to select the appropriate type of solar cells and integrate them into the aircraft's wings. Three generations of solar cells can be identified based on the materials used in their manufacturing. The first generation consists of silicon wafer-based solar cells characterized by quite a high efficiency (exceeding 20% in the case of monocrystalline solar cells) and long life cycles (more than 20 years). However, an excessive size may be a drawback for some UAV applications [53]. The second generation of solar cells emerged with the challenge of reducing the weight and size while maintaining reasonable efficiency. The examples of this generation are amorphous silicon (a-Si) solar cells (characterized by the highest reported efficiency of 14%), cadmium telluride (CdTe) solar cells (23.4%), copper indium gallium selenide (CIGS) solar cells (23.4%), and gallium arsenide (GaAs) solar cells (28.8%) [54,55]. The latest generation of solar cells is based on abundant materials, utilizing nanostructures or organic materials to achieve a photovoltaic conversion efficiency exceeding 60%. On the other hand, perovskite solar cells are by far the photovoltaic technology with the fastest evolution, now reaching the astonishing power conversion efficiency (PCE) of 25.2% [56]. In this context, one emerging technology that can be utilized for avionics is the new generation of flexible printed photovoltaic cells [57]. The innovative method of printing perovskite on flexible foils was developed and introduced by the Saule company [58]. Furthermore, Sampaio Saloio et al. [59] investigated the development of a solar-powered UAV designed to enhance the flight endurance and minimize the environmental impact by utilizing lightweight Cu–In–Ga–Se (CIGS) solar cells. The solar power management system, featuring an MPPT and a DC-DC converter, achieved an efficiency of 96%, while the solar cell efficiency ranged from 11.3% to 14.1%. Ground tests and simulations indicated a potential flight endurance of nearly 8 h under average irradiation conditions. In addition, NRL has developed a variety of UAV wings utilizing solar cell technologies, including Si, thin, flexible GaAs, triple-junction InGaP/GaAs/Ge, and Inverted Metamorphic Multi-Junction (IMM) for comparison. NRL has flown these solar technologies and demonstrated flights of over 10 h with only 4 h of onboard energy storage [60]. Moreover, NASA's Glenn Research Center has developed a high-efficiency multi-junction solar cell that utilizes a thin layer of selenium as a bonding material between wafers. This innovation enables the development of a multi-junction solar cell without the constraints of lattice matching, utilizing a low-cost, robust silicon wafer as the supporting lower substrate and lower cell. It can deliver unprecedented efficiencies for UAV auxiliary power units [61]. In addition to improvements in solar cell efficiency, advanced MPPT methods can significantly improve the performance of solar-powered UAVs. Several MPPT techniques can be integrated into the aircraft, including Incremental Conductance (IC) MPPT, Fuzzy Logic MPPT, Neural Network-based MPPT, and Particle Swarm Optimization (PSO) MPPT. Among the other available options, AI-based and hybrid MPPT techniques are gaining traction due to their ability to dynamically optimize power harvesting with superior efficiency.

Considering the construction aspects, solar cells can be integrated into the wings in several ways, including attaching them to the existing wings, integrating solar modules into the mold, and using solar modules as the wing surface. The first method is suitable for retrofitting solar cells to existing UAVs, while the last two options are dedicated to new UAVs. In the approach covering the integration of solar cells into the mold, they become an integral part of the wings. The main advantage is the ease of wiring, but on the other hand, a disadvantage is that the PV modules cannot be replaced if damaged. In the method, when solar modules are used as wing surfaces, PV modules form the upper surface of the wings. While this design allows for an easy wiring layout, it requires additional internal ribs within the wing structure to increase the overall strength of the UAV [62]. Also, Łopusiewicz and Książek [63] conducted studies on advancing solar-powered UAV technology by developing two novel methods for integrating solar cells into composite wing structures. The first method involved laminating successive glass or carbon fiber layers onto an existing glass fiber composite with solar cells. The underside of the wing was laminated separately, and then the two layers were carefully laid over the wing core and left under a vacuum for at least 24 h. The second method involved pre-laminating the wing separately and then laminating the pre-prepared fiberglass cell module. It was demonstrated that the first method yielded a wing with a higher stiffness and strength, which was also reflected in the improved performance of the PV modules. The proposed solution was patented and incorporated into the solar-powered UAV "Foton", which was developed by the AGH Solar Plane Student Research Group (see Figure 8).

Furthermore, Ionescu et al. [64] discussed an efficient method of incorporating solar cells into UAV wings. Instead of gluing solar cells to the wings, the new approach was to embed the solar cells into the wing structure and develop a new type of wing that is significantly lighter to compensate for the weight added by the solar cells. It was demonstrated that by using this approach, a 33% increase in flight time can be achieved with only one modified wing in a prototype aircraft. The developed construction of ultra-light wings with embedded micro-texturized solar cells is shown in Figure 9.

Figure 8. Solar-powered UAV "Foton" created by AGH Solar Plane.

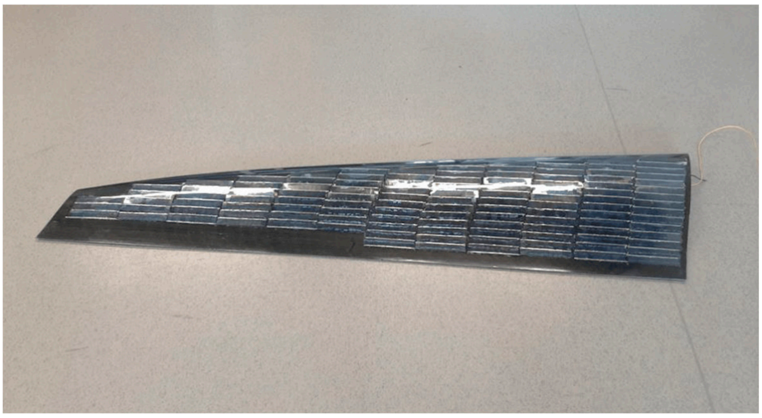


Figure 9. Ultra-light wings with embedded micro-texturized solar cells [64].

Cosson et al. [65] developed a simulator for predicting the photovoltaic power generation and its storage in Li-ion batteries for an autonomous drone with four wings covered with thin-film gallium arsenide (III-V) solar cells. The simulator accurately estimated the effective photovoltaic power output and battery pack voltage during flight. It incorporated key flight parameters such as irradiance, solar tilt angles, and the drone's Euler angles as the input variables. The measured photovoltaic power and battery voltage closely matched the simulated values. The results demonstrated that the drone can achieve flight durations of up to 12 h under optimal conditions. Chu et al. [66] modified a market-available 2 m wingspan remote-controlled (RC) UAV by implementing a hybrid power system that combines solar energy and battery storage. The primary goal of his study was to extend the UAV's flight endurance. As was shown, the solar power system achieved a 22.5% reduction in battery consumption under favorable experimental conditions with optimal weather. Additionally, during stable-level flight, the battery voltage depletion rate was considerably slower in the solar-powered UAV compared to the same configuration without the solar integration. The aircraft constructed by the authors is shown in Figure 10.

The integration of solar cells can impact the aerodynamic performance of solar-powered UAVs, namely the heat transfer and surface roughness of the solar cells. Maliky et al. [67] conducted simulations using the CFD method based on the solution of the RANS equations to investigate the interaction between flow motion, heat transfer, and surface roughness. Their results showed that heat transfer significantly altered the flow density near the surface, leading to buoyancy effects and changes in the flow velocity profile. Meanwhile, the surface roughness affected the flow characteristics by inducing turbulence. As a result, the aerodynamic drag increased by 2.6%, while the aerodynamic efficiency improved by 5%. Also, Emad et al. [68] assessed the impact of attaching solar panels to a UAV's wing on its aerodynamic performance and structure. The authors performed their analyses using CFD simulations and FEA approaches. In opposition to previous work, they found that the solar cells had a minor effect on the aerodynamic performance of the wing, while it had a bigger effect on its structure. Furthermore, Carmo et al. [69] researched into the installation of solar cells in the structure of a UAV, aiming to study their influence on flight time. A prototype was constructed using a finite element tool and used to evaluate the possible air–structure interactions in harsh environments. A Reynolds Averaged Navier–Stokes (RANS) model was used to evaluate the equations for a more streamlined approach with lower computational requirements. The results were used to assess the credibility of the chosen solar technology. Considering the results obtained, it was concluded that the solar panels could only significantly extend the flight time under very specific conditions. Perez-Rosado et al. [70] investigated the integration of solar cells not only into the wings but also in the tail and body of a flapping UAV (FUAV). The study highlighted that increasing the wing area allows for incorporating additional solar cells, but this comes with trade-offs, including torque limitations of the servomotors used for wing actuation and changes in lift and thrust forces that can affect the payload capacity. These effects were modeled as a function of the wing area to assess their influence on the flight endurance. In addition, solar cells were embedded in the body and tail of the considered UAV. The redesigned "Robo Raven" aircraft demonstrated a 64% increase in onboard solar power generation and achieved a 46% improvement in flight time compared to its predecessor.

Figure 10. The solar-powered UAV developed by Chu et al. [66].

In contrast to the solutions discussed above, Liller et al. [52] investigated a battery-free fixed-wing UAV, constructed using cost-effective, off-the-shelf components capable of takeoff, sustained flight, and safe landing solely on solar energy. A comprehensive analysis and design space exploration was conducted within the modern solar energy harvesting framework, providing a detailed assessment of the prototype's mechanical and electrical performance. Additionally, two solar energy control algorithms were developed to mitigate the power system brownouts and total loss-of-thrust scenarios, enabling the UAV to execute maneuvers without relying on a battery.

As most solar-powered UAVs are fixed-wing aircraft, Abidali et al. [71] developed a prototype of a multi-rotor UAV (MAV) with integrated solar cells, a BMS, automatic on/off, low-power sleep, and a first-person-view camera. While overcoming the limitations of battery-only systems, the discussed study contributed to the development of cleaner, longer-lasting designs for UAVs. Additionally, researchers at Johannes Kepler University

Linz (JKU) in Austria conducted a study to develop ultra-thin and lightweight solar cells, enabling drones to achieve energy autonomy. The developed quasi-2D perovskite solar cells delivered a 20.1% efficiency. To test this technology, the researchers fitted a small commercial quadcopter drone with 24 solar cells, making up 1/400 of its total weight [72]. Given this type of aircraft, MAVs have the potential to be used in areas where the access to power is rare or non-existent, such as offshore missions, deserts, or the exploration of other planets such as Mars, depending on the atmospheric and gravimetric properties of the planet [73].

6. Selection of Energy Storage Technology for Solar-Powered UAVs

The fundamental problem with UAVs is that they must constantly use a significant amount of power from their battery source to counteract gravity. Thus, a highly efficient storage system is crucial to provide reliable flights over a longer period. Due to the limited flight time of battery-powered UAVs, which is approximately 4 h, despite reducing their attractiveness, hybrid solar and battery systems for UAVs are being developed [74]. When selecting a battery cell type for a solar-powered UAV, several factors must be considered, including the temperature range, lifespan, energy density, charging time, safety, shape, and overall performance. Moreover, the safety of battery energy storage systems is of paramount importance. State of charge (SOC) monitoring enables comprehensive decision making within the system, ultimately improving its safety and performance [75]. The SOC is directly affected by the intensity of the sunlight. The higher the light intensity, the faster the battery will charge and the higher the SOC will be. However, various factors such as battery type, solar panel efficiency, and environmental conditions also affect the charging process and overall performance. Furthermore, for the optimal operation of the solar cells and the battery, the power supply system should be equipped with MPPT (Maximum Power Point Tracking) and a BMS [76].

The various energy storage technologies for UAVs can be considered, including Lithium-Ion (Li-Ion), Lithium Polymer (LiPo), Lithium Iron Phosphate ($LiFePO_4$), Lithium–Sulfur (Li–S), Nickel Metal Hybrid (Ni-MH), Lead Acid (LA), and Nickel–Cadmium (NiCd) batteries [77]. Each type of battery has its own set of properties, as summarized in Table 1.

Table 1. Comparison of selected battery technology properties [78].

Battery Technology/Parameter	Li-Ion	LiPo	Ni-MH	NiCd	LA
Nominal cell voltage, V	3.60–3.85	2.70–3.00	1.20	1.20	2.10
Energy density, Wh/kg	100–265	100–265	60–120	40–60	30–40
Power density, W/kg	250–340	245–430	250–1000	150	180
Cycle life, cycles	400–1200	500	180–2000	2000	<1000
Charge/discharge efficiency, %	80–90	90	66–92	70–90	50–95
Depth of discharge, %	80	80	100	60–80	50
Cost, USD/Wh	0.94	2.31	0.85	2.68	0.70

It can be seen that when examining batteries, several key characteristics are emphasized: the energy and power capacity, depth of discharge, charge/discharge efficiency, cycle life, nominal cell voltage, and cost [78]. Moreover, the selection of the appropriate battery technology is closely tied to the considered UAV application and mission. In general, Li-Po and Li-Ion batteries are the most commonly used in UAVs due to their high energy density and lightweight nature, which enables them to be manufactured in various sizes and shapes and have high discharge rates [79,80]. Considering the battery cell's shape, cylindrical cells offer strong mechanical durability, high specific energy, and good energy density; however, they suffer from poor heat management. Prismatic cells offer good mechanical strength, effective heat management, high specific energy, and high energy density; however, their heavy casing imposes certain limitations on the overall energy density of the battery pack. Pouch cells excel in heat management, energy density, and specific energy, but their main drawback is their low mechanical strength [81]. Although Li-ion batteries have many advantages, they can pose additional safety risks due to their high energy density and flammable electrolytes. Among other safety-critical issues, thermal problems, overcharging or over-discharging, overcurrent, and exposure to excessive mechanical and physical stress can lead to thermal runaway, which in turn can result in venting, leakage, explosion, and setting on fire of the battery cells. To minimize these risks in the UAVs' operation, the proper selection of the BMS system is required [82]. Since the BMS performs critical functions such as charge and discharge control, state detection, fault diagnosis and warning, data recording, and other essential tasks, it is an essential component of each UAV. With the rapid advances in the battery-related materials and electrochemistry, as well as the development of new battery types, the design methods of the BMS must be continuously adapted and improved [83].

In modern solutions dedicated to the electromobility sector, the combined fuel cell and battery systems have been proven to be a suitable option. At the current stage, such systems are still unable to provide the required power for large passenger planes. However, they may be used in smaller applications, including UAVs [84].

7. Energy Management in Solar-Powered UAVs

High-performance power systems are critical to ensure long-flight endurance and strong power performance of aircraft. In this context, energy management plays a dominant role in determining the comprehensive performance of solar-powered UAVs.

The worldwide literature encompasses various studies on optimizing the energy flow in solar-powered UAVs. Gao et al. [85] discussed the work focused on optimizing the energy consumption during the climb and glide phases by analyzing the variable climb speeds and glide power levels. To achieve this, fitness functions were formulated for both phases, taking into account the aircraft's maximum climb speed and glide power constraints. The problem was solved using the Particle Swarm Optimization algorithm, resulting in significant energy savings, specifically over 68% during climb and 4.8% during glide. By studying the optimization trends, the authors introduced an energy management strategy tailored to the needs of long-endurance flights. Martin et al. [86] demonstrated the use of nonlinear dynamic optimization to determine the energy-efficient trajectories for a high-altitude solar-powered UAV. The study aimed to maximize the total system energy while maintaining a flight radius of 3 km. The solar energy capture was modeled based on the UAV's orientation and the sun's position, with energy stored both in onboard batteries and as potential energy through altitude gain. Additionally, energy capture was maximized by optimally adjusting the aircraft's surface angle relative to the sun. The simulated flight results were analyzed for all four seasons and showed an 8.2% increase in the end-of-day battery energy under the most challenging condition, the winter solstice. Dwivedi et al. [87] discussed the methodology for selecting the battery and flight trajectory for a solar-powered UAV to achieve maximum endurance. The study aimed to estimate the battery capacity required for installation and to determine the optimal altitude profile during flight. The authors analyzed in detail the variations in endurance concerning various factors, including the geographical location, aircraft aerodynamic parameters, propulsion system, battery size, and flight parameters. They concluded that a longer endurance can be achieved for the tested aircraft by properly selecting the battery and the flight pattern for the mission. Mateja et al. [62] presented a mathematical model designed to predict the solar irradiation and energy harvesting in solar-powered UAVs. The proposed model considered various factors affecting energy harvesting, including the date and altitude. The authors identified the critical factors necessary to achieve a 24 h endurance flight by analyzing the simulations performed and the flight scenarios prepared. Zhang et al. [88] developed a 3D numerical model to investigate the effect of the flight speed, altitude, and time of day on the thermal and energy dynamics of the solar-powered UAV. The results of the conducted tests show that the altitude has a significant effect on the internal temperature of the aircraft, with the battery temperature decreasing by approximately 5 K as the altitude increases from 11 km to 20 km. The improved thermal management system maintained the battery temperature at around 220 K, representing a 50 K increase in the minimum battery temperature compared to conventional designs. Additionally, the modified structure enhanced the heat transfer within the aircraft, resulting in a 3 K increase in the minimum temperature of the solar panels, which further improved the overall thermal performance. The authors in Ref. [89] developed a mathematical model of a power balance system and then investigated the impact of various factors on the power balance and the critical energy cycle. They found that the effect of random wind on energy storage batteries is relatively small. However, the obtained results only reported the energy management in the part or sample structure of UAVs. Oktay and Coban [90] designed simultaneous longitudinal and lateral flight control systems for passive and active morphing TUAVs. In their study, the ZANKA-III aircraft was tested, characterized by a weight of 50 kg, a range of approximately 3000 km, an endurance of approximately 28 h, and a ceiling altitude of approximately 12,500 m. Von Karman turbulence modeling was used to model the atmospheric turbulence during the flight. A stochastic optimization method was employed to determine the optimal dimensions of the morphing parameters and the optimal magnitudes of the longitudinal and lateral controller P, I, and D gains while minimizing the cost index terms and capturing both the longitudinal and lateral autonomous flight performance.

Many research studies have also focused on path planning, which is particularly challenging because it must consider the energy consumption and solar energy harvesting. By employing intelligent path-planning techniques, solar-powered UAVs can optimize their energy balance, thereby improving both operational performance and reliability across a variety of environmental conditions. Moreover, a collision-free path during taking off and landing in complex environments is critical to mission success. Traditional path planning algorithms such as a Rapidly Exploring Random Tree (RRT) generate an initial path based on an environmental map [91]. This method was examined by Huang and Savkin [92] when the path planning problem for a solar-powered UAV inspecting a set of sites for safety and rescue in a mountain area was considered. Although RRT is a widely used method, it has significant limitations, particularly in finding an optimal path. Thus, optimization-based approaches yield near-optimal solutions by utilizing mathematical objective functions. For example, advanced optimization techniques have been applied to enhance the path planning of solar-powered UAVs. In this context, Fu et al. [93] investigated an optimization of 3D trajectory and scheduling for solar-powered aircraft. The work was aimed to maximize the residual energy of the UAV while satisfying the requirements of Internet of Things Devices (IoTDs) by jointly optimizing the three-dimensional (3D) trajectory of UAVs and scheduling for IoTDs. The authors formulated multiple objective functions to model the system mathematically and used a convex optimization solver with an interior-point method to find optimal solutions.

Another way to enhance the capabilities of UAVs and enable them to perform a wider range of tasks with greater efficiency and accuracy is by using machine learning. Machine learning models can be applied to UAVs in various ways, including object detection, autonomous navigation, mission planning, and predictive maintenance. In this context, Sehrawat et al. [94] conducted a study to enhance the solar energy harvesting capabilities of UAVs, focusing on utilizing solar energy to improve the overall energy of harvesting systems. The wings of the UAV were equipped with solar panels that harvest solar energy using optimal power point tracking to maximize the efficiency. Geographical solar irradiance data, daytime information, cloud cover, temperature ranges, and specific UAV characteristics, including the time, day, yaw angle, pitch angle, roll angle, and latitude, were used to perform simulations. The simulation results utilized an ensemble machine learning algorithm that incorporated environmental variables and UAV flight data to predict the solar power output. Additionally, a comparative analysis of various machine learning models offers deeper insights derived from the UAV dataset. As concluded, by leveraging the predicted power outputs, future flight paths can be dynamically adjusted to ensure the optimal exposure to sunlight. Vashisht and Jain [95] proposed a unique software-defined network-enabled opportunistic offloading and charging scheme for multi-UAV ecosystems. A software-defined network (SDN)-enabled opportunistic offloading and charging scheme (SOOCS) was evaluated to address the above-mentioned issues.

There are also numerous works devoted to optimizing the energy efficiency in solar-powered UAVs used in communication systems. Flying at an altitude of around 20 km, aircraft can revolutionize the telecommunications sector and improve Internet accessibility. Liu et al. [96] investigated the use of solar-powered UAVs for wireless communication. This study focused on the 3D position optimization of an aircraft connecting a remote sensor array to an optical ground station (OGS) for data processing. Since atmospheric conditions affect both solar energy harvesting and optical wireless signal transmission, the study addressed UAV position optimization under various environmental factors, including the cloud cover, atmospheric turbulence, and airborne particles. The results showed that the optimal UAV position, which maximizes the end-to-end channel capacity, was strongly dependent on the prevailing atmospheric conditions. Also, Song et al. [97] investigated the optimization of energy efficiency for a solar-powered UAV communication system. The authors considered a scenario in which multiple ground users (GUs) establish wireless connections with a solar-powered, multi-antenna UAV. To maximize the energy efficiency in terms of both the uplink data rate and power consumption, a dynamic optimization strategy was proposed. This strategy adjusted the trajectory and orientation of the UAV by fine-tuning its speed, acceleration, heading angle, and transmission power to the ground user. Performance evaluations highlighted the effectiveness of the proposed approach in improving the design of low-power UAV communication systems. Arum et al. [98] investigated the energy management of solar-powered aircraft-based high-altitude platforms (HAPs) for providing wireless communication services in equatorial and northern regions. They analyzed the total solar energy harvested and consumed on the shortest day of the year, highlighting the implications for the feasibility of long-endurance, semi-permanent missions. The results have shown that solar-powered HAPs are constrained by power and weight, primarily influenced by the platform's wingspan, which determines the area available for solar panels. As discussed, platforms with wingspans of 25–35 m can operate for 15–24 h per day, depending on the configuration and coverage radius. Doubling an aircraft's wingspan can increase its payload capacity by six times, significantly improving its viability for wireless communication applications.

Furthermore, UAVs can serve as data collectors, supporting the IoT in data collection. In this context, Cheng et al. [99] proposed a reconfigurable intelligent surface-supported solar-powered drone optimization framework, which comprised two main stages: shift optimization and resource allocation decision making. This allocation included the transmission power, flight speed, and solar energy harvesting mechanisms. Deep Deterministic Policy Gradient (DDPG) techniques were employed to optimize the decision making and minimize the total task execution time, taking into account constraints such as the limited battery capacity.

8. Selected Applications of Solar-Powered UAVs

Solar-powered UAVs have garnered considerable attention in various civil and military applications, expanding the range of applications beyond the traditional drones due to the significantly longer range and flight time. The areas of possible implementation of such aircraft include surveillance and reconnaissance (mapping and aerial surveying, border and infrastructure monitoring, early threat detection, land and maritime patrolling, etc.), environmental and climate monitoring (weather forecasting, wildlife conservation, deforestation and land use monitoring, oceanic and marine observations, etc.), agriculture and precision farming (crop health monitoring, irrigation management, pest and disease surveillance, etc.), disaster response and humanitarian aid (search and rescue operations, real-time damage assessment, emergency communication networks, etc.), telecommunications and connectivity (high-altitude communication platforms, 5G and beyond infrastructure, etc.), and fire detection [100]. The selected civil applications are discussed in the following subsections. On the other hand, solar-powered UAVs also offer significant advantages for military operations, including persistent surveillance, low operating costs, and the reduced risk of detection due to their high-altitude and long-endurance capabilities. Aircraft dedicated to military missions must meet stringent operational requirements, as discussed in Section 3.

8.1. Surveillance Applications

The problem with surveillance is that many applications require continuous monitoring. Solar-powered UAVs offer a viable option for surveillance and monitoring, as the use of solar power mitigates the battery life issue typically associated with traditional drones. The authors in Ref. [101] presented the design and implementation of a solar-powered UAV specifically tailored for surveillance purposes. The system architecture was developed to include the solar power generation subsystem, the surveillance payload, and the control system. The experimental results demonstrated the feasibility and effectiveness of the proposed aircraft, suggesting promising applications in the construction and manufacturing sectors as a sustainable substitute for conventional materials. Betancourth et al. [102] designed and built a prototype lightweight solar-powered UAV for civilian surveillance missions in Colombia. The research process included analytical, computational, and experimental methods, allowing an in-depth analysis and validation of the key design findings. CFD tools were used to study and compare the aerodynamic performance, revealing that the optimum lift-to-drag (L/D) ratio occurs at an angle of attack of 4°, which is recommended for achieving cruise efficiency. An experimental study of the solar panel system was also carried out to analyze the voltage, current, and power requirements under real operating conditions. It was found that the solar power system was effective in powering onboard systems but remained insufficient to fully support the propulsion system, requiring auxiliary battery support. Overall, the research discussed demonstrated the significant advances in the design of solar-powered UAVs, with potential enhancements to improve the energy efficiency and autonomy in future iterations. Dwivedi et al. [103] presented the detailed design, fabrication, and validation of a low-altitude, long-endurance solar-powered UAV for day–night operation in a subtropical region. The solar-powered UAV prototype was fabricated at the Unmanned Aerial Laboratory, IIT Kanpur, and is characterized by a wingspan of 5.35 m, a maximum endurance of 18 h, and a maximum payload capability of 6 kg. The conceptual design process, along with simulation results, was presented, accompanied by a detailed description of the solar cell installation process.

Nabisha et al. [104] developed a solar-powered drone equipped with the latest surveillance technology, enabling threat detection and continuous monitoring. By providing continuous surveillance capabilities without the need for manual recharging, the aircraft addressed the need for enhanced campus security. Shanmugasundar et al. [105] discussed the possibility of using solar-powered aircraft to monitor the nooks and crannies of the city for women's safety. Zhang [106] considered the application of covert surveillance for a solar-powered UAV targeting a suspicious mobile object on the ground while disguising its intentions. A Q-learning-based covert surveillance method was formulated to maximize the disguising metric and minimize the energy consumption. Computer simulations demonstrated the performance of the proposed method, which outperformed the baseline method from both eavesdropping and disguising perspectives. Vijayanandh et al. [107] conducted research on the computation and design of an e-aircraft model capable of operating on solar power for full-time border surveillance. The entire 3D solar UAV was modeled using CATIA V5, incorporating theoretical design values. Border intrusion detection through image processing was completed using MATLAB. Al Dhafari et al. [15] designed and analyzed a solar-powered HALE UAV. The proposed aircraft was intended for various civilian and military applications, including communication, weather monitoring, land and coastal border surveillance, and fire detection. Solar cells were incorporated into a UAV to generate energy during the day and store excess energy for nighttime use. The results obtained during simulations performed in ANSYS and Xfoil were compared with the published studies on similar designs. Another example of a solar-powered surveillance UAV—the M5D—was presented in Ref. [108]. The aircraft discussed was characterized as having a range of 18 nautical miles, battery autonomy of up to 10 h, and a zero-carbon footprint. It was described as ideal for military surveillance and security operations, border protection and control, natural disaster management, monitoring marine species, or supporting maritime rescue operations. Huang and Savkin [109] considered the navigation of a group of solar-powered UAVs for the periodic surveillance of a set of mobile ground targets in an urban environment. The periodic monitoring problem resulting from the presence of tall buildings was formulated as an optimization problem to minimize the target revisit time while taking into account the effects of the urban environment. A nearest neighbor-based navigation method was proposed to guide the movements of the UAVs. Additionally, a partitioning scheme was implemented to group the targets, thereby reducing the movement space required by the UAVs, which in turn decreased the time required for target revisits. Computer simulations verified the effectiveness of the proposed method.

8.2. Environmental Monitoring

In recent years, drones have gained popularity as a tool for monitoring the environment and climate change. UAVs can be equipped with cameras, multispectral sensors, LiDAR, and other sensors that gather information on the variations in temperature, precipitation, and vegetation cover. This information can then be used to monitor the development of climate change, its impacts on the environment, and the development of mitigation strategies [110]. For example, Simo et al. [111] presented a low-cost air quality monitoring system using LoRaWAN communication technology. The proposed solution was based on a single-chip microcontroller and several simple and dedicated air pollution monitoring sensors, including PM10, PM2.5, SO_2, NO_2, CO, O_3, and CO_2 sensors. The monitoring system was mounted on drones. Sensors were placed on the sensor board to monitor environmental parameters continuously. Almalki et al. [112] described a pioneering approach to developing smart agriculture using multimission drones equipped with dual cognitive modules (brains) powered by a machine learning (ML) framework. The dual architecture of the drones, combined with the ground-level IoT system, created a comprehensive framework that not only enhanced agricultural technologies but also aligned with the environmental conservation goals. Watai et al. [113] integrated a non-dispersive infrared (NDIR) sensing system with a small UAV to monitor atmospheric CO_2 concentrations. The authors designed and built an economic and accurate gas sensor system and performed several flight tests with a one-hour flight autonomy and 3.5 kg payload. Examining various examples, it can be observed that drones, in general, have revolutionized the field of environmental monitoring and conservation, providing previously unavailable data-gathering capabilities. However, traditional drones are being replaced by solar-powered UAVs, which can fly for extended periods without refueling or landing and can gather information on a wide range of applications, from environmental monitoring to climate change, thanks to advanced features such as GPS, sensors, and cameras. In this context, Wang and Zhou [114] presented a hand-launched solar-powered UAV designed for long-term ecological environmental monitoring and rapid takeoff and landing missions in Tibet. The low Reynolds number (LRN) flow was simulated using a quasi-steady approach by solving the full three-dimensional RANS model. Both cruise and low-speed takeoff aerodynamics were analyzed, focusing on the aerodynamic forces and the integrated flow mechanism between the propeller and the wing. The results show that the UAV effectively meets the high-efficiency cruise requirements while also achieving a successful low-speed manual takeoff. Thipyopas et al. [115] developed a small solar-powered UAV for environmental monitoring applications, capable of six hours of continuous flight. The design process involved varying the wing aspect ratio between 5 and 12, and comparing different engine configurations to determine the optimum aircraft configuration. The aircraft developed had a wingspan of 4.06 m and was designed to generate a minimum electrical power of 100 W. Two brushless electric motors were incorporated to maintain a cruising speed of 8 m/s, enabling the vehicle to fly against wind speeds of up to 5 m/s and reach an altitude of 1 km above sea level for effective environmental monitoring. Zhao et al. [116] discussed the possibility of using a small, hand-launched, solar-powered UAV suitable for low temperatures and high altitudes for conservation missions involving rare animals in the plateau area during the winter. The authors presented the detailed design of an aircraft, encompassing the layout, structural, load, and avionics design. To increase the proportion of solar cells covered, the ailerons were removed, and a rudder was used to control both roll and yaw. During the discussed test, the developed UAV took off and landed at the altitude of 4500 m on the plateau in Qiantang, Tibet. Malaver et al. [117] developed and integrated a wireless sensor network (WSN) with a solar-powered UAV to enhance its functionality and expand the applications. A gas sensing system using nanostructured metal oxide (MOX) and non-dispersive infrared sensors was developed to detect CH_4 and CO_2 concentrations. Field tests involved integrating ground sensor nodes with the UAV to simultaneously measure the CO_2 levels at ground level and at low altitudes. The data collected during the mission were transmitted in real time to a central node for analysis and the generation of a 3D gas concentration map. The results highlighted the successful completion of the first flight mission of the developed aircraft. Another example is the SolarXOne drone, developed by XSun, which was equipped with an all-electric, solar-powered system that enabled it to fly for up to 12 h at a distance of 600 km without emitting any emissions. The aircraft integrates advanced safety, communication, and energy systems for extended and efficient aerial missions, including aerial monitoring [118].

8.3. Agricultural Applications

Many agricultural activities rely heavily on manual labor, resulting in higher costs and a longer uptime. Agricultural automation has, therefore, become essential. The integration of UAVs can significantly reduce the labor dependency and minimize the operational time, contributing to a more sustainable and technologically advanced agricultural sector [119]. UAVs can be used in such fields as crop monitoring and health assessment [120,121], the precision application of inputs (herbicide, fertilizers, pesticides, etc.) [122,123], field mapping and analysis [124], crop spraying [125,126] and harvesting [121,127], planting and seeding [128], livestock monitoring [129,130], irrigation management [120], geofencing [131], soil and field analysis [132,133], and thermal imaging [134]. There are various requirements for UAVs depending on their specific applications. For example, aircraft used for crop monitoring and health assessments are typically equipped with multispectral and hyperspectral cameras that can capture high-resolution images to identify plant stress, nutrient deficiencies, and pest infestations [135]. Field mapping requires aircraft with mapping software and GPS technology that can create accurate 3D maps of fields, helping farmers to assess the field topography, drainage patterns, and soil variability [136]. The ability to fly at low altitudes and follow precise flight paths is required in drones dedicated to crop spraying. Drone-based automated spraying systems can autonomously navigate fields and apply inputs based on predefined parameters, improving the efficiency and reducing the labor costs [137]. Additionally, drones equipped with seed dispensers and robotic arms enable accurate planting depths, minimize waste and multiple losses, and facilitate precision planting [128]. Livestock monitoring is based on UAVs equipped with integrated infrared cameras, enabling the identification of health issues, the location of missing animals, and the effective detection of sick or injured animals [138]. Regardless of the specific application, integrated GPS technology, automated systems, and the integration of real-time data processing algorithms (i.e., artificial intelligence) enable aircraft to perform tasks with unprecedented accuracy, resulting in cost savings and enhanced environmental sustainability.

Traditional drones play a dominant role in agriculture applications. However, solar-powered UAVs are constantly gaining in popularity. For example, Samanta et al. [139] developed a solar-powered drone exclusively for agricultural purposes. This drone was equipped with a camera to detect the color of the soil by creating an efficient algorithm using digital image processing. A GPS device was connected to the drone, allowing the user to track its location. Xu et al. [140] proposed a solar-powered quadcopter with independent attitude control to meet the requirements of ultra-low space flight in pesticide-spraying applications. The innovation of this study was the adoption of a circular frame structure, which increased the solar panel mounting area. Based on the flight results, it was concluded that the quadcopter's performance indicators met the design requirements. This research has had a positive impact on the development of agricultural equipment. Herwitz et al. [141] presented the use of a heavy-lift, solar-powered NASA Pathfinder-Plus to acquire high-resolution, multispectral imagery of the Kauai coffee plantation in the USA. Image analysis and ground data acquisition revealed a positive relationship between the brightness of the coffee canopy and the yield of ripe coffee cherries. Qi et al. [142] conducted a study that integrated the benefits of multi-scale data and proposed an effective satellite–UAV–ground collaborative inversion approach for soil salinity, providing more accurate soil information and better technical support for agricultural production. The soil salinity was identified as a key factor affecting the winter wheat growth in coastal areas. The Kenli area in the Yellow River Delta was selected as the study area. Three machine learning inversion models were developed, and the selected one was then applied to UAV imagery to obtain the salinity inversion result, which was used as the true salinity for the Sentinel-2A image. The inversion results were validated against the measured soil salinity data from the study area and showed significantly better accuracy compared to the direct satellite remote sensing inversion method.

8.4. Wildfire Detection

Forest fires are a significant threat to ecosystems, property, and human life. The traditional methods of wildfire detection, such as satellite imagery and remote camera-based sensing, often suffer from high latency and limited reliability. As a result, advanced detection and management strategies are required. These challenges can be met by introducing innovative UAV-based IoT systems designed for real-time wildfire sensing, detection, and suppression. An example of such solutions was presented, among others, in Refs. [143–145]. Furthermore, to overcome some limitations of optical cameras, the usage of thermal camera technologies is increasing in popularity. For example, Sousa et al. [146] investigated the effectiveness of thermal images acquired from static and UAV platforms in detecting fire outbreaks. Moreover, Shamsoshoara et al. [146] implemented a DJI Matrice 200 equipped with an infrared camera to collect thermal heatmaps providing a dataset of heat distribution. The UAVs also utilize artificial intelligence (AI) and are equipped with onboard processing capabilities. This enables them to use computer vision techniques to detect and recognize smoke or fire using still images or video input from their onboard cameras [147,148]. On the other hand, Hamza et al. [149] developed a solar-powered UAV to enhance wildfire monitoring, incorporating real-time feedback communication for enhanced monitoring. The drone's performance was evaluated through extensive testing, demonstrating its effectiveness in wildfire detection and reliable point-to-point communication. The results highlighted the drone's accuracy in providing timely wildfire alerts, as well as its extended flight time enabled by an onboard solar panel and battery storage system. Another example is the use of solar-powered UAVs to fly over wildfires in the Western US, enabling firefighters to better assess and manage the incidents. The solar-powered UAVs, manufactured by Silent Falcon UAS Technologies, are part of a fleet of unmanned aerial systems that will be deployed in 2018 as part of a US Department of the Interior contract for air support companies to deploy commercial aircraft as needed to wildfires in all 50 US states [150]. Also, aircraft developed by the AGH Solar Plane Student Research Group may be prepared in the future for fire detection missions. In addition, where the conventional methods fail, they can play an important role in search and rescue operations [43].

9. Future Research Directions for the Development of Solar-Powered UAVs

The future research on solar-powered UAVs should focus on enhancing their capabilities and extending the mission endurance. This can be achieved through further developments in key areas, such as solar energy harvesting, energy storage, aerodynamic and structural parameters, autonomous flight control, and AI optimization, as well as extended operational capabilities. For more efficient energy harvesting, two main areas of research should be explored: the development of the next-generation photovoltaic cells with higher energy conversion efficiencies (e.g., perovskite–silicon tandem or multi-junction solar cells), and the investigation of new materials and manufacturing techniques to create ultra-lightweight, high-efficiency solar arrays to optimize energy harvesting without significantly increasing the weight of the UAV. From an energy storage perspective, the key issue is to explore high-energy-density batteries, such as lithium–sulfur, solid-state, or metal–air batteries, to improve the energy storage without excessive weight. Another interesting option is the development of hybrid storage solutions that integrate supercapacitors with batteries to improve the power delivery and longevity. Considering the aerodynamic and structural parameters, the key option is to develop ultra-light materials, such as advanced composites, and nano- and metamaterials, which enable a reduction in structural weight while maintaining durability. Additionally, it is crucial to investigate adaptive wing structures that can change shape to optimize the aerodynamics during different phases of flight, as well as innovative coatings and airflow control methods to minimize drag and enhance the efficiency. Autonomous flight control requires the development of AI algorithms that dynamically adjust flight paths, altitudes, and power consumption in response to the real-time environmental conditions. AI can also help to introduce self-healing and fault-tolerant systems. Finally, when discussing extended operational capabilities, it is essential to investigate suitable materials and control systems that enable UAVs to operate effectively in various weather conditions, including cloud cover and turbulence, as well as innovative energy storage and power management techniques to facilitate continuous 24 h flight operations. By overcoming the challenges outlined above, the potential of solar-powered UAVs can be increased, enabling persistent aerial operations for a wide range of applications.

10. Conclusions

Solar-powered UAVs can be considered an example of the synergy between clean energy solutions and technological innovation. This synergy enables the development of long-endurance aerial platforms for various civil and military applications, including surveillance and reconnaissance, environmental and climate monitoring, agriculture and precision farming, disaster response and humanitarian aid, telecommunications and connectivity, and fire detection, while minimizing the carbon footprint and operating costs. However, there are many challenges related to the development of solar-powered aircraft, which were discussed in this review. The review aimed at a summarization of the actual achievements in the field of developing solar-powered UAVs, along with a discussion of the most significant challenges associated with their implementation for selected commercial applications. These challenges have been grouped according to the subsequent steps involved in the development of solar-powered UAVs, including the design of the structure and materials used in solar-powered aircraft, the integration of solar cells into the wings, the selection of appropriate battery technologies, and the optimization of energy management to ensure their efficient and reliable operation. General information on the above areas was supplemented by the presentation of results discussed in the worldwide literature sources. Summarizing the discussed aspects, it can be concluded that solar-powered UAVs have expanded the range of applications beyond traditional drones, thanks to their significantly longer range and flight time. However, further advances in solar energy harvesting, energy storage, aerodynamic and structural parameters, lightweight materials, autonomous flight control, and AI optimization are still required to enable solar-powered UAVs to play a key role in shaping the future of sustainable aviation and the next generation of autonomous flight systems.

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