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A Review of Research on Drone Energy Endurance Enhancement Technologies

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Abstract

Drones are now widely deployed in power inspection, last-mile delivery and emergency response, fueled by fast growth in the low-altitude economy. Their limited flight endurance, however, remains the core obstacle to broader large-scale application.Lithium-ion batteries serve as the only power source for most civilian drones on the market. Such a power scheme falls short of endurance demands for prolonged operations. Raising battery capacity without systematic design, in turn, creates potential safety risks. Relying on one energy source alone makes it hard to strike a balance among endurance, green performance and operational feasibility. Two main technical frameworks are examined in full in this paper: optimizing on-board energy systems and replenishing energy from external sources. It assesses multiple technologies ranging from high-density batteries and hybrid powertrains to fuel cells and various charging solutions. For each technology, the paper sorts through current research progress, practical benefits and unresolved drawbacks.Existing research suffers from three key limitations, including isolated energy supply and replenishment analysis, oversimplified models and weak adaptability to dynamic working conditions. This paper therefore advocates collaborative optimization across multiple technologies as a key future research direction. The study's findings offer reference value for developing and applying long-endurance UAV systems in engineering practice.

Keywords

Unmanned Aerial Vehicle; Endurance Technology; Hybrid Electric System; Wireless Charging; Energy Replenishment; Low-Altitude Economy.

1. Introduction

As a strategic emerging industry receiving key support from the government, the low-altitude economy has entered a period of rapid growth in recent years. [1]Thanks to their agility, low operational and maintenance costs, and the absence of risk of injury or death to personnel, drones have gradually expanded from military applications to civilian scenarios, becoming essential equipment for industrial production and public services. Driven by rapid industry growth and supporting policy frameworks for the low-altitude economy [1], drones are now widely deployed across multiple industrial scenarios. For power line and pipeline inspection work, they replace human staff to carry out long patrols in dangerous environments. Urban delivery scenarios let drones avoid ground congestion and lift last-mile transport efficiency. When earthquakes or floods strike, drones become indispensable for fast disaster assessment and emergency supply drops [2]. Pure lithium-ion batteries serve as the main power supply for civilian drones, which usually stay airborne for 30 to 60 minutes. Such flight endurance fails to support long-haul, uninterrupted work tasks. Short battery life has become a core challenge holding back drone industry development. To extend flight duration, field teams in some cases simply increase battery count. Adding batteries lowers how much weight a drone can carry.

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Worse still, it strains the battery pack's thermal control system and raises short-circuit and fire risks. No fundamental fix for the endurance bottleneck comes from this approach [3-4]. Two main research threads have emerged for UAV endurance solutions. High-density batteries and hybrid electric systems work to upgrade on-board energy storage and delivery. Meanwhile, technologies like magnetic resonance wireless charging move past contact-charging limits for more flexible, efficient energy replenishment [5-6]. Full details are given on how each above-mentioned technology has developed so far. The paper also evaluates advantages, drawbacks and real-world application barriers for each solution, highlights unaddressed research gaps, and supports further optimization and progress in UAV endurance technology.

2. Research Background and Current State of Research at Home and Abroad

2.1. Research Background and Significance

Evaluating drone operational performance relies heavily on flight endurance. This indicator also underpins efforts to tap industry application value and boost low-altitude economic development. The Low-Altitude Economy Development Plan (2023–2035) [1] is a national policy document for the sector. It defines the low-altitude economy as a strategic emerging industry, and outlines goals to advance UAV equipment and broaden long-duration operation use cases. Top-level policy design guides R&D work on UAV endurance technology and drives faster progress in energy supply and replenishing core technologies. For industrial-grade drones, single-mission coverage and efficiency depend directly on flight duration. One-hour flight endurance only supports short-distance line inspection tasks. Drones that stay airborne for more than three hours work continuously across regional backbone power grids, with markedly improved operational efficiency.[3] Delivery radius of logistics drones is directly decided by flight endurance. This factor is critical for broadening last-mile logistics reach in cities and rural regions alike.[5] Lithium-ion battery power comes with built-in performance constraints. It holds only about 1/50 of the energy density of aviation gasoline. Such a physical limit blocks fundamental improvements to all-electric drone flight endurance.[7] Ambient temperature heavily affects how lithium-ion batteries charge and discharge. Severe hot or cold conditions reduce battery capacity considerably. Drones thus face tighter limits on their usable application range.[5] Studying drone endurance technology in a systematic way delivers both theoretical insights and practical benefits. It supports the search for holistic solutions that reconcile efficiency, safety, green performance and cost control. [3,6]

2.2. Current State of Research at Home and Abroad

The evolution of drone power and endurance technologies takes two distinct directions. Energy systems transition from single to hybrid multi-source designs. Refueling methods shift from fixed contact modes to flexible contactless solutions. [3-4]

Performance comparisons of all-electric and fuel-only systems formed the core of early research.

High fuel energy density gives pure-fuel drones long flight endurance. Technology still faces notable flaws: loud noise, high emissions and complicated operations and upkeep. Large-scale civilian deployment thus faces clear barriers.

Zero emissions, low noise and easy operation define all-electric drone designs. Short flight range holds back their use, as they cannot satisfy requirements for long continuous operations.

Hybrid electric technology has become a core industry research focus, driven by inherent limits of single-energy schemes. [3,7-8]

Drone Endurance Technology research began earlier in other countries. The field has a well-developed research system, with engineering application and standardization as core priorities.

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NASA, the European Space Agency, academic institutions and firms collaborate on onboard power system research. They develop hydrogen fuel cells, efficient hybrid electric systems and solar-hybrid architectures, and refine energy management strategies and lightweight integrated designs. Multiple long-endurance prototypes have logged over 8 hours of continuous flight time. [4,7]

Wireless charging commercialization moves fastest in overseas markets. International groups such as the IEEE lead standard-setting work for drone wireless charging technology. Teams from many countries have broken new ground on anti-offset coils, dynamic charging control, laser energy transfer and other core technologies. The work builds a mature experimental and theoretical foundation for contactless energy supply.[9]

Developing a self-sufficient technical system stands as a key goal of domestic research.

Research on motor-aviation jet engine hybrid power systems began in Fu Changqing's team in 2013. The team has designed and tested both series and parallel hybrid configurations. These achievements underpin power system development for eVTOL aircraft. [3,10]

Tsinghua University's Shuai Shijin leads research into hybrid system topologies and energy management strategies. The team studies both gasoline-electric and hydrogen fuel cell hybrid setups in detail. They note that lighter systems and better energy distribution represent the core paths forward for hybrid technology.[3]

A hydrogen-lithium dual-engine system comes from Hefei University of Technology. It combines power output from hydrogen fuel cells and lithium batteries and drastically expands how far industrial drones can fly on a single mission.[2]

Comparative analysis of multiple onboard power schemes exists in international research. Work on lithium-ion batteries, fuel cells and hybrid systems has built a structured research system for UAV power technology.[7]

Wired charging and manual battery swapping were the main early energy supply approaches. Such methods had low automation rates and narrow applicability. Field and remote-area use cases thus faced considerable constraints.[4]

Research on magnetic-coupled resonant wireless charging has attracted growing attention recently. Technology brings benefits including contactless use, automated operation and strong safety performance. Most current studies use static ideal models and ignore real operating issues like drone landing offset and posture disturbance. This creates barriers to stable, efficient charging performance. [4,6]

Huang Weiyi's work identifies key hurdles that stand in the way of large-scale wireless charging use. Electromagnetic compatibility, misalignment tolerance and harsh-environment reliability all need to be addressed. [5,9,11-12]

Existing studies share several notable shortcomings. Onboard power and off-board replenishment are mostly studied in isolation, without coordinated optimization design. Idealized models dominate wireless charging research, leading to weak adaptability in dynamic operation scenarios. Integrated multi-energy and replenishment systems also lack systematic solutions for lightweighting and smart energy management. [3-4,6]

3. Mainstream Technologies for Improving Drone Flight Duration

Technologies for extending drone flight endurance can be broadly categorized into two main systems: on-board power supply technologies that increase flight duration at the source, and off-site energy replenishment technologies that indirectly extend flight range through external power replenishment.

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Table 1. Comparison of UAV Charging Technical Schemes

Technical Category	Dynamic Operating Condition Adaptability	Extra Weight of On-Board Receiving Module	Core Limitation Data	Typical Application Scenarios	Citation Source
Magnetically Coupled Resonant Wireless Charging	Poor: 20 mm horizontal offset of the coil reduces the efficiency from 92% to 44%; 20 mm offset along the Y-axis decreases the mutual inductance by approximately 50%	Medium	Electromagnetic interference affects flight control, and stability is weak in harsh environments	Fixed charging stations in industrial parks, base stations for mountain patrol	[4][5][6]
Laser Wireless Power Transmission	Medium: supports air-to-air dynamic charging	Light	Extremely high aiming accuracy requirements, significant atmospheric attenuation, and high laser safety hazards	Remote emergency power supply for long-endurance cruising UAVs	[4][7]
Ground Solar Charging Station + Wireless Charging	Extremely poor: power fluctuates sharply day and night, and is severely affected by rainy and cloudy weather	Medium	Must be equipped with large-capacity energy storage equipment, and deployment flexibility is poor	Remote off-grid areas without municipal power supply	[4][7]
Traditional Wired Contact Charging	Good static stability, no adaptability to dynamic operating conditions	Almost no extra on-board weight	Manual plug-in operation is required, and autonomous docking cannot be realized	Temporary ground charging for small consumer UAVs	[4]
Automatic Battery Swapping	Good adaptability to static docking; insufficient stability of mechanical docking in windy environments	Medium (swapping interface structure)	Unified industry interface standards are lacking, and the construction cost of swapping stations is high	High-frequency urban logistics UAV clusters	[4][7]

3.1. Technologies for Extending the Endurance of Airborne Power Supply Systems

This subsection introduces four mainstream airborne energy schemes: high-energy-density batteries, oil-electric hybrid systems, hydrogen fuel cells, and auxiliary solar/supercapacitor units. All core performance parameters are summarized in Table 1 Comparison of On-Board Energy Supply Technologies for UAVs.

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3.1.1. High-Energy-Density Energy Storage Battery Technology

High-energy-density batteries are at the heart of all-electric drones; research and development efforts focus on increasing energy density while ensuring safety, longevity, and environmental adaptability. [4,7,13,14]Commercial drones primarily use lithium-polymer batteries (150–250 Wh/kg) and lithium iron phosphate batteries; the former offers superior rate performance, while the latter is safer and more cost-effective, but both are approaching their technical limits in terms of energy density. [5]

Among new battery technologies, solid-state batteries offer an energy density exceeding 400 Wh/kg, along with high safety and a wide operating temperature range, making them the most promising for commercialization. [4,13]Lithium-sulfur batteries have an extremely high theoretical energy density, but they suffer from poor cycle stability and significant swelling, and remain in the laboratory stage. [4]The advantages of high-density batteries include their simple structure, zero emissions, and strong adaptability; their drawbacks are high costs and immature engineering, making large-scale commercialization difficult in the short term. [6,7]High-density batteries are currently used for light-duty applications such as small-scale logistics and other tasks where quiet operation is a priority.

3.1.2. Hybrid Electric Drone Technology Technology

Hybrid electric systems combine the high energy density of internal combustion engines with the high efficiency of electric motors, making them the most mature solution for achieving long flight times in industrial drones. [3,4,8]By generating electricity with the engine and using the battery for peak shaving, the engine operates within its optimal range, thereby improving energy efficiency.[3]

Based on the coupling configuration, they are classified into series, parallel, and hybrid configurations: Series configurations are simple and the most widely used; parallel configurations are highly efficient but complex, and are commonly used in heavy-duty fixed-wing aircraft; hybrid configurations are highly adaptable but have a heavy weight, and are rarely used in multirotor applications. [3,4,7]Hybrid systems can extend flight time from 1 hour to 3–8 hours, while fixed-wing aircraft can reach up to 20 hours; the drawbacks include increased weight, reduced payload capacity, high noise and vibration levels, emissions, and high maintenance and operating costs. [3,4,7]It is currently used primarily for large-scale operations such as monitoring extensive forest fires.

3.1.3. Fuel Cells and Other New Aircraft Energy Technologies

Fuel cells offer high energy conversion efficiency, zero emissions, and long operating ranges, making them a key area of research. [4,7,15]Hydrogen fuel cells have an energy density of 500–1,000 Wh/kg, offering a runtime of well over 3 hours, with some models exceeding 8 hours[2,7]; Methanol and propane fuel cells are easy to store and transport, but their energy density is slightly lower. [4]

Fuel cells have significant shortcomings: difficulties in hydrogen storage and refueling, inadequate infrastructure, high costs, and slow startup times. They need to be combined with lithium-ion batteries in hybrid systems to adapt to dynamic power demands, and integration and weight reduction still require optimization. [3,7,15]In addition, solar power is only suitable for high-altitude, long-endurance fixed-wing aircraft, while supercapacitors are often paired with lithium-ion batteries to handle high-rate discharge scenarios. [4,7]

3.2. Technology for Extending Range via Off-Vehicle Energy Supply

3.2.1. Magnetically Coupled Resonant Wireless Charging Technology

Magnetically coupled resonant wireless charging is the most mature wireless power delivery solution, enabling contactless power transfer via resonant coils and supporting autonomous landing and charging. [6,12]Magnetically coupled resonant wireless charging is the most

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mature wireless refueling solution. Using a resonant coil, drones can autonomously return to base for recharging, enabling 24-hour unmanned operation, with laboratory efficiency exceeding 90%.[4-6]

There are numerous issues with engineering applications: coil misalignment and attitude wobble cause a sharp drop in efficiency; the receiver module adds to the system's weight; electromagnetic interference affects flight control and navigation; and stability is poor in harsh environments. [4,5]It is currently suitable for scenarios such as deploying charging stations in industrial parks.

3.2.2. Wireless Laser Power Transmission Technology

Laser charging enables remote, directional power delivery, supports charging while flying, and eliminates the need for base stations [4,7]However, the overall system efficiency is only about 20%; it poses high laser safety risks, requires extremely high aiming accuracy, is susceptible to atmospheric attenuation, and has poor environmental adaptability. [4,7]

3.2.3. Solar Charging Technology

Ground-mounted solar power stations combined with wireless charging can be deployed in areas without access to the power grid, offering a green and renewable energy solution. [4,7]However, due to significant fluctuations in weather conditions throughout the day and night, unstable power supply, and low photovoltaic efficiency, large-capacity energy storage systems are required, and deployment flexibility is limited. [4,7]

3.2.4. Traditional Contact-Based Charging and Battery Replacement Technologies

Wired charging is a mature, efficient, and low-cost technology, but it requires manual operation and cannot recharge autonomously. [4]Automatic battery swapping is fast, but interfaces are not standardized, standards are low, swapping stations are complex and expensive, and reliability in remote areas is limited. [4,7]

4. Key Challenges and Research Gaps in the Current State of the Art

Although progress has been made in various technologies, the following common challenges remain

4.1. Lack of Coordinated Optimization between Energy Supply and Replenishment

Onboard and off-site systems are usually optimized in isolation in current studies. This separate approach prevents the formation of a fully integrated design.

Existing hybrid energy management takes no account of wireless power transfer features. Onboard power and weight constraints are not factored into wireless charging design. Such siloed research cannot produce a globally optimized outcome. [3-4,6]

4.2. Insufficient Stability of Wireless Charging in Dynamic Scenarios

Existing research mostly builds static, idealized scenarios. Nonlinear elements like landing deviation, posture disturbance and wind interference are rarely considered. This gap limits the engineering applicability of laboratory findings. Few studies explore performance in harsh operating environments. [4-6,11]

Conventional magnetic-coupling resonant wireless charging systems show clear performance drops with coil offset. When the drone coil shifts 20 mm horizontally, transmission efficiency plummets from 92% (lab setting) to 44%. A 20 mm Y-axis offset lowers mutual inductance by about 50%, and charging interruption risk rises notably. [4-6,11]

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4.3. The Conflict between Weight Reduction and Integration is Particularly Pronounced

Improvements in the performance of energy and supply systems are often accompanied by increased complexity and weight, which conflicts with the sensitive nature of UAV payloads. Hybrid and wireless charging modules suffer from insufficient lightweight design and integration, and the weight gain offsets the benefits in terms of endurance. [3-5]The hybrid electric-gasoline module for multi-rotor drones weighs approximately 7–10 kg, which reduces the payload capacity; as a result, nearly 30% of the gain in flight endurance is offset by the increase in weight. [3-5]

4.4. High Engineering Barriers and Cost Constraints

Much of the technology remains confined to the laboratory, and wireless charging lacks standards and regulations; airworthiness certification for hybrid and fuel cell UAV is incomplete; and new battery technologies and high-power charging systems are hindered by high costs, high maintenance expenses, and short lifespans, which limit their commercialization. [3,5,14,16]

4.5. Inadequate Adaptability to Extreme Environments

Most existing technologies are developed under standard temperature and pressure conditions, resulting in significant performance degradation in extreme cold, high heat, high-altitude, and strong wind and dust environments. Lithium-ion battery capacity is halved at low temperatures, fuel cell efficiency drops at high altitudes, and wireless charging is susceptible to humidity and dust, with a lack of systematic optimization.[4]

5. Future Trends

5.1. Integrated Optimization of Multi-Energy and Supply Chains

Global system optimization requires tighter integration of power supply and replenishment.The core architecture is an “airborne multi-energy + wireless replenishment” integrated system.A full-link energy coupling model will be built to enable hardware reuse and unified control. [3-4].

5.2. Engineering Implementation of Dynamic Wireless Charging

The field will move past static research and adapt to complex dynamic operating environments. Developers will create coils and compensation networks that tolerate offset and disturbance. Dynamic coupling models deliver adaptive, stable charging and stronger harsh-environment resilience. [5,11]

5.3. Breakthroughs in New Energy Materials and Integration

The field will push solid-state and lithium-sulfur batteries into engineering use. It will also improve hydrogen fuel cell catalysts and hydrogen storage solutions. New devices and materials support high integration and lightweight design. This approach balances performance gains and weight constraints more effectively. [3-4,15]

5.4. Intelligent Energy Management and Autonomous Replenishment System

Autonomous drone replenishment systems will rely on high-precision Beidou and IoT infrastructure. Each drone calculates the best refueling path from battery status and mission timeline. It aligns precisely with charging stations or automatic battery swap sites. Fleet-wide scheduling and AI task allocation support round-the-clock unmanned operation. The system delivers clear improvements in overall energy utilization.[3]

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5.5. Improvements to Industry Standards and Safety Regulations

Compatibility issues can be solved through unified standards for multiple core links. These include battery interfaces, wireless charging, power safety and base station construction. The industry will also upgrade airworthiness certification and define explicit safety rules. This regulatory framework enables compliant, large-scale technology application. [3-4,16]

6. Conclusion

Limited flight range is a key bottleneck constraining the development of drones and the low-altitude economy. This paper systematically reviews two major technological approaches: on-board power supply and off-site energy replenishment. The on-board approach primarily relies on high-density batteries, hybrid electric systems, and fuel cells to extend single-flight endurance, while the off-site approach focuses on wireless charging and battery swapping to enable flexible energy replenishment.

Each technology has its own advantages and disadvantages: all-electric systems are clean but have limited range; hybrid systems offer long flight times but suffer from significant noise and weight; and wireless charging is autonomous and convenient but lacks dynamic stability. Current research faces key gaps, including a disconnect between power supply and replenishment, poor dynamic adaptability, conflicts in lightweight design, high engineering barriers, and insufficient adaptability to extreme environments.

In the future, UAV endurance technology will evolve toward multi-energy synergy, intelligent dynamic replenishment, lightweight system integration, and standardized industry applications. As technological breakthroughs continue, the bottlenecks in UAV endurance will be gradually overcome, and their application potential will be continuously unlocked, providing strong support for the high-quality development of the low-altitude economy.

References

[1] State Administration for Market Regulation, Civil Aviation Administration of China (Low-Altitude Airspace Office), & National Development and Reform Commission. (2025). Guidelines for the construction of the low-altitude economy standard system (2025 edition).

[2] Hefei University of Technology. (2025, August 11). Hydrogen-lithium dual engine extends the route of industrial UAVs. Science and Technology Daily.

[3] Shu, S. J., Wang, Z., Zhang, Y. L., et al. (2025). Research progress and prospect on key technologies of hybrid electric power system for low-altitude aircraft. Journal of Propulsion Technology, 46(11), 31–52.

[4] Mohamed, A., Hassan, M., & Ahmed, S. (2025). A comparative study of energy sources, docking stations and wireless charging technologies for certain quadrotor unmanned aerial vehicles. ScienceDirect.

[5] Zhang, Y., Huang, W. Y., Li, Y. B., et al. (2025). Design of UAV wireless charging system with high anti-offset capability and stray magnetic field constraint. Transactions of China Electrotechnical Society, 40(12), 3692–3701.

[6] Li, Y., Wang, H., & Zhang, L. (2025). Research review on magnetic coupling resonant wireless charging technology of UAV. In 2025 IEEE International Conference on Power Electronics and Motion Control (pp. 1–6). IEEE.

[7] Boukoberine, M., Zhou, Z. B., & Benbouzid, M. (2019). A critical review on unmanned aerial vehicles power supply and energy management: Solutions, strategies, and prospects. Applied Energy, 255, 113823.

[8] Lei, T., Min, Z. H., Fu, H. J., et al. (2020). Dynamic balance energy management strategy for hybrid power system of fuel cell UAV. Acta Aeronautica et Astronautica Sinica, 41(12), 324048.

ISSN: 2664-9640

[9] Chittoor, P. K., Chokkalingam, B., & Mihet-Popa, L. (2021). A review on UAV wireless charging: Fundamentals, applications, charging techniques and standards. IEEE Access, 9, 69235–69266.

[10] Zong, J., Wang, Y., Mao, J. S., et al. (2016). Design and performance analysis of multi-rotor UAV hybrid power system. International Aerospace Science, 4(2), 25–33.

[11] Rong, C. C., He, X. R., Wu, Y. T., et al. (2022). Research progress and development trend of wireless charging technology for multi-rotor UAVs. Transactions of China Electrotechnical Society, 37(5), 927–942.

[12] Rong, C., Wu, S., Cai, C., et al. (2023). Critical review of recent development of wireless power transfer technology for unmanned aerial vehicles. IEEE Journal of Emerging and Selected Topics in Industrial Electronics, 4(1), 147–158.

[13] Liu, Z. T., Fu, Z. J., Gao, J., et al. (2025). Comparative analysis of technical schemes for UAV power system. Journal of Shandong Jiaotong University, 33(6), 1–8.

[14] Yin, Z., Zhu, J. G., Lv, L. C., Dai, H. F., & Wei, X. Z. (2025). Solid-state battery technical routes and management system for eVTOL. Automotive Engineering, 47(12), 1689–1698.

[15] Xiang, J. W., Ma, K., Kan, Z., et al. (2025). Research progress on key technologies of hydrogen energy UAVs. Acta Aeronautica et Astronautica Sinica, 46(5), 531603.

[16] State Administration for Market Regulation, & Standardization Administration of China. (2023). Safety requirements for civil unmanned aircraft systems (GB 42590-2023). China Standards Press.