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(Research Article)

Evaluating autonomous perovskite solar drones for use in remote areas

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Abstract

This paper investigates the integration of perovskite solar cells into lightweight drones, aiming to improve their flight duration and efficiency. The integration of advanced drone technologies with cutting-edge perovskite solar cells presents unique opportunities for exploration in remote environments such as jungles, high-altitude regions, and extraterrestrial terrains like Mars. This paper investigates the potential of combining advancements in drone design and materials, with the high-efficiency, lightweight perovskite solar cells being developed, such as the super thin design recently created at Kepler University. Through a detailed analysis, and a prototype 3D-printed solar drone, we research how advancements in the operational capabilities, energy efficiency, and durability of drones, combined with perovskite innovations enable sustained missions in challenging and energy-scarce environments. We focus on the efficiency, weight impact, and operational benefits of using perovskite cells for extending drone flight times in various environmental conditions. This paper concludes by outlining the future directions and research opportunities necessary to overcome current limitations and enable the widespread adoption of these advanced drones in remote explorations.

Keywords: Drone; Perovskite; Solar; Remote; Autonomous

1. Introduction

The use of drones in various applications has been rapidly growing. Enhancing their flight duration is crucial for their effectiveness. Perovskite solar cells, known for their high efficiency and lightweight properties, present a promising improvement. This study evaluates the feasibility and performance of integrating perovskite solar cells into lightweight drones.

Drones are incredibly useful in remote or difficult environments, such as the wilderness, ocean, high altitude or even other planets. However, it is exactly in these locations where access to power can be the most challenging. With sunlight available in many of them it makes sense that a drone enhanced with solar cells on it could be more efficient with longer flight times and more flight distance.

However, current solar drones are limited in their usefulness by the weight to efficiency ratio of the solar cells, making docking and battery recharging more logical than inflight recharging or recharging in the field. Examples of such drone usage include the Ingenuity drone on Mars that had solar cells attached to it and did 90 s flights sometimes once per day. At the other extreme there are fixed wing drones in high altitude environments such as the Zephyr that have achieved flights of over 2 months on just solar power with silicon cells. However, these work mainly at large scales of wingspans of up to 30 m, and are too inefficient for smaller wingspans.

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Advancements in materials will make smaller drones able to do the same inflight solar charging in the future. For instance, halide perovskites and other perovskites are rapidly becoming more efficient, cheaper, thinner and more durable. They are already very flexible compared to silicon. They have also been found to not only survive the rigors of space but interestingly have higher efficiency after 10 months in space [1].

Finally, a team at Kepler university has created an almost 2D perovskite quad-copter drone with 1-inch long cells and 1/20 the width of a human hair, that demonstrates the ability of this material to be light enough to open many new uses in drones, particularly as it has power to weight output of 44 watts per gram of weight [2].

In this research, a common 3D printed drone is modified with perovskite solar cells and performance data is collected. Using calculations based off of it and advancements in drones and solar cells, we evaluate the future of perovskite drones.

1.1. Section 1: Drone usage in remote areas

Drones have demonstrated their versatility in challenging environments such as jungles, oceans, high altitudes, and even beyond Earth on Mars. This section aims to focus on the recent improvements to drones for use in many different environments and missions.

1.1.1. Jungles: XPRIZE Rainforest

In jungle settings, drones equipped with advanced sensors and artificial intelligence play crucial roles in environmental monitoring, wildlife tracking, and combating illegal logging. For instance, in this year's XPRIZE Rainforest, five of the six finalist teams utilized drones as key parts of their solutions for measuring the biodiversity. These drones navigate dense vegetation with agility, transmitting real-time data that revolutionizes conservation efforts and ecological research, providing new insights into remote and inaccessible areas.

Navigating the jungle creates challenges for drones, mainly due to the obstruction of GPS signals by foliage. Researchers at the University of Maryland have addressed this issue by developing drones equipped with LiDAR (Light Detection and Ranging) technology. LiDAR allows drones to create high-resolution 3D maps of the jungle canopy, enabling precise navigation even in complex terrain [3]. This technology has been key in wildlife tracking and environmental monitoring efforts, helping researchers with detailed insights into remote areas.

Despite advancements in technology, drones in jungles still encounter challenges like sudden wind changes and unpredictable wildlife. These issues can impact flight stability and create risks to both the drone and the ecosystem. Upcoming research aims to enhance drone resilience and improve their autonomous operation in tough jungle conditions, and this will improve our understanding of biodiversity and supporting global conservation efforts.

1.1.2. Oceans: Hopper prototype

In oceanic environments, drones have become indispensable tools for marine biologists. With capabilities such as underwater cameras and sensors, drones explore deep-sea habitats, map coral reefs, and monitor marine life without disturbing the ecosystems.

Above the ocean, drones represent a leap forward for aerial remote sensing, enabling data collection, and integration at new scales of biological importance. According to David Johnson of Duke University, "Drone methods and data types provide four key opportunities for wildlife surveillance that are already advancing pinniped research and management: (1) repeat and on-demand surveillance, (2) high-resolution coverage at large extents, (3) morphometric photogrammetry, and (4) computer vision and deep learning applications". Drone usage can reshape this type of research as they reach the full potential [4].

Dr. Johnson has pioneered research using ocean drones equipped with advanced acoustic and satellite tracking technologies. His team's work focuses on understanding marine species' migration patterns and behaviors, such as tracking sea turtles across vast oceanic distances. Ocean drones like his face significant challenges in remote marine environments, where recharging and communication can be particularly difficult. These drones play a crucial role for tracking animal movements, monitoring ocean health, and exploring deep-sea habitats even from the air. Their reliance on battery power without readily available recharging stations in remote areas restricts the duration and range of missions, requiring innovative solutions to extend operational capabilities.

Researchers are exploring energy-efficient designs and alternative power sources, such as integrating solar panels or developing energy harvesting systems from ocean currents. The design includes small commercial solar cells on the wings' surface to allow the system to regenerate power while in flight and at rest. Applications will include both defense and civilian maritime uses since the Hopper drone can "hop" across the ocean for weeks at a time, for instance from San Diego to Hawaii, recharging via solar power [5].

1.1.3. High Altitudes: Zephyr UAV

At high altitudes, drones can conduct atmospheric research, take measurements to predict the weather, and even help with disaster management. They collect info via specialized sensors for air quality, temperature, and atmospheric composition. This supports meteorologists in weather forecasting and aids climate scientists in understanding dynamics. Also, high-altitude drones enable telecommunications services in remote regions where traditional infrastructure is impractical or unreliable.

High-altitude drones, also known as pseudo-satellites or High-Altitude Pseudo-Satellites (HAPS), operate at altitudes nearing the edge of space, typically above 20 km (65,000 feet). These drones bridge the gap between traditional aerial drones and satellites, offering prolonged flight durations and persistent coverage of large areas.

Pseudo-satellite drones are equipped with solar panels to harness sunlight for continuous energy, allowing them to operate for weeks or even months at high altitudes without the need for landing or refueling. This capability makes them ideal for applications such as telecommunications, environmental monitoring, and scientific research.

One example is the Airbus Zephyr, a solar-powered HAPS designed for stratospheric operations. The Zephyr drones have set endurance records, flying continuously for over two months at altitudes above 20 km. Launched by hand, these drones utilize lightweight materials and efficient propulsion systems to navigate harsh atmospheric conditions, including low temperatures and thin air, encountered at such high altitudes.

However, the challenges for pseudo-satellite drones include maintaining stable flight in stratospheric winds, optimizing energy management to sustain operations during extended periods of darkness, and ensuring reliable communication links with ground control stations [6]. Engineers and researchers are continuously improving designs and autonomy systems to enhance endurance, reliability, and data transmission capabilities for applications requiring long-duration, high-altitude operations.

The deployment of pseudo-satellite drones is a promising advance, offering a cost-effective alternative to traditional satellite. As technology evolves, these drones are expected to play a pivotal role in expanding connectivity, enhancing global surveillance capabilities, and advancing atmospheric and climate research at the edge of the atmosphere. As HAPS like the Zephyr are very large, they require less energy to fly, allowing for the solar power that is harnessed to be used most efficiently.

1.1.4. Planetary Flyers: Ingenuity and Dragonfly drone

Looking beyond Earth, drones, of various types, are at the forefront of exploration and scientific discovery on other planetary bodies in our solar system. For instance, in Mars exploration a drone was used, and in future missions one proposal is to use two drones in place of rovers.

Drone missions might include mapping, studying geology, and finding places for humans to live or gather resources on other planets or moons. These drones are designed to navigate and communicate in space, allowing for accurate exploration and helping us learn more about places beyond Earth. As drone technology improves, it will expand the possibilities for scientific research and exploration in tough environments.

Drones on Mars face similar challenges as those on the Moon, with additional complexities posed by the Martian atmosphere and terrain. NASA's Perseverance rover successfully deployed Ingenuity, demonstrating the first controlled flight in the thin atmosphere of Mars. This was made possible by the use of a solar array for charging its on-board battery. However, due to its small size and limited solar regeneration capabilities, Ingenuity was limited to 90 s flights once per day.

While the aerodynamics and suitability of drones, especially fixed wing drones, varies greatly across the vacuum of space compared to the higher gravity but thinner atmosphere of Mars, we will consider them all together when later reviewing the suitability of perovskite.

Additionally, Dragonfly, NASA's octocopter for Titan, which is a moon of Saturn, features eight 1.35 m rotors optimized for the moon's dense atmosphere and low gravity. Its design allows 10 m/s flights covering up to 16 km per charge, powered by lithium-ion batteries and an RTG. The 450 kg craft can fly at 4 km altitude, leveraging Titan's unique conditions for efficient exploration. The dragonfly uses nuclear power (RTG) to fly. However, solar power could be an advantageous alternative as it wouldn't contribute to the drones weight as much as the RTG does [7].

1.2. Section 2: Recent advancements in drone technology

Now that we have considered the drone usages and challenges, we review the three main areas where drones have improved or are anticipated to improve significantly in the next few years.

Those areas are the weight of the drone declining due to advances in material and/or design, improved battery efficiency including the use of solid-state batteries, and usage of technologies including control algorithms for managing fuel or flight operations [8].

1.2.1. Improved Drone Materials and Design

Modern drones have undergone significant advancements in materials and design, enhancing their performance and durability. Lightweight yet robust materials such as carbon fiber and advanced polymers are now commonly used in drone construction, resulting in improved flight characteristics and longevity, even in challenging environments [9].

Aerodynamic improvements have led to extended flight times and increased maneuverability [10]. Additionally, features like foldable arms and modular components have enhanced portability and versatility, allowing for quick adaptation to various tasks [11].

1.2.2. Better Batteries and Energy Use

The evolution of drone battery technology has significantly improved energy efficiency and flight duration. While lithium-polymer (LiPo) batteries remain prevalent, recent developments focus on increasing energy density and reducing charging times. Solid-state batteries show promise, offering higher energy capacity, improved safety, and potentially longer lifespans. These advancements could substantially extend flight ranges and enhance reliability for applications such as long-distance surveillance or exploration of remote areas.

1.2.3. Algorithms and Programs for Managing Power and Flight

Automated algorithms are playing an increasingly crucial role in drone power management and flight control. They enable real-time flight path optimization, allowing drones to navigate around adverse weather conditions and obstacles while minimizing energy consumption [10]. More accurate fuel level monitoring helps prevent unexpected power depletion during missions [12]. This approach to energy management is particularly valuable for complex operations, such as remote area exploration or space missions, where efficient power utilization is critical to success [11].

1.2.4. Composite Materials

Drones are increasingly being constructed using advanced composite materials, particularly carbon fiber and carbon-reinforced composites [13]. These materials are preferred for drone bodies due to their high strength-to-weight ratio, allowing drones to be both lightweight and durable. When even higher strength is required, manufacturers are turning to alloys made from metals such as aluminum, titanium, and magnesium [13].

1.2.5. Ultra-thin Coatings

Innovative coating technologies are being applied to improve drone performance and protection. Parylene coatings, which are ultra-thin and lightweight, are being used to provide superior thermal stability and high tensile strength [13]. These coatings are applied using a chemical vapor deposition process, resulting in highly conformal films that can wrap around every edge of the drone, enhancing aerodynamics and protecting against harsh environments.

1.2.6. Next-generation Batteries

While lithium-ion batteries remain common, new battery technologies are being developed to extend flight times. Solid-state batteries and lithium-sulfur batteries are emerging as promising alternatives, offering improved energy density and longer lifespans compared to traditional lithium-ion batteries [13]. These advancements are crucial for increasing the range and operational capabilities of drones.

1.2.7. Green Propulsion Systems

Efforts to make drones more sustainable have led to the development of eco-friendly propulsion systems. Some drones are being designed to run on solar power, with solar panels installed on their wings to harness the sun's energy for extended flight times [14]. Additionally, researchers are exploring the use of biofuels derived from organic materials as a more sustainable alternative to fossil fuels [14]. These green propulsion systems not only make drones more environmentally friendly but also have the potential to significantly extend their operational range.

These advancements collectively contribute to creating drones that can fly longer, higher, and with greater efficiency, while also being lighter and stronger. As research continues, we can expect further innovations in materials science and energy storage to push the boundaries of drone capabilities even further.

1.2.8. Summary of drone improvements

Drones are lighter than before due to advances in materials, and incrementally even lighter still due to design improvements. Graphene could be a key material in doing this.

Solid state batteries could improve this even more, where structural components of the drone will be themselves batteries.

Possibly these structural components could not only be batteries but also coated so the pieces themselves are generating solar energy, even side pieces.

Autonomous operation via algorithms and sensors makes it easier for drones to operate in remote environments, including not needing to return to base, charging in place via solar could make even returning for charging unnecessary.

1.3. Section 3: Improvements in perovskites related to drone applications

First, here is a summary of silicon cells versus perovskites (Table 1):

Table 1 Perovskite and silicon cell comparison. https://solarmagazine.com/solar-panels/perovskite-solar-cells/ accessed 20 August, 2024

	Monocrystalline Silicon (Mono c-Si)	**Polycrystalline Silicon (Poly c-Si)**	**Perovskites**
Highest Recorded Efficiency	25.4%	24.4%	29.15%
Lifespan	25–30 years		30 months (2.5 years)
Light Absorption Potential	Wavelengths of light of 1100 nm		Wavelengths of light of 850 nm

This section reviews perovskite progress across the key components most relevant to usage in drones.

- Efficiency
- Flexibility
- Stability
- Thickness

1.4. Efficiency

This section reviews perovskite progress across the key components most relevant to usage in drones. Over the past decade, perovskite solar cell efficiency has significantly improved, rising from around 10% in 2014 to over 30% in 2024. Advances in material stability, multi-junction designs, and fabrication methods have contributed to this progress, making perovskites highly competitive with traditional silicon-based solar cells (Figure 1).

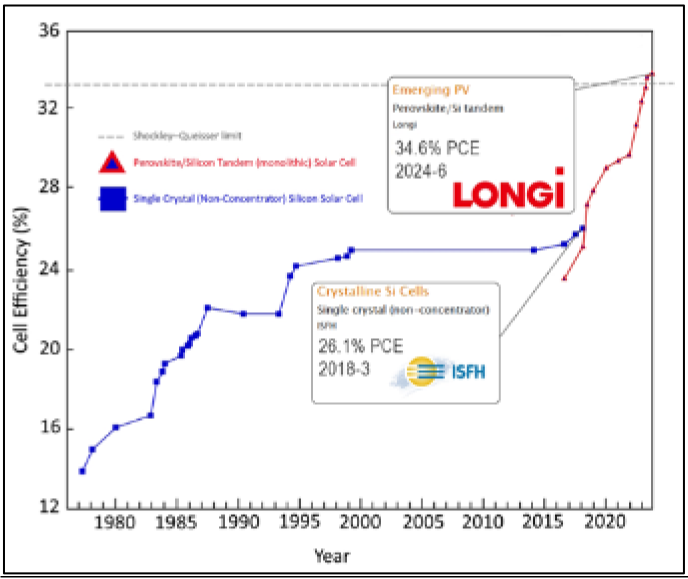


Figure 1 Increasing efficiency of perovskite solar panels [15]

Perovskite can also be used as a layer in a multi-junction cell (Figure 2):

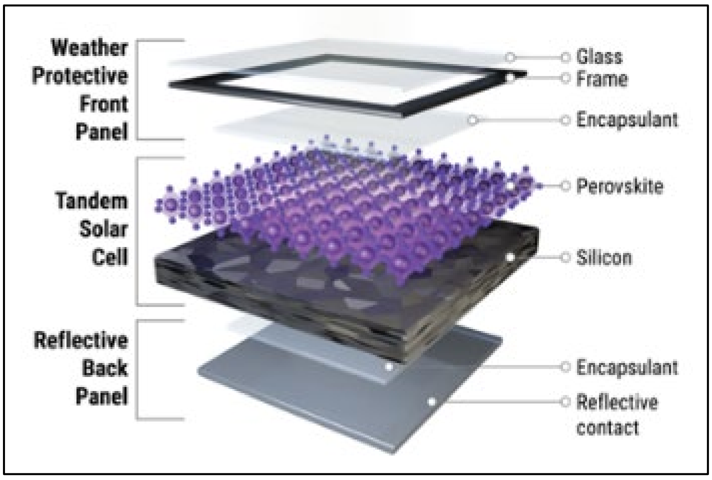


Figure 2 Multi-junction cell (Image: Daniel Morton/CU Boulder) [16]

In fact, using 4 layers of materials, Fraunhofer Institute for Solar Energy Systems in 2022 created a four-junction cell that reached 47% efficiency [17]. For this investigation, we are focusing on only perovskites, but given the potential for even higher efficiencies at acceptable thicknesses it is important to note that multi-junction cells might be preferrable in some cases.

1.5. Flexibility

Drones are meticulously designed to control the aerodynamics of the flight, which can be negatively impacted by the use of rigid and heavy solar cells.

It has been shown that ultra-flexibility is needed such that the solar cells fully conform to the curved surfaces of the drone. In addition, stretchability would be necessary in advanced drones with foldable components [18].

1.6. Stability

The stability of perovskites over time has been a limiting factor, but this is being overcome with barriers, compositional modifications, or the use of stable transport layers. Since the average drone lifespan is much shorter than the 25+ years needed by the energy industry the key to using perovskite in such drones is more around lower cost, flexible, efficient output and power-to-weight ratio rather than long term durability. Their stability is reaching the 3-to-5-year length needed for drone usage [19].

Perovskite shown to be useful in space orbit. Dr. Lyndsey McMillon-Brown, a NASA research engineer, led a spaceflight experiment to test perovskite solar cells on the International Space Station. After 10 months in space, the film remained dark black, indicating the material's durability and efficiency in harsh space conditions. This success suggests that perovskites could be key in creating thinner, lighter, and more flexible solar cells for long-duration space missions, potentially providing reliable power for future Moon and Mars explorations [20].

Metal halide perovskites (MHPs) are promising materials for solar cells, offering high efficiency similar to silicon, with added benefits like adjustable properties for specialized devices. They are also highly resistant to temperature changes and defects, making them good candidates for space use [21]. To test their space durability, a thin film of perovskite was placed on the International Space Station for 10 months. After the mission, tests showed that the material was stable, didn't suffer irreversible radiation damage, and had an improved operational range. Additionally, surface defects actually improved with exposure to light. These findings confirm that MHPs can be effectively used in space [22].

1.7. Thickness

While thickness is not completely correlated to efficiency, it is true that earlier perovskite cells were thicker and only recently have they been reduced to the micron range.

Some thicknesses work better for various wavelengths and applications as seen in Figure 3:

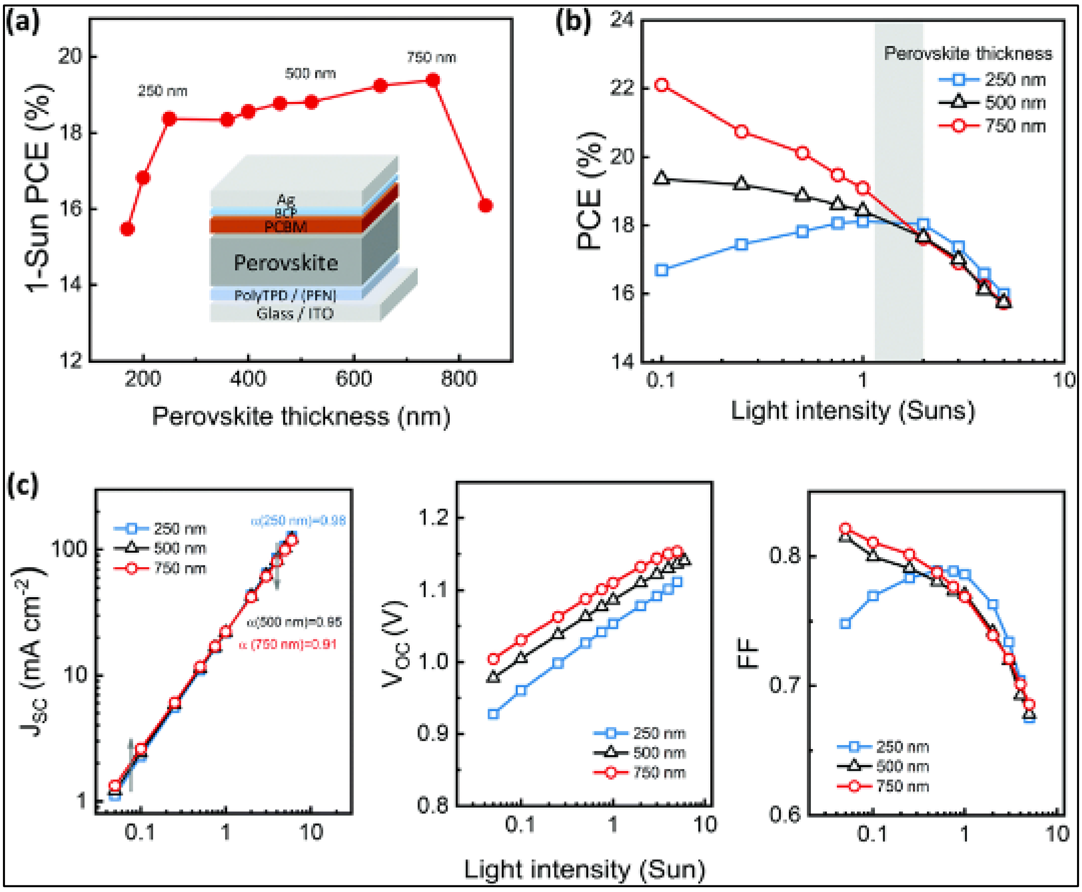


Figure 3 Thickness and light-intensity dependent performance of p–i–n PSCs. (a) Power conversion efficiency (PCE) versus perovskite layer thickness (AM 1.5, 1 sun intensity, 50 mV s^{-1} scan rate), the inset figure plots a schematic illustration showing p–i–n device configuration and layer composition. (b) Dependence of PCE on light intensity of representative solar cells comprising MAPI perovskite films of 250 nm, 500 nm and 750 nm, measured with an intensity-tunable LED array. (c) Photovoltaic parameters versus light intensity for devices with 250, 500 and 750 nm MAPI active layer thickness. Left panel: short-circuit current density (J_{SC}), with the linearity of J_{SC} with light intensity (α) indicated; Middle panel: open-circuit voltage (V_{OC}); Right panel: fill factor (FF) [23]

However, by reviewing various articles since perovskites were first developed in 2010 a general trend can be visualized in Figure 4:

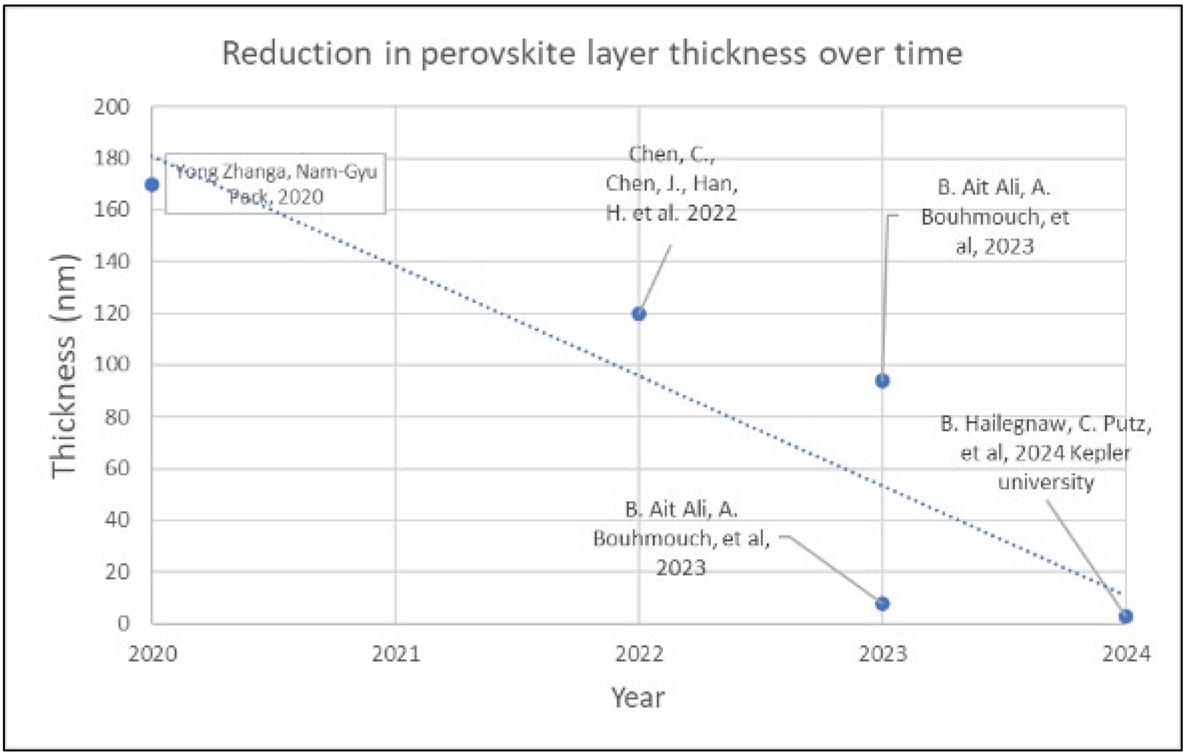
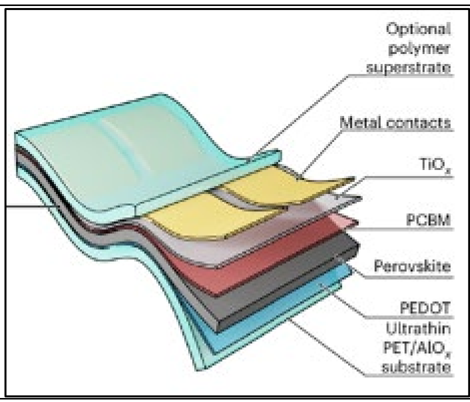


Figure 4 Chart pulled from various studies [2,24–26].

And most recently (2024) Kepler University developed lightweight, thin (<2.5 μm), flexible and transparent-conductive-oxide-free quasi-two-dimensional perovskite solar cells by incorporating alpha-methylbenzyl ammonium iodide into the photoactive perovskite layer. They fabricated the devices directly on an ultrathin polymer foil coated with an alumina barrier layer to ensure environmental and mechanical stability without compromising weight and flexibility.

Most impressively, it demonstrated a champion specific power of 44 W g^{-1} (average: 41 W g^{-1}), an open-circuit voltage of 1.15 V and a champion efficiency of 20.1% (average: 18.1%) [2].

To show its actual potential, they built a photovoltaic drone module consisting of 24 interconnected 1 cm^2 solar cells and demonstrate energy-autonomous operation of a hybrid solar-powered quadcopter. The solar cells made up only 1/400 of the drone's weight and were 70 times thinner than a human hair. See Figure 5 for the construction of the solar cells and resulting drone [2] including the configuration and dimensions in Figure 5, subfigure a and the finished drone in sub-figure b.



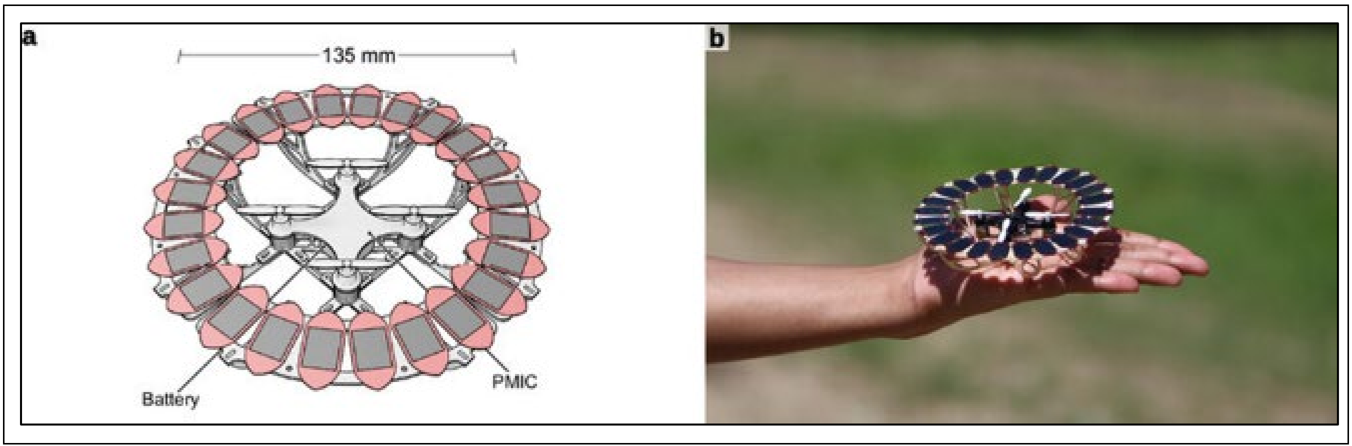


Figure 5 Kepler University solar cell composition and drone design

The key of the Kepler University work is not just the thickness, but the champion efficiency at that thickness yields a high power to weight ratio. With that, we can summarize that the key perovskite improvements are flexibility, stability, cost, efficiency and low weight—also meaning high power per weight. The key aspects of these for drones are the low weight, high efficiency, and flexible shape, as shown in Figure 6:

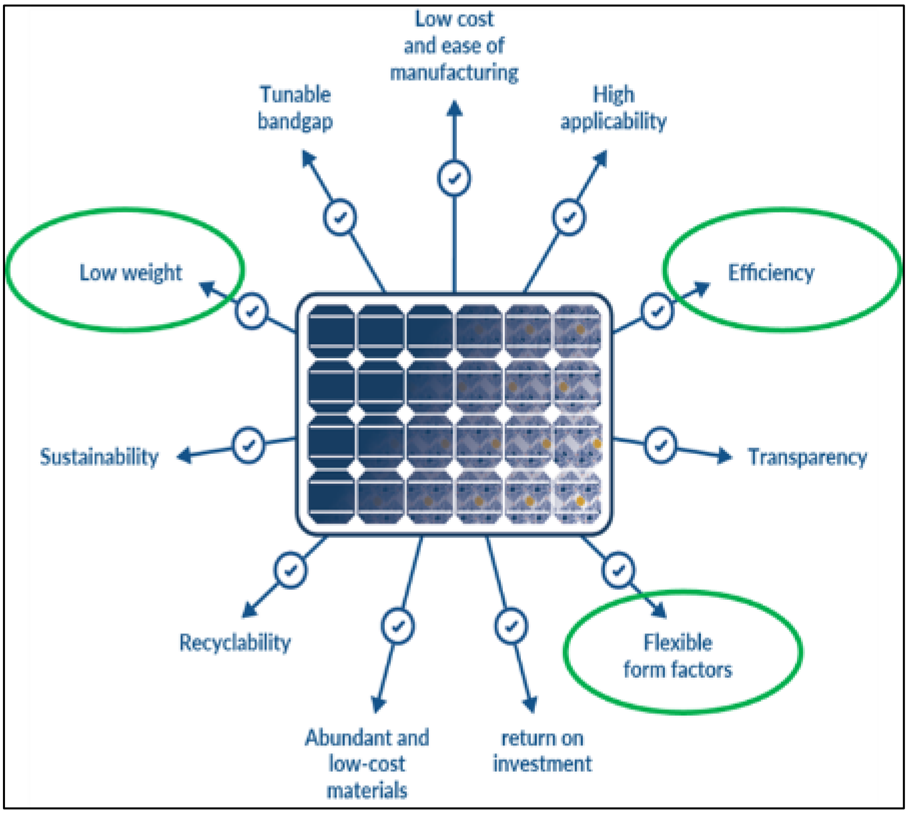


Figure 6 Perovskite key aspects [27]

So, both drones and perovskite cells have had substantial improvements over the years. If we combine them, will we reach the point where lightweight drones can be self-sufficient?

2. Methodology

A fixed-wing drone with a nominal mass of 286 g was 3 D printed for this study and modified slightly for the solar cells as well as weight and balance, see Figure 7. Perovskite solar cells were made, heated, sealed and attached but not integrated into the drone's wing. We conducted tests of the cells' efficiency, the thrust created, and the extension of the limited glide with the solar cells on and off. Fragility of the glider and lack of sufficient thrust to achieve true flight limited the number of repetitions possible, so calculations were performed to estimate the prototypes potential.

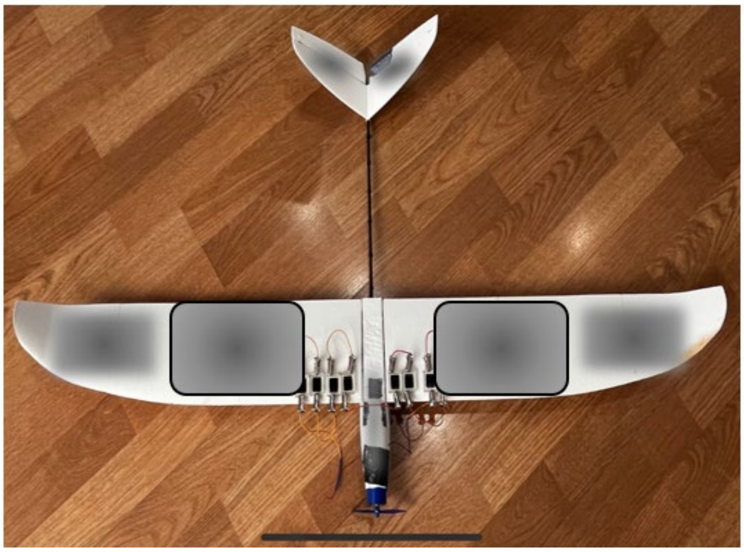


Figure 7 Image of drone used in investigation

Eight fully functional cells were made, but they resulted in just 12% efficiency [28].

From prior research characterizing these cells, the optimum conditions for the solar panel should be sunny, relatively low temperature and slightly windy. This would maximize the efficiency of the solar cells and therefore result in the maximum flight time for the drone.

The measurement stand was set up with the solar cells already connected to the wings. The motor was then connected to the L shaped piece of wood and raised by the metal piece shown in the figure, to be at the same height as the balance. The balance was set to 0, and the motor was connected to show how much thrust the solar cells provide.

Hand launching was used, as seen in Figure 8, adding another variable to the data. Eight test flights were then conducted 4 with the motor and 4 without. Ideally this method of hand launching would be done 100's or 1000's of times to average out the uncontrollable variables and isolate the additional distance achieved by the cells, but the fragility of the glider prevented that. The thrust produced in the tests is captured in Figure 9.

Figure 8 Launching mechanism

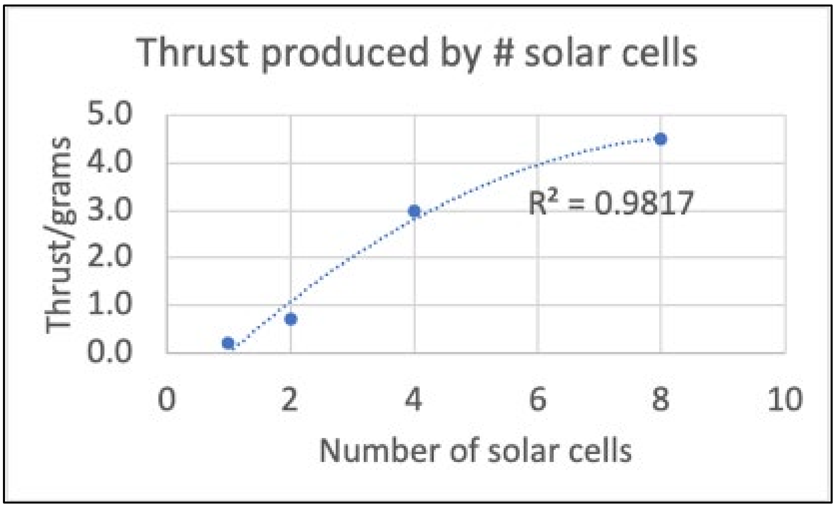


Figure 9 Thrust of solar cells

3. Results

In a fully functioning prototype, we would use the quasi 2D perovskite in 15 by 30 cm panels, but for these tests eight 1 cm^2 cells each creating 11 mA were installed. The initial plan included a launch mechanism to calibrate a careful angle, loft, and force of launch, however this had to be abandoned as the mechanism was precise but impractical. The results we achieved for the distance flown with and without the motor are shown in Figure 10:

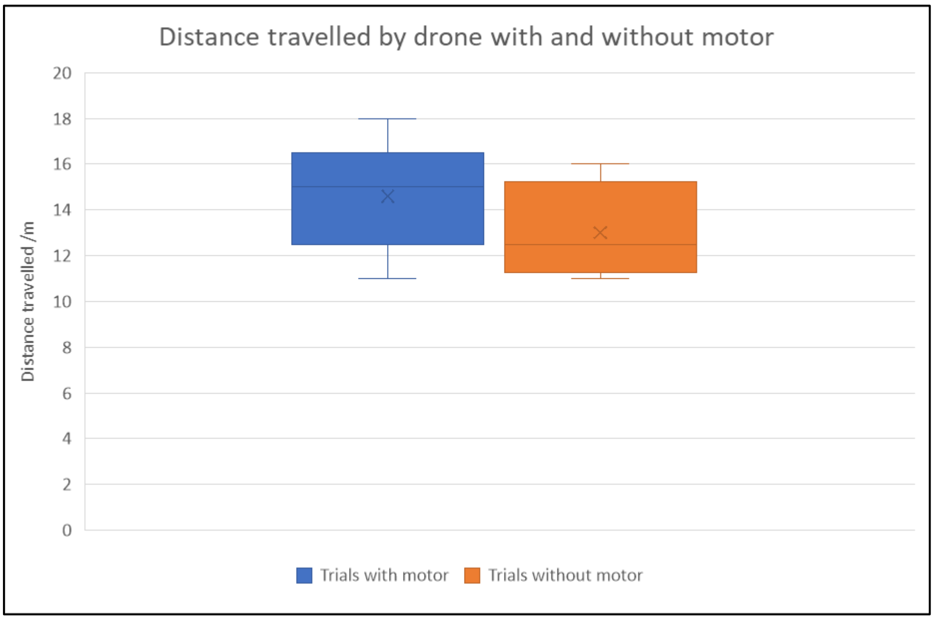


Figure 10 Distance travelled by drone with and without the motor

The drone equipped with perovskite solar cells did show an average flight distance increase of 5% but with such limited launches and the variability of launch angle, force, and wind it is not statistically useful to confirm any potential.

To better determine the viability, we returned to calculations of the cell output, the gliders known aerodynamics and solar efficiencies to evaluate the prototype's potential in optimum design and conditions.

3.1. Calculations

We analyzed our glider with perovskite solar panels at 20% efficiency, using several steps of calculations.

Assumptions were that the base glider is 240 g, and 60 g would be needed for the additional solar panels and wires.

Assuming the drone will be flying at a constant speed and height, without wind affecting it, the following calculations have been explained to outline how the plane would be able to fly.

The calculations section has been split up into thrust, power and solar panel calculations.

Thrust Calculation

To estimate the thrust required for the glider to maintain level flight:

- Estimating lift-to-drag ratio:

We assume a lift-to-drag ratio of about 10:1. This is a reasonable estimate for a small, well designed, efficient glider [29].

- Calculating thrust:

In level flight, thrust equals drag. We can calculate the required thrust using the glider's weight and the lift-to-drag ratio:

$$\text{Thrust} = \text{Weight}/\text{Lift-to-drag ratio}$$

$$\text{Thrust} = 300\ \text{g}/10$$

$$\text{Thrust} \approx 30\ \text{g.}$$

Based on this analysis the required thrust to achieve level flight would be approximately 30 g.

3.2. Power Requirements

Using a small lightweight Xing Nano 1103 8000kv 7o5V from Unmanned Tech Sho, UK Company Registration No: 10922443, with HQ T1o9X3X3 test data, it comes with the following calculations of static thrust:

27 W results in 35.5 g of thrust. This value should be just enough thrust to achieve level flight.

This results in the following power to mass ratio 0.76 W/g. This number already accounts for the losses due to the motor and propeller.

Using the following equation:

$$\text{Theoretical Power} = \text{Mass} \times \text{Power to Mass Ratio}$$

We can calculate that:

The power we would need is:

$$Power = 35.5\ \text{g} \times 0.76\ \text{W/g} = 27\ \text{W}$$

Furthermore, to achieve this power:

We know that the solar constant is 1000 W/m^2 [30], which is:

$$1000\ \text{W}/10{,}000\ \text{cm}^2$$

Which equals:

$$0.1\ \text{W/cm}^2$$

Accounting for an efficiency of the solar panels of 20%, we get:

$$0.02\ \text{W/cm}^2$$

The measurement of the drone wings yields 1286 cm^2 of space.

Multiplying the available wing space by the W/cm^2:

$$1286 \times 0.02 = 25.72 \text{ W}$$

This doesn't account for losses due to connections or power management.

This value doesn't achieve the 27 W that we would need to fly at steady level flight, however below we show how with higher efficiencies this would be achievable.

3.3. Solar Panel Requirements

Now we can calculate the required solar panel area to generate this power.

Assuming we need 27 W output for flight for our glider to achieve consistent flight:

3.3.1. Calculations for 20% Efficient solar panels

Actual power needed from solar panels:

$$P_{actual} = \frac{P_{input}}{Solar\ Panel\ Efficiency} = \frac{27 \text{ W}}{0.20} = 135 \text{ W}$$

Area needed:

$$A = \frac{P_{actual}}{Solar\ constant} = \frac{135 \text{ W}}{1000\ W/m^2} = 0.135 \text{ m}^2$$

Converting to square centimeters:

$$A_{cm^2} = 0.135 \text{ m}^2 \times 10000 \frac{\text{cm}^2}{\text{m}^2} = 1350 \text{ cm}^2$$

3.3.2. Calculations for 30% Efficient solar panels

Actual power needed:

$$P_{actual} = \frac{P_{input}}{Solar\ Panel\ Efficiency} = \frac{27 \text{ W}}{0.30} = 90 \text{ W}$$

Area needed:

$$A = \frac{P_{actual}}{Solar\ constant} = \frac{90 \text{ W}}{1000 \text{ W/m}^2} = 0.090 \text{ m}^2$$

Converting to square centimeters:

$$A_{cm^2} = 0.090 \text{ m}^2 \times 10000 \frac{\text{cm}^2}{\text{m}^2} = 900\text{cm}^2$$

Table 2 Calculation outputs for different efficiencies

17.7-Watt Output Needed		**Perovskite Efficiency**				
		10%	15%	20%	25%	30%
Cm^2 needed		2700	1800	1350	1080	900
Cm^2 avail. no fuselage/tail	1286					
Cm^2 available full plane	1580					

For the glider, if coverage entailed full wings, tail and fuselage (see Figure 7) with 30% efficiency perovskite, at less than 200 nm thickness, and assuming 80% engine efficiency and optimal sunlight, it would be able to glide autonomously (see Figure 11). Using such perovskite to complement battery power for longer flights, or for charging the battery away from a base for repeat flights, are more practical applications.

4. Discussion

The integration of perovskite solar cells into drones significantly enhances their flight duration, especially in sunny conditions. At the top of the atmosphere where high-altitude pseudo satellites fly the irradiance is around 1360 making it even easier for these types of drones to work. The lightweight nature of perovskite cells makes them ideal for applications where weight is a critical factor. However, further research is needed to improve the durability and environmental resistance of these cells.

A typical silicon solar cell can produce about 0.7 watts of power under standard conditions [31]. The material usage for silicon cells has been significantly reduced over the years, with modern cells using approximately 2.2 g of silicon per watt of power output [32]. Therefore, the power output of a typical silicon solar cell is approximately 0.32 watts per gram of silicon.

The cells from Johannes Kepler University Linz are ultra-thin, flexible perovskite solar cells. They have a power density of up to 44 Wg^{-1} (41 Wg^{-1} average), and 20% champion efficiency (18% average) and have been successfully used in palm-sized quadcopter drones, significantly extending their flight time without the need for recharging [33].

Therefore, from 0.32 watts per gram, to 44 watts per gram—a 100× increase in power to weight. This is perhaps a bit exaggerated as the Kepler cells might need structure around them that the silicon estimate is assuming, but nonetheless it is a step change in power to weight for solar.

Graphically here are the converging trends in Figure 11:

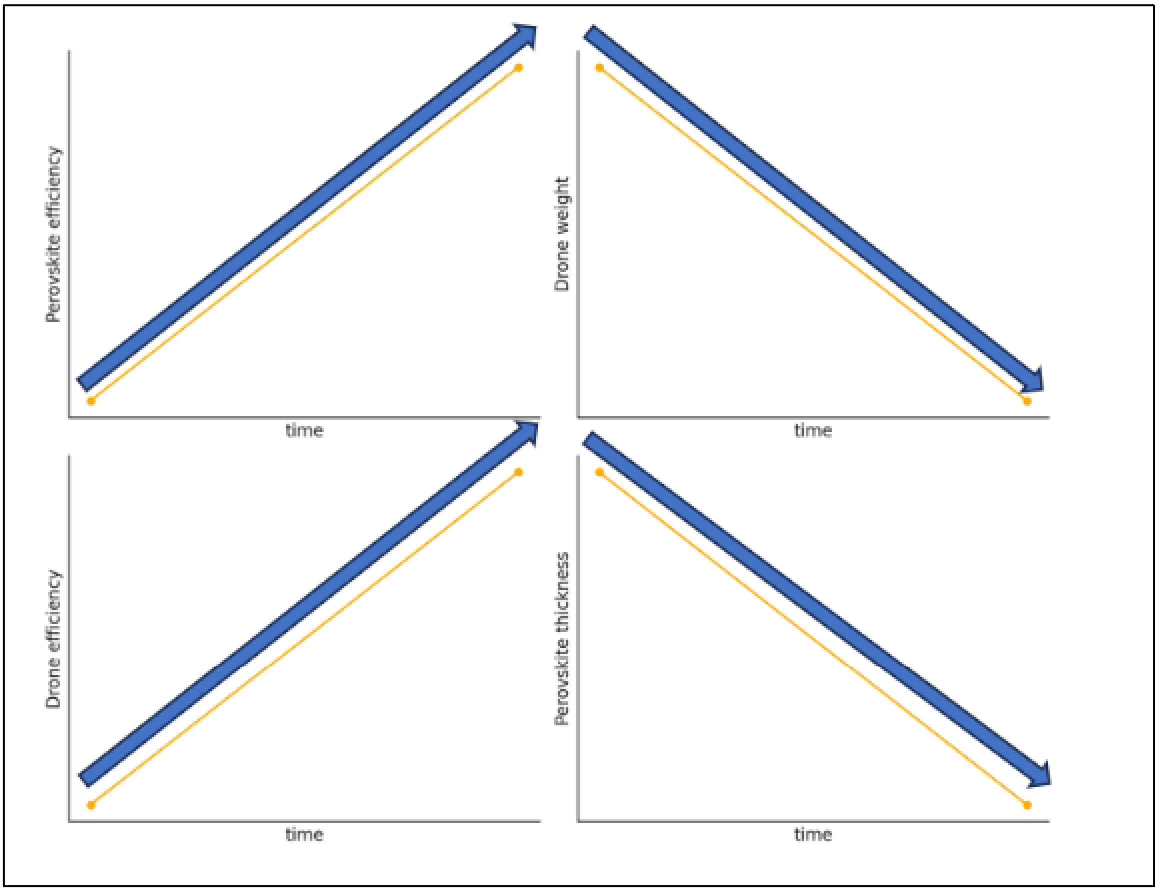


Figure 11 Illustrative trend lines of drone and perovskite trends over time

The (illustrative) trend lines of drone weight, drone efficiency, perovskite weight, perovskite efficiency led to the conclusion that autonomous, self-charging drones are imminent. They might come with tandem cells, or graphene, and be improved with solid state batteries but in some form, they are coming soon. Previously such solar drones aiming for autonomous flight were incredibly large like Zephyr, but soon, much smaller drones will be capable of ongoing flight, or at least repetitions of take-off, land, charge, and take-off again.

5. Conclusions

Perovskite solar cells offer a viable solution to extend the flight time of lightweight drones, particularly at high altitudes. They have the potential to reach recharge in place, or even continuous flight on solar power alone. This paper summarizes the current progress in both drones and perovskites, provides initial analysis of a perovskite glider prototype, and highlights areas for future research to optimize their performance and integration.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare no conflicts of interest. Matias Maurer and Alex Sirvent declare that they have no conflicts of interest or competing interests regarding the publication of this manuscript. None of the authors are affiliated with, nor do they have any financial or personal relationships with any institutions, organizations, or products that are discussed in the manuscript, nor with any entities that could be considered to influence or benefit from the outcomes of the study presented. Furthermore, none of the authors are involved with any products that compete with those mentioned in this manuscript.

Author Contributions

Conceptualization, M.M. and A.S..; methodology, M.M. and A.S..; validation, M.M.; formal analysis, M.M. and A.S..; investigation, M.M. and A.S.; resources, M.M. and A.S.; data curation, M.M.; writing—original draft preparation, M.M.; writing—review and editing, M.M. and A.S..; visualization, M.M.; supervision, A.S.. All authors have read and agreed to the published version of the manuscript. The authors thank Spencer Folk, University of Pennsylvania for advice on experimental design and review of the final paper.

Data Availability Statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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