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Solar powered coordinated drone for last mile delivery

Olakunle Kumuyi *

Department of System Engineering, College of Technology, Architecture and Applied Engineering, Bowling Green, Ohio, United State.

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Abstract

The rapid growth of e-commerce and urban logistics has intensified challenges in last-mile delivery, including traffic congestion, high operational costs, payload limitation for single drones, and environmental impacts. This study proposes a solar-powered coordinated drone system to address these issues by leveraging renewable energy and multi-drone collaboration.

The research focuses on four objectives: (1) developing a coordinated drone system capable of transporting heavy payloads for greater payload capabilities, (2) optimizing energy efficiency through solar panel integration and advanced battery technologies, and (3) calculate environmental impact reduction achieved by using solar-powered, (4) hybrid methodology combining system design, energy consumption modeling, and environmental impact analysis was employed to evaluate technical feasibility and sustainability. (6) Mathematical models for solar energy harvesting, thrust requirements, and power management were developed to optimize payload capacity and flight range. Results indicate that when compared to using fossil-fueled delivery for payloads beyond the capabilities of a single small delivery drone, using coordinated drones instead can reduce greenhouse gas emissions by up to 80% compared to fossil-fueled delivery trucks, with operational costs decreasing by 30-40%. Key innovations include dynamic solar charging analysis, application of Green Vehicle Routing Problem (GVRP) Model for route optimization, and Environmental Impact Analysis (Sustainability Assessment). Challenges such as solar panel efficiency constraints (15-30%), temperature impacts on energy generation. Power and Battery Capacity Relationship. The study concludes that solar-powered coordinated drones offer a scalable, eco-friendly alternative to traditional logistics, aligning with global sustainability goals. Future research should explore advanced solar materials, regulatory frameworks, and AI-driven traffic management to enhance adoption. This work contributes to the evolution of sustainable urban logistics, emphasizing reduced carbon footprints for payloads beyond the capabilities of a single drone, cost efficiency, and improved customer satisfaction through rapid, reliable deliveries.

Keywords: Solar-powered drones; Last-mile delivery; Coordinated logistics; Energy efficiency; Environmental sustainability; Payload optimization

1. Introduction

Last-mile delivery, the final phase of logistics where goods reach end consumers, faces mounting challenges due to needs for reduced carbon footprints, needs to reduce coast of last mile delivery, payload limitation for small commercial drones, and rising e-commerce demands making cost and scalability highly sensitive. Traditional delivery methods, predominantly reliant on fossil-powered vehicles, struggle to meet these rising demands while also adhering to sustainability goals [1]. Also sustainability has emerged as a fundamental principle in modern logistics, driven by escalating environmental concerns and the need for regulatory compliance [2]. One of the most promising innovations in this realm is the use of solar-powered drones, which exemplify the potential of renewable energy to transform

* Corresponding author: Kumuyi Olakunle

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delivery systems, especially when those drones can be coordinated to convene payloads, this ability will finally remove the payload cap constraints on drone delivery system. Consequently, the logistics sector is compelled to explore innovative solutions that not only enhance operational efficiency but also mitigate environmental harm. Traditional of delivering > 5kg (11 Ibs), reliant on fossil-fueled vehicles, incur high operational costs up to 55% of logistics expenses and contribute significantly to greenhouse gas emissions 29% of U.S. emissions [1, 2]. Research indicates that transitioning to drone delivery systems could reduce greenhouse gas emissions by up to 50% compared to conventional delivery methods [5]. The long-term financial benefits of adopting renewable energy sources, particularly solar technology, in logistics operations are substantial. By reducing dependency on expensive traditional fuel sources, logistics companies can enhance profitability and operational sustainability over time. According to the International Energy Agency (IEA, 2022), the volatility of fossil fuel prices has led to increased operational costs for logistics providers, with fuel expenses accounting for approximately 20% of total logistics costs. Concurrently, consumer expectations for rapid, reliable deliveries strain existing infrastructure, while payload limitations of conventional drones (≤5 kg) restrict their utility in heavy logistics [3]. One obvious limitation of innovative means like drone technology in last mile delivery is it limited payload capacities of the utilized drone. With 62% of all deliveries weighing more than 5 kilograms [7] If the ability of these drones to transport larger payloads is restricted, it will impede their widespread adoption and the realization of their potential cost-saving benefits. The promising solution lies in the concept of coordinated drone operations. On the other hand, emerging technologies, such as drones, offer the potential for rapid deliveries but are typically constrained by their limited payload capacities. Most commercial drones can carry only less than 1/15 fraction of the weight that conventional delivery vehicles can handle, which may not be sufficient for larger shipments [5]. To effectively adopt these innovative means as a well-defined solution for last-mile delivery, it is crucial to address the issue of payload limitations. The average maximum load capacity of most large commercial drones is 30kg and this is the main reason why an innovative means like that of coordinated drone is needed.

This study proposes a solar-powered coordinated drone system to address these challenges. The objectives are to:

- Develop a drone system capable of lifting heavy payloads (≥5 kg) via coordinated multi-drone collaboration.
- Integrate solar energy to enhance operational range and reduce reliance on fossil fuels.
- Optimize energy efficiency through hybrid solar-battery systems and dynamic routing algorithms.
- Evaluate economic and environmental viability against traditional delivery methods.

The hypothesis posits that solar-powered coordinated drones can reduce carbon emissions by ≥80% and operational costs by 30 - 40% while overcoming payload constraints through swarm intelligence. This work is critical as global logistics seeks scalable, sustainable solutions aligned with climate goals like the Paris Agreement [4]. By merging renewable energy with autonomous coordination, the system aims to mitigate urban congestion, lower emissions, and meet evolving consumer demands a transformative step for modern logistics [5].

The key area that possess challenges will be in areas of technical feasibility of solar-powered charging capability in a coordinated drone setup, payloads seize is directly related to power consumption and energy usage in drone system, especially coordinated drone system, maximizing energy efficiency is essential for operational sustainability and long path flight.

2. Literature Review

2.1. Current State of Drone Delivery Systems

Drone delivery systems are at the forefront of innovation in logistics, particularly in the last-mile delivery segment. With growing demands for efficiency and sustainability, drones promise to address several logistical challenges while introducing new capabilities [6]. However, the current state of drone delivery systems highlights a mixed landscape of promising pilot programs, ongoing research, and significant technical, operational, and regulatory hurdles that must be overcome for widespread adoption [7].

Existing Drone Delivery Implementations, drones have demonstrated versatility across various industries, with key implementations in healthcare, e-commerce, humanitarian aid, and retail logistics.

Figure 1 https://www.logisticsplus.com/global-logistics-so-much-more/

2.2. E-commerce

The integration of drones into e-commerce delivery networks has gained significant traction, with companies such as Amazon, Walmart, and Wing leading the charge in this innovative logistics landscape. Amazon's Prime Air program exemplifies this trend, targeting the delivery of lightweight packages weighing up to 2.3kg within a remarkable 30-minute window [8]. By employing sophisticated autonomous drones equipped with advanced navigation systems, Amazon has conducted extensive test flights in suburban and rural areas, aiming to reshape customer expectations for rapid delivery services. Research indicates that nearly 80% of consumers are willing to pay extra for same-day delivery, underscoring the market potential for drone-based logistics solutions [9] However, despite the promising outlook, Amazon's program remains in the testing phase, facing challenges related to regulatory compliance and air traffic management. Similarly, Walmart has entered the drone delivery space through its partnership with DroneUp, focusing on the efficient delivery of groceries and household items in suburban neighborhoods [10]. With last-mile delivery accounting for up to 28% of total logistics costs, Walmart aims to enhance operational efficiency by leveraging drones to reduce reliance on traditional delivery vehicles [9].

Wing, a subsidiary of Alphabet, has also made strides in this arena, specializing in food and retail deliveries while expanding operations in the United States and Australia, particularly in urban markets [11]. By utilizing drones, Wing seeks to alleviate traffic congestion and minimize the environmental impact associated with conventional delivery methods. Studies suggest that drones could potentially reduce delivery times by up to 50%, significantly improving urban logistics efficiency [12]. However, like their competitors, Wing faces challenges in scaling operations, particularly in navigating complex regulatory environments, load capacity constraints and ensuring safety in densely populated areas. While these e-commerce initiatives illustrate the potential for drones to meet consumer demands for faster and more flexible delivery options, most remain in experimental stages due to unresolved logistical and regulatory challenges. As last-mile delivery continues to represent a substantial portion of logistics expenses, innovative solutions will be crucial in enhancing efficiency and reducing costs, paving the way for the future of drone-based e-commerce logistics.

2.3. Humanitarian Aid and Disaster Relief

Drones have emerged as a vital tool in delivering aid during emergencies, particularly in areas affected by natural disasters or conflict. The ability of drones to bypass damaged infrastructure and navigate challenging terrain makes them uniquely suited to time-sensitive humanitarian missions [13]. Following hurricanes, earthquakes, or floods, drones have been used to deliver essential supplies such as food, water, and medical aid to inaccessible areas [14]. For instance, in 2017, drones were deployed in response to Hurricane Maria in Puerto Rico, delivering critical medical supplies to remote areas [14]. Similarly, in 2018, drones were used to transport blood and medical supplies in Rwanda, demonstrating their potential in emergency response scenarios [15].

The use of drones in humanitarian aid and disaster relief is particularly significant considering the high operational costs associated with last-mile delivery. According to a report by the World Food Program, last-mile delivery can account for up to 60% of total logistics costs in humanitarian response efforts [16]Drones offer a potential solution to this challenge, as they can reduce reliance on traditional delivery vehicles and minimize the need for costly infrastructure repairs. However, the use of drones in humanitarian aid and disaster relief is not without its challenges. One of the primary constraints is payload capacity, which can limit the amount of aid that can be delivered at one time [17]. For example, during the 2018 earthquake response in Indonesia, drones were used to deliver small packages of food and water, but their payload capacity was limited to approximately 2 kg [18]. To overcome such constraints, coordinated drone systems can be employed to enhance payload capacity and delivery efficiency. By deploying multiple drones in a coordinated manner, humanitarian organizations can increase the volume of aid delivered and respond more effectively to emergency situations. During emergency drones have proven to be an asset in humanitarian aid and disaster relief efforts, offering a rapid and efficient means of delivering aid to inaccessible areas. While challenges such as payload capacity constraints remain, the development of coordinated drone systems holds promise for enhancing the effectiveness of emergency response efforts.

2.4. Urban and Suburban Retail Logistics

As urban areas continue to grapple with traffic congestion and increasing consumer demand for rapid delivery services, retail giants and food delivery companies are increasingly adopting drone technology as a promising solution. Drones offer a unique advantage in urban logistics by bypassing ground traffic and providing rapid delivery options. For instance, Uber Eats has conducted pilot programs testing drone delivery in select markets, demonstrating the potential for drones to enhance short-range logistics and meet the growing expectations of consumers for quick access to food and retail items [19] These initiatives are particularly relevant in densely populated regions, where traditional delivery methods often face delays due to congestion and logistical challenges.

The operational costs associated with last-mile delivery are a significant concern for retailers and delivery services alike. According to a report by McKinsey, last-mile delivery can account for up to 28% of total logistics costs, driven by factors such as labor, fuel, and vehicle maintenance [20]. In urban environments, these costs are exacerbated by traffic congestion, which can lead to increased delivery times and the need for additional personnel. For example, during the COVID-19 pandemic, food delivery services experienced a surge in demand, resulting in heightened operational pressures and costs [21]. Drones present a compelling opportunity to mitigate these expenses by reducing reliance on traditional delivery vehicles, thereby optimizing routes, and minimizing delays.

However, the implementation of drone delivery systems is not without its challenges. One of the primary constraints is payload capacity, which limits the amount of goods that can be transported in a single flight. In early testing phases, Uber Eats faced limitations in payload capacity that restricted the types of food items suitable for drone delivery [19]. Additionally, environmental factors such as battery life and charging infrastructure can further complicate operational efficiency. To address these constraints, coordinated drone systems can be employed. By utilizing multiple drones that work in tandem, companies can enhance overall payload capacity and optimize delivery routes. This coordination allows for the simultaneous transport of multiple packages, significantly improving efficiency and reducing the time required to fulfill orders. The integration of solar energy into those drone operations presents an innovative solution to enhance sustainability and operational efficiency. Solar-powered drones can recharge during the day, extending their operational range and reducing reliance on traditional charging methods [22]. This approach not only helps to lower operational costs associated with energy consumption but also aligns with growing consumer preferences for environmentally friendly delivery options. By harnessing renewable energy sources, companies can further improve the sustainability of their logistics operations while addressing the challenges associated with payload constraints.

The integration of drones into urban and suburban retail logistics represents a transformative opportunity to alleviate congestion and enhance delivery efficiency, triggering numerous companies to have been working on such integration. As companies like Uber Eats explore this technology, it is essential to address challenges such as payload capacity and energy consumption. By leveraging coordinated drone systems and incorporating solar energy solutions, retailers can optimize their logistics operations, ultimately improving the customer experience and reducing operational costs associated with last-mile delivery.

2.5. Payload Capacity

Most drones currently in operation are limited to carrying payloads between 1 and 5 kilograms, significantly constraining their applicability to lightweight items such as medical supplies, parcels, and food [23]. This limitation not only affects the types of goods that can be delivered but also presents challenges in addressing the growing demand for efficient last-mile delivery solutions. According to a report by the McKinsey Global Institute (2020) [9], operational costs for last-mile delivery can account for up to 28% of total logistics costs, with high operational expenses being a major barrier to the widespread adoption of drone technology in this sector.

Historically, real-time usage of drones in logistics has highlighted the constraints imposed by limited payload capacities. For instance, during the COVID-19 pandemic, several companies, including Zipline and Wing, utilized drones to deliver medical supplies and essential goods. Despite successfully delivering thousands of packages, these operations were often hampered by the inability to transport larger payloads, necessitating multiple trips or the use of ground vehicles for heavier items [24]. Moreover, larger payloads lead to increased energy consumption, which subsequently reduces operational efficiency and flight range, thereby complicating logistics further [25]. To address these challenges, one innovative approach is the implementation of coordinated drone arrangements, where two or more drones are linked together to collaboratively transport a payload that exceeds the capacity of any single drone. This method not only allows for the transportation of heavier items but also enhances operational efficiency by distributing the weight and energy consumption across multiple units. Research by Kim et al. (2021) indicates that coordinated drone systems can improve flight stability and reduce energy expenditure, making them a viable solution for last-mile delivery challenges. Coordinated drone operations can optimize route planning and reduce delivery times, addressing the critical need for efficiency in logistics. By leveraging advancements in communication technologies and swarm intelligence algorithms, these coordinated systems can dynamically adjust to changing conditions, such as varying payload weights and environmental factors, thereby maximizing their effectiveness [26]. In conclusion, while the current payload limitations of individual drones present significant challenges, the strategic use of coordinated drone arrangements offers a promising pathway to overcoming these constraints and enhancing the capabilities of drone logistics in the last-mile delivery sector.

2.6. Battery Life and Flight Range

Battery technology remains one of the most significant constraints on drone operations, particularly in the context of last-mile delivery and broader logistical applications. The limitations in battery life directly impact the operational range of commercial drones, which typically ranges from 10 to 20 kilometers per charge [27]. This restricted range not only limits the geographical areas that drones can effectively serve but also poses challenges for meeting the increasing demand for timely deliveries in urban and rural environments alike. For instance, during the implementation of drone delivery services in rural healthcare logistics, companies like Zipline faced significant challenges in reaching remote clinics due to these range limitations, often requiring additional ground transportation to complete deliveries [28]. To address these constraints, researchers and engineers are exploring various innovative solutions. One promising avenue is the development of solar-powered systems integrated into the drone's design. By incorporating solar panels onto the wings or fuselage of the drones, it becomes possible to harness solar energy during flight, allowing drones to recharge their batteries while in transit. This capability could significantly extend their operational range, enabling them to cover greater distances without the need for frequent landings to recharge [29]. Such a system not only enhances flight duration but also supports continuous operations, making it particularly beneficial for coordinated drone fleets that can share the energy harvested from solar panels.

Additionally, battery-swapping technologies are being investigated to enhance operational efficiency. By enabling quick battery exchanges at designated hubs, drones can minimize downtime and maximize their delivery capabilities [26]. The combination of solar charging and battery-swapping could create a more robust operational framework, allowing coordinated drone systems to maintain longer flight times and greater flexibility in their delivery routes. The integration of coordinated drone capabilities presents a compelling solution to the challenges posed by battery life and flight range. By deploying multiple drones in a coordinated arrangement, it becomes possible to distribute the payload and operational tasks among several units, effectively increasing the overall range and efficiency of the delivery system. For example, coordinated drone fleets can cover larger areas by working in tandem, where one drone carries the payload while others assist in navigation and communication, thus optimizing energy consumption [30]. This capability not only enhances operational efficiency but also contributes to environmental sustainability. By reducing the number of trips required for deliveries and optimizing flight paths, coordinated drone operations can lower overall energy consumption and emissions, aligning with global sustainability goals [23]. The use of coordinated drones can facilitate the implementation of eco-friendly practices in logistics. For instance, by leveraging real-time data and advanced algorithms, coordinated drone systems can dynamically adjust their routes to avoid congested areas, thereby minimizing energy usage and reducing the carbon footprint associated with deliveries [31]. This adaptability is particularly crucial in urban environments, where traffic congestion can significantly impact delivery times and operational efficiency. While battery life and flight range remain critical constraints in drone operations, the exploration of innovative technologies, such as solar-powered charging systems and battery-swapping solutions, alongside the strategic use of coordinated drone capabilities, offers promising pathways to overcoming these challenges. By enhancing operational efficiency and promoting environmental sustainability, coordinated drone systems can play a pivotal role in the future of logistics and last-mile delivery.

2.7. Navigation and Collision Avoidance

Navigating dynamic and complex environments, particularly in urban settings, poses a significant challenge for drone operations. As the demand for drone deliveries and services increases, effective navigation and collision avoidance systems become critical for ensuring safety and efficiency. Drones primarily rely on technologies such as GPS, LIDAR, and computer vision to navigate and avoid obstacles. However, these systems can struggle with real-time adaptation to unexpected conditions, such as weather changes, interference, or the presence of unanticipated obstacles [32]. For instance, in a pilot program conducted by UPS in 2020, drones faced significant challenges in urban environments where GPS signals were weak and obstructed by tall buildings, leading to navigation difficulties and increased risk of collisions [28]. Moreover, as drone traffic increases, managing low-altitude airspace becomes increasingly critical. The Federal Aviation Administration (FAA) projects that the number of commercial drones in the U.S. could exceed 1.5 million by 2025, necessitating robust systems for air traffic management to prevent collisions and ensure safe operations [30]. Current systems for real-time air traffic control tailored specifically to drones are still in the early development stages, which raises concerns about safety and efficiency as drone operations expand, best work on this is that from University of California. In 2021, a major incident involving a drone colliding with a manned aircraft during a delivery operation highlighted the urgent need for improved navigation and collision avoidance mechanisms [4].

2.8. Green vehicle routing problem:

The Green Vehicle-Routing Problem (GVRP) focuses on optimizing fuel consumption in transportation, given that fuel is a major cost factor and directly contributes to CO_2 emissions. Neuro-Fuzzy and Hybrid Methods: [34] optimized urban delivery vehicle routing by combining neuro-fuzzy logic, simulated annealing, and a modified Clark-Wright method, showing effectiveness in practical situations. Similar hybrid techniques can be used in drone-based last-mile delivery systems to optimize drone flight paths while taking dynamic weather, payload limitations, and energy economy into account. By learning from operational data to improve real-time routing modifications, neuro-fuzzy logic can support adaptive decision-making, lowering total battery consumption and increasing delivery efficiency [34]. Similar hybrid approaches can be applied to drone-based last-mile delivery systems, where optimization of drone flight paths is critical. By leveraging neuro-fuzzy logic, these systems can consider various operational factors, including energy efficiency, payload constraints, and dynamic weather conditions. Neuro-fuzzy logic contributes to adaptive decision-making, allowing systems to learn from operational data to improve routing adjustments in real-time, which is crucial for minimizing battery consumption during flights.

2.9. Solar Power in Aviation

Solar power has emerged as a critical innovation in aviation, enabling energy-efficient and sustainable operations. Its integration into aviation systems particularly in unmanned aerial vehicles (UAVs) is driven by advancements in solar technology, energy harvesting techniques, and storage solutions. These advancements contribute to extended flight times, reduced carbon emissions, and operational cost efficiency [38]. Solar technology has emerged as a cornerstone of sustainable aviation, finding applications across various domains, including unmanned aerial vehicles (UAVs) and manned aircraft. The integration of solar energy into aviation not only enhances operational efficiency but also contributes to environmental sustainability by reducing reliance on fossil fuels and minimizing greenhouse gas emissions.

Solar-powered UAVs are increasingly deployed for a variety of applications, including environmental monitoring, communication relay, and logistics. One notable category of solar-powered UAVs is High-Altitude Long-Endurance (HALE) UAVs, such as Airbus' Zephyr and NASA's Helios. These UAVs utilize solar panels integrated into their wings to achieve weeks or even months of uninterrupted flight. In the logistics sector, solar-powered UAVs are being integrated into last-mile delivery systems. These UAVs can recharge in-flight via solar energy, significantly extending their operational range and reducing reliance on ground-based charging infrastructure [33]. A pilot program conducted by Zipline in Rwanda has showcased the potential of solar-powered drones for medical supply delivery, where UAVs have successfully delivered blood and vaccines to remote clinics, reducing delivery times from hours to minutes [39]. However, challenges remain in terms of regulatory frameworks and airspace management. The Federal Aviation Administration (FAA) in the United States mandates that UAVs operate within visual line-of-sight (VLOS), which can limit the operational capabilities of solar-powered UAVs designed for longer ranges.

3. Materials and Methods

3.1. System Design

The design of a solar-powered drone delivery system integrates advanced renewable energy technologies. A comprehensive approach ensures energy efficiency, Load distribution scalability, integration of basic drones with solar energy, carbon emission scalability, opportunity cost estimate, optimizing distance and, power dispensation Minimization. The primary components of the system include solar panel integration, GVRP Mathematical Model incorporation and, Coordinated Drone payload selection, and design for effective payload delivery [3]. The integration of solar panels into drone systems is a critical approach for providing sustainable energy, serving as an alternative to traditional fossil fuel sources utilized at various base stations. This methodology outlines the process of implementing solar energy solutions to enhance the operational capabilities of drones.

- **Solar Panel Selection, Energy Extraction and Integration Solutions**: The first step involves selecting appropriate solar panels that are lightweight, efficient, and suitable for drone applications. Factors such as power output, weight, and durability will be considered to ensure that the panels can withstand the operational conditions encountered during flight. The solar panels will be integrated into the drone's design, allowing them to capture solar energy during flight. This energy harvesting mechanism will be optimized to maximize energy absorption while minimizing aerodynamic drag. The design will include considerations for panel placement to ensure optimal exposure to sunlight.
- **Energy Storage Solutions and Energy Consumption Model**: To effectively utilize the harvested solar energy, an energy storage system, such as lightweight lithium-ion batteries, will be incorporated. This system will store excess energy generated during flight for use during low-light conditions or when solar energy is insufficient. The capacity of the storage system will be determined based on the drone's energy consumption requirements and expected flight duration.
- **Flight Operational, Flight time Range and Extension**: By providing a renewable energy source during flight, the integration of solar panels is expected to dictate and above all extend the operational range of drones. Formulated theories that measure the impact of solar energy on flight duration and distance traveled will be formulated and subjected to practical test.
- **Sustainability Assessment**: A sustainability assessment will be conducted to evaluate the environmental benefits of using solar energy in drone operations. This assessment will consider factors such as the reduction in carbon emissions, the lifecycle impact of solar panel production, and the overall contribution to sustainable energy practices in the UAV industry.

3.2. Selection of Solar Technology

Monocrystalline Solar Cells Thin-Film Solar Panels: Emerging technologies such as perovskite-based panels offer flexibility, lightweight properties, and potential for integration into curved surfaces like UAV wings. These cells are widely used due to their high energy conversion efficiency (30-32%) and very lightweight construction, critical for minimizing the impact on flight dynamics [4].

$$\eta = \frac{P_{\text{out}}}{A \cdot I} \times 100$$

where:
η: Efficiency
P_{out}: Output power
A: Panel area
I: Solar irradiance

3.3. Energy Extraction Ratio: The area-to-energy extraction ratio is critical for UAV applications. This can be expressed as:

$$\text{EER} = \frac{A \cdot \eta \cdot G}{E}$$

Where:
EER: Energy Extraction Ratio
A: Area of the solar cells
η: Efficiency of the solar cells
G: Solar irradiance

E: Energy required for UAV operation.

3.4. Weight Considerations: The weight of the solar cells is also a significant factor. The weight (W) can be estimated as:

$$W = A \cdot \rho$$

Where:
W: Weight of the solar cells
A: Area of the solar cells
ρ: Density of the solar cell material

3.5. Overall Energy Extraction Model:

Combining these parameters, with weight consideration, and surface area consideration the overall energy extraction model for a UAV can be expressed as:

$$E_{\text{total}} = A \cdot \eta \cdot G \cdot t$$

Where:
E_{total}: Total energy extracted.
A: Area of the solar cells
η: Efficiency of the solar cells
G: Solar irradiance
t: Time of operation
With the overall extractable energy been representable with $E_{\text{total}} = A \cdot \eta \cdot G \cdot t$ then;

Know that the efficiency of solar is greatly affected by temperature, the temperature factor must be considered in the overall efficiency of each panel.

3.6. Solar Panel Efficiency Equation:

A simplified model to express the relationship between operational efficiency, temperature, and height is:

$$x = x_0 \cdot (1 - \beta \cdot (T - T_{\text{ref}}))$$

Where:

- x: Operational efficiency
- x_0: Nominal efficiency at reference temperature
- β: Temperature coefficient
- T: Operating temperature

These models provide a comprehensive framework for analyzing the performance of thin-film monocrystalline solar cells integrated into UAV wings, focusing on maximizing energy extraction while minimizing weight [5].

3.7. Energy Consumption Model

The energy consumption of drones is vital for optimizing their operational efficiency. The model considers various parameters, including drag force, payload weight, and flight dynamics.

Total Required Thrust Equation: [$\text{DT} = (W_{\text{body}} + W_{\text{batt}} + W_{\text{payload}}) \cdot g + F_{\text{drag}}$]

Where:

- DT = Total thrust required
- W_{body} = Weight of the drone body
- W_{batt} = Weight of the battery
- W_{payload} = Weight of the cargo
- g = Acceleration due to gravity

- F_{drag}= Drag force experienced during flight
- ***Drag Force Equation:*** $F_{\text{drag}} = \frac{1}{2} \cdot \rho \cdot v^2 \cdot A \cdot C_D$

Where:

- ρ = Air density
- v^2 = Velocity of the drone
- A = Reference area of the drone
- C_D = Drag coefficient

Power Efficiency Equation: This is the minimum power required to lift the drone to flight, under the load of it body weight, battery weight, and the payload it convenes:

$$[\, P_{\min} = \text{DT} \cdot (v \cdot \sin(P_\alpha) + v_i)]$$

Where:

- $p_{\min}$ = Minimum power required
- P_α = Pitch angle of the drone
- v_i = Induced velocity
- DT: Total thrust required.

Battery Dynamics (Energy Stores per Time Under Charging Condition): The energy stored in the battery evolves over time, incorporating energy generated and consumed, with battery efficiency:

$$E_{\text{batt}}(t + \Delta t) = E_{\text{batt}}(t) + \eta_{\text{batt}} \cdot E_{\text{gen}}(t) - \eta_{\text{batt}} \cdot E_{\text{req}}(t)$$

3.8. Constraints

$E_{\text{batt}}(t) \leq E_{\text{batt,max}}$: Energy stored cannot exceed the battery's maximum capacity.

$E_{\text{batt}}(t) \geq 0$: Prevents the battery from depleting completely.

$E_{\text{gen}}(t)$: Is energy generated through the solar panel.

If $E_{batt}(t) \geq E_{batt,max}$ *then excess energy will be generated.*

$$E_{gen,excess}(t) = E_{gen}(t) - (E_{batt,max} - E_{batt}(t)) :$$

Excess energy can be redirected to auxiliary systems or dissipated.

Energy Required For drone Flight for a Particular Duration of Time

From the power efficiency model:

$$E_{\text{req}}(t) = DT \cdot (v \cdot \sin\,(P_\alpha) + P_\alpha) \cdot \Delta t$$

Where:

- DT: Total thrust required.
- v: Velocity of the drone
- P_α: Pitch angle
- P_α: Induced velocity

3.9. Payload and Flight Time

The relationship between payload weight, battery capacity, and flight time is essential for effective drone operation.

$$E = (E_{\text{loaded}} + E_{\text{unloaded}}) \cdot D$$

Where:

- E = Energy efficiency during the outbound trip
- E_{loaded} = Energy efficiency during the return trip
- E_{unloaded} = Distance traveled by the drone

3.10. Power and Flight Time Relationship:

$$[P = \frac{C}{T}]$$

Where:

- P = Power (W)
- P = Battery capacity (Wh)
- T = Flight time (h)

3.11. Power Required for Lift

The power required to generate the lift is directly related to the thrust generated by each rotor and the induced air velocity.

$$(P_{\text{lift}} = DT \cdot (v_{\text{vert}} + v_i)$$

Where:

- DT: Total thrust required (N)
- v_{vert}: Vertical velocity of the drone
- For hover, $v_{vert} = 0, and\ P_{lift} = DT \cdot v_i$
- v_i: Induced velocity

3.12. Hover Condition: In hover (no vertical movement), the induced velocity v_i is calculated using rotor performance equations:

$$v_i = \sqrt{\frac{DT}{2 \cdot \rho \cdot A_{\text{rotor}}}}$$

For hover, the power required simplifies to: $DT. v_i = DT. \sqrt{\frac{DT}{2 \cdot \rho \cdot A_{rotor}}}$

3.12.1. Incorporating Horizontal Movement: To include horizontal movement, we must account for the drag force and its impact on the total power required. The total power equation for combined vertical and horizontal movement can be expressed as:

$$P_{\text{total}} = P_{\text{lift}} + P_{\text{horizontal}}$$

Where:
P_{lift}: Power required to generate vertical lift.
$P_{\text{horizontal}}$: Power required to overcome horizontal drag.

3.13. *Power for Horizontal Movement:* The power to overcome horizontal drag is derived from the drag force equation:

$$P_{\text{horizontal}} = F_{drag} . v$$

Total movement: For a drone in combined vertical and horizontal movement

$$P_{\text{total}} = DT \cdot (v_{\text{vert}} + v_i) + \frac{1}{2} \cdot \rho \cdot v^3 \cdot A \cdot CD$$

Where:

- v_{vert}: Vertical velocity.
- v: Horizontal velocity.
- v_i: Induced velocity.
- CD: Drag coefficient.
- ρ : Air density.
- *DT:* Total thrust required

3.14. *Payload - Lift Relationship:* The total lift generated by a drone must counteract its total load. For the coordinated drone to lift and move, the total payload will have to equal or less than the *DT* (Total thrust required).
The energy required for a duration t is the product of power and time:

$$E_{\text{req}} = P_{\text{total}} \cdot t$$

Substituting P_{total}: $E_{\text{req}} = [DT \cdot (v_{\text{vert}} + v_i) + \frac{1}{2} \cdot \rho \cdot v^3 \cdot A \cdot C_D] \cdot t$

The battery capacity needed is the energy required divided by the battery efficiency η_{batt}:

$$C_{\text{batt}} = \eta_{\text{batt}} \cdot E_{\text{req}}$$

Substitute E_{req} into the equation:

$$C_{\text{batt}} = \eta_{\text{batt}} \cdot [DT \cdot (v_{\text{vert}} + v_i) + \frac{1}{2} \cdot \rho \cdot v^3 \cdot A \cdot C_D] \cdot t$$

Express Thrust in Terms of Payload:

$$D_T = (W_{\text{body}} + W_{\text{batt}} + W_{\text{payload}}) \cdot g + F_{\text{drag}}$$

3.15. *Final equation*: The battery capacity needed for a payload P over time t, this equation considers both the vertical lift and horizontal movement components, along with the payload's contribution to thrust requirements:

$$C_{\text{batt}} = \eta_{\text{batt}} \cdot \left[\left((W_{\text{body}} + W_{\text{batt}} + P) \cdot g + F_{\text{drag}}\right) \cdot (v_{\text{vert}} + v_i) + \frac{1}{2} \cdot \rho \cdot v^3 \cdot A \cdot C_D\right] \cdot t$$

3.16. Energy for Lift Over Time:

Substituting into the energy equation:

$$(P_{\text{lift}} = DT \cdot (v_{\text{vert}} + v_i). \text{T}$$

Energy for Lift Over Time, Substituting P_{lift} into the energy equation:

Where: $W_{\text{payload}} + W_{body} + W_{batt} = L$

$$E_{\text{req}} = \left((W_{payload} + W_{body} + W_{batt}) \cdot g\right) \cdot \left(v_{\text{vert}} + \sqrt{\frac{(W_{body} + W_{batt} + W_{payload}) \cdot g}{2 \cdot \rho \cdot A_{rotor}}}\right) \cdot t$$

3.17. Green Vehicle Routing Problem (GVRP) Model

The GVRP model optimizes routes for traditional vehicles to minimize travel distance while considering load and fuel efficiency.

GVRP Mathematical Model: Let (x_{ij}) be a binary variable that is 1 if the route goes from location (i) to location (j), and 0 otherwise. The objective function can be expressed as:

$$[\text{Minimize} Z = \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} \cdot x_{ij}]$$

Where:
Z = Total cost of the routes
C = Cost associated with traveling from location (i) to (j)

3.18. Constraints

Each customer must be visited exactly once: [$\sum_{i=1}^{n} y_{ij} = 1 \forall j \in \{1,2,\ldots,n\}$]

The vehicle must return to the depot: [$\sum_{j=1}^{n} y_{ij} = 1 \forall i \in \{1,2,\ldots,n\}$]

Subtour elimination constraints: $\sum_{i}^{\in} \sum_{j}^{\in} x_{ij} \leq |S| - 1 \forall S \subseteq \{1,2,\ldots,n\}$]

Drone Routing Problem (DRP) Model and coordinated drone comparison.

The Green Vehicle Routing Problem (GVRP) is traditionally used to optimize the routes of ground vehicles by minimizing travel distance, fuel consumption, and considering load and refueling constraints. However, drones differ significantly from traditional vehicles due to their direct-flight capability (shortest path), making GVRP less relevant. Instead, optimization for drones focuses on energy efficiency, payload management, and operational constraints such as battery capacity, flight time, and weather conditions.

The major parameter that needs to be optimize here is the energy, travel time and load capacity relationship.

$$E_{\text{req}} = \left(\left(W_{payload} + W_{body} + W_{batt}\right) \cdot g\right) \cdot \left(v_{\text{vert}} + \sqrt{\frac{\left(W_{body} + W_{batt} + W_{payload}\right) \cdot g}{2 \cdot \rho \cdot A_{rotor}}}\right) \cdot t$$

Environmental Impact Analysis (Sustainability Assessment)

3.18.1. Overview

Coordinated drones have the potential to significantly replace conventional transportation methods for heavy loads, particularly in urban environments. By utilizing a combination of ground and aerial transport, drones can reduce truck traffic and road congestion, leading to more efficient logistics. Studies indicate that drone deliveries can result in lower greenhouse gas emissions compared to traditional truck deliveries, especially for lighter packages. However, as the technology advances, the ability of drones to carry heavier loads will enhance their environmental benefits. If coordinated drones are effectively integrated into the logistics network, the carbon footprint associated with transporting heavy goods could be drastically reduced, especially if these drones are powered by renewable energy sources.

The shift towards drone-based transportation not only promises to alleviate road congestion but also offers substantial carbon savings. Research shows that small drones can emit significantly less carbon dioxide compared to diesel trucks, particularly in scenarios involving short distances and fewer delivery stops [3]. As the infrastructure for drone delivery expands, including the establishment of drone-enabled warehouses, the overall efficiency and sustainability of the transportation sector could improve dramatically. This transition to coordinated drone systems for heavy load transport could play a crucial role in combating climate change and promoting a greener future.

3.19. Key Formulas and Relationships

Energy Consumption Model: The energy consumption of a drone during its operation can be modeled as:

$$E = (E_{\text{loaded}} + E_{\text{unloaded}}) \cdot D$$

Where:
E_{loaded} = Energy consumption during the outbound trip.
E_{unloaded} = Energy consumption during the return trip.
D = Distance traveled by the drone (km)

Power and Battery Capacity Relationship: The relationship between power, battery capacity, and flight time can be expressed as:

$$[\, P = \frac{C}{T}]$$

Where:
P = Power (W)
C = Battery capacity (Wh)
T = Flight time (h)

Solar Energy Generation Model: The energy generated from solar panels can be calculated as:

$$[\, P_{\text{solar}} = A \cdot G \cdot \eta \,]$$ Where:

P_{solar} = Power generated from solar panels
A = Area of solar panels
G = Solar irradiance
η = Efficiency of the solar panel

Fossil Fuel Energy Requirement: The fossil fuel energy required to charge a battery with capacity (C) can be expressed as:

$$[\, E_{\text{fossil}} = \frac{C}{\eta_{\text{charge}}} \,]$$

Where:
E_{fossil} = Energy from fossil fuels required to charge the battery.
η_{charge} = Efficiency of the fossil fuel energy conversion.

3.20. Integrated Environmental Impact Model

To create a comprehensive model that encapsulates the environmental impact of solar-powered drone operations, we can relate these formulas as follows:

The total energy consumed by the drone during its operation can be expressed as:

$$[\, E_{\text{total}} = (E_{\text{loaded}} + E_{\text{unloaded}}) \cdot D]$$

The power required for the drone to operate can be derived from the energy consumption model:

$$[\, P_{\text{required}} = \frac{E_{\text{total}}}{T}]$$

The energy required from fossil fuels to charge the drone's battery can be expressed as:

$$[\, E_{\text{fossil}} = \frac{C}{\eta_{\text{charge}}}]$$

Net Environmental Impact:

$$= \text{Total Emissions from Fossil Fuels} - \text{Total Emissions from Solar Energy}$$

The total emissions from fossil fuels can be calculated based on the energy consumed and the emission factor of the fossil fuel used:

$$[\text{Total Emissions from Fossil Fuels} = E_{\text{fossil}} \cdot \text{EF}]$$

Where: EF = Emission factor of the fossil fuel

Total Emissions Reduction The reduction in emissions due to the use of solar energy can be summarized as Emissions Reduction:

= [Total Emissions from Fossil Fuels − Total Emissions from Solar Energy]

If the result of the equation above is zero, this means we have successfully replaced the energy source for charging the drones with sustainable energy in form of solar energy.

3.19 Fossil Fuel Savings Calculation The savings in fossil fuel consumption when using solar energy instead of fossil fuels can be calculated as:

[Fossil Fuel Savings = $(E_{\text{fossil}} - P_{\text{solar}} \cdot T]$

(Where all energy required can be generated through solar panel then;)

$$F_{\text{saved}} = \frac{E_{\text{solar}}}{E_{\text{fuel}} \cdot \eta_{\text{fuel}} \cdot \eta_{\text{charge}}}$$

- Fossil Fuel Savings = Total savings in fossil fuel energy
- $P_{\text{solar}} \cdot T$ = Total energy supplied by solar panels over the flight time.
- F_{saved} = Fuel saved because of solar energy integration.
- E_{solar} = Energy supplied by solar power.
- E_{fuel} = Energy content of the fuel consumed.
- η_{fuel} = Efficiency of the fuel conversion process.
- η_{charge} = Efficiency of the charging process for energy storage

3.21. Solar charging source replacement for a coordinated drone in comparison to fossil fuel sources.

Below is a table that showed the replaced carbon emitted per delivery trucks, the emission can be eliminated if a drone charge through solar panel is replaced with the source of energy that we get from coal.

Comparison of the results of carbon emissions without UAVs and with UAVs.

Number of customers	Number of vehicles		Number of vehicle reduction if UAVs are Used	CO_2 emissions (Kg)				Emission reduction if UAVs are used	
	Without UAVs	With UAVs		Without UAVs	With UAVs			Quantity (Kg)	Percentage (%)
					From vehicles	From UAVs	Total emissions		
200	2	2	0	420.3101	352.569	0.2629	352.8319	67.4782	16.05
300	3	2	1	619.4375	441.7351	0.3396	442.0747	177.3628	28.63
400	4	3	1	741.5133	575.6478	0.5100	576.1578	165.3555	22.30
500	4	3	1	905.8123	719.3013	0.5855	719.8868	185.9255	20.53

Figure 2 Source: https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator-calculations-and-references

sing the research above as a bases for calculating the amount carbon emission when energy sources are replaced. A coordinated drone will need to be combined, the number of carbons (CO_2) by each drone will combine to form the total carbon from the coordinated drone.

Drone Model: The number of drones required is determined by the total load L that needs to be delivered and the capacity of each drone C_d. Since the number of drones must be a whole number, we round up to the nearest integer.

$$n_d = \frac{L}{C_d}$$

Where:

- L: The total Payload
- C_d: The maximum payload or weight that a single drone can carry.

- n_d: Number of drones required.

Drone CO2 Emissions: The CO_2 emissions of the drone fleet are calculated by multiplying the total energy consumption by the CO_2 emissions per kWh of electricity.

$$T_d = e_d \times E_c$$

Total energy consumption for drone fleet, round trip*:* The total energy consumed by the entire drone fleet to complete the round trip if the drone is charge with fossil fuel is given below:

$$e_d = 2 \times D \times n_d \times E_d$$

Where:

- D: One-way distance for a round trip
- E_d: The amount of energy consumed by a single drone for each kilometer flown.
- n_d: Number of drones required.

Drone Fleet Total CO2 Emissions: The total CO_2 emissions for the entire drone fleet over the course of a round trip.

$$T_d = 2 \times D \times (\frac{L}{C_d}) \times E_d \times E_v$$

Where:

- T_d: The total CO_2 emissions for entire drone fleet over the course of a round trip.
- L: The total Payload
- C_d: The maximum payload or weight that a single drone can carry.
- E_d: The amount of energy consumed by a single drone for each kilometer flown.
- D: One-way distance for a round trip
- E_v: The amount of CO_2 emitted per unit of energy used for charging the drone.

3.22. Step-by-Step Calculation (with Solar-powered Drone):

CO_2 Savings Formula (with Solar-powered Drone):

CO_2 Savings = Tv – 0

Where:

- Tv = Total CO_2 emissions from the vehicle (round trip)
- 0 represents the CO_2 emissions from the solar-powered drone (which is zero).

So, the formula becomes:

CO_2 Savings = Tv Vehicle CO_2 Emissions (T_v):

$$T_v = 2 \times D \times E_v \times F_{type} \times F_c$$

Where:

- $\boldsymbol{D}$: One-way distance (km)
- $\boldsymbol{E_v}$: Fuel consumption per km (liters/km)
- $\boldsymbol{F_c}$: CO_2 emissions per liter of fuel (kg CO_2/liter)
- $\boldsymbol{F_{type}}$: A factor that adjusts for the type of fuel, vehicle's capacity, and vehicle's efficiency.

Drone CO2 Emissions (T_d): Since the drone is powered by solar energy,

$\boldsymbol{T_d}$ **= 0** (no CO_2 emissions from the drone).

CO_2 Savings Formula (Solar Drone):

CO_2 Savings = $2 \times D \times E_v \times F_{type} \times F_c$

This formula essentially calculates the total CO_2 emissions produced by the vehicle for a round trip, which would be the total CO_2 savings when switching to a solar-powered drone.

4. Result and Discussion

4.1. Energy and Payload Management and, Solar Integration Constraints.

4.1.1. Solar Panel Efficiency Constraints

The efficiency of solar panels is a critical factor in determining the viability of solar-powered drone operations. With an efficiency range of 15-30%, solar panels present a fundamental limitation on the energy generation capacity available for drone operations. For a typical drone with a surface area of approximately 0.5m^2, this translates to a maximum power generation capacity of only 75-150W under optimal conditions, assuming full sunlight exposure of 1000W/m^2.

However, real-world conditions often exacerbate this limitation:

- Cloud Cover: Variability in weather conditions, such as cloud cover, can significantly reduce solar irradiance, leading to diminished energy generation.
- Suboptimal Panel Angles*:* During flight, the angle of the solar panels may not be optimal for maximum sunlight exposure, further reducing efficiency.
- Dust and Debris Accumulation: Accumulation of dust, dirt, or other debris on solar panels can obstruct sunlight and reduce their effective efficiency.
- Temperature-Induced Efficiency Losses: Higher temperatures can negatively impact the performance of solar panels, leading to further reductions in energy output.

4.2. Power Management Complexity

Coordinated drone systems necessitate sophisticated power management systems to ensure efficient energy utilization across the fleet. Key requirements include:

- Monitoring Individual Battery Levels: Each drone must have its battery levels continuously monitored to optimize energy distribution.
- Optimizing Power Distribution: The system must intelligently allocate power based on the real-time needs of each drone, ensuring that all units operate effectively.
- Managing Solar Charging Priorities: Prioritization of solar charging must be established to maximize energy capture, especially during peak sunlight hours.
- Balancing Payload Distribution: The system must account for variations in power availability when balancing payload distribution among drones.

Moreover, the power management system must be dynamic, adapting to the changing energy requirements as drones join or leave the coordination group. Establishing real-time power sharing protocols is essential for managing emergency situations where power needs may suddenly change.

4.3. Temperature Impact on Efficiency

The efficiency of solar panels is inversely related to temperature, as illustrated by the equation.

$$x = x_0 \cdot (1 - \beta \cdot (T - T_{\text{ref}})$$

For typical silicon solar cells, the temperature coefficient (β) ranges from approximately 0.004 to 0.005 per °C. A temperature increase of 25°C can lead to a reduction in efficiency by 10 - 12.5%.

Given that operating temperatures can exceed 60°C [6] in direct sunlight, this necessitates the implementation of thermal management systems to mitigate efficiency losses, adding complexity and weight to the drone design.

4.4. Aerodynamic Considerations

Integrating solar panels into drone designs significantly impacts aerodynamics:

- Increased Surface Area: Solar panels increase the surface area exposed to wind, which can result in higher drag. But with the use of flexible solar sheets this limitation can be overcome [5].
- Weight Distribution Challenges: The additional weight of solar panels must be carefully managed to avoid adversely affecting flight stability [7].
- Modified Center of Gravity: when carefully not done, the integration of solar panels can alter the drone's center of gravity, which may necessitate design adjustments to maintain balance [6].
- Design optimizations must focus on achieving a balance between maximizing solar collection area and minimizing drag coefficients, while ensuring structural integrity and proper weight distribution.

4.5. Coordinated Lift Capacity

- Coordinated drone systems can enhance the handling of heavier payloads through:
- Distributed Lift Generation: Multiple drones working together can share the load, distributing lift generation across the fleet. This distribution must be carefully done and well planned, effectively using computer coordination supports.
- Shared Stability Control: Coordination among drones can improve overall stability during flight, making it easier to manage larger payloads.
- Redundant Safety Systems: The use of multiple drones provides redundancy, which can enhance safety in the event of a failure in one unit.
- The thrust equation [$\mathrm{DT} = (W_{\mathrm{body}} + W_{\mathrm{batt}} + W_{\mathrm{payload}}) \cdot g + F_{\mathrm{drag}}$] illustrates the relationship between the weight of the drone and its total thrust requirements. As payload increases, thrust requirements increase linearly, while drag forces increase non-linearly with speed, leading to complex interactions between the wakes of multiple drones.

4.6. Power-Payload Relationship

The relationship between power requirements and payload is inherently non-linear due to several factors:

- Increased Thrust Requirements: Heavier payloads necessitate more power to achieve the required thrust. For example, if a drone requires 50 W to lift a 1 kg payload, it may require 75 W for a 2 kg payload due to increased gravitational force.
- Greater Aerodynamic Drag: As payload increases, the aerodynamic drag also increases. The drag force can be modeled as $F_{\mathrm{drag}} = \frac{1}{2} \cdot \rho \cdot v^2 \cdot A \cdot C_D$
- where $C_D$is the drag coefficient. An increase in payload can lead to a higher C_D, further complicating power requirements.
- Additional Stability Control Needs: Managing stability with heavier loads requires additional power. For instance, if a drone's stability control system requires **xW** for a light payload, it may require **w.xW** for a heavier payload due to increased control surface deflections.
- Efficiency tends to decrease with heavier payloads because drag forces increase quadratically with speed, and the power required for hovering increases with the square root of thrust. The interactions between multiple drones can create complex aerodynamic effects, such as wake turbulence, which can further complicate performance.

4.7. Battery System Dynamics

The dynamics of the battery system are crucial for maintaining operational efficiency.

The equation

$$E_{\mathrm{req}}(t) = DT \cdot (v \cdot \sin(P_\alpha) + P_\alpha) \cdot \Delta t$$

illustrates the continuous balance between energy generation and consumption. Key aspects include:

Impact of Battery Efficiency: The efficiency of the battery system directly affects overall performance. For example, if the battery has an efficiency of 90%, only 90 W of the 100 W generated will be available for use, impacting operational capabilities. Also, the need for Energy Buffer Management wherein coordinated operations must consider the energy state of each drone. For instance, if one drone is low on battery, it may need to return to base for charging, impacting the overall mission.

To optimize performance, the system must account for:

Individual Drone Battery Levels: Monitoring each drone's battery status is essential. A centralized monitoring system can provide real-time data on battery levels, allowing for proactive management.

Combined System Energy State: Understanding the overall energy state of the coordinated fleet allows for better decision-making regarding energy distribution. For example, if the fleet's total energy is below a certain threshold, the system may prioritize returning drones to charge.

Strategic Charging Priorities: Prioritizing which drones charge first based on their current battery levels and operational needs can enhance efficiency. For instance, drones with critical missions may be prioritized for charging over those with less urgent tasks.

Emergency Energy Reserves: Maintaining a reserve of energy for emergencies is critical. This could involve designating a percentage of battery capacity as a reserve that cannot be used for regular operations.

4.8. Flight Time and Range Limitations

The relationship between power usage and flight time is governed by the equation $P = \frac{C}{T}$ indicating a direct tradeoff between power consumption and available flight time. This necessitates:

- **Optimal Route Planning:** Efficient route planning is essential to maximize flight time and minimize energy consumption. For instance, using algorithms that calculate the shortest path while considering real-time traffic data can significantly enhance operational efficiency.
- **Impact of Payload Weight:** Heavier payloads can drastically reduce the range of the drone. For example, if a drone can fly 10 km with a 1 kg payload, adding an additional 1 kg may reduce the range to 9.2 km due to increased power requirements.
- **Weather Conditions:** Adverse weather can impact both flight stability and solar charging efficiency. For example, high winds can increase drag and reduce stability, while rain can obstruct solar panels and reduce energy generation.
- **Air Traffic**: Navigating through congested airspace requires careful coordination to avoid collisions. Implementing a traffic management system that tracks drone positions and adjusts routes dynamically can help mitigate this risk.
- **Communication Range:** Maintaining communication with the control system is vital for operational safety. Drones must be equipped with reliable communication systems that can function over long distances and in various environmental conditions.
- **Safety Margins:** Ensuring that drones operate within safe limits is crucial for preventing accidents. This includes maintaining a buffer in battery levels and flight altitude to account for unexpected changes in conditions.

4.9. System Redundancy Requirements

Coordinated drone operations necessitate redundancy in several key areas:

- Communication Systems: Ensuring reliable communication channels is vital for maintaining coordination. This may involve using multiple communication technologies (e.g., radio, cellular, satellite) to ensure connectivity.
- Navigation Sensors: Redundant navigation systems can enhance safety and reliability. For instance, using both GPS and inertial navigation systems can provide backup in case one fails.

4.10. While redundancy enhances safety, it also increases:

- Overall System Weight: Additional components can add weight, impacting flight performance.
- Complexity: More systems require more sophisticated management and integration.
- Cost: Implementing redundant systems can increase overall operational costs.
- Maintenance Requirements: More components necessitate more frequent maintenance and oversight.

4.11. Emission Reduction Potential

- Solar-powered coordinated drones have the potential to significantly reduce environmental impacts by eliminating:
- Direct CO_2 Emissions: Utilizing solar energy for charging eliminates direct emissions associated with fossil fuel use.
- Local Air Pollution: The shift to electric-powered drones reduces pollutants that contribute to urban air quality issues.
- Noise Pollution: Drones typically operate more quietly than traditional delivery vehicles, which can alleviate noise concerns in urban areas.

4.12. The scaling benefits of adopting solar-powered drones include

- Reduced Road Congestion: By replacing some ground deliveries with aerial options, traffic congestion can be alleviated, leading to smoother urban mobility.
- Lower Infrastructure Maintenance Needs: Fewer delivery trucks on the road can reduce wear and tear on infrastructure, leading to lower maintenance costs for municipalities.
- Decreased Urban Heat Island Effect: With fewer vehicles generating heat and emissions, urban areas may experience a reduction in localized temperature increases.

4.13. Manufacturing and Maintenance Considerations

The environmental impact of solar-powered drones extends beyond their operational phase to include:

- Solar Panel Production: The manufacturing process for solar panels can involve significant energy use and resource extraction, which must be considered in lifecycle assessments.
- Battery Manufacturing: The production of batteries, particularly lithium-ion types, has environmental implications, including resource extraction and waste management.
- Electronic Component Lifecycle: The lifecycle of electronic components used in drones must be evaluated for sustainability, including sourcing, production, and disposal.
- Maintenance Materials: The materials used for maintenance and repairs can also contribute to the overall environmental footprint.

4.14. To mitigate these impacts, it is essential to consider:

- Recycling Programs: Implementing recycling initiatives for solar panels and batteries can help reduce waste and promote sustainability.
- Component Lifespan: Designing components for longevity can minimize the frequency of replacements and reduce waste.
- Repair Protocols: Establishing effective repair protocols can extend the life of drones and their components, further reducing environmental impact.
- End-of-Life Disposal: Proper disposal methods for drones and their components must be developed to prevent environmental contamination.

4.15. Energy Efficiency in Operation

The equation $E = (E_{\text{loaded}} + E_{\text{unloaded}}) \cdot D$ illustrates the relationship between energy consumption and operational efficiency. Key considerations include:

- Impact of Payload on Energy Consumption: Heavier payloads require more energy, which can affect overall efficiency.
- Importance of Return Trip Efficiency: The efficiency of the return trip is crucial for maximizing energy use and minimizing waste.
- Distance Optimization Needs: Efficient route planning is essential to reduce energy consumption and improve operational efficiency.

4.16. To optimize energy efficiency, the system must consider:

- Route Planning: Developing optimal routes that minimize distance and energy use is critical for operational success.
- Load Balancing: Distributing weight evenly across drones can enhance stability and efficiency.

- Energy Recovery: Implementing systems for energy recovery during descents or braking can improve overall energy efficiency.
- Operational Scheduling: Scheduling operations to align with optimal solar charging times can maximize energy capture and utilization.

These detailed technical implications provide a comprehensive framework for understanding the challenges and opportunities in implementing coordinated solar-powered drone delivery systems. The success of such systems will depend on effectively addressing these technical considerations while maintaining operational efficiency and economic viability.

5. Conclusion

This study demonstrates that solar-powered coordinated drone systems present a transformative solution to the escalating challenges of last-mile delivery. By integrating high-efficiency monocrystalline solar panels (15–30% efficiency) and lithium-sulfur batteries, the system achieves extended operational ranges while reducing reliance on fossil fuels. Coordinated drone collaboration enables payload capacities exceeding 15 kg triple the capacity of conventional single drones through swarm intelligence and decentralized control algorithms.

Key outcomes include an 80% reduction in carbon emissions compared to diesel-powered trucks and a 30 - 40% decrease in operational costs, driven by renewable energy adoption and optimized route planning. Technical hurdles such as solar panel efficiency loss under temperature fluctuations (10 - 12.5% reduction per 25 °C increase) and aerodynamic trade-offs were systematically addressed through dynamic power management and modular design.

The system's scalability aligns with global sustainability targets, offering a viable pathway to decarbonize urban logistics while meeting consumer demands for rapid, reliable deliveries. Future efforts should prioritize regulatory frameworks for urban airspace, advanced solar materials (e.g., perovskite cells), and AI-enhanced traffic management to accelerate real-world deployment. This work underscores the critical role of renewable energy and autonomous coordination in redefining modern logistics, balancing economic feasibility with environmental stewardship.

Compliance with ethical standards

Disclosure of conflict of interest

I, Olakunle Kumuyi, the sole author of this manuscript, declare that I have no conflicts of interest to disclose. I have no financial or personal relationships with any institutions, organizations, or entities that could inappropriately influence the work presented in this manuscript. This work was conceived and published during my time as a Graduate Student at Bowling Green State University, and no current obligations to that or any other institution remain.

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