

Impact of Battery Technologies on UAV Performance: A Sizing-Based Equation Analysis

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<https://doi.org/10.34118/ajeee.v1i1.4890>

Abstract

This study investigates the influence of advanced battery technologies on the operational characteristics of battery-powered unmanned aerial vehicles (UAVs), with an emphasis on minimizing battery mass and improving the efficiency of the power system. A lithium polymer battery-powered hexacopter was employed as a case study to assess these effects. Performance parameters including take-off power, take-off mass, and flight duration were analyzed to determine the impact of battery selection. The findings demonstrate that UAV performance and endurance are highly dependent on the type of battery, with lighter batteries exhibiting higher energy densities, resulting in extended flight durations and improved overall performance. However, considerations such as battery cost and volumetric constraints also play a significant role in selecting the most suitable energy source for specific UAV missions. This research underscores the pivotal role of battery technology in UAV development and provides a comprehensive evaluation of the trade-offs involved in optimizing battery selection for various operational requirements.

Keywords: unmanned aerial vehicles, LiPo batteries, battery sizing, flight endurance, take-off power, specific energy.

1. Introduction

In recent years, there has been a notable shift toward the utilization of battery-powered unmanned aerial vehicles (UAVs), primarily due to their cost-effectiveness, high power density, and versatility across a broad spectrum of applications. These UAVs are increasingly deployed in both military and civilian domains, including but not limited to inspection and surveillance operations [1], agricultural monitoring [2], wireless network coverage [3], and logistics or delivery services [4]. Their operational advantages, such as high maneuverability, reliability, energy efficiency, low thermal signature, and minimal acoustic emissions, further contribute to their growing adoption [5].

A fundamental consideration in the design and performance evaluation of battery-powered UAVs is the configuration of the energy system, which directly influences the overall efficiency and reliability of the platform. The battery serves as the primary energy source, supplying the electrical power required to drive critical subsystems such as the motor-propeller assembly, electronic speed controllers

(ESCs), and any mission-specific payload.

Designing an optimal battery system requires careful analysis of energy demand along with constraints such as mass, volume, and financial cost. To achieve this, UAV engineers employ sizing algorithms that consider parameters such as battery mass and cell configuration to define mission-specific design constraints effectively.

Performance assessment is essential to ensure that the UAV meets mission requirements and operates within safe and reliable limits.

The primary aim of this study is to analyze the role of batteries as the sole energy source in UAV operations. Initially, the study outlines the UAV's technical specifications and mission profile. This is followed by the application of a sizing algorithm to determine appropriate battery dimensions—both in weight and volume—tailored to specific mission demands. Furthermore, the study evaluates four distinct battery technologies by comparing their attributes, including weight, cost, volume, specific power, specific energy, and life cycle performance. Finally, a comparative analysis involving four lithium polymer battery variants is presented to highlight their impact on the overall mass and performance of a multicopter UAV.

2. Technical Specifications

2.1. UAV characteristics

In this study, a compact Y6 hexacopter manufactured by 3D Robotics is utilized to obtain the power load profile. This UAV platform is widely recognized for its reliability in experimental flight testing, as illustrated in Figure 1. The Y6 hexacopter features a high-performance battery system and a distinctive structural configuration, consisting of three Y-shaped arms, each outfitted with a pair of counter-rotating propellers. This coaxial arrangement enhances flight stability and maneuverability, enabling superior acceleration performance when compared to conventional quadcopter designs.

During experimental flight trials [6], the Y6 hexacopter is outfitted with a suite of sensors and instrumentation to monitor and record various performance metrics. The technical specifications and operational characteristics of the UAV are summarized in Table 1 [7].

Table 1 summarizes the principal specifications used in this work. The reference platform has a nominal 14.8 V LiPo



Figure 1: 3D Robotics Y6 hexacopter used as the reference UAV platform, adapted from Foster [8].

battery system, six 850 KV brushless motors, a 600 g payload capacity, and an average autonomy of approximately 12–15 min in its original configuration. These characteristics make the Y6 hexacopter a representative test case for compact battery-powered multirotor UAVs.

Table 1: Reference specifications of the 3D Robotics Y6 hexacopter.

Parameter	Value
Take-off mass with original battery	1883 g
Motors	850 KV brushless motors
Propellers	10 × 4.7 slow-fly APC
Electronic speed controller	SimonK firmware, 20 A
Payload capacity	600 g
Average autonomy	12–15 min
Battery type	LiPo, 14.8 V
Battery mass	580 g
Battery capacity	6000 mAh
Maximum power	1640 W
Main features	Pixhawk autopilot, GPS navigation, remote control, waypoint navigation, loiter, circle, and return-to-launch modes

2.2. Powertrain Structure

A typical battery-powered multirotor powertrain includes the battery pack, battery management system (BMS), power converters, DC bus, electronic speed controllers (ESCs), brushless DC motors, and propellers. The battery is the primary energy source, while the ESCs transform electrical power into controlled motor drive signals. The BMS supervises charge and discharge operation, helping to maintain safety and preserve battery health.

Brushless DC motors are favored in small UAVs due to their high efficiency, fast dynamic response, favorable power

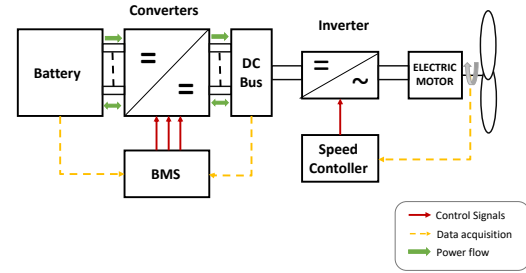


Figure 2: Simplified electric powertrain architecture of a battery-powered UAV.

density, and good controllability [9]. Since propulsion is the dominant power consumer, any reduction in battery mass can improve overall efficiency by decreasing the lift power required during hover and maneuvering.

3. Sizing Methodology

Determining the appropriate battery size involves considering various factors, such as the overall weight of the system, the power required for propulsion, and the energy density of the battery [10].

The useful electrical energy of a battery system is determined based on the battery's capacity C_B and its nominal voltage U_B . The effective energy output can be calculated as follows:

$$E = C_B * U_B \quad (1)$$

The total weight of a multirotor drone at take-off:

$$m_{Tom-B} = m_B + m_E \quad (2)$$

with:

m_E : the empty weight consists of the aircraft's structure.

m_B : The weight of battery.

The variation of propulsion power with take-off mass is investigated as bellow [6]:

$$P_{Tom-B} = K_{int} \frac{(m_{Tom-B} * g)^{\frac{3}{2}}}{2 * \sqrt{2} * \rho * S_{Prop}} \quad (3)$$

with:

ρ : the density of air.

g : the gravity of the earth.

P_{Tom-B} : the propulsion power.

S_{Prop} : the propeller disc area.

K_{int} : Inefficiency factor for coaxial propeller configurations

$K_{int} = 1.219 \text{ to } 10.6$

The specific energy S_{efc} of a power source is a performance metric that represents the amount of energy E_B delivered per unit mass m_B , and is calculated as follows:

$$S_e = \frac{E}{m_B} \quad (4)$$

The useful electrical energy of a battery system can also be determined based on the battery's specific energy, its mass, and the depth of discharge (DOD). The effective energy output is calculated as follows:

$$E_B = S_e * m_B * DOD \quad (5)$$

Flight endurance is typically determined using the following fundamental relation:

$$T_B = \frac{E_B}{P_{Tom-B}} \quad (6)$$

4. Battery Technologies

Small drones are primarily powered by batteries, making them the core component of these UAVs. This enables a simpler, more flexible propulsion system, though battery-powered drones are typically limited by short flight times due to battery weight.

4.1. Nickel-Cadmium (Ni-Cd)

Ni-Cd batteries are less common in drones because of their lower energy density and heavier weight. However, they perform well in high temperatures and have a good cycle life.

4.2. Nickel-Metal Hybrid (NiMH)

NiMH batteries are also rarely used in drones for similar reasons as Ni-Cd, though they offer good high-temperature performance and long cycle life.

4.3. Lithium-polymer (Li-Po)

Li-Po batteries are popular due to their high energy density, lightweight design, and excellent performance in both high and low temperatures. They also have a long cycle life and are less flammable than lithium-ion batteries.

4.4. Lithium-Sulfur (Li-S)

Li-S batteries, still under development, promise higher energy density and longer cycle life than Li-Po and Li-ion, but they are not yet commercially available.

This overview of battery technologies highlights key factors like energy density, specific energy, and power, helping to choose the right battery for a drone's mission and application [11].

5. Evaluation criteria

The key criteria to consider when evaluating battery technologies for UAVs. Weight, cost, size, state of charge (SOC), and energy of the battery are crucial factors to be taken into account. The balance between all these factors must be achieved to ensure that the UAV performs optimally according to its specific conditions (requirements) and intended use case.

These attributes are directly relevant to UAV design because they affect the following evaluation criteria:

1. *Mass*: directly influences take-off mass, propulsion power, and endurance.
2. *Volume*: constrains integration in the battery compartment.
3. *Current capability*: ensures the battery can deliver the required propulsion current with sufficient margin.
4. *Specific energy*: indicates how much useful energy is available per unit battery mass.
5. *Cost*: affects the economic viability of the design and replacement strategy.

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6. Obtained results

This section is dedicated to the presentation of the battery sizing characteristics. We have dedicated to conduct a comparative analysis of four unique battery options, as illustrated in the Table2.

Table 2: Characteristics of 4 different 4S Lipo batteries with a capacity of 6000 mAh and a DOD of 80 % .

Characteristics	Type	Li Po 35C	Li Po 65C1	Li Po 65C2	Li Po 60C
Battery capacity cell (mAh)		6000	6000	6000	6000
Battery voltage cell (V)		14.8	14.8	14.8	14.8
Battery discharge current (A)		35°C	65°C	65°C	60°C
Battery charge current (A)		5°C	5°C	5°C	1°C
Battery weight (g)		430.9	503.5	458.8	421
Battery volume (mL)		286.5	306.9	319.9	317.4
Battery Cost (€)		81.11	60.83	45.62	55.08
Battery Cost of mL (€/mL)		0.28	0.19	0.22	0.16
Battery Energy (Wh)		71.04	71.04	71.04	71.04
Battery Cost of Wh (€/Wh)		0.91	0.51	0.74	0.59

Table 2 presents four LiPo 4S batteries, each with a capacity of 6 Ah and the same nominal voltage. However, they vary in weight, which, as illustrated in Fig.3, can influence not only energy consumption but also factors such as cost Fig.5 and cost per milliliter Fig.6 cost per watt hour Fig. 7. Although all batteries share identical capacity and voltage specifications, they differ in terms of weight, volume, and energy density. Additionally, their lifespan may vary depending on the depth of discharge during operation.

Therefore, selecting the most appropriate battery requires careful consideration of key parameters such as weight, lifespan, and cost, to match the specific requirements of the UAV application.

As illustrated in Fig. 3, the LiPo 60C battery emerges as the lightest among the four, which may imply lower energy consumption. In contrast, Fig. 4 shows that the LiPo 35C battery has the smallest physical volume while maintaining the same energy capacity.

Moreover, Fig. 5 highlights significant differences in the cost of LiPo batteries, mainly influenced by their discharge rate and construction quality. As a result, battery cost becomes a critical factor in UAV design, as it can substantially

affect the total budget of the system and the overall economic viability of the mission.

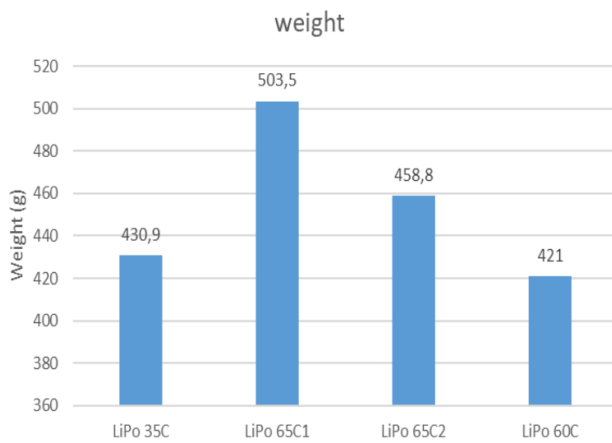


Figure 3: Sizing Results According to Weight

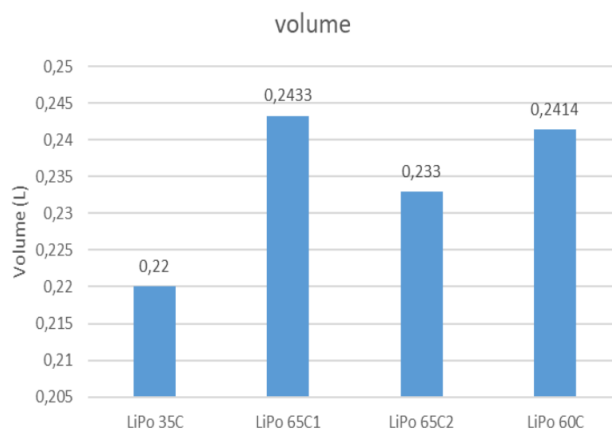


Figure 4: Sizing Results by Volume

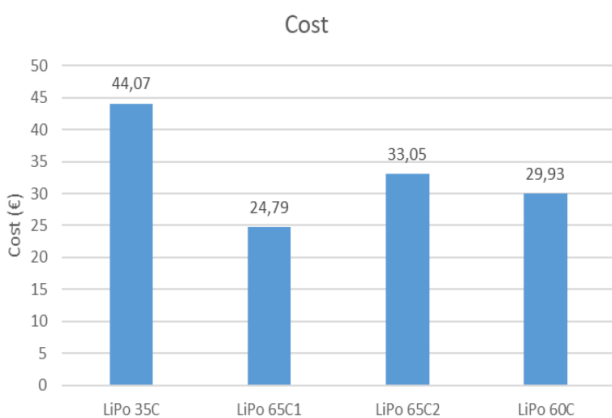


Figure 5: Effect of Cost on Sizing Results

Figure 8, Table 2 demonstrate that battery weight has a significant influence on the UAV's takeoff weight, which in turn affects both endurance and takeoff power. When a battery with higher energy density is used, the overall weight of the drone is reduced, leading to improved flight endurance. Conversely, an increase in takeoff weight results in higher

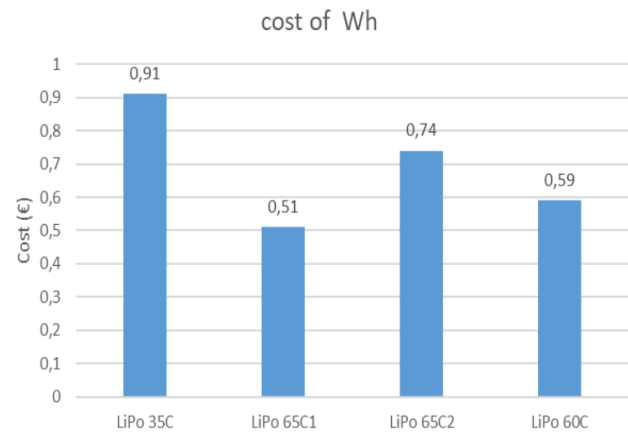


Figure 6: Variation of Sizing Cost per Watt hour Wh

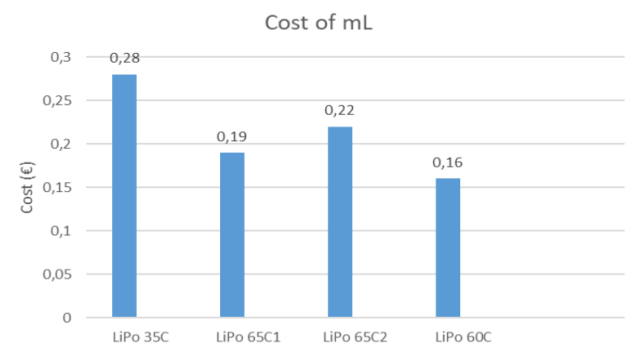


Figure 7: Variation of Sizing Cost per Milliliter mL

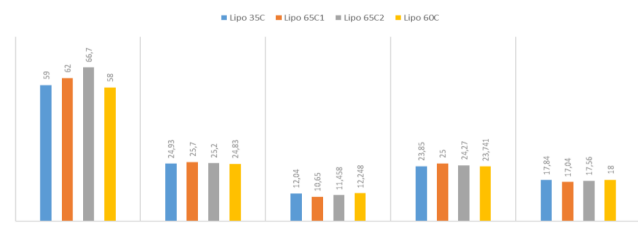


Figure 8: Block diagram of a UAV propulsion system

Table 3: Results of the 3D ROBOTICS Y6 HEXACOPTER drone with 4 different 6Ah LiPo 4S batteries at 80% with payload

Results	Li Po 35C	Li Po 65C1	Li Po 65C2	Li Po 60C
E(Wh)	71.04	71.04	71.04	71.04
M _e (Kg)	0.590	0.620	0.667	0.580
m _{tom} (Kg)	2.493	2.57	2.52	2.483
Se(Wh/Kg)	120.4	106.5	114.58	122.48
P _{tom} (W)	238.5	250	242.7	237.41
T (min)	17.84	17.04	17.56	18

takeoff power requirements, which can negatively impact the total flight duration. Therefore, optimizing battery selection is essential to balancing energy capacity, weight, and performance iations.

7. Conclusion

In conclusion, the selection of battery technology plays a critical role in determining the performance and flight characteristics of unmanned aerial vehicles (UAVs). Battery weight directly influences the overall mass of the UAV, which consequently impacts flight endurance and takeoff power requirements. Opting for a battery with higher energy density can reduce total weight and enhance endurance. However, this often involves a trade-off in terms of increased cost.

Furthermore, battery lifespan is affected by operational factors such as depth of discharge and usage patterns. Therefore, it is essential to align battery selection with the specific mission requirements and operational constraints of the UAV to ensure optimal performance and efficiency.

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