Mathematical Modeling of Photovoltaic Generation Applied to Unmanned Aerial Vehicles

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Abstract: The increasing use of Unmanned Aerial Vehicles (UAVs) in long endurance and range missions has intensified the demand for energy solutions capable of extending operational autonomy. Among the energy sources most employed, electrochemical batteries remain the predominant solution. However, the available energy depends on the energy density of these devices, meaning that extending autonomy requires the installation of additional units or higher-capacity batteries, resulting in a significant increase in aircraft mass. A complementary alternative consists of integrating photovoltaic cells into the UAV structure, operating in conjunction with batteries to partially provide the power demand of on-board systems and contribute to the recharging of the energy storage system during flight. In this context, this work presents a mathematical modeling approach based on the single-diode equivalent circuit to represent the electrical behavior of photovoltaic cells under varying irradiance conditions, enabling the estimation of solar generation potential considering the expected operational profile of the UAV. The results indicated an additional autonomy of 4 hours and 14 minutes in the most favorable irradiance scenario and 2 hours and 51 minutes in the least favorable scenario, corresponding to increments of 70.55% and 47.50%, respectively. The integration of the photovoltaic system added 575 g to the total aircraft mass, equivalent to 1.44%. The trade-off analysis between energy gain and mass impact demonstrated a favorable relationship, reinforcing the potential of on-board solar generation as a complementary strategy for UAV projects still in the early design phase, in which extending autonomy constitutes a design guideline and the feasibility of photovoltaic integration remains under evaluation.

Keywords: UAV. Solar Energy. Autonomy. Photovoltaic Cells. Mathematical Modeling.

1. Introduction

Applications of Unmanned Aerial Vehicles (UAVs) have become increasingly popular due to their versatility to operate in different types of missions, such as remote sensing, cargo transportation, search and rescue operations, military and agricultural activities. Among the challenges associated with these operations, one of them would be energy autonomy, which directly influences flight time and mission range [1].

Among the energy sources used to power on-board systems, electrochemical batteries are the most recurring solution [2]. The main limitation of these devices, in the context of UAVs, relates to their energy density, defined as the amount of energy stored per unit of mass or volume, so that extending autonomy requires the installation of additional batteries or batteries with a higher nominal capacity, which significantly increases the mass of the aircraft [3]. This restriction compromises the capacity for continuous energy supply during prolonged missions, imposing periodic interruptions for recharging or replacing the batteries, which negatively impacts logistical and economic efficiency in long-range missions that require greater energy autonomy [1].

Given this scenario, various studies have investigated the use of complementary energy sources as a strategy to reduce exclusive dependence on batteries and, consequently, increase the operational autonomy of UAVs [4].

Among the alternatives analyzed, the integration of photovoltaic systems into the structure of the aircraft has been considered, allowing the energy generated to act as an auxiliary source during flight, with the capacity to partially supply the energy demand of the on-board systems and contribute to the gradual recharging of the storage system [5], [6].

In this context, this work aims to analyze the contribution of on-board photovoltaic generation to partially recharge the storage system during flight, with a view to extending the UAVs autonomy. In addition, it analyzes the trade-off between additional autonomy and the mass impact of photovoltaic integration in UAV projects still in the early stages of development.

2. Methodology

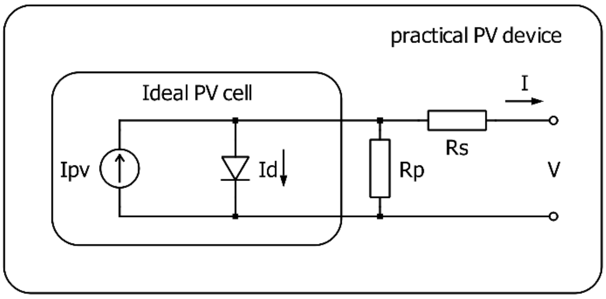
2.1 Mathematical modeling of a photovoltaic cell

The mathematical modeling of photovoltaic devices consists of formulating equations that describe the electrical behavior of the device, based on an equivalent circuit built to represent the main electrical characteristics associated with the conversion of solar energy into electrical energy. This modeling approach has been applied in computer simulations, in the development and evaluation of control strategies, in dynamic analysis of converters and in the study of Maximum Power Point Tracking (MPPT) algorithms [7].

The work by Treter *et al.* presented different photovoltaic models based on equivalent electrical circuits, classified according to the number of parameters that describe the device's characteristics [8]. Among the models, the single diode model stands out because it presents a favorable relationship between the accuracy in the representation of electrical behavior and the computational complexity associated with its implementation.

Figure 1 illustrates equivalent circuit of the single diode model. The circuit consists of a current source, a diode, an equivalent resistance in series (R_s) and an equivalent resistance in parallel (R_p).

Figure 1. Equivalent circuit of the single diode model.



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Equation (1) relates the model's output current and voltage, which was proposed by Wolf and Rauschenbach, and is described by [9]:

$$I = I_{pv} - I_0 \left[\exp\left(\frac{V + R_s I}{V_t a} \right) - 1 \right] - \frac{V + R_s I}{R_p} \quad (1)$$

Where:

I_{pv}: current generated by the incident light;

I_0: diode's leakage current;

a: diode's ideality constant ($1 \leq a \leq 1.5$);

V_t: thermal voltage.

The modeled expression to determine the current I_0, proposed by Souza, is expressed in Equation (2) [4].

$$I_0 = \frac{I_{sc,n} + K_I \Delta T}{\exp\left(\frac{V_{oc,n} + K_V \Delta T}{a V_t}\right) - 1} \quad (2)$$

Where:

$V_{oc,n}$: nominal open circuit voltage;

K_V: coefficient of variation of the voltage as a function of temperature.

The current I_{pv} varies linearly with the effective irradiance (G) and is influenced by the variation between the operating temperature and the nominal temperature, as seen in Equation (3) [10].

$$I_{pv} = \left(I_{pv,n} + K_I \Delta T\right)\frac{G}{G_n} \quad (3)$$

Where:

K_I: coefficient of variation of the current as a function of temperature.

The current generated by the incident light in nominal condition $I_{pv,n}$ is determined by the Equation (4) [10].

$$I_{pv,n} = \frac{R_p + R_s}{R_p} \cdot I_{sc,n} \quad (4)$$

Where:

$I_{sc,n}$: nominal short-circuit current.

The work by Villalva *et al.* proposed an iterative method for estimating the parameters R_s and R_p, assuming the existence of a specific pair capable of ensuring that the maximum power calculated from the model ($P_{max,m}$) equals the maximum experimental power given in the datasheet ($P_{max,e}$) [7]. This equality criterion, applied specifically at the point of maximum power (V_{mpp}, I_{mpp}), guided the adjustment of the parameters to minimize the error in representing the electrical behavior of the photovoltaic device under Standard Test Conditions (STC) [11]. According to this criterion, the maximum power calculated from the model is given by the following expression:

$$P_{max,m} = V_{mp}\left\{ I_{pv} - I_0\left[\exp\left(\frac{q(V_{mp} + R_s I_{mp})}{a N_s k T}\right) - 1\right] - \frac{V_{mp} + R_s I_{mp}}{R_p} \right\} = P_{max,e} \quad (5)$$

The combination of Equations (1) to (5) enables the computational implementation of the photovoltaic model, which represents the electrical behavior of the device under varying irradiance and temperature conditions, and provides a basis for quantitative analyses in simulation, system design, and performance evaluation of photovoltaic systems [12].

2.2 Correction of the area available for photovoltaic cell installation

Determining the area effectively available for integrating photovoltaic cells into the wing surface requires taking into account geometric constraints that reduce the useful surface in relation to the aerodynamic reference area (S_{ref}). To reflect these limitations, specific correction factors are applied: the leading-edge factor (CF_{LE}), the trailing-edge factor (CF_{TE}) and the span factor (CF_W) [5].

The correction factor applied to the leading edge takes into account the sharp curvature of this region, which makes it impossible to install photovoltaic cells properly due to the rigidity of the cells [6]. The correction factor applied to the trailing edge considers the need to preserve the operation of movable surfaces positioned at the rear end of the wing, such as ailerons and flaps, which act directly in controlling the aircraft [5]. Meanwhile the factor applied to the ends of the wingspan seeks to represent the safety zone, due to the susceptibility to structural deformations in flight and the installation of auxiliary components such as navigation lights and antennas [13]. These factors vary according to the geometric and functional characteristics of the aircraft.

Applying the correction factors in Equations (6) and (7) allows the average corrected wing chord (C_{PV}) and corrected wingspan (B_{PV}) to be calculated [5].

$$C_{PV} = \frac{100 - CF_{LE} - CF_{TE}}{100} - c \tag{6}$$

$$B_{PV} = \frac{100 - CF_{W}}{100} - b \tag{7}$$

Based on these corrected geometric parameters, Equation (8) makes it possible to determine the effective area available for the installation of photovoltaic cells (S_{PV}).

$$S_{PV} = C_{PV} - B_{PV} \tag{8}$$

3. Case study

The case study was based on a fixed-wing UAV with a combustion propulsion system. The on-board electronic systems include avionics (navigation, flight control and communication) and payload, powered by batteries. The UAV has a required autonomy of 6 hours, maintaining a constant energy consumption of 150Wh. To meet this demand, two Tattu Plus 22 Ah/22.2V LiPo batteries were used, with a mass of 5.3kg, as specified in the Gens Ace Tattu datasheet [14]. The main parameters of the UAV used in this study are shown in Table 1.

Table 1. UAV data.

Parameter	Symbology	Value
Maximum take-off weight (N)	W_{TO}	40
Wingspan (m)	b	4.660
Average wing chord (m)	c	0.358
Wing area (m^2)	S_{ref}	1.668

In this study, the mathematical modeling of the photovoltaic cell was proposed with a view to estimating energy generation under a given operating profile, considering the application in battery recharging. To determine the model parameters, the iterative method proposed by Villalva *et al.* was implemented in MATLAB, which enabled the resistances R_s and R_p to be obtained [7].

The photovoltaic cells were installed on the surface of the wing, respecting the geometric limitations of the structure. The wing's reference area was corrected by application of the factors CF_{LE} = 15%, CF_{TE} = 10% and CF_W = 18%, resulting in an effective area of 1.03m². For this application, SunPower C60 monocrystalline silicon photovoltaic cells were selected. The main electrical characteristics of the cell are presented in Table 2, according to the specifications provided in the PV cell C60 datasheet [15].

Table 2. Photovoltaic cell data.

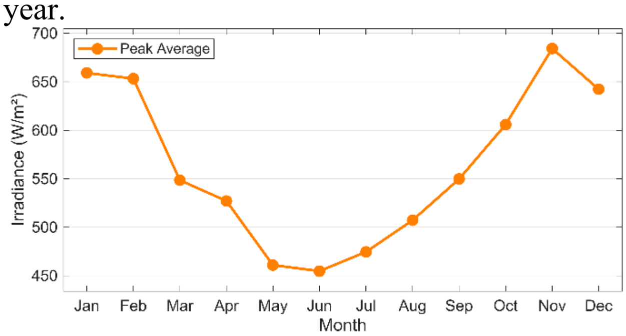
P_{mpp} (W_p)	$Eff.$ (%)	V_{mpp} (V)	I_{mpp} (A)	V_{oc} (V)	I_{sc} (A)
3.42	22.5	0.58	5.93	0.68	6.28

The photovoltaic cell has a K_V of -1.8mV/°C and a K_I of - 0.32%/°C, with a mass equivalent to 6.5g, as also described in the C60 cell datasheet. A photovoltaic array consisting of 60 cells was defined, distributed in the 30S2P configuration.

The connection between the photovoltaic array and the batteries was implemented by means of an MPPT charge controller, model Genasun GVB-8-Li-25.0V, with a reported mass of 185g, according to Genasun's product specifications [16].

The energy generated over time was estimated based on the Direct Normal Irradiance (DNI) for the year 2024, considering the operating site located in the city of Salvador, Bahia. The irradiance data was obtained from the Global Solar Atlas platform [17]. For the analysis, we considered the monthly average of daily irradiance during the period of highest solar incidence, between 10:00 AM and 03:00 PM, as illustrated in Figure 2.

Figure 2. Average peak irradiance throughout the year.



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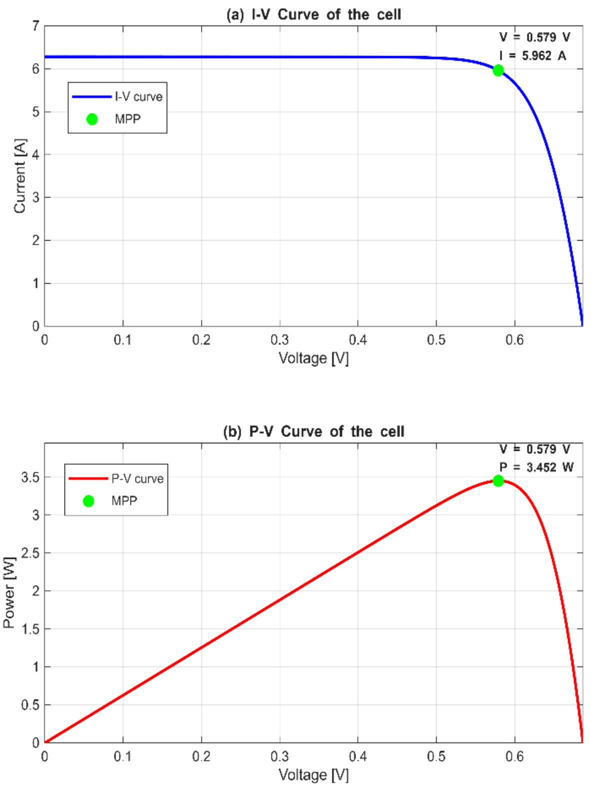
Although as known that the continuous movement of the UAV implies variations in the angle of incidence of solar radiation, irradiance and cell temperature, the profile shown in Figure 2 was adopted as an approximation of the irradiance conditions to which the UAV would be exposed during operation. This approach was compatible with the exploratory nature of the study and could be improved in future work to more faithfully represent dynamic operating conditions.

4. Results and Discussions

The mathematical modeling strategy implemented resulted in the estimation of the electrical parameters of the photovoltaic cell that allowed the MPP to be reproduced. The result was $R_s = 0.003535\Omega$, $R_P = 5.407216\ \Omega$ and $a = 1$. Figure 3 shows the simulated I-V and P-V characteristic curves with the parameters obtained. The maximum power point was reproduced with $V_{mpp} = 0.579$V, $I_{mpp} = 5.962$A and $P_{mpp} = 3.452$W. These values are close to the data supplied by the manufacturer, as shown in Table 2, with a relative error of less than 1%. This result reinforces that the mathematical modeling of the C60 photovoltaic cell implemented was able to represent the cell's electrical behavior with satisfactory accuracy under STC, set at 1000W/m² and 25°C.

Figure 3. I-V and P-V characteristic curves of the photovoltaic cell.



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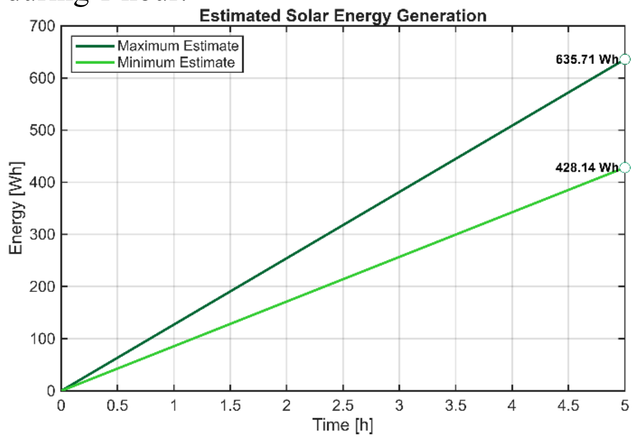
The mathematical modeling implemented made it possible to estimate the daily power generated by the photovoltaic cell under different irradiance conditions. As illustrated in Figure 2, the maximum and minimum monthly average daily irradiance values occurred in November (684.4W/m²) and June (461.0W/m²), respectively. These conditions were incorporated into the modeling, resulting in an estimate of the power generated by a photovoltaic cell, with $P_{(mpp,max)} = 2.493$W and $P_{(mpp,min)} = 1.679$W.

Figure 4 shows the estimated daily solar energy generated over 5 hours. Under these conditions, the maximum estimated generation was 635.71Wh and the minimum 428.14Wh, considering the system performance of 85% to take into account the losses associated with tracking the MPP and the variations in temperature and irradiance over time.

Figure 4. Estimated solar energy generated during 1 hour.



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Based on the estimate of the daily energy generated by the arrangement, it was possible to quantify the contribution of solar generation to the battery recharging system during the flight. In the simulated maximum and minimum irradiance scenarios, the estimated additional autonomy was 4 hours and 14 minutes, and 2 hours and 51 minutes, respectively. These results correspond to maximum and minimum increases of 70.55% and 47.50% in the autonomy of the aircraft.

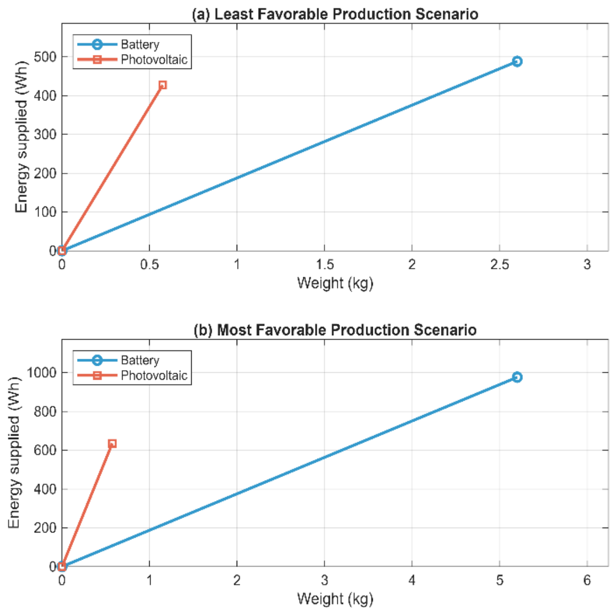
The insertion of the photovoltaic array showed considerable potential for extending the UAVs operational autonomy. However, the precise quantification of this extension requires the consideration of a more dynamic operational profile, incorporating variables such as flight path, altitude and environmental conditions. Due to the exploratory nature of this study, the estimate of additional autonomy presented should be interpreted as preliminary, and may be progressively refined in subsequent analyses by incorporating more representative operational mission scenarios, including these variables.

It should be noted that the UAV considered in this study was used exclusively as a reference for the trade-off analysis between additional autonomy and the mass impact of photovoltaic integration. The adoption of on-board solar generation requires the architecture of the aircraft to be designed to accommodate the associated structural, aerodynamic and balancing constraints. In this sense, the obtained results regarding autonomy extension provide quantitative support for UAV projects still in the initial design phase, in which extending operational autonomy constitutes a design guideline and the feasibility of solar energy integration remains under evaluation.

The additional mass introduced by the photovoltaic system must be carefully evaluated, given that mass represents a highly sensitive design variable in unmanned aircrafts. In the configuration adopted, the integration of the system resulted in an increase of 575g, corresponding to approximately 1.44% of the UAV weight. Although this percentage may seem small, it represents a significant fraction in the context of aeronautical design, where minimal variations in mass can directly impact the aircraft's performance.

Figure (5) shows the relationship between energy supplied and mass impact, comparing the battery-only configuration with the hybrid configuration consisting of batteries and a photovoltaic system. The results indicate that photovoltaic integration allows the UAVs autonomy to be extended with a smaller increase in mass, since to achieve the same length of autonomy with batteries alone, it would be necessary to install one or two additional units, depending on the irradiance scenario evaluated. Alternatively, replacing the battery considered in the case study with one with a higher nominal capacity would also result in a greater increase in mass compared to the photovoltaic system.

Figure 5. Relationship between energy supplied and mass impact.



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5. Conclusion

The insertion of on-board solar generation proved to be a viable solution for considerably extending the UAVs energy autonomy. The analysis of the trade-off between the increase in mass and the associated energy gain indicated a favorable relationship, reinforcing the potential of photovoltaic integration as a complementary solution in prolonged missions, especially in UAV projects still in the initial design phase, in which the architecture of the aircraft can be adapted to accommodate the incorporation of the photovoltaic system.

The objectives of this work were achieved within the established limitations, and, as prospects for continuity, with highlight on the incorporation of operational scenarios that consider variables such as flight altitude, flight path and environmental conditions throughout the flight. Additionally, technical-structural feasibility analyses should be conducted to evaluate the integration of the photovoltaic system in UAVs during early design stages, allowing the aeronautical project to accommodate such integration, as well as in to existing UAVs of similar class and size.

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