

Determination of solar UAV design parameters for continuous flight with minimum power consumption by ABC algorithm based

Emin Tugay Kecec

Aircraft Technology, Cappadocia Vocational College, Cappadocia University, Nevşehir, Turkey, and Aircraft Electrical and Electronics, Graduate School of Natural and Applied Sciences, Erciyes University, Kayseri, Turkey

Mehmet Konar

Department of Aircraft Electrical and Electronics, Faculty of Aeronautics and Astronautics, Erciyes University, Kayseri, Turkey

Mustafa Samet Gencag

Aircraft Technology, Cappadocia Vocational College, Cappadocia University, Nevşehir, Turkey, and Aeronautical Electrical and Electronics, Graduate School of Natural and Applied Sciences, Erciyes University, Kayseri, Turkey, and

Fatma Yildirim Dalkiran

Department of Aircraft Electrical and Electronics, Faculty of Aeronautics and Astronautics, Erciyes University, Kayseri, Turkey

Abstract

Purpose – The purpose of this study is to introduce an innovative approach that uses the artificial bee colony (ABC) algorithm to optimize the wingspan, aspect ratio (AR) and mass estimation, which constitute the most critical design variables for the low altitude long endurance (LALE) class solar unmanned aerial vehicle (UAV).

Design/methodology/approach – In this study, upper and lower limits are established to encompass the design parameters from prior solar UAV studies. A novel model is proposed to minimize the required power using the ABC algorithm, considering iterative and simultaneous calculations of wingspan, AR and mass. Wingspan, AR and mass are treated as input parameters, with the required power (P_{req}) designated as the output parameter. The objective is to ascertain the minimum output parameter for the optimal input parameters.

Findings – Improvements have been made by determining the input parameters with the ABC algorithm-based model in order for the LALE class solar UAV to fly continuously every day with minimum required power.

Research limitations/implications – In solar UAV designs, wingspan, AR and mass are directly interrelated design variables. In this study, all input parameters are considered equally important for achieving the minimum required power output.

Practical implications – Artificial intelligence techniques can be used swiftly, simply and effectively to maximize flight endurance, the paramount objective in solar UAV designs. Simulation studies using the ABC algorithm-based model yield satisfactory results. Future technological advancements, such as improvements in battery and solar cell efficiency, will allow for practical predictions of their impact on UAV flight time and endurance.

Social implications – The results obtained in this study indicate that the proposed method can serve as a practical tool for solar UAV designers in determining the most critical design parameters.

Originality/value – The LALE class provides a novel, fast, solvable and cost-effective model for determining the fundamental design parameters that iteratively change in solar UAV designs, thereby enabling continuous flight with optimal power consumption.

Keywords Solar powered UAVs, Artificial intelligence, Optimization, Heuristic algorithms, Solar UAV conceptual design, ABC algorithm

Paper type Research paper

Nomenclature

Symbols

Symbol Definition Dimension

S = Wing area m^2 ;
 P_{req} = Required power W ;

b = Wing span m ;
 c = Wing chord m ;
 AR = Aspect ratio $[-]$;
 L = Lift N ;
 ρ = The air density Kg/m^3 ;
 C_L = Lift coefficient $[-]$;
 V = UAV speed $m.s^{-1}$;

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Aircraft Engineering and Aerospace Technology
© Emerald Publishing Limited [ISSN 1748-8842]
[DOI 10.1108/AEAT-11-2024-0312]

This work was supported by Research Fund of Erciyes University Scientific Research Projects (BAP) Coordination Unit under Project Number: FDK-2024-13270.

Received 4 November 2024
Revised 21 January 2025
27 March 2025
Accepted 30 March 2025

C_D	= Drag coefficient $_{[]}$;
c_d	= Profile drag $_{[]}$;
C_{Di}	= Induced drag $_{[]}$;
e	= Oswald efficiency factor $_{[]}$;
m_{total}	= UAV total mass kg;
g	= Gravitational force $m.s^{-2}$;
T	= Thrust force N;
D	= Drag N;
$P_{elec\ tot}$	= Required electrical power W;
$E_{elec\ tot}$	= Required electrical energy J;
I_{max}	= Total solar energy W/m ² ;
k_{bat}	= Lithium ion battery energy density J/kg;
k_{sc}	= Solar cell mass density kg/m ² ;
k_{enc}	= Encapsulation efficiency kg/m ² ;
k_{strct}	= Structure mass prediction constant kg/m ³ ;
$m_{avionics}$	= Avionics mass kg;
P_{av}	= Power required for avionics W;
η_{bec}	= BEC efficiency-;
η_{sc}	= Solar cell efficiency-;
η_{cbr}	= Losses due to airfoil-;
η_{chrg}	= Battery charging efficiency-;
η_{ESC}	= ESC efficiency-;
η_{dchrg}	= Battery discharge efficiency-;
η_{grb}	= Gearbox efficiency-;
η_{mot}	= Motor efficiency-;
η_{mppt}	= MPPT efficiency-;
η_{prl}	= Propeller efficiency-;
m_{pld}	= Payload weight kg;
η_{wthr}	= Sky factor-;
P_{pld}	= Power consumed by the payload W;
T_{day}	= Day time length sn;
T_{night}	= Nighttime length sn;
$E_{daydensity}$	= Solar energy density W/m ² ;
$E_{total\ gen}$	= Generated solar energy W;
A_{sc}	= Solar cell area m ² ;
m_{fixed}	= Fixed mass kg;
$m_{solarcells}$	= Solar cell mass kg;
m_{bat}	= Battery mass kg;
m_{strct}	= Structure mass kg;
$m_{propulsion}$	= Propulsion mass kg; and
$m_{payload}$	= Payload mass kg.

Abbreviations

Abbreviation Definition

ABC	= Artificial Bee Colony;
ESC	= Electronic Speed Control;
LiPo	= Lithium Polymer;
AR	= Aspect Ratio;
UAV	= Unmanned Air Vehicle;
LALE	= Low Altitude Long Endurance;
HALE	= High Altitude Long Endurance;
MPPT	= Maximum Power Point Tracker; and
Li-Ion	= Lithium Ion.

Introduction

Increased consumption of carbon-containing fuel worldwide has occurred to climate change on a global scale. To mitigate this issue, various measures have been implemented, such as the promotion of renewable energy solutions (Saboochi and

Karimi, 2022). The solar energy is the most preferred renewable energy source. Although the idea of using solar energy was introduced in the 19th century, it has been used in many different fields in recent years with the production of more efficient solar panels. One of these fields is aviation. The idea of flying by using solar energy has dated back several decades (Noth, 2008). First, the first flight of a solar-powered aircraft, named Sunrise 1, transpired on November 4, 1974, at a dry lake in Camp Irwin, CA. On December 19, 1978, David Williams and Fred to achieved a significant milestone in this realm, covering a distance of 1.2 km aboard the Solar One, which featured a glider-like configuration (Rajendran and Smith, 2018).

Following major solar-powered unmanned aerial vehicle (UAV) projects such as the Solar Challenger, AeroVironment Inc. received funding from the US Government to explore the class of high altitude long endurance (HALE) solar projects. The first prototype project, named HALSOL was implemented in 1983 (Bakar et al., 2021). Many aircraft with variable wing spans and different configurations have been developed and manufactured for the solar UAV. Especially since the 2000s, due to improvements of high-efficiency batteries and solar cells, the popularity of mini and medium-sized experimental aircrafts has increased. Thus, researches into solar UAVs, which offer longer flight time and range guarantees at smaller scales, have developed rapidly and have been produced and tested in different concepts (Konar and Kekec, 2021). An example of these studies is the solar UAV named Solong, with a wingspan of 4.75 m, which flew for 48 h on June 1, 2005, enduring two consecutive nights in the air before landing successfully with half-filled batteries (Sri et al., 2016). Key contributors to Solong's success included solar cells with 20% efficiency, highly efficient engines and enhanced battery performance. In addition, Solong leveraged indirect solar energy utilization by exploiting thermal air currents under the guidance of experienced pilots. By harnessing thermal air currents generated from disparate thermal zones resulting from solar energy absorption by the Earth's surface, Solong could sustain flight without expending additional energy, thereby maximizing UAV endurance levels (Ahn and Ahn, 2019).

Solar-powered UAVs typically consist of solar cells placed on both the fuselage and wings, batteries capable of storing the energy generated by these cells, and efficient propulsion systems (Karaburun et al., 2024). Some of the studies in the literature have focused on quantifying solar radiation and the energy obtainable and storable during daylight hours (Bakar et al., 2021; Sri et al., 2016). Moreover, various studies have been conducted to develop sustainable and cost-effective UAVs, leveraging advancements in solar cell efficiency, battery technologies, Maximum Power Point Tracker (MPPT) systems and propulsion systems (Chu et al., 2021; El-Atab et al., 2021; Noth, 2008). There are also studies in the literature concerning mass estimation, UAV size optimization, energy management systems, factors influencing UAV performance and the analysis thereof (Betancourth et al., 2016; da Silva and Pacheco, 2021; Jashnani et al., 2013; Oettershagen, 2018). Studies have been conducted to demonstrate the importance of aspect ratio (AR) in the design of solar UAVs by simulating different models in MATLAB/Simulink. According to simulation results, a UAV with a high AR is capable of flying for

11 h, while a UAV with a medium AR can achieve 10 h of flight (Golmakani *et al.*, 2024). (Golmakani *et al.*, 2024).

In some studies, the impact of solar incidence angle and solar radiation, calculated for a predetermined flight duration based on specific geographic coordinates, on the performance of UAVs has been investigated (Leutenegger *et al.*, 2011). Furthermore, in the proposed studies it has been indicated that a limited number of parameters are included during the design process within UAV design methodologies (de Carvalho Bertoli *et al.*, 2015; Konar *et al.*, 2024; Arik *et al.*, 2018). In addition, some studies have analyzed a limited number of airfoils for UAV airfoil selection, which is one of the important design criteria (da Silva and Pacheco, 2021; Leutenegger *et al.*, 2011; Ünler and Seyfi, 2022; Ünler, 2024; Panagiotou *et al.*, 2016).

However, the development of low altitude long endurance (LALE) class of UAV systems may appear very simple, low-altitude meteorological conditions can significantly influence the performance of energy storage systems. These conditions should be taken into consideration during the design process (Rajendran and Smith, 2018). In this study, the conceptual design of a LALE class UAV predicated on solar energy analysis, aimed at achieving continuous flight over 24 h every other day throughout a two-month summer period characterized by peak daily insolation levels has been presented. The modeling of continuous flight every other day for the UAV design, including required power analysis, mass estimation methods and the parameters of efficient Li-Ion batteries and solar cells available in the market, has been performed. First, in this context, the conceptual design phase for a solar-powered UAV is explained in detail. The wing span, AR and mass for the proposed UAV are optimized with the artificial bee colony (ABC) algorithm. The city of Kayseri, located at an average altitude of 1,050 m with continental climate conditions, is selected as the designated flight region, with solar energy metrics calculated accordingly. Subsequently, an assessment of UAV performance is undertaken. In addition, the increasing importance of UAV projects designed using alternative energy systems and information that can be subject to future studies have been presented in the study.

Methodology

In the solar UAV design process, two different methodologies have been observed in the literature. In the first approach, the design process starts with a detailed calculation of the required power (Preq) for the UAV during level flight. Variables such as engine, solar cell and battery parameters should be specified at the outset. Then, sizing is conducted by factoring in parameters including total mass estimation and wingspan to compare the power generated by solar cells with the power required for level flight. Through an iterative process, various combinations of selected equipment and parameters are assessed until the desired flight endurance is achieved (Karaburun *et al.*, 2024).

In the second approach, the system is considered as a whole and all components are individually modeled, and their interrelations are established through analytical equations. This approach is more advantageous for finding the optimum design. Parameters such as power required for level flight, daily and hourly solar radiation models for specific regions and

weight estimation methods are interrelated. Optimum results can be obtained more precisely with the help of graphs.

In this study, the design of a LALE class solar UAV for continuous flight during the summer months when sunlight duration peaks for two months in Kayseri, Türkiye, under continental climate conditions is realized. By optimizing the design parameters using the ABC algorithm, the most suitable wingspan and wing AR have been determined. In addition, the study includes comparative analyses of Li-Ion batteries and solar cells available in the market and accessible to end-users. Therefore, in this study the solar UAV, wing aerodynamics, required power and energy calculations, solar irradiance modeling, solar cell characteristics, mass estimation methodology and the ABC algorithm are discussed, respectively.

Solar unmanned aerial vehicles

The operational principles of a solar-powered LALE class UAV are explained. Similar to conventional aircraft, the weight of the UAV and the carrying force on the wing are equal to each other during constant level flight for solar-powered UAV systems. In addition, the thrust generated by the engine and propeller is considered equal to the total drag (Noth, 2008).

Solar cells, generally positioned on the UAV, are typically integrated into the wing, fuselage and horizontal stabilizer. However, when considering conventional aircraft design, the wing typically offers the largest surface area compared to other components, making it the most common location for solar cell integration in the literature. Solar cells possess the capability to directly convert daylight and sunlight into electrical energy. However, due to the dynamic positioning of sunlight and the continuously changing angles of the panels, the electrical energy produced demonstrates considerable variability, depending on a number of parameters. To mitigate this variability, MPPT technology is commonly used in all projects using solar panels (Oettershagen, 2018).

Aerodynamics of a wing

The wing design methodology used for UAVs aligns with conventional aircraft design principles. However, the solar UAV design process entails distinct considerations. Throughout the entirety of the design phase, particular attention is dedicated to integrating solar cells onto the wings. Profile selection must meticulously account for the airfoil hump, along with considerations of lift and drag coefficients (Chu *et al.*, 2021). Excessive airfoil humps can lead to inclined placement of solar cells, consequently reducing energy production (Sri *et al.*, 2016).

Wing area for rectangular wing type:

$$S = b.c \quad (1)$$

Where b is the wing length and c is the chord length. AR is:

$$AR = \frac{b}{c} \quad (2)$$

The lift force acting on the wing is directly influenced by the characteristics of the airfoil. Thus, when considering lift and drag:

$$L = \frac{\rho}{2} C_L S V^2 \quad (3)$$

$$D = \frac{\rho}{2} C_D S V^2 \quad (4)$$

In [equation \(3\)](#), L represents the lift force, D is the drag force, C_L is the lift coefficient, C_D is the drag coefficient, ρ is the air density ($kg.m^{-3}$), S is the wing surface area (m^2) and V is the cruise speed of the UAV ($m.s^{-1}$). The values of C_L and C_D are highly dependent on the airfoil, angle of attack and Reynolds number, which represents the viscosity of the airflow. The drag coefficient C_D for the wing is equal to the sum of the induced drag C_{Di} generated by the wingtip vortices and the airfoil drag c_d as shown in [equation \(5\)](#):

$$C_D = c_d + C_{Di} \quad (5)$$

The induced drag coefficient can be calculated as shown in [equation \(6\)](#):

$$C_{Di} = \frac{C_L^2}{\pi * e * AR} \quad (6)$$

Profile drag can be obtained from airfoil data for the desired angle of attack. Induced drag is a function of the coefficient of drag (C_{Di}), AR and Oswald efficiency factor (e). In [equation \(6\)](#), e represents the Oswald efficiency factor, which is also known as the wingspan efficiency factor. This factor has a value between 0 and 1 ([Jashnani et al., 2013](#)). The Oswald efficiency factor (e) is accepted between 0.85 and 0.95 in the analyzed studies. For this wing design, the value $e \cong 0.90$ will be used for the Oswald efficiency factor.

Calculating the power and energy required in the level flight phase of a solar unmanned aerial vehicle

The power consumption required in the level flight phase of the solar UAV depends on many parameters. It is important to consider these parameters carefully and analyze the relationships between them. Therefore, in this section the equations of the parameters that are important for the power consumption are analyzed in detail. Variables such as weight, transport, drag, thrust and speed are considered in the analysis. The weight of the UAV is shown in [equation \(7\)](#) as the product of mass and gravitational acceleration. In the equation, W is the weight, m_{total} is the mass of the UAV in kilograms (kg) and g is the gravitational acceleration ([Sri et al., 2016](#)):

$$W_{total} = m_{total} \cdot g \quad (7)$$

The lift force is shown in [equation \(3\)](#). In a stable and level flight at a constant altitude, the support force to be generated by the wings is equal to the weight of the UAV, whereas the thrust is equal to the drag force. From [equations \(3\)](#) and (7), [equations \(8\)](#) and (9) can be constructed:

$$m_{total} \cdot g = \frac{\rho}{2} C_L S V^2 \quad (8)$$

$$V = \sqrt{\frac{2 \cdot m_{total} \cdot g}{C_L \rho S}} \quad (9)$$

The relationship between thrust and drag is shown in [equation \(10\)](#):

$$T = D = \frac{\rho}{2} C_D S V^2 \quad (10)$$

where D is the drag force, T is the thrust force and C_D is the drag coefficient. The drag coefficient is the sum of the airfoil drag coefficient c_d and the induced drag C_{Di} as shown in [equation \(6\)](#). The induced drag can be calculated from [equation \(6\)](#). The power required for level flight, P_{req} is given by [equation \(11\)](#):

$$P_{req} = T \times V \quad (11)$$

Using [equations \(9\)](#) and (10), the power required for level flight can be expressed as shown in [equation \(12\)](#):

$$P_{req} = T \times V = \frac{C_D}{C_L} \sqrt{\frac{(m_{total} \cdot g)^3}{S}} \sqrt{\frac{2}{\rho}} \quad (12)$$

S , the surface area, and AR , the aspect ratio, given in [equation \(12\)](#), can be adjusted. In this way, the power required for level flight in [equation \(13\)](#) can be calculated differently:

$$P_{req} = T \times V = \frac{C_D}{C_L} \sqrt{\frac{2ARg^3 m_{total}^3}{\rho b}} \quad (13)$$

Given the efficiency of the various components of the propulsion system, the electrical power required for constant level flight is determined as shown in [equation \(14\)](#):

$$P_{elec \ tot} = \frac{1}{\eta_{ESC} \eta_{mot} \eta_{grb} \eta_{prl}} P_{req} + \frac{1}{\eta_{bec}} (P_{av} + P_{pld}) \quad (14)$$

η_{prl} stands for propeller efficiency, η_{mot} for motor efficiency, η_{grb} for gearbox efficiency and η_{ESC} for electronic speed controller (ESC) efficiency. P_{av} is the power required for avionics and P_{pld} is the power required for payload. In addition, if the power required for avionics and payload is provided by the battery elimination circuit (BEC), the efficiency η_{bec} should also be taken into account. [Equation \(15\)](#) shows the electrical energy consumption ($E_{electot}$):

$$E_{elec \ tot} = P_{elec \ tot} \left(T_{day} + \frac{T_{night}}{\eta_{chg} \eta_{dchg}} \right) \quad (15)$$

The charging and discharging efficiency of the battery during the night is given by η_{chg} , η_{dchg} , respectively. T_{day} stands for daytime and T_{night} for nighttime.

Solar irradiance model

The amount of energy that solar-powered UAVs can generate depends on many parameters. The location, day and time of the flight are very important parameters. In this section,

an understandable methodology of the electrical power parameters to be obtained from solar energy is presented with some equations. The daily solar energy per square meter, depending on the location and time, can be calculated by equation (16):

$$E_{day\ density} = \frac{I_{max} T_{day}}{\pi/2} \eta_{wthr} \quad (16)$$

where I_{max} is the maximum irradiance and η_{wthr} is the sky factor, which symbolizes the blocking of the sun in the sky due to cloud cover and other factors. The total electrical energy that can be produced can be calculated using equation (17):

$$E_{total\ gen} = E_{day\ density} * A_{sc} * \eta_{sc} * \eta_{cbr} * \eta_{mppt} \quad (17)$$

where A_{sc} is the solar cell area, η_{sc} is the solar cell efficiency, η_{cbr} is the reduced efficiency due to the camber ratio, η_{mppt} is the MPPT efficiency. T_{day} represents the average daily sunshine hours, which can be obtained by analyzing data from local meteorological stations.

Solar cell

Solar cells are emerging as crucial components for the capture and conversion of solar energy, facilitating the seamless transformation of sunlight into electricity in a sustainable and enduring manner. These cells have been successfully used in both space and aviation for many years. Solar cells, mostly made of semiconductors such as silicon, offer a combination of wide availability and cost-effectiveness. The photovoltaic industry is comprised a multitude of solar cell types, which are classified according to the materials used in their construction and the manufacturing processes used. Among these, silicon cells stand out as the most preferred option due to their affordability and accessibility. They are further classified into three categories based on crystal type: monocrystalline silicon cells, characterized by high efficiency (20–24%) due to their use of pure semiconductors; polycrystalline cells, which offer a more cost-effective but exhibit relatively lower efficiency (11–16%); and amorphous silicon cells, distinguished by their eco-friendly composition free of toxic heavy metals but with lower efficiency. Although alternative materials like gallium arsenide and copper indium diselenide could be more efficient, they are too expensive to produce.

Mass model

The estimation of weight has a direct impact on the cost and performance of a UAV and, thus, represents a crucial aspect of the design process. Currently, there is a considerable number of solar UAVs in active use. However, it is challenging to identify a weight estimation model that is applicable to all of these UAVs. It is evident that there are insufficient studies on solar UAV weight estimation models in the literature. There are two distinct classes for weight estimation: finite element, empirical and semiempirical methods. Finite element weight estimation is a specialized estimation method for each aircraft. Empirical methods are used to estimate the weights of main components, such as the UAV fuselage and wing, using curves and equations that combine geometric shape, speed, load and statistically generated coefficients. Semiempirical methods consist of

statistically derived equations obtained by analyzing past data. As these equations can be applied more easily than other methods, they provide sufficient results for the mass estimation required in the UAV conceptual design phase. In this study, the semiempirical weight estimation method will be used to calculate the UAV's total take-off mass (Karaburun *et al.*, 2025), as given by equation (18) (da Silva and Pacheco, 2021):

$$m_{total} = m_{fixed} + m_{solarcells} + m_{bat} + m_{strct} + m_{propulsion} \quad (18)$$

where m_{fixed} denotes the fixed mass component of the UAV, which remains constant and is independent of other main component dimensions, such as AR as shown in equation (19). This fixed mass component typically includes essential elements like the flight control card, MPPT, payload and other predetermined components specified at the initial stages of the design process:

$$m_{fixed} = m_{payload} + m_{avionics} \quad (19)$$

$m_{payload}$ is the mass of the payload and $m_{avionics}$ is the mass of the avionics. $m_{solarcells}$ is the mass of the solar cells, as shown in equation (20):

$$m_{solarcells} = A_{sc} * k_{sc} * k_{enc} \quad (20)$$

where k_{sc} is the surface density of the solar cell, and k_{enc} is the constant representing the weight fraction of the encapsulation of the solar panel with a value less than 1. k_{bat} represents Lithium-ion battery energy density. m_{bat} is the weight of the energy storage system. m_{bat} is directly proportional to the energy to be stored in the battery and inversely proportional to the gravimetric energy density, as given in equation (21):

$$m_{bat} = \frac{T_{flight}}{\eta_{dchrg} k_{bat}} P_{elec\ tot} \quad (21)$$

Estimating the weight of the UAV structure is a highly complex and challenging task. There are several methods for estimating the structure weight in the literature. In this study, Noth's method is used, which is one of the most extensively developed methods. In his study, Noth proposed a comprehensive empirical model that included a total of 415 different manned and unmanned RC models of various sizes and characteristics. The weight of the UAV structure has been estimated using equation (22) (Noth, 2008):

$$m_{strct} = k_{strct} b^{x1} AR^{x2} \quad (22)$$

AR is the aspect ratio and k_{strct} , $x1$ and $x2$ are constants that vary according to the construction quality of the aircraft (Noth, 2008). For UAV systems designed in the LALE class, hand-launched take-off is the most frequently used method. Landing gear is typically avoided as it adds to the weight and drag of the UAV. Hence, the design aims to facilitate hand-launched as well as landing on the fuselage. However, it is worth noting that UAVs relying on hand-launch require higher engine power during take-off compared to models using a runway for take-off. Consequently, it is imperative to consider a propulsion system capable of delivering the requisite power for hand-launch take-off during the design phase.

In this study, equation (23), proposed by Noth, was used to account for the effect of the propulsion system on the total weight of the UAV. This equation encompasses the contributions of the engine, ESC and propeller, offering a comprehensive assessment of the propulsion system's impact on the UAV's overall weight:

$$m_{propulsion} = 0,008 * P_{req} \quad (23)$$

Once the estimated total weight has been calculated, if it exceeds the previously assumed weight, this value is updated, and the power required for constant level flight must be recalculated.

Artificial bee colony algorithm

The ABC algorithm, inspired by the foraging behavior of honeybees, was introduced by Karaboğa and has demonstrated notable efficacy in addressing various optimization challenges documented in the literature. The algorithm harnesses swarm intelligence principles to navigate solution spaces effectively (Karaboga and Basturk, 2007). The decision to use the ABC algorithm in this study was driven by its proven track record of delivering optimal outcomes across a range of problem domains.

In the ABC algorithm, bees are categorized into different groups: foraging, scout and explorer bees. Foraging bees, also known as worker bees, are tasked with spreading information among other bees and collecting nectar from food sources. Scout bees assimilate information provided by the foraging bees to identify high-quality food sources. Explorer bees, meanwhile, engage in random exploration for food sources and transition into task bees upon discovering a viable food source (Karaboga and Akay, 2009; Karaboga and Basturk, 2007).

During the modeling of the ABC algorithm for problem-solving, some simplifications were adopted. Firstly, the number of worker bees was equated with the number of food sources to facilitate exclusive nectar collection by individual worker bees. In addition, the number of worker bees was assumed to equal the number of scout bees. The initialization of the ABC algorithm entails randomly generating the initial population, as facilitated by equation (24) (Karaboga and Akay, 2009; Karaboga and Basturk, 2007; Konar, 2020):

$$x_{ij} = x_{min}^j + rand[0, 1] \left(x_{max}^j - x_{min}^j \right) \quad (24)$$

In equation (24), x_{ij} denotes a solution for the population. $i = \{1, 2, \dots, SN\}$, $j = \{1, 2, \dots, D\}$, where SN is the population size and D is the number of parameters to be optimized. x_{max}^j and x_{min}^j denote the lower and upper limits of the variables (Karaboga and Basturk, 2007). In the MATLAB problem optimization based on the ABC algorithm, the colony size, boundary value and maximum iteration value are the control parameters. One of the most important aspects when optimizing with the ABC algorithm is determining appropriate bounds. This ensures that effective solutions can be achieved.

Simulation results

In this study, the optimization of required mechanical power, electrical power, wingspan, mass and AR for a LALE class solar UAV design is undertaken by using scientific equations and the

ABC algorithm. The ranges for wingspan (4–7 m), AR (AR, 10–20) and mass (2–7 kg) used in this study were determined by considering the values recommended in the literature for LALE-class UAVs. The wingspan was optimized to increase carrying capacity while minimizing power consumption (Bakar et al., 2021). The AR was selected to improve aerodynamic performance while maintaining structural integrity, with the chosen values supported by the literature as providing an optimal balance (Noth, 2008). The mass range was determined by considering commercially available lightweight materials and solar panels (Oettershagen, 2018). These parameters were optimized to ensure continuous flight capability and energy efficiency under the specific meteorological conditions of the Kayseri region. The objective is to ensure continuous flight of the UAV, focusing on the months of June and July, which are characterized by continental climate conditions and peak sunshine hours. Equations (1)–(24) are used in the calculations, with equation (13) serving as the basis for optimizing the required mechanical power, while subsequent equations are solved accordingly.

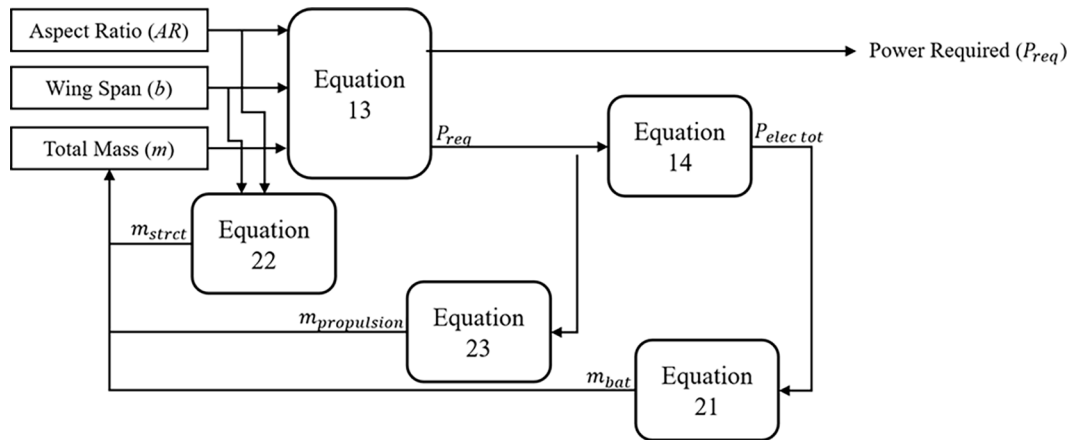
By optimizing equation (13), the required electrical power can be determined using equation (14), which subsequently serves as an input value for equations (21) and (23) in an iterative synthesis process. Figure 1 illustrates that minimizing both the required electrical and mechanical power also minimizes the total mass. This iterative approach enables the determination of optimal design parameters for the solar UAV, ensuring efficient performance and long endurance flight duration under specified climatic conditions.

This figure illustrates the relationship between the critical input parameters (AR, wing span and total mass) and the equations used in the proposed optimization model. It demonstrates the iterative process through which the power required P_{req} is calculated, linking it to the total electrical power $P_{elec\ tot}$ through aerodynamic and structural dependencies. The diagram highlights how equations (13), (14), 21, 22 and 23 interconnect to form the basis of the optimization process, ensuring that the UAV design minimizes power consumption while maintaining structural integrity and aerodynamic performance.

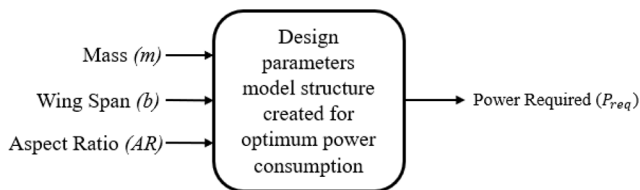
In this study, a model structure with three inputs and one output, as shown in Figure 2, was created to optimize the required power for the LALE-class solar UAV. The ABC algorithm was used to obtain the minimum required power for the optimum input values. The limits of the input parameters used in the study – AR, wingspan and mass – are 10–20, 4–7 m and 2–7 kg, respectively. These ranges align with those used in previous studies while considering the specific conditions of the region to be flown. The values of the constants and coefficients used in the equations presented in the previous sections are presented in Table 1.

In this study, the control parameters of the ABC algorithm used for optimization were chosen as 50 colony size, 2,500, 5,000 and 10,000 iterations and 30 run times.

The variation of iteration-AR, iteration-wingspan, iteration-mass and iteration- P_{req} obtained from the ABC algorithm used in the study are shown in Figure 3(a), (b), (c) and (d), respectively. It can be clearly observed that the wingspan increases rapidly at the beginning but stabilizes in subsequent iterations with respect to the number of iterations. The evolution of the input and output parameters of the best model

Figure 1 Required power calculations

Source: Figure by authors

Figure 2 The block diagram of the proposed model

Source: Figure by authors

for a span of 4–7 m and an AR of 12–20 is clearly shown. In addition, the optimal input and output values of the best models obtained over 30 iterations, according to the specified input values, are presented in Table 2 for three different iteration counts.

This figure displays the convergence behavior of the input parameters – AR, wing span (b) and total mass (m), – and the corresponding required power P_{req} during the optimization process. Sub-figures (a), (b), (c) and (d), respectively, show how (AR), (b), (m) and P_{req} stabilize after initial fluctuations. The results indicate rapid convergence within the first 1,000 iterations, confirming the efficiency of the ABC algorithm in reaching optimal values. This stability ensures the reliability of the selected parameters in achieving the desired power efficiency for the UAV.

The optimization results clearly demonstrate that the proposed ABC algorithm-based model offers a reliable and innovative approach to solar UAV design. Compared to similar studies in the literature, the proposed methodology stands out by simultaneously and iteratively optimizing multiple design parameters (wingspan, AR and total mass). For instance, studies using genetic algorithms (GA) generally focus on a single design parameter and are limited in exploring a broader solution space (Bakar et al., 2021; Panagiotou et al., 2016). The high convergence capacity and low computational cost of the ABC algorithm overcome these limitations, providing a more effective optimization process (Karaboga and Akay, 2009).

The results obtained using the proposed methodology show a 28% improvement compared to other solar UAV designs in

the literature. For example, Jashnani et al. (2013) reported that optimization methods used for solar UAVs had limited effects on flight duration and energy consumption, whereas this study successfully minimized power consumption while significantly increasing flight duration. Furthermore, the proposed model's optimization based on the meteorological data specific to the Kayseri region provides a design process sensitive to regional differences, a dimension often overlooked in the literature (Oetershagen, 2018).

In conclusion, the proposed methodology not only addresses the current design problem but also offers an adaptable and expandable solution model for future UAV design processes. This enhances the value of the ABC algorithm as an innovative method in solar UAV design.

Conclusion

This study has the potential to enhance the energy efficiency of solar UAVs, providing economic benefits in commercial sectors such as agriculture, logistics and cargo transportation. With extended flight durations and low energy costs, this technology is likely to gain widespread adoption in commercial applications while also contributing to green energy policies by reducing the carbon footprint. From a societal perspective, it offers advantages in areas such as disaster management, environmental monitoring and rapid response to natural disasters, while supporting sustainable development goals. By promoting the efficient use of renewable energy sources, this study holds significance for the development of national energy policies and serves as a guide for public projects. This study discusses the power calculation required for the LALE class UAV with maximum endurance and all day flight capability. For this purpose, the wingspan, AR and mass of the UAV are selected as inputs, and the required power is determined as output. The range of 4–7 m for the wingspan and 12–20 for the AR is considered to cover all LALE class UAVs used in the literature and in various projects.

A model using the ABC algorithm was developed to optimize the wing span and AR values for achieving the desired power efficiency. Through the ABC-based optimization process, the

Table 1 Fixed and task-dependent parameters required for design

Parameter	Value	Unit	Description
Fixed parameters			
C_L	0.92	–	Airfoil lift factor
C_d	0.0107	–	Airfoil drag coefficient
C_{Di}	0.0051	–	Induced drag coefficient
E	0.90	–	Oswald's efficiency factor
I_T	950	W/m^2	Total solar energy
k_{bat}	$240 \times 3,600$	J/kg	Lithium ion battery energy density
k_{sc}	0.448	kg/m^2	Solar cell mass density
k_{enc}	0.49	kg/m^2	Encapsulation efficiency
k_{struct}	0.44/9.81	kg/m^3	Structure mass prediction constant
m_{av}	850	g	Avionics mass
P_{av}	1.5	W	Power required for avionics
x_1	3.1	–	Structure mass prediction wing span upper constant
x_2	–0.25	–	Structure mass prediction wing AR upper constant
Efficiencies			
η_{bec}	0.85	–	BEC efficiency
η_{sc}	0.237	–	Solar cell efficiency
η_{cbr}	0.97	–	Losses due to the shape of the airfoil
η_{chrg}	0.95	–	Battery charging efficiency
η_{ESC}	0.95	–	ESC efficiency
η_{dchrg}	1.03	–	Battery discharge efficiency
η_{grb}	0.97	–	Gearbox efficiency
H_{mot}	0.85	–	Engine efficiency
H_{mppt}	0.99	–	MPPT efficiency
η_{prl}	0.85	–	Propeller efficiency
Task-dependent parameters			
m_{pld}	0	kg	Payload weight
η_{wthr}	0.7	–	Sky factor
P_{pld}	0	W	Power consumed by payload
ρ	1.111	kg/m^3	Air density (1,200 m)
T_{day}	$12.14 \times 3,600$	sn	Day length

Source(s): Table by authors

optimal wing span was determined to fall within the range of 4–7 m, with the lowest value identified at 4 m, while the corresponding AR was computed as 19.96. Furthermore, it was inferred that the power required for these specified input values would amount to 5.75 watts.

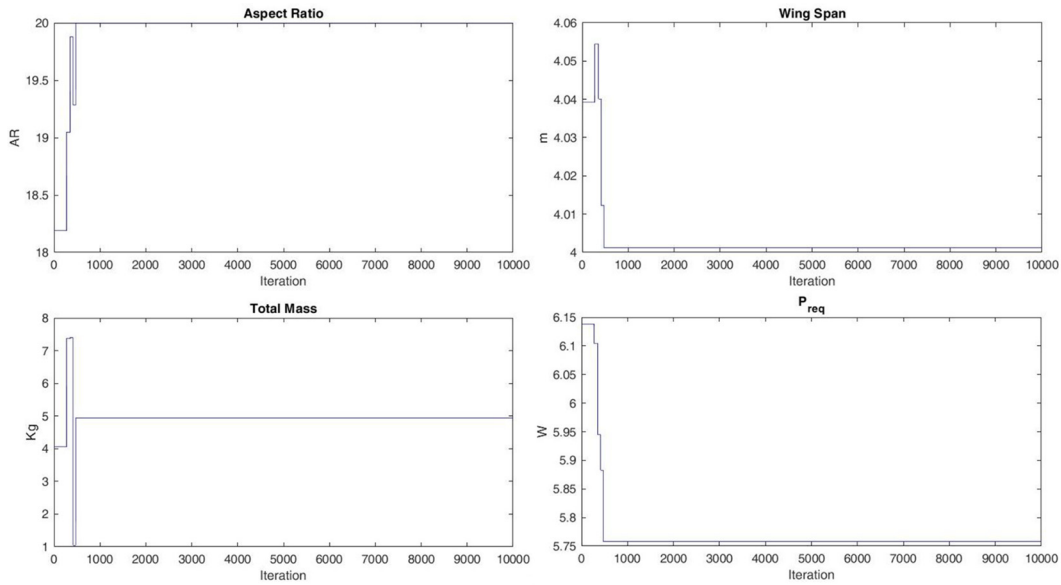
A comparison of the power required for the wingspan and AR ratios, obtained through the ABC algorithm-based model and the two most prominent solar UAV studies in the literature, reveals a noteworthy improvement of 28% in the design parameters derived from our optimization process.

The simulation results obtained in this study were compared with both optimization-based works in the literature and real-world solar UAV projects. For instance, Bakar *et al.* (2021) achieved approximately 6.5 h of flight time using a UAV optimized with a GA, equipped with 17% efficient solar panels and a wingspan of 2.51 m. One of the notable practical projects, SkySailor, performed a successful 27-h flight with a 3.2-m wingspan. Atlantic Solar also achieved flights exceeding 24 h; however, its development process was considerably longer and involved more complex system integration. In contrast, the model developed in this study achieved over 24 h of flight using 23% efficient panels, a 4-m wingspan and 4.44 kg take-off

weight, while following a relatively simpler and faster design process. The use of the ABC algorithm enhanced the efficiency of the optimization, minimized power consumption and maximized endurance. These results demonstrate that the proposed framework offers a competitive and practical alternative compared to both theoretical models and real-world implementations in the literature.

To the best of the authors' knowledge, this study marks the first instance in the literature where the ABC algorithm is used for the optimization of solar UAV design parameters. The results demonstrate a significant improvement over comparable studies, further validating the effectiveness and applicability of the proposed design methodology. As a result, the model can be considered a promising and practical tool for LALE-class solar UAV designers.

Although the proposed methodology has been optimized using regional meteorological data from Kayseri, the model demonstrates high adaptability to various climatic conditions. The ABC algorithm used in this study provides a broad solution space for optimizing design parameters, enabling customization of inputs such as solar radiation, air density and daylight duration. The literature indicates that similar

Figure 3 Change of input parameters against iteration

Source: Figure by authors

Table 2 Input and output values obtained in the optimization process

Iteration	P_{req}	b	AR	m
2,500	5.763	4.001	19.969	5.464
5,000	5.761	4.001	19.959	6.861
10,000	5.757	4.000	19.964	4.443

Source(s): Table by authors

methodologies have been successfully adapted to tropical regions with extended daylight hours or high altitudes with lower air density (Oettershagen, 2018; Bakar et al., 2021). For instance, in desert climates with high solar radiation potential, the energy production capacity of solar panels can be increased, whereas in oceanic climates with lower radiation conditions, the efficiency of energy storage systems can be optimized (Sri et al., 2016). The solar radiation value obtained in equations (16) and (17) can be updated based on the radiation data of different regions, which directly impacts energy production capacity. In addition, in tropical regions with longer daylight durations (T_{day}), energy production can be optimized to achieve extended flight durations (De Soto et al., 2006).

The ABC algorithm offers faster convergence and lower computational cost compared to other methods. It operates effectively over a wide solution space, enabling rapid attainment of optimal design parameters. This capability provides a significant advantage in addressing complex, multidimensional optimization problems such as solar UAV design. Methods like GA and Particle Swarm Optimization (PSO) typically optimize only a single parameter or a limited number of parameters. This study aims to fill the gap in the literature regarding multiparameter optimization. In our research, the ABC algorithm simultaneously optimized multiple design parameters, achieving 28% higher energy efficiency compared to existing methods in the literature.

This study represents a novel contribution to the field by demonstrating the application of the ABC algorithm to solar UAV design for the first time. This contribution holds the potential to serve as both a foundation for the development of new design approaches and a reference point for future research.

Moreover, this research showcases that heuristic methods, such as the ABC algorithm, can efficiently determine crucial parameters essential for UAV design. The success of this approach suggests that similar algorithms hold promise for addressing various UAV design challenges documented in the literature, thereby offering valuable insights for future research endeavors in this field.

Further work

Future studies will address how new developments (such as battery and solar cell efficiencies) can change the design parameters in LALE class solar UAV design using heuristic algorithms.

The proposed methodology is not limited to the conditions in Kayseri and can be applied in different climates by adapting the parameters to regional meteorological data. This demonstrates the generalizability and design flexibility of the methodology. However, future studies focusing on detailed analyses of applications under various climatic conditions will provide a more comprehensive evaluation of the model's overall applicability.

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Corresponding author

Mehmet Konar can be contacted at: mkonar@erciyes.edu.tr

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