Design of Power Device Sizing and Integration for Solar-Powered Aircraft Application

Safyanu Bashir Danjuma, Zamri Omar*
Faculty of Mechanical and Manufacturing Engineering,
Universiti Tun Hussein Onn Malaysia (UTHM),
86400 Parit Raja, Batu Pahat, Johor, Malaysia
**bashir.12393@yahoo.com*

Mohd Noor Abdullah
Faculty of Electrical and Electronics Engineering,
Universiti Tun Hussein Onn Malaysia (UTHM),
86400 Parit Raja, Batu Pahat, Johor, Malaysia

ABSTRACT

The power device constitutes the PV cell, rechargeable battery, and maximum power point tracker. Solar aircraft lack proper power device sizing to provide adequate energy to sustain low and high altitude and long endurance flight. This paper conducts the power device sizing and integration for solar-powered aircraft applications (Unmanned Aerial Vehicle). The solar radiation model, the aerodynamic model, the energy and mass balance model, and the adopted aircraft configuration were used to determine the power device sizing, integration, and application. The input variables were aircraft mass 3 kg, wingspan 3.2 m, chord 0.3 m, aspect ratio 11.25, solar radiation 825 W/m^2, lift coefficient 0.913, total drag coefficient 0.047, day time 12 hour, night time 12 hours, respectively. The input variables were incorporated into the MS Excel program to determine the output variables. The output variables are; the power required 10.92 W, the total electrical power 19.47 W, the total electrical energy 465.5 Wh, the daily solar energy 578.33 Wh, the solar cell area 0.62 m, the number of PV cell 32, and the number of the Rechargeable battery 74 respectively. The power device was developed with the PV cell Maxeon Gen III for high efficiency, the rechargeable battery sulfur-lithium battery for high energy density, and the Maximum power point tracker neural network algorithm for smart and efficient response. The PD sizing was validated with three existing designs. The validation results show that 20%

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reduction of the required number of PV cells and RB and a 30% increase in flight durations.

Keywords: *Power Device; Solar Radiation Model; Energy Balance Model; Aerodynamics Model; Solar-Powered Aircraft*

Introduction

Solar-powered aircraft (SPA), in this era, have witness a technological advancement in terms of energy conversion efficiency, energy storage capability, and energy utilization [1]. Solar aircraft can fly at high altitudes and long endurance from 24 to 72 hours and fly across the world, both unmanned and manned aircraft [2]. These fits were achieved based on the technological advancement in the solar aircraft power device (PD) and technological improvement in structural materials with lighter and stronger materials [3, 4].

The (PD) of solar aircraft constitutes the photovoltaic cell (PV), the rechargeable battery (RB), and the maximum power point tracker (MPPT). The PD is the main component that powered solar aircraft [5]. The efficiency of the solar aircraft is the function of an efficient PD. Solar aircraft required more solar energy, which means more PV cells are needed and required more conserved energy when solar energy is not available. Therefore, it required more RB. Consistently, more energy means more PD, and more weight is added to the aircraft. And the more the weight, the more energy is required to power the aircraft. For the PD problem to be solved, a PD sizing is imperative to determine the number of PV cells required and the number of RB needed [6]. Given the total weight and aircraft configuration, the PD size can be calculated using Microsoft Excel.

The main drawback of the solar-powered aircraft is the PD sizing and the energy management system to power the solar aircraft. These are significant issues that are affecting solar aircraft to compete with conventional aircraft. The energy density of solar aircraft's energy storage is too low to sustain a high altitude and long endurance flight. In contrast, conventional aircraft that use fossil fuel has a far higher energy density that can support long flight hours [7, 8]. A solar aircraft has a long way to go if it must compete or replace conventional aircraft. But, indeed, steady progress has been achieved recently.

The study aimed to design PD sizing and integration for solar aircraft unmanned aerial vehicles (UAV) with efficient PD to sustain low and high altitude and long endurance flight. The PD sizing is essential to provide the actual number of PV cells and RB to power the solar aircraft.

Methodology

The design concept methodology in Figure 1 clearly shows the procedure the study is carried out. The approach involves implementing a solar radiation model, energy and balance model, aerodynamic model, and adopted aircraft configuration into the MS Excel program. These are used to develop PD sizing (number of PV cells and RB required). The developed PD is integrated into the solar aircraft to power the system.

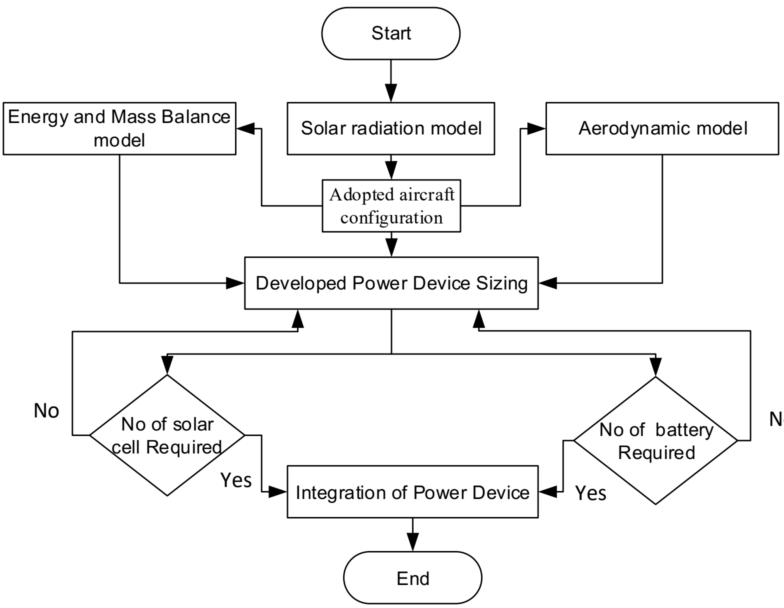

Figure 1: Design concept methodology.

Solar radiation model

Solar energy is the primary energy source for solar aircraft; for this reason, it becomes imperative to determine its operation and the best way to harness it. Solar energy varies from a particular place, the period of the year, and the time of the day. A software using Photovoltaic Geography Information System (PVGIS) and R.SUN IET 2015 was used to obtain an annual daily average solar radiation of Malaysia as a case study for both peninsula and Borneo. Figure 2 shows the solar radiation map of Malaysia obtained from PVGIS, a free software. The model was formulated using the 6^{th} order polynomial.

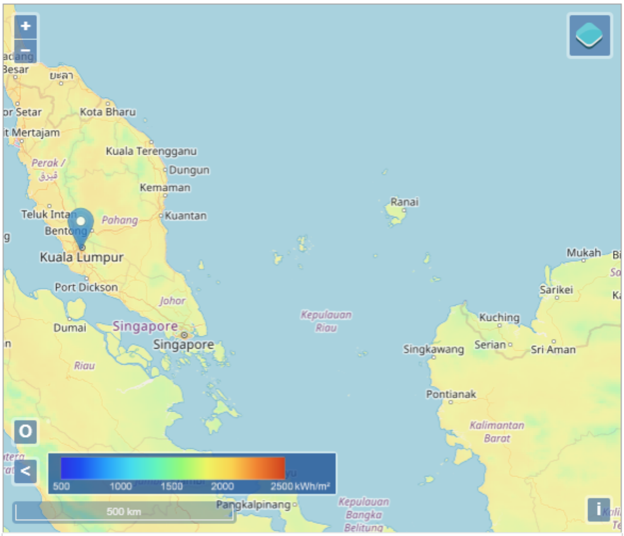

Figure 2: Solar radiation map for Malaysia [9].

<u>Available daily solar energy</u>

The daily solar energy is the maximum daily energy available when considering the average annual daily solar radiation from the sun. Therefore, the daily electrical energy [10] is given as:

$$D_{se} = \frac{I_{max} T_{day}}{\frac{\pi}{2}} A_{SC}\ \eta_{wthr}\ \eta_{sc}\ \eta_{cbr} \qquad (1)$$

Where daily solar energy - D_{se}, solar cell efficiency - η_{sc}, cambered efficiency - η_{cbr}, MPPT efficiency - η_{mppt}, maximum irradiance - I_{max}, solar cell area- A_{SC} and the day duration - T_{day}

Aerodynamic model

The aerodynamic model was used to analyze the lift and drag coefficient of an airfoil. In this present study, five airfoils were selected from the literature, and analysis was conducted to determine the high lift coefficient, low drag coefficient, and the high ratio of lift/drag. The five airfoils are namely; AQUILA 9.3%, LA2573, S9000 (9%), S9037 (9%) and WE-3.55 respectively. The airfoils were analyzed using XFLR5 v6.0. The batch and the direct foil analysis were conducted at Reynold number ($5.0 \times 10^5 - 6.0 \times 10^5$) with an interval of 1.0×10^4 and angle of attack -3° to 15° increment of 1°.

Energy and mass balance model

The energy and mass balance model deals with the mass of the individual part that constitutes the aircraft's total mass. The total mass is a prerequisite that determines the total sum of energy required to produce a lift force equivalent to the aircraft's total mass, known as energy and mass balance. The mass and energy balance must be achieved for the aircraft to fly successfully.

Total mass

The total mass is all the various masses that constitute the aircraft mass. The total mass m_{tot} [10];

$$m_{tot} = m_f + m_{af} + m_{sc} + m_{mppt} + m_{bat} + m_{prop} \tag{2}$$

Refer to Table 1 for values of constant and variable and their corresponding definitions.

$$m_f = m_{av} + m_{pld} \tag{3}$$

Fixed Masses - m_f ; Avionic mass - m_{av}; payload mass - m_{pld}.

$$m_{af} = k_{af} AR^{x_2} b^{x_1} \tag{4}$$

Airframe structure mass - m_{af}; structural mass area exponent - x_1 ; structural mass aspect ratio component; structural mass constant - k_{af}; wingspan – b; aspect ratio – AR.

$$m_{sc} = (k_{sc} + k_{enc}) A_{sc} \tag{5}$$

Mass of the solar cell - m_{sc}; solar cell area - A_{sc}; mass density of solar cell - k_{sc}; mass density of encapsulation - k_{enc}.

$$m_{mppt} = k_{mppt} \times I_{max} \times \eta_{sc} \times \eta_{cbr} \times \eta_{mppt} \times A_{sc} \tag{6}$$

Mass of the MPPT - m_{mppt}; mass/power ratio of MPPT - k_{mppt}; maximum solar radiation - I_{max}; solar cell efficiency - η_{sc}; MPPT efficiency - η_{mppt} ; Camber efficiency - η_{cbr}.

$$m_{bat} = \frac{T_{night}}{\eta_{dchrg}\ k_{bat}} P_{elec\ tot} \tag{7}$$

Mass of the battery - m_{bat}; Night duration - T_{night}; energy density of battery - k_{bat}; discharge efficiency - η_{dchrg}; total electrical power - $P_{elec\ tot}$.

$$m_{prop} = k_{prop} P_{Eflight} \tag{8}$$

Mass of the propulsion group – m_{prop}; mass/power ratio of propulsion – k_{prop}; electrical power for level flight – $P_{Eflight}$.

Power required for level flight

The power required is the amount of power needed to fly the aircraft on a level flight.

$$P_{mech} = \frac{C_D}{{C_L}^{3/2}} \sqrt{\frac{(mg)^3}{S}} \sqrt{\frac{\rho}{2}} \tag{9}$$

$$C_D = C_{D\,afl} + C_{D\,ind} + C_{D\,par} \tag{10}$$

C_L and C_D are the lift and drag coefficients, ρ is the air density, S is the wing area, and v is the aircraft's relative speed; this is comparable to the ground speed when the wind is approximately negligible. C_L and C_D, are both determined by the airfoil, the angle of attack α, and the *Reynold* number Re, which is the function of airflow viscosity, $C_{D\,afl}$ is airfoil drag, $C_{D\,ind}$ is induced and $C_{D\,par}$ parasitic drag.

$$C_{D\,ind} = \frac{{C_D}^2}{e\pi AR} \tag{11}$$

e is the Oswald efficiency factor, a variable with a number between 0 to 1. In reality, the values range from 0.75 to 0.85 and in an ideal situation is 1, as when the load distribution is elliptical. AR is the aspect ratio, a relationship between the wingspan and the chord length i.e. AR = b/c = b^2/(bc) = b^2/S.

Total electrical power consumption

The total electrical power is the sum of all electrical power; avionic, payload, and battery elimination circuit [10].

$$P_{elec\,tot}, = P_{Eflight} + \frac{1}{\eta bec} (P_{av} + P_{pld}) \tag{12}$$

where electrical power - $P_{Eflight}$, the avionics power - P_{av} and the payload power - P_{pld}. and the BEC (Battery Elimination Circuit) efficiency - η_{bec}.

Daily energy consumption

The daily energy consumption is the total electrical energy required to fly the aircraft for 24 hours [10]. The total electrical energy considered the duration of the aircraft T_{day} for daytime and T_{night} for the nighttime. The T_{day} is the period when solar energy is available, 12 hours. The period when solar energy is not available in the nighttime is T_{night} 12 hours. Therefore, the duration is included in the calculation of PD sizing for solar aircraft. Also, the total electrical power and the charging and discharging efficiencies of the battery are included in calculating the total electrical energy required.

$$E_{elec\ tot} = P_{elec\ tot}\ (T_{day} + \frac{T_{night}}{\eta chrg\ \eta dchrg}) \tag{13}$$

where total electrical energy - $E_{elec\ tot}$, total electrical power - $P_{elec\ tot}$, the charge efficiency - $\eta chrg$, discharge efficiency of the battery for the night period - $\eta dchrg$, the night duration - T_{night} and the day duration - T_{day}.

Solar cell area

The solar area is the surface area required by the PV cell to be arranged on the wings [10].

$$A_{sc} = P_{Etot}\ \frac{\pi}{2\eta_{sc}\ \eta_{cbr}\ \eta_{mppt}\ \eta_{wthr}} \left(1 + \frac{T_{night}}{T_{day}}\ \frac{1}{\eta_{chrg}\eta_{dchrg}}\right) \frac{1}{I_{max}} \tag{14}$$

where total electrical power - P_{Etot}, solar cell efficiency - η_{sc}, cambered efficiency - η_{cbr}, MPPT efficiency - η_{mppt}, the efficiency of the solar cell in different weather conditions - η_{wthr}, length of the - dayT_{day}, length of the night - T_{night}, the charging η_{chrg} and discharging efficiency - η_{dchrg} and the maximum irradiance - I_{max}.

Table 1: Variable and constant [9, 10]

Constants /Variables	Value	Units	Notes
C_L	0.913	-	Airfoil lift coefficient
C_{D-afl}	0.008	-	Airfoil drag coefficient. To be added to the parasitic and induced drag
$C_{D\text{-Parasitic}}$	0.0065	-	Parasitic drag
e	0.9	-	Oswald's efficiency factor (assumed value)
ρ_{air}	1.1655	kg/m^3	The density of air at 500 m altitude
I_{max}	825	W/m^2	Maximum sun irradiance [9] (a typical value for Malaysia)
k_{bat}	700	Wh/kg	The energy density of LS battery (assumed value)
k_{sc}	0.32	kg/m^2	The mass density of solar cells (based on ([10])
k_{enc}	0.26	kg/m^2	Mass density of encapsulation (based on ([10])
k_{mppt}	0.00047	kg/W	Mass/power ratio of MPPT (based on ([10])
k_{prop}	0.008	kg/w	Mass/power ratio of the propulsion system (based on ([10])
m_{av}	0.15	kg	Mass of avionics system (based on ([10])
m_{pld}	0.05	kg	Mass of telecommunication payload (based on ([10])
η_{bec}	0.65	-	The efficiency of the step-down converter (based on ([10])
η_{wth}	1	-	Weather factor, which reduces the energy captured. Value of 1 is the clear sky (assumed value)
η_{sc}	0.169	-	The efficiency of solar cells (based on ([10])
η_{cbr}	0.90	-	The efficiency of curved solar panels (based on [10])
η_{chr}	0.95		The efficiency of the battery charge (based on [10])
η_{ctr}	0.95		The efficiency of the motor controller (based on [10])
η_{dchr}	0.95		The efficiency of battery discharge (based on [10])
η_{grb}	0.97		The efficiency of the gearbox (based on ([10])
η_{mot}	0.85		The efficiency of the motor (based on [10])
η_{mppt}	0.97		The efficiency of MPPT (based on ([10]))
η_{plr}	0.85	-	The efficiency of the propeller (based on ([10])
P_{av}	1.5	W	Power for avionics (based on [10])
P_{pld}	0.5	W	Power for telecommunication payload (based on [10])
T_{day}	43200	s	Day duration (based on [9])
T_{night}	43200	s	Night duration (based on [9])

Develop a power device for solar aircraft

The PD is the main engine and only source of energy for solar aircraft; thus, it is essential to develop a very efficient PD that can efficiently and effectively perform the mission. For solar aircraft (UAV) to efficiently fly near-space; so that, it can be applied in intelligent surveillance and renaissance (ISR) and relay communication [11], hazard warning, rescue and assessment, agricultural surveillance and decision support systems, and near-future planetary atmospheric exploration by NASA [12, 13]. The application of manned solar aircraft demonstrated by Solar Impulse II makes the aviation industry's prospect very bright [8].

Calculation of the number of solar cells for the design

The calculation of the required number of solar cells is derived from the mechanical power for level flight and the total electrical power consumption, with the flight profile mission's duration. All these factors are considered concerning peak solar hour (PSH); it is the day that the solar intensity is high [14, 15]. Table 2 is the specification of the PV cell used in the design.

$$Solar\ cell\ wattage = \frac{Daily\ energy}{PSH} \tag{15}$$

$$No.of\ solar\ cell = \frac{solar\ cell\ wattage}{solar\ cell\ power} \tag{16}$$

Table 2: Specification of sun power maxeon GEN III solar cell [16]

Material	SI Unit
Mass of the solar cell	0.0065 kg
Length and Width	0.125 × 0.125 m
Area of single solar Panel	0.0156 m^2
The efficiency of the solar cell	22%
Rated voltage	0.580 V
Rated current	6.01 A

Calculation of number of batteries for the design

The number of batteries in the design is a function of the daily energy available for the autonomous days of the non-availability of solar radiation [17]. Table 3 depicts the specification of the RB used in the design.

$$Ampere\ Hour = \frac{Available\ daily\ Solar\ Energy}{Battery\ Charge\ Voltage} \tag{17}$$

$$Number\ of\ Batteries = \frac{Ampere\ Hour\ (Ah)}{Battery\ Nominal\ capacity(Ah)} \tag{18}$$

Table 3: Specification of lithium-sulfur rechargeable battery [18]

Electrical Specifications		Mechanical Specifications	
Parameter	SI Unit	Parameter	SI Unit
Nominal voltage	2.15 V	Length (top flanged folded)	55 mm
Max charge voltage	2.5 V	Width	37 mm
Min voltage on discharge	1.7 V	Thickness	11.5 mm
Nominal capacity @ 25ºC	2.5 Ah@C/5	Weight	16 g
Max continuous discharge rate	2C		
Max charge rate	C/5		
Specific Energy	350 Wh/kg		
Energy Density	320 W/l		
Cell Impedance	25 mΩ		

Integration of power device in solar-powered aircraft

Arrangement of solar cell and rechargeable battery

The number of solar cells on the wing was designed, then the arrangement and minimum area of the wing were calculated. A type of wing with a 7º polyhedral angle is shown in Figure 3. The wing is tapered, tip chord 0.2 m, length 0.5 m, and root chord 0.3 m. The solar cells are arranged in rows on the wingspan. The number of RB was designed and arranged in rows and packed inside the fuselage.

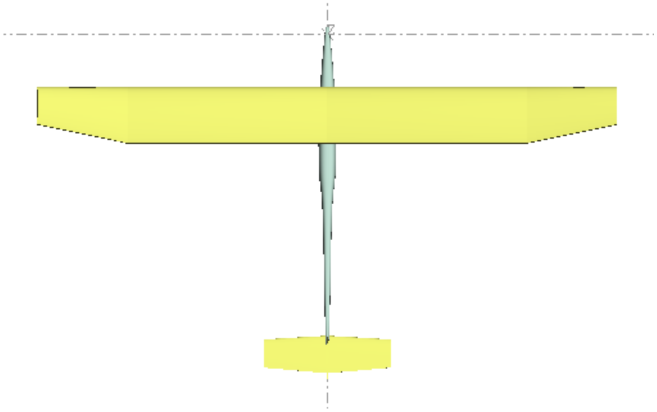

Figure 3: A wing with 7º polyhedral and conventional-tail.

Results and Discussion

Solar radiation model for Malaysia

The solar radiation model for Malaysia was formulated using the 6th polynomial. Figure 4 presented the global radiation graph with blue lines, the diffuse radiation with a brown line, the direct radiation with a brown line, and Malaysia's predicted model radiation with a yellow dotted line. The coefficient of correlation of the global radiation and Malaysia's predicted radiation model is very strong, with the value of R^2 = 0.998, which shows that they are 100% convergence and positive. The highest value of the solar radiation model of Malaysia, i.e., the maximum irradiance I_{max} of the annual daily average was found to be 825 W/m^2, and the time duration for the availability of solar radiation (T_{day}), was 12 hours [9]. The data is incorporated into the MS Excel program to calculate the PD sizing of solar aircraft.

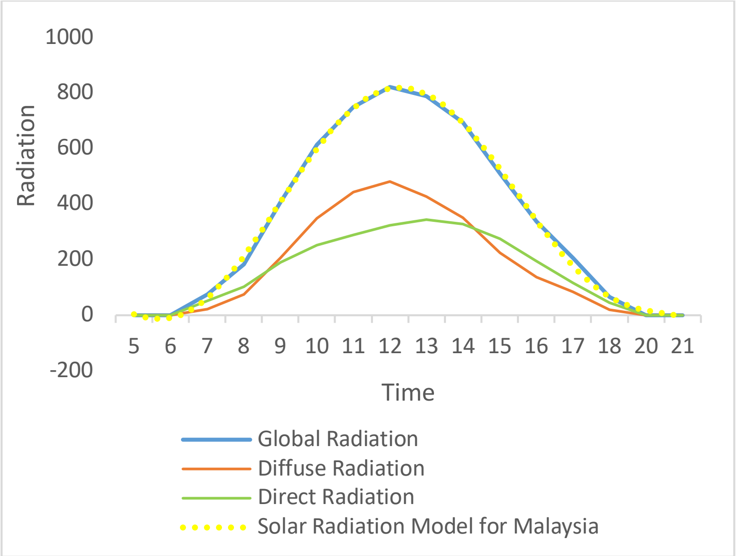

Figure 4: Solar radiation model for Malaysia.

Aerodynamic airfoil analysis

Table 4 presents the results of five airfoils, namely; AQUILA 9.3%, LA2573, S9000 (9%), S9037 (9%) and WE-3.55 respectively [17, 18]. The airfoils were analyzed using XFLR5 v6.0. The batch and direct foil analysis conducted, Reynolds number ranges ($5.0 \times 10^5 – 6.0 \times 10^5$), 1.0×10^4 intervals. The angle of attack ranges from -3° to 15° increment of 1°. The aerodynamic characterization and the comparisons of the five airfoils of the direct foil analysis were determined at 500,000 Reynolds number and 4° angles of attack and view at the operating point. The angle of attack and the Reynold number was chosen because it presents the best aerodynamic characteristics. The high lift and low drag coefficient and high lift/drag ratio were the criteria for selecting the best airfoil.

Table 4 shows that WE-3.55 airfoil has the highest lift coefficient C_L of 0.913, lowest drag coefficient C_D of 0.008, and the highest ratio of lift/drag coefficient C_L/C_D of 117.248 [19]. The airfoil was selected and incorporated into the MS Excel program to develop the PD sizing for solar aircraft.

Table 4: The aerodynamic characterization and comparisons of the airfoils

Airfoil	AQUILA-9.3%	LA2573A	S9000 (9%)	S9037 (9%)	WE-3.55
Thickness (%)	9.3	13.70	9.01	9.00	9.30
Max Camber (%)	4.05	3.19	2.37	3.49	3.55
C_L	0.833	0.630	0.757	0.828	0.913
C_D	0.008	0.012	0.008	0.008	0.008
C_L/C_D	101.911	53.004	93.235	104.897	117.248
No.of Panels	69	101	121	121	117

Aircraft configuration

Table 5 depicts aircraft configuration adopted from [10, 17] and slightly modified to give a robust and efficient PD sizing performance. The aircraft was incorporated into the MS Excel program that was used for PD sizing design.

Table 5: Aircraft configuration

Parameter	Value	Unit
Aspect Ratio (AR)	11.25	
Wingspan (b)	3.2	m
Total Mass (m)	3	kg
Chord (a)	0.3	m

Power device sizing

Table 6 presents the input variables that range from; aircraft configuration, solar radiation annual daily average data, the aerodynamic configuration of lift and drag coefficients, and various constants and variables in Table 1 are incorporated in the MS Excel program. And the output variables were determined as; the Powered required, the total electrical power, total electrical energy, the daily solar energy, and the number of PV cells and RB's.

Table 6: Design of power device sizing for solar-powered aircraft

Input Variable	Output Variable

Parameter	Value	Units	Parameter	Value	Units
Mass (m)	3	Kg	Mechanical Power	10.92	W
Wing Span (b)	3.2	m	Total Elect Power	19.47	W
Chord (a)	0.3	m	Total Elect Energy	465.55	Wh
Radiation (H)	825	W/m^2	Daily Solar Energy	578.33	Wh
Aspect Ratio (AR)	11.25	-	Solar Cell Area	0.62	m^2
Lift Coefficient (CL)	0.913	-	Total Wattage	107.09	W
Drag Coefficient (CD)	0.047	-	No. of Solar Cell	32	-
Velocity	10	m/s^2	No of Battery	74	-
Day duration	12	h	Total Mass	2.72	kg
Night duration	12	h			

Develop a power device for solar-powered aircraft

Figure 5 presents the developed, efficient PD for solar aircraft application. The technology advancement of PD provides the opportunity to develop efficient PD in solar aircraft applications. The PV cell monocrystalline (MAXEON GEN III) was selected due to its high energy conversion efficiency of 25% to 30% [16]. The MPPT, intelligent, and smart algorithm (Artificial Neural Network) was proposed for its effectiveness in partial shading, and the response/speed is fast. The rechargeable battery (Li-Sulfur) was used for its possible theoretical high energy density of 700 Wh/kg; prolong's flight endurance [2, 20].

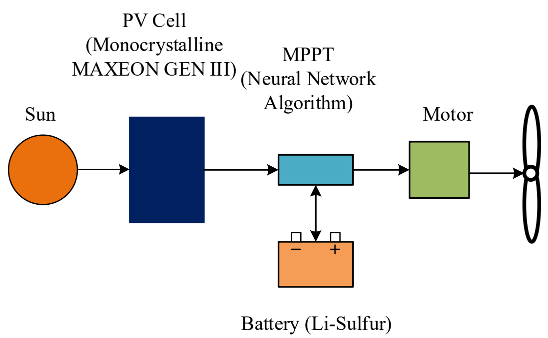

Figure 5: Developed efficient power device for solar aircraft applications.

Integration of power device in solar-powered aircraft

Figure 6 presents the integration of PD in solar aircraft. The PV cells are 32 cells arranged in two rows of 16 cells each on the aircraft's wingspan. The RB is 74 in number, arranged in 12 rows, and packaged in an RB pack situated in the aircraft's fuselage [8, 17]. Note: the arrangement of the PD in the solar aircraft is not drawn to scale.

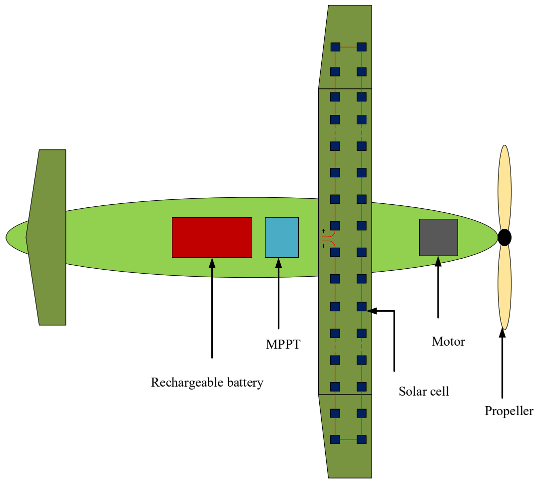

Figure 6: Integration of power device in solar-powered aircraft.

Validation of the PD sizing using existing solar-powered aircraft design

Three solar aircraft designs were used to validate the efficacy of the developed PD sizing. The input variables are; mass, wingspan, chord, radiation, velocity, lift coefficient, and drag coefficient. And the output variables are; total electrical energy, daily solar energy, number of the solar cell, number of batteries, duration, and total mass. Table 7 presents the results of the previous three solar aircraft designs. Table 8 presents the improved results of the previous three solar aircraft designs obtained from the developed PD sizing and the results of the current research design. The output variables results of Table 8 show that the number of solar cells and number RB required reduced by 20%, except for design 2 because of ineffectiveness in determining the total electrical energy required and the available solar energy. And the flight duration increased by 30% from previous designs for all three designs. When compared with the output variable result of Table 7. The improved results of the previous designs in Table 8 conform to the current study and conventional domestic solar energy sizing. Based on the validation results, the developed PD sizing is viable and effective for designing PD sizing for solar aircraft.

Table 7: Result of the previous PD designs for solar aircraft

Variable	Design 1 [10]	Design 2 [22]	Design 3 [23]
Mass (kg)	2.6	3.46	5
Wingspan (m)	3.2	3	3
Chord (m)	0.25	0.25	0.32
Radiation (W/m^2)	950	950	900
Velocity (m/s^2)	8.3	9.85	10

Lift coefficient	0.8	0.8	0.8
Drag coefficient	0.037	0.038	0.036
Total elect energy (Wh)	431.51	616.56	484
Daily solar energy (Wh)	605.24	924.75	557
No. of solar cell	72	46	48
No. of battery	62	130	125
Duration (hours)	27	19	24
Total mass (kg)	2.68	3.35	4.35

Note: All three designs used a Monocrystalline PV cell, and the rechargeable batteries used are Lithium-ion and Lithium Polymer but were replaced with Lithium-Sulfur for fair comparisons. Lithium-sulfur rechargeable batteries were used in the current study. Therefore, the batteries' numbers have increased from previous designs due to the lighter weight and higher ampere-hour (Ah) of Lithium-sulfur batteries.

Table 8: Result of the improved previous PD design run on the developed PD sizing and current research (CR) design

Variable	Design 1 [10]	Design 2 [22]	Design 3 [23]	Design CR
Mass (kg)	2.6	3.46	5	3
Wingspan (m)	3.2	3	3	3.2
Chord (m)	0.25	0.25	0.32	0.3
Radiation (W/m^2)	950	950	900	825
Velocity (m/s^2)	8.3	9.85	10	10
Lift coefficient	0.8	0.8	0.8	0.913
Drag coefficient	0.037	0.038	0.036	0.041
Total elect energy (Wh)	425.51	646.47	906.81	465.55
Daily solar energy (Wh)	608.66	924.75	1160.61	578.33
No. of solar cell	30	46	66	32
No. of battery	68	104	146	74
Duration (hours)	34	34	31	30
Total mass (kg)	2.68	3.35	4.35	2.76

Note: The input variables are; mass, wingspan, chord, radiation, velocity, lift coefficient, and drag coefficient. And the output variables are; total electrical energy, daily solar energy, the number of solar cells, number of batteries, duration, and total mass. Table 7 is the previous results from the literature on the PD design of solar aircraft. While Table 8 is the results of the current research and improved output variable results of previous designs obtained from the developed PD sizing with the inputted variables of the previous designs in Table 7. The output variable results in Table 8 show a significant reduction in the number of solar cells, the number of batteries and improvement in the duration of the aircraft, when compared to the output variables results of the previous designs of Table 7. The results in Table 8 show the efficacy of the developed power device sizing of solar-powered aircraft.

Conclusion

Photovoltaic information system (PVGIS) software was used to develop the solar radiation model for Malaysia, and the annual average daily solar radiation was obtained. The aerodynamic model analyzed five airfoils at 500,000 Reynolds numbers and a 4-degree angle of attack. The WE-355 airfoil was selected because it was the best lowest drag coefficient and highest lift coefficient, and the highest lift/drag ratio, and used for the PD design. The aircraft configuration was adopted from the literature and modified to give a robust and efficient performance. The configurations of the aircraft are; mass, wingspan, and chord. All the variables were incorporated into the MS Excel program.

The power required for the level flight was calculated as 10.92 W, the daily total electrical energy required by the solar aircraft was determined as 465.55 Wh. Also, the available daily solar energy was determined as 578.33 Wh. The efficient PD was developed, the number of PV cells required was calculated as 32, and the number of RB was calculated as 74. The integration of the PD on the solar aircraft, the PV cells were arranged on the wing in two rows of 16 cells. The RB's were arranged in a pack of 12 rows of 6 batteries situated in the solar aircraft's fuselage. The developed PD sizing was validated with the previous existing three solar aircraft designs. The results show improvement in the flight duration by 30%, and the numbers of PD were reduced by 20%.

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