SOLAR ENERGY POTENTIALS TO DEVELOP POWER DEVICE SIZING AND INTEGRATION FOR SOLAR-POWERED AIRCRAFT (UAV) APPLICATION

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Abstract

Solar-powered aircraft use solar energy as a source of energy to power the aircraft. Solar aircraft has limited capacity to harness the available solar energy and lacks proper power device sizing. Photovoltaic geography information system software was employed to harness solar energy and obtain Malaysia's solar radiation model. The model developed an energy balance and mission path to effectively conserve solar energy for efficient solar aircraft performance. Power device sizing was designed with the required PV cell as 32 and rechargeable battery as 74. The power device is integrated into the aircraft, the PV cells on the wings, and the batteries are inserted in the aircraft's fuselage.

Keywords: Solar radiation model; solar-powered aircraft; power device sizing; integration and Applications.

1. Introduction

Photovoltaic geographic information systems (PVGIS) is free software that provides solar energy potentials in photovoltaic (PV) systems. The software provides solar energy potentials worldwide. The software harness the solar radiation model of a particular region and country (PVGIS, 2019). The solar radiation model is used to develop a solar energy balance and mission path diagram for solar aircraft unmanned aerial vehicles (UAV) (Mattos, Secco, & Salles, 2013), (Safyanu, Omar, & Abdullahi, 2018).

Solar aircraft use solar energy as a source of power to airborne. The PV cell, rechargeable battery, and maximum power point tracker (MPPT) are termed as the power device (PD) and are the main components that power the motor and propeller that provides a thrust that airborne the aircraft (Safyanu, Abdullah, & Omar, 2019).

Solar aircraft have limitations in harnessing the available solar energy required to fly the aircraft for a long time. Also, the rechargeable battery energy density is very low when compared to fossil fuel. To effectively and efficiently fly solar aircraft for medium and high altitude and long-endurance (HALE), the power device needs to be sized accordingly (Safyanu et al., 2019). The proper power device sizing ensured the number of PV cells and rechargeable batteries required to fly the aircraft is calculated. Consequently, a particular region or country's solar radiation model is crucial for developing the mission path diagram's solar energy balance (Wei, Yao, & Xie, 2020) and (Danjuma, Omar, & Abdullahi, 2021)**.** These provide the utilisation of solar energy and the path for the aircraft to airborne to conserved energy.

This paper aims to harness solar energy potential using PVGIS software to provide a solar radiation model for Malaysia to develop a solar energy balance and mission path diagram. And provide proper power device sizing for solar aircraft unmanned aerial vehicles (UAV) for medium and high altitude and long endurance.

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2. Methodology

2.1 Photovoltaic geographical information system

PVGIS software is freely available online developed by the European Commission's science and knowledge service. The software comprises three tools: PV performance, solar radiation, and typical meteorological year (TMY); Figure 1 shows the tools. The PVGIS potential includes:

- PV perspective for diverse technologies and capabilities of grid-connected and stand-alone systems.
- Solar radiation and temperature, as monthly averages or daily profiles.
- Full-time series of hourly values of both solar radiation and PV performance.
- TMY data for nine climatic variables.

Fig. 1: PVGIS tools

Figure 2 depicts the PVGIS software window used to provide the solar radiation data for a particular region of the world at a specific time. The software PV performance includes the grid-connected, tracking PV, and the off-grid. The data are monthly, daily, and hourly.

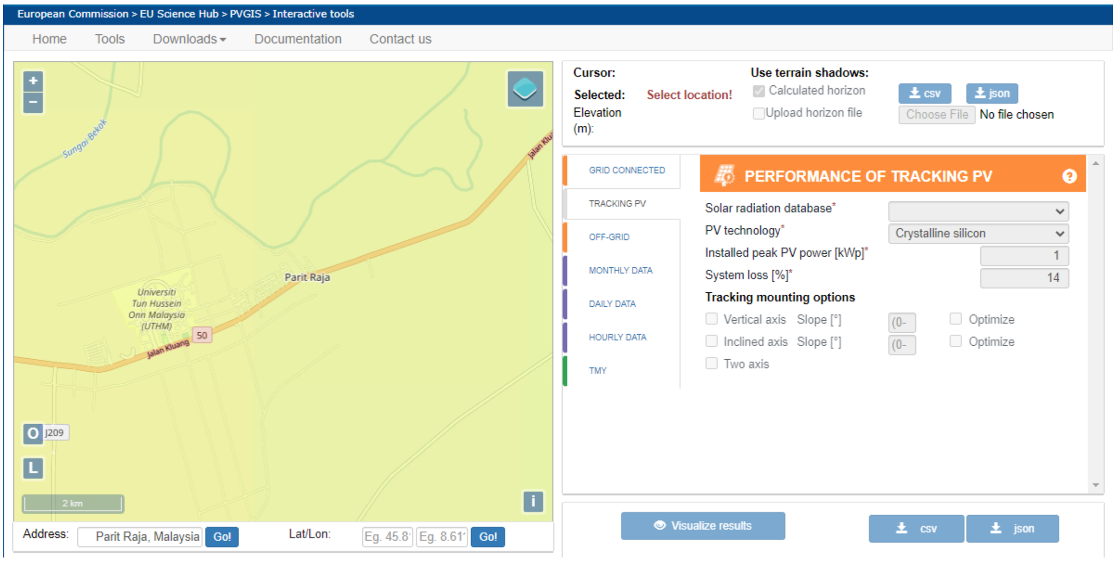

Fig. 2: PVGIS software window

The PVGIS software is used to provide the solar radiation model for Malaysia. The model will be verified with 6th order polynomial. The model will harness Malaysia's solar energy potential and developed the energy balance and the mission path diagram. The energy balance is the average yearly daily available energy of Malaysia and its utilisation to ensure efficiency. However, the mission path is a profile to utilising solar aircraft's available daily energy to ensure efficiency.

2.2 Development of Power Device Sizing

The next stage of the methodology is to develop power device sizing to provide the PV cells and the battery required to efficiently power the solar aircraft. Lastly, the power device is integrated into solar aircraft as a power source to propel the aircraft (Danjuma et al., 2021).

The (PD) is the primary energy for solar aircraft (UAV). Aircraft configurations; total mass of the aircraft, wingspan, and chord are adopted from articles and improved. Aerodynamic characteristics are the lift and drag coefficients (airfoil, induced, and parasitic drags inclusive). And the average annual daily solar radiation for Malaysia. The parameters were integrated into the MS Excel program as input variables and other required input variables shown in Table 1 to calculate the PD sizing, such as the required number of PV cells and the aircraft's rechargeable battery (Danjuma et al., 2021).

Tab 1: Variable and constant (PVGIS, 2019), (Noth, 2008)

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 & induced drag
$C_{D-Parasitic}$	0.0065	-	Parasitic drag
e	0.9	-	Oswald's efficiency factor (assumed value)
ρ_{air}	1.1655	Kg/m3	The density of air at 500m altitude
I_{max}	825	W/m2	Maximum sun irradiance (PVGIS, 2019) (a typical value for Malaysia)
k_{bat}	700	Wh/kg	The energy density of LS battery (assumed value)
k_{sc}	0.32	Kg/m2	The mass density of solar cells (based on ((Noth, 2008))
k_{enc}	0.26	kg/m2	The mass density of encapsulation (based on ((Noth, 2008))
k_{mppt}	0.00047	kg/W	Mass/power ratio of MPPT (based on ((Noth, 2008))
k_{prop}	0.008	kg/w	Mass/power ratio of the propulsion system (based on ((Noth, 2008))
m_{av}	0.15	kg	Mass of avionics system (based on ((Noth, 2008))
m_{pld}	0.05	kg	Mass of telecommunication payload (based on ((Noth, 2008))
η_{bec}	0.65	-	The efficiency of the step-down converter (based on ((Noth, 2008))
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 ((Noth, 2008))
η_{cbr}	0.90	-	The efficiency of curved solar panels (based on (Noth, 2008))
η_{chr}	0.95		The efficiency of the battery charge (based on (Noth, 2008))
η_{ctr}	0.95		The efficiency of the motor controller (based on (Noth, 2008))
η_{dchr}	0.95		The efficiency of battery discharge (based on (Noth, 2008))
η_{grb}	0.97		The efficiency of the gearbox (based on ((Noth, 2008))
η_{mot}	0.85		The efficiency of the motor (based on (Noth, 2008))
η_{mppt}	0.97		The efficiency of MPPT (based on ((Noth, 2008)))
η_{plr}	0.85	-	The efficiency of the propeller (based on ((Noth, 2008))
P_{av}	1.5	W	Power for avionics (based on Noth 2008)
P_{pld}	0.5	W	Power for telecommunication payload (based on (Noth, 2008))

Constants /Variables	Value	Units	Notes
T_{day}	43200	s	Day duration (based on (PVGIS, 2019))
T_{night}	43200	s	Night duration (based on (PVGIS, 2019))

However, the calculations of daily solar energy, mechanical power, total electrical power, total electrical energy and solar cell area Equation 1 to 7 were used, adopted from (Noth, 2008). The variables/constants and equations were adopted from (Noth, 2008) because they reflect current PV technology (in respect to power device sizing of solar aircraft).

$$\text{Daily solar energy} = \frac{I_{max} T_{day}}{\pi/2} A_{SC}\, \eta_{wthr}\, \eta_{sc}\, \eta_{cbr} \quad \text{(eq. 1)}$$

Where; η_{sc} = solar cell efficiency, η_{cbr} = cambered efficiency, η_{mppt} = MPPT efficiency, I_{max} = maximum irradiance, A_{SC} = solar cell area and T_{day} = the day duration.

$$\text{Mechanical power} = \frac{C_D}{{C_L}^{3/2}} \sqrt{\frac{(mg)^3}{S}} \sqrt{\frac{\rho}{2}} \quad \text{(eq. 2)}$$

$$C_D = C_{D\,afl} + C_{D\,ind} + C_{D\,par} \quad \text{(eq. 3)}$$

Where; C_L = lift coefficients, C_D = drag coefficients, $C_{D\,afl}$ = drag coefficient airfoil, $C_{D\,ind}$ = drag coefficient induced, $C_{D\,par}$ = drag coefficient parasitic, ρ = air density, S = wing area, and υ = aircraft's relative speed.

$$\text{Electrical power} = P_{mech} \frac{1}{\eta_{mot}\, \eta_{ctrl}\, \eta_{grb}\, \eta_{plr}} \quad \text{(eq. 4)}$$

Where; P_{mech} = mechanical power, η_{mot} = motor efficiency, η_{ctrl} = motor controller efficiency, η_{grb} = gearbox efficiency and η_{plr} = propeller efficiency.

$$\text{Total electrical power} = P_{Eflight} + \frac{1}{\eta bec}(P_{av} + P_{pld}) \quad \text{(eq. 5)}$$

Where; $P_{Eflight}$ = Electrical power, P_{av} = Avionics power, P_{pld} = payload power. and η_{bec} = BEC (Battery Elimination Circuit) efficiency

$$\text{Total electrical energy} = P_{elec\,tot}\, (T_{day} + \frac{T_{night}}{\eta chrg\, \eta dchrg}) \quad \text{(eq. 6)}$$

Where; $P_{elec\,tot}$ = total electrical power, $\eta chrg$ = the charge efficiency, $\eta dchrg$ = discharge efficiency of the battery for the night period, T_{night} = the night duration and T_{day} = the day duration

$$\text{Solar cell area} = P_{Etot} \frac{\pi}{2\eta_{sc}\, \eta_{cbr}\, \eta_{mppt}\, \eta_{wthr}} \left(1 + \frac{T_{night}}{T_{day}} \frac{1}{\eta_{chrg}\eta_{dchrg}}\right) \frac{1}{I_{max}} \quad \text{(eq. 7)}$$

Where; P_{Etot} = total electrical power, η_{sc}, = solar cell efficiency, η_{cbr} = cambered efficiency, η_{mppt} = MPPT efficiency, η_{wthr}= efficiency of the solar cell in different weather conditions, T_{day} = day duration, T_{night} = night duration, $\eta chrg$ = the charge efficiency, $\eta dchrg$ = discharge efficiency of the battery for the night period, and I_{max} = the maximum irradiance.

2.2.1 Calculation of the Number of Solar Cells for the Design

The required number of solar cells is calculated from the daily solar energy available with the flight profile mission's duration and the peak solar hour (PSH); it is the day that the solar intensity is high (Li, 2019) & (Chiras, 2020).

$$\text{Solar cell wattage} = \frac{\text{Daily Energy}}{PSH} \quad \text{(eq. 8)}$$

$$\text{No. of solar cell} = \frac{solar\ cell\ wattage}{solar\ cell\ power} \quad \text{(eq. 9)}$$

2.2.2 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 (Dwivedi, Kumar, Ghosh, & Kamath, 2018) and (Danjuma et al., 2021)

$$\text{Ampere hour} = \frac{Available\ daily\ Solar\ Energy}{Battery\ Charge\ Voltage} \quad \text{(eq. 10)}$$

$$\text{Number of batteries} = \frac{Ampere\ Hour\ (Ah)}{Battery\ Nominal\ capacity(Ah)} \quad \text{(eq. 11)}$$

3. Results and Discussions

3.1 Solar radiation model of Malaysia

The solar radiation model for Malaysia was obtained from photovoltaic geographic information software data for Malaysia, 2019, as shown in Table 2, and Figure 3 shows the solar radiation map for Malaysia. The model (solar radiation data from PVGIS) was validated using the 6th polynomial. The coefficient of correlation has a value of $R^2 = 0.998$. which shows that (solar radiation data from PVGIS) is 100% convergence and positive, as shown in Figure 4. The maximum irradiance I_{max} of the annual daily average was found to be 825W/m^2 (the cloudness was taken into consideration), and the time duration for the availability of solar radiation (T_{day}), was 12 hours (PVGIS, 2019). The data is incorporated into the MS Excel program to calculate the PD sizing of solar aircraft. However, the model was used to develop the energy balance and the mission path for both Malaysia.

Tab 2: PVGIS solar radiation data 2019 for Malaysia

Time (h)	7	8	9	10	11	12	13	14	15	16	17	18	Total	Average
Month	Radiation (W/m^2)													
January	335	299	512	677	752	755	759	651	529	412	239	92	6012	501
February	216	309	582	759	822	853	807	730	550	401	299	113	6441	536.8
March	213	281	535	701	795	819	785	650	524	370	258	83	6014	501.2
April	217	334	570	725	796	811	795	673	552	382	221	53	6129	510.8
May	225	351	568	669	722	754	739	641	512	388	226	38	5833	486.1
June	164	295	510	652	716	754	732	679	554	453	247	64	5820	485
July	151	246	464	618	687	722	732	671	576	437	288	85	5677	473.1
August	172	251	500	625	705	740	689	609	537	394	245	72	5539	461.6
September	195	214	485	645	730	731	705	620	508	383	219	38	5473	456.1
October	194	282	515	677	784	775	702	564	434	302	157	4	5390	449.2
November	208	343	570	671	753	761	692	548	420	270	137	2	5375	447.9
December	251	258	470	616	693	702	663	604	407	279	208	38	5189	432.4

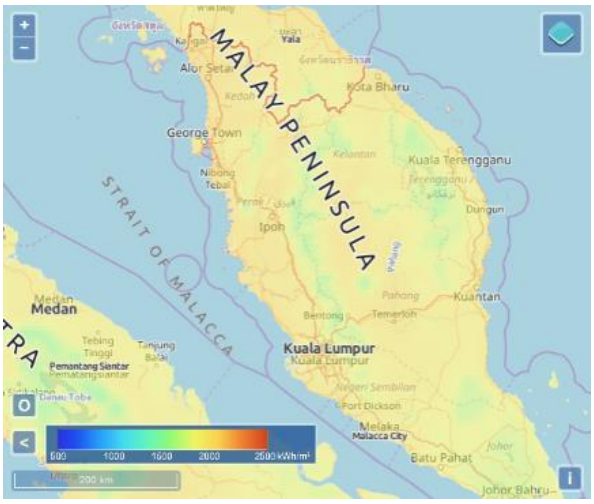

Fig. 3: Solar radiation map of Malaysia

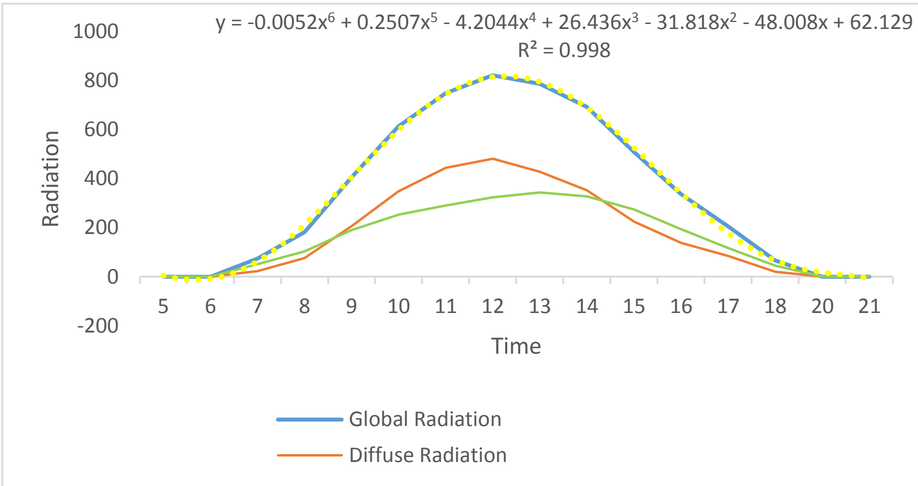

Fig 4: Solar radiation model for Malaysia

3.1.1 Energy balance

The energy balance is a graphical representation of the daily solar energy obtained which was calculated as 578.33 Wh using Equation 1 within 12 hours from Malaysia's solar radiation model, as shown in Figure 5. The green line is the solar energy collected with the period of 6 am to 6 pm. And the yellow line is the excess energy stored in the battery. Also, the energy balance depicts the utilisation of solar energy to power the solar aircraft during the day. And the excess energy is stored in the rechargeable battery to power the solar aircraft at night, while the blue line is the energy used from the battery**.** At the same time, the red line is the total electrical power required by aircraft 18 W.

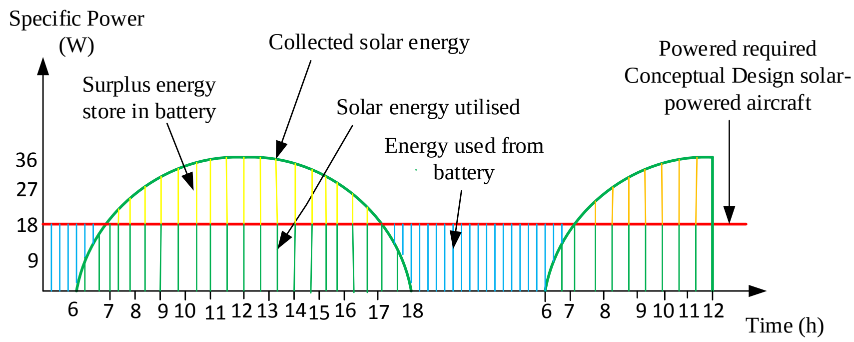

Fig 5: Solar energy balance for Malaysia.

3.1.2 Mission path

The mission path is a profile used to launch the solar aircraft based on the available solar energy collected from Malaysia's solar radiation, as shown in Figure 6. The mission is designed for medium and high-altitude missions to efficiently conserve energy. The mission was launched at 7 am and climbed to an average altitude of 500 m when solar energy is available and dwells at the altitude. After 6 am when solar energy starts to diminish, the aircraft cruise to a lower altitude of 200 m and dwell all through the night. And move to the higher altitude in the morning continuously until the mission is terminated.

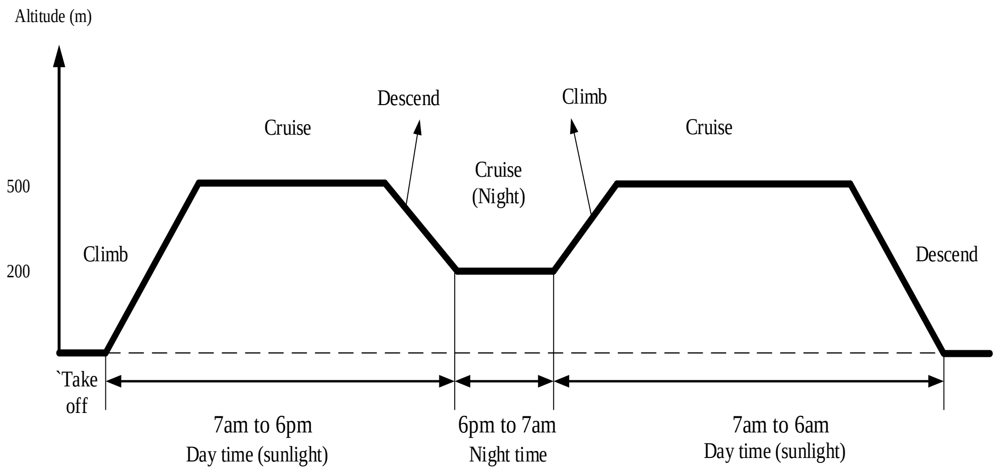

Fig 6: Mission path

3.2 Developed power device

Table 3 presents the result of the power device sizing for solar-powered aircraft. Aircraft configurations, aerodynamic characteristics, and the average annual daily solar radiation for Malaysia were used as the input variable integrated into MS Excel. The output variable determined the number of solar PV cells and rechargeable batteries for the design.

Tab. 3: Design of Power Device Sizing for Solar-Powered Aircraft Table

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 Electrical Power	19.47	W
Chord (a)	0.3	m	Total Electrical 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	-
			Total Mass	2.72	kg

3.2.1 Integration of power device to the solar-powered aircraft

The power device sizing was derived from Equations 9 and 11 used to calculate the number of PV cells as 32 and the number of batteries as 74, respectively. Table 3 depicts the input variable used to calculate the power device sizing of the solar-powered aircraft and the output variable of the results. Figure 7 shows the integration of the power device for solar-powered aircraft applications.

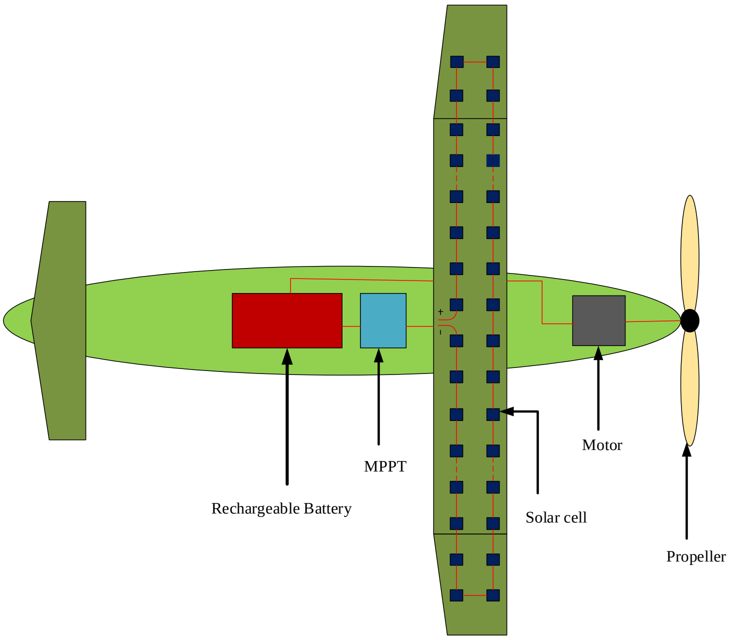

Fig. 7: Integrated power device for solar-powered aircraft

4. Conclusion

PVGIS harnessed solar energy potentials and obtained solar radiation data for Malaysia, and the data was used to develop a model. The model was used to develop both the energy balance and mission path for Malaysia. The energy balance displays the solar energy collected during the daytime from 6 am to 6 pm. The available energy is calculated as 578.33, and the required power is 18 W. The mission path provides an avenue in which the aircraft can take off and navigate from a minimum of 200 m to a maximum of 500 m to conserved energy. The Power device sizing provides the number PV cell as 32 and the rechargeable as 74. The power device was integrated into the solar-powered for effective and efficient application of the solar-powered aircraft.

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