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Impact Analysis of Solar Cells on Vertical Take-Off and Landing (VTOL) Fixed-Wing UAV

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Abstract: A vertical take-off and landing (VTOL) is a type of unmanned aerial vehicle (UAV) that allows for flight in harsh weather for surveillance and access to remote areas. VTOL can be performed without a runway. As such, VOTL UAVs are used in areas where there is limited space and in urban locations. The structural endurance of VTOL UAVs is limited and is further reduced in the case of fixed-wing UAVs. Long-endurance aerial vehicles allow for continuous flight, but their power supply systems must be able to harvest energy from external sources in order to meet the guidelines. The wings of these UAVs are often covered with solar cells. This article presents the extended range and flight time of a tail-sitter VTOL that incorporates solar cells on the UAV structure. A VTOL powered by solar cells can perform aviation missions with fewer landings, allowing for the performance of such UAVs to be increased and for their flight time to be extended several times over those without solar cells. Simulations accounting for the use of PV panels on the UAV structure show that depending on the scenario and flight date, VTOLs can double the flight time on the spring equinox and increase the flight time by more than six times on the summer solstice.

Keywords: VTOL; UAV; renewable energy; model-based design

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1. Introduction

Unmanned aerial vehicles (UAVs) are one of the fastest growing industries, and new applications contribute to the progress of this technology. UAV construction may be defined in many ways depending on the geometry, the way the drive is transferred, and the final destination of use. Vertical take-off and landing (VTOL) is one type of UAV. The ability to take off vertically allows the flight to commence at any location without the need for a runway [1]. We can include multi-rotor drones, tilt-wing UAVs, tail-sitter UAVs, and other hybrid structures in this group. Hybrid VTOLs combine the features of fixed-wing vehicles (wings and fuselage) and multi-rotor drones (horizontal propellers). After reaching the set ceiling, the UAV is able to “transform” into a horizontal position to continue the flight with the help of its wings. This design allows us to extend the UAV’s endurance and obtain better performance during flight. [2].

VTOL UAVs are used in both research and commercial applications. These UAVs are more failproof, making them more reliable than other configurations. This makes them suitable for use in surveillance during harsh weather and for accessing remote areas [3]. A few examples of VTOL UAVs are: SKYX [4], E-flite Convergence [5], VALAQ Patrol [6], WingtraOne [7], and SkyEye Sierra [8]. As in other UAVs, the equipment of VTOL UAVs are based on control, research, and measurement devices. VTOL UAVs can be used to inspect transmission networks and pipelines [9] as well as during various military activities [10].

Long-endurance UAVs use renewable energy sources to extend their flight range and duration [11]. These types of UAVs are sometimes classified as high-altitude long-endurance (HALE) or high-altitude pseudo-satellite (HAPS) [12]. Solar cells are primarily used for energy harvesting and energy production [13–15]. Solar radiation is a common source of energy. During the day, solar energy is consumed according to the current needs of the flight mission, and surplus energy is stored in the batteries. At night or on a cloudy day, the power supply system uses previously stored energy to maintain flight continuity [16].

There are many approaches to solving the problem of building a UAV solar system, including the optimization of its load-bearing features. Some approaches are based on new materials and additive manufacturing [17–19]; others include solar cells with a higher efficiency [20]. Modeling the power supply system of a solar-powered UAV consists of many elements. New designs should consider solar irradiance, aircraft parameters, aerodynamics, the airfoil section, mission profile, mass estimation, etc. [21]. MTOW (Maximum take-off mass), payload, and the mass of the batteries should be considered alongside the intended use of the UAV. If the mass of the battery is too high, the battery will not be able to fully charge, and the UAV will consume more energy [22].

In order to ensure energy autonomy, it is necessary to use the largest possible surface to mount the solar cells. For this reason, the most suitable location for these solar cells is the wing [15,16]. The optimization of the entire structure and the choice of proper materials are the first issue. The second issue, however, relates to the flight scenario. The performance of the assumed mission may change significantly in the event that energy must be saved due to unfavorable weather conditions or other phenomena. In in long-endurance UAVs, energy can be stored in the batteries; this can be combined with the potential energy accumulated in the form of height [23]. This kind of energy can be used as a time buffer.

Based on existing solutions and products, we developed a conceptual model of the tail-sitter VTOL. This conceptual model, based on existing constructions, was used to examine the possibilities of extending the endurance of the flight by installing a power support. Photovoltaic panels were used for this specific UAV. These analyses are to be used to assess the advisability of integrating such systems into this type of UAV. The advantage of the tail-sitter model is a reduction in the number of electric motors when compared to other VTOL models, thereby reducing the weight of the UAV [24]. The tail-sitter model uses the same motors for vertical take-off and horizontal flight. This model ensures that mechanical components are less complex, thereby reducing the cost and risk of failure [24]. On the other hand, the disadvantages of this model are its more complex aerodynamics and the need to develop a control system for different types of flights [25].

Our team developed a number of simulation models based on the model-based design (MBD) methodology, i.e., for general aviation aircraft [26], battery-powered and fuel cell-stack-powered ultra-efficient racing vehicles [27,28], automated guided vehicles (AGVs) [29], and the Twin Stratos (TS) solar-powered UAV [23]. Our experience with the MBD method and analytical calculations shows a similarity of results. The MBD method is often used to design complex mechatronic systems. The use of such a methodology is particularly advantageous when designing systems that require cooperation with specialists from various fields [30]. The simulation model of the Twin Stratos power supply system allowed us to compare the obtained results with the real-environment values. The comparability of the results and the possibility of obtaining full energy autonomy with the Twin Stratos fixed-wing UAV convinced us to begin analyses on increasing the endurance of the VTOL flight. Vertical take-off and landing UAVs use much more energy than a runway take-off UAV. For this reason, achieving full energy autonomy by adopting a tail-sitter type of UAV is a big challenge.

The purpose of this article is to analyze the impact of the use of solar cells on the VTOL structure and investigate how much the use of photovoltaics (PVs) can extend both the VTOL range and flight time. The development of photovoltaic technology and a wide spectrum of VTOL applications create potential for this UAV in the fields of research and commercial services. The developed simulation models will show if the use of the solar cells are profitable for this type of UAV. Increasing the endurance of the UAV allows us to reduce the number of landings and enhance its performance. Increased endurance and flight range open up new possibilities and applications for new types of UAVs.

2. Tail-Sitter VTOL UAV and Mission Parameters

This article analyzes the energy demand of a VTOL UAV whose design is based on SkyX (Figure 1). SkyX is equipped with motors; however, we decided to combine the SkyX structure with a propulsion system such as the one used in WingtraOne—i.e., with two electric motors [7]. The UAV is equipped with solar panels on the wings to charge the batteries while flying using the lift generated by wings.

(**a**) (**b**)

Figure 1. UAV SkyX [4]: (**a**) front view and (**b**) three-dimensional view.

NACA0010 was chosen as the airfoil and the angle of attack of the wing was constant throughout the flight phase at 4.25°. This angle provides a good lift-to-drag ratio.

The highest energy demand occurs during vertical take-off and climb in a horizontal configuration. Therefore, the same method of reaching the designated cruising altitude was developed for each mission scenario. First, the UAV ascends vertically to an altitude of 200 m, followed by a transition to a fixed-wing UAV configuration. This moment involves a loss of altitude and the need to accelerate the vehicle to the appropriate speed using gravity (this can be compared to a glider recovering from a stall). After that, there is a leveling off, and the climb to cruising altitude in the new configuration begins. A diagram of the take-off and climb is shown in Figure 2.

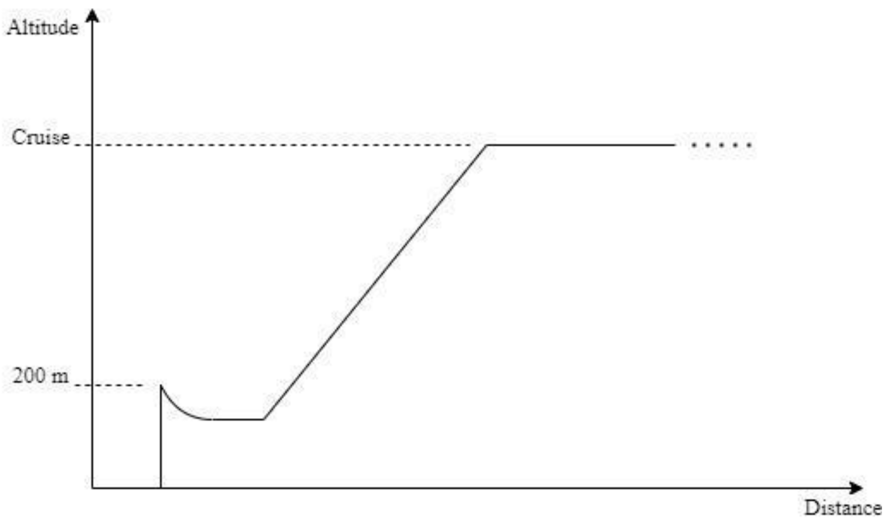

Figure 2. A diagram of the vertical take-off and the further climbing as fixed-wing UAV until the cruise altitude.

Table 1 shows the parameters of the simulated UAV and the parameters of the flight mission. The data in the table combine the design feature and initial analytical calculations. The flight speeds have been selected economically and not optimally, i.e., their value is to maximize flight endurance, not the range. To obtain the maximum flight endurance, the parameters with the lowest power consumption were selected.

Table 1. Parameters of the designed VTOL and mission.

Parameters	
VTOL UAV	
Mass (kg)	10
Wingspan (m)	2.5
Standard Mean Chord (m)	0.5
Payload (kg)	0
Wing area (m^2)	1.25
Angle of attack (deg)	4.25
Maximum altitude (m)	4000
Propeller diameter (m)	0.75
Motor number	2
Battery connection layout	12S6P
Battery voltage (V)	44.4
Battery capacity (kWh)	0.932
Battery mass (kg)	3.6
Number of solar cells	80
Solar cell connection	40S2P
PV mass (kg)	0.528
Take-off and climb	
Vertical T/O speed (m/s)	5
Climb speed (km/h)	30
Rate of climb (m/s)	2.5
Cruise and descent	
Cruise speed (km/h)	50
Descent speed (km/h)	30
Rate of descent (m/s)	0.5

The entire process of developing the design and power supply system was based on the following simple design steps (Figure 3).

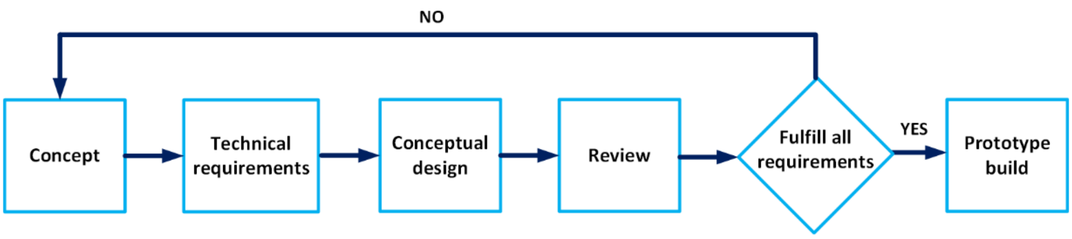

Figure 3. Schematic of the design steps.

2.1. Simulation Model of the Propulsion System

The purpose of simulating UAV under study was to determine the energy requirements to verify the propulsion parameters. For this reason, a backward approach was used in the modelling. The operating principle of both models was based on calculating the required torque of the electric motors based on defined flight parameters. This determined the power consumption. As this UAV belongs to a hybrid class, two simulation models developed with MATLAB/Simulink were used. One model was used to simulate the energy requirements during vertical take-off, while the other was used to simulate a flight in a configuration with the wings aligned horizontally.

The first model allows for vertical take-off to be simulated and was based on the "Electric Aircraft (VTOL) Battery Pack Model with Simscape" developed by S. Miller

(Figure 4) [31]. The "Aerodynamic Propeller" blocks from the Simulink library were used in this model, allowing the propeller diameter to be verified. As this is the most energy-consuming moment of flight, the carried simulation allowed the power of the electric motors and batteries to be determined. In this model, we considered two basic forces acting on the VTOL: thrust and weight. These forces were calculated based on the following equations [32]:

$$T = k_T \rho D^4 \varepsilon n \sqrt{n^2 + n_{thr}^2}$$

$$W = mg$$

where T—thrust (N), k_T—thrust coefficient with respect to the propeller rotational speed, ρ—air density (kg/m^3), D—propeller diameter (m), ε—propeller direction, n—propeller angular speed (rev/sec), n_{thr}—rotational speed threshold, W—weight (N), m—VTOL mass (kg), and g—standard gravity (m/s^2).

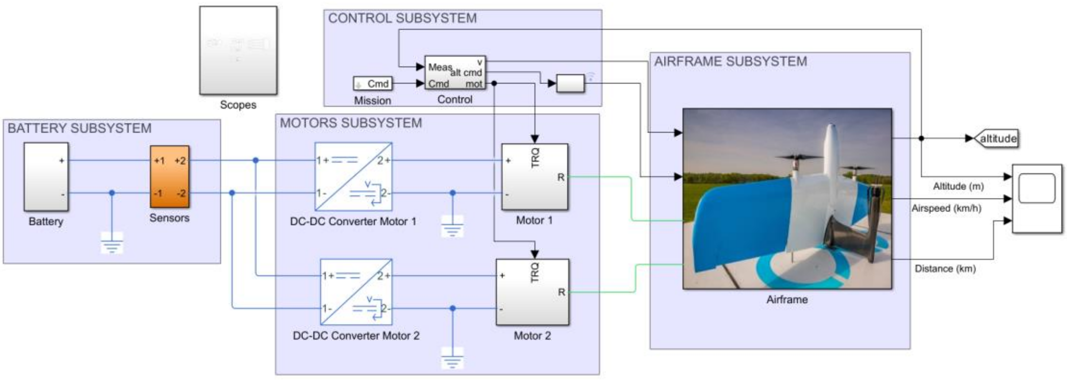

Figure 4. Model for vertical flight simulation.

The model developed for previous simulations of electric aircraft and fixed-wing UAVs (Figure 5) [23,26] was used as the second model. It allows for the simulation of a climb, level flight, descent, or glide of the UAV using the lift force created on the wing.

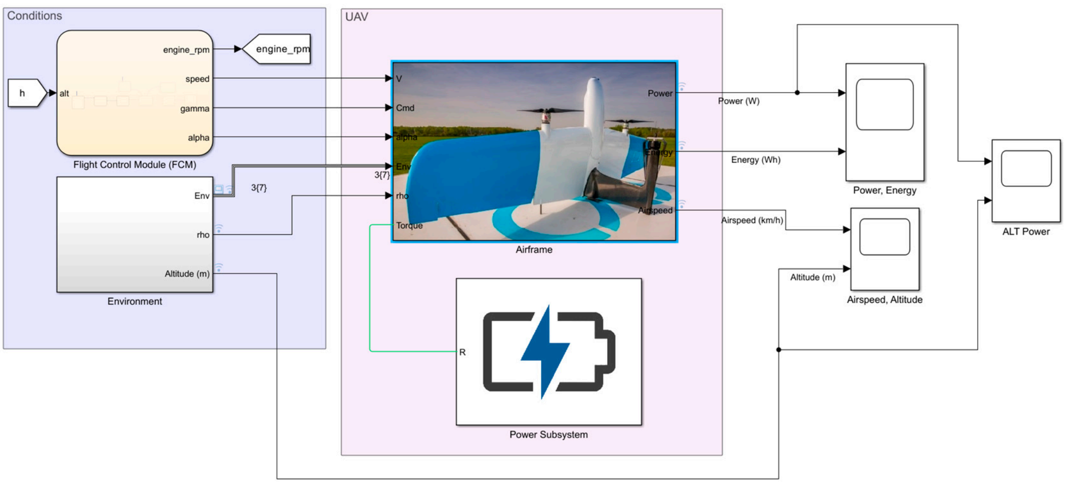

Figure 5. Model for fixed-wing UAV flight simulation.

This model is based on the following basic equations:

$$T = D + W\sin\gamma$$

$$q = 0.5\rho v^2$$

$$L = qSC_L$$

$$D = qSC_D$$

where: T—thrust (N), D—drag (N), W—weight (N), γ—flight path angle (rad), q—dynamic pressure (Pa), ρ—air density (kg/m^3), v—aircraft velocity (m/s), L—lift (N), S—VTOL wing area, C_L—lift coefficient, and C_D—drag coefficient.

In each of the models, it was assumed that the flight takes place in windless conditions and, to simplify the simulation, the effect of temperature on battery operation was not taken into account. In addition, the developed simulation models did not consider the power consumption of additional equipment.

2.2. Simulation Model of the Power Supply System

To assess the energy balance of the analyzed VTOL, we used the simulation model developed in our previous research. The exact parameters of this model are more precisely described in the article [23].

The simulation model input parameters were divided into two groups. The first contained external data beyond our control, e.g., weather conditions. The second group contained internal data that we could interfere with, e.g., by changing the flight path. The integration of external and internal input data allowed us to obtain information about the amount of produced solar energy. This value was then transferred to the model of the solar power management system (SPMS). The SPMS contains information about the parameters of the used solar cells, maximum power point tracking (MPPT), battery management system (BMS), and battery cells. The power supply system allows for the determination of the energy stored in the batteries and the current value of the energy produced by the PV panels. The system is then connected to the load (electric motors, on-board, measuring, and control devices). Its feedback enabled us to control and know the state of charge (SOC) and energy balance of the UAV. The general process is shown in Figure 6.

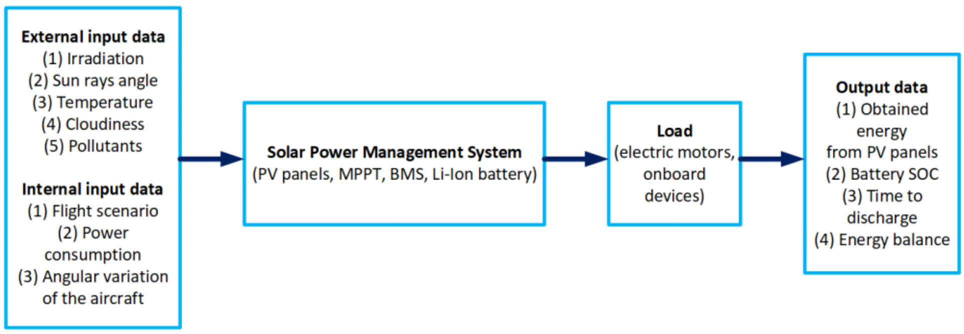

Figure 6. The process of defining parameters in the simulation model.

We decided to use the SunPower Maxeon Ne3 as our solar cell. Additionally, the PV panels were coated with the PVC (Polyvinyl Chloride) film. Film laminations improve the aerodynamics of the wings and protect the solar cell surface from scratching, ill effects of chemicals, or poor weather conditions. The lamination causes a decrease in the efficiency of the PV panel but extends the life of the system. The process of laminating solar cells for UAVs was described more precisely described in [33]. A total of 80 solar cells could be placed on the VTOL wings in the connection layout of 40S2P. The use of 80 solar cells allowed for the entire surface of the wings to be covered with PV panels. This is a considerable simplification due to the fact that part of the wing structure was occupied by, e.g., ailerons, which were not covered by solar cells. The arrangement of the solar cells is not important in this kind of VTOL, e.g., there was no high fuselage which could darken part of the wing. As many solar cells as possible should be placed on the VTOL wings to obtain more energy.

VTOLs can take off at different positions with respect to the direction of the sun rays. External conditions may cause a change in the take-off position, e.g., depending on the direction of the wind. This prevents the full definition of the position of the UAV in space relative to the sun. Due to the very short period of vertical climbing compared to the duration of the entire mission, it has been assumed that in this time, the system will be irradiated with the value without the climb angle change.

Take off and climbing consume most of the energy. The purpose of the cruise stage is to maintain flight at altitude and also to recharge the batteries under proper conditions. The energy used by the electric motors depends on the situation and the stage of the flight. For other onboard devices which control the work of the VTOL, the power consumption can be set as a constant. Due to the low percent of the whole energy consumption, we can take into account the maximum value of power consumption of additional systems. For our VTOL, this value was defined as 20 watts.

The battery pack used was built with Li-Ion cells. We decided to use Samsung INR18650-35E. Samsung battery cells provide a high energy density and allow for operation at wide range of temperatures (from −10 °C to 60 °C). Built energy storage provided the capacity equal to 932Wh. The cells in the battery were connected in a 12S6P layout.

2.3. Prepared Scenarios of Flight

In the simulation model, we divided operational missions into two categories. The first category was related to the possible end use. In this kind of mission, the VTOL will take off and climb to the set height. Next, at this altitude, the UAV will continue the flight. This type of flight is mainly used for pipeline leak monitoring, border control, etc. The second scenario is based mainly on maximizing the flight endurance. After taking off, the UAV will ascend to the highest possible altitude and then maintain flight at this altitude.

A graphic representation of the simulated scenarios is presented in Figure 7. For the first scenario, we used a 1 km altitude to perform a controlled flight that monitored a specific transmission line. For the latter scenario, we used a maximum height of 4 km. At this altitude, the flight was continued. For both scenarios, we checked the maximum time of flight at the height up to 0% of the SOC. The goal was to determine how much further VTOLs can fly with the PV panels. The 0% SOC is simply for theoretical research. In the practical flight, a surplus of SOC must be provided to bring the UAV down safely.

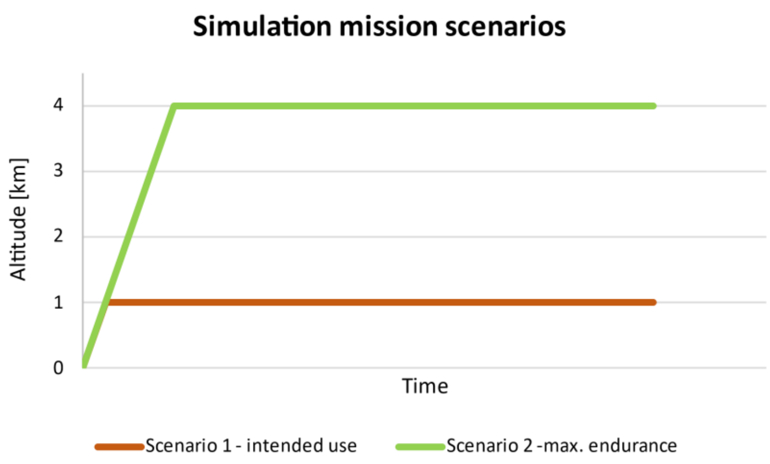

Figure 7. Mission scenarios considered in the simulation model.

Another case will investigate how long the VTOL is able to fly at 1 km and 4 km altitude to 20% of the SOC. This value is safe to ensure appropriate work of the system during gliding and landing.

The vertical climb to an altitude of 200 m lasted 40 s. The transition to a fixed-wing UAV allowed for a change in the flight parameters, and first 1000 m was achieved in 6 min. The altitude of 4000 m was reached by the VTOL after 26 min.

In the target scenario, which should also include gliding, the time needed for the operation should also be considered. Using the ROD (rate of descent) value, we can calculate that the gliding and landing time for the 1 km flight scenario was extended to approximately 33 min, whereas the gliding and landing time for the 4 km scenario was extended to approximately 2 h 13 min. During gliding, only on-board devices which consume a low percent of the energy work. An increased energy demand occurs during landing, when the VTOL changes its position by 90 degrees.

Prepared flight paths were be simulated for the Gliwice location in Poland. In simulation, the different dates were taken into account. In the research, we aimed to discover how large the variation in the time of flight is on the spring equinox and summer solstice.

3. Results and Discussion

3.1. Power Consumption

First, the power demand during the vertical take-off and subsequent climb was simulated (as described in Section 2). The power demand for the vertical flight compared to climbing in a fixed-wing configuration was approximately 3.5 times higher (Figure 8). When using the wings for climbing, the analyzed UAV had an almost constant power demand up to the maximum altitude, which oscillated around a value of 250 W.

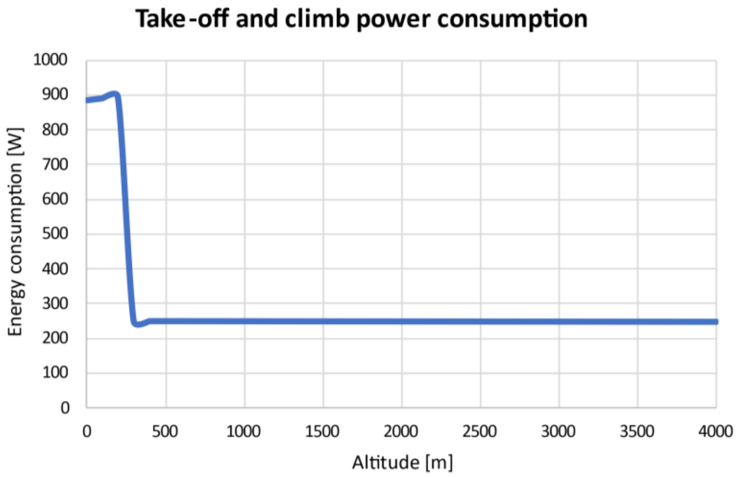

Figure 8. Energy consumption during take-off and climbing.

When flying horizontally, altitude has a huge impact on power requirements, which affects the air density. Between horizontal flight at 100 and 4000 m above sea level, the difference is 10.43 W on the minus side of the lower altitude (Figure 9).

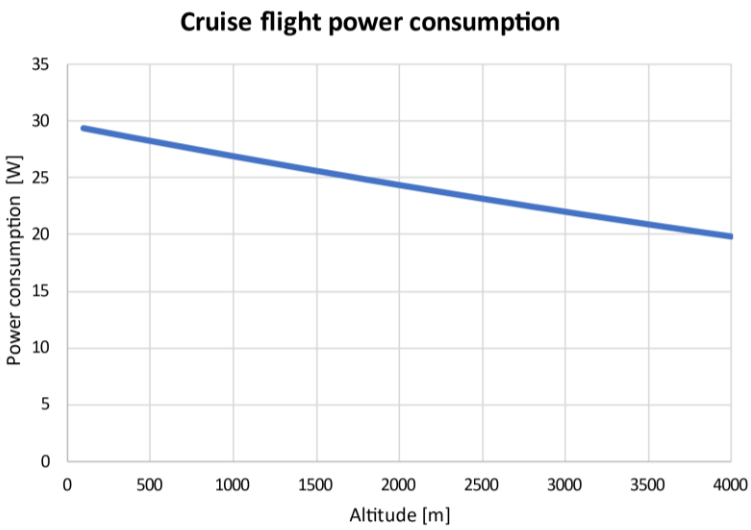

Figure 9. Power consumption during cruising for different altitudes.

Regarding the take-off power consumption, an efficiency of 90% was taken into account. An efficiency of 50% was taken into account for climbing and 20% for cruising. The difference is due to the large differences in the energy requirements of these stages of flight. These values result from the map of the proportions of the expected load to the nominal load [34].

3.2. Power Supply System

The value of the power consumption is the sum of the power needed by the electric motors, the efficiency of the electric motors, and the constant value of the on-board devices. Each scenario excluded the gliding and landing stage. The main assumption was to know the value of flight time extension.

Each flight mission was conducted for three versions:

1. Without photovoltaics and solar energy generated by PV panels;
2. With solar energy generated by PV panels on the spring equinox;
3. With solar energy generated by PV panels on the summer solstice.

All simulations considered perfect weather conditions without cloudiness, pollutants, and other external conditions that limit the PV power. In case of bad weather conditions, it would be necessary to take into account the okta scale, which is related to cloudiness [17,35]. Sunrise was used as the time for take-off. The take-off and climb consumed most of the energy. Achieving the set ceiling allows for a change in the position of the VTOL and continuing the flight with a lower power consumption. It allows the battery to recharge in the event of obtaining a positive energy balance, the peak of which is at noon. Figure 10 presents the SOC of the battery in the case of three versions of Scenario 1—1 km continuous flight.

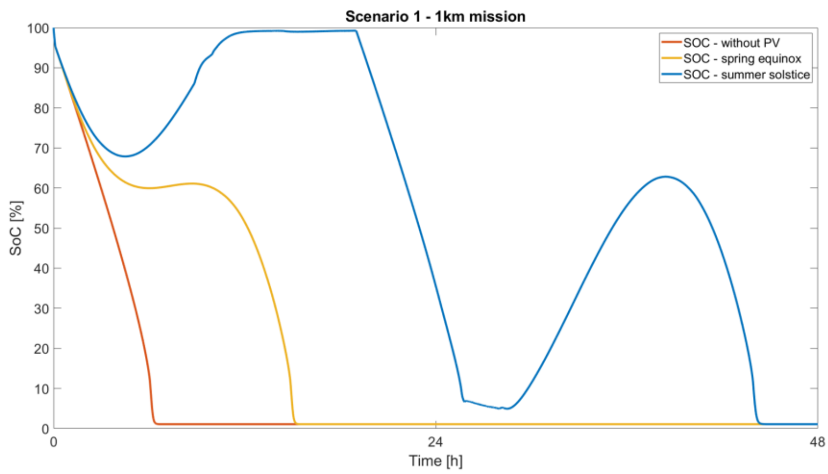

Figure 10. State of charge of the battery during the continuous flight at 1 km.

Without PV panels, the VTOL was able to fly for 6 h and 20 min. With the solar cells on the spring equinox, the UAV was able to fly for 15 h and 10 min, and on the summer solstice for 44 h and 10 min. The critical moment for flight during the summer solstice was the time around sunrise on the next day. Until the VTOL is unable to achieve a positive energy balance, the SOC gradually decreases. At its worst, the SOC was below 5%.

Figure 11 presents the dependencies of the UAV energy demand and the power that the PV panels were able to produce. We can observe time intervals in which the energy produced by the PV panels exceeded the energy consumption and allowed batteries to charge.

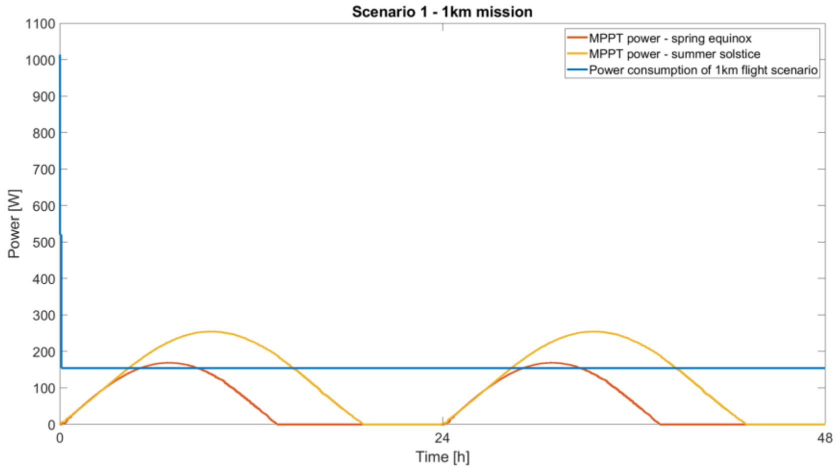

Figure 11. Power consumption and MPPT power produced by solar cells for 1st scenario.

It can be observed that on the spring equinox that the energy from the PV panels was higher than the energy consumption for only 3 h. On the summer solstice, this time extended to 10 h. During this time, batteries are able to recharge. It can be observed that a small excess of energy on the spring equinox maintained the SOC at the same level, while the SOC was able to recharge to 100% on the summer solstice.

The second mission scenario was developed in a similar way. A longer climbing time caused a larger SOC drop. The cruise flight at the higher altitude required a lower energy consumption by the electric motors. Using the maximum height of flight allowed the flight duration to be extended in relation to the first scenario mission. In addition to the energy accumulated in the batteries, a significant reserve of potential energy was also accumulated during the large surplus in the production of energy from the PV system. The SOC of the second mission scenario—4 km of continuous flight—is presented in Figure 12.

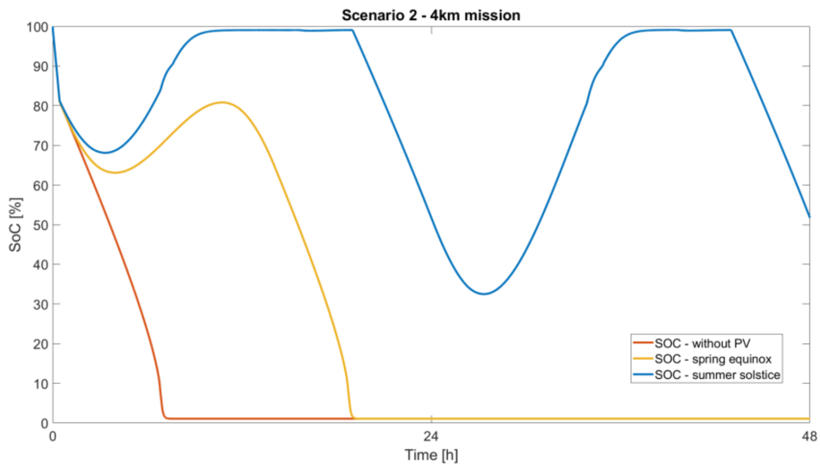

Figure 12. State of Charge of the battery during the continuous flight at 4 km.

In this type of flight, the VTOL without solar energy was able to fly for 7 h. On the spring equinox, this time was extended to 19 h, and for the summer solstice the VTOL was able to fly for over 48 h. The slight variation between the flight times for Scenario 1 and 2 (without PV) caused the energy "lost" in climbing 3 km higher to be "made up" in cruising flight at a higher altitude. Figure 13 presents the power consumption and MPPT power from the second scenario.

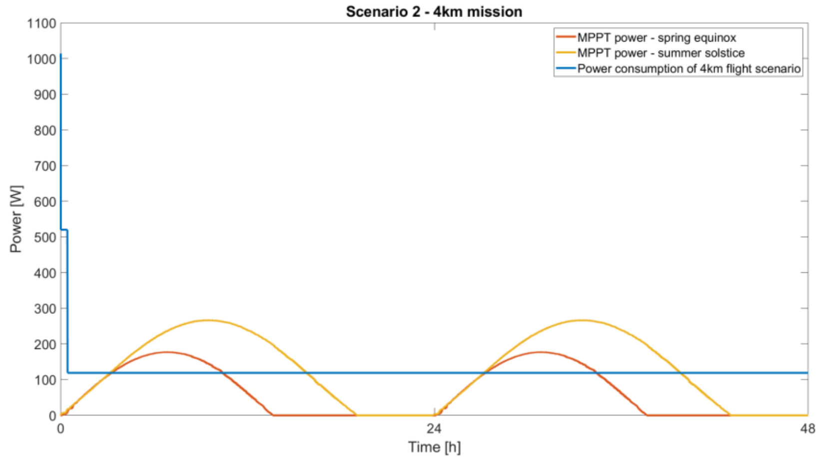

Figure 13. Power consumption and MPPT power produced by solar cells for the second scenario.

The MPPT power was the same as for the first scenario. In Figure 12, we can observe a longer time of power consumption during the climb to higher altitude and a lower power consumption for cruising than in the previous flight mission. By analyzing Figures 12 and 13, it can be seen that the batteries in this scenario were able to recharge during both the spring equinox and summer solstice. On the summer solstice, batteries were able to charge to 100%; however, on the spring equinox, the batteries charged to 74%.

The higher SOC recharge values of Scenario 2 compared to Scenario 1 were caused by the longer time and the higher amplitude of energy surplus. For the spring equinox, this time surplus duration was approximately 6 h, and it was 10 h on the summer solstice.

Parameters of both missions are presented in Table 2.

Table 2. VTOL flight parameters.

	Without PV	Spring Equinox	Summer Solstice
MPPT energy during the day [kWh]	-	4.02	7.68
Time of day duration (h)	-	12:15	16:25
1 km flight			
Flight time to 0% SOC (h)	6:20	15:10	44:10
Average increment	-	1.35 times	5.8 times
Flight time to 20% SOC (h)	5:40	14:30	25:00
Average increment	-	1.5 times	3.3 times
4 km flight			
Flight time to 0% SOC (h)	7:00	19:00	>48:00
Average increment	-	1.5 times	over 5 times
Flight time to 20% SOC (h)	6:10	18:10	>48:00
Average increment	-	1.65 times	over 5 times

4. Conclusions

The simulation results show that a VTOL power supply system additionally equipped with solar cells can extend the flight duration. The preliminary calculations, despite the concept of the solution, have great potential, as shown in the results.

For both scenarios, sunny weather was adopted without cloud cover, which additionally allowed the UAV to obtain more energy from the PV panels. While such a simplification can be adopted for summer, a specific cloudiness factor should be assumed in other periods. The winter and autumn periods were not taken into account due to numerous rains and snowfalls which would not only significantly reduce the PV power but also worsen flight conditions.

Between the spring equinox and the summer solstice it can be observed that the flight time increased several times. This value can vary for each scenario and location. VTOL inspection missions are intended mainly for flight at a constant altitude.

By analyzing the results, it can be concluded that:

- Take-off at sunrise allows for the flight duration to be maximized due to the high energy consumption during climbing and the recovery at cruise flight around noon, when the irradiation is at its greatest;
- The altitude can be used as a time and energy buffer which can additionally extend the flight duration;
- Cruising flight should be performed at the highest altitudes if the goal is long-endurance flight;
- The mission type can change the power consumption, especially at unexpected moments, which will cause the need to climb;
- Cruising flight consumes a constant energy value (for perfect conditions), which makes it possible to calculate the distance and time for which the VTOL is able to fly at a given altitude to set a limit for the SOC level.

It can be observed that when flying at 1 km and 4 km on the summer solstice, the PV energy was able to charge the batteries to 100% SOC. Analyzing the graphs (Figures 9 and 11), it can be seen that then the energy from the solar cells was not fully used and could additionally charge the batteries if they had a larger capacity. During the summer solstice, for 10 h and 12.5 h, respectively, the MPPT power was higher than the power consumption for the 1 km and 4 km missions. A higher battery capacity involves increasing the weight of the power supply system and the entire VTOL. Increasing the number of battery cells could result in the battery not reaching a 100% charge from the PV panels before and after the summer solstice period. Another option to use the surplus energy is to climb the UAV to a higher altitude. However, this requires changing the design of the VTOL and performing additional calculations to achieve a higher flight altitude.

Analyzed mission scenarios were initially aimed at determining the impact of using PV panels on VTOL wings. More precise flight paths should take into account the wind speed and direction. Each flight should also be reported and approved by an Air Navigation Services Agency. This can result in significant changes in the flight scenario related to the specific time in a specific zone.

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Abbreviations

AGV	Automated Guided Vehicle
BMS	Battery Management System
HALE	High Altitude Long Endurance
HAPS	High Altitude Pseudo Satellite
MBD	Model-Based Design
MPPT	Maximum Power Point Tracking
PV	Photovoltaics
PVC	Polyvinyl Chloride
ROD	Rate of Descent
SOC	State of Charge
SPMS	Solar Power Management System
TS	Twin Stratos
UAV	Unmanned Aerial Vehicle
VTOL	Vertical Take-Off and Landing

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