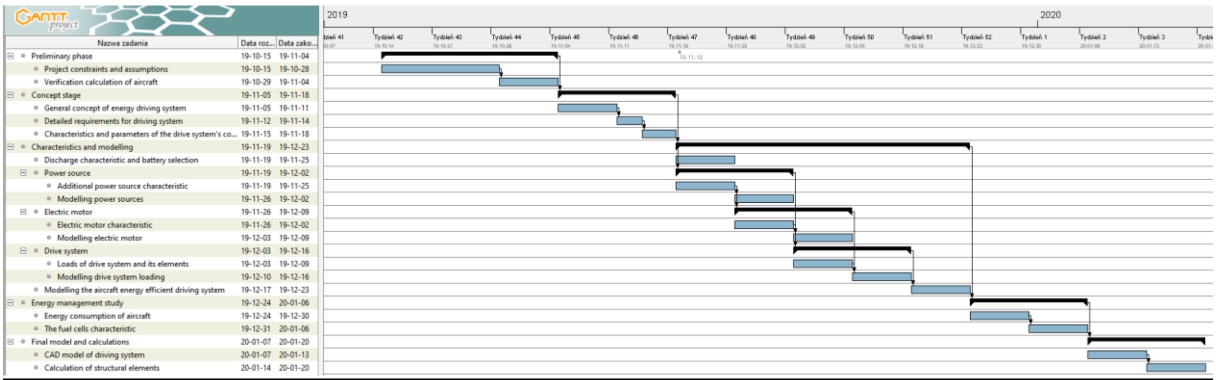
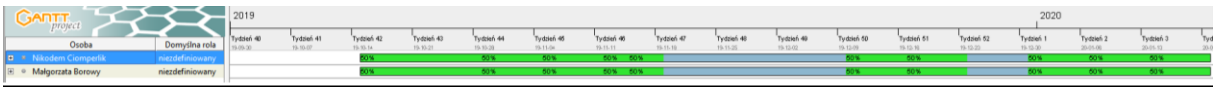
STAGE 1: PRELIMINARY PHASE

1. ORGANIZATIONAL DETAILS – GANTT'S CHART

Nazwa zadania	Data roz...	Data zako...
Preliminary phase	19-10-15	19-11-04
Project constraints and assumptions	19-10-15	19-10-28
Verification calculation of aircraft	19-10-29	19-11-04
Concept stage	19-11-05	19-11-18
General concept of energy driving system	19-11-05	19-11-11
Detailed requirements for driving system	19-11-12	19-11-14
Characteristics and parameters of the drive system's co...	19-11-15	19-11-18
Characteristics and modelling	19-11-19	19-12-23
Discharge characteristic and battery selection	19-11-19	19-11-25
Power source	19-11-19	19-12-02
Additional power source characteristic	19-11-19	19-11-25
Modelling power sources	19-11-26	19-12-02
Electric motor	19-11-26	19-12-09
Electric motor characteristic	19-11-26	19-12-02
Modelling electric motor	19-12-03	19-12-09
Drive system	19-12-03	19-12-16
Loads of drive system and its elements	19-12-03	19-12-09
Modelling drive system loading	19-12-10	19-12-16
Modelling the aircraft energy efficient driving system	19-12-17	19-12-23
Energy management study	19-12-24	20-01-06
Energy consumption of aircraft	19-12-24	19-12-30
The fuel cells characteristic	19-12-31	20-01-06
Final model and calculations	20-01-07	20-01-20
CAD model of driving system	20-01-07	20-01-13
Calculation of structural elements	20-01-14	20-01-20





Main tasks are split in several smaller ones. All tasks were divided equally between both students. To each task, time for completing it was assigned. Some tasks would be performed at the same time. In that case one task is provided for one student. When there's only one task to do, it would be done by both students. All dates may change.

2. DESIGN ASSUMPTIONS AND CRITERIAS

The aim of this project is to create low altitude long endurance UAV. An example of such UAV is Atlantic Solar. Main parameters of this aircraft are shown in the table 1 and technical drawing is in the attachments.

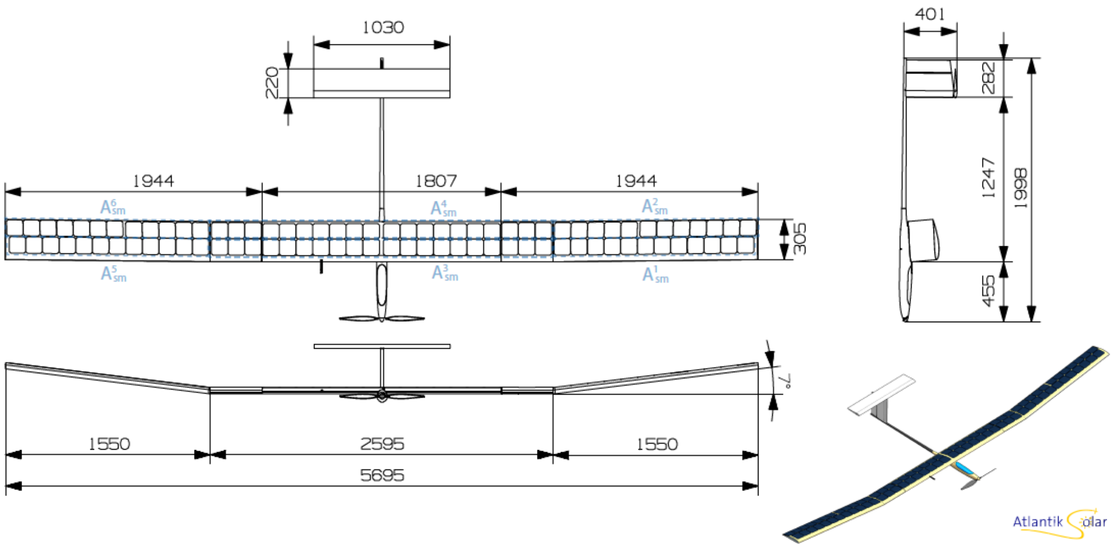


Figure 1 AtlantikSolar UAV

AtlantikSolar UAV – Technical Overview

Wingspan	5,6m
Mass	6,3kg
Structure	Lghtweight carbon fibre & kevlar composite
Power System	1,4m^2 solar panels with Li-ion batteries
Flight Control	Autonomous control system, GPS-Navigation
Payload	Digital HD camera, live-image transmission

Solar powered electrical drive instead of conventional combustion engines allow to minimize the dimensions of an aircraft. There is no need to carry fuel tanks, only the batteries. Reducing its size.

General assumption of the mission profile is that the UAV climbs during the day, while charging the batteries, and glides during night. Safety systems, that need energy supply, use the energy stored in batteries. Power supply and drive system ensures continuous operation of engine only during the day hours. At night the UAV's engine doesn't need power supplied to it, so the aircraft sinks with constant velocity. Initial mission profile is shown of the fig. below.

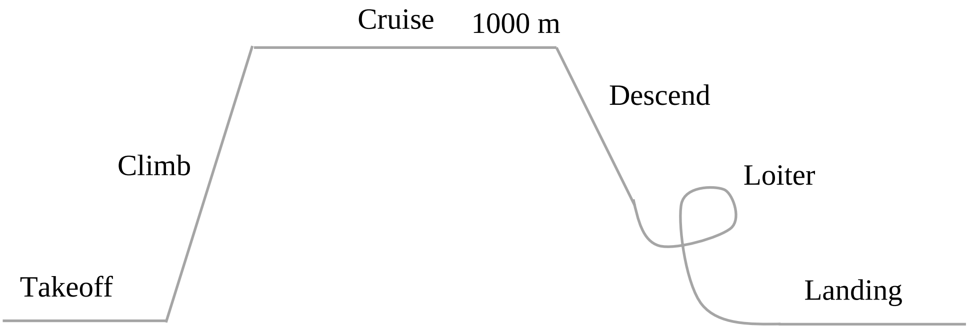


Figure 2 Mission profile

Main part of the mission is Cruise at the altitude 1000 m. This part of the mission takes part during day and during the night. Charging and discharging the batteries was described above. Other parts of the mission – take-off and climb should be performed during the day at hours when the irradiance performance is the most satisfying. Descend and landing probably also should be performed during day, when maneuvering and steering of the aircraft will be much easier than during night.

Solar panels would be mounted on the wings, Li-Ion batteries would be in the fuselage and an electric engine would be mounted in the nose part. While gliding, propeller's blades would fold along fuselage to decrease drag. To decrease weight, it would not be any landing gear attached to the fuselage.

Material for structure: carbon fibre

3. Ideation method and optimal concept choice, state of art

The best ideation method for this case is brainstorm and reverse engineering. All ideas and concepts would be discussed between both members of the group. The project would be conducted basing on an existing UAV's project, so some of the solutions would be similar to the original ones. The best solution for the problem should be chosen taking into account estimated costs of the project, influence of the driving system on the whole aircraft (weight, size, performance), the most beneficial properties of the driving system.

https://www.sciencedirect.com/science/article/pii/S1000936119301268

Solar panels at the top part of the wing – they will cover whole top surface, possibly can also cover horizontal tail if needed.

Battery distributed within the wing. As in the AtlanticSolar the batteries can be hided inside the spar – long spar, most of the loads carried by spar (this concept was chosen).

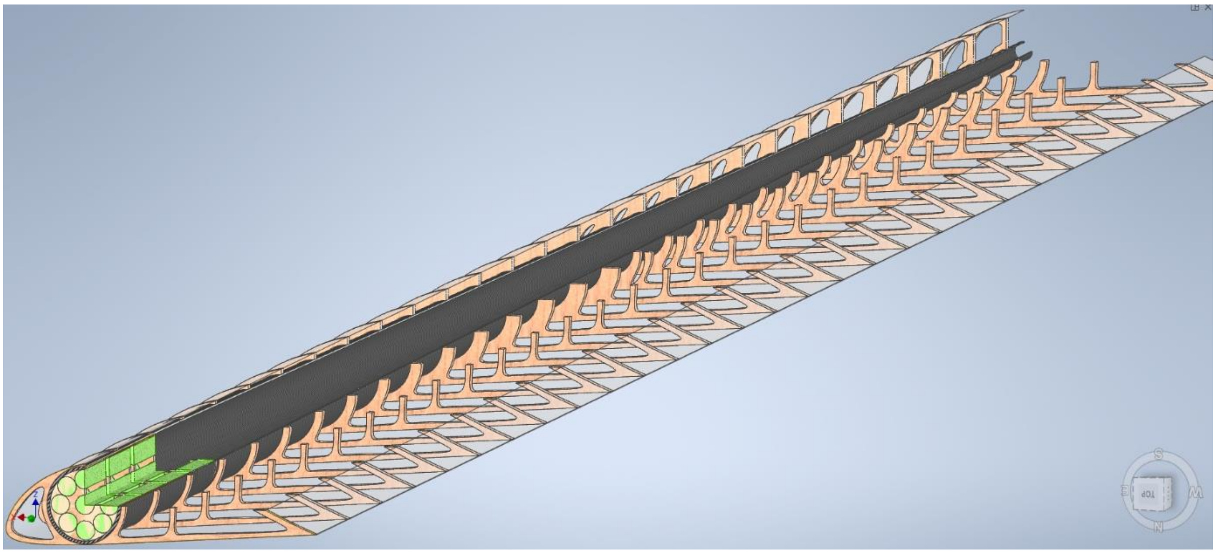


Figure 2 Wing structure with batteries placement

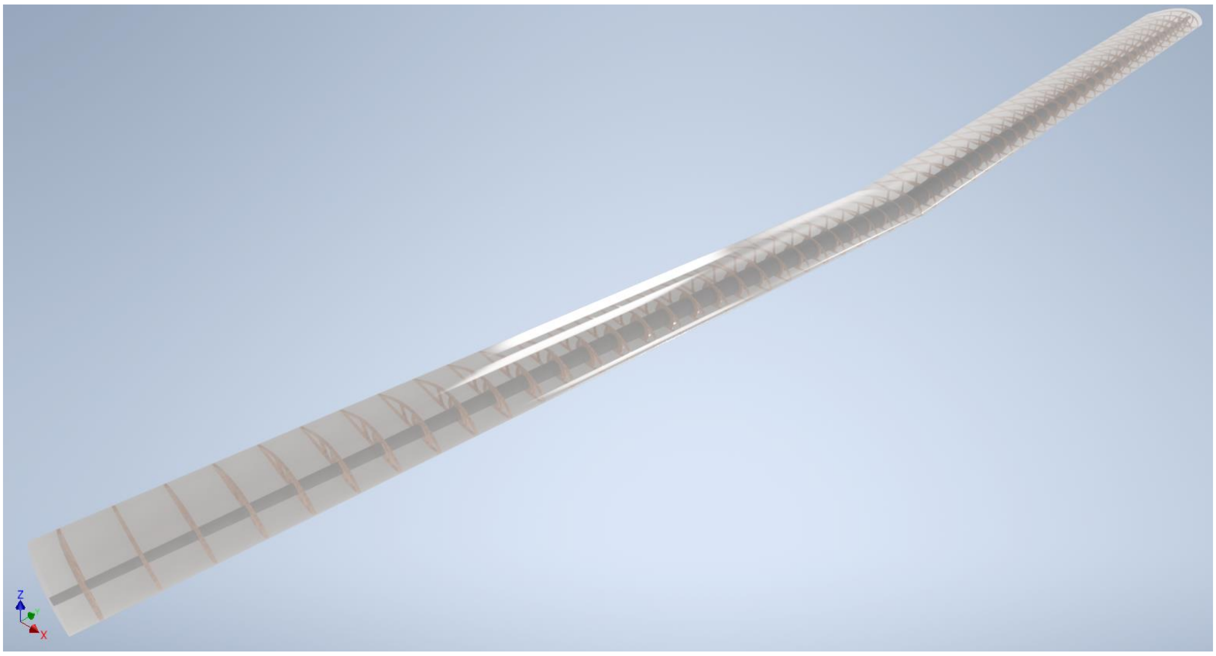
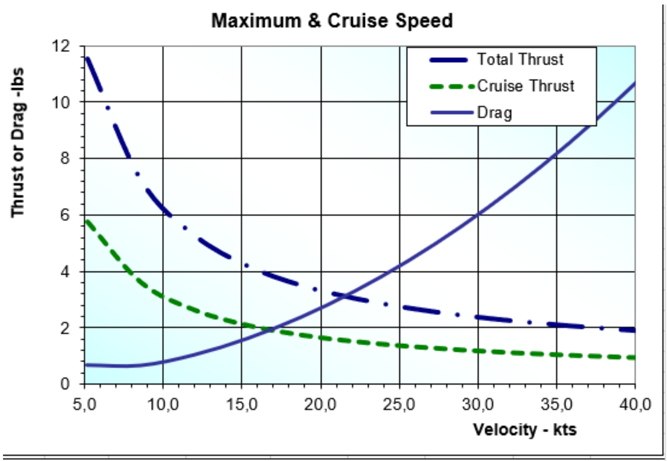
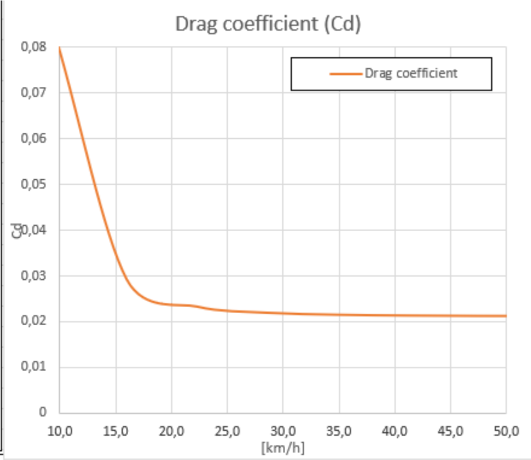


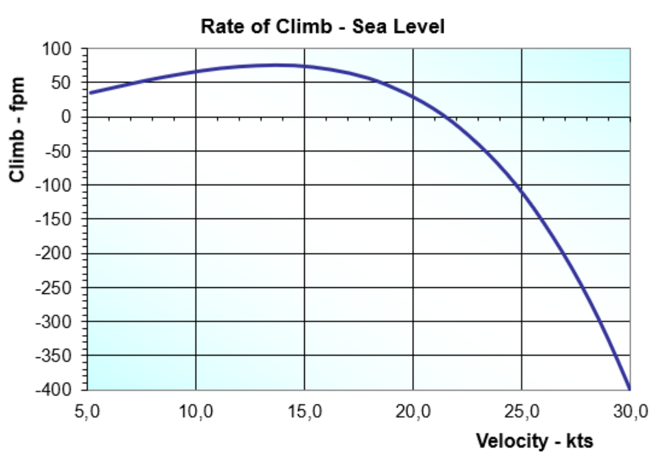
Figure 3 Wings

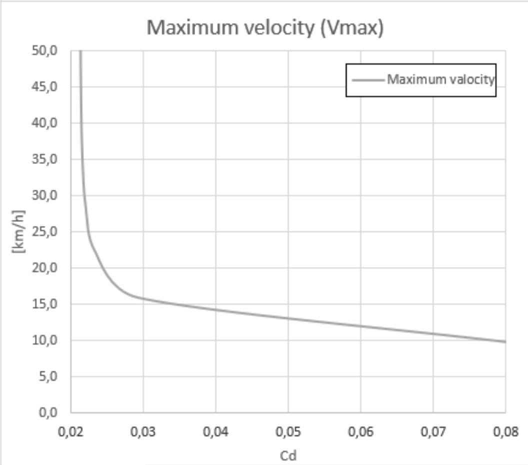
STAGE 2:

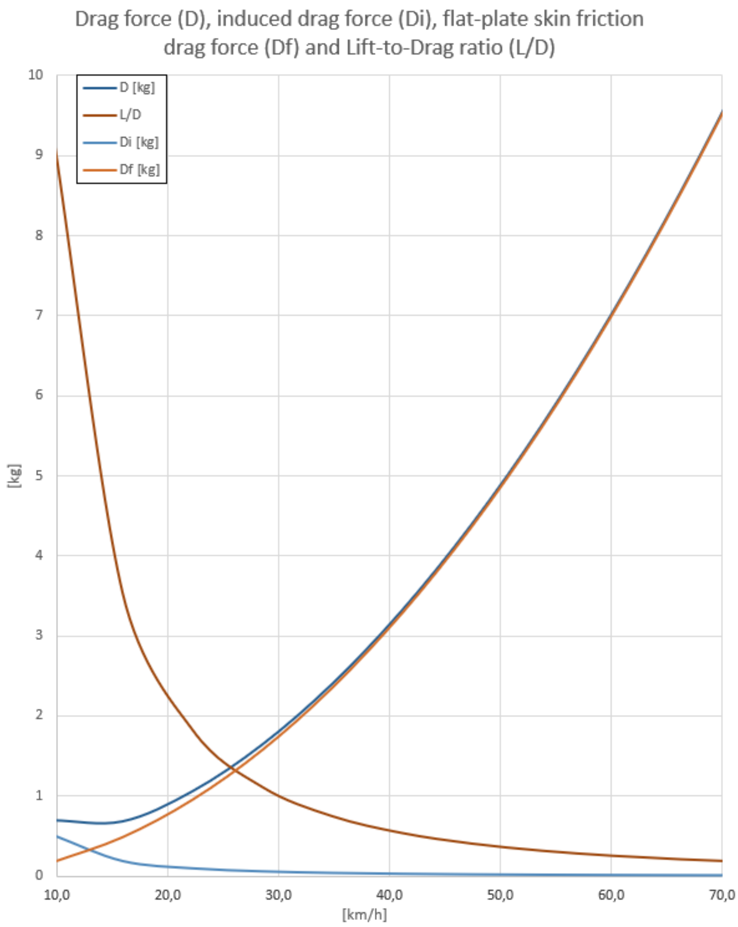
VERIFICATION CALCULATIONS OF AIRCRAFT CONCEPT











Wight Sheet

	Weight [lbs]
STRUCTURES	**9,7**
Wing	6,2
Horizontal Tail	0,7
Vertical Tail	0,3
Ventral Tail	0,0
Fuselage	2,5
Canopy	0
Nacelle on wing	0
Nacelle/cowling	0
Motor Mount	0
Main Landing Gear	0
Nose Landing Gear	0

PROPULSION	**3,5**
Engine	0,5
Air Induction	0
Cooling	0
Misc. Engine Inst	0
Engine Controls	0
Battery	2,5
Propeller	0,5
Starter	0
Fuel System	0

	Weight [lbs]
EQUIPMENT	**0,0**
Flight Controls	0
Instruments	0
Hydraulics	0
Electrical	0,0
Avionics	0
Air Conditioning	0
Anti-Icing	0
Furnishings & Equipment	0

(% We Allowance)	5
Empty Weight Allowance	0,7

TOTAL WEIGHT EMPTY	**13,9**

USEFUL LOAD	**0,0**
Crew	0,0
Fuel	0,0
Oil	0
Passengers	0
Payload	1

Total required electric output power is a sum of power needed for propeller, avionics and payload:

$$P_{out} = P_{prop} + P_{av} + P_{payload}$$

Basing on data for similar constructions:

$P_{av} = 6\ [W]$ (historical data)

$P_{payload} = 1{,}5\ [W]$ (provided for camera)

$P_{prop} = 128$ [W]

STAGE 3: GENERAL CONCEPT OF EEDS, REQUIREMENTS AND PARAMETERS OF THE DRIVING SYSTEM

Requirements for the driving system – based on preliminary design of the aircraft (stage 2) and conditions of flight :

- Capacity of the batteries should be enough to power servos that steer control surfaces, communication devices, sensors and main control unit during night. There should be a margin for a situation when the weather (clouds) doesn't allow to charge the batteries constantly – continuous operation of the engine during day should be provided;
- Range of rotational speeds of the engine should be equal to required rotational speed of the propeller for different parts of the mission. If this condition is not fulfilled, then there is a need for gear box;
- Servos providing sufficient moment for controlling the control surfaces;
- Communication devices – their range is sufficient for given mission and operational area;
- Solar panels – weight as low as possible, voltage, etc.
- Devices that would be included in the payload will be powered from the same source as the rest of devices of driving system.

Elements of the EEDS system of the AtlanticSolar UAV. Information was gathered thanks to well-developed documentation of this aircraft made by its constructors. Unfortunately, not all elements of the system was fully described. Below there is a table with description of AtlanticSolar's elements and most important features.

Element	Name	Specification
Battery	Panasonic NCR18650b	Fitted in wing spars, amount: 60, cylindrical, Lithium-Ion, 251 Wh/kg, connected in a 6S configuration, mass 2,92kg
Solar panels	SunPower E60	88 cells, max power output 275W, aerial density k_sm=590g/m2, module-level efficiency 23,7%
Energy generation and storage system control	Custom-made	Maximum Power point Trackers (MPPTs)and battery management system
Engine	RS-E Strecker 260.20	Brushless DC motor, kv=470 RPM/V
Motor controller	Kontronik Koby 55 LV	
Gearbox		All-steel planetary gearbox with four pinion gears and a 5:1 reduction ratio with a foldable custom built carbon-fiber propeller with diameter D= 0.66 m and pitch H= 0.6 m attached to the motor output shaft
Actuation servos	Volz DA 15-N	4 servos control 2 ailerons, elevator and rudder
Avionics	Pixhawk PX4 Autopilot (Meier,Honegger, & Pollefeys, 2015)	An open-source software and open-source hardware project initiated at ETHZurich; provides a real-time operating system and features a 168 MHz Cortex M4F microprocessor with 192 KB RAM
Attitude estimation		ADIS16448 10-Degrees of Freedom (DOF)Inertial Measurement Unit (IMU), u-blox LEA-6H GPS receiver, Sensirion SDP600 differential pressure sensor interfaced to the autopilot;
Communication		433 MHz medium-range telemetry link and a long-range Iridium-based satellite backup link are integrated
Light position indicators		Night operations are possible due to four on-board high-power indicator LEDs.
Payload applience		2 cameras, memory card and other devises

Preliminary selection of the motor (it is needed for initial calculation and selection of solar panels and batteries – next two stages). Technical data of selected motor:

Daten des Herstellers (ergänzt):

Motor:	**RS 330/20/14-14p**	**RS 330/25/14-14p**
Umdrehungen/Volt:	840 rpm/V	600 rpm/V
Pole:	14	14
Betriebsspannung:	10-20 V	10-20 V
Empfohlene Stromlast:	max. 60 A	max. 60 A
Zellen:	10-16 NiCd/NiMH bzw. 3s-5s LiPo	
Empf. Luftschraube:	9" bis 14"	11" bis 18"
max. Leistung:	700 W	800 W
Länge ohne Welle:	36 mm	41 mm
Motordurchmesser:	40,5 mm	40,5 mm
Wellendurchmesser:	5 mm	5 mm
Länge Motorwelle:	20 mm	20 mm
Lochkreis:	25 mm	25 mm
Befestigung:	2/3x M3	2/3x M3
Gewicht:	202 g	242 g
Preis:	169,50 Euro	177,50 Euro

https://www.aufwind-magazin.de/redaktion/Strecker209/index.html

This type of engine can be air-cooled, so there is no need for another liquid cooling system that would rise the mass of the whole UAV and cost of production and exploitation.

Other motor considered:

Technical data sheet:

Test Report									
Test Item		MN3510 KV360		Report NO.			MN.00014		
Specifications									
Internal Resistance		188mΩ		Configuration			12N14P		
Shaft Diameter		4mm		Motor Dimensions			Φ41.8×28.5mm		
Stator Diameter		35mm		StatorHeight			10mm		
AWG		18#		Cable Length			600mm		
Weight Including Cables		117g		Weight Excluding Cables			97g		
No.of Cells(Lipo)		3-6S		Idle Current@10v			0.4A		
Max Continuous Power 180S		330W		Max Continuous Current 180S			15A		
Load Testing Data									
Ambient Temperature		/		Voltage			DC Power Supplier		
Item No.	Voltage (V)	Prop	Throttle	Current (A)	Power (W)	Thrust (G)	RPM	Efficiency (G/W)	Operating Temperature (℃)

Load Testing Data										
Ambient Temperature			/		Voltage			DC Power Supplier		
Item No.	Voltage (V)	Prop	Throttle	Current (A)	Power (W)	Thrust (G)	RPM	Efficiency (G/W)	Operating Temperature (℃)
MN3510 KV360	14.8	T-MOTOR 14*4.8CF	50%	1.2	17.76	280	2600	15.77	40
			65%	2.5	37.00	500	3400	13.51	
			75%	3.5	51.80	620	3800	11.97	
			85%	4.9	72.52	760	4300	10.48	
			100%	5.7	84.36	870	4600	10.31	
		T-MOTOR 15*5CF	50%	1.5	22.20	340	2600	15.32	42
			65%	3	44.40	580	3300	13.06	
			75%	4.5	66.60	760	3800	11.41	
			85%	5.8	85.84	900	4100	10.48	
			100%	6.8	100.64	1000	4400	9.94	
		T-MOTOR 16*5.4CF	50%	1.73	25.60	380	2450	14.84	40
			65%	3.6	53.28	630	3200	11.82	
			75%	5.3	78.44	800	3700	10.20	
			85%	6.9	102.12	1000	4000	9.79	
			100%	8.1	119.88	1100	4300	9.18	
	22.2	T-MOTOR 12*4CF	50%	1.6	35.52	350	4300	9.85	43
			65%	2.7	59.94	560	5300	9.34	
			75%	4	88.80	760	6000	8.56	
			85%	5.5	122.10	930	6600	7.62	
			100%	6.4	142.08	1060	7000	7.46	
		T-MOTOR 13*4.4CF	50%	1.8	39.96	460	4200	11.51	43
			65%	3.4	75.48	730	5300	9.67	
			75%	4.8	106.56	900	5900	8.45	
			85%	6.2	137.64	1100	6500	7.99	
			100%	7.5	166.50	1300	6900	7.81	
		T-MOTOR 14*4.8CF	50%	2.5	55.50	660	4000	11.89	50
			65%	4.7	104.34	1000	4900	9.58	
			75%	6.8	150.96	1280	5500	8.48	
			85%	8.8	195.36	1500	6000	7.68	
			100%	10.6	235.32	1700	6500	7.22	
		T-MOTOR 15*5CF	50%	3	66.60	780	3800	11.71	60
			65%	5.6	124.32	1180	4500	9.49	
			75%	7.7	170.94	1460	5300	8.54	
			85%	10.6	235.32	1700	5720	7.22	
			100%	12.5	277.50	1900	6040	6.85	
Notes:The test condition of temperature is motor surface temperature in 100% throttle while the motor run 10min.									

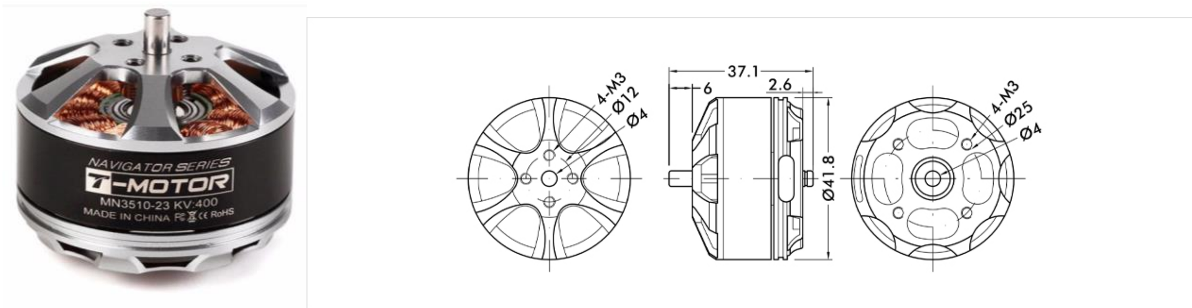
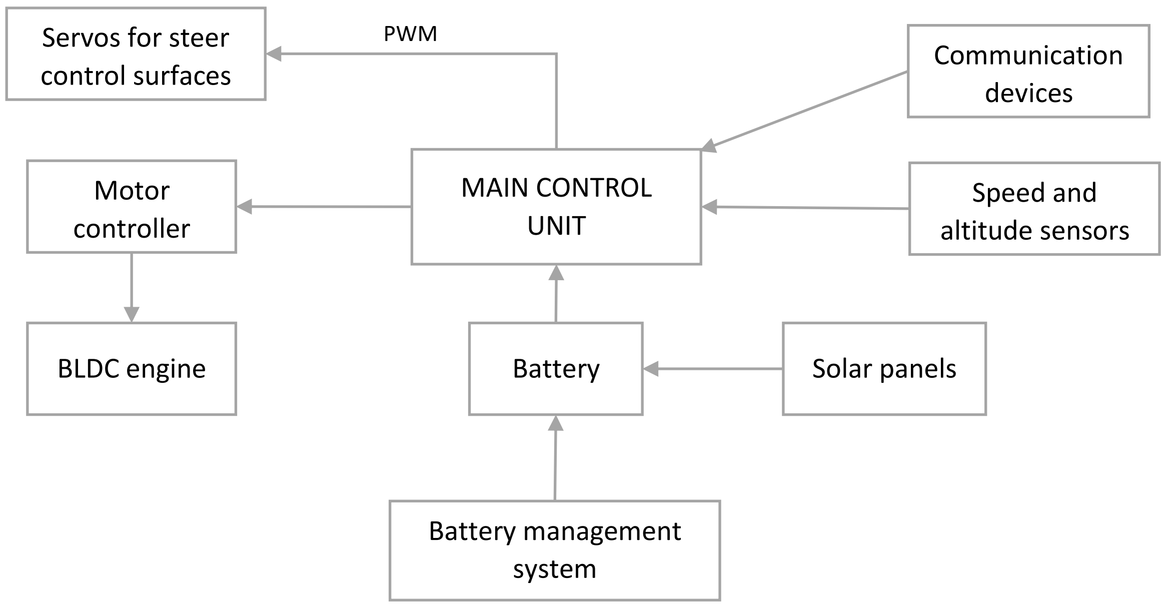


Figure 4 Chosen BLDC motor

This motor (MN3510 KV360) was chosen as it has parameters and performance more suitable for our need.

Elements of the driving system for a solar panel powered aircraft of our design and conceptual sketch:



STAGE 3: ANALYSIS OF DISCHARGE CHARACTERISTIC OF BATTERY AND BATTERY SELECTION ELABORATION

Preliminary calculation for battery selection.

Climb will occur at 7,2 m/s horizontal speed, 0,73 m/s rate of climb optimally, where motor power is 240 W, this stage lasts for about 1377 seconds up to the target altitude of 1000 m. Cruise with 128 W for 8h, at 8,75 m/s. Battery is arranged in a 4 series, 7 parallel configuration. About 2 such packs would be required if solar panels are taken into account – 4 packs without solar panels.

Calculation was performed in Excel file. The results and initial parameters are presented in the following tables.

General parameters	Value	Unit
BatteryMaxV	*4,2*	*V*
BatteryMinV	*2,5*	*V*
BatteriesS	*4*	*pcs*
MaxV	*16,8*	*V*
MinV	*10*	*V*
BatteryDischA	*3,28*	*A*
ServoMaxA	*1,5*	*A*
Servos	*4*	*pcs*
ControlMaxA	*6*	*A*
MotorMaxW	*330*	*W*
MotorMaxA	*15,00*	*A*
AvionicsMaxW	*4,5*	*W*
AvionicsMaxA	*0,9*	*A*
MaxClimbA	*21,90*	*A*
MinReqBatteriesP	*7*	*pcs*
BatteryMinCap	*3,28*	*Ah*
BatteriesPerPack	*28*	*pcs*
MinCap	*22,96*	*Ah*
CruisePerPackMin	*1,530667*	*h*
MissionReqMin	*8*	*h*

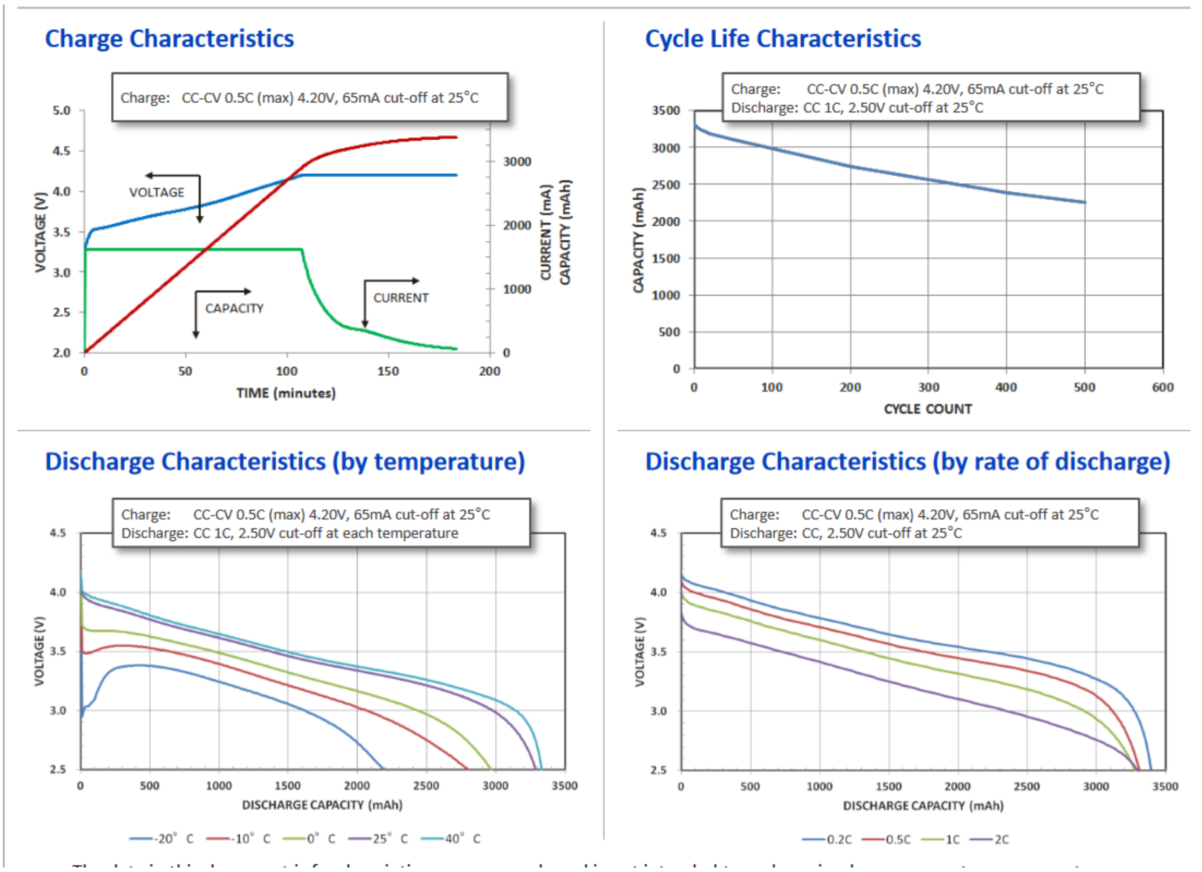
Simple Mission Case	Value	Unit
MotorClimbA	*15,00*	*A*
MaxClimbA	*21,90*	*A*
MotorCruiseA	*8,888889*	*A*
MaxCruiseA	*10,78889*	*A*
CruiseCapMax	*82,18563*	*Ah*
MinReqBatteriesP	*7*	*pcs*
TotalReqBatteries	*104*	*pcs*
PacksReq	*3,714286*	*pcs*

<u>Analysis of discharge characteristic of battery according to flight scenario and battery selection</u>

Discharge scenarios that should be analyzed.

- Charging the battery during day while simultaneously the engine is being powered
- The battery is fully charged and then is being continuously discharged during night.
- The battery has to power the engine during cloudy day
- The battery has to power engine during take-off, climb and cruise.

Characteristic of a single battery Panasonic NCR18650B:



Specifications

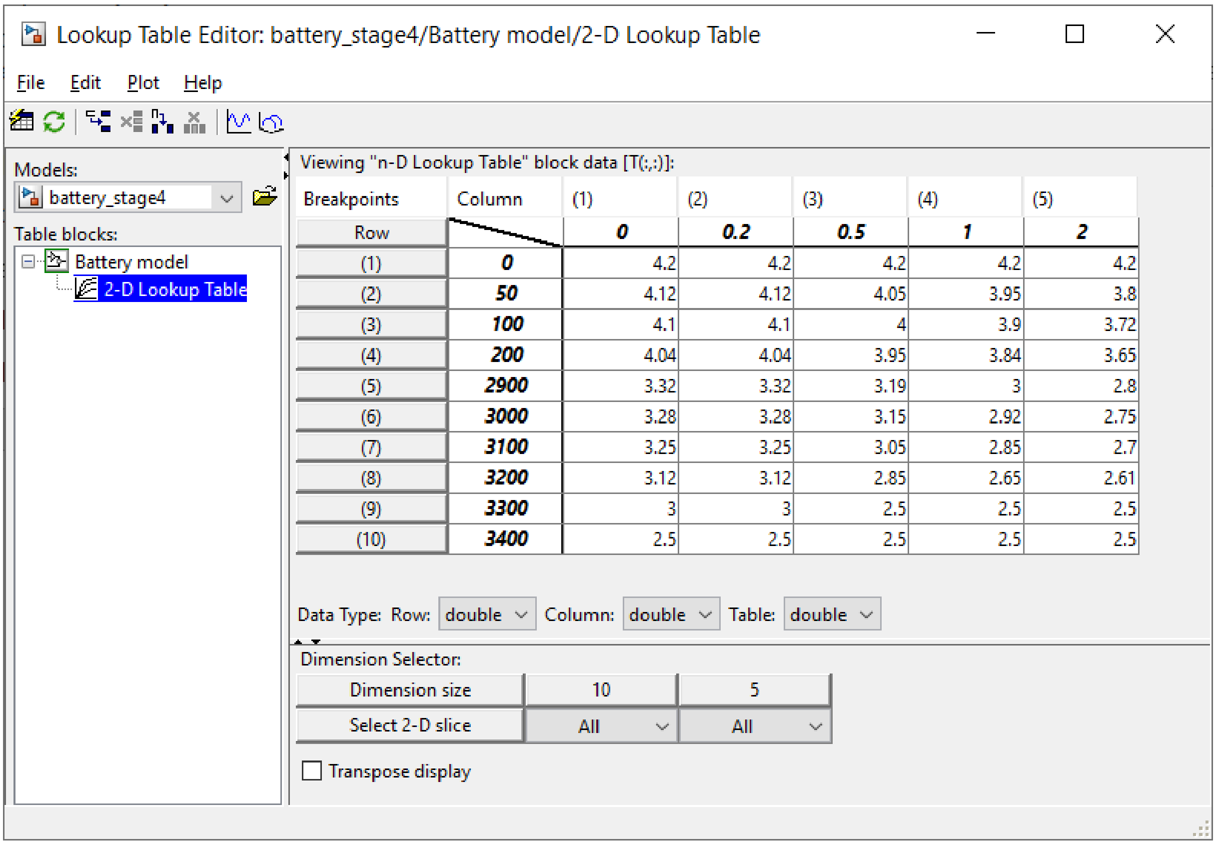
Rated capacity[(1)]	Min. 3200mAh
Capacity[(2)]	Min. 3250mAh Typ. 3350mAh
Nominal voltage	3.6V
Charging	CC-CV, Std. 1625mA, 4.20V, 4.0 hrs
Weight (max.)	48.5 g
Temperature	Charge*: 0 to +45°C Discharge: -20 to +60°C Storage: -20 to +50°C
Energy density[(3)]	Volumetric: 676 Wh/l Gravimetric: 243 Wh/kg

[(1)] At 20°C [(2)] At 25°C [(3)] Energy density based on bare cell dimensions

Temperature at maximum ceiling (1000m) is ~8,5 degC which is in the allowed range of temperatures for chosen battery.

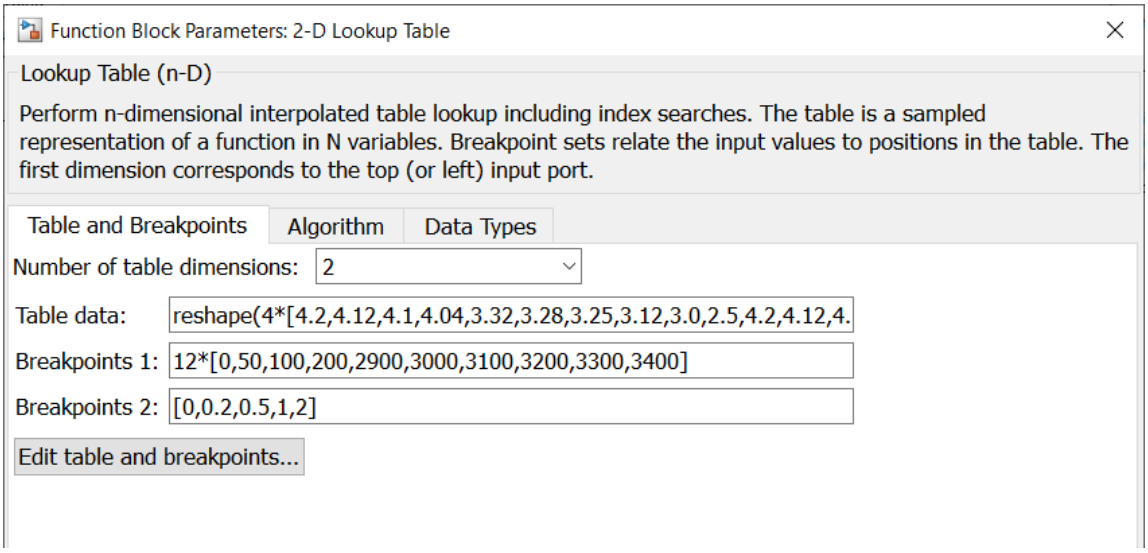
The battery discharge characteristic (by rate of discharge) has been implemented in MATLAB Simulink, and also a model has been created. The values needed has been taken from Panasonic 18650b datasheet.

Data implemented in Lookup Table:

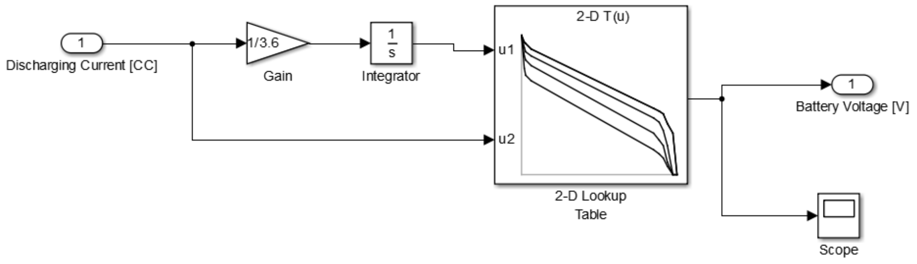


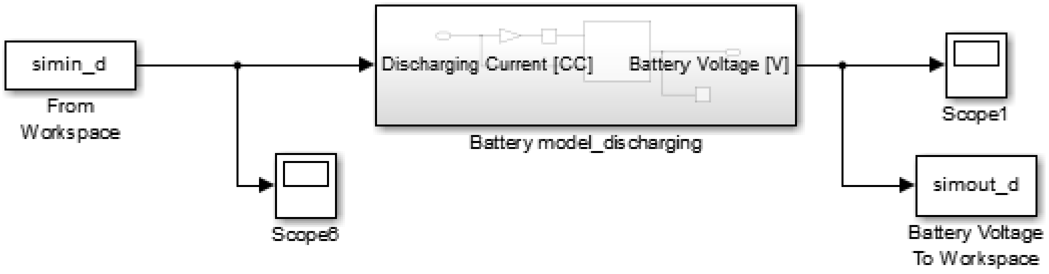
Breakpoints	Column	(1)	(2)	(3)	(4)	(5)
Row		0	0.2	0.5	1	2
(1)	0	4.2	4.2	4.2	4.2	4.2
(2)	50	4.12	4.12	4.05	3.95	3.8
(3)	100	4.1	4.1	4	3.9	3.72
(4)	200	4.04	4.04	3.95	3.84	3.65
(5)	2900	3.32	3.32	3.19	3	2.8
(6)	3000	3.28	3.28	3.15	2.92	2.75
(7)	3100	3.25	3.25	3.05	2.85	2.7
(8)	3200	3.12	3.12	2.85	2.65	2.61
(9)	3300	3	3	2.5	2.5	2.5
(10)	3400	2.5	2.5	2.5	2.5	2.5

Parameters of the 2-D Lookup Table. In order to simulate the configuration of cells in a pack, the values of voltage (Table data) have to be multiplied of number of cells in series - 8. The values of discharge capacity (Breakpoints 1) have to be multiplied of number of parallel connections - 12. The number of cells parallel and in series was established in the previous stage. The updated Lookup Table is shown on the figure below.



Battery model used for simulation is as presented below. The first figure presents the subsystem od *Battery model_discharging*.





Input current (for test) was defined in Matlab script. The value of discharge current in time is presented on the figure below. This is the simulation of take-off, climbing and cruise during 12 hour flight.

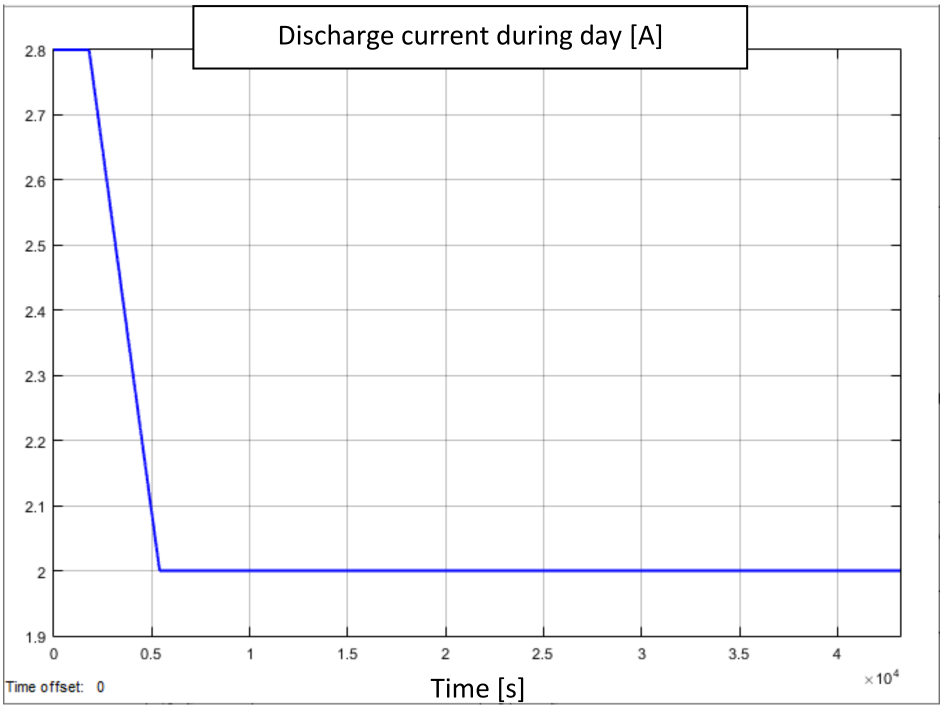
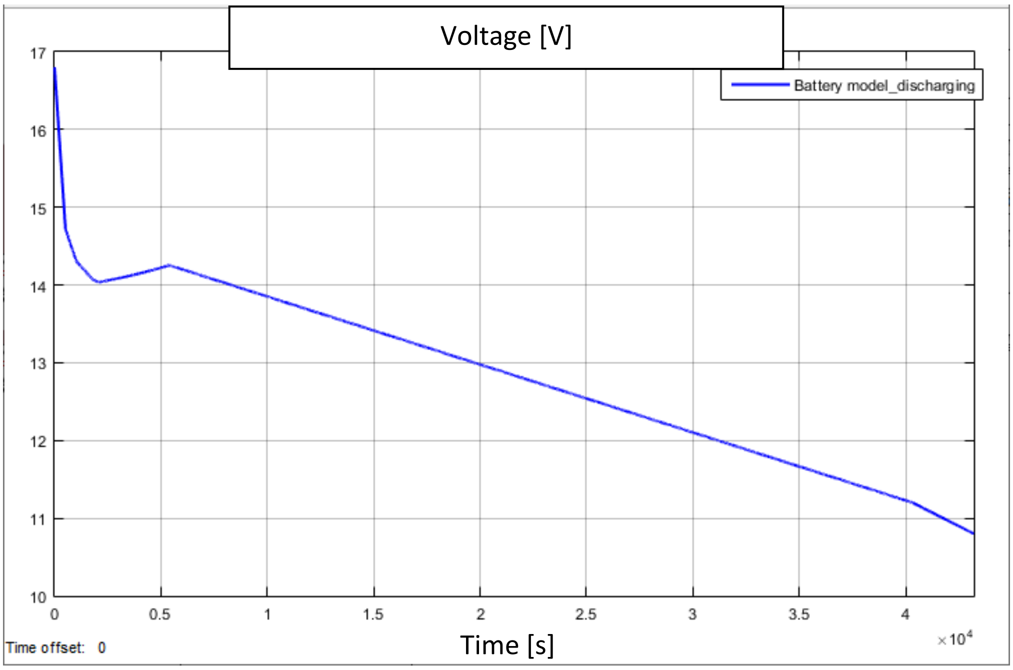
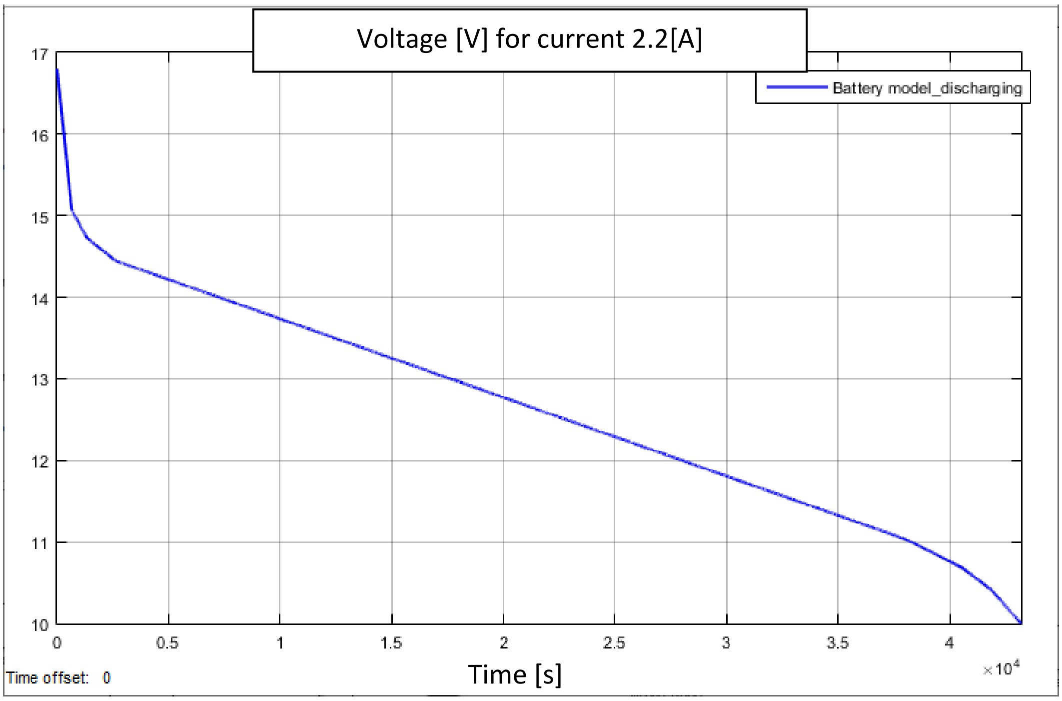


Chart of voltage for given discharge current scenario:

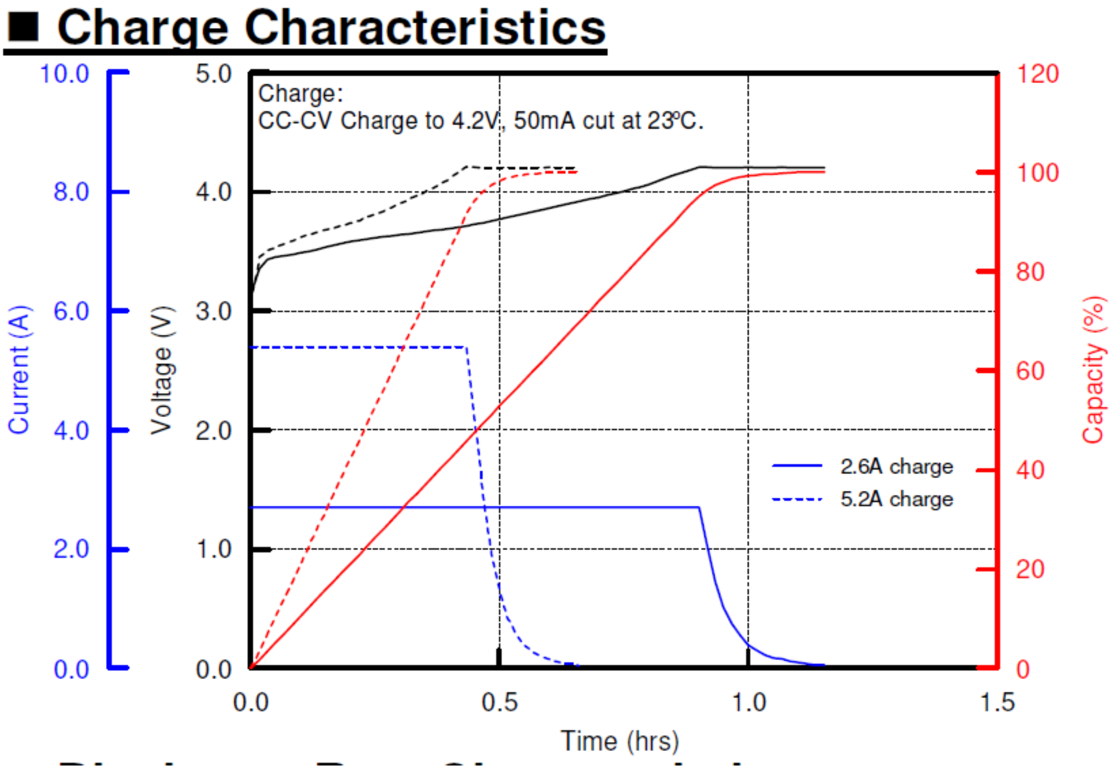


Considered set of battery cells (8 in series, 12 parallel) is discharged during 12h with a constant current 2.2A. Discharge characteristic for constant discharge current 2.2A:

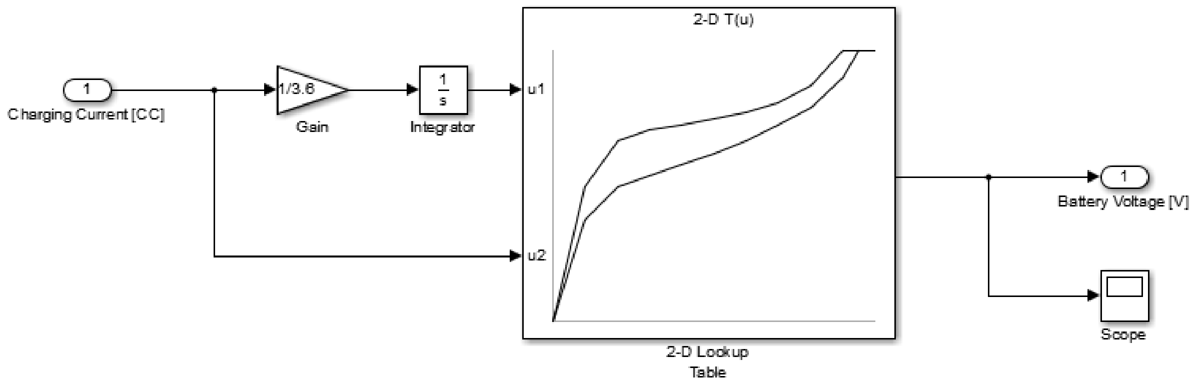


It means that number of batteries should be increased to ensure steady flight during night.

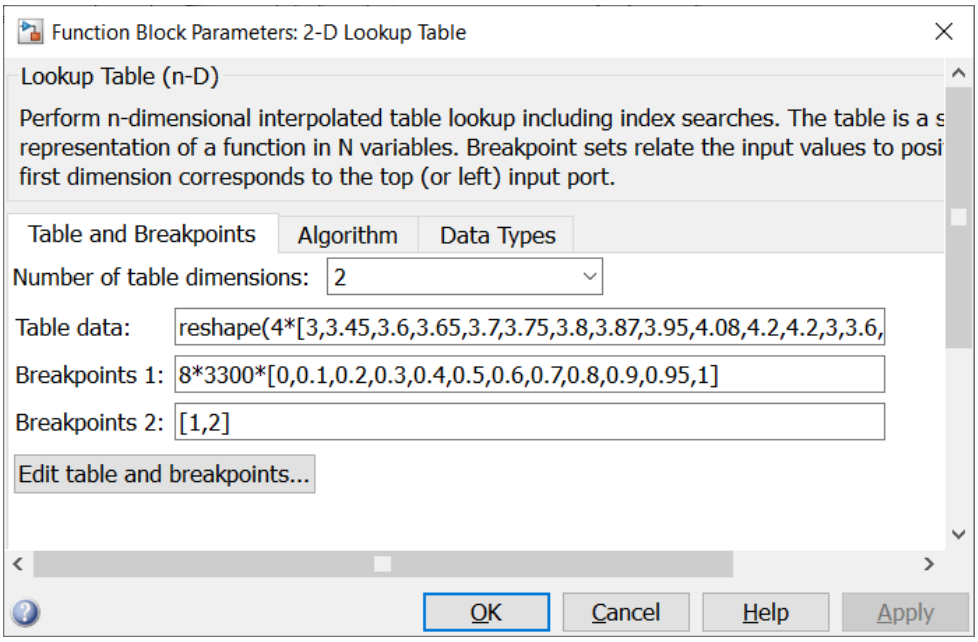
Model for charging of the battery. On the basis of data sheet for Panasonic NCR18650B and Molicel INR-18650-P26A the same procedure of creating the Simulink model was followed. In the specification of charging the battery cell for Panasonic there were not sufficient data to run the simulation. For that reason the charge characteristic of Molicel INR-18650-P26A was used to complete missing data from first battery. Following figure presents charging characteristic for two different C-rates of charge.. Shape of those two characteristics was used to fill the unknown values.



Model of charging the battery:



Lookup Table:



Also here the configuration of the cells was included – 8 in series and 12 parallel.

For the chosen BLDC engine maximum recommended current load is. The simulation was performed for that value and the results are presented below.

Options of different sets of batteries and their position.

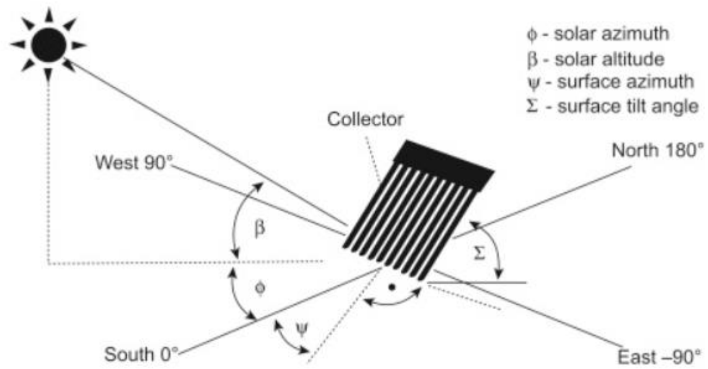
Analysis of subsystems connected with power source and their specification:

- Engine
- Motor controller
- Solar panels
- Main control unit
- Servos
- BMS – Battery Management System

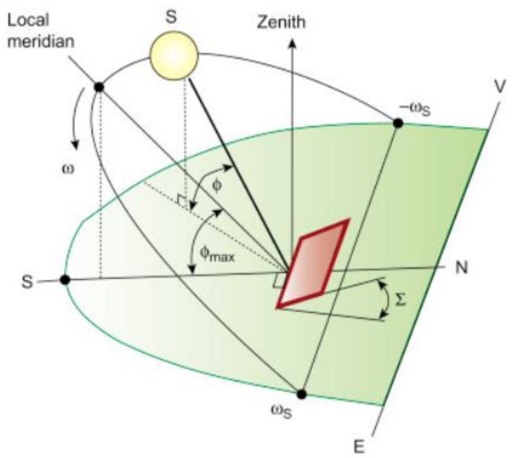
STAGE 4: ANALYSIS OF ADDITIONAL POWER SOURCE CHARACTERISTIC

Analysis of irradiance during day:

Solar angles with respect to tilted surface [1]:



Hour angle



The earth's axis results in a day-by-day variation of the angle between the earth–sun line and the earth's equatorial plane called the solar declination δ. This angle may be estimated by the following equation:

$$d = 23{,}45 \sin\left[\frac{360}{365} * (284 + N)\right]$$

where

d – declination

N – day of year

Hour angle ω is the angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15 degrees per hour; morning negative (−ωs) and afternoon positive (+ωs). The sun position at any hour τ can be expressed as follows:

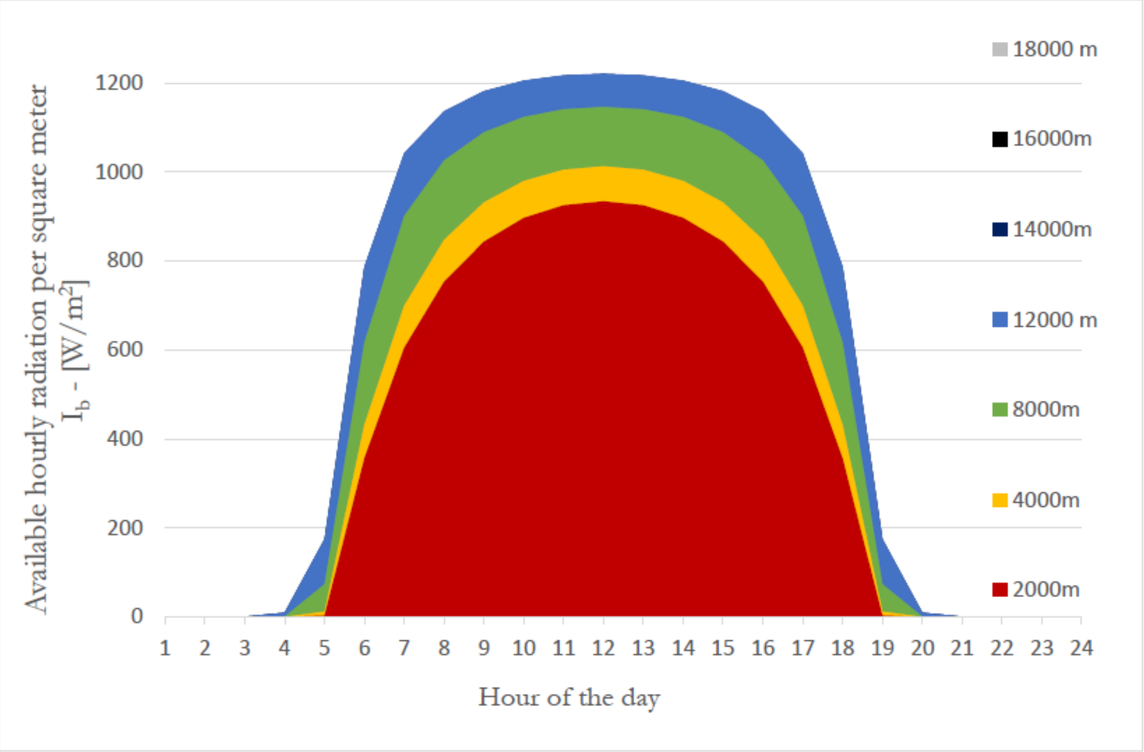
$$\omega = 15(12 - \tau)$$

ω – Hour angle

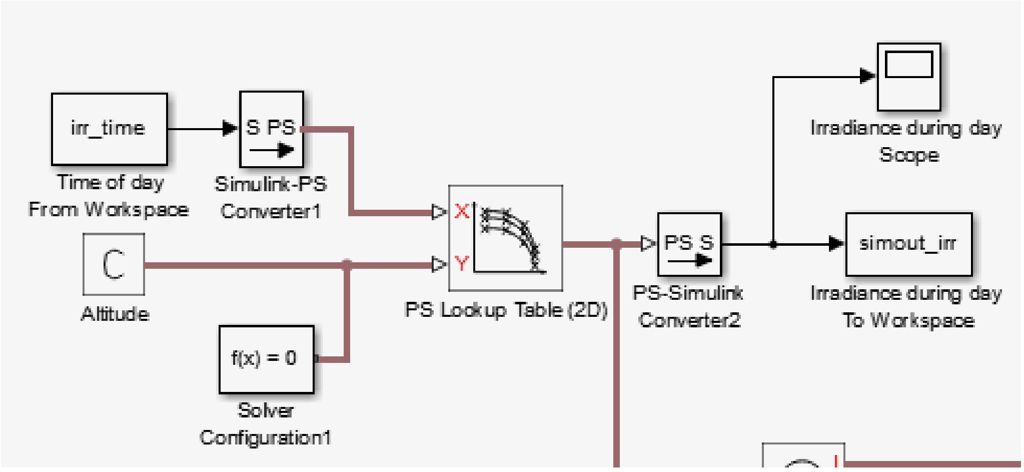
τ – hour

For calculation we used the first day of summer which is 21st of June. It is the 172nd day of the year

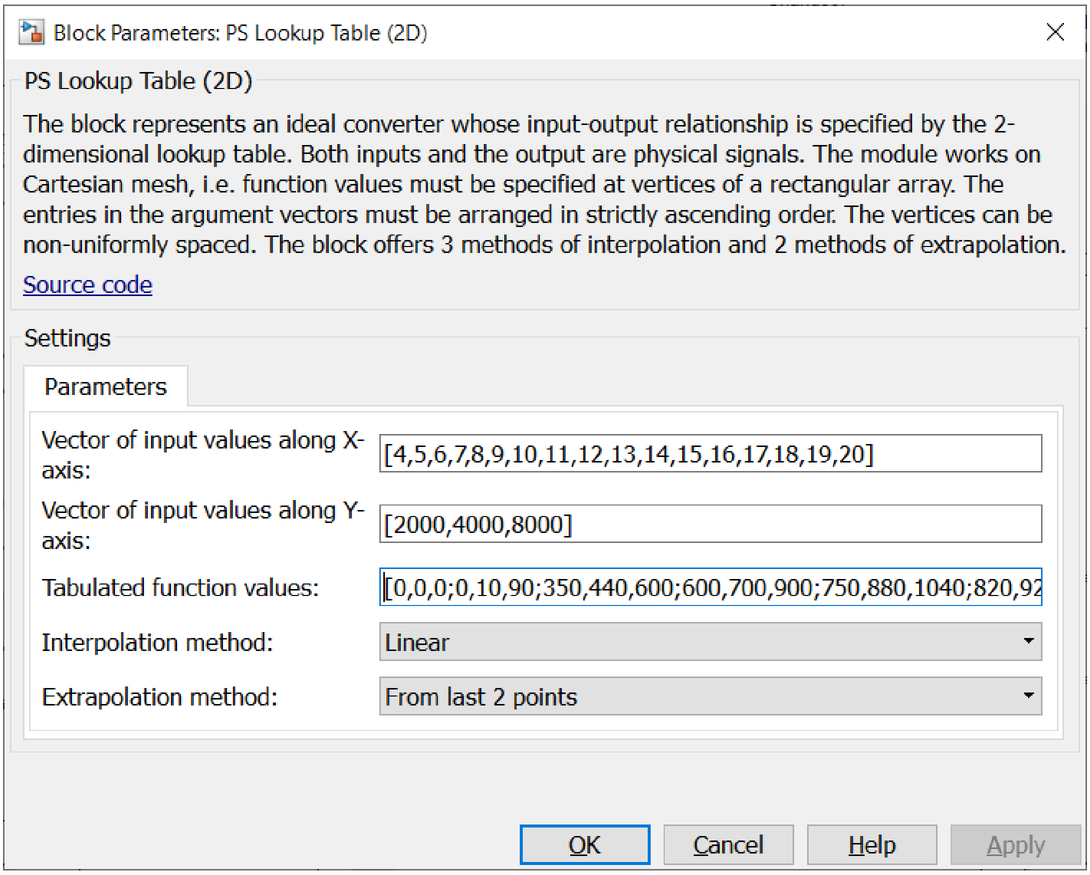
Also the irradiance has to be calculated. It should change during day. This data will be applied to Matlab simulation. The irradiance is defined in the script and then sent to Simulink to be used in the block Solar Cell. The irradiance can be established using experimental data from [3]. The picture below presents available hourly radiation per square meter. Data is presented for four different altitudes: 2000m, 4000m, 8000m and 12000m. Thanks to it the irradiance at the max ceiling (1000m) can be easily estimated.



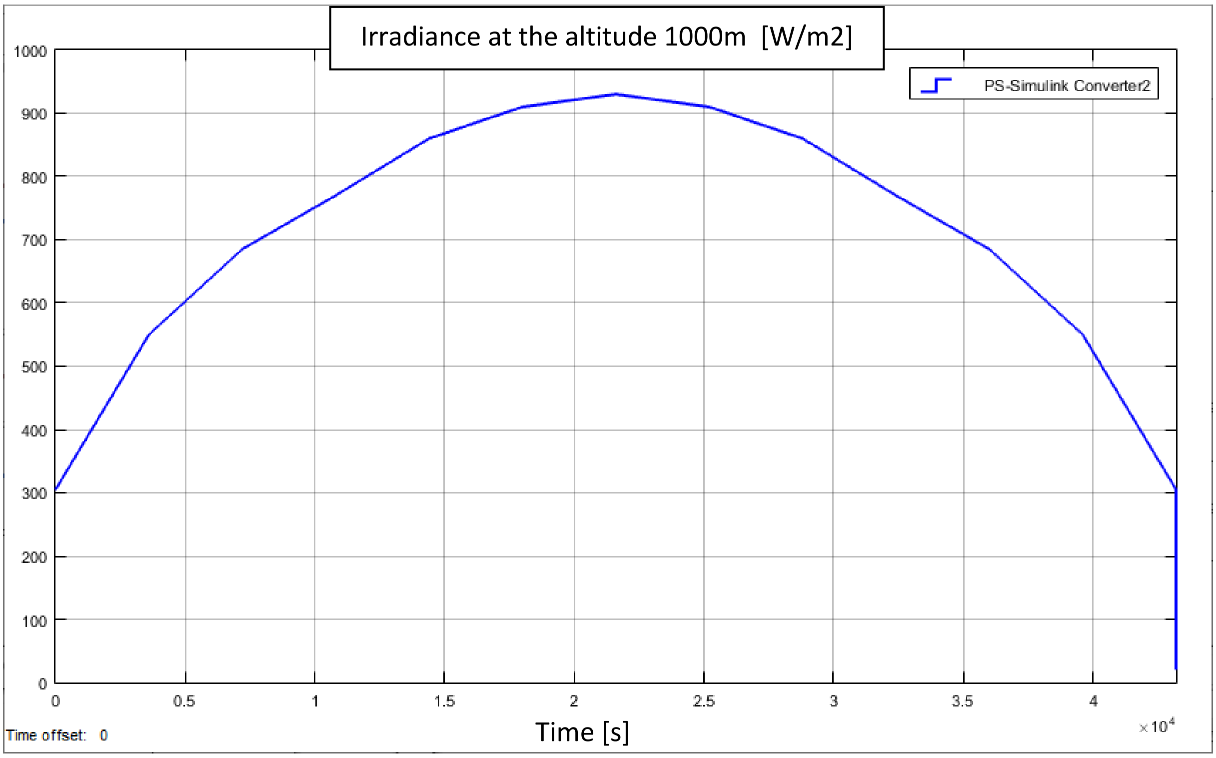
In the Simulink project the following model was created. Variable *irr_time* is the parameter defined in the Matlab script, which is a time during day. The constant *Altitude* was set to 1000m.



The data irradiance data [3] was implemented in the PS Lookup Table as shown below.



The result of calculation for this part of Simulink model is the graph of irradiance for hour 6AM to 18AM, which is 12 hours.



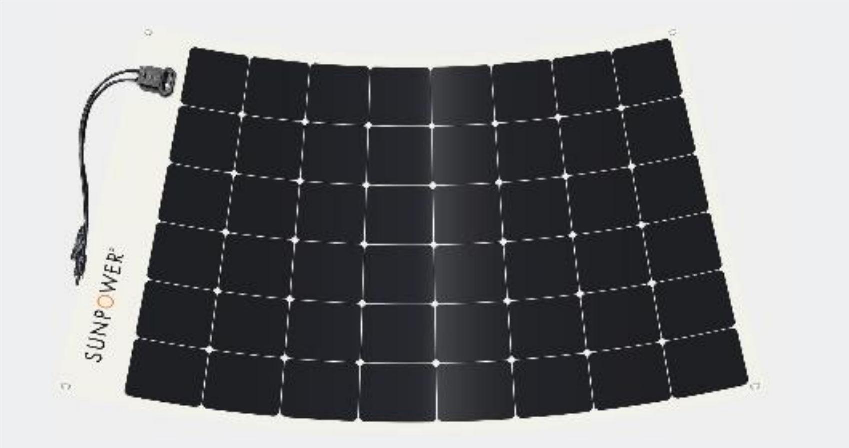
Solar cells selection

Solar panels used in AtlanticSolar UAV are from SUNPOWER manufacturer, model E60. Unfortunately the data sheet is not commonly available, thus it is not possible to implement data for that type of panels.

Following flexible solar panels were found during research:

- SUNPOWER SPR-E20-327
- SUNPOWER SPR-E-Flex
- eFilm by Flisom

SUNPOWER SPR-E-Flex:

- 

- *Figure 5 Solar cells*

Solar cells datasheet (1)

Typical Electrical Data at STC: 25° C, 1000 W/m² and AM 1.5	
Model	SPR-E-Flex-170 6x8
Nominal Power (Pnom)	170 W
Power Tolerance	+/–3%
Rated Voltage (Vmpp)	29.4 V
Rated Current (Impp)	5.84 A
Open-circuit voltage (Voc)	34.6 V
Short-curcuit current (Isc)	6.15 A
Power Temp Coeffiecient	–0.30%/° C
Voltage Temp Coefficient	–83.7 mV/° C
Current Temp Coefficient	3.5 mA/° C
Max. System Voltage	45 V
Series Fuse Rating	15 A

Solar cells datasheet (2)

Mechanical Data	
Solar Cells	Prime monocrystalline 25% efficiency SunPower IBC cells
Junction Box	TE 1-21-2152049-1 with by-pass diode
Connectors	PV4-S (Compatible with MC4)
Cables	4 mm² (0.16 in²), 12 AWG, 450 mm (17.7 in) long
Grommets	316 Stainless Steel
Charge Controller	None provided
Weight	6.3 lbs (2.9 kg)
Panel Dimensions	1153 x 810 x 20 mm with Jbox, 2 mm w/o Jbox (45.4 x 31.9 x 0.8 in)

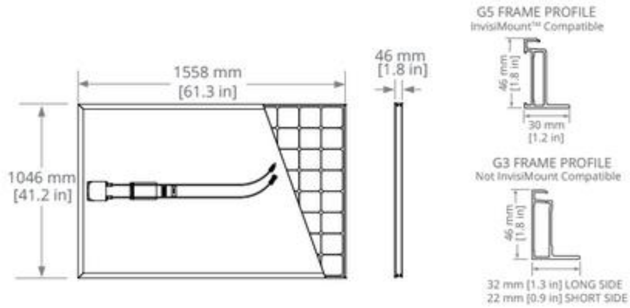
Documentation of solar panel SUNPOWER SPR-E20-327

Electrical Data		
	SPR-E20-327	SPR-E19-320
Nominal Power (Pnom)[11]	327 W	320 W
Power Tolerance	+5/–0%	+5/–0%
Avg. Panel Efficiency[12]	20.4%	19.9%
Rated Voltage (Vmpp)	54.7 V	54.7 V
Rated Current (Impp)	5.98 A	5.86 A
Open-Circuit Voltage (Voc)	64.9 V	64.8 V
Short-Circuit Current (Isc)	6.46 A	6.24 A
Max. System Voltage	600 V UL & 1000 V IEC	
Maximum Series Fuse	15 A	
Power Temp Coef.	–0.35% / °C	
Voltage Temp Coef.	–176.6 mV / °C	
Current Temp Coef.	2.6 mA / °C	

REFERENCES:
1 All comparisons are SPR-E20-327 vs. a representative conventional panel: 250 W, approx. 1.6 m², 15.3% efficiency.
2 Typically 7–9% more energy per watt, BEW/DNV Engineering "SunPower Yield Report," Jan 2013.
3 SunPower 0.25%/yr degradation vs. 1.0%/yr conv. panel. Campeau, Z. et al. "SunPower Module Degradation Rate," SunPower white paper, Feb 2013; Jordan, Dirk "SunPower Test Report," NREL, Q1-2015.
4 "SunPower Module 40-Year Useful Life" SunPower white paper, May 2015. Useful life is 99 out of 100 panels operating at more than 70% of rated power.
5 Second highest, after SunPower X-Series, of over 3,200 silicon solar panels, Photon Module Survey, Feb 2014.
6 8% more energy than the average of the top 10 panel companies tested in 2012 (151 panels, 102 companies), Photon International, Feb 2013.
7 Compared with the top 15 manufacturers. SunPower Warranty Review, May 2015.
8 Some restrictions and exclusions may apply. See warranty for details.
9 5 of top 8 panel manufacturers tested in 2013 report, 3 additional panels in 2014. Ferrara, C., et al. "Fraunhofer PV Durability Initiative for Solar Modules: Part 2". Photovoltaics International, 2014.
10 Compared with the non-stress-tested control panel. Atlas 25+ Durability test report, Feb 2013.
11 Standard Test Conditions (1000 W/m² irradiance, AM 1.5, 25° C). NREL calibration Standard: SOMS current, LACCS FF and Voltage.
12 Based on average of measured power values during production.
13 Type 2 fire rating per UL1703:2013, Class C fire rating per UL1703:2002.
14 See salesperson for details.
15 Only SPR-E20-327 has JET certification.

Tests And Certifications	
Standard Tests[13]	UL1703 (Type 2 Fire Rating), IEC 61215, IEC 61730
Quality Certs	ISO 9001:2008, ISO 14001:2004
EHS Compliance	RoHS, OHSAS 18001:2007, lead free, REACH SVHC-163, PV Cycle
Sustainability	Cradle to Cradle Certified™ Silver (eligible for LEED points)[14]
Ammonia Test	IEC 62716
Desert Test	10.1109/PVSC.2013.6744437
Salt Spray Test	IEC 61701 (maximum severity)
PID Test	Potential-Induced Degradation free: 1000 V[9]
Available Listings[15]	UL, TUV, JET, MCS, FSEC, CEC

Operating Condition And Mechanical Data	
Temperature	–40° F to +185° F (–40° C to +85° C)
Impact Resistance	1 inch (25 mm) diameter hail at 52 mph (23 m/s)
Appearance	Class A
Solar Cells	96 Monocrystalline Maxeon Gen II
Tempered Glass	High-transmission tempered anti-reflective
Junction Box	IP-65, MC4 compatible
Weight	41 lbs (18.6 kg)
Max. Load	G5 Frame: Wind: 62 psf, 3000 Pa front & back Snow: 125 psf, 6000 Pa front G3 Frame: Wind: 50 psf, 2400 Pa front & back Snow: 112 psf, 5400 Pa front
Frame	Class 1 black anodized (highest AAMA rating)

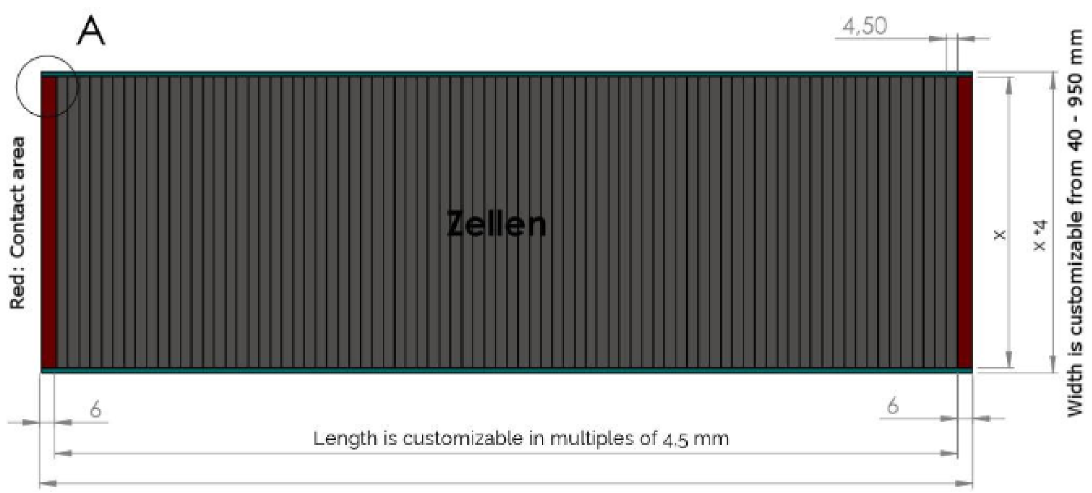


Technical data of standard eFilm submodule of Flisom company.

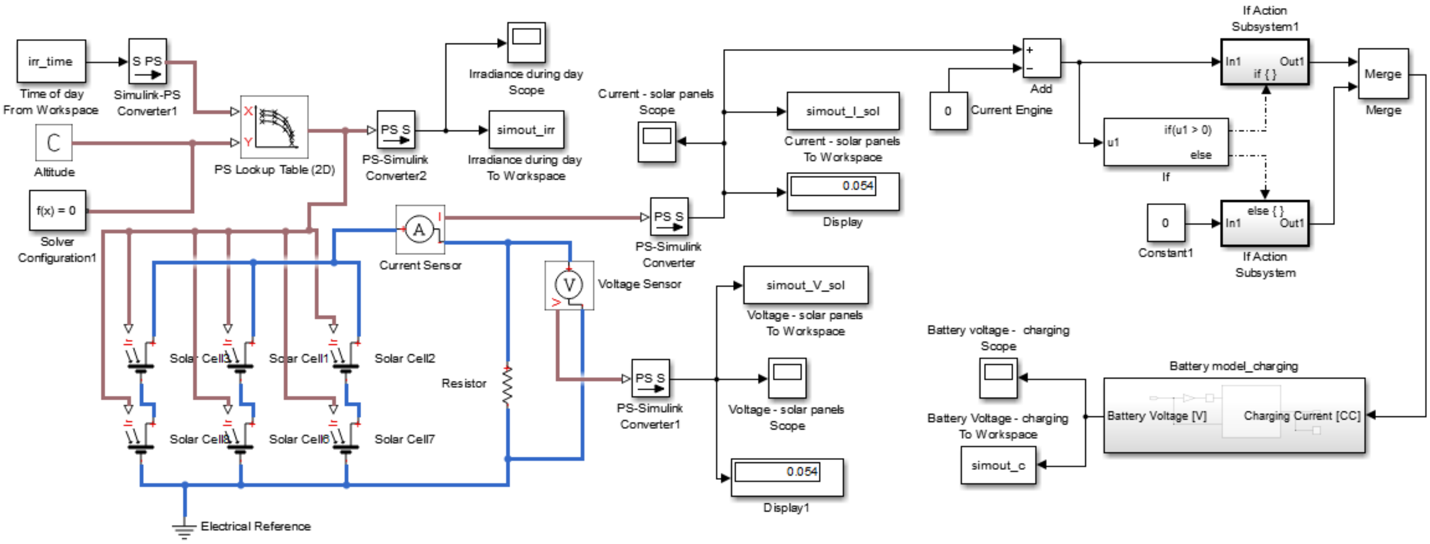
Dimensions of standard submodule			
Length		[mm]	742
Width		[mm]	372
Thickness of solar film		[micron]	< 30
Weight		[g / m2]	60
Nominal power		[W / m2]	100-140
Electrical characteristics of standard submodule			
Open circuit voltage Voc		[V]	48 ±3
Short circuit current		[A]	0.9 ±0.3
Voltage at nom. Power Vmpp		[V]	36 ±3
Current at nom. Power Impp		[A]	0.8 ±0.3
Thermal characteristics			
Temperature coefficient	Voc	[%/°C]	-0.3
Temperature coefficient	Isc	[%/°C]	0.01
Temperature coefficient	Pmpp	[%/°C]	-0.35
Additional data			
Cell type			Flexible CIGS based on polymeric substrate
Electrical connection			Laser scribed intercell connection; two contact pads for busbars
Delivery			1. Standard submodules are delivered cut out / singulated. 2. Customized submodules are delivered on rolls and require expertise for unwinding, singulation, contacting and encapsulation.

This solar panel is flexible, so there will be a possibility to attach it to the upper surface of the wing. There is a possibility to customize the cell for our use. This solar panels are chosen and will be considered during calculation at next stages of the project. The total required area of solar panels will be calculated using Simulink model and then number of submodules customized for dimensions of wing and tail will be established.

Drawing indicating customization possibilities

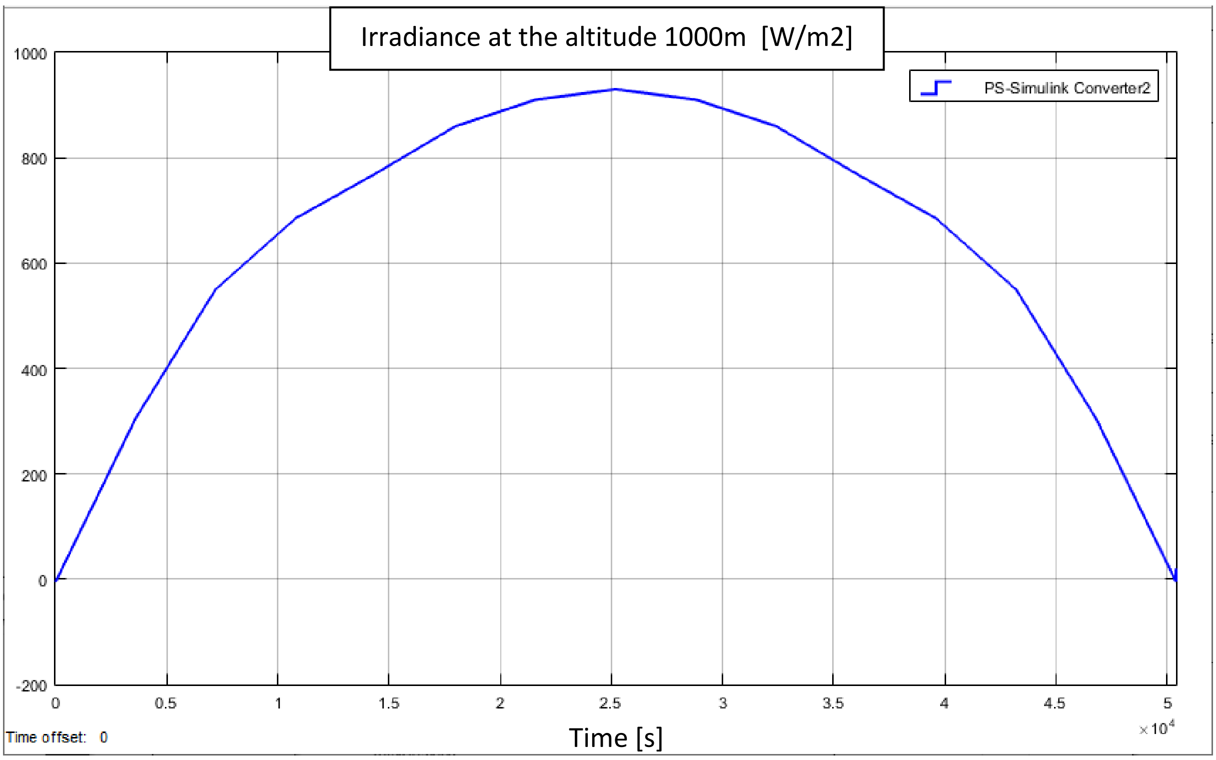


Simulink model prepared for solar cells and charge analysis:

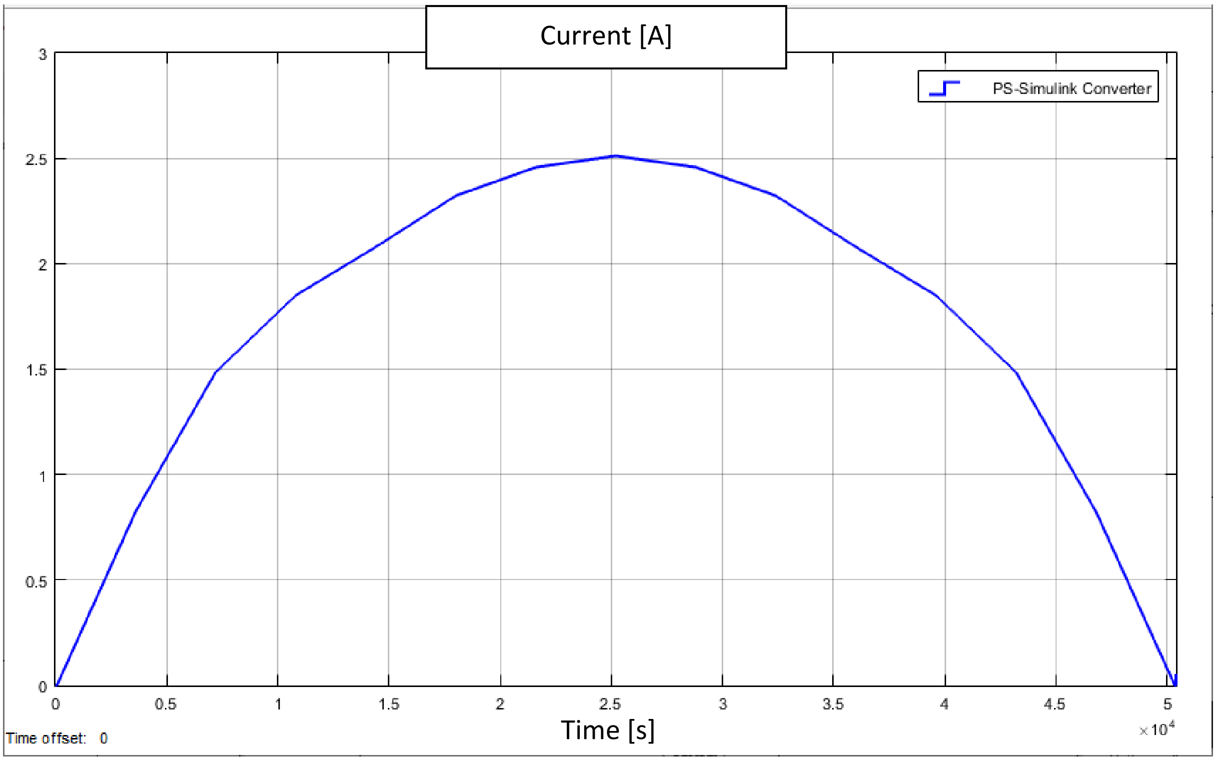


According to irradiance data, the day time (when irradiance is greater than 0) is between 5AM and 19AM. For this time (which is 14 hours) the simulation was run. It was done to establish how many solar panels are needed to fully charge the batteries during a whole day. Following chart present irradiance at the altitude 1000m from 5AM to 19 AM.

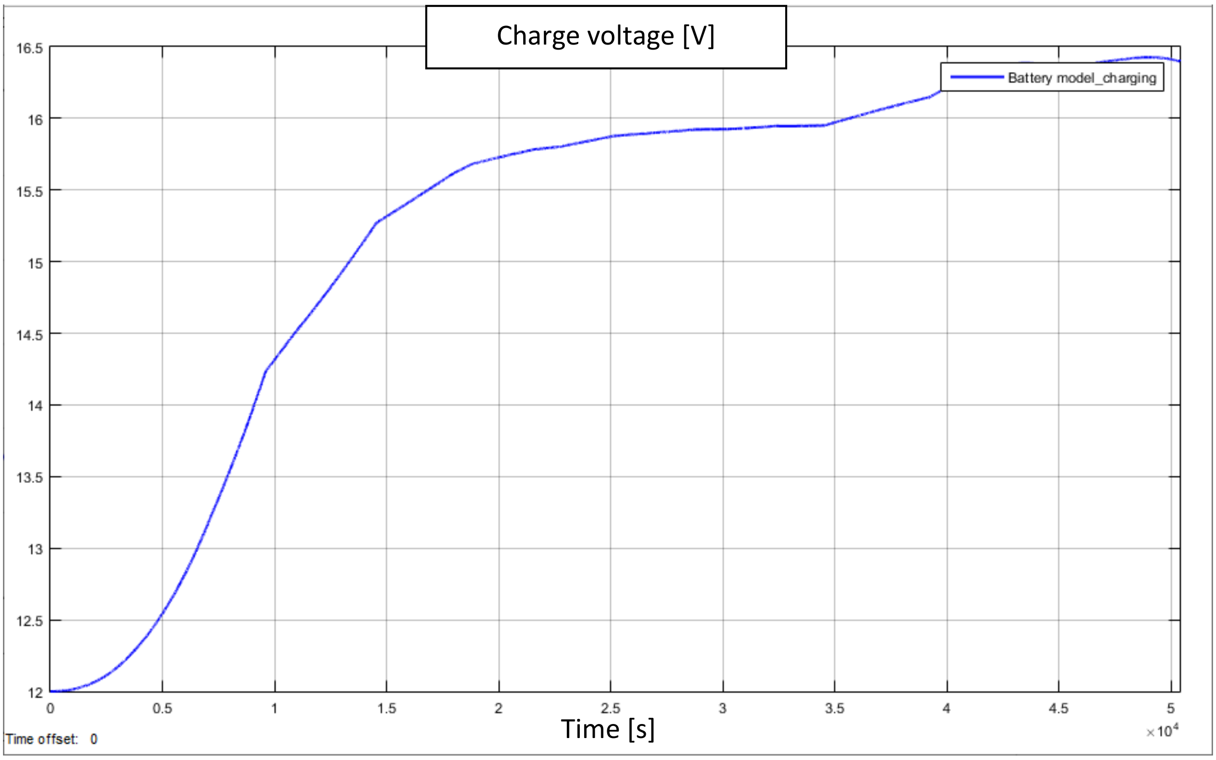
This analysis does not consider the energy consumed by engine during day.



Current generated by solar cells during day:



Charge characteristic:

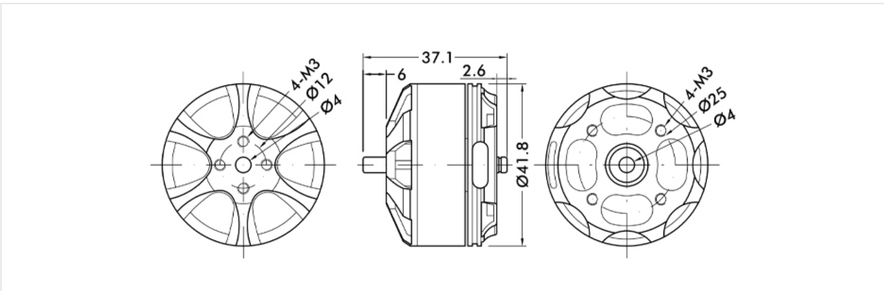


Required number of solar cells connected parallel needed to charge all batteries is 3. This means that it is 0,828072 m^2 of solar panels. The next step is to estimate how many solar panels are needed to fully charge the batteries and power the motor at the same time. Calculation regarding BLDC motor are in the next section.

STAGE 5: ANALYSIS OF ELECTRIC MOTOR CHARACTERISTIC

Data sheet of chosen BLDC motor by manufacturer T-motor. Motors of that manufacturer are specially dedicated for UAVs' propulsion systems, thus they are able to operate at various altitudes and temperatures. Simultaneously its dimensions and mass are quite small, so it is very suitable for our project.

Test Report			
Test Item	MN3510 KV360	Report NO.	MN.00014
Specifications			
Internal Resistance	188mΩ	Configuration	12N14P
Shaft Diameter	4mm	Motor Dimensions	Φ41.8×28.5mm
Stator Diameter	35mm	StatorHeight	10mm
AWG	18#	Cable Length	600mm
Weight Including Cables	117g	Weight Excluding Cables	97g
No.of Cells(Lipo)	3-6S	Idle Current@10v	0.4A
Max Continuous Power 180S	330W	Max Continuous Current 180S	15A



As there is not included information about parameters we need for running the motor's model in MATLAB, these data was taken from similar BLDC motor specification file. Specification of another motor:

Series 3216 ... BXT R

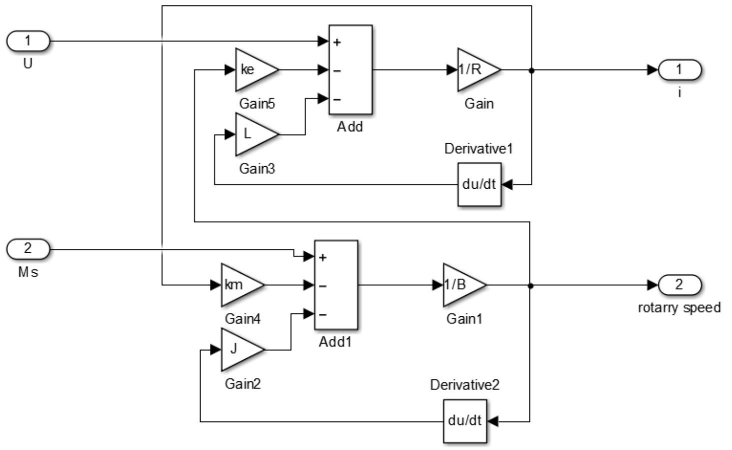
	Values at 22°C and nominal voltage	3216 W		009 BXT R	012 BXT R	024 BXT R	
1	Nominal voltage	U_N		9	12	24	V
2	Terminal resistance, phase-phase	R		0,55	0,88	3,26	Ω
3	Efficiency, max.	η_{max}		82	83	82	%
4	No-load speed	n_0		6 020	6 240	6 200	min^{-1}
5	No-load current, typ. (with shaft ø 4 mm)	I_0		0,179	0,129	0,084	A
6	Starting torque	M_A		225	245	263	mNm
7	Speed constant	k_n		691	530	267	min^{-1}/V
8	Back-EMF constant	k_E		1,45	1,89	3,75	mV/min^{-1}
9	Torque constant	k_M		13,8	18	35,8	mNm/A
10	Current constant	k_I		0,0724	0,0555	0,0279	A/mNm
11	Slope of n-M curve	$\Delta n/\Delta M$		27,5	25,9	24,3	min^{-1}/mNm
12	Terminal inductance, phase-phase	L		191	331	1 290	µH
13	Mechanical time constant	τ_m		5,28	4,97	4,66	ms
14	Rotor inertia	J		18,3	18,3	18,3	gcm^2
15	Angular acceleration	α_{max}		123	134	144	$\cdot 10^3 rad/s^2$
16	Operating temperature range:						
	– motor		-40 ... +100				°C
	– winding, max. permissible		+125				°C
17	Shaft bearings		ball bearings, preloaded				
18	Shaft load max.:						
	– with shaft diameter		4				mm
	– radial at 3 000 min^{-1} (5 mm from mounting flange)		15				N
	– axial at 3 000 min^{-1} (push / pull)		3				N
	– axial at standstill (push / pull)		50				N
19	Shaft play:						
	– radial	≤	0,015				mm
	– axial	=	0				mm
20	Mass		57,9				g
21	Direction of rotation		electronically reversible				
22	Speed up to	n_{max}	10 000				min^{-1}
23	Number of pole pairs		7				
24	Hall sensors		digital				
25	Magnet material		NdFeB				
	Rated values for continuous operation						
26	Rated torque	M_N		39,5	40	41	mNm
27	Rated current (thermal limit)	I_N		2,87	2,28	1,17	A
28	Rated speed	n_N		3 320	3 750	4 150	min^{-1}
29	Rated slope of n-M curve	$\Delta n/\Delta M$		68,4	62,3	50	min^{-1}/mNm

Note: Rated values are measured at nominal voltage and 22°C ambient temperature.

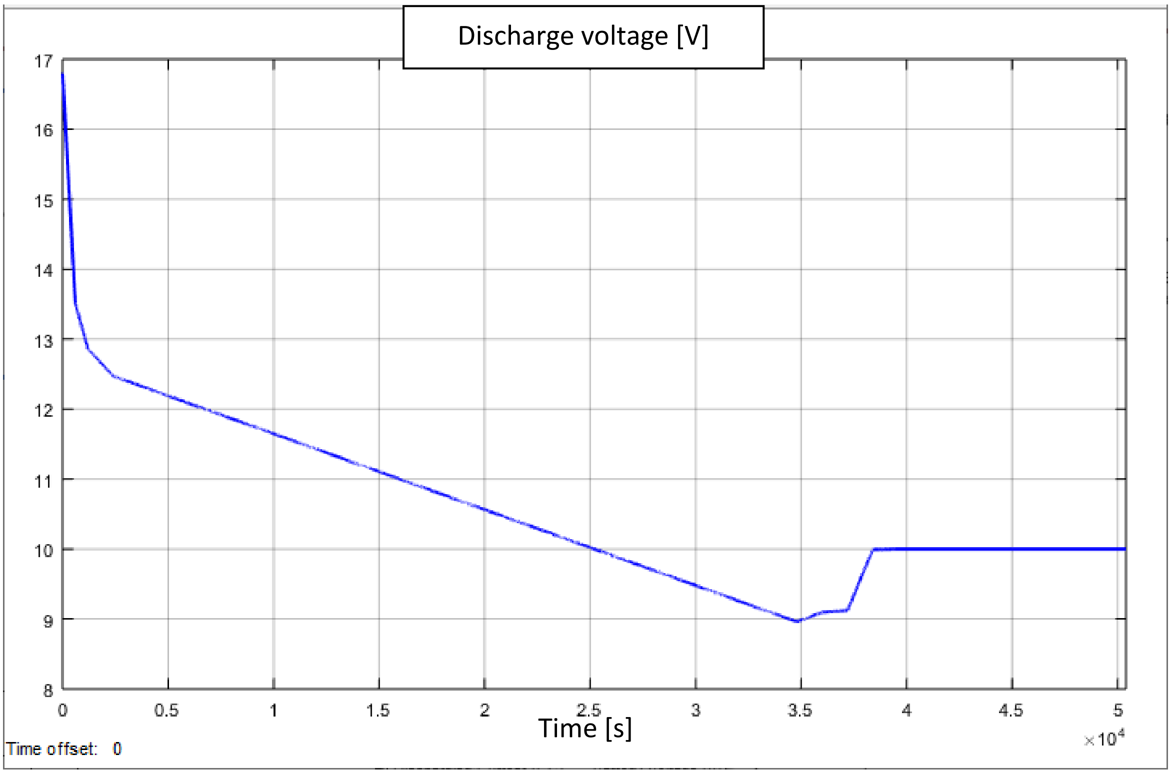
BLDC motor parameters implemented in Matlab script:

```
%-------------------MOTOR PARAMETERS-------------------------

%R - Terminal Resistance [ohm]
%km - Torque constant/100 [NmA^-1]
%L - Terminal inductance/1000 [H]
%J - Rotor inertia/(1000*100^2) [kgm^2]
%Rs0 - No load speed [rpm]
%ke=(Nominal voltage-Terminal Resistance*Nominal current)
%B=((km*Nominal current)-(Friction torque/100))

%for motor e.g.24V,48V,60V
%V12 RPX32-090
R=0.88;
km=(18/1000)/100;
L=331/(10^(-6)); %[H]
J=18.3/(1000*100^2) %[kgm^2]
Rs0=6240;
V=6; %Nominal voltage [V]
A=0.129; %Nominal current [A]
F=260; %Friction torque [mNm]
ke=(V-R*A);
B=km*A-F/100;
```

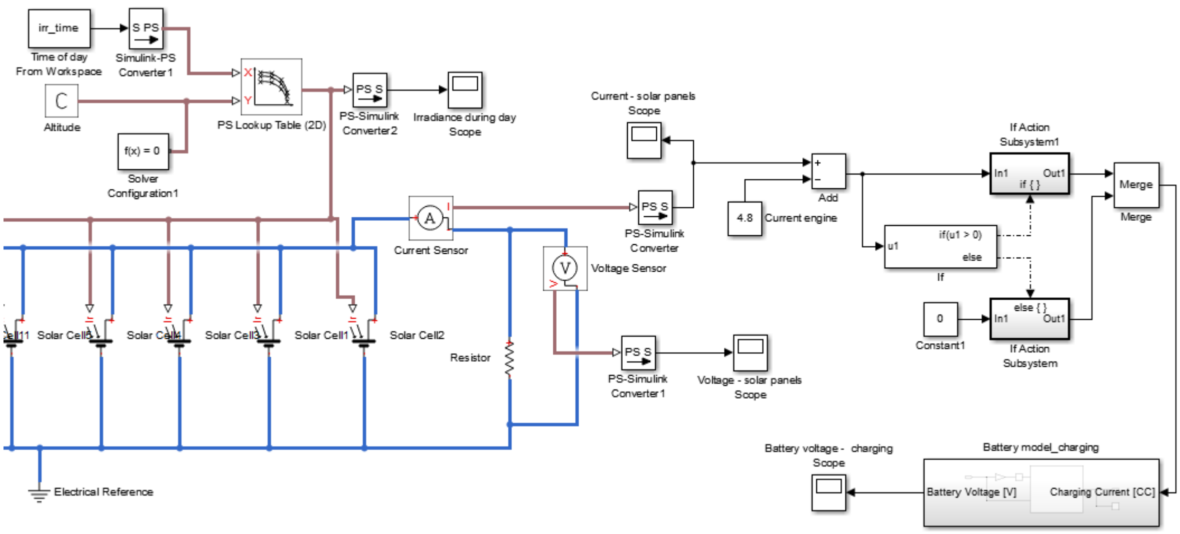
Model of motor used for simulation:

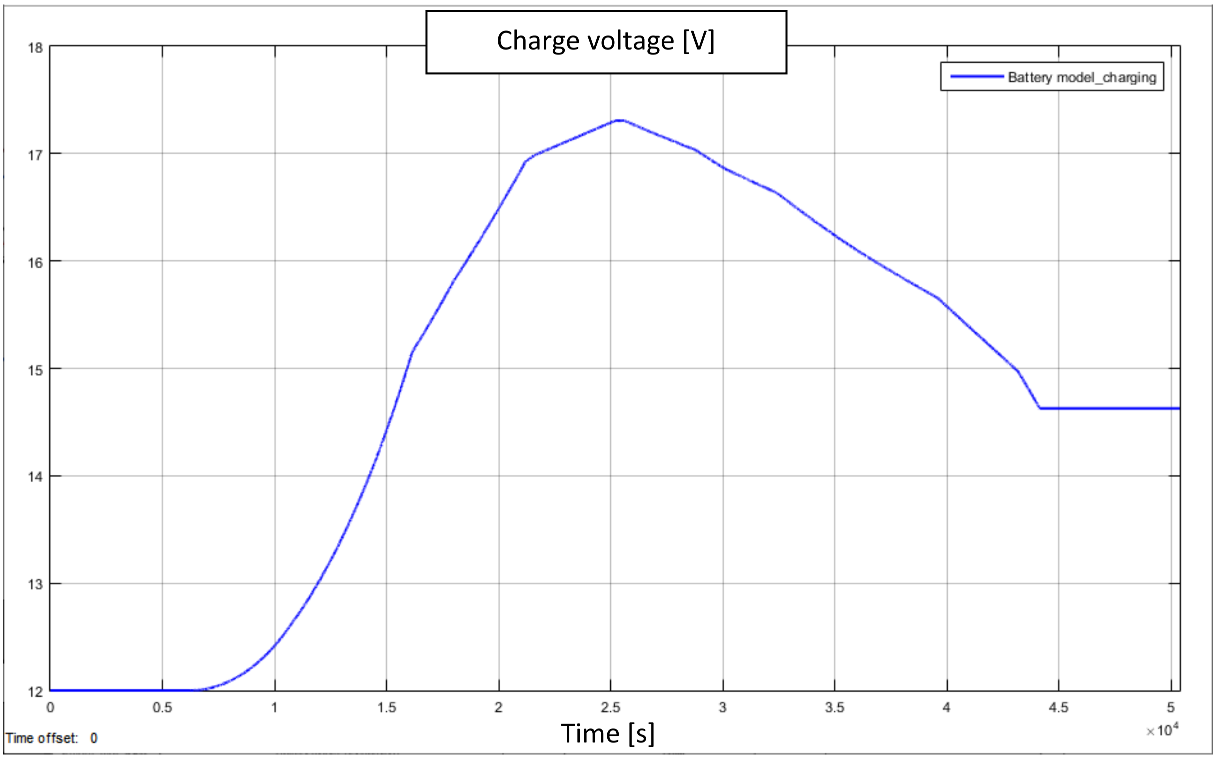


Calculated current for a steady flight mission part (cruise) is 4.8 A. It discharges the given set of batteries during 10 hour 25 min flight. Discharge characteristic for given mission is shown below:



Established discharge current now was used to estimate how many solar panels will be needed to simultaneously charge the battery set and power the motor. Simulink model is shown below.

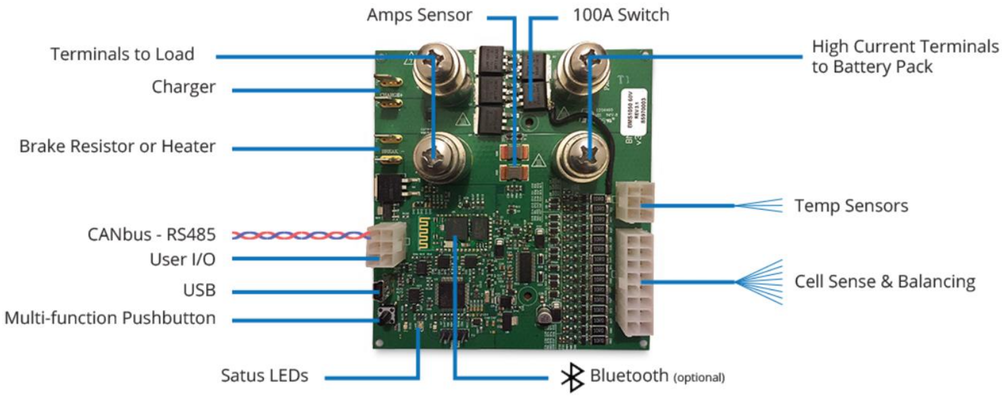




Number of solar panels required to charge the given set of batteries is 11 submodules of initial dimensions provided in data sheet. Total required area of solar panels is 3.03 m^2. Chord of the UAV's wing is 305 mm and length of submodule is 742mm, so number of submodules is 13.

STAGE 6: ADDITIONAL ELEMENTS OF DRIVE SYSTEM

- Battery management system for Li-Ion batteries – Roboteq's BMS1060. Specification data is shown below.



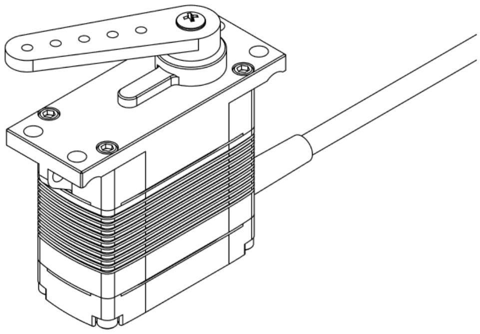
Serial Interface	1 x RS232, 1 x RS485
CAN Interface	up to 1Mbit/s
Operating Voltage	27 to 60V
Operating Temperature	-40 to +85oC operating environment
Enclosure	Conduction plate & Cover
Min Cells	11
Max Cells	15
Bluetooth	No
Dimensions	145mm x 115mm x 23mm
Weight	100g

- BLDC motor controller – Kontronik Koby 55LV

KOBY 55 LV

- 2-6 Lipo, 6-25 V
- 55 A continuous current
- 65 A peak current
- BEC 3 A continuous current
- BEC 10 A peak current
- 40 g without cable
- 55 g with cable
- Size without capacitor 55x30x11 mm

- Servos for control surfaces – Volz DA 15-N



	DA 15-N-06-BLDC-...	DA 15-N-12-BLDC-...	DA 15-N-12-BLDC-...
Supply Voltage (rated)	6 VDC	12 VDC	14 VDC
Supply Voltage Range	5 ... 9 VDC	10 ... 16 VDC	10 ... 16 VDC
Standby Current [1] at rated voltage	0.05 A	0.05 A	0.05 A
Rated Current [1] at rated voltage	0.5 A	0.35 A	0.35 A
Peak Current [1] at rated voltage	1.5 A	0.85 A	0.95 A
Rated Torque [1] at rated speed	16 Ncm (22.7 ozf-in)	25 Ncm (35.4 ozf-in)	25 Ncm (35.4 ozf-in)
Peak Torque [1] at rated voltage	60 Ncm (85 ozf-in)	60 Ncm (85 ozf-in)	60 Ncm (85 ozf-in)
No Load Speed [1] at rated voltage	290 °/s	330 °/s	390 °/s
Rated Speed [1] at rated torque	235 °/s	240 °/s	290 °/s
Default Travel Angle	±45° = 90° total travel		
Max. Travel Angle [2]	±90° = 180° total travel		
Backlash (mechanical)	≤ 0.5°		
Position Error under Temperature [3]	≤ ±1.0°		
Operating Temperature Range	-30°C ... +70°C (-22°F ... +158°F)		
Storage Temperature Range	-35°C ... +80°C (-31°F ... +176°F)		

STAGE 7: CAD MODEL OF DRIVE SYSTEM AND ITS COMPONENTS

Layout

SUMMARY

The aim of the project was to design a multi-day operational UAV with an electric driving system flying at low altitudes. The UAV should use only internal sources of energy – batteries and solar panels. The goal was to:

- conduct preliminary analysis to determine structure and driving system's parameters,
- propose a general concept of driving system and requirements that it should fulfil,
- select battery type, additional elements of power system – solar panels, motor type and other components for the project,
- simulate the components of driving system in Matlab Simulink and use it to adjust drive system's parameters
- present drive system layout as a CAD model.

The preliminary analysis was conducted using the spreadsheet shared by D. Raymer on his website. It was adapted for our use, because type of the both designed aircrafts is different. Flight parameters and aircraft dimensions were established. The stage of general concept of the UAV concerned reverse engineering and initial scheme of the system. During next stages specific elements of drive system were chosen and were modelled in Simulink. First the charge/discharge model of battery was prepared. Following parameters were calculated: irradiance at cruise altitude, amount of solar panels needed to charge the battery set during day, engine current consumption, time of discharge of batteries during night. Number of batteries needed was increased, because the amount we established at preliminary phase was not sufficient for motor power consumption. Then the solar panels calculation was repeated and we established required surface of solar panels. The results will cause changing the UAV's parameters as wing surface or mass. In the last stage the initial drive system configuration and UAV structure was proposed.

RESOURCES

[1] https://www.sciencedirect.com/topics/engineering/solar-declination

[2] Molicel Product data sheet model INR-18650-P26A

[3] Rodrigo Mozo Ordóñez: Design of HALE UAV wings, Faculty of Mechanics – Vilnius Gediminas Technical University, 2017

[4] https://www.atlantiksolar.ethz.ch/wp-content/downloads/publications/JFR_81hFlight_paper_final.pdf