ANKARA YILDIRIM BEYAZIT UNIVERSITY GRADUATE SCHOOL
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REDESIGNING FIXED-WING LOITERING MUNITION AS SOLAR SUPPORTED BY USING REVERSE ENGINEERING METHOD

M.Sc. Thesis by

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ANKARA

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M.Sc. THESIS EXAMINATION RESULT FORM

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REDESIGNING FIXED-WING LOITERING MUNITION AS SOLAR SUPPORTED BY USING REVERSE ENGINEERING METHOD

ABSTRACT

Conventional warfare has been transformed into hybrid warfare or asymmetric threat in recent decades. Due to this reason, the world's armed forces are constantly taking innovative steps to improve their defense technologies. Thanks to this technological development, armed forces all over the world are begun to equip with a variety of UAVs in accordance with their military mission. One of these UAVs, supplanted in army inventories, loitering munitions, also known as kamikaze drones, which create an explosive effect on the target by hitting the in defilade position, are autonomous weapon systems that operate on the "search-find-destroy" principle.

In this thesis, first the history of solar-powered manned/unmanned aerial vehicles (UAVs) all over the world, , the development process of UAV technology in Turkey and classification of UAVs and the place of loitering munitions will be explained in details. Then, one of the fixed-wing loitering munitions, ALPAGU which are effectively used in today's battlefields will be taken on board and its working principles, features and specifications will be explained. Subsequently, taking into account the irradiance values of the Şırnak province, it will be calculated whether the flight duration of 15 minutes can be extended by reverse engineering method with the additional solar support components. Whether its cost-efficient or not, this study is the first of its kind to apply a solar support system to a loitering munition in order to extend its flight endurance by harnessing solar energy.

Finally, as a result of the calculations made on regarding the solar support components applied to the ALPAGU loitering munition, it will be theoretically proven that the time in the air can be extended by 11.2%, in numerical terms, 1.76 minutes (105.6 seconds).

Keywords: Loitering Munitions, Kamikaze Drones, Suicide Drones, Solar Cells, Solar Energy, Solar Supported, UAVs, MPPT, LiHV Batteries

SABİT KANATLI DOLANAN MÜHİMMATLARIN TERSİNE MÜHENDİSLİKYÖNTEMİYLE SOLAR DESTEKLİ OLARAK TASARIMI

ÖZ

Son yıllarda, konvansiyonel savaşlar hibrit savaşa ya da asimetrik tehdide dönüşmüştür. Bu nedenle, dünya orduları savunma teknolojilerini geliştirmek ve daha ileriye taşımak maksadıyla sürekli yenilikçi adımlar atmaktadır. Söz konusu, teknolojik gelişmeler sayesinde dünyanın dört bir yanındaki silahlı kuvvetler, askeri misyonlarına uygun olarak çeşitli İHA'larla donatılmaya başlanmıştır.

Ordu envanterlerinde yerini alan bu İHA'lardan biri de, kamikaze drone olarak da bilinen, sütre gerisinden hedefi vurarak hedef üzerinde patlayıcı etkisi yaratan, "ara-bul-yok et" prensibiyle çalışan dolanan mühimmatlardır.

Bu tezde, ilk başta güneş enerjili insanlı/insansız hava araçlarının (İHA) dünyadaki tarihçesi, Türkiye'de İHA teknolojisinin gelişim süreci, İHA'ların sınıflandırılması ve dolanan mühimmatların bu sınıflandırmadaki yeri detaylı olarak anlatılacaktır.

Günümüz muharebe sahalarında etkin olarak kullanılan sabit kanatlı dolanan mühimmatlardan ALPAGU ele alınacak, çalışma prensipleri, özellikleri ve adedi bilgileri anlatılacaktır. Müteakiben, Şırnak ilinin ışıma verileri dikkate alınarak, tersine mühendislik ile, eklenecek solar destek sistemi ile 15 dk. olan havada kalma süresinin uzatılıp uzatılamayacağı hesaplanacaktır. Bu çalışma, maliyet-etkin olsun ya da olmasın, solar destek sisteminin dolanan mühimmata uygulanması nedeniyle bir ilk olma özelliği taşır.

Sonuç olarak, ALPAGU dolanan mühimmata uygulanan solar destek birleşenlerine ilişkin yapılan hesaplamalar neticesinde havada kalma süresinin yüzde 11,2 oranında, sayısal değer olarak 1,76 dk.(105,6 sn) uzatılabileceği teorik olarak gösterilmiştir.

Anahtar Kelimeler: Dolanan Mühimmatlar, Kamikaze Dronlar, İntihar Dronları, Solar Enerji, Solar Destekli, İHA, MPPT, LiHV Piller

CONTENTS

ABBREVIATIONS

UAV	Unmanned Aerial Vehicle
UCAV	Unmanned Combat Aerial Vehicle
TAF	Turkish Armed Forces
LHD	Landing Helicopter Dock
HALE	High Altitude Long Flight Endurance
MALE	Medium Altitude Long Flight Endurance
LALE	Low Altitude Long Flight Endurance
FAI	International Aviation Federation (Fédération Aéronautique Internationale)
RAF	Royal Air Force
ERAST	Environmental Research Aircraft and Sensor Technology
DLR	German Aerospace Center (Deutschen Zentrum für Luft- und Raumfahrt)
EPFL	Polytechnic University Of Lausanne (Ecole Polytechnique Fédérale de Lausanne)
ETH	Swiss Federal Institute of Technology (Eidgenössische Technische Hochschule)
PHASA	Persistent High Altitude Solar Aircraft
EUROUVS	The European Organization for Unmanned Aerial Systems
RSTA	Reconnaissance, Surveillance, and Target Acquisition
EW	Electronic Warfare
TBD	To be determined and decided
GCS	Ground Control Station
AI	Artificial Intelligence
STM	Savunma Teknolojileri Mühendislik ve Ticaret A.Ş
MPPT	Multiple Power Point Tracker
PV	Photovoltaic
STC	Standard Test Conditions
Li-Po	Lithium Polymer
Li-Ion	Lithium Ion

Li-S	Lithium Sulfur
LiHV	Lithium High Voltage
AUW	All-Up Weight
AAD	Average Amp Draw

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CHAPTER 1

INTRODUCTION

Unmanned Aerial Vehicles are of significance in many application areas from military purposes to agriculture all around the world. In parallel with the technological developments, the diversity of unmanned aerial vehicles and intended purpose has increased simultaneously. With this scope, loitering munitions are undoubtfully one of the unmanned aerial vehicles that have taken their place in this diversity [1].

The usage of loitering munitions has changed the course of conflict especially in the Russian-Ukrainian war, in the second Nagorno-Karabakh war between Azerbaijan and Armenia [2], in the Libyan operations [3], in Syrian armed conflagrations [4], and in the strikes by Iranian-backed groups on several military posts and oil facilities in Saudi Arabia and the UAE [5][6].

Moreover, the experience of loitering munitions used in the Russia-Ukraine War has shown that the countries possess unmanned aerial systems technology and even the most powerful armies of the world such as Great Britain have been triggered to establish their own kamikaze drone units [7].

However, there are some constraints about loitering munitions with a view hovering endurance along the fixed-wing types. Because of their engineering design and specifications such as weight, fixed-wing types are more efficient to take the advantage of solar cells, that is harnessing solar energy. That’s why; fixed-wing loitering munitions will be handled in this article whether their endurance could be extended for longer missions via solar cells which are applied onto their structure, wings and tails.

1.1 Historical Development of Solar Powered Aerial Vehicles

On June 30, 1957, British Colonel H. J. Taplin who wants to make use of electricity energy developed a permanent magnet synchronous motor and the first to use silverzinc batteries, officially recorded with the UAV "Radio Queen" and radio-controlled flight powered by electricity [8].

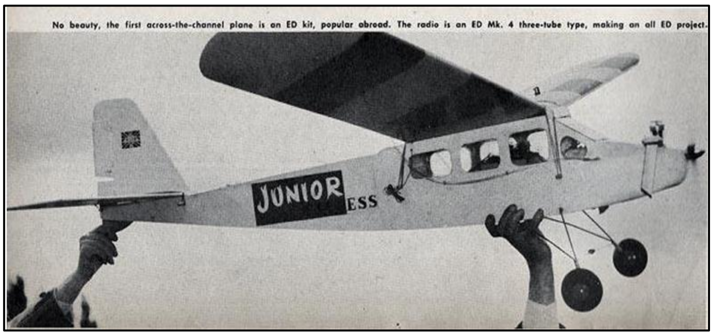


Figure 1.1 Radio Queen, powered by electricity [8]

On November 4, 1974, the first flight of solar-powered UAV was performed on a dry lake in Camp Irwin, California by R.J. Bouncer who served for AstroFlight company. The designed solar UAV "Sunrise I" flew for 20 minutes at an altitude of about 100 m on its first flight. The wingspan of the UAV was 9.76 m, the weight was 12.25 kg and the power output of the 4096 solar cells was 450 W power [9].

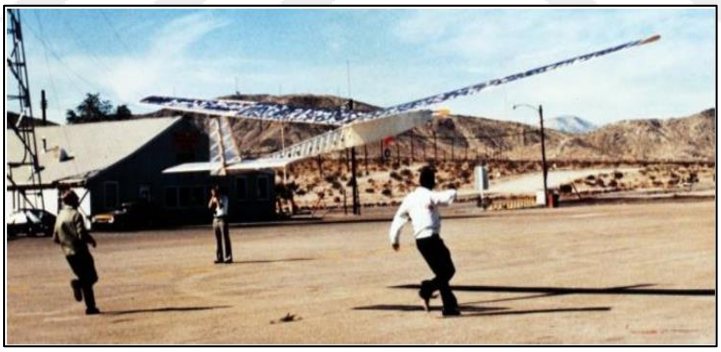


Figure 1.2 Sunrise I, by R.J. Bouncer [9]

On its 28th flight, the first prototype of Sunrise I was seriously damaged in turbulence. One year later, on September 12, 1975, an improved version, the "Sunrise II", was built with the same wingspan, however the aircraft's weight was reduced to 10.21 kg. In addition, this time with 14% efficiency, 4480 solar cells were used which were able to produce 600 W power [10].

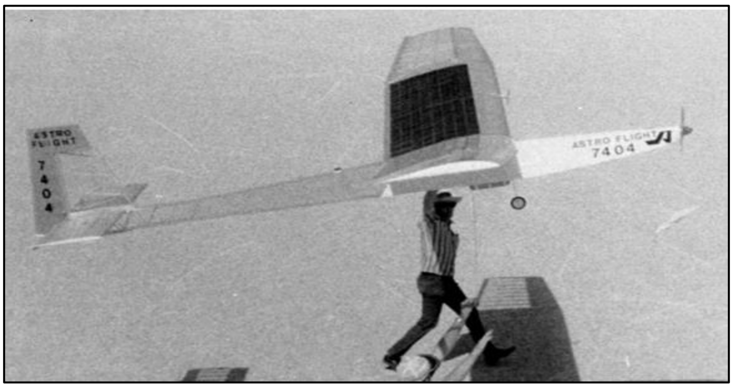


Figure 1.3 Sunrise II [10]

Across the Atlantic, in the summer of 1975, Helmut Bruss from Germany was working on a solar-powered model airplane, unaware of Bouncer's project. Unfortunately, the solar cells of the aircraft overheated and failed to accomplish the flight. But a year later, together with his friend Fred Militky, managed to produce "Solaris", the first solar-powered UAV in Europe. On August 16, 1976, it reached an altitude of 50 m with 3 flights of 150 seconds [11].

Figure 1.4 Solaris, by Helmut Bruss & Fred Militky [11]

Subsequently, because of its cost-effective features, many model airplane manufacturers experimented solar power aircrafts. Over time, this ambition had become even more and more. The most authoritative foundation in sport aviation, The International Aviation Federation (FAI/ Fédération Aéronautique Internationale) held a contest for F5 Open (Radio Controlled Flight) class competition and "Solar Solitude" UAV by Dave Beck broke two records and made its name stand out [12].

Figure 1.5 Solar Solitude, by Dave Beck & his team [12]

In the 1990s, Wolfgang Schaeper broke many records in this field with his "Solar Excel" model. He is also the author of the small UAVs called "MikroSol", "PicoSol" and "NanoSol" [13].

Figure 1.6 MikroSol (top-left), PicoSol (top-right) and NanoSol (below) by W. Schaeper [13]

These studies were a great inspiration for solar-powered manned airplanes and various models have been developed. Although models such as Solair I and Solair II were designed by Günther Rochelt at that time, the "Solar Challenger" designed by MacCready had 16128 solar cells providing 2500 W power at sea level and a wingspan of 14.2 m. On July 7, 1981, it completed its 262.3 km flight from Puntoise-Cormeilles near Paris to RAF Manston Base near London in 5 hours and 23 minutes, using solar energy as the only power source, without even a backup battery [14].

Figure 1.7 Solar Challenger designed and flew by MacCready [14]

This achievement of Solar Challanger paved the way for the first time the U.S. government to fund AeroVironment Company, which products durable aerial vehicles and UAV systems. As a result of the works accomplished in 1993 "Pathfinder" (with a wingspan of 30 m and a weight of 254 kg) appeared and made its first flight in Dryden. When the earmarked funding ended for this program, Pathfinder included in NASA's ERAST (Environmental Research Aircraft and Sensor Technology) program [15].

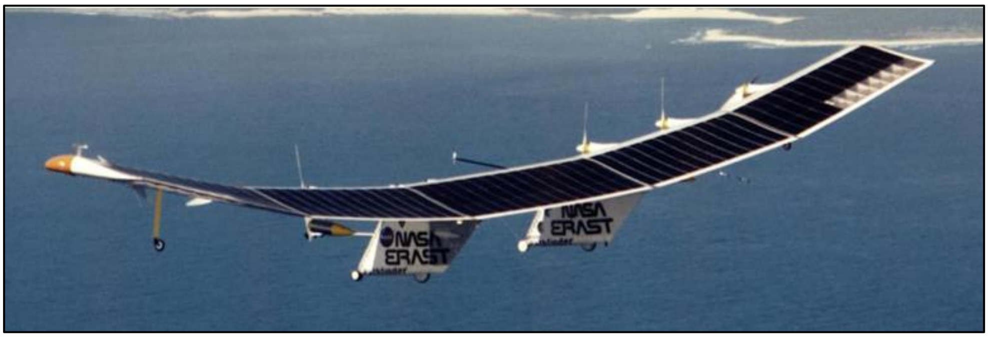


Figure 1.8 Pathfinder flying over Hawaii [15]

In 1998 an upgraded model "Pathfinder Plus" was developed. A new prototype called "Centurion" was developed under the ERAST program. The aim was to develop a prototype technology for a future fleet of solar-powered aircraft that could stay in the air for weeks or months and be used for scientific sampling or telecommunications missions.

The fourth and final work of ERAST program was the UAV called "Helios". The UAV, which made its first flight in 1999, entered turbulence 30 minutes after take-off during a test flight on June 26, 2003, and its wings broke apart due to high positive dihedral and then fell into the Pacific Ocean [16].

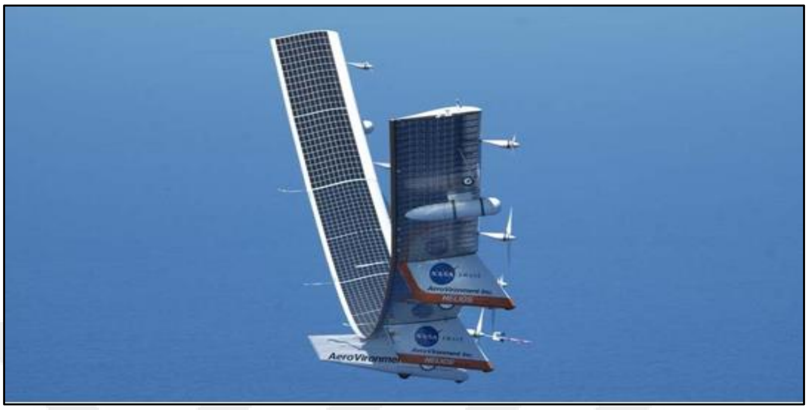


Figure 1.9 Helios, just before disintegrated [16]

Researches on UAVs to prioritize endurance at high altitudes had been ongoing in Europe. German Aerospace Center (DLR/Deutschen Zentrum für Luft- und Raumfahrt) hard works from 1994 to 1998 led to the development of the "Solitair". It is designed for long-term missions in mid-latitudes (roughly between 35 and 65 degrees North and South.) by meeting all energy needs with adjustable solar panels for the best solar radiation absorption [17].

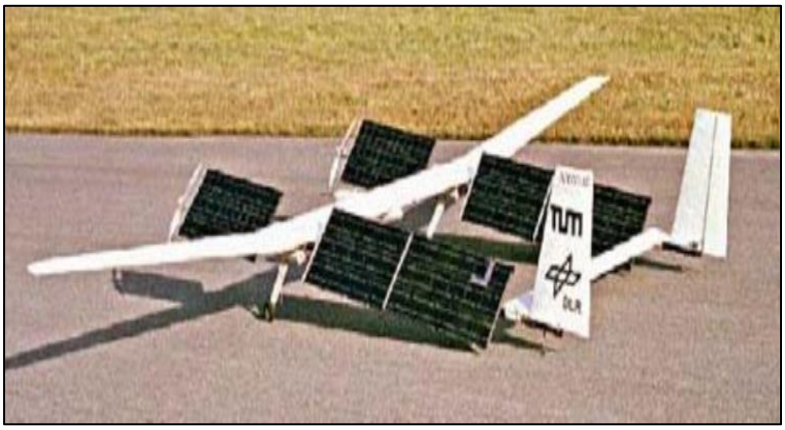


Figure 1.10 Solitair,1998 [17]

Thanks to "Helinet Project" funded by the European program, between January 2000 and March 2003, feasibility studies were conducted for a solar-powered "Heliplat" platform with a wingspan of 73 m and a weight of 750 kg. Due to its high bandwidth, it was intended to be used for communication and earth observation like a satellite [18].

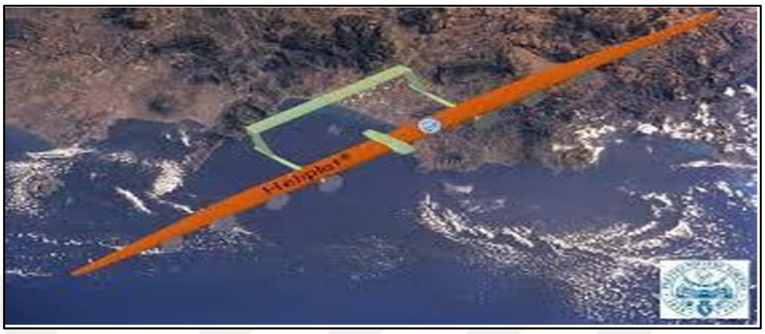


Figure 1.11 Heliplat,2000 [18]

The "Sky-Sailor" project, backed up by the European Space Agency in 2004, began at EPFL (Ecole Polytechnique Fédérale de Lausanne) in Lausanne, Switzerland. Solar-powered aerial vehicles are expected to play a major role in planetary exploration. The aim was to develop a UAV that could be used for the exploration of Mars. On June 21, 2008, covering 874.4 kilometers, Sky-Sailor performed a 27-hour non-stop Zurich-London journey [19].

Figure 1.12 Skysailor, 2008 [19]

In 2006, inspired by Günther Rochelt, a German firm called Solar Flight developed a piloted aerial vehicle Sunseeker II, after long series of modifications and refinements on Sunseeker I. More surface area for solar cell coverage applied on designed wings by integrating the new generation of solar cells into the actual wing structure rather than sticking them on the surface. Besides, the new propulsion system produced for the Sunseeker II was twice as efficient as Sunseeker I's. After these developments the project evolved into a new two-seated aircraft, Sunseeker Duo which has 1510 solar cells with wingspan of 22 meters and weight of 280 kg [20].

Figure 1.13 Sunseeker I, Sunseeker II, Sunseeker Duo (right to left) [20]

In 2015, ETH Zurich (Swiss Federal Institute of Technology) has constructed a pioneering low-altitude long-endurance (LALE) solar-powered UAV which is capable of flying for multiple days, for the first-ever crossing of the Atlantic Ocean. Swiss Glaciologists used AtlantikSolar to monitor glaciers in Greenland. Ongoing daylight situation in the Arctic Summer ensured potentially ideal solar energy. As a result, between July 14th-17th 2015 AtlantikSolar performed 2338 km and 81.5 hours (4 days and 3 nights) during its continuous flight and broke the flight endurance world record for all solar aircrafts below 50kg total mass [21].

Figure 1.14 AtlantikSolar while landing & monitoring glaciers [21]

In 2020, BAE Systems, a British aerospace company based in London, developed a HALE UAV called Persistent High Altitude Solar Aircraft (PHASA-35) in collaboration with Prismatic. PHASA-35, has been used for border control, disaster relief, surveillance, telecommunications as a cheaper alternative to satellites thanks to its ability to stay in the air for up to 12 months [22].

Figure 1.15 PHASA-35 [22]

1.2. Development Process of Unmanned Aerial Vehicles in Turkey

For the last few years, our country, Turkey has been on the world media agenda with its Unmanned Combat Aerial Vehicles (UCAVs). From Syria to Libya, from Iraq to Nagorno- Karabakh, these UCAVs, which act as game changers in the field and create a new concept of warfare, attract the attention of defense industry analysts and the world's militaries.

Turkey's introduction to UAVs dates back to the 1990s. In the early 1990s, the first steps were taken with the purchase of the GNAT 750 from the USA and the start of development work within Turkish Aviation Industry (TAI). The first national UAV work began in 1992 with the İHA-X1 contract between the Defence Industry Agency (DIA) and TAI. The İHA-X1, for which TAI successfully completed the development process, was shelved due to the lack of vision and concept at the time [23].

Figure 1.16 The first national UAV of Turkey in 1992, İHA-X1[23]

Although a contract was signed to develop İHA-X1 between TAI and DIA, works regarding the design details of the vehicle had continued. In 2007, the design was frozen and the production of a new UAV began within TAI, which was renamed ANKA. While TAI had started its projects with the assignment it received from the DIA, BAYKAR (a private defense company) had started working on UAV on its own initiative in 2000. The company first developed the small-scale BAYRAKTAR-MINI UAV, which made its first flight in 2004 [24].

Figure 1.17 Bayraktar-Mini UAV, utilized in Internal Security Operation [24]

BAYKAR did not limit itself to the Bayraktar-Mini UAV, but started working on the development of a larger-scale UAV. Following these efforts, the company manufactured the tactical class UAV named Bayraktar-TB1 (Çaldıran) and flew the UAV for the first time in 2009 and completed all of its flights in the same year [25].

Figure 1.18 Bayraktar-TB1 (Çaldıran) [25]

In 2010, important developments took place both in foreign procurement and in the ANKA project. Although Turkey had started work on national UAVs, it would take time for them to enter the inventory, so Turkey purchased 10 HERON Unmanned Aerial Vehicles from Israel, and the HERONs were delivered in 2010.

In the ANKA project, the first ANKA, ANKA-A, left the hangar in July 2010 and successfully made its first flight on December 30, 2010. With this flight, Turkey produced a MALE class UAV for the first time. After the first flight, the flight tests of the ANKA-A continued intensively, and by May 2013, Turkey took the first step in the transition from UAV to UCAV. ANKA-A conducted Turkey's first UCAV test by firing two ROKETSAN-made CİRİT missiles on its wings at the target marked by the ASELSAN-made ASELFLIR-300T electro-optical camera. However, after this test, due to the current conjunctural situation and the fact that CİRİT is not suitable for use in UAVs, the work on UCAVs could not be completed and was limited to that shot [26].

Figure 1.19 ANKA-A, loaded with CİRİT [26]

By October 2013, the ANKA-A had completed acceptance. In the same month, a serial production contract was signed between TAI and DIA. The UAV to be delivered under the serial production contract was a very different UAV than the ANKA-A. The UAV in the contract, called ANKA-S, had many new features, including satellite control. Although it was very important for a UAV like the ANKA-S to enter the Turkish Armed Forces' inventory, the high-level requirements caused both the Turkish Armed Forces to be deprived of field experience for a long time. The project and ANKA-S deliveries which were scheduled to start in 2016 was delayed, did not start until 2018.

Back in 2010, a new UAV decision was made by the Defense Industry Executive Committee. The Committee authorized DIA to procure new domestic and national 12 tactical UAVs. Contract negotiations between DAI and BAYKAR, which began in early 2010, were concluded in December 2011. Having signed a contract with Bayraktar TB-1, BAYKAR delivered six Bayraktar TB-2s on November 22, 2014. In the process, the company took the UAV to a much more advanced level. The UAV evolved from the Tactical class to the Medium Altitude Long Endurance (MALE) class. While the BAYRAKTAR TB1 was a UAV with a wingspan of 9 meters and a total take-off weight of 450 kg, the BAYRAKTAR TB-2 is a much more advanced UAV with a wingspan of 12 meters and a total take-off weight of over 700 kg.

Figure 1.20 Bayraktar TB-2, the first operational UCAV of Turkey [27]

In July 2015, Turkey entered a new era in the fight against terrorism, at a time when the need for UAVs was felt the most. In the same year, TAI carried out the first flight of the ANKA-B, a lightened version of the ANKA-A that can reach an altitude of

30,000 feet and stay airborne for 24 hours. By 2015, BAYKAR had completed its contract by delivering the remaining six Bayraktar TB-2s [27].

In 2016, the existing Bayraktar TB-2s were converted into UCAVs through agreements with ROKETSAN and began participating in Internal Security Operations, and became Turkey's first operational UCAV. Thus, Turkey conducted its first UCAV operation in 2016. The Gendarmerie received three ANKA-Bs in 2016, and shortly after the Bayraktar TB-2s, the ANKA-Bs were also armed and put into operational use. In 2016 and 2017, increasing the number of UCAVs, new Bayraktar TB-2s were taken into TAF inventory.

In 2018, TAI began deliveries of the ANKA-S and for the first time, an unmanned aerial vehicle with a range of hundreds of kilometers and satellite communication was included in the TAF inventory. ANKA-Ss were also rapidly armed. Although UCAVs were used in Operation Euphrates Shield between 2016 and 2017, the first operation in which UCAVs emerged as a game changer was Operation Olive Branch in January 2018. This operation also played an important role in the development of UCAVs. In the operation, where intensive Electronic Warfare was applied, engineers took part in the field to keep UCAVs operational, and our UCAVs performed thousands of flight hours and destroyed thousands of targets belonging to the separatist terrorist organization YPG/PKK [28].

Figure 1.21 ANKA-S [28]

On August 29, 2021, the doors of the new era opened and the first AKINCI UCAVs were delivered to the TAF. Both BAYRAKTAR TB2s and ANKA-B and ANKA-S performed/are performing all their missions with 22 kg MAM-L and 6.5 kg MAM-C ammunition. With the introduction of the BAYKAR-developed AKINCI into the inventory, this situation has completely changed. With AKINCI, which has a payload carrying capacity of 1.5 tons, the attack missions of UCAVs continued to increase [29].

Figure 1.22 AKINCI, Tactical Unmanned Aerial Vehicle [29]

BAYKAR, which has been carrying out domestic and international deliveries of Bayraktar TB-2s, as well as development and testing activities for AKINCI, continued its efforts to add new capabilities to the Bayraktar TB2, and introduced the SATCOM-integrated Bayraktar TB-2/S in 2020. BAYKAR also had one more surprise in 2020 by announcing Bayraktar TB-3 UCAV which has planned to put upon the market in 2024, which can take off and land on the TCG ANADOLU LHD [30].

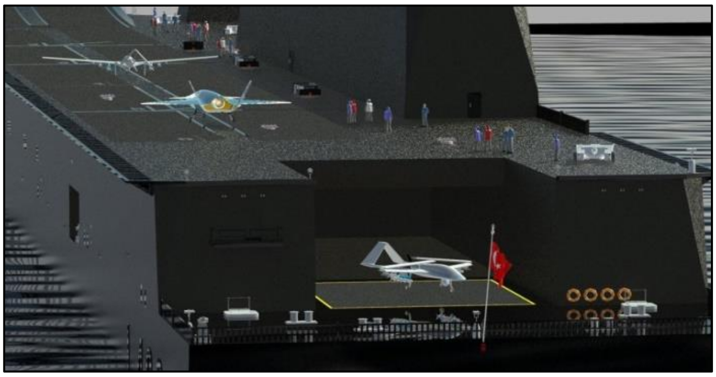


Figure 1.23 Bayraktar TB-3s on TCG ANADOLU LHD [30]

As one of the 8 countries in the world that produces its own UCAVs, Turkey has reached a very advanced point in the combat field. In the coming years, it will reach much more advanced points with new future projects such as Bayraktar Kızılelma, national UCAV developed by BAYKAR [31].

Figure 1.24 Bayraktar Kızılelma [31]

In line with all information above, it is obvious that Turkey has covered a distance in UAV technology. However, although there are 37 solar panel manufacturers in Turkey, there are no remarkable researches concerning the development of solar-powered unmanned aerial vehicles yet. [32].

1.3 Classification of Unmanned Aerial Vehicles

Due to the fact that there is no standardized approach for the classification of UAVs all over the world, there is one widely accepted three main prerequisite criteria for classification methods. First criteria is flying ability without operator (human), second one is moving ability via remote-controlling systems or autonomous way, the last one is capability of carrying lethal or non-lethal payloads. However, not all aircrafts can be considered as UAVs that meet this criteria. For instance, ballistic and semi-ballistic aircrafts and cruise missiles are not considered as UAVs.

Examining the studies in the literature, there are UAVs classifications based on different parameters. These classification parameters could be analyzed under 16 headings as sorted in the Table 1.1 below [33].

Table 1.1 Parameters for UAV Classification

Classification Parameters			
1	The usage area of the aircraft	9	Fuel system
2	The type of control system	10	Fuel tank type
3	Flight rules	11	The number of fuel system utilization
4	Wing type	12	The type of aircraft
5	The condition of the space used in the air	13	General category (UAV maximum take-off weight, range, hover time, maximum altitude it can reach values)
6	The direction of buoyancy at take-off and landing	14	Realizable distance according to the radius
7	Take-off - landing type	15	Flight altitude
8	Engine type of the aircraft	16	Function and fields of application

Classification for UAV's is based on one or several of these parameters in different combinations. However, the most common accepted classification parameter in the literature is the 13th one which based on the UAV's take-off weight, range, hover time or endurance, and maximum altitude. Considering the practical usage areas, functional/operational characteristics, commercial and educational activities, it could be easily understood why this classification standard is prevalent and why the method is useful. The most commonly used assessment, in this type classification parameter can be summarized as follows [33]:

- Weight (Gross take-off weight + Payload weight)

- Operation (flight) altitude

- Duration in the air

- Distance at which data can be collected

- Field of usage (intended use)

- The task performed by the UAV

When the classifications made according to these parameters are analyzed in the most general and broad sense, the main subgroups are Micro/Mini UAVs, Tactical

UAVs, Strategic UAVs and Special Mission UAVs.

The European Organization for Unmanned Aerial Systems (EUROUVS), based on various criteria which was inspired by this classification is demonstrated in Table 1.2 [34].

Table 1.2 UAV Classification adopted by EUROUVS

	Category (acronym)	Maximum Take Off Weight (kg)	Maximum Flight Altitude (m)	Endurance (hours)	Data Link Range (Km)	Example	
						Missions	Systems
Micro/Mini UAVs	Micro (MAV)	0.10	250	1	<10	Scouting, NBC sampling, surveillance inside buildings	Black Widow, MicroStar, Microbat, FanCopter, QuattroCopter, Mosquito, Hornet, Mite
	Mini	<30	150-300	<2	<10	Film and broadcast industries, agriculture, pollution measurements, surveillance inside buildings, communications relay and EW	Mikado, Aladin, Tracker, DragonEye, Raven, Pointer II, Carolo C40/P50, Skorpio, R-Max and R-50, Robo-Copter, YH-300SL
Tactical UAVs	Close Range (CR)	150	3.000	2-4	10-30	RSTA, mine detection, search & rescue, EW	Observer I, Phantom, Copter 4, Mikado, RoboCopter 300, Pointer, Camcopter, Aerial and Agricultural RMax
	Short Range (SR)	200	3.000	3-6	30-70	BDA, RSTA, EW, mine detection	Scorpi 6/30, Luna, SilverFox, EyeView, Firebird, R-Max Agri/Photo, Hornet, Raven, phantom, GoldenEye 100, Flyrt, Neptune
	Medium Range (MR)	150-500	3.000-5.000	6-10	70-200	BDA, RSTA, EW, mine detection, NBC sampling	Hunter B, Mücke, Aerostar, Sniper, Falco, Armor X7, Smart UAV, UCAR, Eagle Eye+, Alice, Extender, Shadow 200/400
	Long Range (LR)	-	5.000	6-13	200-500	RSTA, BDA, communications relay	Hunter, Vigilante 502
	Endurance (EN)	500-1.500	5.000-8.000	12-24	>500	BDA, RSTA, EW, communications relay, NBC sampling	Aerosonde, Vulture II Exp, Shadow 600, Searcher II, Hermes 450S/450T/700
	Medium Altitude, Long Endurance (MALE)	1.000-1.500	5.000-8.000	24-48	>500	BDA, RSTA, EW weapons delivery, communications relay, NBC sampling	Skyforce, Hermes 1500, Heron TP, MQ-1 Predator, Predator-IT, Eagle-1/2, Darkstar, E-Hunter, Dominator
Strategic UAVs	High Altitude, Long Endurance (HALE)	2.500-12.500	15.000-20.000	24-48	>2.000	BDA, RSTA, EW, communications relay, boost phase intercept launch vehicle, airport security	Global Hawk, Raptor, Condor, Theseus, Helios, Predator B/C, Libellule, EuroHawk, Mercator, SensorCraft, Global Observer, Pathfinder Plus,
Special Task UAVs	Lethal (LET)	250	3.000-4.000	3-4	300	Anti-radar, anti-ship, anti-aircraft, anti-infrastructure	MALI, Harpy, Lark, Marula
	Decoys (DEC)	250	50-5.000	<4	0-500	Aerial and naval deception	Flyrt, MALD, Nulka, ITALD, Chukar
	Stratospheric (Strato)	TBD	20.000-30.000	>48	>2.000	-	Pegasus
	Exo-stratospheric (EXO)	TBD	>30.000	TBD	TBD	-	MarsFlyer, MAC-1

Source: Adapted from "UVS-International-"UAV System producers & Models: All UAV Systems Referenced," 2006

Especially when we examine the classification table loitering munitions could be placed Special Task UAVs, furthermore Lethal (LET) types. Adopted in 2008, this classification could be evaluated as a study lagging behind technological developments, because specifications has not been involved such as endurance lower than 1 hours, data link range lower than 10 km. Additionally, one more criteria had better be attached to those parameters to classify such as *"Propulsion System"*. The types of propulsion system based on energy types are given in Figure 1.25 below [35].

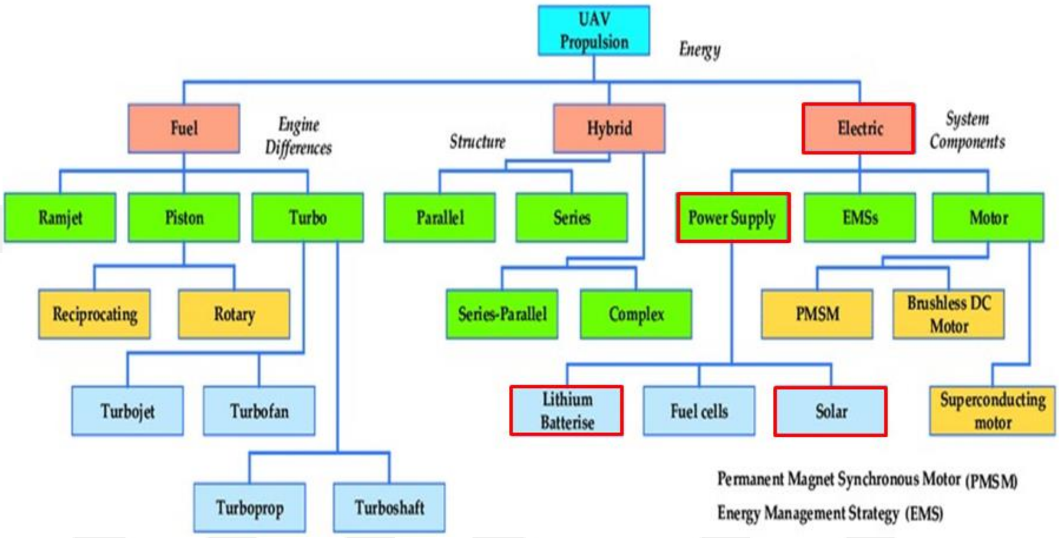


Figure 1.25 UAV propulsion classification based on energy types [35]

In this study, it will be examined whether the flight endurance could be extended by utilizing solar energy for loitering munitions powered by lithium batteries. In other words, the main purpose of this thesis is while exploiting electricity from the lithium battery; refill it by converting solar energy to electrical energy.

1.4 Literature Review

1.4.1 Loitering Munitions

The development of artificial intelligence (AI) in the defense industry produces unprecedented smart systems that redefine how the fighting units are projected on the battleground. Weapon systems are progressively getting more intelligent, more precise, more flexible, and smaller.

Loitering munitions, also dubbed as kamikaze drones, are the most recent example in this regard. These suicide drones are remote controlled aerial weapons with a niched explosive substance (warhead), which can recon until the objective is detected, then attack and destroy the target by crashing into it.

Loitering munitions are low-cost guided precision munitions that can be maintained in a holding pattern in the air for a certain time and rapidly attack land or sea non-line-of-sight targets. Loitering munitions are under the control of an operator who sees a real-time image of the target and its surrounding area, giving the capacity to control the exact time, attitude, and direction of the attack of a static, relocatable, or moving target, including providing a contribution to the formal target identification and confirmation process [36].

Furthermore, loitering munitions can conduct a birds-eye view patrol duty around the target area within its range and duration time. In line with these explanations kamikaze drones are not to be confused with “Cruise Missiles” or “UCAVs” [37]. Although sharing some similar characteristics, they are different from cruise missiles and UCAVs in terms of loitering time around the target area and homecoming to base dependently for its type. The comparative similarities and differences of these three highly confusable flying weapon systems are as shown in Table 1.3 [38].

Table 1.3 Comparative Similarities/Differences Between Loitering Munitions, Cruise Missiles and UCAVs

Characteristic	Cruise missile	Loitering munition	UCAV
Cost appropriate for expendable one-time use	Yes	Yes	No, but high cost allows for higher-quality platform
Recovery possible after launch	No	Usually no	Yes, typical mission profile is round-trip
Built-in warhead	Yes	Yes	No
Stealthy final dive to target	Usually yes	Usually yes	Usually no
Loitering	No or limited	Yes	Usually yes
Sensors for target acquisition	Limited	Yes	Usually yes
Command and control during flight	Usually limited	Yes	Yes
Range	Longer, optimized for constant speed flight	Shorter	Shorter, even shorter for typical round-trip mission
Speed	Typically higher	Typically lower	Depends on role

1.4.2 Types of Loitering Munitions

Early examples of loitering munitions, which emerged in the 1990s, were developed for use against targets such as radar sites and missile launchers. Subsequently, both the nature of the targets and the types of products have diversified rapidly within the following years due to the technological changes in defense. Currently, loitering munitions designed for different and diverse missions across the world can be divided into four different categories according to their wing types. These are given in Figure 1.26 below.

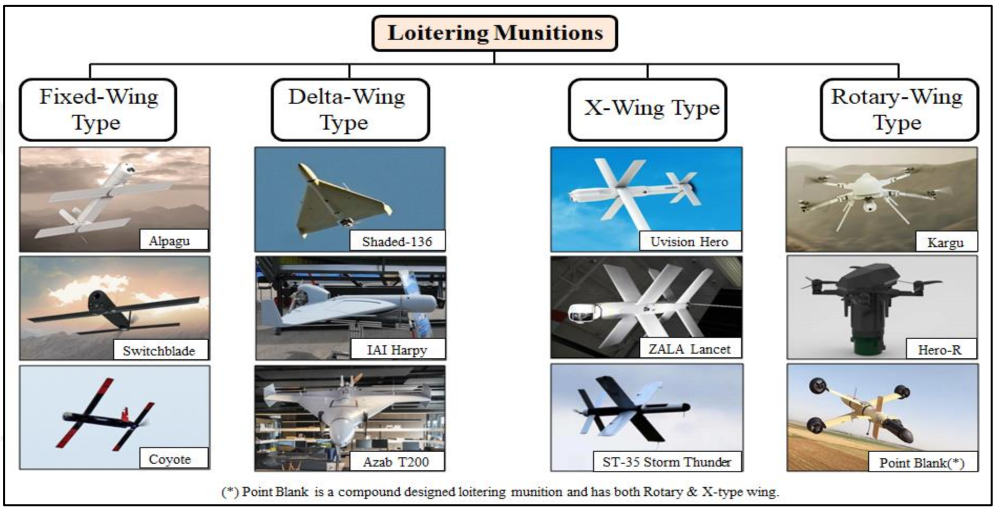


Figure 1.26 Classification of Loitering Munitions in accordance with Wing-Type

Fixed-wing type loitering munitions can be divided into two categories as “conventional” and “tandem” types. The only difference between these two types is that the tail wing of the tandem type is longer than the conventional one in terms of the aerodynamic system. In a tandem design, there is slight difference between the length of the tail wing and the length of the main wing. Fixed-wing type loitering can be launched by hand, rail, canister or launcher.

Delta-wing type loitering munitions can be divided into two categories as well. One of them is “Single Delta-Wing” Type, the other one is “Double Delta-Wing” or “Canard” type. Delta-wing loitering munitions usually can be launched by catapult or multiple launcher.

X-wing types, also known as “Cruciform”, loitering munitions can be divided into two categories as well. “Twin X-Wing” type and “X-Wing with Rotary Support”. While Uvision Hero, ZALA Lancet and ST-Storm Thunder are the prominent examples of Twin X-Wing type, Point Blank is the noticeable example of X-Wing with Rotary Support type.

1.5 Fixed-Wing Loitering Munition, ALPAGU

1.5.1 Components and Specifications of the Weapon System

When their components are analyzed as shown in Figure 1.27, they are comprised of “Tube Launcher”, Fixed-Wing Smart Ammunition System (Drone)” and “Ground Control Station (GCS/Tablet)”. Fixed-wing loitering munitions can be operated autonomously or with GCS by remote controlling, besides all these components can be carried by a single soldier [39].

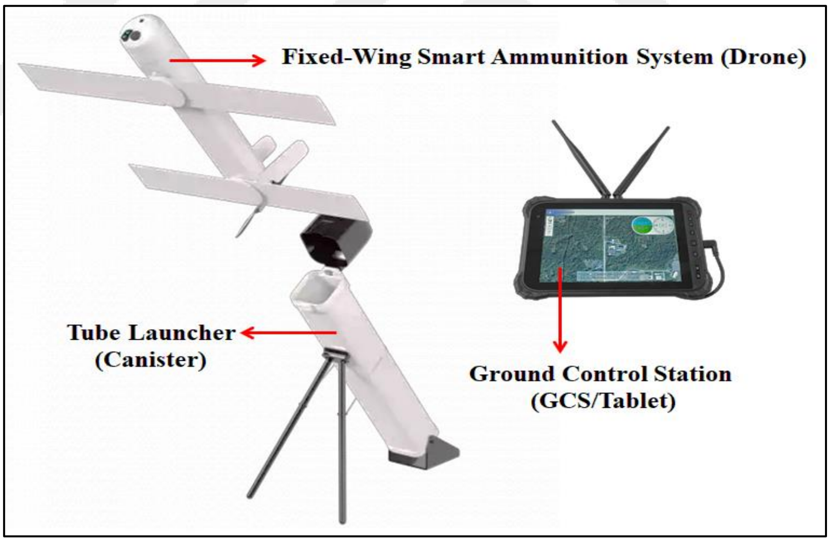
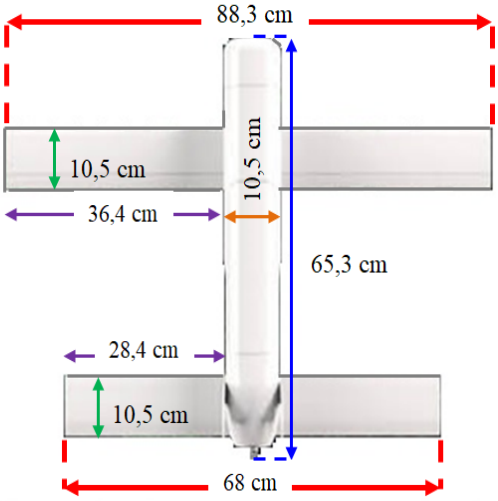


Figure 1.27 Components of ALPAGU Loitering Munition [39]

This article will be based on the specifications and design features of the ALPAGU fixed-wing loitering munition produced by STM, which means “hero who attacks the enemy alone” in Turkish etymology. For this paper, all the scientific and experimental studies done in this field, in the past periods will be taken into account. Specifications of ALPAGU fixed-wing loitering munition are given in Table 1.4 below [40]:

Table 1.4 Dimensions & Specifications of ALPAGU Loitering Munition



Operational Range	8 km (LOS)
Wingspan	88,3 cm
Length	65,3 cm
Diameter	10,5 cm
Weight	1950 gr
Warhead	270 gr
Endurance	15 minutes
Power Source/Weight	Li-Po, 270 gr
Operating Temprature	-20 C°/+40°

1.5.2 Working Principle of the System

Fixed-wing loitering munitions have almost the same working principle and they are usually utilized to demolish strategical enemy target. Thanks to its design, initial launch is provided by compressed air (pneumatic launch) from tube launcher (canister) just as mortar shell. As soon as Smart Ammunition System is launched, its aerofoil and tail wings are opened automatically to transform into a plane. Simultanously, propulsion system is activated by electricity storage unit, Li-Po or Li-Ion battery, which gives the electricity energy to propeller. After reaching target sight of view, the Smart Ammunition System begins to loitering and gathering intelligence about the enemy area and target.

After acquiring the target, the loitering munition is locked onto the enemy vehicles, radars or opponents by the operator with GCS remote control system.

Subsequently, the loitering munition gets kamikaze position to hit and destroy the target for precise attack. If its risky and impossible, the operator can abort the mission to hit another target or recon to gather intelligence within its duration time. Working principle of a fixed-wing loitering munition is given in Figure 1.28 below.

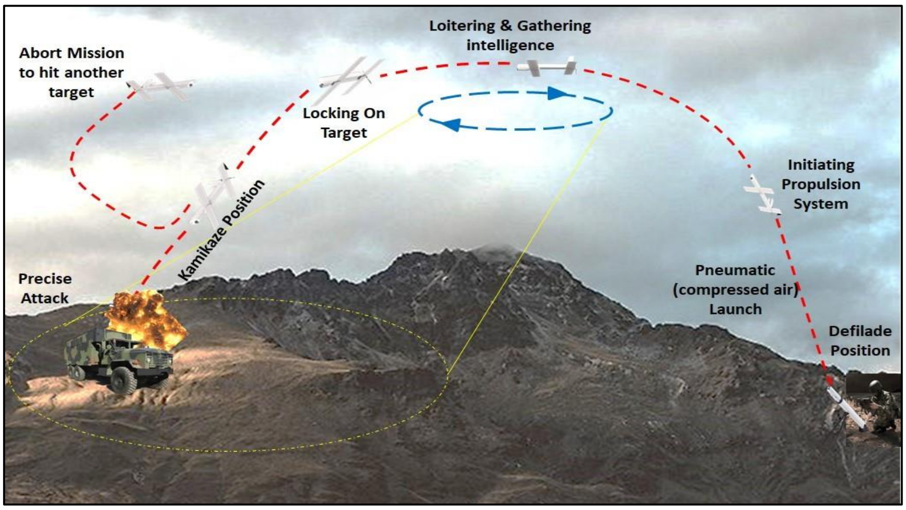


Figure 1.28 Working Principle of a Fixed-Wing Loitering Munition

1.6 Description of the Problem

According to a report by the The Study Center of The Drones, the advantages of loitering munitions are as follows [41].

- Compared to alternatives such as mortars, rockets and small-sized missiles, it is easier to distinguish between armed and unarmed people.
- Depending on the duration of their stay in the air, they enable target detection and tracking.
- They have higher hitting accuracy compared to their alternatives.
- They are more cost-effective compared to alternatives that will allow attacks to be carried out with equal precision.
- Unlike rockets, missiles and mortars particularly rotary-wing loitering munitions, allow for mission abortions.

However, in addition to the above-mentioned advantages, fixed-wing, delta-wing, X-wing designs are not subject to mission termination, return and reuse for incomplete missions. Moreover, the biggest constraint is the limitation of the flight duration of the munitions, especially those with fixed-wings, depending upon the amount of energy in the battery. For instance, the flight endurance of ALPAGU is totally 15 minutes.

What if mission abortion and additional time needed to accomplish the mission?

1.7 Scope and Purpose

The scope of the research thesis will center around, one of the fixed-wing loitering munitions, ALPAGU, its features and specifications. This study is a good example of reverse engineering. The main purpose of this thesis is to extend the total flight duration of ALPAGU (15 min.) via additional solar-support components such as solar cells and MPPT. While conducting the research and calculations the irradiation values of the Şırnak province, an internal security operational area will be taken into account. Whether its cost-efficient or not, this study is the first of its kind to apply a solar support system to a loitering munition in order to extend its flight endurance by harnessing solar energy.

CHAPTER 2

SOLAR ENERGY AND IRRADIATION

2.1 Photovoltaic Power Potential of the Globe and Turkey

Solar energy is a main source of renewable energy, harnessing the irradiance from the sun beam to obtain solar power to generate electricity or thermal energy by using a range of technologies.

In order to calculate the solar energy efficiency, firstly irradiance model must be handled. Model of irradiance depends on some variables such as such as daytime, solar cell efficiency, geographical location, albedo and so on. Photovoltaic power potential of the Globe and Turkey is given in Figure 2.1 below [42]:

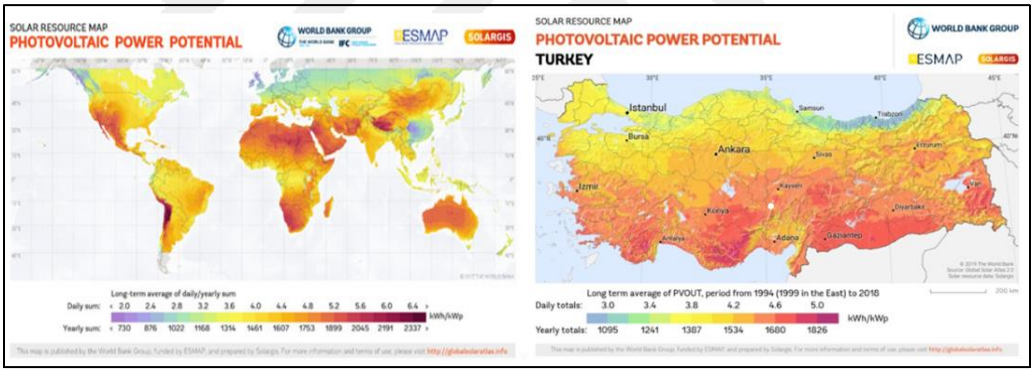


Figure 2.1 Photovoltaic power potential of the Globe and Turkey [42]

Examining daily and total sum of irradiance and long term avarage, Turkey is located in the "solar belt" with high solar energy potential region. Annual average 1311 kWh/m2 year and the average sunshine duration is 2640 hours. This figure averages 3.6 kWh/m2 power for about 7.2 hours per day, for a total of 110 days of sunshine duration. Furthermore, considering internal security operations are conducted mostly in South-Eastern Anatolian Region, in the provinces such as Şırnak and Hakkari, new designed solar-supported loitering munitions can be easily used [43]. With this scope, subsequent calculations will be based on average irradiational values of Şırnak province.

2.2 Irradiation of Şırnak Province and Calculating Daily Energy Density

Because of operational activities in the region could be conducted any time in the year, yearly average values will be taken into account for the calculations as presented in Figure 2.2 and Table 2.1-2.3 [44].

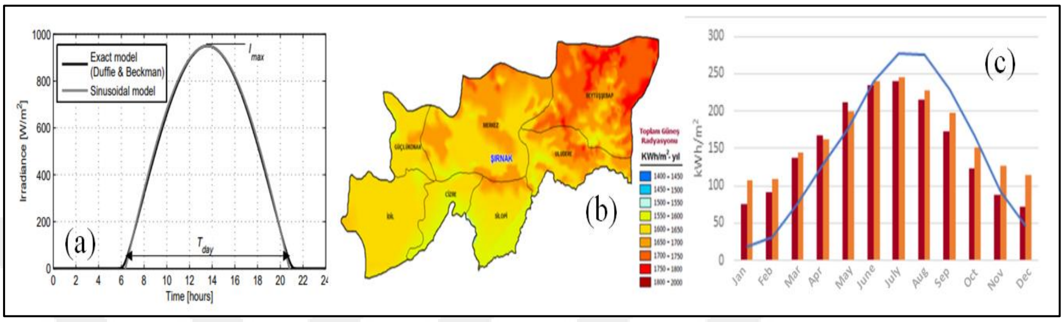


Figure 2.2. (a) Approximation Of Irradiance With A Sinusoid, **(b)** Irradiation Map of Şırnak **(c)** Monthly Solar Irradiance and Daytime of Şırnak [44]

Table 2.1 Average Irradiation (I_{max}) of South-Eastern Anatolian Region by Districts

Province	Average Irradiation Duration (hour-year)	Ave. Max. Irradiation (kW/m²)
Adıyaman	2961	1564
Batman	2873	1576
Diyarbakır	2613	1473
Gaziantep	2978	1582
Kilis	2975	1575
Mardin	3033	1588
Siirt	2828	1591
Şanlıurfa	3030	1586
Şırnak	**2975**	**1601**

Table 2.2 Monthly Average Irradiance Duration of the Day (T_{day}) In Şırnak Province by Districts

Month	1	2	3	4	5	6	7	8	9	10	11	12	Pro. Ave.
Beytüşşebap	4,49	5,61	6,70	7,59	9,79	11,75	12,00	11,30	9,86	7,29	5,79	4,41	**8,05**
Cizre	4,29	5,57	6,73	7,67	9,97	12,48	12,83	12,05	9,89	7,49	6,00	4,64	**8,30**
İdil	4,29	5,54	6,78	7,77	10,01	12,63	12,97	12,15	9,95	7,53	5,99	4,61	**8,35**
Güçlükonak	4,13	5,26	6,42	7,58	9,86	12,07	12,36	11,62	9,96	7,39	5,72	4,40	**8,06**
Merkez	4,18	5,35	6,47	7,53	9,86	12,01	12,31	11,57	9,90	7,34	5,77	4,44	**8,06**
Silopi	4,34	5,73	6,83	7,65	9,90	12,53	12,90	12,12	9,93	7,47	6,09	4,70	**8,34**
Uludere	4,41	5,68	6,75	7,55	9,80	12,05	12,38	11,66	9,82	7,34	5,91	4,55	**8,16**
Average	**4,30**	**5,53**	**6,67**	**7,62**	**9,88**	**12,22**	**12,53**	**11,78**	**9,90**	**7,41**	**5,89**	**4,53**	

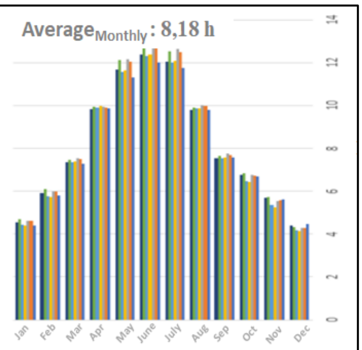
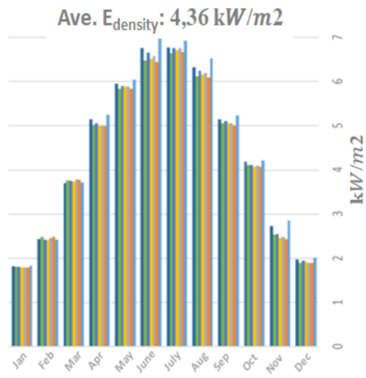
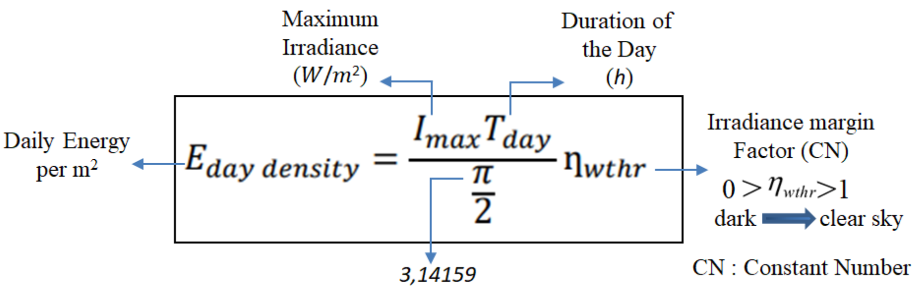


Table 2.3 Monthly Average Radiation Density ($E_{density}$) In Şırnak Province by Districts

Month	1	2	3	4	5	6	7	8	9	10	11	12	Pro.Ave.
Beytüşşebap	2,01	2,85	4,21	5,23	6,52	6,92	7,08	6,04	5,25	3,71	2,42	1,83	**4,51**
Cizre	1,90	2,44	4,07	5,01	6,09	6,66	6,44	5,84	4,99	3,77	2,48	1,80	**4,30**
İdil	1,90	2,49	4,09	5,06	6,19	6,75	6,58	5,89	5,01	3,79	2,46	1,80	**4,33**
Güçlükonak	1,92	2,46	4,07	5,06	6,15	6,71	6,51	5,88	5,00	3,74	2,41	1,80	**4,31**
Merkez	1,95	2,55	4,11	5,10	6,24	6,75	6,65	5,90	5,06	3,75	2,42	1,81	**4,36**
Silopi	1,90	2,54	4,11	5,05	6,12	6,64	6,48	5,84	5,02	3,76	2,49	1,81	**4,31**
Uludere	1,97	2,73	4,18	5,15	6,32	6,77	6,75	5,95	5,15	3,70	2,44	1,82	**4,41**
Average	**1,94**	**2,58**	**4,12**	**5,09**	**6,23**	**6,74**	**6,64**	**5,91**	**5,07**	**3,75**	**2,45**	**1,81**	



Analyzing the average sunshine duration of the day in Şırnak province, the highest point is reached in July with 12.53 hours, while the lowest sunshine duration is realized in January with 4.30 hours. The maximum radiation intensity is reached in June with 6.74 kWh/m^2-day, while the minimum radiation intensity is realized in December with 1.81 kWh/m^2-day [45]. Equation of the daily energy density per square meter is given in Formula 2.1 below [46]:



(2.1)

Monthly average irradiation (I_{max}) in Şırnak province is **1601 W/m²**, additionally Monthly average irradiance duration of the day (Tday) is S = **8,18 hours**.

So, the daily energy density is:

$$E_{day\ density} = \frac{\mathbf{1601\ W/m^2 * 8.18\ h}}{\mathbf{3.14/2}} * \mathbf{0.8}(assumption) = \mathbf{6673.2\ Wh/m^2}$$

CHAPTER 3

SELECTION OF THE ADDITIONAL COMPONENTS

3.1 Choosing the Solar Cell Type

One of the renewable, clean and cost-effective energy sources Solar energy, is obtained by converting heat energy into electrical energy through photovoltaic (PV) cells from the sun. Connecting solar cells in series or parallel, constitutes solar modules (panels) and they are applied primarily the surface of wing then other parts of the airplane such as fuselage or tail if needed.

According to the fabrication process and type of the raw material, there are various types of PV cells that can be sorted. Because of its low cost and abundance, the most common used type of material is silicon. According to the type of crystal, there are three types of silicon solar cells [47]:

• *Monocrystalline silicon solar cells* have typically very high efficiency roughly 15:20% and are made of a high incidence of silicon, so this characteristic brings about high price. Although they are not cost-effective they can provide the highest power outputs. Hence, of all the types of silicon solar cells, it is the most efficient solar cells available. However, one of its disadvantage is that the whole solar system can get out of order even if the solar cells are partly covered with dirt or snow.

• *Polycrystalline solar cells,* is also known as multi-crystalline silicon (mc-Si) or polysilicon (p-Si). This type of solar cell is inexpensive if compared with monocrystalline. Polycrystalline solar cell efficiency is around 13:16%, additionaly it is less temprature resistant than monocrystalline type.

• *Amorphous silicon (a-Si) solar cells,* have good response to weak sun light. Although the production costs are very cheap, the conversion efficiency is low around 6-8% for this type.

Other type solar cells made of different materials:

• *Cadmium telluride (CdTe) solar cells,* are named due to the component chemical elements cadmium and telluride. This type has the only thin-film technology with low cost The conversion efficiency of cadmium telluride solar cells works around 9:11%.

• *Copper indium gallium selenide (CIS/CIGS) solar cells,* have showed the most potential in terms of efficiency in the range 10:12 %.compared to Cadmium telluride (CdTe) solar cells. They have also wide applicability of substrate, adjustable optical band and strong antiradiation ability.

To summerize and compare the characteristics types of solar cells explained above Table 3.1 is given below.

Table 3.1 Comparative Characteristics of Solar Cell Types

	Monocrystalline	Polycrystalline	Amorphous	CdTe	CIS/CIGS
Typical Module Efficiency	15:20%	13:16%	6:8%	9:11%	10:12%
Best Research Cell Efficiency	25%	20.4%	13.4%	18.7%	20.4%
Area Required for 1Kw	6-9 m^2	8-9 m^2	13-20 m^2	11-13 m^2	9-11 m^2
Lowest price	0.75 $\$/W$	0.62 $\$/W$	0.69 $\$/W$		
Temperature Resistance	Performance drops 10-15% at high temperature	Less temperature resistant than monocrystalline	Tolerates extreme hear	Relatively low impact on performance	Temperature resistance
Flexibility	Not flexible	Not flexible	Can be flexible	Can be flexible	Can be flexible

According to above informations and considering energy efficiency, it is clear that monocrystalline solar cells is the most suitable solar cell type to be used in fixed-wing loitering munitions design. Furthermore, among all monocrystalline types, the lightest one, GEN II solar cells (Figure 3.1) manufactured by a firm called Sunpower, provides today's highest performance and energy-efficiency by Maxeon cell technology. Compared to standart conventional solar cells, GEN II solar cells generates 25-35% more energy with its long term performance in that when the surface exposed to sunlight, GEN II enables 1% more sun beam absorption in overcast and low light conditions. Corrosion resistance with its thin copper metal system and crack resistance with its lead-free components provide outstanding resilience and eco-friendly energy delivery as well [48].

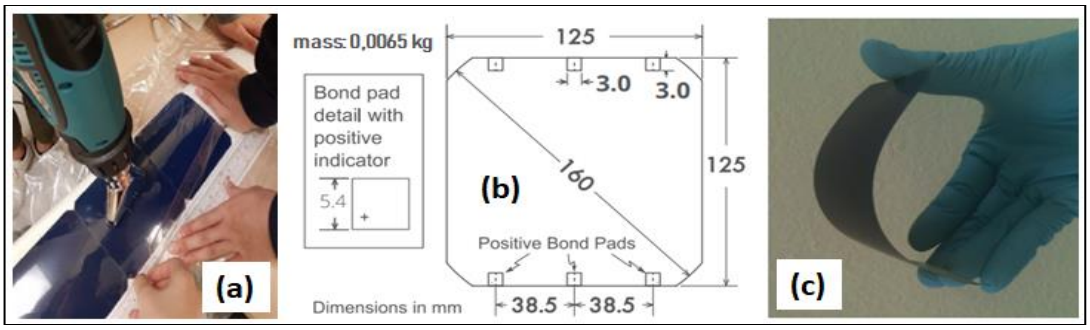


Figure 3.1 (a) Application of GEN II PV Cell on the wing with hot shrink plastic wrap. **(b)** GEN II PV Cell Bond Pad Original Dimensions. **(c)** Resilience of GEN II PV cell [48]

In line with all informations given above, due to structural dimensions of ALPAGU fixed-wing loitering munition, new design can be accomplished by new manufactured GEN II solar cells with 90x90 mm dimensions as explained in Figure 3.2 below:

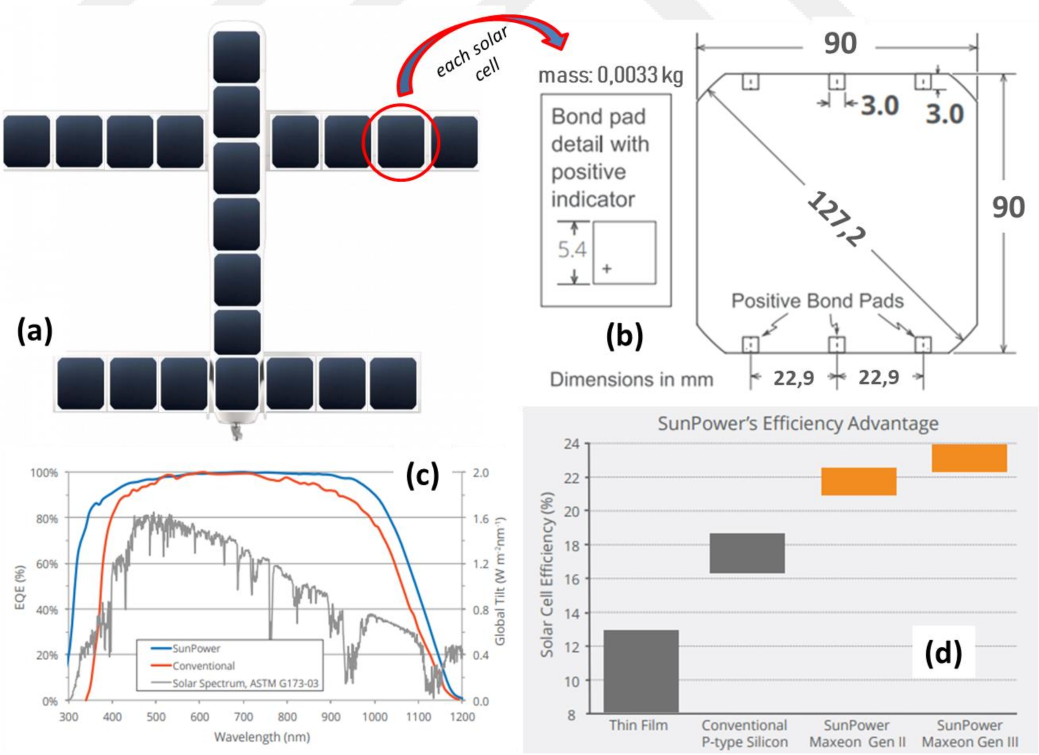
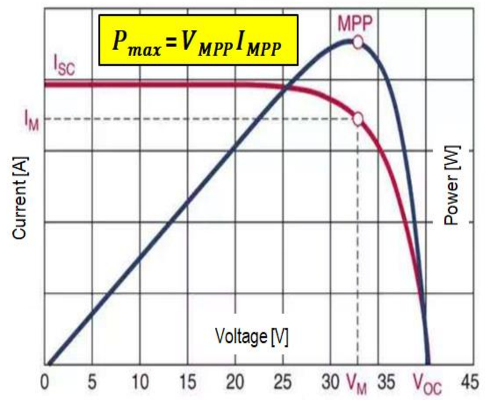


Figure 3.2 (a) Birds-eye view of solar cell applied ALPAGU. **(b)** New Manufactured GEN II PV Cell Bond Pad Dimensions (presume). **(c)** Spectral Response of Typical GEN II **(d)** Average efficiency of GEN II PV cell

3.2 Current and Voltage of a Solar Cell

The current to voltage curve of a solar cell has a very characteristic shape, as presented in Figure 3.3 and can be explained by the mathematical models of an ideal or real photovoltaic generator [49]. Instead of Standard Test Conditions (STC) of the planned solar cells Maxeon GEN II, the real photovoltaic values and the new manufactured cell values are calculated in this article. Standard Test Conditions are at 1000 W/m^2, air mass 1.5 G Spectrum and 250 shown in Table 3.2 below [48].



Electrical Characteristics of a typical Maxeon Gen II Cell At Standard Test Conditions (STC) STC: 1000W/m^2, AM 1.5G and cell temp 25°C							
	Cell Bin	Pmpp (Wp)	Eff. (%)	Vmpp (V)	Impp (A)	Voc (V)	Isc (A)
Peak Performance	Kp	3.48	22.7	0.580	6.00	0.680	6.34
Premium Performance	Jp	3.46	22.4	0.580	5.97	0.680	6.32
Superior Performance	Hp	3.43	22.3	0.580	5.92	0.680	6.29

Figure 3.3 Characteristic Graphic of Current to Voltage Curve

Table 3.2 STC of the Maxeon GEN II solar cells

3.3 Maximum Power Point Tracker (MPPT) Selection

Depending on the inclination of the sun rays and sun irradiance along the daytime, a solar charge controller, called Maximum Power Point Tracker (MPPT) converts sunlight into electrical energy via solar cells. This converter maintains the maximum amount of power which is provided by the solar modules. Firstly, the obtained power is used for the propulsion group (engine, propeller) and the onboard electronics, secondly to charge the electrical storage unit with sufficient energy. Due to the fact that no more power comes from the solar modules at nighttime, solely the electrical storage unit energise those elements. Brief description of a solar-support design of a fixed-wing loitering munition is schematically represented in the Figure 3.4 below [49].

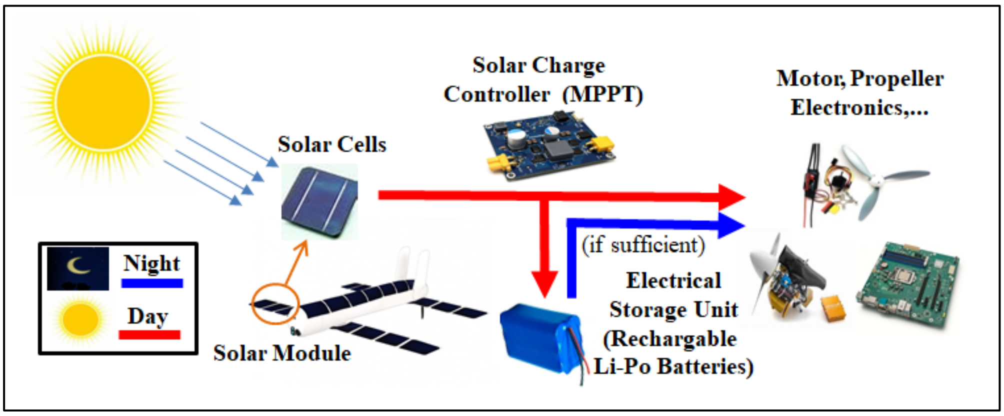


Figure 3.4 Brief description of Solar-Support Design of a Fixed-Wing Loitering Munition

Considering that there are many types of MPPTs available on the market, it is important to choose the lightest MPPT that will minimize the total weight increment and will not adversely affect the propulsion system of the Fixed-Wing Smart Ammunition System. Some lightest MPPT types available on the market are given in the Table 3.3 below.

Table 3.3 Comparison & Specifications of lightest MPPTs available on market

MPPT	Product Name	Current	Voltage	Weight
	Botlink MPPT	5A	12.5-50V	31 gr
	Morningstar Sunguard	4,5A	12V	141,7 gr (5 ounces)
	Provista ISC 3042	30A	12V/24V	160 gr
	Sunrock20	20A	12V/24V	478 gr (15.8 Ounces)

The lightest MPPT, Botlink MPPT, is chosen to minimize the total weight of the structure [21]. Totally, 21 (twentyone) GEN II solar cells can be applied in serial configuration and the total energy gained from the solar can be calculated by Formula 3.1 [50]:

$$E_{elec_{tot}} = \overbrace{\frac{I_{max}\,T_{day}}{\frac{\pi}{2}}}^{E_{day\ density}} \eta_{wthr}\, A_{sc}\,\eta_{cbr}\,\eta_{sc}\,\eta_{mppt} \tag{3.1}$$

Efficiency of the curved solar Panels (CN) (η_{cbr}); Efficiency of MPPT (CN) (η_{mppt}); Area of Solar Cell (m^2) (A_{sc}); Efficiency of solar cells (CN) (η_{sc})

According to a research on Skysailor first prototype carried out in ETH Autonomous Systems Laboratory, parameters for a smooth flight which are constant or assumed constant are given in Table 3.4 below [49]:

Table 3.4 Parameters that are constant or assumed constant made for Skysailor in Zurich (example)

Parameter	Value	Unit	Description
C_L	0.8	-	Airfoil lift coefficient
C_{Da}	0.013	-	Airfoil drag coefficient
e	0.9	-	Oswald's efficiency factor
I_{max}	950	[W/m^2]	Maximum irradiance
k_{batt}	190·3600	[J/kg]	Energy density of battery
k_{cells}	0.32	[kg/m^2]	Mass density of solar cells
k_{encaps}	0.22	[kg/m^2]	Mass density of encapsulation
k_{mppt}	0.00047	[kg/W]	Mass to power ratio of mppt
k_{prop}	0.013	[kg/W]	Mass to power ratio of propulsion unit
k_{struct}	0.44/9.81	[kg/m^3]	Structural mass constant
m_{elec}	0.25	[kg]	Mass of navigation & control system
η_{bec}	0.7	-	Efficiency of step-down converter
η_{cells}	0.169	-	Efficiency of solar cells
η_{chrg}	0.98	-	Efficiency of battery charge
η_{ctrlr}	0.95	-	Efficiency of motor controller
$\eta_{dischrg}$	0.98	-	Efficiency of battery discharge
η_{grbox}	0.95	-	Efficiency of gearbox
η_{mot}	0.85	-	Efficiency of motor
η_{mppt}	0.97	-	Efficiency of mppt
η_{prop}	0.85	-	Efficiency of propeller
P_{ctrl}	1	[W]	Power of navigation & control system
x_1	3.1	-	Structural mass area exponent
x_2	-0.25	-	Structural mass aspect ratio exponent

The total area (m^2) of solar cells (A_{sc}) applied on the new design is:

(0.090 m x 0.090 m) x 21 = **0.1701 m^2**,

Efficiency of the curved solar cells on the main body is assumed as **0.5 (CN)**

Efficiency of GEN II solar cells given by Sunpower Firm is **%22.4=0.224 (CN)** [19],

In accordance with the information obtained from Botlink Firm, efficiency of MPPT is **%98=0.98 (CN),** Taking into account all above mathematical analysis datas, calculation result gives the ***total electric energy generated*** by solar cells,

$$E_{elec_{tot}} = \underbrace{6673.2\ Wh/\cancel{m^2}}_{E_{\text{day density}}} * \overbrace{0.1701\ \cancel{m^2}}^{\text{Area of Solar Cell } (m^2)} * \underbrace{0.5}_{\substack{\text{Efficiency of the curved solar}\\ \text{Panels (CN)}\\ \text{(assumption)}}} * \overbrace{0.224}^{\substack{\text{Efficiency of}\\ \text{solar cells (CN)}}} * \underbrace{0.98}_{\substack{\text{Efficiency of}\\ \text{MPPT (CN)}}} = \boxed{124.58\ Wh}$$

As mentioned in ALPAGU loitering munition specifications the flight endurance is totally 15 minutes. Considering the total electricity energy gained via solar cells is 124.58 W per hour, so the gained energy during the flight endurance (15 min) is;

$$E_{elec_{flg}} = 124.58\ W * \frac{15\ min}{60\ min} = 31.145\ W$$

Returning back to Botlink MPPT which planned to use in the new design, its seen that input/output current specifications are 5A and 12.5-50 V, ***the required electricity energy can be only counterposed by the electricity storage unit.***

The minimum required power of MPPT can be calculated as follows:

$$\boxed{P_{MPPT} = V_{MPPT} * I_{MPPT}} \tag{3.2}$$

$$P_{MPPT} = 12.5\ V * 5\ A = 62.5\ W$$

The required power of MPPT for the flight duration is;

$$E_{elec_{flg}} = 62.5\ W * \frac{15\ min}{60\ min} = 15.625\ W$$

When the operating power of the MPPT is subtracted from the power obtained from the solar cells, the total power value feeds the battery can be calculated during the 15 minute flight:

$$\boxed{P_{bat.feed} = P_{SC} - P_{MPPT}} \tag{3.3}$$

$$P_{bat.feed} = 31.145\ W - 15.625\ W = 15.52\ W$$

3.4 Electricity Storage Unit (Battery) Selection

The primary goal of assembling a solar power system into a UAV is to extend the duration and range by providing an extra power source during flight. Despite there are many types of lithium based electricity storage units are in use such as Li-Ion and Li-S batteries, Lithium-polymer (Li-Po) batteries are mostly preferred in unmanned aerial vehicles that use electricity as an energy source due to their high current output. In addition, Li-Po batteries are the most popular energy source in unmanned aerial vehicles because of their high power, light weight and long life. However, Li-Po batteries have some disadvantages as well as advantages. For instance, their sensitive chemical structure is susceptible to combustion [51].

Although 270 g, 11.4 V 4300 mAh Li-Po battery pack used in ALPAGU fixed-wing loitering munition, in its original design, lighter Li-Po batteries can be used in order to reduce the total weight. One of the lighter rechargable high voltage Li-Po battery (LiHV) avaible on the market is given in Figure 3.5 below with its specifications in Table 3.5 [52]:

Figure 3.5 Gens Ace 4300mAh 3S1P 11.4V 60C LiHV Battery [52]

Cutting-edge technology new LiHV batteries has a special characteristics to increase its **voltage capacity almost 1 to 10 times.**

Table 3.5 New Battery Pack Specifications

SKU	GEA43003S60T3	Voltage	3S (11.4V)
Article Category	Gens-Car Gens ace	Length (±5mm)	90
Article No.	B-60C-4300-3S1P-HV-SoftCase-1TO3	Width (±5mm)	40
Net Weight (±10g)	246	Thickness(±5mm)	29
Brand	Gens ace	Wire Gauge	12#
Capacity	4300 mAh	Wire Length (C/D)	60mm/120mm
Discharge Rate (C)	60C	Connector Type	XT60/T-plug
Parallel (P)	1	Balancer Connector Type	JST-XHR

$$P_{battery} = V_{battery} * I_{battery} \tag{3.4}$$

$$P_{battery} = V_{battery} * I_{battery} = 11.4\,V * 4.3\,Ah = 49.2\,Wh$$

$$T_{charge_{batt}} = \frac{P_{battery}}{P_{batt.feed}} = \frac{49.2\,Wh}{15.52\,W} = 3.23\,h$$

With the total power which is feeding the battery, the battery used in the new design of the loitering munition can be charged in **3.23 hours (193.8 min).**

Since the battery can be charged in 193.8 minutes, ***the additional solar capacity*** provided to the battery by solar energy, during the flight time in 15 minutes is given in equation 3.5;

$$Capacity_{solar} = \frac{Capacity_{Battery} * T_{flight}}{T_{charge_{batt}}} \tag{3.5}$$

$$Capacity_{solar} = \frac{4300\,mAh * 15\,min}{193.8\,min} = 332.8\,mAh$$

Calculation of ***the total battery capacity*** in the final state (equation 3.6), with the additional capacity obtained from the solar cells:

$$Capacity_{Total} = Capacity_{Battery} + Capacity_{Solar} \tag{3.6}$$

$$Capacity_{Total} = 4300\,mAh + 332.8\,mAh = 4632.8\,mAh$$

CHAPTER 4

TOTAL WEIGHT OF THE NEW DESIGN

4.1 Forces on the Fixed-Wing Loitering Munition

There are four forces which affects on the loitering munition during the flight. These are basically Lift, Drag, Thrust and Weight as illustrated in Figure 4.1 [53].

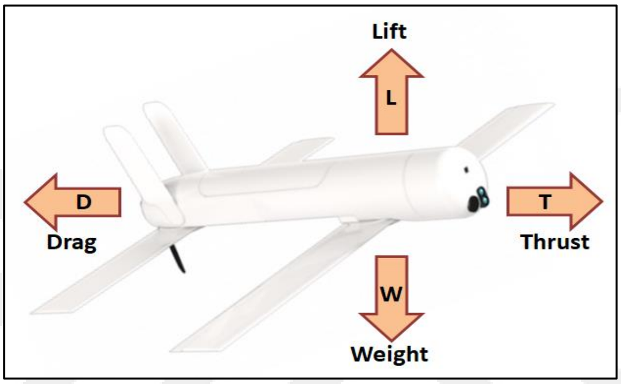


Figure 4.1 Forces on the Loitering Munition [53]

Lift, is the force hold upward on the structure and provides the main body stay in the air thanks to the special shaped wings, known as airfoil. This special shape provides lift effect by deflection and air pressure on the airfoil.

Drag, also called *air resistance* is the force that affects in the opposite direction of the flight direction and it slows the main body down because of air molecules density.

Thrust is the force that propels the structure in a forward direction, and thrust is the opposite force of the drag. The motor and the propeller blades provide this propulsion force.

Weight is the downward force on the structure which is caused by the gravity. Weight has direct proportional to the total mass of the structure.

Since no changes have been made to the contents of the propulsion system such as motor, motor controller, gearbox and propeller, the lift force, thrust and drag forces will not be affected. However, due to the additional contents for solar support (solar cells, MPPT) the total weight of the structure will be altered upwards.

4.2 Total Weight Calculation

The total weight of the new designed loitering munition will increase depending on solar support components (solar cells, MPPT) and the replaced LiHV battery. So, the latest weight will be as follows in Figure 4.2:

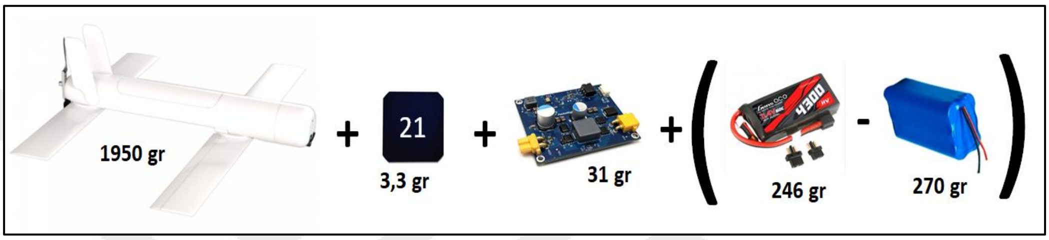


Figure 4.2 Components to Change the Total Weight

$$W_{total} = W_{original} + 21 * W_{SC} + W_{MPPT} + (W_{newbatt} - W_{origbatt}) \quad (4.1)$$

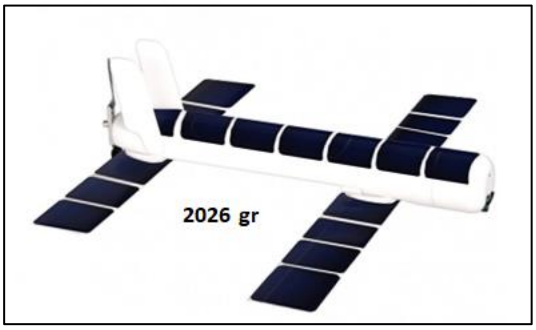


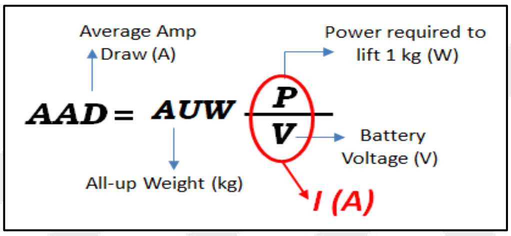
Figure 4.3: Total Weight of the New Design

$$W_{total} = 1950\ gr + 21 * 3.3\ gr + 31\ gr + (246\ gr - 270\ gr)$$
$$= 2026\ gr$$

CHAPTER 5

CALCULATING THE ADDITIONAL FLIGHT TIME

As for calculating flight time of the new-designed loitering munition, firstly average amp draw must be known. Average Amp Draw, expressed in amperes (A), is the ratio of total weight (AUW) and power required to lift 1 kg in watts (P) to battery voltage (V). According to Ohm’s Law, P/V stands for the current (I) in amperes required to lift one kilogram into the air [54].

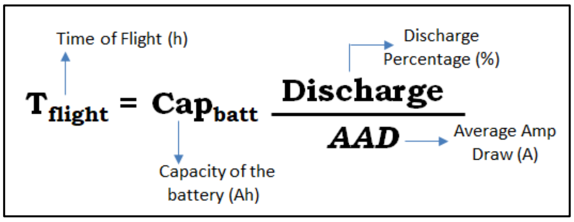


(5.1)

During the flight required maximum power of ALPAGU fixed-wing loitering munition is 150 W. To calculate the power to lift 1 kg (P) for both initial and solar-supported design:

$P_{original} = \dfrac{P_{flight}}{W_{original}}$	$P_{solar} = \dfrac{P_{flight}}{W_{solar}}$
$P_{original} = \dfrac{150\ W}{1.950\ kg}$ =**76.92 W**	$P_{original} = \dfrac{150\ W}{2.026\ kg}$ =**74.03 W**

Secondly, to calculate the flight time of the new-designed loitering munition, seems like a daunting task, but it's actually quite easy by a single formula. Time of flight is the ratio of capacity of the battery (Cap_{batt}) and discharge percentage of the battery (%) to average amp draw (AAD) in amperes.



(5.2)

Capacity of the battery, expressed in milliamp hours (mAh) or amp hours (Ah) could be found printed on the choosen LiHV battery. The higher the capacity, the more electricity energy is stored in the battery.

Battery discharge during the flight depends on the operator who is remote controlling the loitering munition with GCS. Discharge is the percentage value and usually accepted as a ***common practice never to discharge them by more than 80%*** in that LiPo batteries can be damaged if fully discharged [55].

So, comparative flight endurance of the original design and the new design with solar support contents can be calculated as follows:

Flight Endurance-1 (Initial/Original Design)	**Flight Endurance-2 (Designed with Solar Cells)**
Verification $AAD = AUW \frac{P}{V}$	$AAD = AUW \frac{P}{V}$
$AAD = 1{,}950\ kg \frac{76{,}92\ W}{11{,}4\ V}$	$AAD = 2{,}026\ kg \frac{74{,}03\ W}{11{,}4\ V}$
$AAD = 13{,}157\ A$	$AAD = 13{,}157\ A$
$T_{flight} = Cap_{batt} \frac{Discharge}{AAD}$	$T_{flight} = Cap_{batt} \frac{Discharge}{AAD}$
$T_{flight} = 4{,}3\ Ah \frac{80\%}{13{,}157\ A}$	$T_{flight} = 4{,}63\ Ah \frac{80\%}{13{,}157\ A}$
$T_{flight} = 0{,}261\ h$	$T_{flight} = 0{,}281\ h$
$T_{flight} = 0{,}261\ h \times 60\ min$	$T_{flight} = 0{,}281\ h \times 60\ min$
$\mathbf{T_{flight} = 15{,}66\ min}$	$\mathbf{T_{flight} = 17{,}42\ min}$

$$\Delta T_{flight} = T_{flight(1)} - T_{flight(2)}$$

$$\Delta T_{flight} = 17.42\ min - 15.66\ min = 1.76\ min$$

$$\%T_{flight} = \frac{\Delta T_{flight}}{T_{flight(1)}} = \frac{1.76\ min}{15.66\ min} * 100 = 11.2\%$$

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

To recapitulate, in line with technological developments, new-age weapon systems such as loitering munitions are entering the military arena so rapidly and to be used in the recent battlefields effectively. The development of artificial intelligence (AI) in the defence industry produces unprecedented smart systems. The use of loitering munitions in warfare reflects the efficacy of these munitions by overriding the risk and presents unrisky assault/defence plan for military planners.

Both technological developments and necessity for renewable, clean energy sources, made aeronautical engineers and aviation companies search for a new efficient and inexpensive energy source such as solar.

Although there are 37 solar panel manufacturers in Turkey, there are no remarkable researches concerning the development of solar-powered unmanned aerial vehicles yet [27].

Due to the fact that solar technology can be applied only to wide-wing HALE/MALE UAVs or light weight UAVs, this paper is committed on these light-weight futuristic weapons, loitering munitions.

Returning back to all informations and calculation given above on ALPAGU, fixed-wing loitering munition’s **15,66 minutes** flight endurance could be extended theoretically to **17,42 minutes** via applied solar cells and additional contents such as MPPT and LiHV battery. With this method, the extension on the flight endurance equals to 1,76 minutes (105,6 seconds) which is corresponding **%11,2** to the total flight time.

6.2 Recommendations

It is clear that countries with UAV technology will gain a wide range of initiatives and technological gains in the field of next-generation aviation, leaving other countries behind. Although there are 37 solar panel manufacturers in Turkey, there are no remarkable researches concerning the development of solar-powered unmanned aerial vehicles yet. This study may strike a match to combine these two industry fields to develop technological achievements exponentially.

As for the outcome of this thesis, the total flight time extension 1.76 minutes (105.6 seconds) may be seen as a short time in casual life, but it is a very long duration in the battlefield for loitering, gathering intelligence and chasing moving targets. Furthermore, it is considered that this academic study will form the infrastructure for an actual multi-disciplinary application and will shed light on other studies to be conducted in this field.

REFERENCES

[1] Paul Scharre and Michael C. Horowit, “An Introduction to Autonomy in Weapon Systems”, Center for a New American Security ,February 2015.

[2] Shaan Shaikhand & Wes Rumbaugh “The Air and Missile War in Nagorno-Karabakh: Lessons for the Future of Strike and Defense”, from https://www.csis.org/analysis/air-and-missile-war-nagorno-karabakh-lessons-future-strike-and-defense, December 8, 2020.

[3] Joe Hernandez, “A Military Drone With A Mind Of Its Own Was Used In Combat, U.N. Says”, from https://www.npr.org/2021/06/01/1002196245/a-u-n-report-suggests-libya-saw-the-first-battlefield-killing-by-an-autonomous, June 1, 2021.

[4] Ridvan Bari Urcosta, the US Air University, “The Revolution in Drone Warfare: The Lessons from the Idlib De-Escalation Zone”, August 31, 2020.

[5] Sean Gallagher, from https://arstechnica.com/tech-policy/2019/09/missiles-and-drones-that-hit-saudi-oil-fields-made-in-iran-but-fired-by-whom, September 17, 2019.

[6] Tamara Qiblawi, CNN, from https://edition.cnn.com/2022/01/18/middleeast/uae-abu-dhabi-houthi-yemen-explainer-intl/index.html, January 18, 2022

[7] Mark Hodge, the Sun, from https://www.thesun.co.uk/news/14327606/uk-military-upgrade-kamikaze-drones-nukes/ March 13, 2021.

[8] Mike Goulette, The History of Electric Flight – from https://medium.com/rc-soaring-digest/the-history-of-electric-flight-12a78926ade4, April 30 2023.

[9] Boucher, Robert J.. “Sunrise, The World's First Solar-Powered Airplane.” Journal of Aircraft 22 (1985): 840-846., October 1 1985.

[10] Robert J. Boucher, AIAA-84-1429 “History of Solar Flight”, https://arc.aiaa.org/ doi/epdf/10.2514/3.45213, May 22, 2012.

[11] Helmut Bruß, “ Solar Modellflug Grundlagen (Book), Enwicklung, Praxis, Verlag für Technik und handwerk, Baden-Baden,1991

[12] International Aviation Federation Official Website, from https://www.fai.org/ record/5686

[13] André Noth, History of Solar Flight, Autonomous Systems Lab, Swiss Federal Institute of Technology Zürich, July 2008.

[14] Lindsey, Robert, "Physicist's Solar Airplane Set to Challenge the English Channel", New York Times, June 9, 1981.

[15] NASA Dryden Flight and Research Center Official Web Page, from https://web.archive.org/web/20030810185046/http://www.dfrc.nasa.gov/Newsroom/ Fact Sheets/FS-034-DFRC.html

[16] Thomas E. Noll, John M. Brown, Marla E. Perez-Davis, Stephen D. Ishmael, Geary C. Tiffany, Matthew Gaier “Investigation of the Helios Prototype Aircraft Mishap (Report Vol.1)”, Jan, 2004.

[17] Runge, Hartmut & Rack, Wolfgang & Hepperle, Martin. A Solar-Powered HALE-UAV for Arctic Research, September 2007.

[18] Giulio Romeo, Giacomo Frulla, Enrico Cestino and Guido Corsino, “HELIPLAT: Design, Aerodynamic, Structural Analysis of Long- Endurance Solar-Powered Stratospheric Platform”, May 22, 2012.

[19] Swiss Federal Institute of Technology (Eidgenössische Technische Hochschule) from http://www.sky-sailor.ethz.ch/

[20] Solar flight official web page, from https://www.solar-flight.com/news/

[21] AtlantikSolar official web page, from https://www.atlantiksolar.ethz.ch/, "AtlantikSolar returns from its mission above the Arctic Ocean", October 4, 2017.

[22] BAE Systems Official Web Page, Persistent High Altitude Solar Aircraft, from https://www.baesystems.com/en/product/phasa-35.

[23] Selma Göktürk Çetinkaya, Murat Koç, "Turkey's Unmanned Aerial Vehicles Adventure", Journal of Anadolu Strategy (ANASAM),February 20, 2023.

[24] "Bayraktar Mini Unmanned Aerial Vehicle, from https://www.army-technology.com/projects/bayraktar-uav/,", June 20 2011.

[25] "IDEF 2011: Bayraktar tactical UAV nears production", from https://www.shephardmedia.com/news/uv-online/idef-2011-bayraktar-tactical-uavnears-p/, , May 13, 2011.

[26] Airforce Technology, Anka MALE UAV from https://www.airforce-technology.com/projects/anka-male-unmanned-aerial-vehicle-uav-turkey/?cf-view, February 5, 2013.

[27] Baykar Official Web Page, from https://baykartech.com/en/uav/bayraktar-tb2/

[28] Turkish Aerospace Official Web Page, from https://www.tusas.com/medya-merkezi/haberler/anka-s-projesi

[29] "Bayraktar Akıncı Unmanned Combat Aerial Vehicle (UCAV), Turkey", from www.airforce-technology.com. Retrieved 2021-04-12.

[30] Joe Saballa, The Defence Post "Turkey Unveils Shipborne Bayraktar TB-3 Drone", from https://www.thedefensepost.com/2023/03/28/turkey-shipborne-bayraktar -drone/, March 28, 2023

[31] "Turkey's Kizilelma Unmanned Fighter Jet Continues Flight Test Program" https://www.defense-aerospace.com/turkeys-kizilelma-unmanned-fighter-jet-continues-flight-test-program/, April 3, 2023.

[32] Yeşilhaber, “Türkiye’de 37 Güneş Paneli Üreticisi Var” from https://yesilhaber.net/turkiyede-37-gunes-paneli-ureticisi-var, April 24, 2023.

[33] Korchenko A.G., Illyash O.S., (2013), “The Generalized Classification of Unmanned Air Vehicles”, (2013) IEEE 2nd International Conference “Actual Problems of Unmanned Air Vehicles Developments” Proceedings pp.28-34

[34] Bento, Maria de Fátima. "Unmanned aerial vehicles: an overview." Inside GNSS 3.1 (2008): 54-61.

[35] Bowen Zhang, Zaixin Song, Fei Zhao, Chunhua Liu, MDPI (Multidisciplinary Digital Publishing Institute), “Overview of Propulsion Systems for Unmanned Aerial Vehicles”, January 10, 2022.

[36] Mark Voskuijl, KeAi Chinese Roots Global Impact, Defence Technologies, “Performance Analysis And Design Of Loitering Munitions: A Comprehensive Technical Survey Of Recent Developments”, March 22.

[37] “Watch This Drone Turn Into A Missile”, by Kelsey D. Atherton https://www.popsci.com/authors/kelsey-d-atherton/ Popular Science, August 18, 2015.

[38] Gilli, Andrea, and Mauro Gilli "The Diffusion of Drone Warfare? Industrial, Organizational and Infrastructural Constraints: Military Innovations and the Ecosystem Challenge", pages 21–22, 25–31, 2015.

[39] STM (Savunma Teknolojiler ve Mühendislik) A.Ş. Official Web Page, from https://www.stm.com.tr/en/alpagu/components.

[40] STM (Savunma Teknolojiler ve Mühendislik) A.Ş. Official Web Page, from https://www.stm.com.tr/uploads/docs/1689676408_tacticalminiuavsystems.pdf? , STM Official Website

[41] Arthur Holland Michel, The Study Center of The Drones at Bard College “Loitering Munitions In Focus” February 10, 2017, from http://dronecenter.bard.edu/files/2017/02/CSD-Loitering-Munitions.pdf

[42] Solargis Official Web Page, (Weather data and software for solar power), from https://solargis.com/maps-and-gis-data/download/turkey

[43] Mehmet ÖZEL, "Analysis Of The Method Of Combating Separatist Terrorism By The Ministry Of Interior In Turkey In The Post-2016 Period: Operation And Persuasion", İnönü University, 2021.

[44] İbrahim Baz, Dilan Alp, Öykü Bilgin, "Energy and Mineral Potential of Şırnak", Dicle Kalkınma Ajansı (DİKA-Dicle Development Agency) & Şırnak University, December 2018.

[45] Dilan Alp, Eren Demir "Solar Energy Potential and Usage Rate of Şırnak Province", December 2018.

[46] Safyanu Bashir Danjuma, Zamri Omar and Mohd Noor Abdullah "Review of Photovoltaic Cells for Solar-Powered Aircraft", November 2018.

[47] Peter Asaad Abd El Meseh, Cairo University, "Solar-Powered Unmanned Aerial Vehicle (UAV)" July, 2019.

[48] Sunpower Official Web Site, from https://www.us.sunpower.com/sites/default/files/sp-gen2-solar-cell-ds-en-a4-160-506760e_0.pdf

[49] A. Noth and R. Siegwart, ETH Swiss Federal Institute of Technology, "Design of Solar Powered Airplanes for Continuous Flight", December 2006.

[50] Botlink Web Site MPPT, from https://packetdigital.com/power-products/maximum-power-point-tracker/

[51] Şerife Çamcı, Koray Ülgen "Matlab/Simulink Model for the Use of Supercapacitors in Solar-Powered Unmanned Aerial Vehicles", September 2021.

[52] Gen Ace Official Web Page, RC Systems, from https://www.gensace.de/gens-ace-4300mah-3s1p-11-4v-60c-lipo-battery-with-xt60-t-plug.html