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CONCEPTUAL DESIGN AND MULTIDISCIPLINARY OPTIMISATION OF POWER DEVICE FOR SOLAR POWERED AIRCRAFT

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CONCEPTUAL DESIGN AND MULTIDISCIPLINARY OPTIMISATION OF POWER DEVICE FOR SOLAR POWERED AIRCRAFT

SAFYANU BASHIR DANJUMA

A thesis submitted in
fulfilment of the requirement for the award of
Doctor of Philosophy

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Faculty of Mechanical and Manufacturing Engineering
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MAY 2021

I hereby declare that the work in this project report is my own except for quotations and summaries, which have been duly acknowledged

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DR MOHD NOOR ABDULLAH

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"I dedicate this thesis to my late parents, family, and loved ones."

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In the Name of Allah, the Most Beneficent, the Most Merciful. All the praises and thanks be to Allah, the Lord of the 'Alamin (mankind, jinns, and all that exists). All praises go to Allah (SWT) for giving me good health, strength, wisdom, the will, and the knowledge to complete my PhD thesis in the most fashionable and illustrious way.

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ABSTRACT

Solar-powered aircraft is propelled by a photovoltaic cell that converts solar energy into electrical energy. The extra energy is stored in a rechargeable battery for later use when solar energy is not available. The performance of solar-powered aircraft is limited to solar radiation availability, low efficiency of the photovoltaic cell, and low energy density of the rechargeable battery. The research aims to improve the power device sizing, reduce the aircraft's mass, and improve the flight duration for sustainable flight operations for solar-powered aircraft (CLOUD 1). This was achieved using a multidisciplinary optimisation tool, a commercial package ModeFrontier software. Photovoltaic Geographic information system (PVGIS) software was used to obtain a solar radiation model for Malaysia. The model was used to develop both the energy balance and mission path for Malaysia to facilitate the availability and utilisation of solar energy for successful flight operations. Airfoil analysis was conducted. WE.3.55.9.3 airfoil was the best-chosen airfoil used for the wing design, while the empennage design, NACA 0008, was the most suitable. Hence, the latter was used for horizontal and vertical tail design with XFLR5 v6 software's aid. A novel methodology for the power device sizing was developed on MS Excel with 435.48Wh, 540.96Wh, 32, and 70 as the total required electrical energy, available solar energy, number of solar cells required, and the number of batteries required, respectively. The optimisation strategy embraced ModeFrontier software with the goal set to; minimise total electrical energy required, minimise the total mass, and maximise the available solar energy. The optimisation results show that available solar energy was 283.56Wh, the total electrical power required was 228.32Wh, the number of solar cells was 16, and the number of batteries was 36. The total mass of the aircraft was 2.05 Kg, respectively. The optimisation results achieved 53%, 51%, and 26% reductions in the number of solar cells, the number of batteries, and the aircraft's mass. Also, the flight duration was improved by 33%. The optimal configuration was used to design the solar-powered aircraft (CLOUD I).

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ABSTRAK

Pesawat bertenaga suria didorong oleh sel fotovoltaik yang mengubah tenaga suria menjadi tenaga elektrik dan tenaga tambahan disimpan dalam bateri yang boleh dicas semula untuk digunakan kemudian apabila tenaga suria tidak tersedia. Prestasi tenaga solar terhad kepada ketersediaan sinaran suria, kecekapan rendah sel fotovoltaik, dan ketumpatan tenaga rendah bateri yang boleh dicas semula. Penyelidikan ini bertujuan untuk meningkatkan ukuran peranti kuasa, mengurangkan jisim pesawat, dan meningkatkan jangka masa penerbangan untuk operasi penerbangan pesawat bertenaga suria yang lestari (CLOUD 1) dengan penggunaan alat pengoptimuman multidisiplin, perisian modFrontier pakej komersial. Perisian sistem maklumat Geografi Fotovoltaik (PVGIS) digunakan untuk mendapatkan model sinaran suria untuk Malaysia yang digunakan untuk mengembangkan keseimbangan tenaga dan spesifikasi misi Malaysia untuk memudahkan ketersediaan dan penggunaan tenaga suria untuk operasi penerbangan yang berjaya. Analisis airfoil telah dilakukan, WE.3.55.9.3 pesawat udara adalah pilihan udara terbaik yang digunakan untuk reka bentuk sayap, dan reka bentuk empennage, NACA 0008 adalah yang paling sesuai, dan ia digunakan untuk reka bentuk ekor mendatar dan menegak. Metodologi ukuran peranti kuasa pesawat bertenaga suria dikembangkan dengan jumlah tenaga elektrik yang diperlukan sebanyak 435.48Wh, tenaga suria yang tersedia sebanyak 540.96Wh, jumlah sel suria yang diperlukan ditentukan sebanyak 34 dan bilangan bateri yang diperlukan juga ditentukan sebagai 70. Strategi pengoptimuman digunakan dengan objektif; untuk meminimumkan jumlah tenaga elektrik yang diperlukan, untuk meminimumkan jumlah jisim, dan memaksimumkan tenaga suria yang ada. Hasil pengoptimuman menunjukkan bahawa tenaga suria yang ada adalah 283.56Wh, jumlah tenaga elektrik yang diperlukan adalah 228.32Wh, jumlah sel suria adalah 16, dan jumlah bateri adalah 36 dan jumlah jisim pesawat masing-masing adalah 2.05. Hasil pengoptimuman menunjukkan bahawa jumlah sel suria dikurangkan sebanyak 53%, jumlah bateri dikurangkan sebanyak 51%, dan jisim pesawat dikurangkan

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sebanyak 26%. Juga, tempoh penerbangan ditingkatkan sebanyak 33%. Konfigurasi yang optimum digunakan untuk merancang pesawat bertenaga suria (CLOUD I).

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LIST OF SYMBOLS AND ABBREVIATIONS

Latin Symbols

b	Wingspan [m]
c	Chord [m]
e	Oswald's efficiency
E	Stored energy [Wh]
g	Acceleration due to gravity [m/s^2]
m	Mass [kg]
S	Wing Area [m^2]
V	Relative speed of aircraft [m/s^2]
AR	Aspect ratio
Re	Reynolds number
A_{sc}	Area of solar cell [m^2]
C_L	Lift coefficient
C_D	Drag coefficient
C_{Dafl}	Airfoil drag coefficient
C_{Dind}	Induced drag coefficient
C_{Dpar}	Parasitic drag coefficient
C_m	Moment coefficient
C_p	Pressure coefficient
$D_{se\ consumed}$	Daily solar energy consumed [Wh]
$D_{se\ obtained}$	Daily solar energy obtained [Wh]
$E_{elec\ tot}$	Total electrical energy [Wh]
F_D	Drag force [N]
F_L	Lift force [N]
I_{max}	Maximum solar radiation [W/m^2]
k_{af}	Structural mass constant

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k_{bat}	The energy density for battery
k_{enc}	The energy density for encapsulation of solar cell
k_{mppt}	Mass/power ratio for MPPT
k_{sc}	Mass density of solar cell
k_{prop}	Mass/power ratio for propulsion
m_{av}	Mass for avionics systems [kg]
m_{bat}	Battery mass [kg]
m_{af}	Airframe structure mass [kg]
m_{f}	Fixed mass [kg]
m_{MPPT}	Mass of MPPT [kg]
m_{pld}	Mass of payload [kg]
m_{prop}	Mass of telecommunication propulsion [kg]
m_{tot}	Total mass [kg]
$P_{Eflight}$	Electrical power to sustain flight [W]
$P_{elec\,tot}$	Total electrical power [W]
P_{mech}	Mechanical power for level flight [W]
P_{pld}	Power for communication payload [W]
P_{av}	Power for avionics [W]
T_{day}	Day duration [s]
T_{night}	Night duration [s]
x_1	Structural mass Area exponent [kg-m^2]
x_2	Structural mass Aspect ratio
η_{bec}	The efficiency of the step-down converter
η_{cbr}	The efficiency of curved solar panel
η_{ctrl}	The efficiency of the motor
η_{chrg}	The efficiency of the battery charge
η_{dchrg}	The efficiency of the battery discharge
η_{grb}	The efficiency of the gearbox
η_{mot}	The efficiency of the motor
η_{sc}	The efficiency of the solar cell
η_{wthr}	The efficiency of the weather factor

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Greek Symbols

δ	Dihedral Angle
α	Angle of attack
μ	Dynamic viscosity [kg/m^2]
ρ	Air density [kg/m^3]
ν	Kinematic viscosity [m^2/s]
η	Efficiency

Acronyms

AOA	Angle of Attack
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CFD	Computational Fluids Dynamics
HALE	High Altitude and Long Endurance
ISR	Intelligent Surveillance and Reconnaissance
MDO	Multi-disciplinary Optimisation
MPPT	Maximum Power Point Tracker
PSH	Peak Solar Hour
PVGIS	Photovoltaic Geography Information Systems
OpPoints	Operating points
UAV	Unmanned Aerial Vehicle

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CHAPTER 1

INTRODUCTION

1.1 Research background

Solar-powered aircraft is an amazing, forward-looking technology for the future [1]. The unlimited and countless amount of solar radiation makes this green technology affordable, safe, sustainable, and free of pollution for transportation. Moreover, the aircraft exhibits a huge capability for uninterrupted flight [2]. The power device of solar-powered aircraft comprises; Photovoltaic (PV) cells, a rechargeable battery, and a maximum power point tracker (MPPT), respectively [3], [4]. The PV cell is mounted on the wing, which changes solar energy to electrical energy that propels the aircraft. The battery can be placed on the fuselage or any suitable part; it stores the extra energy when the solar radiation is available in the daytime and provides energy to the systems at night-time [5], [4].

Multidisciplinary optimisation (MDO) is a branch of engineering that deals with engineering problems by applying the optimisation strategy with multiple frameworks [6]. The economic success of any organisation is the capability to produce a successful product [7]. This logic holds in the engineering industries and fields. With the complexity involved in aircraft designs, which evolves more than ever before in the aerospace industry, MDO has emerged as a critical tool to solve complex design challenges. Subsequently, MDO has provided an avenue for future growth and strategic edge for competitors in the industries [8]. Also, statistical studies had shown that MDO is a suitable application for proffering solutions to solar aircraft design issues. This was evidenced by tremendous successes in problem-solving of disciplinary modelling, analysis capabilities, tool implementation, and general application [7]. Regarding the concept of product enhancement in solar aircraft, the application of MDO has traditionally benefited the system. Earlier studies of aircraft

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design have shown remarkable results in both the conceptual (initial) and detailed (later) designs [7].

The disciplines that applied the MDO are flying performances (e.g. aerodynamics, weight, and propulsion) and the energy management approach related to energy components. The goals are often targeted at reducing aircraft's total weight, the power required, and maximising the available power [7], [9]. Similarly, the cruise speed's optimal performance and the lift coefficient of a UAV were considered while the objectives were to maximise the payload for a fixed total mass. The mass of the wing was minimised with the use of composite materials [10]. In an independent study, MDO was deployed in balancing available energy and the aircraft's operational requirement. In the study, the objectives were to maximise the payload mass, minimise both night altitude and the total weight [11]. Aerodynamics, structure, stability, weight, and systems were integrated into the MDO tool. The objectives were weight minimisation and power maximisation [12]. In addition to the objectives mentioned above, other areas where MDO was deployed include drag minimisation and lift maximisation [13].

The constraint of energy and the balance between buoyancy and weight were also studied using MDO, with the primary goal to minimise the total mass of the aircraft [14]. Many objective techniques were compared with different optimisation strategies [11]. In furtherance to the strength of the MDO as a tool, variables like flight mission profile, the size of the energy components, and the energy component systems for a medium altitude long endurance UAV were analysed. The goals were to maximise the electric durability and minimise the hybrid electrical solution, the overall fuel consumption, and the take-off field length. Optimisation of energy storage, standoff tracking of the solar aircraft using the adjustable Lyapunov guidance vector field (ALGVF), and the interfered fluid dynamic system (IFDS) were used to maximise the solar energy storage and minimise the tracking error [15].

The unpredictable solar radiation and mode of application of solar aircraft made it imperative to develop a robust energy component and flight operation to accomplish a nonstop flight duration for 48 hours by analysing the power device [16]. Energy Control System (ECS) is required [17]. To get maximum energy from the PV cell, an MPPT is essential. The MPPT traces and maximise the current and the voltage of the PV cells and rechargeable batteries [18]. Optimal energy is extracted from the

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photovoltaic cells when the gain is varied [19]. The MPPT is incorporated into the ECS in aircraft powered by solar.

The electrical energy component is managed by energy control equipment, determining when the batteries will be charged or propel the aircraft. The thrust force overcomes the aerodynamic drag. The DC/DC converter mostly converts electric energy with different voltages to provide energy to the avionics, payloads, autopilot systems, and communication systems [20].

As mentioned earlier, the energy may lose some energy; even the electric line may lose energy because of inevitable internal energy resistance. Only 11% of solar energy was used by solar-powered aircraft. In contrast, nearly 89% of the remaining energy is lost. Compared with the solar panel's internal combustion engines-to-mass ratio, the resulting efficiency is significantly less than that of the gasoline engine. Thus, solar-powered aircraft are less competitive than traditional internal combustion-powered plane [21]. Figure 1.1 it is obvious that the solar cell and the propeller contribute most of the losses reported in energy. These underscore the issues the research findings are aimed at addressing. For clarification, the study focused on the design, optimisation, and development of power device sizing. The intent was to improve the efficiency of solar-powered aircraft.

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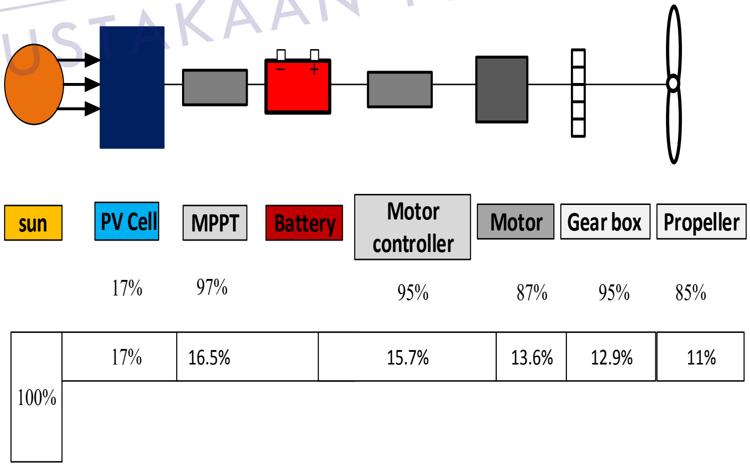

Figure 1.1: The efficiency of energy transformation devices of a solar-powered Aircraft. [22]

1.2 Research problem statement

The solar energy balance diagram provides the available solar energy collected in a particular country and region and its utilisations to conserved energy. Lack of a good solar energy balance diagram developed from Malaysia's solar radiation limits the achievement of solar-powered aircraft design and long or perpetual duration flight in Malaysia. The solar-powered aircraft efficiency is limited to the availability of solar radiation. The solar radiation distribution depends on the earth's position and the location or region of a particular country. Those countries located at the equator have high solar radiation compare to ones towards the poles. Also, the rate of solar radiation is a function of the latitude, time of the year, time of the day, altitude, cell temperature, and cell orientation. To effectively harness solar radiation, a particular country or region's solar radiation model is inevitable. The solar radiation model will give detailed daily, monthly, and yearly solar radiation for a specific area per square meter [23].

Previous designs power device sizing of solar aircraft has a deficit in offering a unique methodology that could stand the test of optimal power delivery to the solar-powered aircraft. Solar-powered aircraft has been developed and widely applied in practice. Some techniques need improvement and further research to achieve reliable, safe, and low-cost flights [24], [23]. Solar-powered aircrafts today are faced with the problem of energy supply from photovoltaic solar cells to power the propulsion and avionics system. It is the key to ensuring the aircraft stay aloft for a long time and sustain a very high altitude 24 hours [25]. The power supply system is the most important component to be improved because it affects the working period and mission path or solar-powered aircraft profile [26], [27]. It limits the use of solar aircraft and makes it less competitive when compared to fossil fuel aircraft. It calls for an improvement in the methodology for power device sizing.

The energy density of energy storage is too low to sustain a high altitude and long endurance flight. In contrast, conventional aircraft that uses fossil fuel have a far higher energy density that can support long flight hours [28], [4]. It necessitated carrying out the conceptual design of power device sizing for solar-powered aircraft.

To address the problems of lack of adequate power device sizing, it becomes pertinent to use the MDO tool to improve the conceptual design and power device sizing of solar-powered aircraft [15].

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1.3 Research objective

The research aim is to improve the power device sizing and conceptual design of solar-powered aircraft by improving the flight duration and reducing the mass for a sustainable flight operation using Malaysia as a case study, through the use of multidisciplinary design optimisation (MDO) tool, with the following objectives:

i. To analyse Malaysia’s solar radiation model obtained from the photovoltaic geography information system (PVGIS) interactive tool software package (R.SUN IET, 2015) and develop an energy balance and mission path diagram for Malaysia.
ii. To analyse various airfoils using XFLR5 v6 software and select the most suitable among them. Using the suitable airfoil to design the wings, the empennage, design the fuselage, and assembled the parts.
iii. To develop a power device sizing of solar-powered aircraft to ascertain the quantity of PV cell and rechargeable battery required to power the aircraft.
iv. To optimise the conceptual design and power device sizing of solar-powered aircraft using a ModeFRONTIER package, a multidisciplinary design, and optimisation (MDO) tool software.

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1.4 Scope of the Research

The scopes of the research are itemised as follow;

i. Malaysia’s solar radiation model and energy balance were developed using a software package (R.SUN IET, 2015). The package provides Photovoltaic Geography Information System (PVGIS) online interactive maps of potentials in Europe, Asia, and Africa. The software has high efficiency and reliability of the data certified by the European Union.
ii. The study focuses on analysing different solar-powered aircraft designs to develop a methodology of power device sizing and the conceptual design of solar-powered aircraft. The XFLR5 v6 software was used for airfoil analysis and conceptual design of the solar-powered aircraft. The software is suitable for aerodynamic analysis of small aircraft designs similar to the present studies.

iii. MS Excel code was used for the calculation of developed power device sizing.
iv. Both the power device sizing and the solar-powered aircraft's conceptual design were optimised using the ModeFrontier (a commercial package and a registered ESTECO SpA). The software is used integration and automation of CAE process, optimization and robust in the field of aerospace and other fields of engineering.

1.5 Significance of the research

The significance of the research are as follows;

i. Solar-powered aircraft exhibit vast potential for high altitude and long-endurance (HALE) flights because of the unlimited supply of solar power in Malaysia. The energy balance diagram and the mission path provide optimum utilisation of solar energy for solar-powered aircraft.
ii. Solar-powered aircraft can be designed to fly near space and below the spacecraft region (approximately 20–100 km). It can fly near-space continuously for months or even years, depending on the reliability of the power device sizing, aircraft system, and sunlight conditions [29]. The conceptual design herein presented could be considered for the preliminary and detailed design of solar-powered aircraft suitable for the Malaysia energy balance diagram and mission path.
iii. The advantage of high altitude makes it possible for the expected applications; Intelligent Reconnaissance and Survey (ISR) and transmit communication (hazard warning, rescue, and assessment), agricultural surveillance and decision support systems, and planetary atmospheric exploration [30]

1.6 Research structure outline

The research outline consists of five chapters that covered the entire thesis. The outline summarised the contents of each of the main chapters that addressed the research findings. The research outline is presented below;

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i. **Chapter 1: Introduction**: This chapter states the background of the study related to the research content. The problem statement that the research sought to solve is specified in a concise and detailed fashion. The research aims and objectives are enumerated. The scope of research is mentioned as a boundary of the research. Also, the significance of the research is specified to bolster the importance of the research.

ii. **Chapter 2: Literature Review:** The chapter review previous studies related to the content of the research. This research is determining to improve the design for the prospect of the aviation industry. The development of solar-powered aircraft, the basic concept of solar-powered aircraft, the aerodynamics of a wing, solar radiation, the powered device of a solar-powered aircraft, and the multidisciplinary optimisation process are all reviewed and discussed in this chapter.

iii. **Chapter 3: Research methodology:** The research methodology is divided into design strategy and optimisation strategy. Design strategy presents the design concept methodology that leads to the design of power device sizing for solar-powered aircraft. The design concept methodology provides a procedure for the design methodology of power device sizing for solar-powered aircraft and the methods, designs, models, and software employed to solve the research objectives. The optimisation strategy is the second part of the research methodology, the multidisciplinary design optimisation framework. It provides a guide on the conduct of the optimisation process using the MDO tool. A multidisciplinary design framework is employed using ModeFrontier (ESTECO, 2018) commercial optimisation package to optimise the power device sizing and conceptual design of solar-powered aircraft by improving the flight duration and reducing the weight of the solar-powered aircraft.

iv. **Chapter 4: Results and Discussion:** The results are being presented, and also, the discussions of the results are analysed in this chapter. The solar radiation model employed the R.SUN (IET, 2015) software PVGIS to obtain a solar radiation model of Malaysia. The model was used to develop an energy balance diagram and mission path. Various airfoils are analysed, and the results were

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presented. The optimal was chosen to design the wing and empennage of the aircraft and the fuselage designs. Subsequently, all the parts are assembled with the aid of XFLR5 v6. The multidisciplinary optimisation framework is employed using the MDO tool, a ModeFrontier software. The optimisation approach is conducted with three objectives; to minimise the total electrical energy required by the aircraft, to minimise the total mass of the aircraft, and to maximise the solar energy available from the solar radiation that can be utilised. The output of the optimisation is presented in the graphs and tables. The optimal configurations are used to design improved solar-powered aircraft named CLOUD I.

i. **Chapter 5: Conclusion and Recommendation:** This chapter summarises the significant findings in the research study. The research main contributions are presented. The recommendation for further works and improvement that needs to be carried out to enhance solar-powered aircraft development to sustain long endurance and high altitude flight are enumerated.

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CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The design of solar-powered aircraft recently has achieved a lot of attention, in a view to replacing fossil fuel with solar energy powered aircraft, due to global warming and providing affordable, reliable, and safe means of transportation in the world. This research is determining to improve the design for the prospect of the aviation industry. The development of solar-powered aircraft, the basic concept of solar-powered aircraft, the aerodynamics of a wing, solar radiation, the powered device of a solar-powered aircraft, and multidisciplinary optimisation are reviewed in the chapter.

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2.2 The trend of solar-powered aircraft

The trend of solar-powered aircraft designs shows solar aircraft technology from the 1970s to dates in chronological order.

2.2.1 Sunrise project

The first solar-powered aircraft in the world was Sunrise I. The aircraft had its first test flight on the 4th of November, 1974, which proves that solar aircraft could fly. The aircraft's wingspan is 9.8m, a length of 4.4m, a wing area of 8.4m^2, and a gross weight of 12.3kg. And it was powered by silicon monocrystalline photovoltaic with 4098 cells, 11% efficiency. In 1975, the Sunrise I was damaged in a wind storm during a test flight. Figure. 2.1 shows the maiden flight of the Sunrise I [31], [32]. Sunrise II was designed and constructed, upgraded design with similar specifications but was 13% lighter to 10.3kg, and had 33% more power than the Sunrise I. Initially, it was designed for 15.2 km, but it could only attain 5.2 km, due to breaking down in the command and control system. The entire project was terminated, and later the solar panel of the Sunrise II was used on Gossamer Penguin, a manned solar-powered aircraft.

Figure 2.1: Sunrise I solar-powered aircraft [31]

The Sunrise I is limited to adequate power device sizing resulted in a lack of sufficient power from the PV cells during the day. No extra energy can be stored in the rechargeable battery to power the aircraft at night.

2.2.2 Environment research aircraft and sensor technology (ERAST) project

United States Government-sponsored research and funded by NASA, initiated by AeroVironment Incorporated. The company was saddle with designing and constructing solar-powered aircraft, the Gossamer Penguin and the Solar Challenger, in the late 1970s and the early 1980s. The Gossamer Penguin, designed by Paul MacCready, Jr., flew on the 18th of May, 1980, and was considered the first manned, solar-powered flight in the world. The Solar Challenger (the Gossamer Penguin's successor) flew from Pontoise-Cormeilles near Paris to the Manston Royal Air Force Base near London on the 7th of July, 1981. The flight lasted for 5 hrs and 23 min and covered a distance of 262.3 km.

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The Pathfinder was the first ERAST project under Dryden's Flight Research Centre (DFRC) supervision adopted in 1993. The prototype design of a high-altitude long-endurance solar-powered aircraft was produced, with a wingspan of 30.0 m. The Pathfinder created a flight altitude record of 15.4 km at DFRC on the 11th of September, 1995. Some modifications were made on the Pathfinder in the spring of 1997 and lifted the world record of flight solar-powered altitude of 21.5 km when it was moved to the Pacific Missile Range Facility (PMRF) the US Navy on the Hawaiian island of Kauai.

The second generation of the ERAST project is the pathfinder plus. The pathfinder plus wingspan was extended to 36.9 m by using four sections of the Pathfinder wing. The Pathfinder Plus attained a new flight altitude record of 24.4 km in 1998 (PMRF) [20].

The Centurion with a wingspan of 63.1 m was designed to reach a flight altitude of 30.5 km. It is the third-generation flight project of the ERAST, and it flew three test flights with the aid of battery power at low altitude at (DFRC) in 1998.

The fourth generation of the ERAST project is the improvement of the Centurion design called the Helios. The aircraft was designed specifically to attain a flight duration 0f 20 hours and a flight altitude of 30.5 km. The Helios (HP01), with a wingspan of 75.3 m, reached a world record flight altitude of 29.5 km for the horizontal winged aircraft on the 13th of August, 2001 PMRF. At the PMRF on the 26th of June, 2003, the long-endurance prototype Helios HP03 attempted a demonstration flight that was not successful because of a strong storm that causes turbulence and structural failure [33]. Figure 2.2 shows the evolution of solar aircraft in the ERAST project.

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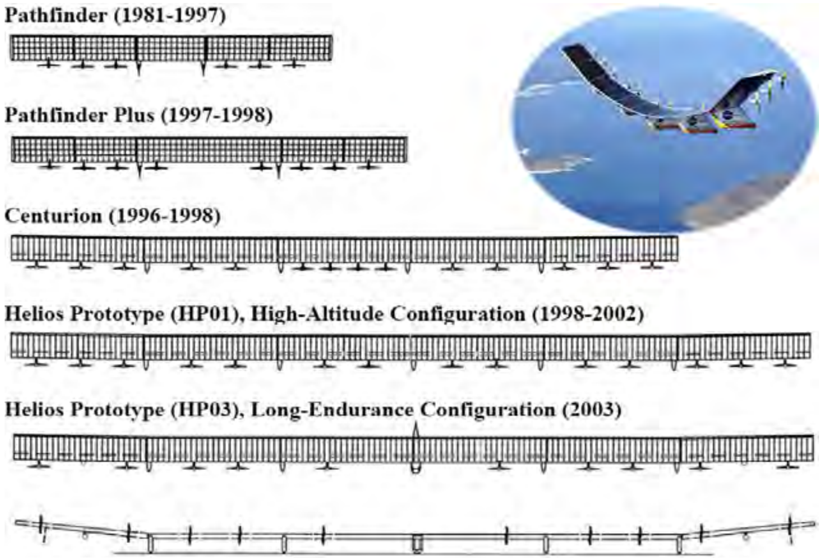

Figure 2.2: Evolution of solar aircraft in the ERAST project [33]

All the ERAST projects have limited flight duration and altitude, and these are caused due to the low energy density of the rechargeable battery used and improper power device sizing

2.2.3 Zephyr project

The Zephyr project had a transition from Zephyr 1,2,3,4,5-1,5-2,6, and 7.
The Zephyr1 was a film balloon designed to reach a world record of high altitude.
In 2001, the Zephyr1 project was changed to the Zephyr2, designed with less than 7 kg weight and test flight in both free and tethered modes (of the Clifton suspension bridge in Bristol, United Kingdom).

In 2002, the Zephyr 3 was designed and constructed with 15 kg weight and 12 m long. Zephyr3 was set to attain an altitude of the world record of 40.2 km attached to a manned balloon. But unfortunately, the balloon had a technical fault, render the Zephyr3 and balloon not to fly.

The Zephyr4 was developed with a wingspan of 12 m and a weight of 17 kg. Zephyr4 conducted a test flight in Woomera, South Australia, in 2005. It reached an altitude of 9.1 km within the flight duration of an hour.

In December 2005, Zephyr5 was developed with the primary aim to display a manual launch instead of a helium balloon. Zephyr5 was divided into Zephyr5-1and Zephyr5-2 with the aid of energy systems. Zephyr5-1 was designed with a solar cell,

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battery, and a total weight of 31 kg, while the Zephyr 5-2 was designed with a non-rechargeable battery and a total weight of 25 kg. Zephyr5-1 flew for 4 hrs, and the Zephyr5-2 flew for 6 hrs in New Mexico, US. In July 2006, the two aircraft flew again in the US. The Zephyr5-1 flew for 18 hrs (including 7 hrs into the night) and reached an altitude of 11.0 km.

The Zephyr 6 has a wingspan of 18 m and a total weight of 30 kg made of ultra-light carbon fibre. Zephyr 6 flew for 54 hrs in New Mexico around July of 2007, attaining the maximum altitude of 17.7 km. It also flew for 82 hrs in Yuma, Arizona, in August 2008 to reach a maximum altitude18.3 km. This flight time was triple the official world record for the longest unmanned flight, 30h (set by the Global Hawkin 2001).

The Zephyr 7 set a new record for flight time length by flying for 14 days (336 hrs) and 21min [34]. In 2013, the Zephyr program was acquired by Airbus's high-altitude pseudo-satellite (HAPS) program, which Airbus initiated in 2008. Meanwhile, all the key Zephyr staff was integrated into the HAPS organisation. On the 23rd of April 2014, Airbus announced that it had launched the Zephyr 8 program to develop the next generation Zephyr unmanned aerial system (UAS) [34]. Figure 2.3 shows the evolution of solar aircraft in the Zephyr project.

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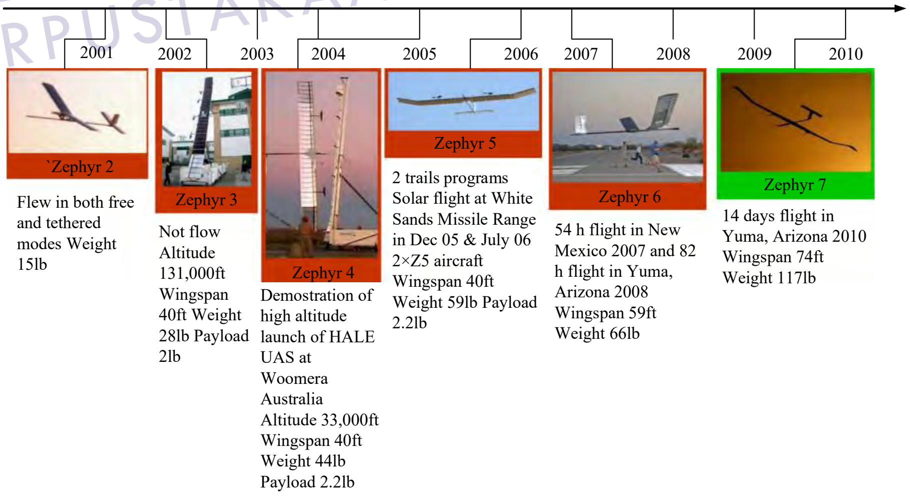

Figure 2.3: The evolution of solar aircraft in the Zephyr project [34]

Although Zephyr 7 design is the most successful in the Zephyr family, this is solely attributed to using a Lithium-sulfur battery, with higher energy density than others. But the aircraft has more weights because of the number of batteries used in the aircraft design. The proper sizing of the power device can reduce the weight of the aircraft.

2.2.4 Solar impulse I

Bertrand Piccard joined Swiss Ecole Polytechnique Federale First State metropolis (EPFL), aiming to circle the world in an exceedingly solar-powered aircraft. This corporation created solar Impulse in 2004. The example aircraft of the solar Impulse, the HB-SIA, was factory-made from 2007 to 2008. The HB-SIA had a distance of 63.4 m and weighed below 1600 kg. Four 10-hp motors high-powered the HB-SIA by the energy collected from 11,628 solar panels. Surplus alternative energy collected throughout the daytime was kept in 400 kg rechargeable batteries. In June 2012, the HB-SIA flew from Suisse (Europe) to Morocco (Africa), which was the primary aim of solar-powered worldwide flights. In the summer of 2013, Piccard and Andre Borschberg completed the "Across America" project by cruising across San Francisco to York. The star Impulse project's final word objective is to fly worldwide, and this endeavour occurred in 2015 [20], [35]. Figure 2.4 shows the two prestigious, best flights of the HB-SIA.

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Figure 2.4: The two notable demonstration flights of the HB-SIA of the Solar Impulse project [20].

2.2.5 SoLong

AC Propulsion funded the Solong project to manufacture long-endurance multiple days and night's solar-powered aircraft. Construction was done by Alan Cocconi, the founder, chairman, and chief engineer of AC Propulsion. The aircraft was developed with a wingspan of 4.75 m and an area of 1.5 m^2, a rechargeable battery that weighs 5.6 kg [Sanyo 18650 lithium-ion (Li-ion) batteries 220 Wh/kg], 76 Sun Power A300 solar cells, and a total mass of 12.6 kg. The aircraft was remotely controlled by six old pilots that centred on using updrafts and avoiding downdrafts. It set a record of 48 h of flight. The aircraft was still capable of flying on the third, fourth, and fifth nights. However, the flight was terminated as a result of the pilots were exhausted [20]. Figure 2.5 shows the SoLong and Alan Cocconi take a look at flight.

Figure 2.5: Alan Cocconi and the SoLong [20]

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The major drawbacks of the SoLong project are the manual control and the use of a Lithium-ion battery which has a low energy density. These contribute to the problems of SoLong. Project.

2.2.6 Helios platform (Heliplat)

Heliplat may be an important project in Europe for a UAV designed to fly at layer altitude 17 km to 25 km to navigate the sea space. This plane had eight brushless motors at the twin-boom tail and 2 rudders [24]. The Heliplat project was initiated as an effect of the HELINET project, a network of stratospheric platforms for traffic observation, environmental police work, and broadband services co-ordinated by the Politecnico di Turin. From January 2000, the EU Commission supported the project at intervals the Fifth Framework Program and conducted it at the metropolis technical school University. The reason for this project was to introduce a high-altitude very-long endurance UAV with a solar-powered and fuel-cell energy system that will stay aloft for a long period (approximately 9 months). Solely a tiny part of the analysis was completed due to the fund’s restricted backing, and a scale-sized solar-powered paradigm was factory-made [24], [36]. Figure 2.6 shows an artist’s conception of Heliplat flying higher than the sea.

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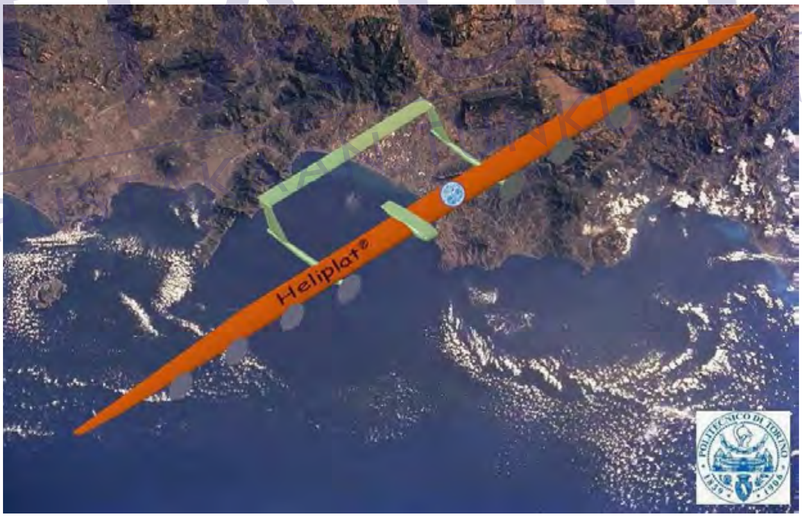

Figure 2.6: An artist’s conception of the Heliplat flying above a Sea [35]

The Heliplat project was terminated halfway into the project because of a lack of funds, which posed a serious setback. The performance is limited because of inadequate power device sizing and lack of compatibility of the fuel cells and the PV cells.

2.2.7 Sky-Sailor project

The sky-sailor project was fully funded by Space Technology Advancements, Resourceful, Targeted, and Innovative Groups of Experts and Researchers of the European Space Agency (ESA). The project was initiated at the end of 2003 in the Autonomous Systems Lab of the EPFL, with the objectives to design and construct; lightweight and long-endurance aircraft and conduct a test flight of Mar’s atmospheric. The aircraft was designed and built-in 2005, with a wingspan of 3.2 m, a total weight of 2.444 kg, and a rechargeable battery of Li-ion of 1.056 kg. The Sky-sailor design was similar to a motorised glider, and its basic layout was similar to the Avance glider, with two world records for distance and duration. In June 2008, a test flight occurred at Niederwil, Switzerland, with a long endurance flight record of 27 hrs was set [37], [38]. Figure 2.7 shows the demonstration flight of the Sky-sailor.

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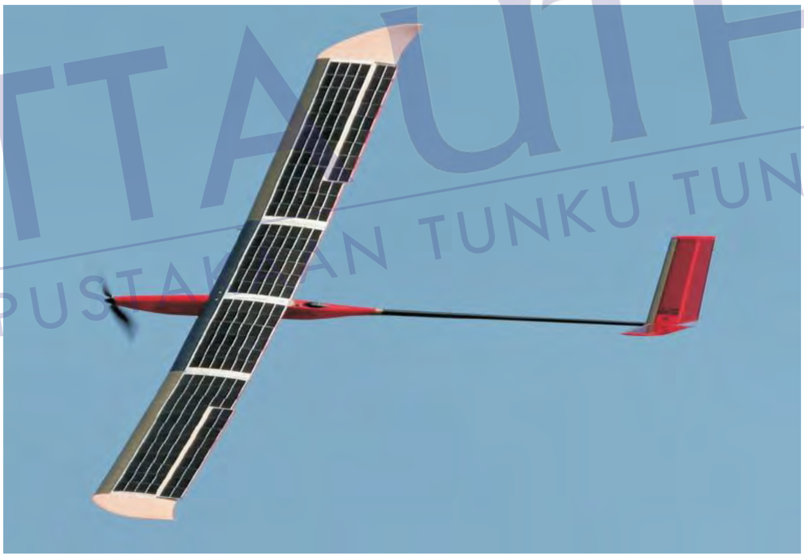

Figure 2.7: The test flight of the sky-sailor [37]

The Sky-sailor design lacks adequate proper power device sizing that could provide more solar energy. The rechargeable battery used has a low energy density that can store more energy during the day and use at night when solar energy was not available.

2.2.8 Vulture project

In 2007 the United States initiated the vulture project, a cheaper and less expensive substitute to the conventional satellite. The alternative should adequately serve the Intelligence, Surveillance, and Reconnaissance (ISR) function or communication platforms to apply the Defence Advanced Research Project Agency (DARPA). The Vulture is a solar-powered aircraft with high altitude long endurance that can navigate aloft for five years, a total weight of 450 kg, and that can carry a payload of 5 kW.

In 2009, the Vulture II project was initiated to design and construct an unmanned aerial vehicle with high altitude long endurance to navigate for three months. Three companies bid for the project. Figure 2.8 shows three company design; QinetiQ collaborated with Boeing Integrated Defense Systems and presented the Solar-Eagle, a scaled-up version of the Zephyr.

Lockheed Martin Inc. presented a unique configuration with ten electric propulsion units and three tilting tailplanes. Aurora Flight Sciences Inc. brought in the Odysseus, which had a Z-wing configuration. The Solar-Eagle of QinetiQ won the bid and performed its maiden flight in 2014 [39].

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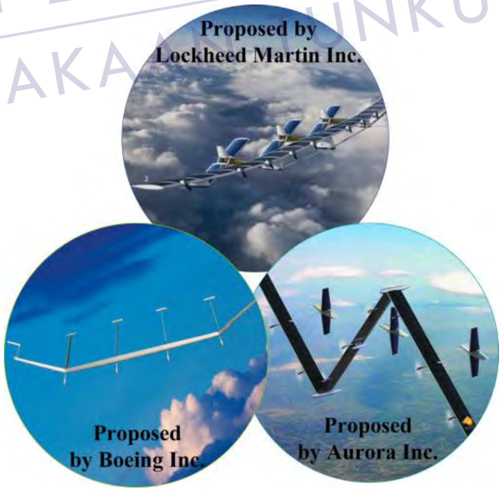

Figure 2.8: The three candidates of the vulture II project [39]

Solar aircraft, in a quest to provide more energy to power the aircraft for high altitude and long endurance, more PV cells need to be added. As such, a long wingspan and weight are added, which can cause structural instability. Careful design and aerodynamic analysis can provide stability [40], [41].

The most significant problem of the vulture's project is the wingspan's structural defect because of the long wingspan to accommodate sufficient solar cells to provide much-needed energy to power the aircraft. Proper power device sizing would have solved the problem of structural defects.

2.2.9 Other notable solar-powered aircraft

Aside from all the projects above, other notable solar-powered aircraft have been produced. The Solair I and sunseeker are shown in Figure 2.9.

The Solair I, produced by Günter Rochelt, flew for 5 hrs and 41 min on the 21st of August, 1983. [42]. The Sunseeker, developed by Eric Raymond, crossed the US in August 1990 and made 21 solar-powered flights within 121 hrs. [43].

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Figure 2.9: Solair I and Sunseeker [43]

The Icare 2, designed by Rudolf Voit-Nitschmann of Stuttgart University [44], is shown in Figure 2.10. The Solitaire was created by the Institute of Flight Systems of the German Aerospace Center, a proof-of-concept air for year-round operations in northern Europe. Figure 2.10 shows Solitaire.

Figure 2.10: Icare 2 and Solitaire [44]

The Sun Sailor was designed and constructed in the Technion – Israel Institute of Technology in Haifa, intending to set a new World Air Sports Federation world-distance record for solar-powered UAVs. However, the Sun Sailor crashed before setting a record in 2006 [45], [26].

All the notable designs mention here have similar problems of proper power device sizing, and the rechargeable batteries used in the designs have limited energy densities.

2.2.10 Solar Impulse II

Bertrand Piccard and Andre Borschberg designed and constructed solar impulse II after the success of solar impulse I. The aircraft flew worldwide from the 24th of July, 2016, covering approximately 40,000km in 17 months. The solar impulse is designed for long-duration flights with a cruising speed of 70 km per hour. The aircraft's total mass was 2,300 kg, installed with 17,248 solar cells and 633 kg of rechargeable batteries of 65.5 kWh of energy. The flights were delayed to fix the damaged batteries. The flight takes off in May after the flying season; the trip was concluded in 17 legs, starting and ending in Abu Dhabi, United Arab Emirates, but with no set flying schedule. The ultra-lightweight aircraft fly's in conducive weather and changes the route when necessary [46]—the image of solar impulse II is shown in Figure 2.11.

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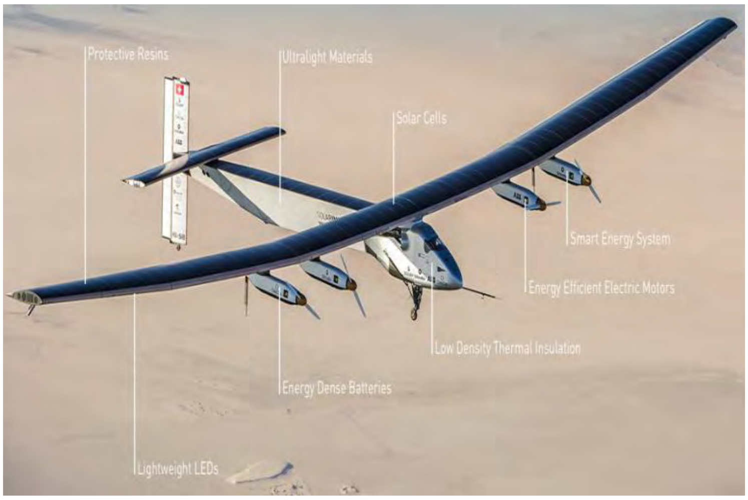

Figure 2.11: Solar impulse 2 [47]

The solar impulse projects both I and II have structural stability problems due to long wingspan to accommodate more solar cells. Also, the rechargeable batteries used have low energy densities. Lack of proper power device sizing is obvious.

2.2.11 EAV-3

The Korea Aerospace Research Institute (KARI), on the 12th of August, 2020, successfully conducted a test flight of 90 minutes in the stratosphere (18.5-22 Km) of its latest Unmanned Aerial Vehicle solar-powered aircraft, EAV-3. The UAV is 9 m long with a wingspan of 20 m, and it used the LG Chem prototype Li-Sulfur rechargeable to store the excess energy during the day and powered the aircraft during the night period. The aircraft launch’s success was attributed to the rechargeable battery produced by LG Chem [48].

Figure 2.12: EAV-3 solar-powered aircraft [48]

2.3 The basic concept of solar-powered aircraft

The basic concept and technologies that are responsible for solar aircraft to fly are explained. The concept is similar to conventional aircraft. During a level flight, the propeller produces a thrust force greater than the drag force, making the aircraft move forward. As the speed increases, the aircraft produces a lift force if the force created is

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higher than the total weight or gravitation force the aircraft takes off [49]. Figure 2.12 below shows forces acting on aircraft on a level flight.

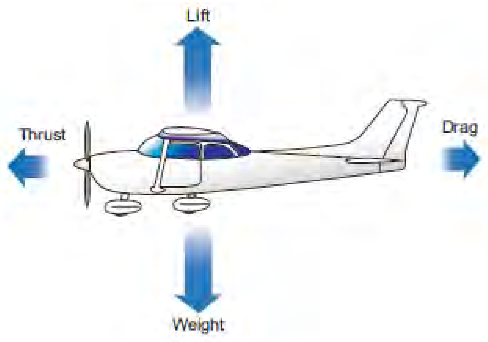

Figure 2.13: Forces acting on an aircraft on level flight [49]

Solar aircraft have a photovoltaic cell mounted on the wing, tail, or body. The PV cell converts solar radiation to electrical energy during the daytime. The MPPT ensures the PV cell gets the maximum power from solar radiation. The rechargeable battery is installed in the fuselage. It is used to store additional energy from the PV cell throughout the daytime and provide energy to systems at nighttime. Figure 2.14 shows the essential construct of solar aircraft.

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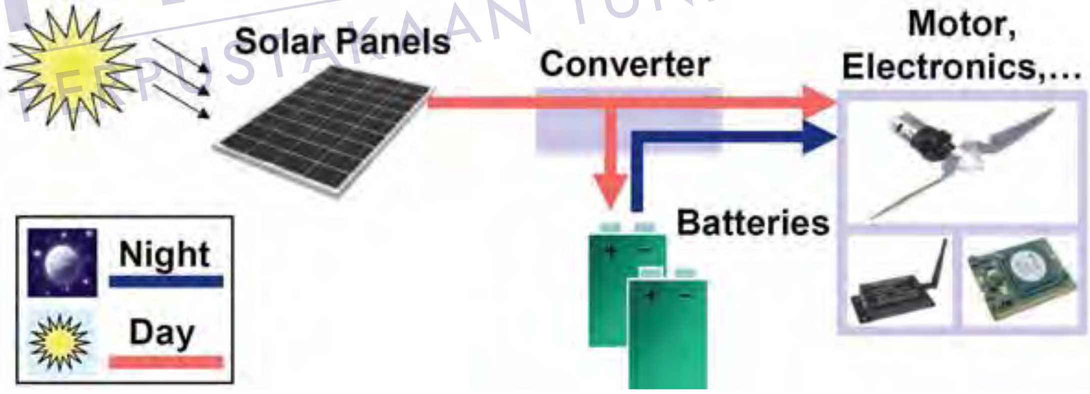

Figure 2.14: Solar-powered aircraft basic concept. [38]

2.4 Aerodynamic Analysis of a Wing and Empennage Profile

As the airflow across the wing section a laminar flow at constant speed υ, pressure distribution on the upper and lower part are created. The pressure translates into lift force and drag force [50]. Figure 2.15 depicts the cross-section of a wing.

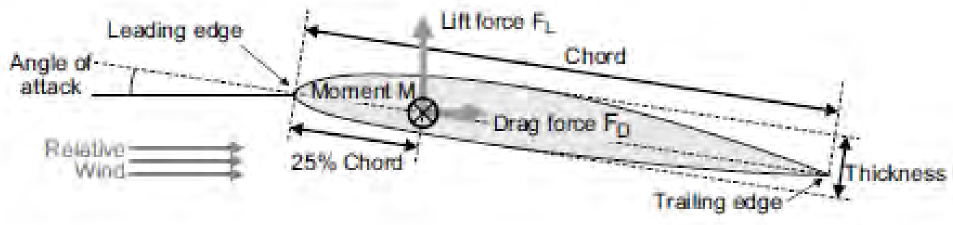

Figure 2.15: Section of an airfoil [50]

The lift and drag forces can be calculated using Equations 2.1 and 2.2 [51];

$$F_L = C_L \frac{\rho}{2} S \upsilon^2 \tag{2.1}$$

$$F_D = C_D \frac{\rho}{2} S \upsilon^2 \tag{2.2}$$

Where F_L and F_D are the lift and drag forces, C_L and C_D - lift and drag coefficients, ρ is the air density, S is wing area, and υ is the aircraft's relative speed; this is comparable to the ground speed when the wind is assumed negligible. C_L and C_D - are determined by the airfoil, the angle of attack α, and the *Reynolds* number Re, which is the function of airflow viscosity shown in Equation (2.3) [51].

$$Re = \frac{\rho \upsilon c}{\mu} = \frac{\nu c}{\upsilon} \tag{2.3}$$

Where μ is the dynamic viscosity, υ is the kinematic viscosity, and c is the chord.

Figure 2.16 depicts the phenomena as the angle of attack is increased, C_L increases, at point 1, a steady flow at the leading edge and the laminar flow at the trailing edge occurred. At point 2, the stall, the C_L is maximum at the leading edge and also C_D increases, and experienced separation point at the trailing edge. C_D increases progressively after the stall and C_L decreases sharply at point 3, separated flow at the leading edge, and turbulent flow at the trailing edge would be experienced [50].

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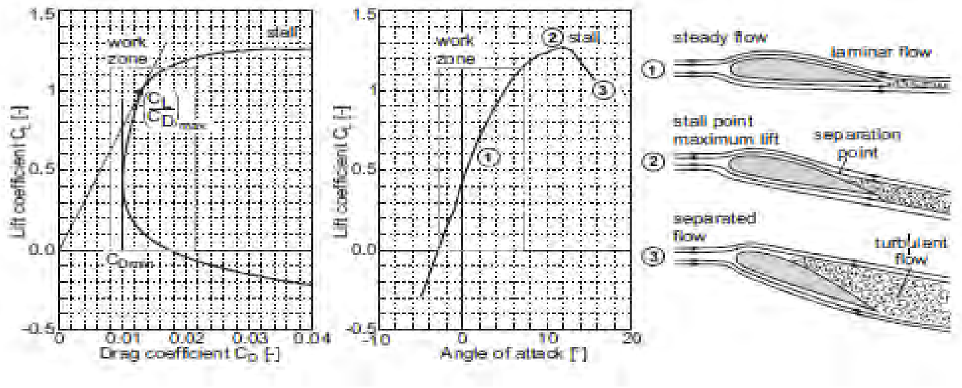

Figure 2.16: Lift and drag Coefficients on the angle of attack [50]

The above scenario is for an infinite wing situation. But in reality, vortices are produced in the wingtips, which attracts additional drag called the induced drag. The induced drag has to be considered mostly for small aspect ratios aircraft. And also, parasitic drag is experienced from non-lifting parts, like the tail and fuselage. The final drag is the sum of all the drags, i.e C_D as presented in Equation 2.5 [51].

$$C_{D\ ind} = \frac{{C_L}^2}{e\pi AR} \tag{2.4}$$

e is the Oswald efficiency factor, a variable with a number between 0 to 1. In reality, the values range from 0.75 to 0.85 and in an ideal situation is 1, as when the load distribution is elliptical.

AR is the aspect ratio, a relationship between the wingspan and the chord length i.e. AR = b/c = b^2/(bc) = b^2/S

$$C_D = C_{D\ afl} + C_{D\ ind} + C_{D\ par} \tag{2.5}$$

where $C_{D\ afl}$ is airfoil drag, $C_{D\ ind}$ is induced and $C_{D\ par}$ - parasitic drag.

2.4.1 Aerodynamic estimation method and Analysis Airfoils and Wings

XFLR5 is software used for aerodynamic analysis of airfoils, wings, and planes with low Reynolds numbers. The software is also used to design wings, elevators, fin, and

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